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ASSESSMENT OF TWO SMALL-SIZED INNOVATIVE NUCLEAR REACTORS FOR ELECTRICITY GENERATION IN BRAZIL USING INPRO METHODOLOGY

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ABSTRACT

This paper presents the results of the assessment study of two small-sized innovative reactors for electricity generation in Brazil using the methodology developed under the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), co-ordinated by the International Atomic Energy Agency (IAEA). INPRO was initiated in 2001 and has the main objective of helping to ensure that nuclear energy is available to contribute in a sustainable manner to the energy needs of the 21st century. Brazil joined the project since its beginning and in 2005 submitted a proposal for the assessment using INPRO methodology of two small-sized reactors (IRIS and FBNR) as potential components of an innovative nuclear energy system (INS) completed by a conventional open nuclear fuel cycle. The assessment study was restricted to the reactor component of the INS and to the methodology areas of economics, proliferation resistance and reactor safety. The results indicate that both IRIS and FBNR innovative designs comply mostly with the basic principles of the areas assessed and have potential to comply with the remaining ones.

1. INTRODUCTION

Recent studies conducted by the Energetic Research Company of the Ministry of Mines and Energy predict an expansion of about 5,300 MWe in Brazil's nuclear-electricity installed-capacity in the next twenty-five years [1]. A first step towards this goal was taken by the National Council for Energy Policy on June 2007 with the approval of the re-start of the construction of the 1,350 MWe Angra 3 Unit, a conventional KWU/Siemens PWR design. Advanced (evolutionary and innovative) nuclear power plants designs and associated fuel cycles are now being considered for future deployment, including but limited to pressurised water reactor technology and improved once-through nuclear fuel cycle with no reprocessing.

The International Project on Innovative Nuclear Reactors and Fuel cycles – INPRO – launched by IAEA in 2000 offers a methodology for the holistic assessment of innovative nuclear energy systems (INS) composed of nuclear power plants and associated nuclear fuel cycles together with all related infrastructure. INPRO also serves as a forum to bring together technology holders and technology users to consider jointly the research and development actions necessary to bring the desired innovations into reality [2]. Brazil joined INPRO since its initial stages and participated in the project Phase 1B by performing the assessment of two small-sized innovative nuclear reactors – the *International Reactor Innovative and Secure (IRIS)* and the *Fixed Bed Nuclear Reactor (FBNR)* – using INPRO methodology. The reactors were assessed independently as part of an innovative nuclear energy system (INS) completed by an indigenous once-through fuel-cycle with enriched uranium oxide and no reprocessing requirements. The scope of the assessment was limited to the reactor component of the INS and to the areas of reactor safety and economics for IRIS, and reactor safety and proliferation resistance for the FBNR reactor. The IRIS reactor was assessed by experts from the CNEN's research institutes, CDTN, IPEN and IEN. The FBNR reactor was assessed by experts from the UFRGS. The objective of this paper is to summarise the main results of the assessment study performed.

2. OUTLINE OF INPRO METHODOLOGY

The INPRO methodology [3] has been developed for screening an innovative nuclear system (INS), for comparing different INSs to find a preferred one consistent with the sustainable development of a given State, and for identifying the research, development and demonstration needed to improve the performance of existing components of an INS and/or to develop new components. An INS encompasses all nuclear facilities of the front and back end of a nuclear fuel cycle, i.e., mining/milling, conversion, enrichment, fuel fabrication, reactor, reprocessing and materials management (including transportation, storage and waste management), together with all related infrastructure measures.

The INPRO methodology identifies a set of basic principles (BPs), user requirements (URs) and criteria (CRs) in a hierarchical manner as the basis for the assessment of a INS. The highest level in the INPRO hierarchy is BP, which is a statement of a general goal that is to be achieved in an INS. The second level is a UR that sets out the measures to be taken (mostly by the designers/developers but also by owners/operators and government institutions) to meet the general goal of the corresponding BP. On the third level of hierarchy, to verify whether the UR have been properly met, the assessor of the INS uses a CR with associated indicators (INs) and acceptance limits (ALs). All indicators have, in principle, the same relative importance but the assessor can apply a weighting method for aggregation of the indicators, if he so wishes.

INPRO takes a holistic approach to assess INSs in seven areas namely, economics, safety, waste management, environment, proliferation resistance, physical protection and infrastructure. The BPs of the areas considered in this study are indicated below. Detailed discussion of the corresponding URs, CRs and ALs can be found in Ref. [3].

Economic Basic Principle BP1: Energy and related products and services from innovative nuclear energy systems shall be affordable and available.

Proliferation resistance BP1: 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.

Safety BP1: Installations of an INS shall incorporate enhanced defence-in-depth as a part of their fundamental safety approach and ensure that the levels of protection in defence-in-depth shall be more independent from each other than in existing installations.

Safety BP2: Installations of an INS shall excel in safety and reliability by incorporating into their designs, when appropriate, increased emphasis on inherently safe characteristics and passive systems as a part of their fundamental safety approach.

Safety BP3: Installations of an INS shall ensure that the risk from radiation exposures to workers, the public and the environment during construction/commissioning, operation, and decommissioning, are comparable to the risk from other industrial facilities used for similar purposes.

Safety BP4: The development of INS shall include associated research, development and demonstration work to bring the knowledge of plant characteristics and the capability of analytical methods used for design and safety assessment to at least the same confidence level as for existing plants.

3. DESCRIPTION OF THE INS CHOSEN

Brazil employs nuclear power since the 80's, with the operation of its first nuclear power plant, Angra 1, a 657 MWe PWR Unit of Westinghouse design. The country has an existing nuclear power infrastructure, including institutional measures, and possesses large reserves of uranium and thorium. Currently, Brazil operates, besides Angra 1, a second larger nuclear power unit, Angra 2, a 1350 MWe PWR of Siemens/KWU design, and dominates the technology of all phases of the nuclear fuel cycle, including enrichment. The government is now considering the construction of an industrial unit for the uranium conversion phase to complete the whole indigenous production chain of the nuclear fuel cycle. This infrastructure was taken into account when selecting the following INS for assessment:

Full INS structure:
Advanced thermal reactor with open fuel cycle based on enriched uranium.

Nuclear reactor technology:
Advanced pressurised water reactor PWR technology, with innovative features. Selected INS nuclear reactor components: *International Reactor Innovative and Secure – IRIS* and *Fixed Bed Nuclear Reactor – FBNR*.

Nuclear fuel cycle technology:
All indigenous nuclear capacity and facilities available, including uranium mining and milling, uranium conversion, uranium enrichment, fuel fabrication, electricity generation and waste management facilities. Waste storage facilities are considered part of the nuclear power plant, but waste disposal facilities are not taken into account.

3.1. Overview description of the IRIS reactor

IRIS [4-6] is a modular, small power (335 MWe per module), pressurised water reactor that utilises an integral reactor coolant system layout and a conventional refuelling scheme. While firmly based on the proven light water reactor (LWR) technology, the IRIS project has introduced many engineering and project innovations that define its unique characteristics, as claimed by its designers, such as: a safety-by-design™ approach, which aims at eliminating by design the possibility for an accident to occur, rather than dealing with its consequences; enhanced and easier to implement security, based on its design characteristics; enhanced proliferation resistance through extended refuelling cycle, while retaining use of current demonstrated fuel, facilitating international safeguards; and economic gains, through simplicity, modularity, and economy of serialisation instead of economy of scale. For illustration the integrated primary system design of IRIS is briefly described next:

The Integral Reactor Coolant System

IRIS employs an integrated primary system that incorporates all main primary circuit components within a single vessel, i.e., the core with control rods and their drive mechanisms, eight helical coil steam generators with eight associated fully-immersed axial flow pumps, and a pressurizer (see Figure 1). This integral reactor vessel arrangement eliminates the individual component pressure vessels and large connecting loop piping between them, resulting in a more compact configuration and in the elimination of the large loss-of-coolant accident as a design basis event. Water flows upward through the core and then through the riser region (defined by the extended core barrel). At the top of the riser, the coolant is directed into the upper part of the annular plenum between the extended core barrel and the reactor vessel inside wall, where the suction of the reactor coolant pumps is located. Eight coolant pumps are employed, and the flow from each pump is directed downward through its associated helical coil steam generator module. The primary flow path continues down through the annular downcomer region outside the core to the lower plenum and then back to the core completing the circuit. The IRIS integral vessel is larger than a traditional PWR pressure vessel, but the size of the IRIS containment is a fraction of the size of corresponding loop reactors, resulting in a significant reduction in the overall size of the reactor plant.

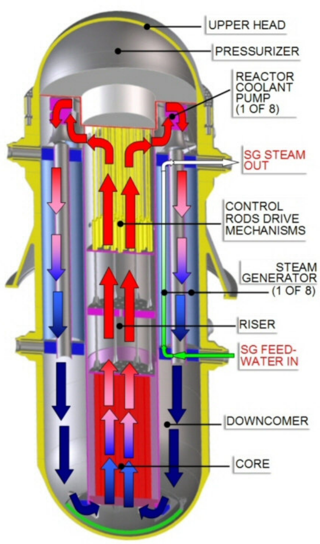

Figure 1. IRIS integral layout

3.2. Overview description of the FBNR reactor

FBNR [7,8] is a small power reactor (70 MWe) without the need of onsite refuelling. It utilises well proven PWR technology and has the characteristics of being simple in design, modular, inherently safe, passively cooled, proliferation resistant and causes reduced adverse environmental impact.

The FBNR has a fuel chamber located below the core. The fuel chamber is to be fuelled in the factory. The fuel chamber in sealed form is then transported to and from the site. Therefore, there is no need for onsite refuelling. The reactor uses PWR technology and has an integrated primary system design. The 15 diameter spherical fuel elements are made of UO2 microspheres embedded in zirconium matrix and cladded by zircaloy. For illustration, the integrated primary system design of FBNR is briefly described below:

The Integral Reactor Coolant System

The reactor as shown in the schematic Figure 2 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 172 cm in diameters inside which, during the reactor operation, the spherical fuel elements are held together by the forced coolant flow in a fixed bed configuration forming a suspended core. The reserve fuel chamber is a 30 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 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. A grid is provided at the lower part of the tube to hold the fuel elements within it. 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.

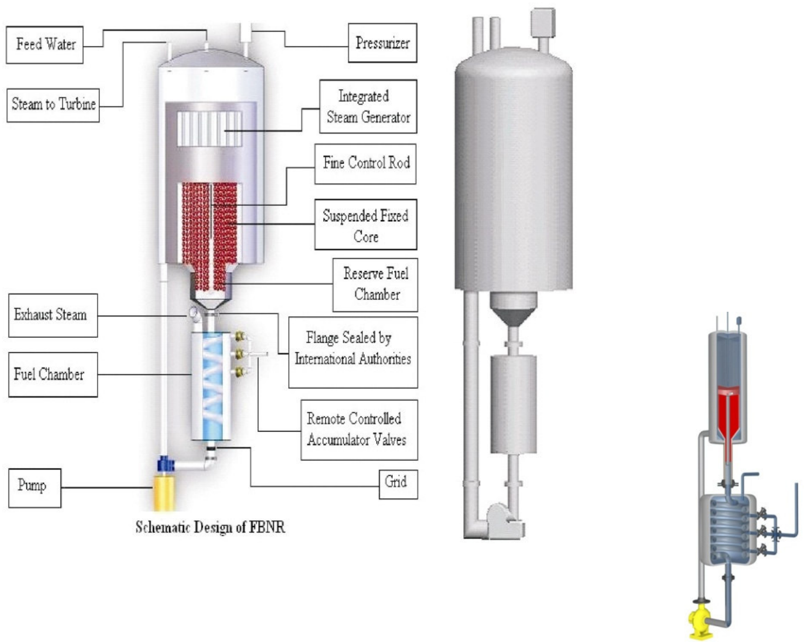

Figure 2. FBNR integral layout

The pump circulates the water coolant inside the reactor moving it 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 shell-and-tube type steam generator integrated in the upper part of the module. 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 fuel elements from the fuel chamber up into the core. A fixed suspended core is thus formed in the reactor. The long-term reactivity is supplied by fresh fuel addition and boron poisoning of the moderator. A fine control rod may be provided to move in the centre of the core that can control the short-term reactivity. 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 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. Any signal from any of the detectors, due to any initiating accident event, will cut-off the power to the pump, causing the fuel elements to leave the core and fall back into the fuel chamber by the force of gravity, 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 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.

3.3. Reference reactor – Angra 2

The application of INPRO methodology requires verification of the compliance of the values of the indicators with the corresponding acceptance limits (ALs). Some of the ALs in the current version of INPRO methodology have been defined as *superior to existing designs* (currently operating plants may refer to a set of plants which are currently under operation and are defined to be the most representative within their category).

For reasons of availability and access to the design data needed for the study, the Angra 2 NPP, located near the city of Angra dos Reis, was selected as the reference reactor. Designers of the plant and containment were KWU Group of Siemens Aktiengesell-schaft (today Framatone ANP), and Nuclebrás Engenharia S.A. – Nuclen, today Eletrobrás Termonuclear S.A. – Eletronuclear, Rio de Janeiro [9].

4. SUMMARY RESULTS OF THE ASSESSMENT

The results of the assessment of the IRIS and FBNR reactors using INPRO methodology are summarised next. Both reactors were initially assessed with regard to safety of the nuclear power plant. IRIS was further assessed with regard to Economics and the FBNR reactor for Proliferation Resistance. The results are summarised in accordance with the terminology introduced in the Head Chapter of INPRO Manual [3]: if the value of the indicator is acceptable, the judgement is that the INS *complies with* or *has potential* to fulfil the specific criterion assessed. Otherwise, the judgement becomes *non-compliant* or *no potential* for this criterion. This judgement procedure is repeated likewise for all criteria of a user requirement, then for all user requirements of a basic principle and finally for all basic principles of a methodology area. The rationale for each judgement is documented in full detail in the Refs. [10-11].

4.1. Economic Assessment of the IRIS reactor

The objective was to perform a fast evaluation of the potential economic competitiveness of the IRIS reactor to contribute to the expansion of the ***nuclear-electricity installed-capacity*** in Brazil between 2005-2030. The reference scenario in the *National Plan of Energy 2030* [1] indicated that new *5,345* MWe of nuclear origin should be deployed in the country during this 25 years period. After the expected start of operation in 2013 of Angra 3 NPP, a 1,350 MWe KWU/Siemens design plant twin to Angra 2 unit, four other units of about 1,000 MWe each shall be deployed at an average time interval of five years.

To fulfil this energy scenario, a plant arrangement of three independent IRIS reactor single units of 335 MWe each, equivalent to a total installed capacity of 1005 MWe, to start full operation in 2020, is assessed here. This plant arrangement is based on the assumption that the three units would be constructed in series in a “slide-along” manner. Thus, the units would be started up in sequence as construction, pre-operation testing, fuel load and start-up testing are all completed for a unit. The units will be spaced sufficiently apart so that the first completed unit could be operated while construction of the subsequent one is still in progress. As an alternative to the deployment of the IRIS three single-units site arrangement, a large unit, similar to Angra 3, was considered in this study in order to exploit the recent feasibility studies performed by Eletronuclear for approval of the completion of Angra 3 construction.

With regard to the nuclear fuel cycle, the INS proposed considers that all the different elements of the once-through (OT) fuel cycle will be bought from the internal market. However, since some stages of the fuel cycle (namely, conversion and enrichment) are not fully commercially available in the country at the time of preparing this report, a different approach was followed for the nuclear options assessed. For IRIS, the fuel cycle costs were determined from the international market, whereas for the Angra 3 reactor type the fuel costs for operating the twin Angra 2 unit were used. These latter costs are a combination of the costs of the fuel cycle services (milling, mining, reconversion and fabrication) already provided by the Brazilian Nuclear Industries (INB) and those services (conversion and enrichment) contracted in the international market. For better comparison with the reference date for the reactor system costs, most of the fuel cycle costs are in US$ of December 2004.

Under these assumptions, 6 out of 8 indicators of the economics area are acceptable (75%) and 2 others have potential to be acceptable (25%) (Table 1). Of the 3 user requirements considered, the first two on *cost of energy* (UR1) and *ability to finance* (UR2) are acceptable and the third one, on *risk of investment* (UR3) has high potential to be acceptable. From these results, it follows that IRIS design has potential to comply with the BP (*energy affordability and availability*) of the economics area.

Table 1. Indicators and judgement of potential of INS: Economics area – IRIS [10]

BP	UR	Indicators	Judgement of Potential
1	1	IN1.1	Compliant
	2	IN2.1/EP2.1.1, IN2.1/EP2.1.2, IN2.2	Compliant
	3	IN3.1, IN 3.2	Potential
		IN3.3, IN 3.4	Compliant

4.2. Safety assessment of the IRIS reactor

IRIS design includes innovative safety features and provides for multiple levels of defence for accident prevention and mitigation (defence-in-depth). Because of the safety by design approach, the number and complexity of these passive safety systems and the required operator actions are further minimised. Thus, it is anticipated that its safety assessment by INPRO methodology, which includes the evaluation of 4 basic principles, 14 user requirements and 38 numerical or logical indicators, should be quite favourable. In fact, the assessment results show that the values of 31 out of the 38 indicators are acceptable (82%) and 4 others have potential to be acceptable (11%). One indicator has yet to be evaluated (analyses and/or experiments have yet to be performed) and 2 indicators were found non-applicable (Table 2).

Table 2. BPs, URs, INs and judgement of potential of INS: Safety area – IRIS [10]

BP	UR	Indicators	Judgement of Potential
1	1	IN1.1.1, IN1.1.3, IN1.1.4, IN1.1.5, IN1.1.6	Compliant
		IN1.1.2	Potential
	2	IN1.2.1	Compliant
	3	IN1.3.1, IN1.3.2, IN1.3.3, IN1.3.4, IN13.5., IN1.3.6	Compliant
	4	IN1.4.1, IN1.4.2, IN1.4.3	Compliant
	5	IN1.5.1, IN1.5.2, IN1.5.3	Compliant
	6	IN1.6.1	Compliant
	7	IN1.7.1	Potential
		IN1.7.2	Compliant
2	1	IN2.1.1, IN2.1.2, IN2.1.3,IN2.1.4	Compliant
3	1	IN3.1.1	Compliant
	2	IN3.2.1	Potential
4	1	IN4.1.1, IN4.1.2, IN4.1.3	Compliant
	2	IN4.2.1	Potential
		IN4.2.2	Compliant
		IN4.2.3	Non applicable
	3	IN4.3.1	Compliant
		IN4.3.2	Non applicable
	4	IN4.4.1	Compliant
		IN4.4.2	To be judged

From the indicators results, it follows that IRIS design complies with 5 out of 7 of the URs of BP1 *(enhanced defence-in-depth)*; complies fully with the BP2 *(inherent safety and reliability)*; and has high potential to comply with BP3 *(risk of radiation)* and BP4 *(Research, Development and Demonstration)* of the reactor safety area.

4.3. Proliferation resistance of the FBNR reactor

FBNR is a small reactor without on-site refueling without any fresh and spent fuel being stored at the site for a long time during its service life. It also ensured difficult unauthorized access to fuel during the whole period of its presence at the site and during transportation, and design provisions are taken to facilitate the implementation of safeguards. FBNR will be factory produced and fueled and brought back to the factory for refueling after its fuel lifetime expires. FBNR fuel chambers are fabricated, fueled, and sealed in the factory under the supervision of the IAEA safeguard program. The fuel chamber is taken to the site and installed in the reactor and will return to the factory sealed for refueling.

The 15 mm diameter spherical fuel elements are stored in the reactor's fuel chamber. The fuel elements, through the flow of coolant, move up into the reactor core when the reactor is in operation. Under a reactor shut-down or any accident condition, the fuel elements fall out of the core by the force of gravity and become stored in the fuel chamber and remain in subcritical and passively cooled conditions. The fuel chamber is made of a helical tube having a grid in its lower part and a flange in the upper part. The fuel chamber is flanged to the reactor and sealed by the safeguard authorities.

The non-proliferation-characteristics of FBNR are thus based on both extrinsic measures and the intrinsic concept of isotope denaturing. Based on the extrinsic measures and the reactor intrinsic features, it is envisaged that FBNR is a foolproof reactor against nuclear proliferation. The diversion of fuel is obviously impossible when the reactor is operation; therefore, care must be taken only during refuelling. The procedure involves bringing the fuelled fuel chamber from the factory to the site and (1) connect the fuel chamber to the reactor, (2) seal the flange by the safeguard authorities, (3) have a camera focused on the seal, and programs it to film only when the reactor is shut down. This procedure should assure the safeguard of the nuclear fuel. The shielding requirements of the FBNR fuel chamber for its transportation from the site to the factory (and vice versa) for refuelling present no extra burden in comparison with those for transportation of spent nuclear fuel from other reactors.

The results of the assessment indicate that all indicators are acceptable. The FBNR design complies with the 5 URs and the BP of the INPRO proliferation resistance area (Table 3).

Table 3. BP, URs, INs and judgement of potential of INS: Prolif. Resist. – FBNR [10]

BP	UR	Indicators	Judgement of Potential
1	1	IN1.1, IN1.2,	Compliant
	2	IN2.1, IN2.2, IN2.3, IN2.4	Compliant
	3	IN3.1, IN3.2, IN3.3, IN3.4, IN3.5, IN3.6	Compliant
	4	IN4.1, IN4.2	Compliant
	5	IN5.1, IN5.2, IN5.3	Compliant

4.4. Safety assessment of the FBNR reactor

With regard to the reactor safety area, the assessments results show that the values of only 29 out of 38 indicators are acceptable (76%) and 9 others have potential to be acceptable (24%). The relatively high percentage of *acceptable* results in the performed judgement reflects that, despite the project's low level of maturity (conceptual stage), the FBNR innovative design is compliant with most of the BPs of the reactor safety area of INPRO methodology (Table 4).

Table 4. BPs, URs, INs and judgement of potential of INS: Safety area – FBNR [10]

<table>
<tr><th>BP</th><th>UR</th><th>Indicators</th><th>Judgement of Potential</th></tr>
<tr><td rowspan="11">1</td><td>1</td><td>IN1.1.1, IN1.1.2, IN1.1.3, IN1.1.4, IN1.1.5, IN1.1.6</td><td>Compliant</td></tr>
<tr><td>2</td><td>IN1.2.1</td><td>Compliant</td></tr>
<tr><td>3</td><td>IN1.3.1, IN1.3.2, IN1.3.3, IN1.3.4, IN13.5., IN1.3.6</td><td>Compliant</td></tr>
<tr><td rowspan="2">4</td><td>IN1.4.1</td><td>Potential</td></tr>
<tr><td>IN1.4.2, IN1.4.3</td><td>Compliant</td></tr>
<tr><td rowspan="2">5</td><td>IN1.5.1, IN1.5.2</td><td>Potential</td></tr>
<tr><td>IN1.5.3</td><td>Compliant</td></tr>
<tr><td>6</td><td>IN1.6.1</td><td>Potential</td></tr>
<tr><td rowspan="2">7</td><td>IN1.7.1</td><td>Compliant</td></tr>
<tr><td>IN1.7.2</td><td>Potential</td></tr>
<tr style="display:none"></tr>
<tr><td>2</td><td>1</td><td>IN2.1.1, IN2.1.2, IN2.1.3,IN2.1.4</td><td>Compliant</td></tr>
<tr><td rowspan="2">3</td><td>1</td><td>IN3.1.1</td><td>Compliant</td></tr>
<tr><td>2</td><td>IN3.2.1</td><td>Compliant</td></tr>
<tr><td rowspan="6">4</td><td>1</td><td>IN4.1.1, IN4.1.2, IN4.1.3</td><td>Compliant</td></tr>
<tr><td rowspan="2">2</td><td>IN4.2.1</td><td>Potential</td></tr>
<tr><td>IN4.2.2, IN4.2.3</td><td>Potential</td></tr>
<tr><td rowspan="2">3</td><td>IN4.3.1</td><td>Compliant</td></tr>
<tr><td>IN4.3.2</td><td>Potential</td></tr>
<tr><td>4</td><td>IN4.4.1, IN4.4.2</td><td>Compliant</td></tr>
</table>

From the indicators results, it follows that FBNR design complies with 3 out of 7 of the user requirements of BP1 *(enhanced defence-in-depth)*; complies fully with the BP2 *(inherent safety and reliability)* and BP3 *(risk of radiation)* and has potential to comply with BP4 *(research, development and demonstration).*

5. CONCLUSIONS

In this work the results of the assessment study using INPRO methodology performed on two small sized reactors as alternatives components of a INS completed with a open fuel cycle based on enriched uranium has been presented.

For IRIS, the high percentage of *acceptable* results for the indicators reflects the maturity of this reactor design (preliminary licensing stage). Overall these results indicate that IRIS innovative design already complies mostly with the BPs of the reactor safety area and fully with the BP of the economics area.

For FBNR, concerning the reactor safety area, the relatively high percentage of *acceptable* results reflects the fact that, despite the project's low level of maturity (conceptual stage), its innovative design already complies with most of the BPs of this area and has potential to comply with the remaining ones. Regarding the proliferation resistance area, the assessment results indicate the FBNR design complies fully with BP of this area.

A natural follow-up action would be the extension of the study to the remaining INPRO areas not covered in this first exercise but no steps have been taken in this direction up to now.

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