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A Conversion Proposal for Iran's IR-40 Reactor with Reduced Plutonium Production

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This article examines possible modifications of Iran's IR-40 (Arak) heavy-water reactor that would limit its plutonium production without compromising its usefulness for civilian purposes. The proposed modifications only involve the fuel composition, avoid changes to the fuel and core geometry, and therefore have the advantage of minimizing the overall complexity and cost of conversion as well as shortening the time period required to implement these modifications. The suggested changes would significantly reduce the reactor's production of plutonium from 7–9 kilograms to less than 1 kilogram per year. The article also examines key safety parameters, medical isotope production rates, and uranium resource requirements for all modifications considered. The analysis is relevant beyond the case of Iran's Arak reactor and may provide some future guidance for converting other heavy-water reactors that continue to operate today.

INTRODUCTION

The future of the IR-40 (Arak) reactor has been a central element of the negotiations between Iran and the countries of the P5+1[1] because of concerns that the reactor could be used to make plutonium for weapons purposes. Heavy water reactors, such as the Arak reactor, are typically fueled with natural uranium, which contains about 99.3 percent of the isotope uranium-238 and only a small fraction of the fissile isotope uranium-235 (0.7%). Plutonium is produced when a uranium-238 nucleus absorbs a neutron and then undergoes two consecutive beta decays. Partly due to the higher percentage of uranium-238 in natural uranium, the plutonium production rates in reactors fueled with

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natural uranium are higher compared to reactors fueled with enriched uranium for any given thermal power. A 40 MWt reactor of the Arak-type produces about 9 kilograms of plutonium per year; this material is embedded in spent fuel and would have to be separated in a reprocessing operation for further use.

Several nuclear weapon states have used heavy-water reactors similar to the Arak reactor to launch their nuclear weapon programs or expand their fissile material production capacities. Notable examples are Israel (Dimona reactor, supplied by France), India (CIRUS reactor, mainly supplied by Canada), and Pakistan (Khushab reactor series).[2] The performance of natural uranium fueled research reactors is low compared to other types of reactors. Strong neutron absorption in natural uranium fuel results in a poor neutron economy of heavy-water reactors and few excess neutrons are left for use in research and radioisotope production. A proposed redesign of the Arak reactor should therefore balance the need to reduce plutonium production and the need to maintain, and perhaps improve, the reactor's usefulness for research and radioisotope production.

One possible scenario is to replace the Arak reactor with a light-water reactor. Since the light water reactor technology uses enriched uranium fuel, thus reducing plutonium production, such a modification would meet the needs of the P5+1. Iran, however, has been reluctant to accept such a proposal as it has already invested substantial resources in the project over the past years, including the construction of a heavy-water production plant. In response to the P5+1 proposal that Iran scrap the Arak reactor project, Ali Akbar Salehi, the head of the Atomic Energy Organization of Iran, stated in February 2014 that "we see no point stopping the work on this reactor."[3] In April 2014, a team from Princeton University, including the authors of this paper, proposed modifications to the Arak reactor that would substantially reduce plutonium production in the Arak reactor without compromising its ability to produce radioisotopes for medical or other peaceful applications.[4] The proposal was partly based on an earlier analysis by a team based in Norway.[5] This follow-on article presents the technical details of the conversion options proposed as well as their impact on plutonium production, radioisotopes production, aspects of reactor safety, and resource requirements.

The proposed reactor modifications are based on two key elements: first, replacing the natural uranium dioxide (UO_2) fuel with a uranium (U_3O_8) dispersion-type fuel enriched to 3.5 percent or 20 percent and, second, lowering the power level from 40 MWt to 20 MWt or even 10 MWt. The proposed modifications therefore only involve the fuel composition and have the advantage of minimizing the overall complexity and cost of conversion as well as shortening the time period required to implement such modifications. The process of changing the fuel enrichment without changing the geometry of the fuel rods or fuel assemblies is well understood and documented.[6] It should be noted,

however, that unlike previous conversions from high enriched to low enriched uranium (LEU) fuel, the proposed modifications in this article reverse this process and further investigation, particularly on reactor thermal-hydraulics, may be required.

In 2014, as part of the negotiations with the P5+1, Iran has indicated that it is considering modifications to the Arak reactor that are consistent with those outlined in this article.[7] The present analysis and proposed modifications options go beyond the case of the Arak reactor, however. There remain a number of operating reactors today that are similar to Iran's heavy-water reactor; in fact, most of them are used for plutonium production in support of a weapons program. They are: the Dimona reactor (40–140 MWt) in Israel, the Dhruva reactor (100 MWt) in India, and four plutonium production reactors at Khushab (40–50 MWt each) in Pakistan.[8,9] It is possible that, for example, as part of a country joining a Fissile Material Cutoff Treaty, some of these facilities could be modified using some of the same strategies examined and proposed here as an alternative of shutting them down. If the political decision is made to continue operating a reactor, there could be a strong interest in maximizing usability for civilian applications once the primary mission of plutonium production is removed. Just as in the case of Iran, fuel and core modifications would reduce proliferation concerns associated with the continued operation of a heavy-water reactor.

PHYSICAL MODELING

The analysis presented in this article is based on multi-zone, full-core neutronics calculations to estimate plutonium and radioisotope production, study some main characteristics relevant for reactor safety, and assess resource requirements for the current IR-40 reactor core and the proposed alternative core configurations. The computational approach uses the MCODE computer code system,[10] which links the Monte Carlo neutron transport code MCNP5[11] with the ORIGEN2[12] point-depletion code and permits reactor burnup calculations with regularly updated neutron flux distributions and spectrum-averaged (effective) neutron cross sections for actinides and fission products.

Figure 1 shows the core configuration of the IR-40 reactor (Core A) and the two alternative designs (Cores B and C). The light-shaded hexagons mark the channels that hold the fuel. The dark-shaded hexagons between the core and the reactor vessel hold heavy water as a neutron reflector. The dark-shaded hexagons within the core mark channels that are available for irradiating targets or for research activities. The design parameters for the different options studied in this article are summarized in Table 1. Because Iran has not publicly released the full design specifications of the Arak reactor, the core and fuel design parameters adopted for the IR-40 reactor in this study are largely

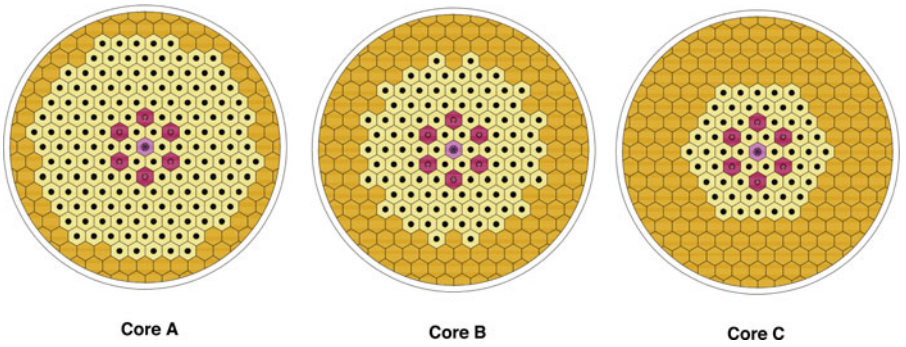

Figure 1: Core designs of the IR-40 reactor (Core A) and the proposed alternative cores (Cores B and C). Geometrical dimensions of cores A, B, and C are listed in Table 1. The outer diameter of the reactor vessels shown is 2.8 meters.

based on the Norwegian study, which has relied on information obtained from non-official Iranian publications.[13]

By adjusting the effective uranium density in Cores B and C and by balancing uranium enrichment and total fuel volume, which scales with the size of the core, the total uranium-235 inventory is held constant for all three cores (A, B, and C). The uranium-238 inventory, however, is greatly reduced for Cores B and C, which use enriched fuel. The dimensions of the lower-power cores have been reduced such that the average power density of the original core is

Table 1: Design and operation parameters of Iran's IR-40 reactor and the modified designs.

	Unit	Core A	Core B (3.5% U)	Core B (20% U)	Core C (3.5% U)	Core C (20% U)
Design Parameters						
Nominal power	MWt	40	20	20	10	10
Moderator		D_2O	D_2O	D_2O	D_2O	D_2O
Coolant		D_2O	D_2O	D_2O	D_2O	D_2O
Reflector		Graphite	Graphite	Graphite	Graphite	Graphite
Reflector thickness	cm	70	70	70	70	70
Fuel assemblies		150	96	96	54	54
Fuel rods per assembly		18	18	18	18	18
Lattice geometry		Hexagonal	Hexagonal	Hexagonal	Hexagonal	Hexagonal
Lattice pitch	cm	26.5	26.5	26.5	26.5	26.5
Tube inner radius	cm	4.00	4.00	4.00	4.00	4.00
Tube outer radius	cm	4.40	4.40	4.40	4.40	4.40
Fuel Parameters						
Fuel		UO_2	U_3O_8	U_3O_8	U_3O_8	U_3O_8
Enrichment		unenriched	3.5%	20%	3.5%	20%
Fuel density	gU/cm^3	9	1.85	0.32	1.85	0.32
Total fuel mass	tons	8.550	0.880	0.154	0.447	0.078
Fuel radius	cm	0.5740	0.5740	0.5740	0.5740	0.5740
Fuel rod radius	cm	0.6815	0.6815	0.6815	0.6815	0.6815
Active fuel length	cm	340	266	266	240	240
Active core radius	cm	172.25	145.75	145.75	119.25	119.25

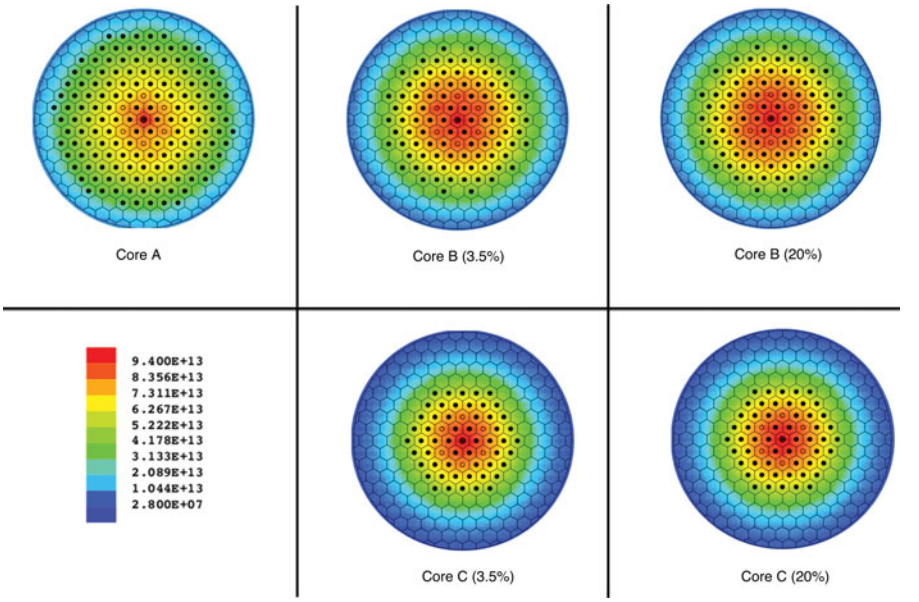

Figure 2: Neutron flux contours in the IR-40 reactor and the modified designs. Values are in n/(cm^2s). See electronic version of article for colors.

maintained. As expected, the neutron flux levels in the lower-power cores are therefore comparable to those of the natural uranium design operating at 40 MWt as shown in Figure 2.

Except for the reduced number of fuel assemblies and the changed fuel composition, core materials, core structure, and core geometry have not been modified.

PLUTONIUM PRODUCTION AND ISOTOPICS

The proliferation risks associated with the Arak reactor are largely determined by the net plutonium production rate and, to a lesser extent, by the plutonium isotopics at discharge. Both metrics depend on fuel inventory, enrichment level, reactor power, and average fuel burnup at discharge. These aspects are examined below.

Plutonium Production

Plutonium buildup in the IR-40 reactor (Core A) and the proposed alternatives (Cores B and C), starting with a fresh core, is shown in Figure 3. The amount of plutonium produced in Cores B and C with 3.5 percent enriched fuel was reduced roughly by a factor of ten compared to Core A. Increasing the fuel enrichment to 20 percent lowers the plutonium production by about

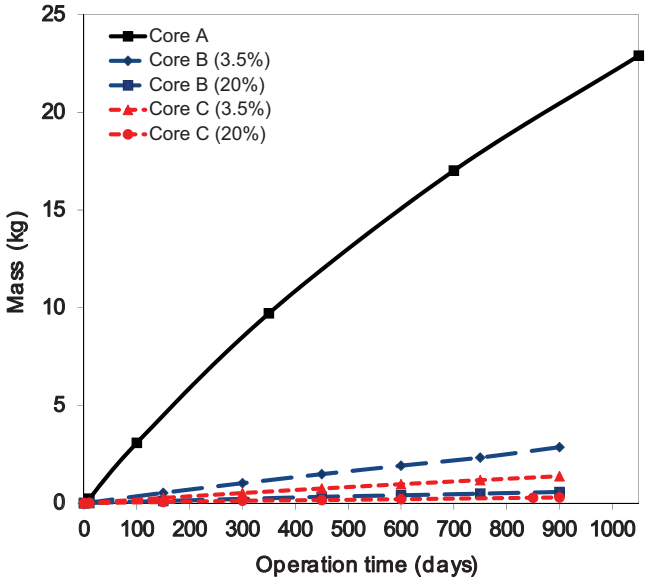

Figure 3: Plutonium production in the IR-40 reactor and the modified designs as a function of the operation time. The operation time in this figure is equivalent to the fuel residence time in the core (3× fuel cycle length).

a factor of 100 compared to Core A. These significant reductions are due to the reduced uranium-238 concentration in the enriched fuel and the reduced operating power.

Assuming 300 effective full-power days per year, all modified cores using enriched fuel produce less than 1 kg of plutonium per year. In the case of 20 percent enriched fuel, the plutonium production can be as low as 0.1 kg per year. In comparison, the amount of plutonium produced in Core A is about 7 kg per year.[14] On the other hand, the presence of a 20 percent enriched uranium stockpile would be a proliferation concern by itself as it requires significantly less additional separative work to reach weapon-grade enrichment levels.

If the thermal power of the Arak reactor is kept at 40 MW while converting the fuel from natural uranium to 3.5 or 20 percent enriched uranium, the plutonium production rate would be about twice as high as the rate in Core B. At 40 MWt and a fuel enrichment of 3.5 percent, the Arak reactor would produce about 2.30 kg of plutonium per year compared to about 0.4 kg if the fuel is enriched to 20 percent.

For further assessments below, it is assumed that the core is operated with three fuel batches, i.e., that one third of the fuel is discharged in every refueling. The in-core residence time of the fuel for Core A is estimated to be about 3.5 years (1,050 effective full-power days),[15] whereas for Cores B and C, the fuel could be kept in the core for about 3 years (900 effective full-power days) before being discharged. The spent fuel assemblies would then be moved to an

Table 2: Plutonium production and cycle length of the IR-40 reactor and the modified designs.

Parameter	Unit	Core A	Core B (3.5% U)	Core B (20% U)	Core C (3.5% U)	Core C (20% U)
Cycle length	days	350	300	300	300	300
Pu production	g/day	23.67	3.18	0.63	1.53	0.32
Pu-239 at discharge	(%)	76	70	67	72	70

onsite spent fuel pool for cooling. The total onsite plutonium inventory is the sum of the in-core plutonium and the plutonium stored in the spent fuel pool.

Compared to an estimated cycle length of 350 days for the IR-40 reactor, the low-enriched uranium (LEU) cores all have a cycle length that is about 50 days shorter. The reason is that the greater amount of plutonium bred in the natural uranium core increases its reactivity and thus prolongs its cycle length. The 50-day difference, however, as discussed below, does not greatly affect the overall resource requirements of the Arak reactor. Moreover, Cores B and C offer a reduced percentage of plutonium-239 in the discharged fuel because of the higher fuel burnup levels achieved in them while increasing the percentage yield of plutonium-238, making it even harder to weaponize the produced plutonium.

Table 2 summarizes the cycle length values, plutonium production rates, and average plutonium isotopics at discharge for the original and the proposed alternative cores.

Breakout Potential

For an assessment of breakout scenarios, the total onsite plutonium inventory should be taken into account. In the case of the IR-40 reactor, after the third spent fuel discharge, the core would contain one third of a fresh core, one third of a once-irradiated core, and one third of a twice-irradiated core. The total core inventory of plutonium after the third discharge would be about 20 kg. The pool would contain an additional 27 kg of unseparated plutonium at this time. Therefore, the onsite plutonium inventory, including the amount in the reactor, can be estimated at about 50 kg after about six years of operation. Most of this plutonium would not be weapon-grade, but it would be weapon-usable.[16] Using the IAEA estimate of 8 kilograms of plutonium for a first-generation nuclear weapon, this inventory would be equivalent to about six weapons. It should be noted that a plutonium breakout scenario would also have to consider the time needed to reprocess the spent fuel and extract the plutonium. Iran does not currently have a reprocessing facility and has repeatedly stated that it has no intention of building one. If Iran decided to replace the LEU with natural uranium fuel, taking fuel fabrication and reprocessing into account, it

would take Iran at least one year to make a single nuclear weapon using plutonium from the Arak reactor. This is significantly longer than the estimated breakout time expected for a scenario using highly enriched uranium produced in one of its enrichment plants even if their total capacity is capped.

REACTOR SAFETY

For a detailed reactor safety analysis, extensive neutronics and thermal-hydraulics calculations would have to be carried out in order to determine various steady-state and transient characteristics that are relevant for the safety of the reactor. In the case of the Arak IR-40 reactor, detailed design information and operating characteristics have not been published. The parameters used in the various calculations throughout this article were either obtained from the available literature or are based on authors' estimates and assumptions. The safety parameters studied in this article are therefore limited to the most basic quantities and reactivity coefficients and reactivity worth of control rods. Conducting a full-core safety analysis would require a complete description of the IR-40 reactor design and thermal-hydraulic analyses, which are beyond the scope of this article.

Reactivity Coefficients

Measuring the effects of varying the reactor power on core reactivity is an essential element of any reactor safety analysis. In water-moderated reactors, such effects are mainly due to variations in neutron absorption in the fuel and neutron moderation in the water with temperature. The MCNP5 code was used to measure both effects by running criticality calculations for two different temperature data points, T_1 and T_2. The fuel (Doppler) reactivity coefficient was estimated by varying the temperature of the fuel cell as well as the neutron cross-section libraries between T_1 and T_2. The moderator (void) coefficient was estimated by varying the moderator density between T_1 and T_2. The corresponding variation in reactivity (ρ) in both measurements can be written as:

$$\delta\rho = \frac{k_2 - k_1}{k_2\, k_1} \tag{1}$$

where k_1 and k_2 are the effective neutron multiplication factors at T_1 and T_2, respectively.

The statistical error of Equation (1) is:

$$\sigma_{\delta\rho} = \sqrt{\left(\frac{\sigma_{k_1}^2}{k_1^4} + \frac{\sigma_{k_2}^2}{k_2^4}\right)} \tag{2}$$

where σ_{k_1} and σ_{k_2} are the statistical errors of k_1 and k_2.

The fuel and void reactivity coefficients of the original Arak reactor as well as the proposed alternative cores are shown in Table 3. According to the design parameters reported in Table 1, Cores A, B, and C all have negative void and fuel-reactivity coefficients. Depending on the type of accident, these negative coefficients would stabilize reactor power: the void coefficient is most relevant in the case of a loss-of-coolant accident, in which the water density drops, and the fuel-reactivity coefficient is most relevant in a loss-of-flow accident, in which the temperature in the fuel increases. As shown in Table 3, using low-enriched fuel in Cores B and C makes the void reactivity coefficient less negative. This is mainly due to smaller fuel-to-moderator ratios in Cores B and C compared to Core A, which in turn is a result of the lower fuel density in the modified cores. Similarly, the reduced fuel density in Cores B and C also makes the fuel reactivity coefficient less negative compared to Core A. This is due to the lower concentration of uranium-238, the main contributor to Doppler absorption in the fuel. The same effects can be observed when comparing Cores B and C of 3.5 percent enrichment with those with 20 percent enrichment.

Control Rod Worth

The second part of Table 3 shows the integrated reactivity worth of a single control rod as well as the total worth of all the available rods in the core. Control rods absorb neutrons and are used to maintain criticality of the reactor or shut it down completely. The core-reactivity change upon withdrawal or insertion of a control rod depends on whether the rod is fully or partially inserted as well as on the fuel and core design. The change of reactivity due to a control rod insertion is known as control rod worth. The reactivity is recorded using the pcm (percent milli-rho) unit: 1 pcm is equal to $0.00001(\delta k)/k$ where δk is the variation in the multiplication factor k.

The reactivity worth of a single control rod inserted between two channels in the inner-most circle is measured using the MCNP5 criticality option. The design parameters of the modeled control rods are shown in Table 4.[17] The effect of spatial variations due to different control rod positions in Cores A, B, and C on rods' worth can be accounted for using the following formula:[18]

$$\delta\rho_i = J_0^2\left(\frac{2.405\, r_i}{R}\right)\delta\rho_0 \tag{3}$$

where $\delta\rho_i$ is the worth of the ith control rod, $\delta\rho_0$ is the worth of a control rod inserted at the center of the core, J_0 is a zero order Bessel function of the first kind, r_i is the radial position of the ith control rod, and R is the radius of the core.

As shown in Table 3, the reactivity worth per rod in Cores B and C is higher than the respective worth in Core A due to the lower active radius of modified cores. It should be noted, however, that the total reactivity worth of a single

Table 3: In-core safety parameters of the IR-40 reactor (Core A) and the modified designs (Core B & Core C).

	Unit	Core A	Core B (3.5% U)	Core B (20% U)	Core C (3.5% U)	Core C (20% U)
			Reactivity coefficients			
Void coefficient	pcm/°C	-6.43 ± 0.21	-4.10 ± 0.18	-2.35 ± 0.17	-4.83 ± 0.23	-3.39 ± 0.22
Fuel coefficient	pcm/°C	-2.23 ± 0.02	-1.03 ± 0.02	-0.55 ± 0.02	-1.21 ± 0.02	-0.81 ± 0.02
			Control rods reactivity worth			
Single CR worth	pcm	-1157 ± 64	-1200 ± 57	-1321 ± 57	-1843 ± 68	-2292 ± 63
Number of CRs	—	27	21	21	15	15
Total CRs worth	pcm	-20.8×10^4	-16.4×10^4	-18.1×10^4	-19.7×10^4	-24.5×10^4
β_{eff}	pcm	668 ± 0.4	670 ± 0.4	696 ± 0.5	651 ± 0.5	656 ± 0.6

Table 4: Control rod design parameters.

Parameter	Unit	Value/Option
Neutron absorber	—	Boron carbide (B_4C)
Boron composition	—	Natural boron
Boron carbide density	g/cm^3	2.5
Cladding material	—	Aluminium
Inner hole radius	cm	2.5
Inner cladding thickness	cm	0.375
Boron carbide thickness	cm	0.375
Outer cladding thickness	cm	0.25

control rod in Cores A, B, and C is higher than the effective delayed neutron fraction (β_{eff}) of these cores. Therefore, in the case of a rod ejection accident (REA), the positive reactivity added to all three cores would be higher than β_{eff}, which would lead to prompt criticality and a sharp increase in the reactor power. As the positive reactivity addition approaches β_{eff}, the reactor system becomes less and less dependent on the delayed neutrons and the reactor period decreases smoothly to shorter and shorter values.[19] This issue, however, can be resolved by changing the design of the control rod so that the total integrated worth is less than β_{eff}. Reducing the poisoning effects of control rods can be achieved either by reducing the density of boron or shortening the length of the rods.

RADIOISOTOPE PRODUCTION

Besides being a research facility, the IR-40 reactor at Arak is also envisaged as a source of medical radioisotopes, particularly molybdenum-99. Maintaining the physical conditions required for conducting research activities as well as allowing for the production of the desired levels of molybdenum-99 in the modified core configurations of the Arak reactor is treated as a technical constraint throughout this study.

Molybdenum-99 Production Model

Molybdenum-99 is mainly produced by neutron irradiation of uranium targets in a nuclear reactor.[20] Molybdenum-99 is a radioactive fission product of uranium-235 and has a half-life of about 66 hours. The β-decay of molybdenum-99 results in the production of metastable technetium-99 (^{99m}Tc), which then decays to technetium-99 with a half-life of about 6 hours. Research reactors are generally well-suited for the production of molybdenum-99 because they have the capacity to irradiate several targets in high neutron-flux environments.

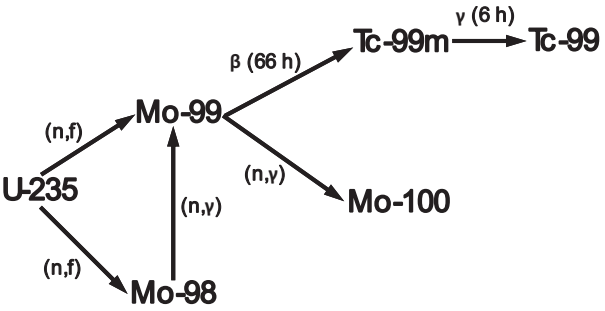

Figure 4: Production of molybdenum-99 in a nuclear reactor.

As shown in Figure 4, the molybdenum-99 produced in a nuclear reactor originates either directly from fission reactions or from radiative neutron capture in molybdenum-98, which is also a fission product. Although molybdenum-99 is essentially produced in all fuel elements within the core, only the part in dedicated targets will be processed because of the speedy operations required. The specifications of the notional molybdenum-99 target used in this analysis are listed in Table 5.[21] Molybdenum-99 targets generally have a particular design that is different to that of a typical fuel element. In this case, we assume that the targets are fueled with 20 percent enriched uranium, which is arranged in a very thin annular shape to minimize the effects of self-shielding and reduce volumetric heating.

Based on scheme shown in Figure 4, the number densities of molybdenum-99 (N^{99}) and molybdenum-98 (N^{98}) can be written as:

$$\frac{\mathrm{dN}^{99}}{\mathrm{d}t} = \alpha N^{235}\sigma_f^{235}\Phi + \sigma_c^{98}N^{98}\Phi - \lambda^{99}N^{99} - \sigma_c^{99}N^{99}\Phi \tag{4}$$

Table 5: Molybdenum-99 target design parameters.

Parameter	Value/Option
Target geometry	Annular
Target inner radius	1.105 cm
Target outer diameter	1.210 cm
Target active length	100 cm
Target fuel	UO_2
Target fuel enrichment	20%
Target fuel density	9 g/cc
Target fuel thickness	150 μm

$$\frac{\mathrm{dN}^{98}}{\mathrm{d}t} = \alpha' N^{235} \sigma_f^{235} \Phi - \sigma_c^{98} N^{98} \Phi \tag{5}$$

where N^i is nuclei number density of isotope i, Φ is the total neutron flux, α is molybdenum-99 fission yield, α' is molybdenum-98 fission yield, $\sigma_{\mathrm{f}}^{235}$ is the spectrum-averaged fission cross-section of uranium-235, σ_{c}^{99} is the neutron capture cross-section of molybdenum-99, σ_{c}^{98} is the neutron capture cross-section of molybdenum-98, and λ^{99} is the molybdenum-99 decay constant. Inserting effective neutron capture cross-sections of molybdenum-99 and molybdenum-98, confirms that both capture reactions are insignificant compared to the other processes and can therefore be dropped. Equations (4) and (5) can then be reduced to:

$$\frac{\mathrm{dN}^{99}}{\mathrm{d}t} = \alpha N^{235} \sigma_f^{235} \Phi - \lambda^{99} N^{99} \tag{6}$$

Since the target residence time in the core is about one week, one can safely assume that the neutron flux and the spectrum-averaged fission cross-section will remain constant. Therefore, the uranium-235 number density (N^{235}) can be expressed as:

$$N^{235}(t) = N_0^{235} e^{-\sigma_a^{235} \Phi t} \tag{7}$$

Substituting Equation (7) in Equation (6) then solving the non-homogenous differential equation, the time-dependent molybdenum-99 activity (A^{99}) can be written as:

$$A^{99}(t) = \lambda^{99} \left[\frac{\alpha N_0^{235} \sigma_f^{235} \phi}{\lambda^{99} - \sigma_a^{235} \phi} \right] \left(e^{-\sigma_a^{235} \Phi t} - e^{-\lambda^{99} t} \right) \tag{8}$$

The values of the various parameters used to calculate the molybdenum-99 activity in Equation (8) are listed in Table 6. The cross section values were calculated using MCNP5 based on the target design parameters in Table 5.

Table 6: Parameters of the molybdenum-99 production model.

Parameter	Unit	Core A	Core B (3.5% U)	Core B (20% U)	Core C (3.5% U)	Core C (20% U)
Φ	n cm^{-2} s^{-1}	9.8×10^{13}	9.5×10^{13}	9.3×10^{13}	9.1×10^{13}	9.0×10^{13}
σ_f^{235}	barn	250	280	285	277	278
σ_a^{235}	barn	294	330	334	325	327
N_0^{235}	nuclei	2.98×10^{23}	2.98×10^{23}	2.98×10^{23}	2.98×10^{23}	2.98×10^{23}
λ^{99}	s^{-1}	2.92×10^{-6}	2.92×10^{-6}	2.92×10^{-6}	2.92×10^{-6}	2.92×10^{-6}
α	—	0.0611	0.0611	0.0611	0.0611	0.0611

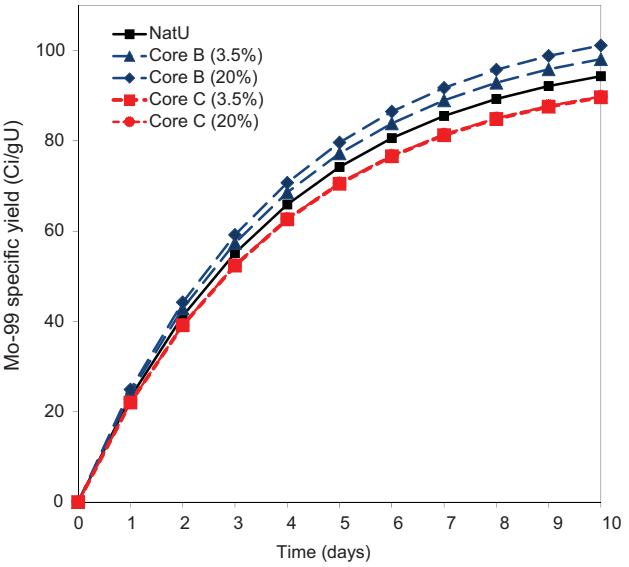

Figure 5: Molybdenum-99 specific yield in the IR-40 reactor (Core A) and the modified designs (Cores B and C).

Molybdenum-99 Production

Since all examined cores (A, B, C) have essentially the same neutron flux at the center of the core, where the molybdenum-99 target would be located, the specific yields in these three cases are nearly identical also (Figure 5). The available quantity of molybdenum-99 to the end-user from an irradiated target is less than the total quantity of molybdenum-99 produced in the target. The end-user quantity of molybdenum-99 is distributed between 2–7 days following the end of target irradiation. One week after discharge, the amount of molybdenum-99 available to the end-user is about 10–15 percent of the amount originally available in the target because of radioactive decay and process losses. The molybdenum-99 market production unit is 6-day curies.[22] The final molybdenum-99 yields (in 6-day curies) produced by the IR-40 reactor and the proposed designs are shown in Table 7. The small variation in the production levels of molybdenum-99 between the cores is mainly due to differences in the spectrum-averaged fission cross-section of uranium-235, which is higher in Cores B and C. The numbers in Table 7 clearly show that the proposed modifications do not compromise the ability of the Arak reactor to produce medical isotopes. Iran currently imports 100 6-day curies of molybdenum-99 per week from Russia to supplement the production by the Tehran Research Reactor. Molybdenum-99 production in the Arak reactor would see Iran achieve self-sufficiency and perhaps offer part of the production for export.

In addition to producing medical radioisotopes, the Arak reactor may also be used for material testing and other research activities. As shown in Figure 1, Cores A, B, and C have six unfueled channels available for research

Table 7: Molybdenum-99 production in the IR-40 reactor and the modified designs.

Parameter	Unit	Core A	Core B (3.5% U)	Core B (20% U)	Core C (3.5% U)	Core C (20% U)
U-235	grams	116.33	116.33	116.33	116.33	116.33
Mo-99 Yield	Ci/gU	81	87	86	86	87
Mo-99 Yield	6-days Ci	1179	1270	1250	1254	1220

purposes. Based on the neutron flux distributions in the studied cases (shown in Figure 2), it is clear that the proposed alternative designs provide a similar, if not an improved, neutron flux available for research. In addition to the six available channels in the core, the proposed designs also offer free extra channels around the core, which could be utilized for research purposes that require less intense neutron flux.

RESOURCE REQUIREMENTS

The neutronics calculations used to estimate plutonium production can also be used to estimate the effect of the proposed modifications on uranium and enrichment requirements. Although the Arak reactor is a research facility and therefore requires much less fuel than a commercial power reactor, a comparative resource analysis helps estimate part of the economic cost of the proposed modifications. The average resource and fuel-cycle requirements of the studied concepts in this paper are summarized in Table 8. The comparison is based on two elements: total natural uranium demand and total separative work units (SWUs) required to supply the fuel for Cores A, B, and C. As it can be seen from Table 8, assuming an operation lifetime of 40 years, the 20 MWt core options

Table 8: Resource requirements of the IR-40 reactor and the modified designs.

	Unit	Core A	Core B (3.5% U)	Core B (20% U)	Core C (3.5% U)	Core C (20% U)
Initial core						
Enriched uranium demand	tons	0	0.880	0.154	0.447	0.078
Natural uranium demand	tons	8.55	6.85	7.28	3.48	3.69
Uranium enrichment	(%)	—	3.5	19.75	3.5	19.75
Separative work	SWU	0	3819	5818	1949	2947
Externally supplied services and materials						
Enriched uranium demand	tons/year	0	0.293	0.051	0.149	0.026
Natural uranium demand	tons	2.44	2.28	2.43	1.16	1.23
Uranium enrichment	(%)	—	3.5	19.75	3.5	19.75
Separative work	SWU/year	0	1273	1939	650	982
Lifetime requirements: Initial core and 40 years of operation						
Natural uranium	tons	106.15	95.77	102.05	48.72	51.66
Separative work	SWU	0	53466	81439	27299	41245

require as much natural uranium feed as the original IR-40 reactor, while the 10 MWt core options would require about half that amount. As for the total enrichment work needed, the proposed modifications, as expected, require modest amounts, especially compared to a commercial-scale power reactor.

CONCLUSION

This article proposes modifications of the Arak reactor that are based on two key elements: replacing the natural uranium fuel with LEU fuel and reducing the power level of the reactor from 40 MWt to 20 MWt or even 10 MWt. The proposed redesigns would dramatically reduce plutonium production in the Arak reactor from 7–9 kg to less than 1 kg per year. For example, the 10 MWt option with 3.5 percent enriched fuel would annually produce only about 360 grams of plutonium. At the same time, the redesigns would not compromise the usefulness of the reactor for making radioisotopes and conducting research. A preliminary safety analysis of the proposed alternative designs shows that, in principle, these designs have negative power-to-reactivity coefficients, an important safety parameter. To support the basic safety analysis presented, full and extensive design information of the IR-40 reactor and thermal hydraulic analyses will be required. Based on the various aspects studied, the conversion scenario proposed in this article should meet Iran's needs and address the concerns of the international community as reflected by the P5+1. The analysis and discussion in this article may also provide some guidance for similar (future) situations, where the conversion of a heavy-water reactor from natural uranium to LEU is considered to address proliferation concerns associated with the operation of such facilities.

NOTES AND REFERENCES

1. The P5+1 are the five permanent members of the United Nations Security Council, China, France, Russia, the United Kingdom, the United States and Germany.

2. Note also that Canada's original NRX reactor, which served as a template for CIRUS, was designed as a plutonium production reactor. For a discussion of plutonium production strategies of all weapon states, see International Panel on Fissile Materials, "Global Fissile Material Report 2010: Balancing the Books," Princeton, NJ, December 2010.

3. "Arak Heavy Water Reactor Is for Peaceful Research: Dr. Salehi (Part 2)," Press TV, 5 February, 2014, www.presstv.ir/detail/2014/02/05/349340/false-allegations-wont-stop-arak-reactor.

4. A. Ahmad, F. von Hippel, A. Glaser, and Z. Mian, "A Win-Win Solution for Iran's Arak Reactor," *Arms Control Today*, (April 2014): 8–13.

5. T. M. Willig, C. Futsaether, and H. Kippe, "Converting the Iranian Heavy Water Reactor IR-40 to a More Proliferation-Resistant Reactor," *Science & Global Security* 20 (2012): 97–116.

6. Between 2001 and 2010, 20 research reactors were converted from using weapons-grade uranium fuel to 19.75 percent enriched fuel. For updates, see www.rertr.anl.gov.

7. Salehi: Arak Reactor Being Modified, Kayhan (Iran), 27 August, 2014, kayhan.ir/en/news/4385/salehi-arak-reactor-being-modified.

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10. Xu et al., "An Improved MCNP-ORIGEN Depletion Program (MCODE) and its Verification for High Burnup Applications," Paper presented at PHYSOR, 7–10 October 2002, Seoul, Korea.

11. X-5 Monte Carlo Team, "MCNP A General N-Particle Transport Code, Version 5." Volume I: Overview and Theory, LA-UR-03-1987 (April, 2003).

12. S. B. Ludwig, and J. P. Renier, Oak Ridge National Laboratory, "Standard- and Extended-Burnup PWR and BWR Reactor Models for the ORIGEN2 Computer Code," TM-11018, 1989.

13. "Converting the Iranian Heavy Water Reactor," This group also examined the possibility of converting the Arak reactor to LEU, but examined only uranium-dioxide fuel.

14. All these production rates would be about 20 percent higher if 365 effective full-power days per year are assumed.

15. Given the assumption that the reactor will be operating for 300 days per year.

16. Weapon-grade plutonium is defined as containing less than 7 percent plutonium-240. See U.S. Department of Energy, "Plutonium: The First 50 Years," DOE/DP-0137, February 1996, 17. On the weapon-usability of non-weapon-grade plutonium, see J. Carson Mark, "Explosive Properties of Reactor-grade Plutonium," *Science & Global Security* 4 (1993): 111–128.

17. The control rods in the IR-40 at Arak are believed to be of the same type as those deployed in the RBMK reactor design. The control rod design parameters were taken from R. T. Perry and G. H. Meriwether, "A WIMS-NESTLE Reactor Physics Model for an RBMK Reactor," Paper presented at the International Conference on the Physics Reactors PHYSOR96, 16–20 September 1996, Mito, Japan.

18. Elmer Lewis, Fundamentals of Nuclear Reactor Physics, (Elsevier, Academic Press: Burlington, MA, 2008) 190.

19. CANDU Reactor Physics, available at canteach.candu.org.

20. Molybdenum-99 can also be produced via neutron activation of molybdenum-98 and via photo-nuclear reaction of molybdenum-100. Neutron activation is only practical for reactor based-production because of its relatively small (n,γ) cross-section. Molybdenum-99 produced through these two processes has a lower specific activity than fission-produced molybdenum-99 because of the other isotopes in natural molybdenum.

21. The molybdenum-99 target specifications are largely adopted from Dong-Keun Cho and Myung-Hyun Kim, "Nuclear Design Methodology of Fission Moly Target for Research Reactor," *Journal of the Korean Nuclear Society* 31 (1999): 365–374.

22. 6-day curies refers to the activity of molybdenum-99 six days after the end of the production process which itself takes about one day after irradiation in the reactor is completed.