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Non- Proliferation Resistance and Physical Protection of FBNR Nuclear Reactor

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Abstract. The greatest concern about nuclear energy is nuclear proliferation and physical protection of the nuclear reactors. Here, the small nuclear reactor FBNR is assessed in these respects using the methodology developed by the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) of IAEA. The results indicate that FBNR innovative design comply with the basic principles of the methodology and thus the FBNR may be considered to be a fool proof nuclear reactor against nuclear proliferation.

1. Introduction

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

The proliferation resistance is that characteristic of the reactor that impedes the diversion or undeclared production of nuclear materials by a country with the intention of acquiring nuclear weapons. The degree of proliferation resistance results from intrinsic features and extrinsic measures. Intrinsic proliferation resistance features result from the technical design of the reactor. Extrinsic proliferation resistance measures are those measures that result from country's decision and undertakings. Safeguard is an extrinsic measure comprising legal agreements between the countries and the IAEA.

There are four types of intrinsic proliferation resistance features. The first consists of the technical features of the reactor that reduce the attractiveness for nuclear weapon program. The second type is to prevent or inhibit the diversion of nuclear material. The third type is to prevent or inhibit the undeclared production of nuclear material. The fourth type is to facilitate verification including continuity of knowledge.

There are five types of extrinsic proliferation resistance measures. The first is the country's commitment to non-proliferation. The second category is the agreement between the exporting and importing countries about the use of the reactor. The third category consists of commercial, legal or institutional agreements on access to materials. The fourth category is application of IAEA verification measures. The fifth consists of legal arrangements against violations of non-proliferation.

Safeguarding nuclear material and facilities can be made more efficient and cost effective by improving the proliferation resistance of the system. By taking into account design features that facilitate the implementation of international safeguards very early in the design phase, a concept known as safeguards by design, the proliferation resistance of system can be improved.

Both the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) of IAEA and the Generation IV International Forum (GIF) present methodologies for the evaluation of nuclear reactors in respect to resistance to nuclear proliferation (PR) and physical protection (PP)..

2. GIF approach

GIF presents an evaluation methodology for proliferation resistance and physical protection (PR&PP) of Generation IV nuclear energy systems (NESs). The outcomes of the system response are expressed in terms of six measures for PR and three measures for PP, which are the high-level PR&PP characteristics of the NES.

Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

Proliferation Resistance (PR) is that characteristic of an NES that impedes the diversion or undeclared production of nuclear material or misuse of technology by the Host State seeking to acquire nuclear weapons or other nuclear explosive devices. *Proliferation Resistance* – Resistance to a Host State's acquisition of nuclear weapons by (1) Concealed diversion of material from declared flows and inventories, (2) Overt diversion of material from declared flows and inventories. (3) Concealed material production or processing in declared facilities, (4) Overt material production or processing in declared facilities, (5) Concealed material production or processing by replication of declared equipment in clandestine facilities.

Physical Protection (PP) (robustness) is that characteristic of an NES that impedes the theft of materials suitable for nuclear explosives or radiation dispersal devices and the sabotage of facilities and transportation by sub-national entities and other non-Host State adversaries. *Physical Protection (robustness)* by (1) Theft of nuclear weapons-usable material from facilities or transportation, (2) Theft of hazardous radioactive material from facilities or transportation for use in a dispersion weapon, (3) Sabotage at a nuclear facility or during transportation with the objective to release radioactive material to harm the public, damage facilities, or disrupt operations.

The basic evaluation approach developed by the GIF Expert Group comprises *definition of a set of threats* or challenges, evaluation of the system's *response* to these challenges, and expression of *outcomes* in terms of measures.

Physical Protection Probability of Adversary Success – The probability that an adversary will successfully complete a pathway and generate a consequence. *Consequences* – The effects resulting from the successful completion of the adversary‘s intended action described by a pathway, including the effects of mitigation measures. *Physical Protection Resources* – The staffing, capabilities, and costs required to provide PP, such as background screening, detection, interruption, and neutralization, and the sensitivity of these resources to changes in the threat sophistication and capability.

The PR&PP methodology provides the tools to assess NESs with respect to the security-related goals for Generation IV technologies to be —*a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.”*

Historically, assessments have considered a PP system consisting of a combination of intrinsic features and institutional framework designed to do the following: (1) Minimize and control access to nuclear material, radioactive material, facilities, and transportation systems, (2) Minimize the vulnerability of plant systems to postulated attack, and (3) Provide adequate response to postulated threats.

3. INPRO approach to proliferation resistance

Proliferation Resistance (PR) – That characteristic of a nuclear system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by States intent on acquiring nuclear weapons or other nuclear explosive device. The degree of proliferation resistance results from a combination of, *inter alia*, technical design features operational modalities, institutional arrangements and safeguards measures. These can be classified as intrinsic features and extrinsic measures. INPRO has defined one basic principle and five user requirements in the area of Proliferation Resistance (PR) for innovative nuclear systems (INS).

Proliferation resistance basic principle BP: *Proliferation resistance intrinsic features and extrinsic measures shall be implemented throughout the full life cycle for innovative nuclear energy systems to help ensure that INSs will continue to be an unattractive means to acquire fissile material for a nuclear weapons program. Both intrinsic features and extrinsic measures are essential, and neither can be considered sufficient by itself.*

This BP emphasizes the importance of both intrinsic features and extrinsic measures for achieving proliferation resistance. The development and implementation of intrinsic features that enhance proliferation resistance and are compatible with other design considerations should be encouraged. At the same time, regardless of the effectiveness of the intrinsic features, extrinsic measures will always be required. Even with the most proliferation resistant INS, extrinsic measures would be required to verify that the INS had not been modified so as to reduce the strength of the barriers provided by the intrinsic features.

The basic principle implies that intrinsic features and extrinsic measures for PR be implemented throughout the full life cycle of an INS. This requires that consideration be given to proliferation resistance in all major decisions made by the responsible bodies regarding an INS, including design concepts, R&D, demonstration facilities etc. The BP goes on to explain that the reason for such implementation is to help ensure that INSs will continue to be an unattractive means to acquire fissile material for a nuclear weapons program. The term *implemented* is used in this BP to refer to the range of activities (as described below) that occur over the life cycle of an INS:

- Early in the conceptual design the term *implemented* refers to consideration of PR in making basic design choices such as the fuel cycle. These design choices can provide intrinsic PR features (e.g. isotopic composition, chemical form, physical form, radiation fields, nuclear material flows and inventories, etc.) that affect the attractiveness of the nuclear material in production, use, transport, storage, and final disposal.
- As design progresses, the term *implemented* refers to making design choices that create other intrinsic PR features in the INS facilities, and policy choices that result in extrinsic measures that strengthen the PR of the INS.
- During construction, *implemented* means that key intrinsic features are verified (verification is an extrinsic measure), as the facilities are built.
- During operation of an INS, safeguards (extrinsic measures) are *implemented*. Operators must consider the impact of facility changes on the PR. In some cases other extrinsic measures such as fuel supply arrangements may be implemented to enhance proliferation resistance.
- During the shutdown and decommissioning phases for an INS *implemented* means that intrinsic features that affect PR, such as the inventories of nuclear material in the facilities, and the ease with which portions of the facilities could be restarted for use in a weapons program, are considered. In the explanation of the reason for requiring that PR features and measures be implemented, the BP includes the phrase “will continue to be”, implying that current nuclear technology provides a baseline standard for PR in a qualitative sense. The term fissile is used in this BP to refer to the fissile material that is ultimately required to make a nuclear explosive device (NED). This does not detract from the role that fertile nuclear material can serve in a nuclear weapons program, but recognizes that fertile material is used to generate fissile material to manufacture the NED.

4. INPRO approach to physical protection and safeguards

The term *physical protection* (PP) refers to the protection of a physical asset (as contrasted from information protection or cyber protection). Safeguard is an extrinsic measure comprising legal agreements between the party having authority over the nuclear energy system and a verification or control authority, binding obligations on both parties and verification using, inter alia, on site inspections. This term has different meanings depending on context. In this report, "safeguards" will refer to IAEA safeguards implemented under Safeguards Agreements between a State and the IAEA. "Regional safeguards" will be used to refer to a regime of independent international verification of commitments made by States within regional agreements such as the Euratom

One basic principle and twelve user requirements under this basic principle have been defined for the INPRO area of physical protection for an innovative nuclear system (INS).

Basic principle (BP): *A physical protection regime shall be effectively and efficiently implemented for the full lifecycle of an INS.*

The fulfillment of the user requirements to this basic principle will result in an effective and efficient PP regime for the full lifecycle of the INS. They address four general areas of the PP regime (1) the legislative and regulatory framework; (2) the siting, layout, and design of the INS components for PP; (3) the design of the PPS; and (4) the contingency planning and consequence mitigation.

It is the overall objective of the PP regime to minimize the susceptibility to and opportunity for unauthorized removal of nuclear material in use, storage or transport and of sabotage of nuclear material and nuclear facilities. This is achieved by implementing an effective and efficient PP regime. The effectiveness of the PP regime refers to its capability to prevent the successful execution of a malicious act and to prevent and/or mitigate radiological consequences thereof. The efficiency of the PP regime refers to the cost and resource use to achieve effectiveness. Both of these considerations are fundamental to developing an evolutionary or innovative nuclear energy system that can be sustained.

The responsibility for the establishment, implementation and maintenance of a PP regime within a State rests entirely with that State. In addition to the responsibility to ensure that nuclear material and nuclear facilities (including transports) are adequately protected within a State, the State is responsible for ensuring physical protection during the international transport there, until that responsibility is properly transferred to another State, as appropriate. The State should clearly identify the responsibility for implementing the various elements of the physical protection within the State. The State should ensure that the prime responsibility for the PPS rests with the holders of relevant licenses. Implicitly, the basic principle requires that an INS, when compared to existing nuclear energy systems today, will provide a *more* effective and efficient level of PP. This improved effectiveness and efficiency is achieved not only through better technology, but also through increased attention and forethought at the INS siting and design stage, and better coordination with and consideration by the other areas of INPRO methodology.

5. Description of the reactor

Small nuclear reactors without the need for on-site refueling have greater simplicity, better compliance with passive safety systems, and are more adequate for countries with small electric grids and limited investment capabilities. The Fixed Bed Nuclear Reactor

(FBNR) is based on the Pressurized Water Reactor (PWR) technology and the concept of a suspended fixed bed core. FBNR has an integrated primary circuit and is simple in design. It has the characteristics of being small (70 MWe), inherently safe and passively cooled reactor with reduced adverse environmental impact. The spherical fuel elements are fixed in the suspended core by the flow of water coolant. Any malfunction in the reactor system will cut off the power to the coolant pump causing a stop in the flow. This results in making the fuel elements fall out of the reactor core by the force of gravity and become stored in the passively cooled fuel chamber under sub critical condition.

The CERMET fuel is proposed for the FBNR reactor. The fuel consists of coated UO2 kernels embedded in a zirconium matrix which is then coated with a protective outer zircaloy 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, have 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 diameters, inside which, during the reactor operation, the spherical fuel elements are held together by the coolant flow in a fixed bed configuration, forming a suspended core. The coolant flows vertically up into the inner perforated tube and then, passing horizontally through the fuel elements and the outer perforated tube, enters the outer shell where it flows up vertically to the steam generator. The reserve fuel chamber is a 60 cm diameter tube made of high neutron absorbing alloy, which is directly connected underneath the core tube. The fuel chamber consists of a helical 40 cm diameter tube flanged to the reserve fuel chamber that is sealed by the national and international authorities. A grid is provided at the lower part of the tube to hold the fuel elements within it. A steam generator of the shell-and-tube type is integrated in the upper part of the module. A control rod can slide inside the centre of the core for fine reactivity adjustments. The reactor is provided with a pressurizer system to keep the coolant at a constant pressure. The pump circulates the coolant inside the reactor moving it up through the fuel chamber, the core, and the steam generator. Thereafter, the coolant flows back down to the pump through the concentric annular passage. At a flow velocity called terminal velocity, the water coolant carries the 15 mm diameter spherical fuel elements from the fuel chamber up into the core. A fixed suspended core is formed in the reactor. In the shut down condition, the suspended core breaks down and the fuel elements leave the core and fall back into the fuel chamber by the force of gravity. The fuel elements are made of UO_2 micro spheres embedded in zirconium and cladded by zircaloy.

The control system is conceived to have the pump in the "not operating" condition and only operates when all the signals coming from the control detectors simultaneously indicate safe operation. Under any possible inadequate functioning of the reactor, the power does not reach the pump and the coolant flow stops causing the fuel elements to fall out of the core by the force of gravity and become stored in the passively cooled fuel chamber. The water flowing from an accumulator, which is controlled by a multi redundancy valve system, cools the fuel chamber functioning as the emergency core cooling system. The other components of the reactor are essentially the same as in a conventional pressurized water reactor.

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

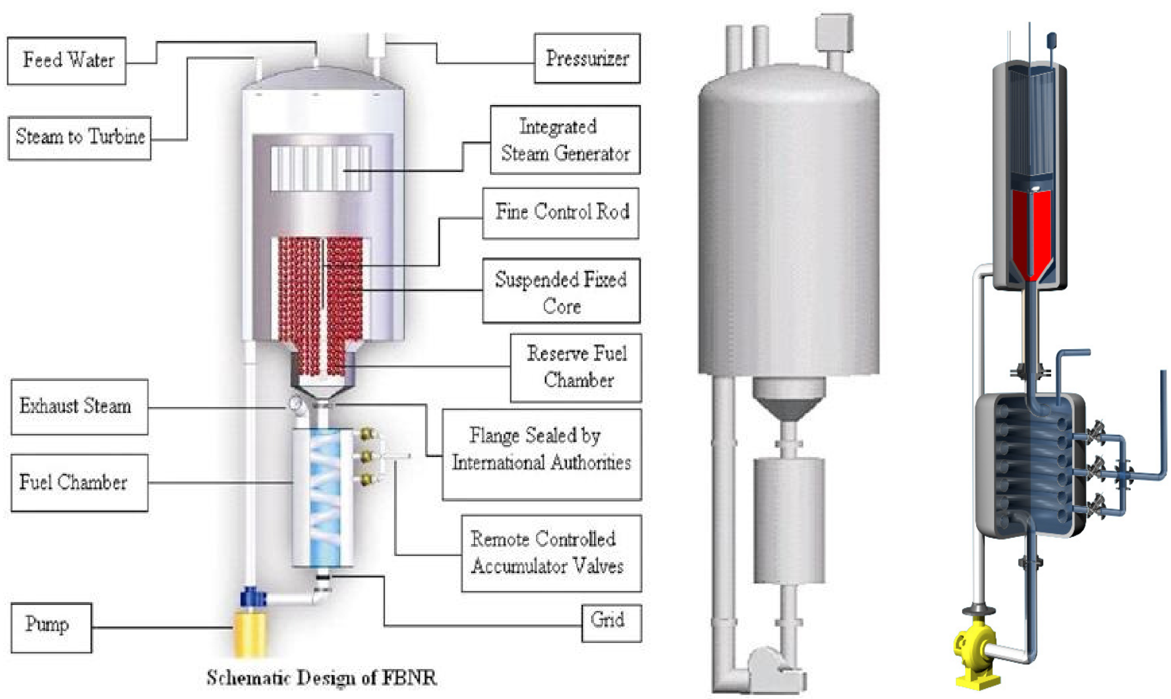

FIG. 2. Schematic Design of the Fixed Bed Nuclear Reactor (FBNR).

FIG. 3. FBNR Underground Containment Building.

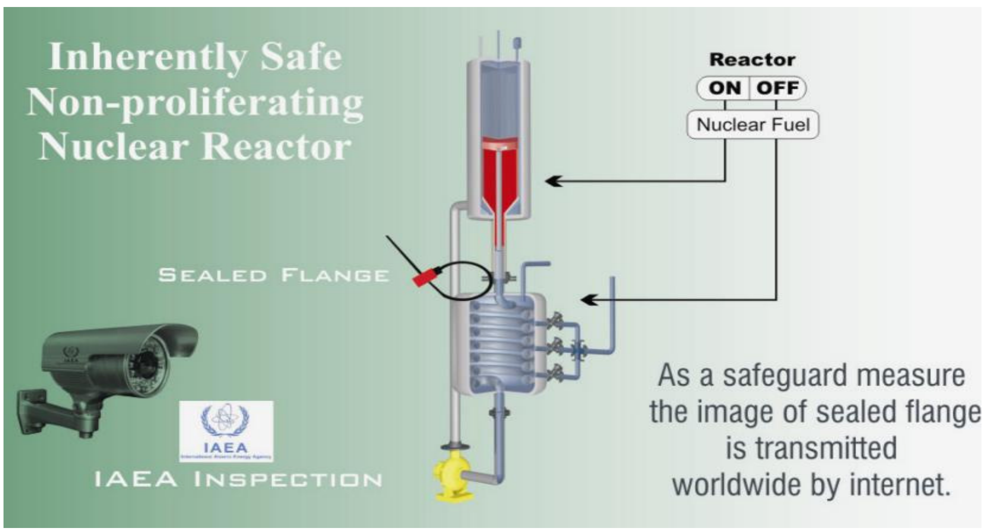

FIG. 4. Safeguard Measure.

6. Compliance of FBNR with INPRO requirements

The compliance of FBNR with the user requirements for proliferation resistance and physical protection is discussed below.

INPRO has defined five user requirements (UR) associated with the basic principle for Proliferation Resistance as follows:

UR1: *States' commitments, obligations and policies regarding nonproliferation and its implementation should be adequate to fulfill international standards in the non-proliferation regime.*

States' commitments, obligations and policies to meet conditions are such as the following: Party to international non-proliferation treaty NPT; Party to regional non-proliferation regimes; Comprehensive safeguards agreements in force; Additional protocol in force; Export control policies of nuclear material and nuclear technology; Regulatory body, designated in national legislation for implementing and applying safeguards agreements.

FBNR Compliance: These are the responsibilities of the State that will be met, but they are independent of the reactor concept.

UR2: *The attractiveness of nuclear material and nuclear technology in an INS for a nuclear weapons program should be low.*

FBNR Compliance: 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.

If the U- Pu cycle is applied, one can increase the Pu-238 concentration by adding Np to the fresh fuel. From a certain concentration of Pu-238 on, the alpha decay heat is so strong that the metallic Pu-sphere, as well as the surrounding chemical explosives, in a nuclear device become plastic or even melts so that the fuel of the reactor at any time is not useful for weapons. Thus, the combination of sealing the fuel chamber of the reactor, and the isotopic denaturing of the fuel will additionally make it unattractive for misuse and increases its proliferation resistance.

The reactor core is surrounded by a jacket of flowing water, thus there is insufficient neutron leakage for irradiation purposes outside the pressure vessel. The reactor vessel may additionally be cladded by neutron absorbing materials, if necessary, to eliminate the possibility of neutron irradiation to any external fertile material. Only the fuel chamber is needed to be transported from factory to the site and return.

UR3: *The diversion of nuclear material should be reasonably difficult and detectable.*

This involves accountancy of nuclear material, Containment/surveillance of nuclear material (NM), Monitoring of nuclear material, Inspection of nuclear material, Information collection and analysis, Difficulty of diversion of NM, quality of measurement system, measures and monitoring, delectability of NM

FBNR Compliance: The FBNR will not be refueled on the site. Refueling is done in the factory. The fuel elements are confined in the fuel chamber. The FBNR modules are fabricated, fueled, and sealed in the factory under the supervision of the IAEA safeguard program.   They are taken to the site and installed in the reactor and the spent fuel chamber will return to its final destination as sealed. The fuel chamber is stored in a passively cooled intermediate storage at the reactor site before going to the final disposal site or to the reprocessing plant or any other future destination. This should assure the safeguard of the nuclear fuel.

The sealed flange is under surveillance by a camera that transmits images to anywhere in the world by internet.

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.

UR4: *Innovative nuclear energy systems should incorporate multiple proliferation resistance features and measures.*

FBNR Compliance: Adopting a thorium cycle as an intrinsic measure will hinder the possibility of misuse of nuclear materials for nuclear weapons. The mixing of thorium with low enriched uranium or plutonium results in the production of U-233 that is diluted along with U-235 in U-238. The access to uranium-233 will only be possible through isotope separation techniques. Additionally the production of gamma emitting Tl-208 in the thorium cycle is hindrance to nuclear proliferation.

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.

UR5: *The combination of intrinsic features and extrinsic measures, compatible with other design considerations, should be optimized (in the design/engineering phase) to provide cost-efficient proliferation resistance.*

FBNR Compliance: 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 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.

The establishment of Multilateral Fuel Cycles (perhaps on a regional basis) will be of benefit to the deployment of many advanced reactors independent of their particular type. Specifically, an option for fuel or nuclear power plant leasing coupled with an option of Multilateral Fuel Cycles may be of essential benefit for the deployment of such reactors in many developing countries that are embarking on a nuclear program without having a sufficient nuclear infrastructure.

The proposed reactor 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 user requirements (UR) for Physical Protection (PP) are:

(UR1) Legislative and regulatory framework: *Prior to the deployment of the INS the legislative and regulatory framework to govern PP should be established.*
(UR2) Integration of PP throughout INPRO: *Physical protection should be integrated into all INPRO areas and throughout all phases.*
(UR3) Trustworthiness: *A program to determine trustworthiness should be defined and implemented.*
(UR4) Confidentiality: *Sensitive information developed for all areas of INPRO should be protected in accordance with its security significance.*
(UR5) Threat: *The physical protection systems should be based on the State's current evaluation of the threats.*
(UR6) Graded approach: *Physical protection requirements should be based on a graded approach.*
(UR7) Quality assurance: *Quality assurance policy and programs for all activities important to PP should be established and implemented.*
(UR8) Security culture: *All organizations involved in implementing physical protection should give due priority to development, maintenance and effective implementation of the security culture in the entire organization.*
(UR9) PP considerations in siting: *The PP should be considered when siting INS components.*

FBNR Compliance: UR1-9 are the responsibilities of the State that will be met, but are independent of the reactor concept.

(UR10) INS layout and design: *INS component layout and design should be developed to minimize susceptibility and opportunities for malicious action.*
(UR11) Design of PPS: *The physical protection system of all INS components should be developed in uniform layers of protection using a systematic approach.*
(UR12) Contingency plans: *Contingency plans to respond to unauthorized removal of nuclear material or sabotage of nuclear facilities/transport or of nuclear material, or attempts thereof, should be prepared and appropriately exercised by all license holders and authorities concerned.*

FBNR Compliance: UR10-12 are easily met by the fact that FBNR is not refueled on the site. Refueling is done in the factory. The fuel elements are confined in the fuel chamber. The FBNR modules are fabricated, fueled, and sealed in the factory under the supervision of the IAEA safeguard program. They are taken to the site and installed in the reactor and the spent fuel chamber will return to its final destination as sealed. The fuel chamber is stored in a passively cooled intermediate storage at the reactor site before going to the final disposal site or to the reprocessing plant or any other future destination. This should assure the safeguard of the nuclear fuel. The fuel chamber is under surveillance by a camera that transmits images to anywhere in the world by internet.

7. Conclusions

The proposed reactor meets all the IAEA-INPRO requirements for non-proliferation. The concept is based on both sealing of the fuel chamber and denaturing of the fuel itself.

The fuel chamber is under surveillance by a camera that transmits images to anywhere in the world by internet. The sealing of the fuel chamber with remote surveillance permits the control from "cradle to grave" allowing the continuity of knowledge (COK) about the fuel, thus guaranteeing an effective safeguard control. There is no possibility of irradiating fertile material in FBNR to produce fissile material illegally.

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 a fool proof reactor against nuclear proliferation that the present world is looking for.

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