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Converting the Iranian heavy water reactor IR-40 to a more proliferation-resistant reactor

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This article assesses the feasibility and benefits of converting the Iranian heavy water research reactor, IR-40, from using natural uranium to low-enriched uranium fuel. Based on neutronics calculations for a detailed model of the two reactor configurations, a conversion would result in a smaller core with a subsequent reduction and degradation of plutonium production. It is argued that the proposed conversion will provide Iran with a research reactor that is better suited for scientific experiments and radioisotope production than IR-40 in its original configuration. It is proposed to introduce the converted IR-40's fuel consumption requirements as a natural cap for Iran's future enrichment efforts.

Introduction

Iran is currently constructing a 40 MW_{th} heavy water research reactor fuelled with natural uranium (NU) near the city of Arak. The construction of the reactor started in 2004, and it is scheduled to commence operations in 2014.¹ Once the reactor starts operating, it is estimated that it can produce up to 10 kg of weapons-grade plutonium (WGPu)² annually, providing sufficient fissile material for approximately two plutonium-based nuclear weapons, depending on the weapons design and processing losses.³ It should be emphasized that so far Iran has neither constructed, nor is officially planning to construct, a reprocessing facility for the extraction of plutonium from irradiated fuel. It is, however, possible to separate plutonium in hot cells.⁴ Iran is constructing a hot cell facility of unknown capacity for separation of radioisotopes in conjunction with the reactor site at Arak.⁵

According to Iranian authorities, the purpose of the IR-40 is to replace the ageing 5 MW_{th} Tehran Research Reactor (TRR) for the production of radioisotopes for civilian applications.⁶ The IR-40 will also enable basic research and training of nuclear personnel. Iran claims to be constructing the reactor using Iranian engineers only.⁷

The idea of converting the IR-40 by employing low-enriched uranium (LEU) instead of NU fuel was initially proposed by former Deputy Director General for Safeguards of the International Atomic Energy Agency (IAEA), Olli Heinonen, in Foreign Policy in January 2011, as a means to get Iran back to the negotiation table over its nuclear program.⁸ This paper concretizes Heinonen's proposal by modeling the original IR-40 in its most probable configuration, and then comparing it to a modified IR-40 with a low-enriched uranium core. Particular emphasis is placed on differences in plutonium and radioisotope production.

Binding resolutions of the United Nations Security Council (UNSC) demand that Iran suspend all activities related to heavy water, reprocessing and enrichment. We presuppose that a negotiated solution to the Iranian nuclear dispute at some point will open for the roll-back of those prohibitions, making it possible to realize the ideas put forward in the following. Technical discussions of this kind may even prove helpful in arriving at such agreements.⁹

Assessed design of the current IR-40 reactor

A full description of the IR-40 is not available. We have, however, compiled information available from various open sources in order to assess the current reactor design. Two IAEA reports on the implementation of NPT safeguards in Iran from 2003 include initial design information on the IR-40. The IR-40 is a heavy water (D₂O) cooled and moderated reactor (HWR). IR-40 is officially

based on an indigenous reactor design, but Iran has also been consulting with foreign experts on the development of certain parts of the reactor.^{10,11} The thermal output of the reactor is stated to be 40 MW_{th} in order to achieve a neutron flux of $10^{13} - 10^{14}$ n/cm² s.¹² The fuel for IR-40 is currently being produced at the Fuel Manufacturing Plant (FMP) in Esfahan, and will be made from natural uranium dioxide (NUO₂) clad in Zircaloy.^{13,14} One NUO₂ rod produced at FMP is currently being tested at the TRR.^{15,16}

Newer IAEA safeguard reports have stated that particular parts for the reactor have been delivered to the reactor site and installed.^{17,18,19} In 2010, a pressurizer for the reactor cooling system was installed, and in 2011 a moderator heat exchanger and a coolant heat exchanger were also installed. The existence of separate coolant and moderator heat exchangers and a pressurizer indicate that IR-40 might employ a pressure tube design with separate coolant and moderator circuits, such as in the Canadian CANDU and the Russian RBMK reactor types.²⁰

Evidence collected from satellite images of the construction site of the reactor is consistent with the stated maximum thermal output of the reactor. The IR-40 will use a mechanical draft cooling tower with four fans for heat dissipation (Figure 1). The maximum effect that can be dissipated by such draft towers is 0.093 – 0.116 MW_{th}/m².²¹ As estimated from Figure 1, the combined area of the draft towers is approximately 11 m x 40 m. The cooling capacity is therefore estimated to 44 MW_{th}, which is consistent with the thermal output as declared by Iran. The satellite image (Figure 1) also sets an upper limit to the size of the reactor pressure vessel by the opening at the base of the concrete dome. Unless the reactor vessel is installed in parts, or the opening in the concrete dome is enlarged, the diameter of the pressure vessel cannot exceed 5 – 6 meters.

Figure 1. An overview of the IR-40 site. The reactor is located under the concrete dome in the center. The mechanical draft towers are located in the lower right corner. (Image courtesy of Google Earth.)

In April 2009, a fuel assembly reportedly intended for the IR-40 was presented by Iranian officials during a press conference at the inauguration of the FMP (Figure 2a).²² The fuel assembly strongly resembles an RBMK-type fuel assembly. The Institute for Science and International Security (ISIS) later received confirmation that the fuel assembly displayed was indeed intended for the IR-40.²³ A standard RBMK assembly is 10 meters long and consists of two vertical fuel regions separated by a small gap. Each fuel region consists of 18 fuel rods, containing stacked UO₂ pellets, and an central carrier rod. The fuel rods are organized in two concentric circles and have an active fuel length of 341 cm.²⁴ Then-Deputy Head of the Atomic Energy Organization of Iran (AEOI), Abdullah Solatsana, claimed in 2009 that the IR-40 core would include a total of 150 fuel assemblies.²⁵

In a handout by the AEOI from 2011, a close-up of a fuel assembly similar to the one presented at FMP in 2009 is displayed (Figure 2b).²⁶ The rods in the assembly are organized in two concentric circles. The assembly shown in Figure 2b appears to possibly contain 19 rods, which corresponds to the number of rods in one fuel region in an RBMK assembly.

Figure 2: (a) Iran's President Ahmadinejad standing next to a fuel assembly presented at the inauguration of FMP.²⁷ (b) A fuel assembly presented in a handout from the AEOI.

Several Iranian scientific papers published between 2007 and 2012 describe different aspects of one particular research reactor. The first paper published in 2007 describes a 40 MW_{th} tank-type HWR where the moderator does not mix with the coolant.²⁸ Of the 40 MW_{th}, 37 MW_{th} is absorbed in the coolant and 3 MW_{th} in the moderator. The core is composed of 150 fuel assemblies arranged in a triangular lattice with a lattice pitch of 26.5 cm. The temperature of the moderator and the coolant is 70 °C, and the pressure of both coolant and moderator is 0.28 MPa.

One paper published in 2010 shows the location of the different control rods used in a reactor consisting of 150 fuel assemblies arranged in a triangular lattice with a lattice pitch of 26.5 cm.²⁹ Some of the figures in the paper describe a reactor called IR-40. A paper published in 2011 describes a generic 40 MW_{th} HWR converted to employ light water.³⁰ In the article, the original HWR fuel assembly consisted of 18 fuel rods, the same as the modified assembly. The modified assembly has an active fuel region of 343 cm. The paper provides a configuration of one modified fuel assembly and the modified core. The paper from 2012 provides an overview of a reactor layout containing 150 fuel assemblies, and describes a core that is 340 cm high, with a radius of 170 cm.³¹

In our judgment, it is highly likely that the HWR discussed in these papers is indeed the IR-40, and that the dimensions provided are similar to its actual dimensions. The number of fuel rods and the length of the described fuel assembly match the dimensions of one fuel region in an RBMK assembly, as well as what Iran has displayed on two occasions (as described above).^{32,33} The description of a separate coolant and moderator circuit also corresponds with information from the before mentioned IAEA safeguards reports.^{34,35} Furthermore, there are no other known HWRs planned or under construction in Iran which these article could describe. The number of fuel assemblies mentioned in several papers also corresponds to the stated number of assemblies intended for the IR-40 reactor.³⁶

In 2003, Iran informed the IAEA that foreign experts had been consulted regarding the development of certain parts of the reactor. Based on interviews with “knowledgeable officials,” ISIS received evidence that Russian expertise provided assistance in modifying the RBMK fuel rod design to be used in the IR-40 reactor.³⁷ This is plausible, given the fact that the RBMK reactors were developed by the Soviet Union.

Compiling the information provided by these sources has led us to a conjecture of the IR-40 design. We assess that the fuel rods have the same radius as ordinary RBMK fuel, but without the characteristic hole in the middle of each fuel pellet.³⁸ The purity of the D₂O is taken to be 99.75%.³⁹ We also assume that the pressure tubes is are made out of Zircaloy and be of the same dimensions as in RBMK reactors, 8 cm in diameter with a wall thickness of 4 mm. A list of specifications for IR-40 is given in Table 1.

Table 1: Estimated specifications of the IR-40 reactor fuelled by NUO₂.

Power	40 MW _{th}
Power absorbed by the moderator	3 MW _{th}
Power absorbed by the coolant	37 MW _{th}
Coolant / moderator	D ₂ O
Reflector	D ₂ O
D ₂ O purity	99.75%
Temperature of coolant and moderator	70 °C
Lattice pitch	26.5 cm
Lattice configuration	Triangular
Number of fuel assemblies	150
Pressure in coolant and moderator	0.28 MPa
Fuel type	UO ₂ , 0.72% U-235
Fuel radius	0.5740 cm
Clad radius	0.6815 cm
Clad material	Zircaloy
Pellet density	10.4 g/cm ³
Assembly geometry	Circular
Number of rods per assembly	19
Fuelled	18
Unfuelled	1
Rod length	350 cm
Active fuel length	340 cm
Outer diameter of pressure tube	8.8 cm
Inner diameter of pressure tube	8.0 cm

The resulting core is illustrated in Figure 3. The specifications in Table 1 yield a core that is 3.4 m high with a diameter of 3.2 m, giving a height-to-radius ratio of 2.1:1.⁴⁰ This corresponds to a total fuel mass of 10 tons of UO₂ and a power level of 4.6 MW_{th}/tU. This is consistent with the target annual production capacity for NUO₂ fuel at the Fuel Manufacturing Plant in Esfahan, according to information provided to the IAEA by Iran in 2004.^{41,42}

Figure 3: Illustration of the conjectured IR-40 core configuration. The innermost hexagons contain fuel assemblies inside individual pressure tubes, while the outermost hexagons contain D₂O. Control rod positions are illustrated as small circles located between the pressure tubes inside the core.

The estimated reactor configuration was simulated using Standardized Computer Analyses for Licensing Evaluation (SCALE version 6.1, Oak Ridge National Laboratories Tennessee, USA). Neutronics calculations were performed using the TRITON control module in SCALE 6.1. TRITON couples the Monte Carlo criticality safety code KENO-VI with ORIGEN for depletion calculations.⁴³

The simulation resulted in an effective multiplication factor, k_{eff} , of 1.06 for a fresh core without control rods or reactor poisons, which is reasonable for standard reactor operations.⁴⁴ The estimated annual production of WGPu at 100% capacity factor (i.e. percentage of time the reactor has been operating) was 10 kg.⁴⁵ This is in accordance with earlier published estimates.⁴⁶ The

amount of plutonium produced and percentage of Pu-239 after 360 days of irradiation is shown in Table 4. After being irradiated for 285 days the Pu-239 content in the fuel is reduced to 93%. The maximum thermal neutron flux is measured in the central empty tube position and is 1.4×10^{14} n/cm² s, which is consistent with the stated target flux for the IR-40. The vacant positions outside the core achieve a thermal neutron flux of 1.9×10^{13} n/cm² s. The overall consistency of these characteristics confirms that our model should be accurate enough for the purpose of our discussions.

The stated main purpose of the IR-40 is the production of radioisotopes for industrial and medical applications. The far most important radioisotope in this context is Mo-99, the parent nuclide of Tc-99m used for diagnostic nuclear medicine.⁴⁷ In a paper from 2003, the demand for Mo-99 in Iran was stated to be 20 Ci per week.^{48,49} To produce Mo-99, a small target made out of uranium is exposed to the neutron flux in a reactor. Mo-99 is produced as a fission product and later extracted from the target in a hot lab.⁵⁰ We have estimated Mo-99 production in the original IR-40 configuration. In the IR-40 core there is one free position in the center of the core and numerous vacant positions outside the core for irradiating targets. The central position receives a much higher thermal neutron flux and is better suited for radioisotope production. The vacant positions outside the core receive a lower flux than in TRR and would not provide a flux high enough for radioisotope production.⁵¹ A small uranium target made out of pressed NUO₂ weighing only 100 grams was exposed to the highest flux in the middle of the central tube position.⁵² The target reached an activity of up to 75 Ci of Mo-99 after seven days of irradiation, more than enough to supply Iran's stipulated weekly Mo-99 demand. The original IR-40 design thus seems suitable for sufficient production of Mo-99 to meet national needs, using only one target position. If a similar target with 19.75% LEU is used the activity in one target reaches 2090 Ci.⁵³

A possible converted reactor core

For a conversion of the IR-40 to be realistic and feasible, as few physical features as possible should be altered from the original design. Important parameters such as the shape and placement of the fuel assemblies and the size of the reactor vessel are thus assumed to be fixed. The power output of 40 MW_{th} is also retained in order to maintain a sufficiently high neutron flux and to avoid a costly enhancement of the cooling system. Furthermore we let the properties of RBMK fuel assemblies decide the maximum burn-up and heat development for the converted fuel assemblies. We choose to limit the burn-up to 25 GWd/tU. This is the mean burn-up of spent RBMK fuel, which varies between 20 and 30 GWd/tU. The heat generation is limited to the average linear heat generation of 150 - 200 W/cm of the fuel rods.⁵⁴

The reactor is assumed to be converted from NU to LEU fuel. Previous conversion of a HWR from NU to LEU fuel has been undertaken at the National Research Reactor (NRU) in Canada.⁵⁵ We do not advocate replacing the heavy water coolant and moderator with light water. Iran has already succeeded in completing and operating a heavy water production plant (HWPP) situated adjacent to its reactor complex.⁵⁶ The primary purpose of this plant is to produce coolant and moderator for the IR-40 reactor, but it also produces deuterated solutions for use in chemistry, particularly in nuclear magnetic resonance spectroscopy.⁵⁷ It is unlikely that Iran will abandon its costly and prestigious HWPP, let alone agree to limit heavy water production or export the heavy water instead of using it for its original intention.

The increased reactivity provided by the LEU enables the construction of a smaller core. A smaller core is presented based on the limitations imposed by the use of RBMK assemblies and the desire to keep the power output at 40 MW_{th}.⁵⁸ This results in a core made up of 60 fuel assemblies, in contrast to the original 150 assemblies. Each assembly consists of 18 fuel rods with an active fuel region of 240 cm and a fuel density of 10.1 g/cm³. This results in a core of 2.7 tons of UO₂, a

power level of $17.6\text{MW}_{\text{th}}/\text{tU}$, a linear heat generation of 154 W/cm and a height-to-radius ratio of 2.1:1. The purity of D_2O is reduced to 99.00%. With a power level of $17.6\text{ MW}_{\text{th}}/\text{tU}$, the fuel may be irradiated for 1463 days, or four years at a 100% capacity factor before reaching $25\text{ GWd}/\text{tU}$. The proposed converted core is illustrated in Figure 4. The converted core contains 13 empty pressure tubes, which can be used for radioisotope production, scientific experiments or as additional control rod positions.⁵⁹ Thermal hydraulic calculations have not been performed, however, to validate the capacity of the cooling system to accommodate the increased heat generation per fuel channel.

Figure 4: Illustration of the converted IR-40 core with a configuration using 2.50 – 3.00% LEU fuel. Hexagons with vertical lines contain fuel assemblies enriched to 3.00%, hexagon with horizontal lines contain fuel assemblies enriched to 2.75%, hexagon with inclined lines contain fuel assemblies enriched to 2.50%, hexagons containing circles are empty pressure tubes while empty hexagons contain D_2O . Control rod positions are illustrated as small circles located between the pressure tubes inside and outside the core.

Different core configurations with fuel enrichment levels varying between 2.5% and 19.0% were simulated in SCALE to test which enrichment level produced the least amount of plutonium, and plutonium of the poorest quality, i.e. the plutonium mixture with the lowest share of Pu-239. The results for three enrichment levels are illustrated in Table 2. A 19% enrichment level resulted in the lowest rate of plutonium production with less than 1.23 kg after one year, but the isotopic composition of the plutonium was weapons-grade. After four years of irradiation at 100% capacity factor, the fuel was still almost weapons-grade. Fuel enriched to below 5.0% had a lower content of Pu-239, but produced more plutonium in total than higher enrichment levels. Enrichment levels above 5% result in a high degree of excess reactivity, making these levels problematic for reactor construction.⁶⁰ Higher enrichment levels also result in low relative burn-ups. Therefore, only enrichment levels equal to or less than 5% were considered further.

Table 2: Mass and percentage of Pu-239 in irradiated fuel for various enrichments levels at a capacity factor of 100%. The numbers are given after one and four years of operation.

Enrichment	5%		10%		19%	
Operating time	365 d	1463 d	365 d	1463 d	365 d	1463 d
Burn-up	14.7%	54.6%	7.8%	30.3%	4.2%	16.7%
Total Pu production	2.60 kg	8.46 kg	1.77 kg	6.21 kg	1.23 kg	4.58 kg
Average Pu-239 content	93.4%	73.0%	96.5%	85.5%	98.1%	92.2%
k_{eff}	1.41	1.23	1.54	1.46	1.62	1.57

Since the use of enriched uranium leads to a higher excess reactivity, the enrichment was reduced below 5 % and various burnable poisons were evaluated to reduce the reactivity.⁶¹ One possible reactor configuration was obtained using fuel enriched to 2.5 – 3.0%, with 1.5% of erbium added homogeneously to each fuel rod.⁶² This is the same enrichment level and choice of burnable poison that is employed in RBMK fuel, although erbium is used in lower concentrations.⁶³ The addition of 1.5% erbium reduced the effective multiplication factor, k_{eff} , from approximately 1.60 to 1.07.⁶⁴ During operation, k_{eff} declines steadily towards one after about 810 – 870 days of operation at 100% capacity factor. This corresponds to a fuel burn-up of approximately half of our limit of $25\text{ GWd}/\text{tU}$. This shows that in terms of reactivity control, adding 1.5% erbium to 2.5 – 3.0% LEU fuel enables a comfortable reactivity development. Lacking international experience with this particular choice of fuel and erbium concentration, however, means that a certain development and

testing period needs to be taken into account, likely delaying start-up of the converted reactor somewhat. Russian RBMK fuel expertise could be made available to assist and facilitate this development.

Other options for lowering k_{eff} could be reducing the quality of D_2O further, or replacing the D_2O coolant with H_2O , to distort the neutron energy spectrum and increase neutron absorption. However, replacing the D_2O coolant with H_2O would lead to a higher so-called positive void coefficient. This is an inherent safety issue for reactors with separate cooling and moderator, including both CANDU and RBMK reactors, as well as the original and the modified IR-40 reactors.⁶⁵ In the case of an instantaneous loss of all D_2O coolant, the reactivity for a fresh core increases with 18 mk from $k_{\text{eff}} = 1.108$ to $k_{\text{eff}} = 1.126$. The original and thus the converted IR-40 core has 27 positions available for control rods.^{66,67} If we assume that the control rods for IR-40 are of the same dimensions as RBMK control rods, the insertion of only the 15 innermost control rods provide a reactivity reduction of 220 mk and would be sufficient to retain reactor control.⁶⁸

The maximum thermal neutron flux of the converted reactor is about 1.2×10^{14} n/cm² s in the central and second circle of vacant positions inside the core. While third circle of vacant positions achieves a thermal flux of 9.0×10^{13} n/cm² s. The different flux positions for the two cores are shown in Table 3. The maximum thermal flux is about the same for the two cores, but the converted core has 12 additional vacant positions inside the core with a flux high enough for radioisotope production. This means that the converted core can potentially produce a greater amount of radioisotopes than the NU core while at the same time conduction other experiments.

Table 3: Thermal neutron flux in NU and LEU fueled core. The numbers are given as neutrons / cm² s.

	Central position	Second circle	Third circle	Outside core
NU core	1.4×10^{14}	N/A	N/A	1.9×10^{13}
LEU core	1.2×10^{14}	1.2×10^{14}	9.0×10^{13}	5.0×10^{13}

The production of plutonium in the converted reactor is shown in Table 4. The mass of plutonium produced is reduced by about 2/3 compared to the original configuration, yielding 3.8 kg after one year of irradiation at a capacity factor of 100%. The isotopic composition of plutonium drops below weapons-grade after 240 days of irradiation, and the level of Pu-239 is reduced to 76.7% after 780 days of irradiation, which is close to the maximum operating time before refueling is needed. Although the isotopic composition of plutonium is not classified as weapons grade after 240 days of irradiation, it is still weapons useable.⁶⁹

Table 4: Plutonium production in original and converted core after 360 and 780 days of operation at 100% capacity factor.

	NU core	LEU core	
Operating time	360 d	360 d	780 d
Burn-up	24.1%	25.6%	51.5%
Total Pu production	10019 g	3873 g	7290 g
Average Pu-239 content	91.4%	89.6%	76.7%

A natural cap on Iran's enrichment capacity

Depending on the capacity factor, 2.7 tons of approximately 3.0% LEU (in reality, about 50% is 3.0% LEU, 30% is 2.75% LEU, and 20% is 2.5% LEU) would need to be replaced after 810 – 870 days. An annual enrichment capacity of 1700–3400 SWU is required to produce this amount of LEU, assuming a capacity factor varying between 50 – 100%.^{70,71} The initial core will consume approximately half of the LEU that Iran has already produced and stockpiled by March 2012. Most of the LEU would need to be slightly blended down to the stipulated enrichment levels, as the current levels are up to 5.0% uranium-235.⁷²

Iran's annual, total enrichment capacity per March 2012 was on the order of 6000 – 9000 SWU.⁷³ We propose a cap on Iran's total enrichment capacity matched exclusively to the needs of the modified IR-40. Such a limit may be acceptable to world powers in a final settlement, defining the terms for the future Iranian nuclear program. This level would, however, require a significant reduction of Iran's current enrichment capacity. Another option, which will appear more attractive for Iranian decision-makers and correspondingly harder to accept for the major powers, would be to restrict enrichment to the needs of all of Iran's research reactors, possibly including future research reactors.

The contentiousness of the latter option is illustrated by the increasing concern expressed by several states regarding Iran's enrichment of near-20% LEU to fuel the TRR. Iran has increased this production even though one of the arguments for constructing the IR-40 was the need to shut down the over 40 years old TRR.⁷⁴ Any excess fuel for the TRR could be blended down to lower enrichment levels. Limiting not only the quantities, but also the enrichment levels achieved, may be useful to alleviate concerns of Iran realizing a rapid break-out capability in facilities normally producing LEU at levels considerably higher than 5%.

Policy implications

We have described a probable design for the IR-40 heavy water research reactor currently under construction near Arak in Iran. Given the information available, we contend that the IR-40 will be a pressurized heavy water reactor with RBMK-derived fuel assemblies placed in individual pressure tubes. In its current configuration, the IR-40 may provide enough fissile material for up to two plutonium-based nuclear weapons annually.

Further, we have proved the feasibility of converting this reactor to employ LEU fuel while retaining most of its original design features, using neutronics calculations. There is still a need to validate the alternative design by thermal hydraulic calculations. There are, obviously, many ways of constructing a HWR using LEU fuel within the given constraints. We have chosen one particular design for the sake of the argument, without excluding the possibility of selecting quite different design features to achieve the same overall benefits.

The converted reactor, as specified in this paper, would be more flexible for radioisotope production than the original reactor, thus fulfilling an important and legitimate need for Iran. Of particular importance for the international community, under regular safeguarded operations the converted reactor would be less suitable for plutonium production. The converted core would result in a 2/3 reduction of annual plutonium production, and the isotopic composition of the plutonium would be less suited for nuclear weapons. The free positions inside and outside the core could be used to irradiate natural or depleted uranium (as blankets or targets), but with proper IAEA safeguards in place, any such deviations would not go unnoticed by regular inspections.⁷⁵ Alternatively it would still be possible to produce WGPu by irradiating the fuel for a conspicuously short time, but as for every other safeguarded reactor, any such operational deviation would be detected by the IAEA in a timely fashion under the current safeguards practice, providing the world

community with some time to muster a proper political response before any nuclear weapons option could be realized.⁷⁶

The proposed fuel enrichment levels, as well as the choice of erbium as a burnable poison, brings the modified IR-40 fuel closer to commercial RBMK fuel. This in turn opens up the possibility of (reestablishing) cooperation between Iranian and Russian experts in fuel development and testing, thus adding another layer of transparency.

Another major, technical benefit of the proposed modification of the IR-40 is an increased number of free positions in the core compared to the original core configuration. These extra positions represent an enhanced capacity for radioisotope production and basic physics experiments.

From the major powers' perspective, the non-proliferation gain is twofold. A conversion will render the IR-40 less proliferation-prone, in terms of reduced plutonium production and coupling its fuel needs to a limitation in the much disputed enrichment efforts. Such an effort represents a potentially significant compromise to alleviate international concerns that Iran's enrichment program will be further ramped up. Thus providing Iran with an option for rapid production of weapons-grade uranium.^{77,78}

Ideally, a reactor conversion along the lines of this paper should be presented by Iran as a major national achievement, providing it with a more advanced research reactor, while establishing a face-saving rationale for reducing the enormous amounts of resources currently being funneled into an enrichment program, which 25 years after its initialization still seems years away from a commercially viable technological level. A small-scale enrichment infrastructure dimensioned to serve a medium-sized research reactor, rather than serving a large-scale nuclear power program, would still represent a realization of Iran's "inalienable right" to develop fuel cycle technology without the need for an extremely costly capacity enhancement. The flip side of the coin from Tehran's perspective is that Iran for all practical purposes relinquishes its ambitions of fuel self-sufficiency in the nuclear power sector. But if such a decision serves as a catalyst for a long-term easing of tensions between Iran and the major powers, Iranian concerns of discrimination in the international uranium fuel market should be reduced, possibly and preferably augmented by the provision of fuel supply assurances from Russia or other major fuel suppliers.

In sum, we have demonstrated that former Deputy Director General Heinonen's proposed reactor conversion is feasible. When linked to Iran's enrichment efforts, a conversion could prove useful in reducing concerns of potential weapons grade plutonium and highly enriched uranium production in Iran, while leaving Iran with a more meaningful fuel cycle and research reactor infrastructure.

NOTES AND REFERENCES

¹ The IR-40 is reported to be completed by 2014. International Atomic Energy Agency (IAEA), "Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran," 24 February 2012, GOV/2012/9, <<http://www.iaea.org/Publications/Documents/Board/2012/gov2012-9.pdf>>.

² WGPU is defined here as plutonium containing more than 93% weight percent of plutonium-239.

³ David Albright and Corey Hinderstein, "Iran, player or rogue?," *Bulletin of the Atomic Scientists*, September / October 2003, Volume 59 (5), pp. 52–58.

⁴ A study conducted by Oak Ridge National Laboratory in 1977 demonstrated that it was possible for a country with a "minimal industrial base" to construct a small reprocessing facility in four to

six months. This facility would be able to reprocess one PWR fuel assembly per day. Given there is not a big difference in reprocessing times for other type of fuel assemblies, for IR-40 this would translate to reprocessing a full core in about 150 days. Victor Gilinsky, Marvin Miller and Harmon Hubbard, "A FRESH EXAMINATION OF THE PROLIFERATION DANGERS OF LIGHT WATER REACTORS," October 2002, <<http://www.npolicy.org/files/20041022-GilinskyEtAl-LWR.pdf>>

⁵ IAEA, "Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran," 6 September 2010, GOV/2010/46, <<http://www.iaea.org/Publications/Documents/Board/2010/gov2010-46.pdf>>.

⁶ Section C.3, paragraph 44 of International Atomic Energy Agency (IAEA), "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran," 26 August 2003, GOV/2003/63, <<http://www.iaea.org/Publications/Documents/Board/2003/gov2003-63.pdf>>.

⁷ The Atomic Energy Organization of Iran (AEOI) distributed a handout during a display in the margins of the IAEA General Conference in 2011 titled "Nuclear Industry in IRAN: An overview on Iran's activities and achievements in nuclear technology."

⁸ Olli Heinonen, "Can the Nuclear Talks With Iran Be Saved?," *Foreign Policy*, January 27, 2011, <http://www.foreignpolicy.com/articles/2011/01/27/can_the_nuclear_talks_with_iran_be_saved?hicomments=yes>.

⁹ United Nations Security Council Resolutions 1696 (2006), 1737 (2006), 1747 (2007), 1803 (2008), and 1929 (2010), <<http://www.un.org/Docs/sc/>>.

¹⁰ The company responsible for the design and construction of the IR-40 is the Arak-based Modern Industries Technique Company (MITEC), which is among the numerous Iranian entities sanctioned under the abovementioned United Nations Security Council resolutions.

¹¹ IAEA, GOV/2003/75, *op. cit.*

¹² Iran reported to the IAEA that the power output of the reactor was necessary for achieving a neutron flux sufficient to meet Iran's isotope production requirements. IAEA, GOV/2003/75, *op. cit.*

¹³ IAEA safeguards report GOV/2003/40 mentions the use of zirconium for the IR-40 reactor, but it is assumed that the cladding will be in the form of Zircaloy.

¹⁴ IAEA, "Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran," GOV/2012/23, <<http://www.iaea.org/Publications/Documents/Board/2012/gov2012-23.pdf>>.

¹⁵ IAEA, "Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran," GOV/2011/54, <<http://www.iaea.org/Publications/Documents/Board/2011/gov2011-54.pdf>>.

¹⁶ IAEA, GOV/2012/09, *op. cit.*

¹⁷ IAEA, GOV/2010/46, *op. cit.*

¹⁸ IAEA, "Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran," GOV/2011/29, <<http://www.iaea.org/Publications/Documents/Board/2011/gov2011-29.pdf>>.

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- ¹⁹ IAEA, GOV/2011/54, *op.cit.*
- ²⁰ John R. Lamarsh and Anthony J. Baratta, *Introduction to Nuclear Engineering*, 2001, Prentice Hall, p. 153 and 163.
- ²¹ Thomas B. Cochran, “What is the Size of Khushab II?,” Natural Resources Defense Council, 2006, <http://docs.nrdc.org/nuclear/files/nuc_06090801a.pdf>.
- ²² David Albright, Paul Brannan, and Robert Kelley, “Mysteries Deepen Over Status of Arak Reactor Project,” *Institute for Science and International Security (ISIS)*, August 2009, <<http://isis-online.org/uploads/isis-reports/documents/ArakFuelElement.pdf>>.
- ²³ David Albright, Paul Brannan, and Robert Kelley, “Update on the Arak Reactor in Iran,” *ISIS*, August 2009, <http://isis-online.org/uploads/isis-reports/documents/Arak_Update_25_August2009.pdf>.
- ²⁴ “Fuel design data,” *Nuclear Engineering International*, September 2008, p. 32.
- ²⁵ Iranian Students’ News Agency (ISNA), “Iran’s FMP to be launched late March,” March 2009, <<http://old.isna.ir/ISNA/NewsView.aspx?ID=News-1307413&Lang=E>>.
- ²⁶ The AEOI, *op. cit.*
- ²⁷ Fuel assembly displayed at the inauguration of the FMP 9 April 2009. Scanpix - AFP Photo - Atta Kenare.
- ²⁸ Farshad Faghihi et al., “Level-1 probability safety assessment of the Iranian heavy water reactor using SAPHIRE software,” October 2008, *Reliability Engineering & System Safety*, Volume 93 (10), pp. 1377–1409.
- ²⁹ Amir Hosein Fadaei et al., “Core design improvement by optimizing the control and protection system elements distribution,” August 2010, *Annals of Nuclear Energy*, Volume 37 (12), pp. 1640–1648.
- ³⁰ Saman Tashakor, Farshid Javidkia and Mehdi Hashemi-Tilehnoee, “Neutronic Analysis of Generic Heavy Water Research Reactor Core Parameters to Use Standard Hydride Fuel,” 2011, *World Journal of Nuclear Science and Technology*, Volume 1 (2), pp. 46-49.
- ³¹ Marzieh Moguiy, Amir Hosein Fadaei and Amir Saeed Shirani, “Analysis of different variance reduction techniques in research reactor beam tube calculations,” March 2012, *Annals of Nuclear Energy*, Volume 41, pp. 104–109.
- ³² The AEOI, *op. cit.*
- ³³ Scanpix – AFP Photo – Atta Kenare, *op. cit.*
- ³⁴ IAEA, GOV/2010/46, *op. cit.*
- ³⁵ IAEA, GOV/2011/29, *op. cit.*
- ³⁶ ISNA, *op. cit.*
- ³⁷ Albright et al., “Update on the Arak Reactor in Iran,” *op. cit.*

³⁸ No fuel pellets seen in Iranian photographs seem to contain holes. The operating temperature stated for the IR-40 is lower than that for RBMK reactors, thus rendering it unnecessary to introduce holes in the pellets.

³⁹ 99.75% heavy water purity is the required level of purity for CANDU reactors. John R. Lamarsh and Anthony J. Baratta, *op. cit.*, p. 217.

⁴⁰ This ratio is consistent with the geometry of cylindrical core reactors such as the Indian Dhruva and the Canadian NRU reactors. The ratio corresponds to the cylindrical configuration most closely resembling a sphere, allowing maximum volume per surface area.

⁴¹ IAEA, "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran," GOV/2004/83, <<http://www.iaea.org/Publications/Documents/Board/2004/gov2004-83.pdf>>.

⁴² Assuming they spend one complete core per year, corresponding to a burn-up on the order of 1.5GWd/tU, which is reasonable for this kind of reactor.

⁴³ Mark. D. DeHart, "HIGH-FIDELITY DEPLETION CAPABILITIES OF THE SCALE CODE SYSTEM USING TRITON", Oak Ridge National Laboratory.

⁴⁴ k_{eff} is a measure of reactivity, defined as the number of neutrons in one fission generation divided by the number of neutrons in the previous generation. k_{eff} equal to one corresponds to criticality, with a constant neutron population. For a reactor to be able to start operation, k_{eff} must initially be greater than one. It can then be reduced to one by reactivity-reducing mechanisms, such as control rods, as soon as the desired neutron flux has been achieved.

⁴⁵ A capacity factor of 100% is used throughout the paper to illustrate the upper boundaries of plutonium production. Realistically, a capacity factor of 70 – 80% would be more probable.

⁴⁶ David Albright and Corey Hinderstein, *op. cit.*

⁴⁷ Sharmila Banerjee et al., "Evolution of Tc-99m in diagnostic radiopharmaceuticals," October 2001, *Seminars in Nuclear Medicine*, Volume 31 (4), pp. 260-277.

⁴⁸ $1 \text{ Ci} = 3.7 \cdot 10^{10} \text{ Bq}$, where 1 Bq is one radioactive disintegration per second. "Curie" is a commonly used unit in nuclear medicine, although "Becquerel" is an otherwise more widely accepted unit for radioactivity.

⁴⁹ R.Sayareh, M.Ghannadi Maragheh and M.Shamsaie, "Theoretical calculations for the production of ^{99}Mo using natural uranium in Iran," May 2003, *Annals of Nuclear Energy*, Volume 30 (8), pp. 883-895.

⁵⁰ Iran will likely seek to produce iodine and xenon isotopes, in addition to molybdenum, in the IR-40. A hot cell facility at Tehran Nuclear Research Center, the so-called "MIX facility", was slated for the production of molybdenum, iodine and xenon, but it has never been commissioned, because the TRR has been unable to reach the necessary flux level for isotope production using natural uranium targets. The IAEA, GOV/2004/83, *op. cit.*

⁵¹ The maximum thermal neutron flux of TRR is calculated to be $5.7 \times 10^{13} \text{ n/cm}^2 \text{ s}$, R. Sayareh et al., *op. cit.*

⁵² The mass and size of the target is based on the dimensions given in the paper by R. Sayareh et al., *op. cit.* The uranium target is 19 cm high, with a 0.6 cm radius and a density of 4.67 g cm⁻². It is clad with 0.2 cm of aluminum.

⁵³ Other ways of increasing the yield of Mo-99 could be by employing a larger target volume, increasing the density of the target, multiple targets, and/or increasing the number of target positions.

⁵⁴ The average linear heat generation is the total power of the reactor divided by the total length of the fuel rods combined, *Nuclear Engineering International, op. cit.*

⁵⁵ NRU was converted first converted from NU to highly enriched uranium, before it was converted to LEU. NRU Canada, “NRU Heritage – AECL’s NRU Reactor,” 2011, <<http://www.nrucanada.ca/en/home/insidenru/nruheritage.aspx>>

⁵⁶ IAEA, GOV/2010/46, *op. cit.*

⁵⁷ AEOI handout picked up at the IAEA General Conference in 2011 titled “NMR Deuterated Solvents – Arak Heavy Water Plant,” 2011.

⁵⁸ An even smaller core could be constructed, if the power output had been reduced from 40 MW_{th} to for example 20 MW_{th}. But this would lead to a reduction in neutron flux and be counterproductive to Iran’s plans of using the reactor for radioisotope production.

⁵⁹ The layout of the converted IR-40 core is partly influenced by the design of the Halden Boiling Water Reactor. This is a 20 MW_{th} HWR using 6% enriched fuel. The reactor has multiple unoccupied locations inside the core for irradiation experiments. It also has the ability to simulate both HWR and LWR operating conditions, <<http://www.ife.no/en/ife/halden/hrpfiles/halden-boiling-water-reactor>>

⁶⁰ For some research reactors there is a regulatory limit to amount of allowed excess reactivity of 15% or 150 mk, whereas the commercial AP1000 reactor does not have such a limit. The maximum excess reactivity for the AP1000 reactor is stated to be 328 mk. A.L Hanson & D.J. Diamond, “Calculation of Design Parameters for an Equilibrium LEU Core in the NBSR,” September 2011. “AP1000 Design Control Document,” National Regulatory Commission, <http://www.nrc.gov/reactors/new-reactors/design-cert/ap1000/dcd/Tier%202/Chapter%204/4-1_r14.pdf>.

⁶¹ A burnable poison is a substance added to a reactor to absorb neutrons. The term “burnable” means that as U-235 is consumed, the burnable poison is also consumed, and the reactivity is maintained at a stable level . John R. Lamarsh and Anthony J. Baratta, *op. cit.*, pp. 395-396.

⁶² Natural erbium is used in its oxide form and is also called erbia, Er₂O₃. Naturally occurring erbium consists of six isotopes: 0.14% Er-162, 1.60% Er-164, 33.50% Er-166, 22.87% Er-167, 26.98% Er-168, and 14.91% Er-170. The most useful isotope as a burnable poison is Er-167. Er-167 can be isolated in a separation process. The isotopic composition used in this paper is 0.07% Er-162, 1.00% Er-164, 30.0% Er-166, 33.00% Er-167, 26.8% Er-168, and 9.13% Er-170. M. L. Grossbeck and J.-P. A. Renier “Development of improved burnable poisons for commercial nuclear power reactors,” September 2003, The University of Tennessee and Oak Ridge National Laboratory.

⁶³ Fuel with an erbium content of up to 0.6% weight percent is being used commercially in RBMK fuel. In order not to deviate too much from this value, 1.5% of erbium was chosen as an upper limit.

“Modernization and life prolongation,” *Rosatom*, <http://www.rosatom.ru/wps/wcm/connect/rosene/goatom/kunpp_en/safety/modernization/>

⁶⁴ The value of k_{eff} is calculated after 30 days of reactor operation to account for reactor poison build-up.

⁶⁵ In the case of a loss of coolant accident (LOCA), the neutrons are still moderated by the moderator. But the loss of coolant means less neutron absorption and an increase in reactivity. Increased reactivity and reduced cooling may in the worst case lead to a core meltdown absent any counter-measures. This effect is quantified by the so-called “void coefficient.” Because the coolant contributes somewhat to the moderation, a loss of coolant actually results in a small shift towards higher average neutron energy, *i.e.* a slight hardening of the neutron spectrum. The use of erbium as a neutron poison takes advantage of this shift, as Er-167 has a strong absorption resonance at 0.47 eV.

⁶⁶ Faghihi et al., *op. cit.*

⁶⁷ Fadaei et al., *op. cit.*

⁶⁸ A shortened version of a standard RBMK control rod was inserted fully into the reactor core. The length of the control rod was set to 240 cm. R. T. Perry and George H. Meriwether, “A WIMS-NESTLE REACTOR PHYSICS MODEL FOR AN RBMK REACTOR”, paper submitted to International Conference on the Physics Reactors, Mito, Japan, September 16-20, 1996.

⁶⁹ J. Carson Mark, “Explosive Properties of Reactor-Grade Plutonium,” *Science & Global Security*, 1993, Volume 4, pp. 111-128.

⁷⁰ Separative Work Unit, SWU, is a measure of enrichment effort and capacity, applicable to all enrichment facilities and their constituent parts, such as individual centrifuges (typically given as annual capacity). Approximately 100 000 SWU are needed to produce a year’s worth of 3 – 5% enriched fuel for a standard, light-water nuclear power reactor with an output of 1 GW_e, while approximately 5000 SWU is needed to produce 25 kg of 90% enriched uranium (weapons-grade) from natural uranium.

⁷¹ The enrichment requirements for an LEU-fuelled IR-40 were estimated by using an online standard enrichment calculator based on mass-flow conservation. The tails assay was set to be 0.3% uranium-235, while the feed was 0.71% uranium-235 (*i.e.* natural uranium), <<http://www.wise-uranium.org/nfcue.html>>.

⁷² According to the IAEA safeguards report on Iran issued before the March 2012 board meeting. IAEAGOV/2012/9, *op. cit.*

⁷³ David Albright, Paul Brannan and Christina Walrond, “ISIS Analysis of IAEA Iran Safeguards Report: Production of 20% Enriched Uranium Triples; Iran Increases Number of Enriching Centrifuges at Natanz FEP by Nearly 50% and Signals an Intention to Greatly Expand the Number of Centrifuges at Both Natanz and Fordow; Advanced Centrifuge Program Appears Troubled,” *ISIS*, 24 February 2012, <http://isis-online.org/uploads/isis-reports/documents/ISIS_Analysis_IAEA_Rerport_24Feb2012.pdf>.

⁷⁴ David Albright and Christina Walrond, “Determining the purpose of Iran’s growing stock of 19.75 percent enriched uranium: Production should be capped,” *ISIS*, 21 September 2011, <http://isis-online.org/uploads/isis-reports/documents/Determining_the_purpose_of_Irans_growing_stock_of_1975_21Sept2011.pdf>.

⁷⁵ H. Gruemm, “Safeguards and Tamuz: setting the records straight,” *IAEA bulletin*, 1981, Volume 23 (4).

⁷⁶ The IR-40 and its associated facilities are currently not subject to regular IAEA safeguards. Iran does not allow regular safeguards to be implemented at its nuclear facilities until 180 days before operations are commenced, but it has allowed some sporadic IAEA visits the last few years on a voluntary basis. The most significant, operational fuel cycle facilities in Iran are, in contrast, subject to as many as two IAEA inspections per month on average, providing an adequately narrow window of detection of proliferation-sensitive operational deviations.

⁷⁷ *ISIS*, “Abbasi-Davani Interview on Iran’s 20 Percent Enrichment,” 31 August 2011, <<http://www.isisnucleariran.org/brief/detail/abbasi-davani-interview-on-irans-20-percent-enrichment>>.

⁷⁸ A comprehensive discussion of the various proliferation paths associated with Iran’s uranium enrichment capabilities is included in David Albright et al., “Preventing Iran From Getting Nuclear Weapons: Constraining Its Future Nuclear Options,” *ISIS*, 5 March 2012, <http://isis-online.org/uploads/isis-reports/documents/USIP_Template_5March2012-1.pdf>.