

## **FLUIDIZED BED NUCLEAR REACTOR AS A IV GENERATION REACTOR**

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### **ABSTRACT**

The fluidized bed nuclear reactor (FBNR) is essentially a pressurized light water reactor (PWR) having spherical fuel elements forming a suspended reactor core. The core is suspended and movable thus under adverse conditions, the fuel elements leave the reactor core through the force of gravity and fall into the passively cooled fuel chamber or leave the reactor permanently entering the spent fuel pool. It is a small and modular reactor being simple in design. Its spent fuel is in such a convenient form and size that may be utilized directly as the source for irradiation and applications in agriculture and industry. This results in a great positive impact on waste management and environmental protection.

The advantages of the proposed design are being modular, low environmental impact, exclusion of severe accidents, short construction period, flexible adaptation to demand, excellent load following characteristics, and competitive economics.

### **1. 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. Nuclear energy produced safely has an important role in solving the world energy problem. The public objections to nuclear energy most often expressed are reactor safety, cost and nuclear waste disposal

About 30% of the world's primary energy consumption is used for electricity generation, about 15% is used for transportation, and the remaining 55% is converted into hot water, steam and heat. Non-electric applications include desalination, hot water for district heating, and heat energy for petroleum refining, for the petrochemical industry, and for the conversion of hard coal or lignite. For non-electric applications, the specific temperature requirements vary greatly. Hot water for district heating and heat for seawater desalination require temperatures in the 80 to 200 C range, whereas temperatures in the 250 to 550 C range are required for petroleum refining processes. Water-cooled reactors can provide heat up to about 300 C.

In order to obtain the public acceptance of nuclear energy, some countries have put emphasis on the development of so called 3<sup>rd</sup> generation reactors namely the Advanced Light Water Reactors (ALWR). These 3<sup>rd</sup> generation reactors are being developed by building upon the experience and applying the lessons learned from existing 2<sup>nd</sup> generation plants. Some examples of large 3<sup>rd</sup> generation are the ABWR of General Electric, USA, the APWR of Westinghouse, USA and Mitsubishi; the BWR-90 of ABB Atom, Sweden, the EPR of Nuclear Power International (NPI), a joint company of Framatome in France and Siemens in Germany; the SWR- (or BWR) 1000 of Siemens, the System 80+ of ABB Combustion Engineering, USA; the WWER-1000 (V-392) of Atomenergoprojekt and Gidropress, Russia; and the KNGR of KEPCO and KAERI, the Republic of Korea. Among the medium-size ALWRs, five typical designs are the AP-600 of Westinghouse, the AC-600 of China National Nuclear Corporation; the MS-600 of Mitsubishi; the SBWR of General Electric; and the WWER-640 (V-407) of Atomenergoprojekt and Gidropress.

## **2. GENERATION IV NUCLEAR REACTORS**

The U.S. Department of Energy's Office of Nuclear Energy, Science and Technology has recently come up with a document saying, "At the end of 2000, 438 nuclear power reactors were in operation in 31 countries around the world, generating electricity for nearly 1 billion people. They account for approximately 17 percent of worldwide installed base capacity for electricity generation and provide half or more of the electricity in a number of countries.

Concerns over energy resource availability, climate change, air quality, and energy security suggest an important role for nuclear power in future energy supplies. Nuclear power plant technology has evolved as three distinct design generations: (1) Prototypes, (2) Current operating plants, and (3) Advanced reactors. The next generation of nuclear energy systems must be licensed, constructed, and operated in a manner that will provide a competitively priced supply of energy, keeping in consideration an optimum use of natural resources, while addressing nuclear safety, waste, and proliferation resistance, and the public perception concerns of the countries in which they are deployed. Recognizing both the positive attributes and shortcomings of the prior generations of reactor designs, it is now time to lay the groundwork for a fourth generation to be called Generation IV.

The U.S. Department of Energy's Office of Nuclear Energy, Science and Technology has engaged governments, industry, and the research community worldwide in a wide-ranging discussion on the development of next-generation nuclear energy systems known as "Generation IV". This has resulted in the formation of the Generation-IV International Forum (GIF), a group whose member countries are interested in jointly defining the future of nuclear energy research and development. In short, "Generation IV" refers to the development and demonstration of one or more Generation IV nuclear energy systems that offer advantages in the areas of economics, safety and reliability, sustainability, and could be deployed commercially by 2030. A Generation IV Technology Roadmap is being prepared by GIF member countries which will identify the six to eight most promising reactor system and fuel cycle concepts and the R&D necessary to advance these concepts for potential commercialization. The Roadmap was initiated in October 2000 and is scheduled for completion in September 2002."

### 3. THE FLUIDIZED BED NUCLEAR REACTOR CONCEPT

The fluidized bed nuclear reactor concept is modular in design such that any size of reactor can be constructed from the basic module. The basic module has in its upper part the reactor core and a steam generator and in its lower part the fuel chamber. The core consists of a 25-cm diameter fluidizing tube in which, during reactor operation, the spherical fuel elements are fluidized. The fuel chamber is a 10-cm diameter tube, which is directly connected underneath the fluidizing tube. A steam generator of the shell and tube type is integrated into the upper part of the module. A neutron absorber shell slides inside the fluidizing tube, acting similarly to a control rod, for the purposes of long term reactivity control.

The pump circulates the water coolant inside the module moving up through the fuel chamber, the core, and the steam generator and thereafter flows back down to the pump through the concentric annular passage. At the maximum or terminal fluidizing velocity, the coolant carries up the fuel elements into the core and fluidizes them. The increase in flow velocity causes higher porosity of the bed. In the shut down condition, the fuel elements leave the core and fall back into the fuel chamber by the force of gravity.

The 8-mm diameter spherical fuel elements are made of slightly enriched uranium dioxide, clad in by zircaloy for normal design, and stainless steel for modified design concept using supercritical steam. The fresh fuel elements are fed into the reactor core from the top of the module. The spent fuel leaves the module through a valve provided at the bottom of the fuel chamber. The valve is operated by a hydraulic system allowing the spent fuel to be discharged from the fuel chamber into a permanently cooled storage tank. The module is provided with a pressurizer system to keep the pressure a constant, and a depressurizer valve which leads the steam to the condenser for reducing pressure to allow opening of the valve for refueling.

Any hypothetical accident will cut-off power from the pump causing the fuel leave the core and fall back into the fuel chamber by the force of gravity where remain in a highly subcritical and passively cooled condition. The fuel chambers are cooled by natural convection transferring heat to the surrounding air or water pool.

The reactivity of the reactor, the degree of the homogeneity of the core, and the heat transfer are all dependent on the porosity of the fluidized bed. The porosity is defined as the ratio of the moderator to total volume. The calculations show that the reactivity increases initially with bed porosity as the neutrons become increasingly thermalized to a maximum and decreases thereafter at higher porosity where the neutron absorption in the moderator dominates the already well thermalized reactor condition.

As the bed porosity is a function of pumped coolant velocity, it is apparent that the reactor can be controlled by fluidizing the bed through the variation of pump speed. It is an interesting inherently safe feature of this reactor concept that the reactivity automatically decreases should the pump either fail or over speed. This is due to the slightly under

moderated state of the operating reactor as operating porosity is a little lower than the porosity corresponding to the peak reactivity.

The effects contributing to negative reactivity, such as depletion and fission fragment buildup, can be compensated by a combination of increased fluidization and changing the absorber shell position. This will eliminate the need to use solid burnable poison in the fuel and mix boron in the coolant, thus resulting in better neutron economy.

A detailed heat transfer analysis of the fuel elements has shown that due to high convective heat transfer coefficient and large heat transfer surface, the maximum power extracted from the reactor core is not limited to the material temperature limits, but to the maximum mass flow of the coolant corresponding to the desired operating porosity.

Assuming entering and exit coolant temperatures of 290° C, and 325° C, and making an energy balance, the thermal power production in Mwt may be calculated by the expression  $P=14.5 \epsilon^{3.4}$ . For operating porosities of 0.43 and 0.5 the power production is about 0.8 and 1.4 MWt per module which makes it a truly small reactor.

The collapsed core height of 70 cm requires 145 kg of UO<sub>2</sub> per module leading to a power density of about 100 MW/m<sup>3</sup> of fuel. The power per unit core volume of the reactor is 33.5 MW/m<sup>3</sup> compared to the 60 and 100 for BWR and PWR respectively. This power density can be increased by increasing the fuel enrichment and decreased by increasing the collapsed core height to be comparable to 3 and 6 MW/m<sup>3</sup> for modular and standard HTGR

respectively. The reactor power increases slightly with burnup as the operating porosity increases to compensate for the loss of reactivity.

The results under exaggerated operating conditions showed a maximum difference in fuel and clad surface temperature of 5° C. The temperature drop from clad surface to coolant varies between 2° C at the bottom and 5° C at the top of the reactor. The maximum fuel center and clad temperatures of less than 400° C are far below the reactor safety limits. Thus due to a high convective heat transfer coefficient and large heat transfer surface, the maximum power extracted from the reactor core is not limited to the material temperature limits, but to the mass flow of the coolant which corresponds to the desired operating porosity.

A thermal analysis of the fuel chamber under transient condition is made assuming that after a hypothetical loss of coolant accident (LOCA), all of the water vaporizes and the fuel elements fall into the fuel chamber in a dry condition. The decay heat is transferred to the chamber walls by conduction and radiation, and the chambers are cooled by natural convection. The results under adverse heat transfer conditions show that the integrity of the fuel and fuel chamber are maintained.

The transients of any nature are assumed to occur when the reactor is in normal operating condition, when the fuel and coolant temperatures are at 320° C and 310° C respectively. The fuel temperature rise assuming the burnout condition of  $h=1000 \text{ W/m}^2 \text{ }^\circ\text{K}$  and the extreme situation of fuel element finding itself in a minimum heat transfer condition, i.e., conduction through static vapor, such that  $h=5 \text{ W/m}^2 \text{ }^\circ\text{K}$ . It is found that even under such improbable

adverse conditions, the fuel pellet must stay under such situations for too long of a time in order to become damaged. Therefore, the transients will not cause sufficient increase in temperatures to damage the fuel elements.

In the analysis of the condition of fuel in the fuel chamber, after a loss-of-coolant accident, it is assumed that the fuel element immediately loses contact with the coolant and becomes surrounded by steam. This causes reduction of its convection heat transfer coefficient for which values of 1000, and 100 W/m<sup>2</sup>°K. are assumed. The decay heat is supposed only to be transported to the fuel chamber tube and moreover, only by convection, making the conservative assumption that the contact area between the spheres and the tube is small. The fuel chamber is 10 cm in diameter having a 1 cm thick wall. The results show that the fuel temperature at the center of the tube rise to a maximum of 890°C and decreases thereafter. This demonstrates the passive cooling characteristics of this nuclear reactor concept.

The fuel elements during operation and under transient conditions will maintain their integrity. A thermal analysis of the fuel chamber under transient condition even assuming that after a hypothetical loss of coolant accident, all of the water vaporizes and the fuel elements fall into the fuel chamber in a dry condition, shows that the reactor is passively cooled.

#### **4. POTENTIAL OF THE CONCEPT FOR MEETING THE GENERATION IV GOALS**

The simplicity of this reactor design results in short lead time, low capital and power generation costs. The likelihood of core damage is extremely low and moreover the suspended core can be removed from the reactor system at any desired instant. The inherent safety characteristic of the reactor makes it tolerant against any human errors or equipment failure. It may even be considered as safe against terrorist activities.

As the spent fuel elements are appropriate to be used directly as radiation source in agriculture and industrial applications, they may not be considered as nuclear waste thus increases the public acceptance of waste solution. If thorium were used in this reactor concept, it will make it less attractive to nuclear proliferates. The smallness of the reactor brings along with it numerous advantages widely described in the publications issued by the International Atomic Energy Agency.

A detailed analysis show that to a great extend the proposed fluidized bed nuclear reactor meets the requirements of the fourth generation nuclear reactors, namely: (1) Provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production. (2) Minimize and manage their nuclear waste and notably reduce the long term stewardship burden in the future, thereby improving protection for the public health and the environment. (3) Increase the assurance that they are a very unattractive and least desirable route for

diversion or theft of weapons-usable materials. (4) Excel in safety and reliability. (5) Have a very low likelihood and degree of reactor core damage. (6) Eliminate the need for offsite emergency response. (7) Have a clear life-cycle cost advantage over other energy sources. (8) Have a level of financial risk comparable to other energy projects.

## **5. STATUS OF TECHNOLOGY, AND TECHNOLOGY NEEDS FOR THE CONCEPT**

The fluidized bed nuclear reactor (FBNR) concept is believed to have inherent safety and passive cooling features. Until present time theoretical calculations with some non-nuclear experiments are performed. A zero power experiment on the reactor is planned in order to determine the feasibility of the reactor concept. To perform a zero power experiment on a simplified reactor module to observe the variation of reactivity of the system as a function of fluidized bed porosity. The degree of smoothness of the expected concave curve will determine the degree of the stability of the reactor core.

An open top aluminum tube of 20 Cm internal diameter connected to another one of 8 Cm in diameter below it will receive a flux of water from a pump. The 7-mm diameter spherical uranium dioxide pellets will be fluidized in the upper larger tube. The increase in the porosity is obtained through increase of flow rate. The system resembling a PWR fuel assembly is put in the LR-0 Facility of UJV (in Czech Republic) and the reactivity as a function of porosity is measured. LR-0 is an experimental facility with adequate instrumentation to determine the neutron characteristics of PWR and WWER type reactor lattices.

The spherical pellets are simply produced from the existing cylindrical PWR pellets by an adequate grinding procedure. This is to simplify and avoid the need to develop a new technology for spherical pellet fabrication. The fuel enrichment is that of common PWR fuel. About 300 Kg of fuel pellets is required for this experiment. The potential fuel pellets furnishers are being contacted for fabrication and cost estimation.

A cost estimate is below one million dollars. The principle expenses are the cost of fuel pellets and the rent of the LR-0 facility with its operator's support. It is hoped to receive financial support from governmental and non-governmental nuclear research and industrial organizations. It is expected that the European Commission will finance 50% of the cost of the project should at least two European countries show interest in the project.

Having performed this relatively simple and inexpensive zero power experiment, should the results confirm the theoretical predictions, we will have proven the existence of an inherently safe nuclear reactor. The rest is the available conventional PWR technology in its simplest form.

## **CONCLUSIONS**

The FBNR uses PWR technology in its simplest form. For its deployment there is no new technology to be developed. At a cost of less than one million dollars, its feasibility can be

fully demonstrated, and in less than 5 years the reactor can enter the market. It is a small and modular reactor being simple in design. Its spent fuel is in such a convenient form and size that may be utilized directly as the source for irradiation and applications in agriculture and industry. This results in a great positive impact on waste management and environmental protection.

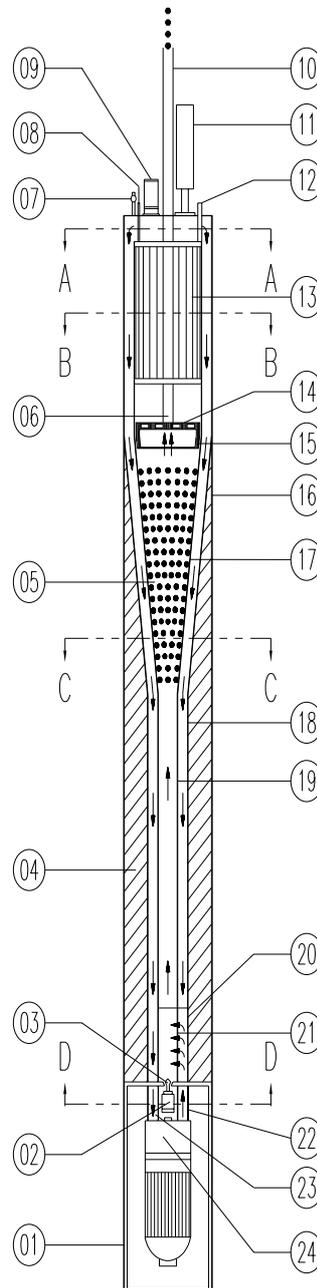
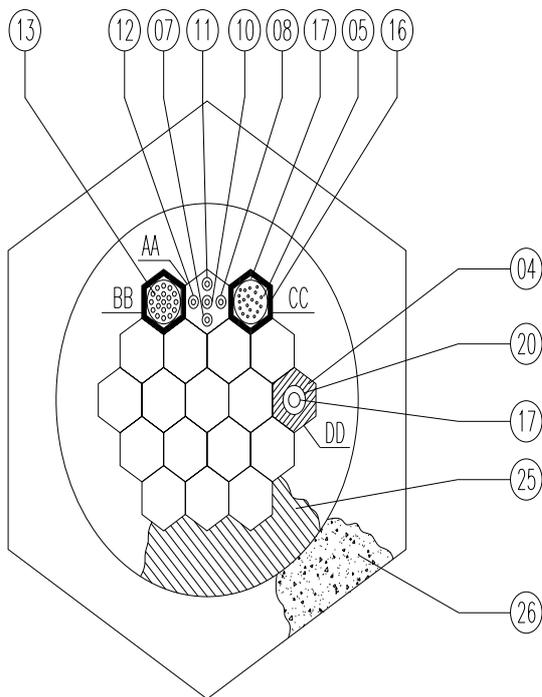
The advantages of the proposed design are being modular, low environmental impact, exclusion of severe accidents, short construction period, flexible adaptation to demand, excellent load following characteristics, and competitive economics.

The characteristics of the Fluidized Bed Nuclear Reactor (FBNR) concept may be analyzed under the light of the requirements set for the IV generation nuclear reactors. It is shown that FBNR meet the goals of (1) Providing sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production, (2) Minimize and manage their nuclear waste and notably reduce the long term stewardship burden in the future, thereby improving protection for the public health and the environment, (3) Increase the assurance that they are a very unattractive and least desirable route for diversion or theft of weapons-usable materials, (4) Excel in safety and reliability, (5) Have a very low likelihood and degree of reactor core damage. (6) Eliminate the need for offsite emergency response, (7) Have a clear life-cycle cost advantage over other energy sources, (8) Have a level of financial risk comparable to other energy projects.

This reactor concept is demonstrating its potential as a simple design using pressurized water reactor technology obtaining the desired characteristics of inherent and passive safety, integral plant having once-through type steam generator inside the module, controllable neutron spectrum, tight lattice, no soluble or burnable poison leading to increased neutron economy and reduced activity level, on load refueling, flexible fuel cycle choice, modular, shop fabrication, possibility of eliminating operators, ease of decommissioning tasks, underground containment, and a host of other positive features including the possibility of using its spent fuel (small clad fuel pellets) as a source of radiation for food irradiation, and industrial applications without the need for reprocessing.  
[http://www.rcgg.ufrgs.br/fbnr\\_ing.htm](http://www.rcgg.ufrgs.br/fbnr_ing.htm)

## REFERENCES

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2. Sefidvash, "Status of the fluidized Bed Nuclear Reactor", Nuclear Engineering and Design 167, 1996, 203-214.
3. Visit [www.rcgg.ufrgs.br](http://www.rcgg.ufrgs.br) about the fluidized bed nuclear reactor and the list of publications.
4. Visit <http://gen-iv.ne.doe.gov> about generation IV reactors.



Schematic diagram of the fluidized bed nuclear reactor: (1) structural support; (2) hydraulic valve opener; (3) fuel discharge valve; (4) graphite jacket; (5) reactor core; (6) level limiter shaft; (7) depressurizer; (8) steam exit; (9) level limiter drive; (10) fuel feed; (11) pressurizer; (12) water entrance; (13) steam generator; (14) level limiter; (15) absorber shell; (16) hexagonal channel; (17) fluidization tube; (18) circular channel; (19) fuel chamber; (20) distributor (21) entrance perforations; (22) coolant entrance; (23) coolant exit; (24) primary pump; (25) reflector; (26) biological shield.