# Status report 72 - Fixed Bed Nuclear Reactor (FBNR)

## Overview

| | |
|---|---|
| **Full name** | Fixed Bed Nuclear Reactor |
| **Acronym** | FBNR |
| **Reactor type** | Pressurized Water Reactor (PWR) |
| **Coolant** | Light Water |
| **Moderator** | Light water |
| **Neutron spectrum** | Thermal Neutrons |
| **Thermal capacity** | 218.00 MWth |
| **Electrical capacity** | 72.00 MWe |
| **Design status** | Concept Description |
| **Designers** | Federal University of Rio Grande do Sul – FURGS |
| **Last update** | 01-04-2011 |

## Description

### Introduction

The solution to the ever increasing demand for energy to satisfy the needs of growing world population and improving its standard of living lies in the combined utilization of all forms of energy.

The problem of global warming is no longer a philosophical discussion, but it is a fact seriously threatening the future of humanity. Energy conservation and alternative forms of energy generation such as solar, wind, and bio even though having important roles, do not satisfy the energy demand generated by an increasing world population that desires to increase its standard of living. The fission process in the nuclear reactors does not produce greenhouse gases that cause global warming. The new paradigm in nuclear energy is the future innovative reactors that meet the new standards set by the INPRO Program of the IAEA. One such a reactor is the Fixed Bed Nuclear Reactor.

Some of the innovative nuclear reactors presently under development have somewhat different characteristics than currently operating reactors, with respect to safety, economics, environmental impact and proliferation. In this manner, the developers of such concepts hope to enhance public perception and public acceptability of nuclear energy.
The objective of the FBNR Project is to develop an innovative nuclear reactor to be small, simple in design, and meet the requirements of being economic, safe, proliferation resistant and sustainable.

The FBNR is an innovative small nuclear reactor (70 MWe) without the need for on-site refuelling. The Small Reactors without On-Site Refuelling are defined by the 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".

## Description of the nuclear systems

The Fixed Bed Nuclear Reactor (FBNR) is a small reactor (70 MWe) without the need for on-site refuelling. It is a pressurized light water reactor having its fuel in spherical form. It has the characteristics of being simple in design, employing inherent safety features, passive cooling for some situations, proliferation resistant features, and reduced environmental impact.

The CERMET fuel is proposed for the FBNR reactor. The fuel consists of coated $UO_2$ 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 $UO_2$ microspheres 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.

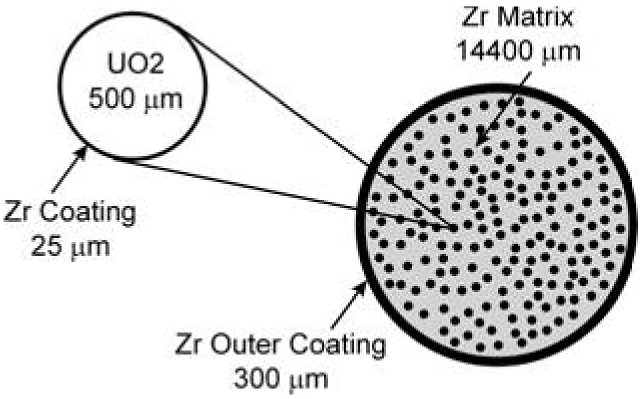


**FIG 2.1: FBNR Fuel Element**

The FBNR fuel chamber is fuelled in the factory. The sealed fuel chamber is then transported to and from the site. The FBNR is an integral design in which the steam generator and the reactor core are housed in the same pressure vessel.

The reactor, as shown Figure 2, has 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 31 cm and 171 cm in diameter, 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.

Any signal from any of the detectors, due to 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 subcritical 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 220 kg/sec, corresponding to the terminal velocity of 1.50 m/sec in the reserve fuel chamber, carries the fuel elements into the core and forms a fixed bed. At the operating flow velocity of 7.23 m/sec, corresponding to the mass flow rate of 1060 kg/sec, the fuel elements are firmly held together by a pressure of 0.188 bars that exerts a force of 27.1 times its weight, thus forming a stable fixed bed. The fixed bed is compacted by a pressure of 1.3 bars. 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 possibly aided by 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 supply is disconnected from 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. It may be visualized that the core is a solid shell of a "porous material" held against the piston like core level limiter by the upward force of a column of flowing water at velocities much higher than the terminal velocity. The "porous material" being the compacted spherical fuel elements.

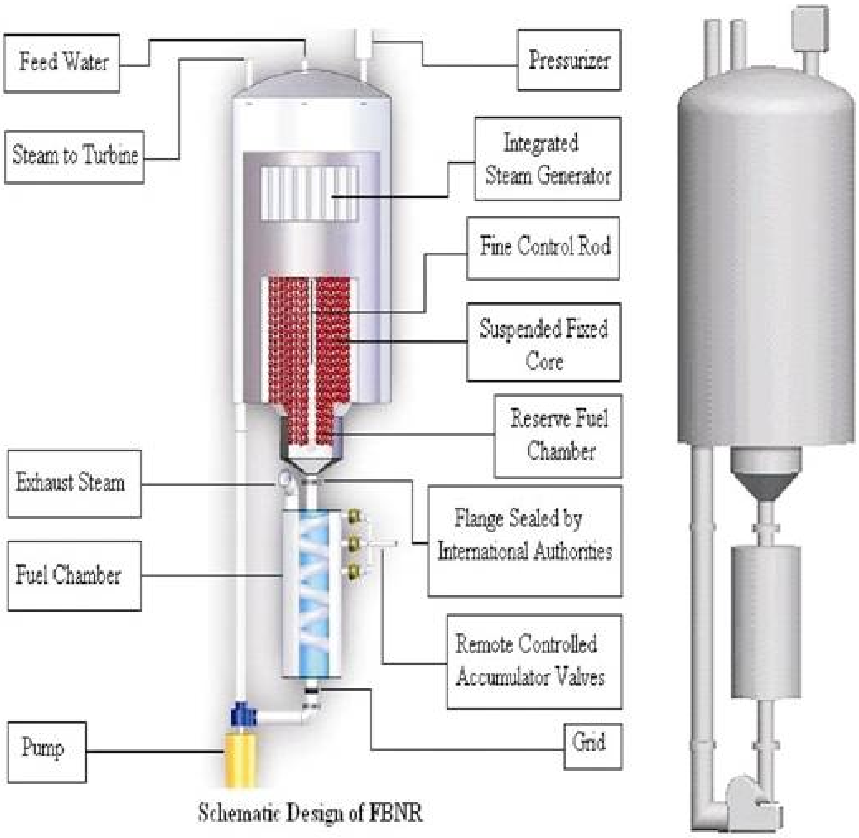


FIG. 2.2: Schematic design of FBNR

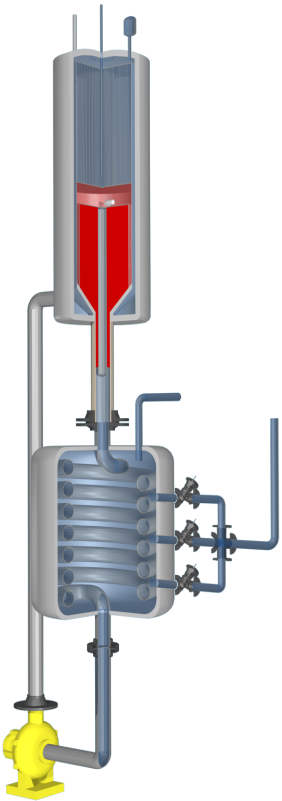


FIG. 2.3: Design of FBNR

The table below shows a summary of features of some small reactors without on-site refueling, and their applicability to FBNR.

| **Features** | **Demonstration of applicability** |
|---|---|
| Small in size | FBNR is small in nature. The optimum size for the FBNR is 70 MWe. The larger size up to a maximum of 165 MWe can be achieved only at the cost of a lower thermodynamic efficiency. |
| Modular | The reactor is modular in design. The modular aspect of the reactor leads to the mass production processes with potential for better economy and higher quality products. |
| No need for on-site refuelling | Each module is 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. |
| Proven Technology | FBNR makes an extensive use of a proven technology namely the PWR. |
| Diversity of applications | 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 co-generation plant producing electricity and desalinated water or steam for industrial purposes. As another option, the FBNR may be designed for district heating. |
| Refuelling in the factory | No refuelling on the site is needed because the fuel elements are contained in the fuel chamber and transported to the factory for refuelling under surveyed condition. Refuelling is done by the replacement of fuel chamber. |
| Long fuel cycle time. | The length of the fuel cycle is flexible and depends on the economic analysis of the fuel inventory and its enrichment for particular situation of the reactor and its application. The replacement of fuel chamber can easily be done at any desired time interval. |
| No fuel reshuffling | No reshuffling of fuel is necessary because the fuel elements go from fuel chamber to the core and vice versa without the need of opening the reactor. |
| No fresh fuel storage on site | 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 refuelling process is performed. |
| Short period of spent fuel storage on site. | The spent fuel that are confined in the fuel chamber and kept cooled by its water tank. It can be sent back to the factory at any time when the radiological requirements are met. |

## Description of safety concept

The key to the safety characteristic of FBNR is simply that the core becomes empty of fuel elements, and nuclear criticality ceases, should any undesired situation occur. Any signal from any of the numerous detectors, due to any accident 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 subcritical and passively cooled conditions. Therefore, the pump is normaly in "off" condition and will turn "on", only when all the signal values are simultaneously within the design range. The fuel chamber is cooled by natural convection transferring heat to the water in the tank that houses the fuel chamber. In this condition the accumulator valves, acting under pressure difference, will open automatically and the fuel chamber cooling tank becomes filled with cold water.

The operating condition of the 70 MWe reactor corresponds to the coolant flow velocity of 7.2 m/s. The terminal velocity being the minimum coolant velocity to carry the fuel elements into the core is 1.5 m/s. The maximum flow velocity above which the reactor operation becomes impractical is 25 m/s. in the operating condition, the fuel elements are held together with a pressure of about 0.2 bar and the force on them is more than 27 times the force of gravity, thus guarantees the bed to remain as a fixed bed during the reactor operation.

In order to be able to judge the safety aspect of the FBNR reactor, some neutronics and thermal characteristics of the reactor are summarized below:

The inlet and outlet temperatures of coolant in the core are 290 $^{\circ}$C and 326 $^{\circ}$C corresponding to enthalpies of 1283 and 1489 KJ/Kg giving an enthalpy rise of 206 KJ/kg. The mass coolant rate at the operating condition is 1060 Kg/s corresponding to a coolant velocity of 7.23 m/s, thus the reactor produces a thermal power of 218.4 MWt corresponding to an electric power of 70 MWe.

The critical core height is about 200 cm. The core height can be changed by the Core Height Level Limiter (CHLL). The largest effect of CHLL is 0.37 mk/cm at the beginning of cycle (BOC) and decreases to 0.059 mk/cm at the end of cycle (EOC). The effect of soluble boron in the moderator is 0.039 mk/ppmB at the BOC. The 200 cm height reactor with 2900 ppmB has $k_e$=0.99160 and with 2700 has $k_e$=0.99981.

It is seen that the moderator coefficient for 3000 ppm is still negative being -3x10$^{-4}$ mk/C. The Doppler coefficient for 3000 ppm boron is -6x10$^{-5}$ mk/ ºC. It is seen that each percent of fuel enrichment contribute to 281 days [5627 MWD/T] of the fuel lifetime.

In the case of a Loss of Coolant Accident (LOCA), the pressure in the reactor core drops and consequently the fuel elements fall out of the core and enter the fuel chamber where they remain under subcritical and passively cooled conditions. The heat transfer calculations show that their temperature will not exceed ~ 542 ºC and only less than 1 m$^3$ of water from accumulator is necessary to evaporate during one month of grace period.

The Loss of Flow Accident (LOFA) will be a more favorable accident condition than the LOCA. Again the fuel elements due to the lack of coolant flow will fall back into the fuel chamber where they remain under subcritical and passively cooled conditions.
The loss of power simply shuts down the pump and the reactor condition will be equivalent to a LOFA case.

The loss of turbine load or secondary loop break accident will cause the temperature of the cold leg of the pump increase and thus the control system will shut down the pump. Also the bubbles formed in the core decrease the moderator density thus due to the negative moderator coefficient, (- 350 mk/(g/cm$^3$)) , the reactor becomes subcritical.

The worst condition that any terrorist action can produce will be similar to the LOCA condition. What is needed will be to protect the fuel chamber physically within a robust structure.

The limit of the reactor power is not dependent on the design temperatures but on the percent of pump power consumption. The standard reactor is chosen to be 70 MWe where about 3% of power is consumed by the pump. One can have a maximum 165 MWe reactor should we accept that 34 % of generated power goes to power the pump. Above this reactor size, the required pump power will exceed the additional energy produced by the reactor and thus the system become unproductive.

The 200 cm height core has 4.78 m$^3$ volume and contain 2.87 m$^3$ fuel that corresponds to 1.62 millions of spherical fuel elements. The volumetric heat generation is 76.10 w/c m$^3$ or 134.40 watts per sphere. Each fuel element having 7.4 g of $UO_2$ contain 6.52 g of uranium metal.

Under normal operating condition, the temperature of the fuel surface is 357.7 °C corresponds to the temperature of 414.3 °C at fuel centre giving a temperature difference of 56.6 °C. *The critical heat flux is found to be 2290 kW/m².*

FBNR is evaluated by the INPRO Methodology. The summary report of IAEA-INPRO on the safety assessment of FBNR states the followings (Item 4.7.3 Safety):

"FBNR is a small innovative PWR (70 MWe) design without the need for onsite refueling. The FBNR design has potential to reach a level of total safety as the law of gravity and heat convection governs its inherent safety characteristics. The reactor core consists of spherical fuel elements held at their axial position by the coolant flow. The coolant pump is normally in "off" position and turns "on" only if all the safety signals are simultaneously correct. Under any conceivable accident scenario, the spherical fuel elements fall out of the core down into a fuel chamber where they remain under passively cooled and subcritical conditions. For the FBNR design all INPRO safety criteria were found to be in agreement or at least to show great potential; i.e. no show stopper was found at this early stage of development. The FBNR design has potential to reach a higher level of safety compared with the reference design of ANGRA-2."

## Proliferation resistance

The FBNR reactor is designed to have proliferation resistant features.

The non-proliferation characteristics of the Fixed Bed Nuclear Reactor (FBNR) are 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 inspection at any time. Only the fuel chamber is needed 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.

The concept is based on both sealing of the fuel chamber and denaturing of the fuel itself.

The sealing of the fuel in the fuel chamber of a long life reactor, permits the control at any time from "cradle to grave" allowing the continuity of knowledge (COK) about the fuel which guarantees an effective control.
The isotopic denaturing of the fissile fuel, both in the U-233/Thorium cycle as well as for the classical Pu-239/Uranium cycle, would further increase the proliferation resistance as it will require isotope separation technology to produce weapon grade materials.

In this way both intrinsic features and extrinsic proliferation resistance measures are provided. The Continuity of Knowledge (COK) and the communication between stakeholders are facilitated due to the nature of the design. The proposed reactor can utilize variety of fuel cycles and can benefit from a Multilateral Fuel Cycle concept.
In conclusion, the FBNR can be considered to have a high resistance against nuclear proliferation.

FBNR is evaluated by the INPRO Methodology from the proliferation resistance. The IAEA-INPRO summary report states the followings ( Item 4.4.3 Proliferation resistance): "The fixed bed nuclear reactor (FNBR) is being developed in Brazil together with other countries. The design of this reactor is at the conceptual level with limited design data available. With regard to proliferation resistance, the key feature of the FBNR design is that, under shutdown condition, all fuel elements remain in the fuel chamber where only a single flange needs to be sealed and controlled for safeguard purposes. The assessor evaluated the design data available against each INPRO criteria in this area and found full agreement, i.e. no show stopper during the evaluation. He concluded that the FNBR will comply with all requirements in this area."

## Safety and security (physical protection)

The key to the safety concept of the FBNR does not allow any abuse of the reactor because whatever undesireable manipulations results in the shuting down of the reactor and consequently the return of all fuel elements in the well protected fuel chamber.

The key to the safety characteristic of FBNR is simply that the core becomes empty of fuel elements should any undesired situation occur. Any signal from any of the numerous detectors, due to any accident 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 subcritical and passively cooled conditions. Therefore, the pump is normaly in "off" condition and will turn "on", only when all the signal values are simultaneously within the design range. The fuel chamber is cooled by natural convection transferring heat to the water in the tank that houses the fuel chamber. In this condition the accumulator valves, acting under pressure difference, will open automatically and the fuel chamber cooling tank becomes filled with cold water.

## Description of turbine-generator systems

Standard system available.

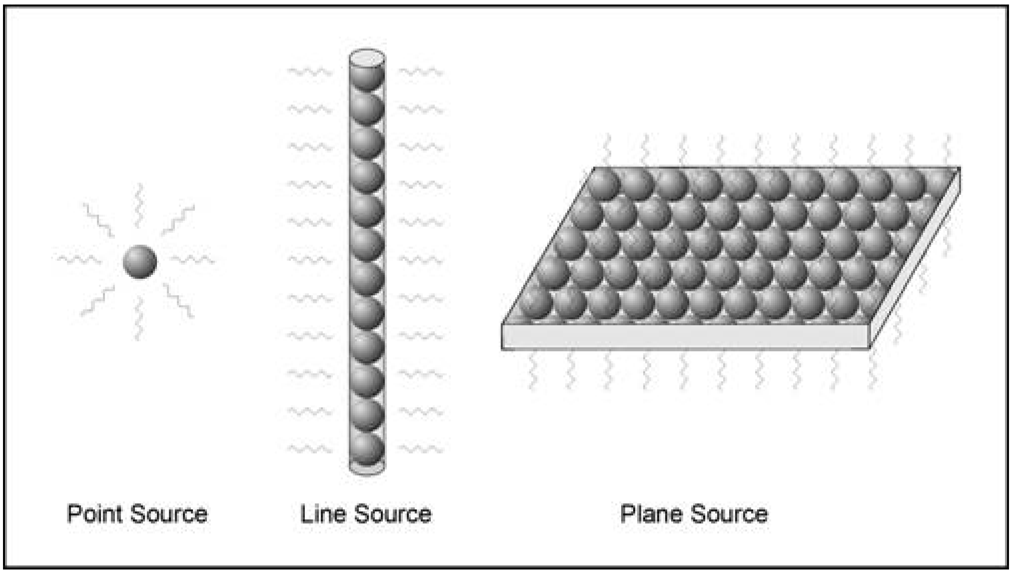
## Electrical and I&C systems

The most modern systems will be adopted.

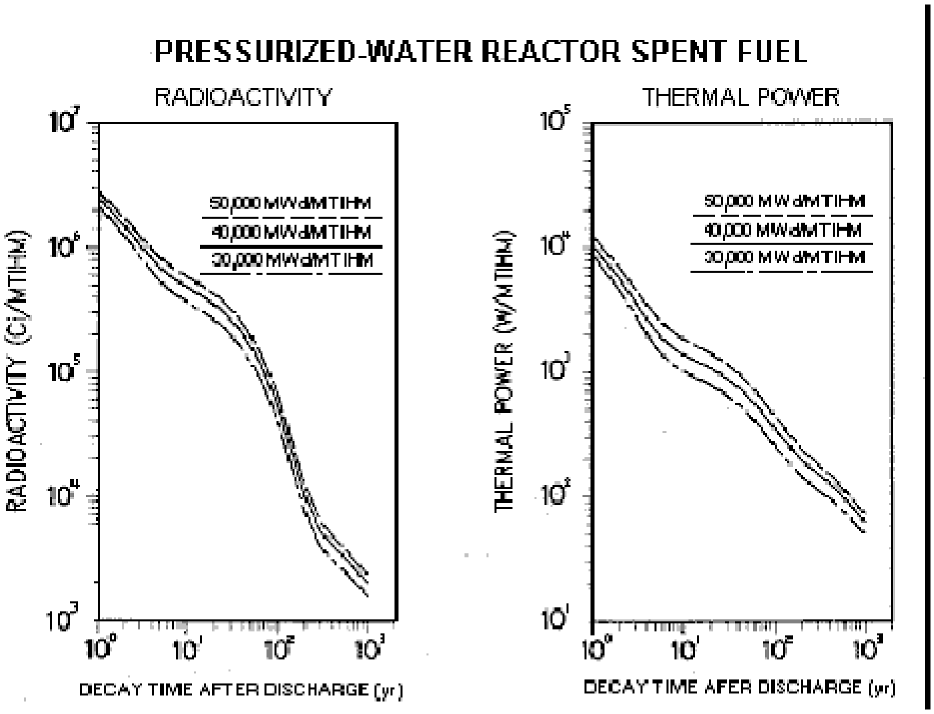
## Spent fuel and waste management

The spent fuel of FBNR may not be considered as nuclear waste because it can serve useful purposes. Nuclear radiation has many useful applications in industry, agriculture and medicine.

The spent fuel of FBNR is in a convenient form and size that can be directly used as a source of radiation for irradiation purposes. A variety of irradiators can easily be constructed for applications in industry, agriculture and medicine.
Each spent fuel element has an activity of about 10.curie. . The 15mm diameter spherical fuel elements can be used to produce sources of gamma radiation in various geometries namely point, line and plane source as schematically shown below:



The radioactivity of the spent fuel as a function of time is shown below:



http://www.nucleartourist.com/basics/sfdecay1.htm

## Plant layout

The inherent safety and passive cooling characteristics of the reactor are claimed by the designer to eliminate the need for containment. However, an underground containment is envisaged for the reactor to mitigate any imagined adverse event. The main objective is to hide the industrial equipments underground and present the nuclear plant as a beautiful garden compatible with the environment acceptable to the public.

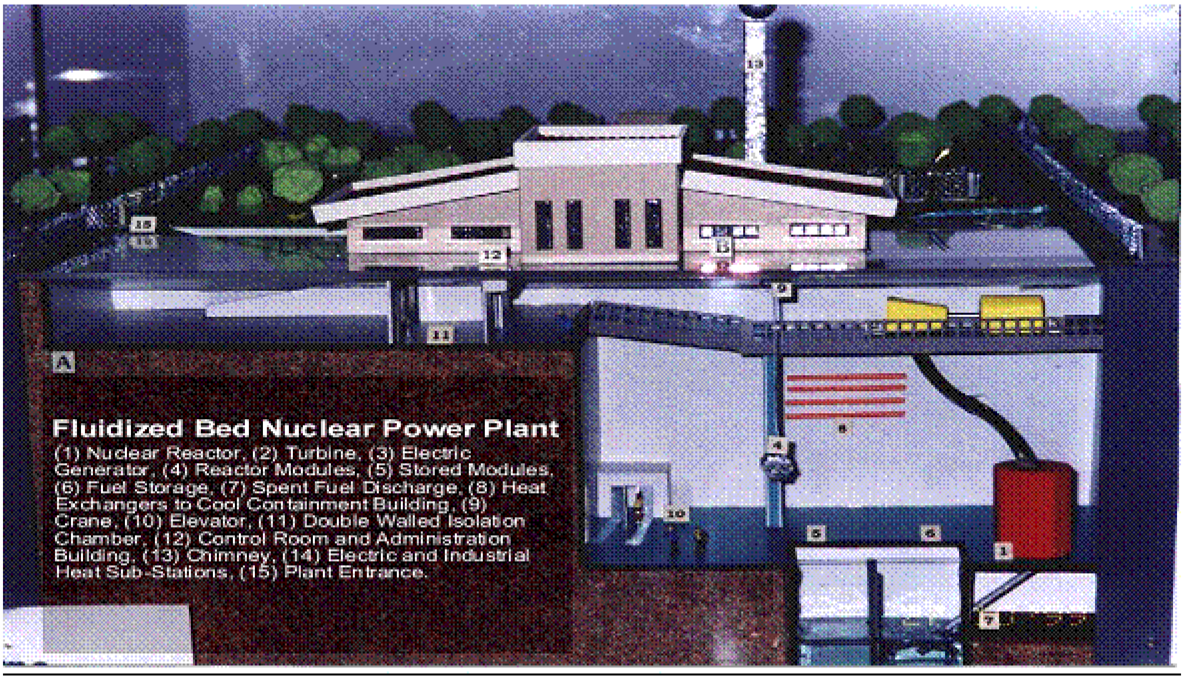


FIG. 9.1: FBNR Underground Containment Building

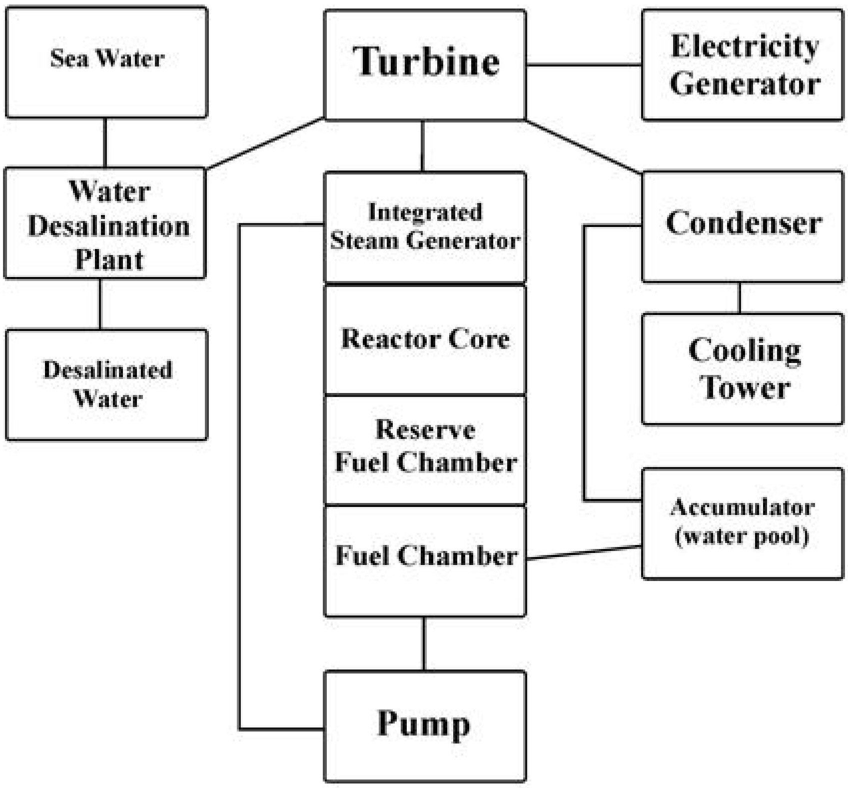


FIG. 9.2: Scheme of the Nuclear Power Plant

## Plant performance

The FBNR plant will be projected to make the best use of automation technology available in order to operate it with minimum number of operators.

## Development status of technologies relevant to the NPP

The designer asserts that the technology requirement is to fabricate the 15 mm diameter CERMET fuel elements.

## Deployment status and planned schedule

*The present efforts are made to bring together the potential investors with industrial partners to build the prototype of the reactor.*

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## Technical data

### General plant data

| | |
|---|---|
| **Reactor thermal output** | 218 MWth |
| **Power plant output, gross** | 72 MWe |
| **Power plant output, net** | 70 MWe |
| **Power plant efficiency, net** | 33 % |
| **Mode of operation** | Baseload |
| **Plant availability target >** | 95 % |
| **Primary coolant material** | Light Water |
| **Moderator material** | Light water |
| **Thermodynamic cycle** | Rankine |
| **Type of cycle** | Indirect |
| **Non-electric applications** | Desalination |

### Safety goals

| | |
|---|---|
| **Operator Action Time** | 200 Hours |

### Reactor core

| | |
|---|---|
| **Active core height** | 2 m |
| **Equivalent core diameter** | 1.7 m |
| **Average linear heat rate** | 135 KW/m |
| **Average fuel power density** | 28 KW/KgU |
| **Average core power density** | 45 MW/m$^3$ |
| **Fuel material** | CERMET |
| **Fuel element type** | Spherical |
| **Cladding material** | Zircaloy-4 |
| **Outer diameter of elements** | 15 mm |
| **Lattice geometry** | Dodecahedron |
| **Number of fuel Elements in fuel assemblies** | 1620000 |
| **Enrichment of reload fuel at equilibrium core** | 5 Weight % |
| **Fuel cycle length** | 25 Months |
| **Average discharge burnup of fuel** | 15.3 MWd/Kg |

| | |
|---|---|
| **Soluble neutron absorber** | Boron |
| **Mode of reactivity control** | Boron and core height level limiter (CHLL) |
| **Mode of reactor shut down** | Turn off the coolant pump |

## Primary coolant system

| | |
|---|---|
| **Primary coolant flow rate** | 1060 Kg/s |
| **Reactor operating pressure** | 16 MPa |
| **Core coolant inlet temperature** | 290 °C |
| **Core coolant outlet temperature** | 326 °C |

## Reactor pressure vessel

| | |
|---|---|
| **Inner diameter of cylindrical shell** | 214 mm |
| **Wall thickness of cylindrical shell** | 15 mm |
| **Total height, inside** | 6000 mm |
| **Transport weight** | 5 t |

## Steam generator or Heat Exchanger

| | |
|---|---|
| **Type** | Tube and Shell type |
| **Mode of operation** | Primary coolant inside /Steam generated outside the tube. |

## Reactor coolant pump (Primary circulation System)

| | |
|---|---|
| **Circulation Type** | Forced |
| **Pump Type** | Centrifugal |
| **Number of pumps** | 1 |
| **Head at rated conditions** | 136 m |
| **Flow at rated conditions** | 1400 $m^3/s$ |

## Primary containment

| | |
|---|---|
| **Type** | Underground |

## Residual heat removal systems

| | |
|---|---|
| **Active/passive systems** | Passive |

## Turbine

| | |
|---|---|
| **Type of turbines** | Conventional |
| **Number of turbine sections per unit (e.g. HP/MP/LP)** | 1 |

## Generator

| | |
|---|---|
| **Type** | Conventional |
| **Number** | 1 |

## Plant configuration and layout

| | |
|---|---|
| **Plant configuration options** | Ground-based |