ANNEX XI

FIXED BED NUCLEAR REACTOR (FBNR)
Federal University of Rio Grande do Sul (Brazil)

XI-1. General information, technical features, and operating characteristics

XI-1.1. Introduction

The Fixed Bed Nuclear Reactor (FBNR) concept assumes the use PWR technology, but incorporates HTGR type fuel and the concept of a suspended fixed bed core. Spherical fuel elements are fixed in the suspended core by the flow of water coolant. Any accident signal will cut off the power to the coolant pump causing a stop in the flow. This would make the fuel elements fall out of the reactor core, driven by gravity, and enter a passively cooled fuel chamber where they would reside in a subcritical condition.

The Fixed Bed Nuclear Reactor (FBNR) is a simplified version of the fluidized bed nuclear reactor concept [XI-1 to XI-9]. In the FBNR, spherical fuel elements are at a fixed position in the core, therefore, there is no concern about the consequences of multiple collisions between them, an issue that may be raised about the fluidized bed concept. Relatively little work has been done for the fixed bed nuclear reactor so far, but the experiences gained from the development of a fluidized bed reactor can facilitate the development of the FBNR.

The FBNR concept is being developed in the Federal University of Rio Grande do Sul, (UFRGS - Brazil) in cooperation with several research groups in the institutes around the world such as the Imperial College of University of London (England), the Institute for Nuclear Science and Technology (Vietnam), and the Catholic University (Uruguay). More broad international cooperation for the development of FBNR is being sought for.

XI-1.2. Applications

The FBNR is designed to produce electricity alone or to operate as a cogeneration plant producing electricity and potable water or steam for industrial purposes. As an option, the FBNR may be designed for district heating.

XI-1.3. Special features

The FBNR is a land-based nuclear power plant for urban or remote localities. A lifetime core operation without on-site refuelling is envisaged.

XI-1.4. Summary of major design and operating characteristics

Some major design and operating characteristics of the FBNR are given in Table XI-1; the major design objectives are outlined in Table XI-2.

TABLE XI-1. MAJOR DESIGN CHARACTERISTICS OF FBNR

ATTRIBUTES	DESIGN PARTICULARS
Thermal power generated per module	15 MW
Electric power generated per module	5 MW
Targeted availability	95%
Core configuration	Suspended core, integrated primary circuit.
Fuel element	15 mm diameter spherical fuel elements made from TRISO type micro spherical fuel particles.

Fuel material	UO_2, (^{233}U-Th) O_2, or MOX
Fuel element cladding	SiC as an option
Moderator / Coolant	Pressurized light water
Coolant flow rate – kg/s	70
Module diameter	1.35 m
Module pressure	160 bar
Active core height	1 m
Specific power density in the core – MW(th)/m^3	16
Shutdown system	Pump turn-off initiated by reactor protection system
Slow reactivity control	Movement of a fuel limiter
Fast reactivity control	Fine-motion control rod

TABLE XI-2. DESIGN OBJECTIVES OF FBNR

OBJECTIVE	DESIGN APPROACH
High level of safety	Strong reliance on inherent and passive safety features and passive systems
Enhanced safeguard ability	Fuel elements are confined in the fuel chamber that could be sealed by authorities for inspection at the end of the fuel life. The reactor vessel is cladded by neutron-absorbing materials to eliminate the possibility of neutron irradiation of any external fertile material.
Enhanced proliferation resistance	Use of thorium based TRISO type fuel.
Reduced nuclear waste	The spent fuel elements have the size and shape adequate to serve as source of radiation for applications in industry and agriculture.
Reduced adverse environmental impacts	Underground containment in a garden like site.
Improved economy	Modular design to be produced in series. Design simplicity. Elimination of burnable poisons.
Technology transfer	The technology could be open to all nations of the world under the supervision and control of international authorities.
Long core lifetime	Insertion of fresh fuel into the core is performed continuously to compensate for fuel burn-up.
Enhanced security	Reactivity excursion accident cannot be provoked. The reactor core is filled with fuel only when all operational conditions are not met.
Mitigation of steam generator leakage problem	The water heated in the reactor core passes through an integrated steam generator producing steam to drive the turbine.
Resistance to unforeseen accident scenarios.	Any probable accident, through cutting off the power to the pump, causes the fuel elements fall out of the core driven by the force of gravity. The normal state of control system is “switch off”. The pump is “on” only when all operating conditions are simultaneously met.

The reactor 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. Else, the reactor makes an extensive use of PWR technology.

The FBNR is modular in design such that any size of reactor can be constructed from the basic modules. It is an integrated primary system design. The basic module has in its upper part the reactor core and a steam generator and in its lower part the fuel chamber, sees Fig. XI-1. The core consists of two concentric perforated Zircaloy tubes 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 fuel chamber is a 20-cm diameter tube made of high neutron absorbing alloy, which is directly connected underneath the core tube. A steam generator of the shell-and-tube type is integrated in the upper part of the module. A control rod slides 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. Each module has an independent pump. The pump circulates the coolant inside the module 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 module. In a shut down condition, the suspended core breaks down and the fuel elements leave the core and fall back into the fuel chamber.

Any signal from any detector due to any initiating event is assumed to cut-off power from the pump, causing the fuel elements to leave the core and fall back into the fuel chamber, where they remain in a highly subcritical and passively cooled condition. The fuel chamber is cooled by natural convection transferring heat to the pool of water or to the air surrounding the fuel chamber.

A detailed heat transfer analysis of the fuel elements has shown that, due to a high convective heat transfer coefficient and a large heat transfer surface-to-volume ratio, the maximum power extracted from the reactor core is restricted by the mass flow of the coolant corresponding to a selected pumping power ratio, rather than by design limits of the materials.

The proposed reactor concept is very flexible in its nature, which makes it possible to devise several alternative designs:

(1) *Fixed bed with supercritical steam as coolant.* The concept of a direct cycle reactor operating at supercritical pressure is attractive for radically improving the thermal efficiency. Such reactor could combine the fixed bed concept with the idea of using a direct cycle reactor operating at supercritical pressure, for example, as proposed in [XI-8]. Supercritical steam is used as the reactor coolant. The critical pressure of water is 221 bar. When the reactor operates at 250 bar, the supercritical water does not exhibit a change in phase and the phenomenon of boiling does not exist. The water density decreases continuously with temperature.

The coolant inlet temperature, in the lower part of the bed, may be 290ºC and the outlet temperature in the upper part of the bed is then ~416ºC. Therefore, the water density decreases continuously from 0.744 to 0.137 g/cm^3 along the bed. The recommended pressure of 250 bar is due to the smooth and mild variation of density with pressure in this region resulting in a stability of flow in the core. The power production is much higher in this option as the difference in inlet and outlet enthalpy is much higher than in a conventional pressured or even boiling water reactor. The plant thermal efficiency is estimated to exceed 40%. By adopting supercritical steam as the coolant, the turbines could be made smaller compared with those used in existing LWRs. The superheated steam is fed directly into the turbine. The steam-water separation is not needed for direct cycle reactor. Other advantages of a supercritical option include the absence of steam generators, and the reduced waste heat. However, a new design of spherical fuel elements will be required, since SiC is not corrosion resistant in water at supercritical parameters [XI-9].

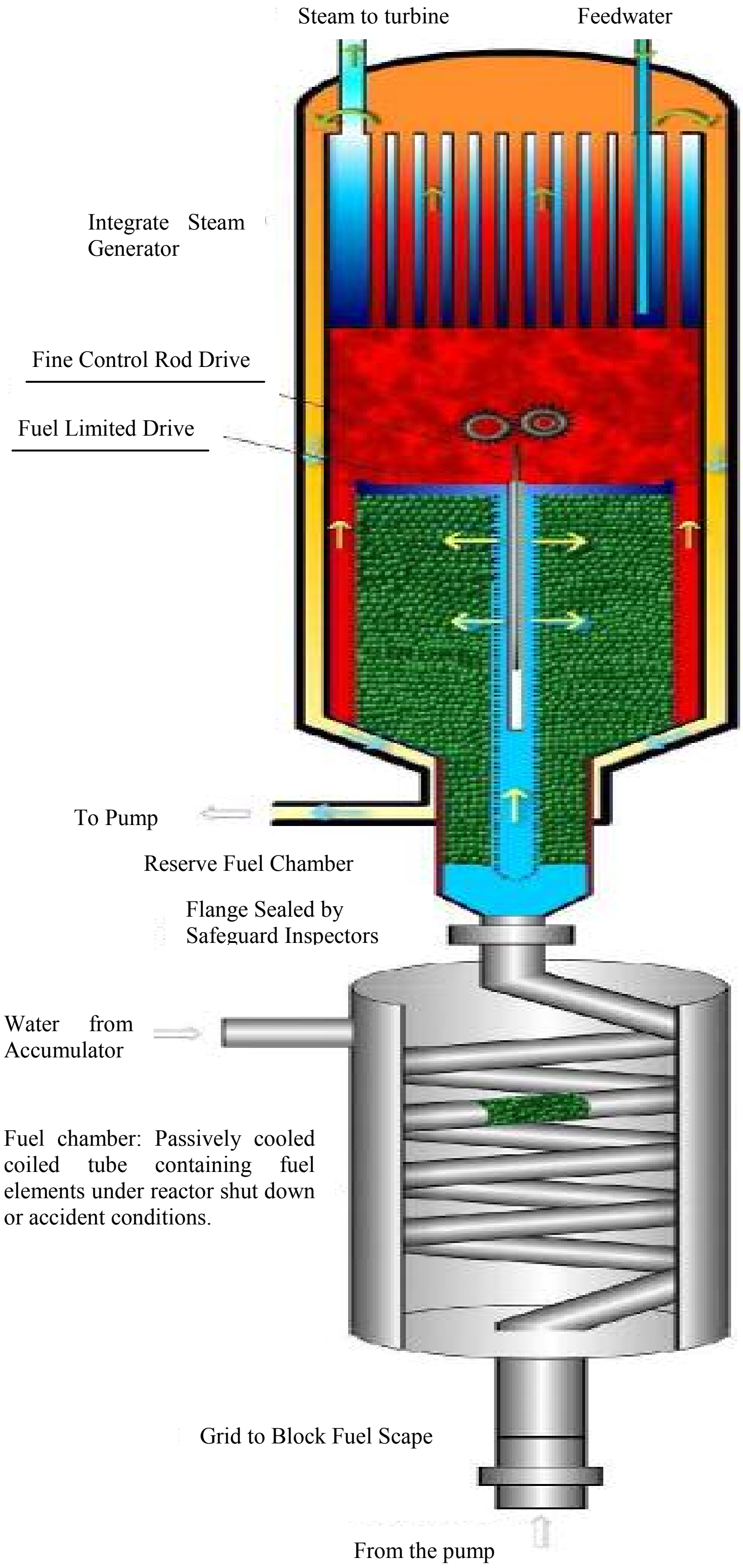

FIG. XI-1. Simplified schematic diagram of FBNR module.

(2) *Fixed bed with helium gas as coolant.* In this option, the fixed bed is cooled by helium, bringing in all advantages of a gas cooled reactor, including the use of a direct cycle gas turbine and the resulting high efficiency. In this case, the reactor has fast neutron spectrum.

Neutron-physical characteristics

The neutron-physical characteristics of the FBNR are not determined as yet. They are expected to be similar to those of the conventional pressurized water reactors.

Reactivity control mechanism

The FBNR does not use burnable poisons, and slow reactivity control to compensate for fuel burn-up is achieved by introducing fresh fuel to the core by raising the fuel limiter and allowing fresh fuel elements enter the module from the reserve fuel chamber, Fig. XI-1. Fast reactivity control is provided by a fine-motion control rod with internal drive mechanism. This rod moves in a guide tube located in the centre of the core. This guide tube also acts as an inlet collector for the core, Fig. XI-1.

Thermal-hydraulic characteristics

A PWR type reactor operating at 160 bar with the selected inlet/outlet temperatures will have about 33% efficiency with an indirect cycle.

The high surface-to-volume ratio of spherical fuel elements results in excellent heat transfer characteristics yielding a low maximum-to-average fuel temperature ratio. The core is cooled by forced convection, but the residual heat produced in the fuel chamber is removed by natural convection. No heat exchange crisis is anticipated.

The water coolant flows into the core at a rate of 70 kg/s with the inlet temperature of 290^{o}C and leaves the core at 326^{o}C being directed to the steam generator.

Fuel lifetime/ period between refuellings

The fuel lifetime is targeted to be more than 10 years, depending on considerations of plant economy and energy security requirements. It is easily achieved by adequate dimensioning of the reserve fuel chamber. Within the fuel lifetime, the reactor is assumed to operate with a weld-sealed vessel.

Design basis lifetime for reactor core, vessel and structures

The module, the fuel chamber and other parts are relatively small pieces and can simply be replaced as needed.

Design and operating characteristics of systems for non-electric applications

The FBNR can operate within a cogeneration plant producing both electricity and desalinated water. A Multi-Effect Distillation (MED) plant may be used for water desalination. An estimated 1000 m^3/day of potable water could be produced at 1 MW(e) reduction of the electric power.

Economics

The total electricity production cost from the FBNR is estimated at 2.1 cents/KWh, with reference to US$. In this, the capital cost is about 1.6, the fuel cost is 0.3, and O&M cost is 0.2 cents/KWh. Costs at this level may compete well with alternative energy sources. The construction cost is estimated as ~1000 US$/kW(e), the construction period is about 2 years.

XI-1.5. Outline of fuel cycle options

A standard fuel cycle of high temperature gas cooled reactors could be used as a basic option for the FBNR. A variety of alternative fuel cycle options could be used according to the demand. These include a plutonium burner mode using plutonium-thorium oxide fuel and a closed fuel cycle based on ^{233}U-Th.

XI-1.6. Technical features and technological approaches that are definitive for FBNR performance in particular areas

XI-1.6.1. Economics and maintainability

The simplicity of design, short construction period, and an option of incremental capacity increase through modular approach are expected to result in a much smaller capital investment for the FBNR as compared to conventional PWRs.

R&D and licensing for the FBNR could be essentially simplified, since it may be enough to develop, validate and license by test only a single module.

The elimination of on-site refuelling and long core lifetime could reduce the operation and maintenance costs of the reactor. The elimination of burnable poison contributes to the improved neutron economy and results in essentially lower fuel enrichment, contributing to reduced fuel enrichment costs. There are no fuel assemblies in the FBNR core, which would also contribute to a reduction in fuel fabrication costs.

The total investments required to design, construct, and commission the FBNR, including the investments during construction, are evaluated to be very low and easy to raise. A single module FBNR plant of 5 MW(e) plant could cost about US$ 5 million. Therefore, the risk of investments in the FBNR could be sufficiently low too.

XI-1.6.2. Provisions for sustainability, waste management, and minimum adverse environmental impacts

The elimination of burnable poison and high fuel burn-up contribute to a more efficient use of uranium resources. Various fuel options available for the FBNR broaden the available resource base, which could also include plutonium from dismantled nuclear weapons and the abundant thorium available in countries like Brazil and India.

The increased fuel burn-up and a fuel form that is capable of perfect confinement of fission products at high temperatures are factors that contribute to the minimization of waste.

The inherent safety feature - each fuel particle having its own containment – reduces the probability of a large release of radioactivity to the environment. Also, each reactor module contains a relatively small quantity of thermal energy, due to low operating temperature of fuel. The envisaged simple underground containment, an additional defence-in-depth feature, also contributes to reduced adverse environmental impacts.

Spent fuel from the FBNR can be treated or reprocessed in a way similar to that for HTGR fuel. Should reprocessing not be allowed, the FBNR spent fuel elements could easily be vitrified within the modules and the whole module could then be deposited directly in a waste repository.

XI-1.6.3. Safety and reliability

Safety concept and design philosophy

The safety philosophy behind the FBNR design is strong reliance on inherent and passive safety features. To the extent possible, laws of nature and physics should govern safety of the reactor.

Provisions for simplicity and robustness of the design

Modularity, strong reliance on passive safety design options, and low power density in the core are the factors contributing to simplicity and robustness of the FBNR design.

Active and passive systems and inherent safety features

A "fail-safe" passive control system is assumed to govern the reactor system. In this system, numerous signals from various redundant detectors of different origin enter the circuit. When all signals are within the pre-defined ranges of values, then the pump power will be in the "on" position. In any other situation, the coolant pump is in its normal "switched off" position, and thus the fuel elements leave the reactor core, driven by gravity, and become deposited in a passively cooled fuel chamber.

The use of HTGR type fuel capable of confining fission products at very high temperatures adds to this a large margin to fuel failure, which is an important inherent safety feature.

The active safety systems include a control rod, which is used only for fine control of reactivity during normal operation, and a slow-movement fuel limiter that allows fresh fuel elements from the reserve chamber enter the core to compensate for the bulk of reactivity change due to fuel burn-up. The design of fuel limiter drive could be made similar to that of contemporary control rod drives, i.e., preventing its inadvertent upper movement to the extent possible.

Structure of the defence-in-depth

In the FBNR, fission products are confined inside the fuel elements of a type designed to resist temperatures of about 1600°C. At the same time, these fuel elements are at temperatures less than 350°C under operational conditions of the FBNR. In other words, each fuel particle has a small containment - SiC coating layer that effectively prevents the release of radioactivity up to very high temperatures, and the margin to fuel failure is around 1250°C. The fuel elements are in the reactor core only when all reactor components operate within the design ranges of parameters. Otherwise, they leave the reactor core and reside in a passively cooled subcritical state. In addition to this, the reactor is located inside an underground containment building.

Design basis accidents and beyond design basis accidents

The safety system of the FBNR could take care of any conceivable design basis or beyond design basis accidents by relying on inherent safety features and passive systems only. Any abnormality in operation is expected to result in a passive shut down of the reactor. Should it for whatever reason fail, a large margin to fuel failure would simplify accident management.

Probability of unacceptable radioactivity release beyond the plant boundaries

The target is 10^{-7}.

Measures planned in response to severe accidents

The target is to eliminate off-site emergency planning.

XI-1.6.4. Proliferation resistance

Adopting a thorium fuel cycle as an intrinsic measure that could hinder the possibility of misuse of nuclear materials for nuclear weapons. Within such cycle, ^{233}U is produced with a noticeable admixture of a highly radioactive ^{232}U, which essentially complicates reprocessing and assembly operations for nuclear weapons. The mixing of thorium with low enriched uranium or plutonium results in the production of ^{233}U that is additionally diluted with ^{235}U or ^{238}Pu. The access to pure ^{233}U will only be possible through isotope separation techniques. The high ^{238}Pu to ^{239}Pu ratio and the production of gamma emitting ^{208}Tl in the thorium cycle are hindrances to nuclear proliferation. ^{238}Pu has a spontaneous fission that contributes to increased residual heat of spent fuel that will complicate the production of nuclear weapons.

An additional barrier is provided by SiC coating layers which need to be mechanically removed before conventional aqueous methods are applied for reprocessing of fuel kernels.

The fuel elements of the FBNR are confined in the fuel chamber, which could be sealed by the authorities and inspected at the end of fuel lifetime.

The FBNR has a very long lifetime (more than 10 years) and will not be refuelled on the site. The fuel is located in the sealed fuel chamber outside the pressure vessel; and the refuelling is performed just by taking the sealed fuel chamber to a factory, which could be performed by an authorized team under strict security measures.

XI-1.6.5. Technical features and technological approaches used to facilitate physical protection of FBNR

The fuel is contained in a sealed module inaccessible to outsiders for a long period of operation without on-site refuelling. It can only be manipulated at the factory. Only under design operating conditions the fuel remains in the core and the reactor becomes critical; under any other situations, the fuel leaves the core and is stored in a subcritical state.

XI-1.6.6. Non-technical factors and arrangements that could facilitate effective development and deployment of FBNR

With its design simplicity and strong reliance on inherent and passive safety features, the FBNR could be a good choice for many developing countries. A long-life core operation without on-site refuelling could provide certain guarantees of sovereignty for those countries that would prefer to lease a nuclear power plant or fuel rather than master an indigenous fuel cycle. The design and technology development for FBNR could benefit from cooperation of the researchers and designers in many developing and industrialized countries around the world.

XI-1.7. List of enabling technologies relevant to FBNR and status of their development:

The list of enabling technologies for the FBNR is given in Table XI-3.

TABLE XI-3. ENABLING TECHNOLOGIES AND THEIR DEVELOPMENT STATUS

DESIGN AREA	ENABLING TECHNOLOGY	DEVELOPMENT STATUS
Fabrication of fuel elements based on coated particles.	Technology for application of SiC coatings to spherical fuel elements of 15 mm diameter. Fabrication technology for coated particles.	Fabrication technology for coated particles is available in several countries. Technology for application of SiC coatings to spherical fuel elements of 15 mm diameter is being developed at UFRGS-Brazil. After the pilot fuel elements are fabricated, irradiation tests and post-irradiation examinations would be required. Since the irradiation could be performed for small batches of spherical fuel elements, it could be performed in various facilities already available around the world.
Long term reactivity control	Method of securing reserve reactivity by fresh fuel insertion without the use of burnable poison.	It is planned to use the existing control rod drive technology to design fuel limiter drive.
Pump control	The normal state of pump control system is “switched off”. The pump is “on” when all signals from all detectors governing the operating conditions are simultaneously within the design ranges of values.	R&D planned
Neutron-physical calculations	Equivalence models to relate cylindrical and spherical geometry.	Equivalence models need to be developed, and then standard codes developed for PWRs could be used.
Thermal-hydraulic calculations	Thermal-hydraulic modelling of a suspended core	Reliable codes for PWRs exist; their applicability to calculation of suspended cores needs to be examined.
Study of FBNR hydraulic performance.	A full size experimental hydraulic module made of transparent materials using stainless steel balls to simulate fuel elements needs is required to perform testing. The module is to be provided with instrumentations to measure the basic hydraulic parameters such as pressure drop as a function of	R&D and construction of test facility are planned.

	coolant flow velocity under different core configurations. Videotape is to be made of the operation in order to analyse the core behaviour under various simulated operational and accidental conditions.	
Passive cooling of fuel chamber	Passive cooling of fuel chamber by natural convection of water with heat transfer to air and water through the chamber wall.	Calculations are being performed.
Reliability of materials under long-life core operation	Relevant experience in validation, testing and demonstration of fuel and structural materials from other designs of small reactors without on-site refuelling around the world could be used to develop a R&D programme	Not started yet.

XI-1.8. Status of R&D and planned schedule

The current design stage is very preliminary, just a start-up of conceptual design. The programme of R&D for FBNR visualizes the following steps:

- Conceptual design development;
- Construction of a full size non-nuclear hydraulic module to verify the hydraulics performance and determine the basic parameters of a suspended core;
- Performance of neutron physical, thermal-hydraulic, fuel behaviour and structural calculations;
- Fabrication and testing of pilot batches of fuel;
- Engineering design of a prototype reactor;
- Performance of a zero power experiment with one module in a nuclear experimental facility;
- Construction of a single module prototype.

The institutions that so far have shown interest in participating in this project include Imperial College of the University of London, ITEP and IPPE in the Russian Federation and some individual scientists in Uruguay, Vietnam, Finland, Switzerland, and the USA. Increased international cooperation would be helpful for the promotion of the FBNR project.

Estimate of an overall time frame within which the design could be implemented under favourable financing conditions is ~10 years. It is estimated that about one million US$ dollars is needed to build a zero power prototype of the FBNR and demonstrate the concept feasibility

XI-1.9. Justification of why a demonstration prototype or a significant amount of demonstrations will be needed

The fixed bed suspended core reactor concept incorporates radical conceptual changes in design approaches and system configurations in comparison with existing practice and would, therefore, require substantial R&D, feasibility tests and a prototype or demonstration plant to be implemented before launching the FBNR into series.

XI-1.10. List of other similar or relevant SMRs for which the design activities are ongoing

There are similar activities ongoing in the All-Russian Nuclear Machinery Institute (VNIIAM) in Moscow (Russian Federation) and in the USA, in the Pacific Northwest National Laboratory (PNNL). These activities are related to the development of a pebble bed boiling water reactor concept with superheated steam [XI-9]. A nuclear reactor with micro fuel elements cooled and moderated by water is proposed. The reactor supplies energy to a 1500 MW(e) plant, and an option of a smaller 300 MW(e) plant has been considered.

XI-2. Design description and data for FBNR

XI-2.1. Description of the nuclear systems

Reactor core and fuel design

The FBNR fuel is a 15 mm diameter spherical fuel element made of compacted Micro-Fuel-Elements (MFEs) with the fuel density of 5.9 g/cm^3, cladded by silicon carbide. The matrix surrounding coated particles to form a fuel element is pyrolithic graphite.

The MFEs are coated particles similar to TRISO fuel with the outer diameters of about 2 mm. They consist of 1.5-1.64 mm diameter uranium dioxide spherical kernels coated with 3 ceramic layers. The inner layer, called a buffer layer, is made of 0.09 mm thick porous pyrolithic graphite (PyC) with the density of 1 g/cm^3, providing space for gaseous fission products. The second layer is made of 0.02 mm thick dense (1.8 g/cm^3) PyC, and the outer layer is 0.07-0.1 mm thick corrosion resistant silicon carbide (SiC). The fourth, outer PyC layer shown in Fig. XI-2 is assumed to be absent. SiC protection layers, manufactured by chemical vapour deposition (CVD) method, create resistance of graphite components against water and steam at high temperatures. Small fuel elements are able to confine fission products indefinitely at temperatures below 1600°C.

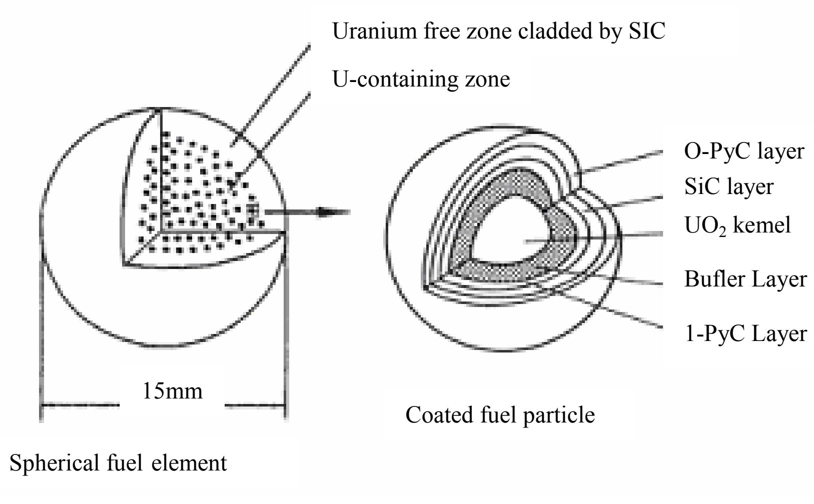

FIG. XI-2. Fuel element of FBNR.

Main heat transport system

A scheme of the FBNR main heat transport system with indication of heat removal path in normal operation and in accidents is given in Fig. XI-3.

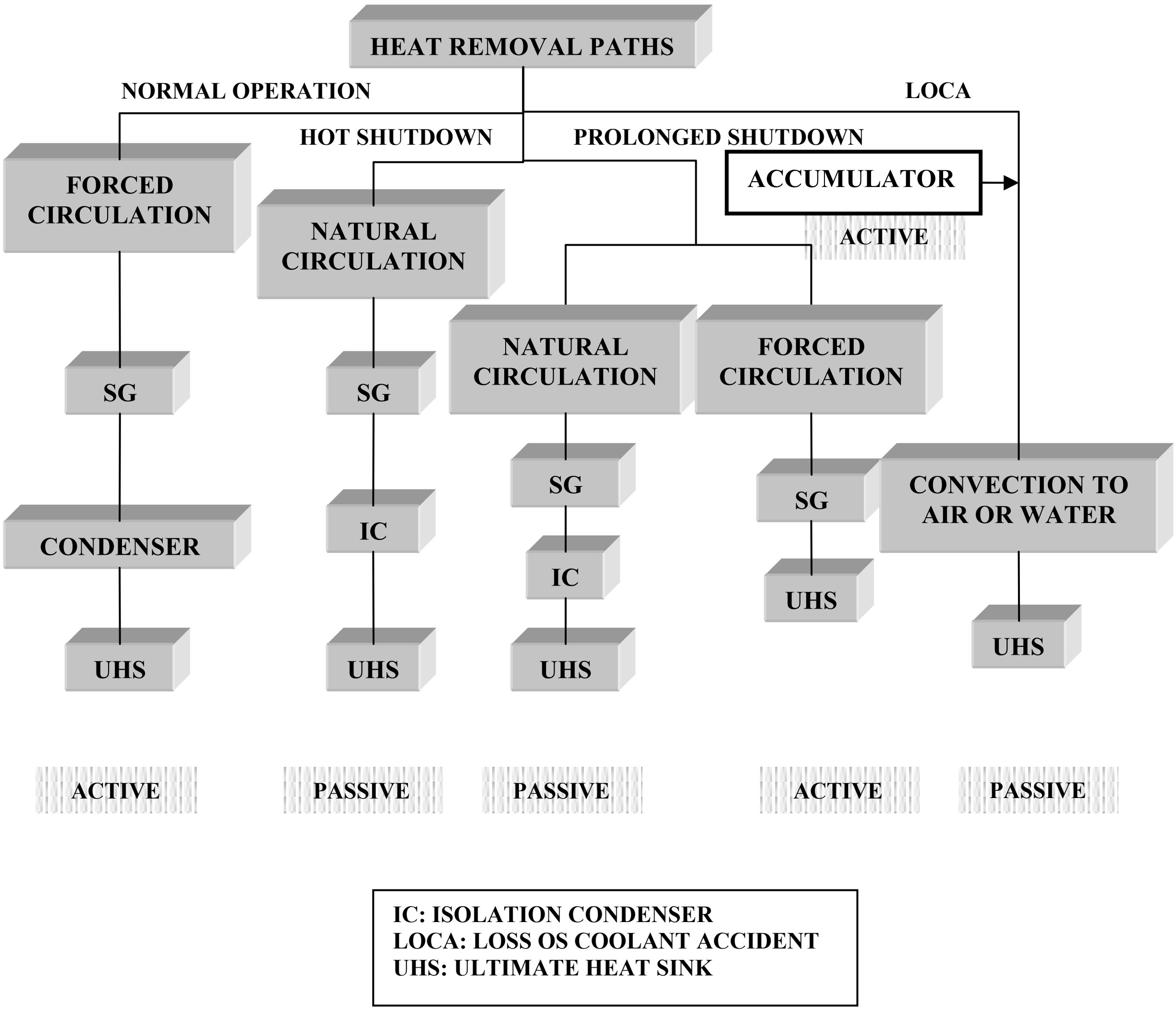

FIG. XI-3. Heat removal paths of FBNR.

XI-2.2. Description of the turbine generator plant and systems

A conventional turbine generator plant could be used.

XI-2.3. Systems for non-electric applications

No information was provided

XI-2.4. Plant layout

The plant is assumed to be located underground to avoid any negative visual impact. The nuclear power plant site is envisaged to incorporate garden like surroundings. The observed part could be the administration building and the chimney for air exhaustion. In this building, the reactor control room could be located. The swimming pool above ground serves as the accumulator to supply water to cool the fuel chamber, and eventually it could be used as a heat sink for the residual heat removal through an isolation condenser (IC).

A vehicle is assumed to transport the reactor module and fuel chamber to the underground building through a double door with an isolation area.

A general view of the FBNR plant is shown in Fig. XI-4.

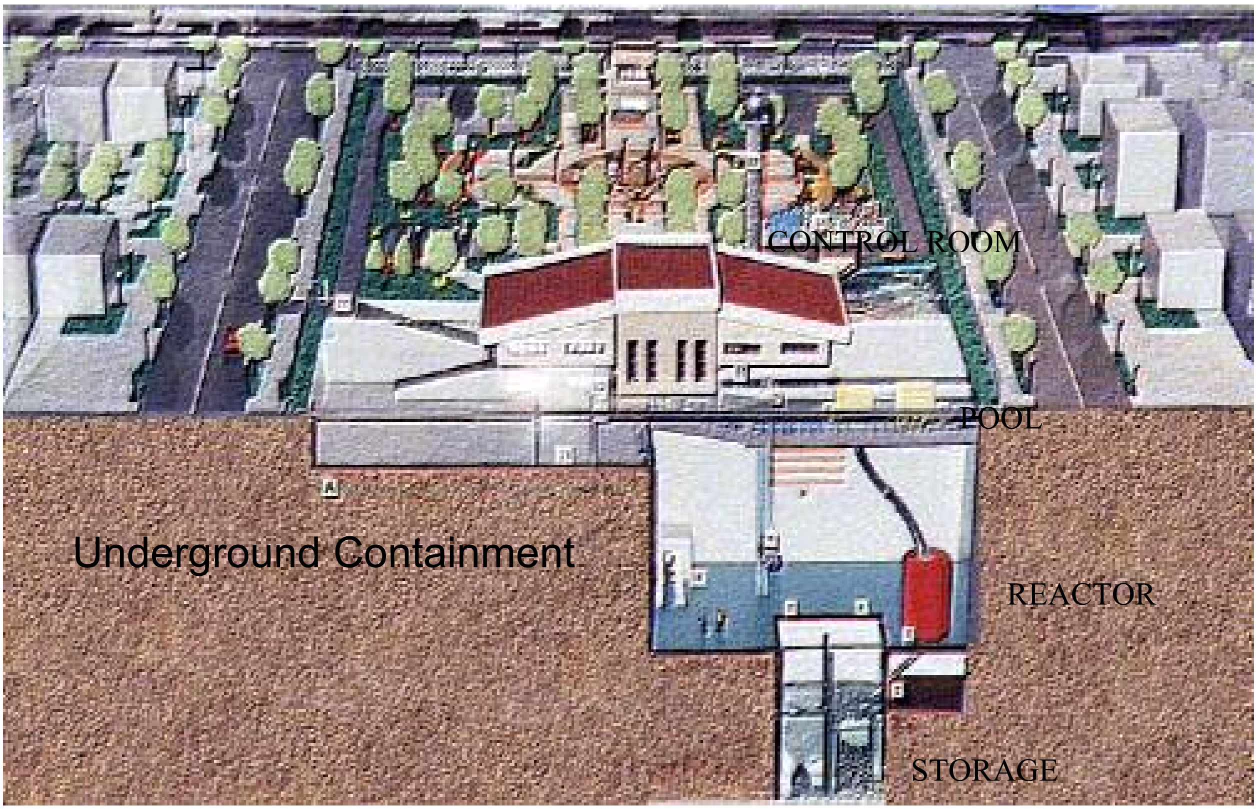

FIG. XI-4. General view of FBNR nuclear power plant.

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