Fixed Bed Nuclear Reactor for Electricity and Desalination Needs of Middle-East Countries

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A new era of nuclear energy is emerging through innovative nuclear reactors that are to satisfy the new philosophies and criteria that are being developed by the INPRO program of the International Atomic Energy Agency (IAEA). It is establishing a new paradigm in relation to nuclear energy. The future reactors should meet the new standards in respect to safety, economy, non-proliferation, nuclear waste, and environmental impact. The Fixed Bed Nuclear Reactor (FBNR) is a small (70 MW_{el}) nuclear reactor that meets all the requirements. It is an inherently safe and passively cooled reactor that is fool proof against nuclear proliferation. It is simple in design and economic. It can serve in a dual purpose plant to produce simultaneously both electricity and desalinated water, thus making it especially suitable to the needs of the Middle-East Countries. FBNR is being developed with the support of the International Atomic Energy (IAEA) under its program of Small Reactors Without On-Site Refueling (SRWOSR). The reactor uses the pressurized water reactor (PWR) technology. It fulfills the objectives of design simplicity, inherent and passive safety, economy, standardization, shop fabrication, easy transportability and high availability. The inherent safety characteristic of the reactor dispenses with the need for containment; however, a simple underground containment is envisaged for the reactor in order to reduce any adverse visual impact.

Keywords Small, innovative, nuclear reactor, inherent safety, passive cooling, proliferation resistant, water desalination.

1. 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. 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. FBNR [1,2] is designed to be such a reactor and to meet the requirements for an innovative reactor established by the IAEA-INPRO Program [3]. FBNR is a small reactor (70 MW_{el}) and simple in design. Small reactors have the advantages of serving the needs of local communities, need low capital investment and do not require expensive power transmission system. FBNR can serve as a multipurpose plant producing electricity, desalinated water, industrial steam, and supply district heating simultaneously. FBNR is inherently safe that implies total safety and environmentally friendly conditions for its surrounding. The used fuel of FBNR may not be considered nuclear waste since it can serve as a source of radiation for irradiation purposes. They have useful applications in agriculture, medicine and industry.

FBNR is a fool proof non-proliferating reactor that cannot be misused for military purposes. It is economic with low capital investment. FBNR uses the well proven PWR technology. The countries that adopt FBNR will participate in the research and development of the technology and become the owners of nuclear technology and not merely the users. Science may be transferred, but technology is not transferable - it is developed.

The new comer countries to nuclear energy can participate in the development of FBNR while they are implementing the IAEA Milestones Guidelines [4]. Any country can become a stakeholder in the FBNR project. Participation in the FBNR project brings with it sophisticated technology and wealth to the country. It will have a positive impact on other industries of that country.

The guarantee that FBNR is a good business comes from the fact that IAEA, being an agency of the United Nations, has put goals for itself to (1) "Help to ensure that nuclear energy is available to contribute in fulfilling energy needs in the 21st century in a sustainable manner"; and (2) "to bring together both technology holders and technology users to consider jointly the international and national actions required to achieve the desired innovations in nuclear reactors and fuel cycles. Therefore, any project that meets the IAEA INPRO criteria will have the support of the highest world authority in nuclear energy such as the IAEA.

The inherent safety and passive cooling characteristics of the FBNR nuclear reactor eliminate the need for containment. However, an underground containment is envisaged for the reactor to mitigate any imagined adverse event, but mainly to help with the visual effects by hiding the industrial equipment underground and presenting the nuclear plant as a beautiful garden compatible with an environment which would be acceptable to the public. The reactor can be operated with a reduced number of operators or even be remotely operated without any operator on site.

Signals transmitted from a multitude of detectors and fed into the control system will make the FBNR a totally safe nuclear reactor, and guard it against, sabotage, terrorist action, explosion, earthquake, flooding, fire, tornado, or any other natural or man-made disaster. Any abnormal signal outside the range of operation from any of the detectors will signal an accident alarm which in turn will automatically cut off power to the pump resulting in the fuel elements to fall out of the reactor core, by the force of gravity, and become stored safely in the passively cooled fuel chamber.

2. Advantages of Small Nuclear Reactors

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 immensely to the sustainable development through electricity production, water desalination, and process heat applications.

Some of the important advantages of the small reactors may be summarized as follows:

- 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 resources.
- They provide an attractive domain for fuel leasing and facilitate an option of factory fuelled and transportable power plant, such as barge-mounted, which may be a solution for countries with limited capabilities in mastering nuclear fuel cycle, or for those who prefer to be just the end users of nuclear power.
- In industrialized countries, electricity market deregulation is calling for power generation flexibility that smaller reactors may offer.
- They provide means for learning knowledge and technology from a small prototype plant.

3. Fixed Bed Nuclear Reactor

The Fixed Bed Nuclear Reactor (FBNR) is a small reactor (70 MW_{el}) without the need for on-site refuelling. It is a pressurized light water reactor having its fuel in spherical form, figure 1. It has the characteristics of being simple in design, inherent safety, passive cooling, proliferation resistant, and reduced environmental impact.

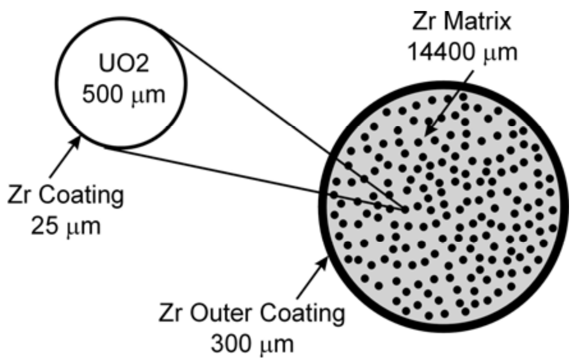

Figure 1. FBNR Fuel Element

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 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.

The FBNR fuel chamber is fuelled in the factory. The sealed fuel chamber is then transported to and from the site. It is an integrated primary system design.

The reactor, as shown in the schematic figure 2, has in its upper part the reactor core and a steam generator and in its lower parts the fuel chamber. 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.

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 conditions.

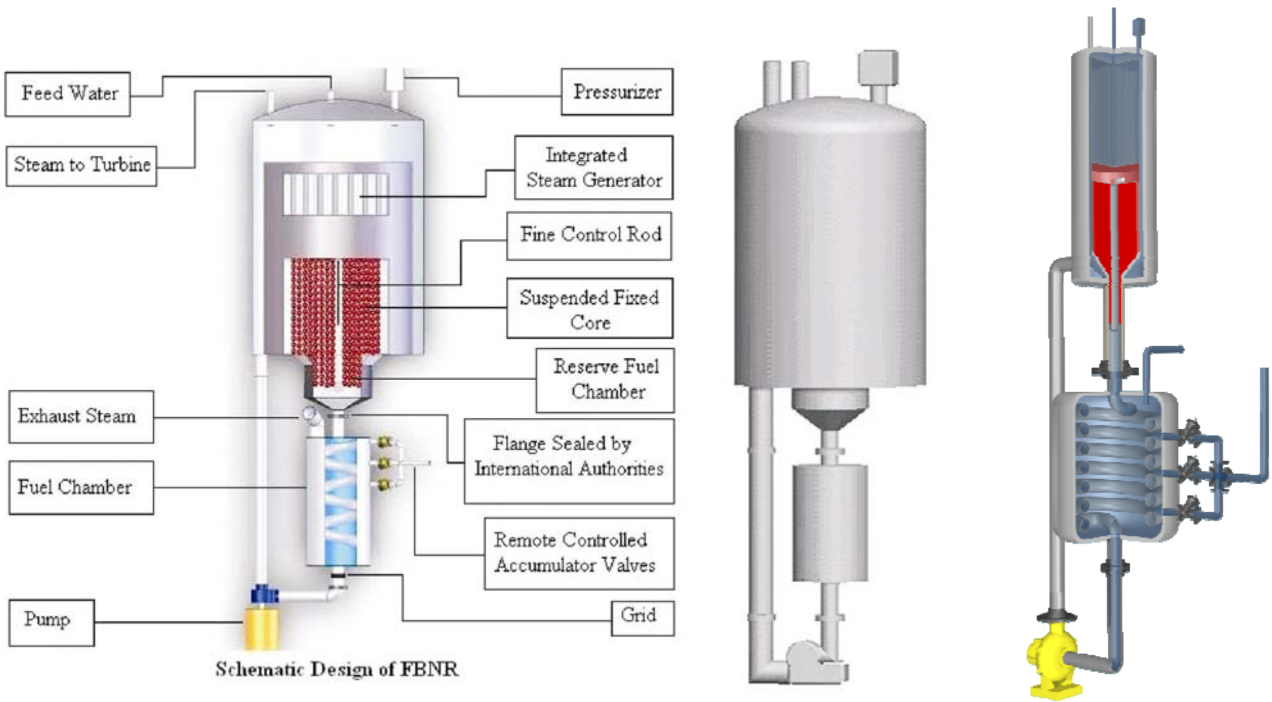

Figure 2. Schematic Design of the Fixed Bed Nuclear Reactor (FBNR).

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

Table I. Summarized Technical Data Fixed Bed Nuclear reactor (FBNR)

General plant data		
Reactor thermal output	218	MW_{th}
Power plant output, gross	72	MW_{el}
Power plant output, net	70	MW_{el}
Power plant efficiency, net	33	%
Mode of operation	Base Load	(Base Load, Load Follow)
Primary Coolant material	Light water	
Moderator material	Light water	
Thermodynamic Cycle	Rankine	
Operator Action Time (Grace period)	200	Hours
Reactor Core		
Active core height	2	m
Equivalent core diameter	1.7	m
Average linear heat rate	135	W/fuel element
Average fuel power density	28	kW/kg U
Average core power density	45	MW/m^3
Fuel material	CERMET	
Fuel element type	Spherical	
Cladding material	Zircaloy-4	
Outer diameter of spherical fuel element	15	mm
Lattice geometry	Dodecahedron	
Number of fuel elements in the core	~ 1.62 millions	
Enrichment of reloaded fuel in equilibrium core	5	Weight %
Fuel cycle length	25	Months
Average discharge burn-up of fuel	15.3	MWd/kg
Mode of reactivity control	Boron and core height level limiter (CHLL)	
Mode of reactor shut down	Turn off the coolant pump	
Soluble neutron absorber, if any	Boron	
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 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 of the Power Circuit		
Type	Tube & Shell	
Mode of operation	Primary coolant inside / Steam generated outside the tube.	
Primary Circulation System		
Circulation Type	Forced	
Pump type	Centrifugal	
Number of Pumps	One	
Head at rated conditions	136	m
Flow at rated conditions	1400	m^3/s
Active/passive systems	Passive System	

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 main technical data of FBNR is listed in table I.

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 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. 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.

Figure 3. FBNR Underground Containment Building.

4. Reactor Safety

It is very desirable to develop nuclear reactor concepts that are inherently safe whose safety features are easily demonstrable without depending on the interference of active safety devices which have some probability of failing, or depend on operator skills and good judgment, which could vary considerably.

There are only four significant sources of energy in a reactor accident: Nuclear power excursion, thermal reactions (steam explosion), chemical reactions (zirconium/water and core/concrete), and radioactive decay heat. The first three can be limited or controlled by proper selection of materials - a form of inherent safety. The fourth energy source, decay heat, is a slow and inherently restricted form of energy release.

All current reactors need to include safety systems to remove decay or residual heat produced after the chain reaction in a reactor has ceased to avoid core melt. The inherently safe reactors are transparently incapable of producing a core melt. They are "forgiving" reactors, able to tolerate human and mechanical malfunctions without endangering public health. Also they are called "walk away" reactors as the key feature of these reactors is their reliance upon passive or non-mechanical, safety systems.

In FBNR any conceivable accident results in the cutting off the power to the pump that causes the fuel elements to fall out of the core by the force of gravity and enter the fuel chamber where they remain under subcritical and passively cooled conditions. The normal state of control system is “switch off”. The pump is “on” only when all the operating conditions are simultaneously met.

The inherent safety and passive cooling characteristics of the reactor eliminate the need for containment. However, an underground containment is envisaged for the reactor to mitigate any imagined adverse event, but mainly to help with the visual effects by hiding all reactor components and the industrial equipments underground and presenting the **nuclear plant as a beautiful garden** compatible with the environment acceptable to the public.

5. Fool Proof Non-Proliferating Nuclear Reactor

Under the present world conditions, the first priority of the governments in relation to nuclear energy is non-proliferation and safeguard of the nuclear reactors. This provides a challenge for the scientists and technologists to come up with a fool proof nuclear reactor concept.

The IAEA through its INPRO recommends that “proliferation resistant features and measures should be provided in innovative nuclear energy systems to minimize the possibilities of misuse of nuclear materials for nuclear weapons. Both intrinsic features and extrinsic measures are essential, and neither should be considered sufficient by itself. Extrinsic proliferation resistance measures, such as control and verification measures will remain essential, whatever the level of effectiveness of intrinsic features. From a proliferation resistance point of view, the development and implementation of intrinsic features should be encouraged. Communication between stakeholders will be facilitated by clear, documented and transparent methodologies for comparison or evaluation/assessment of proliferation resistance”.

The non-proliferation characteristics of 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 $^{233}U/Th$ or $^{239}Pu/U$ cycle increases the proliferation resistance substantially. Therefore, both concepts of “sealing” and “isotope denaturing” contribute to the fool proof non-proliferation characteristics of the FBNR.

The FBNR meets the IAEA requirements for non-proliferation. 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 as a fool proof reactor against nuclear proliferation that the present world is looking for to be assured of both safety and safeguard [5-8].

6. Some Other Characteristics of FBNR

- FBNR is simple in design, inherently safe without adverse environmental impact and passively cooled.
- The FBNR is shop fabricated, thus it guarantees the high quality fabrication and economic mass production process.
- FBNR uses a proven technology namely that of the conventional pressurized water reactors (PWR).
- 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.
- The reactor can be operated with a reduced number of operators or even be remotely operated without any operator on site.
- The FBNR is designed to produce electricity alone or to operate as a cogeneration plant producing simultaneously: electricity, desalinated water, and steam for industrial purposes and heat for district heating. 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 0.6 MW_{el} reduction of the electric power.
- The FBNR can have a very long fuel cycle time depending on the projected size of reserve fuel chamber and the fuel enrichment. The core life is decided according to the user's need. 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. Refuelling 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 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. No unauthorized access to the fresh or spent fuel is possible because the fuel elements are either in the core or in the fuel chamber under sealed condition. Therefore, no clandestine diversion of nuclear fuel material is possible.
- FBNR resists against "Terrorist Action", "Explosion", "Earthquake", "Flooding", "Fire", "Tornado", and "Bombing". Any adverse event disturbs the signals from the multiple detectors that go into the control system. 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.
- A small country with no nuclear technology and modest capital can contribute to the development of the FBNR. The bureaucracy and complicated licensing procedures in industrialized countries make deployment of any new reactor concept too slow in those countries. The country can accept the standards set by the IAEA with minimum additional requirements. The industrial countries have developed many new exigencies that have complicated the deployment of new nuclear reactors.
- FBNR is economically competitive. Innovation creates a new paradigm. FBNR utilizes the "Economy of Numbers" instead of "Economy of Scale". The FBNR components are shop fabricated with much higher quality than is possible to be done on the site. The simplicity and mass production process will make them very economic.

7. Spent Nuclear Fuel and FBNR

FBNR has a partially epithermal and harder neutron spectrum compared to conventional LWRs. This fact opens possibility of non-conventional nuclear fuel, such as, thorium, reactor grade plutonium or a variety of actinides in the spent nuclear waste fuel of conventional LWRs.

Recent studies have evaluated the criticality of FBNR with alternative fuels. It has been shown that either the totality of actinides in the spent nuclear waste fuel of conventional LWRs or extracted reactor grade plutonium with a high fraction of non-fissile even plutonium isotopes would give a new type of excellent fuel for FBNR due to the harder neutron spectrum [9-10]. They can be used either directly or after blending with thorium.

On the other hand, the spent fuel from FBNR is in a form and size (15 mm diameter spheres) that can directly be used as a source of radiation for irradiation purposes in agriculture, industry, and medicine. This feature results in a positive impact on waste management and environmental protection. Therefore, the spent fuel from FBNR may not be considered as waste as it can perform useful functions.

8. Conclusions

FBNR is capable to eliminate the most dangerous nuclear wastes, which constitute a nuisance at present, by extracting additional energy out of them. This will open the possibility of relaxing the repository problems to a great degree.

Utilization of thorium as nuclear fuel in combination with weapon grade plutonium and the actinide waste products of conventional PWRs, including higher plutonium isotopes, will extend the time availability of nuclear fuel resources significantly.

In summary, FBNR is a new pressurized water reactor, realizable in near future. It is based on relatively simple design and already existing technology. Aside from electricity production, mainly for decentralized energy needs in the realm of 40-100 MW_{el}, it can also be used for water desalination and space heating purposes. FBNR can contribute significantly to reduce total nuclear waste output of LWRs making use them as new type nuclear fuel.

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