The Plutonium Option: Iran's Parallel Route to a Military Nuclear Capability

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Since the first announcement in August 2002 that Iran was constructing a heavy water production facility at Arak, there has been little doubt in the minds of many people that in parallel with a uranium enrichment program, Iran has embarked on a plutonium route for the production of fissile materials for military use. With the approaching completion of the IR-40 heavy water natural uranium reactor at Arak, this scenario has commanded more public attention.[1] The potential for using plutonium in the core of a nuclear explosive device is serious, and indeed, this project has proceeded in blatant disregard of Security Council resolutions.[2] Although the estimated date of completion of this route is not imminent, the project is nevertheless nearing a so-called critical point. In contrast to the uranium track, the plutonium route will apparently soon usher in an environmental point of no return. This paper describes the general processes involved in the production of plutonium, and then considers the potential of the Iranian plutonium program, an estimated timeline and other aspects of the program, and prospects for the future.

The Basics of Plutonium Production

Stage 1: The Irradiation of Uranium in a Reactor

Unlike uranium, plutonium is not a naturally occurring element (for a definition of the technical terms, see the Glossary at the end of the article). In general, plutonium is produced in nuclear reactors. In the basic process of "fission" of uranium-235, the uranium nucleus that is "hit" by a particle known as a "neutron" is broken into 2-3 nuclei (known as fission

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products), emitting 2-3 neutrons and releasing a lot of energy. The neutrons emitted during the fission serve a dual purpose in the controlled process of the reactor: they can (after losing some of their energy in a moderator) a) hit another uranium-235 nucleus, thereby enabling a continuation of the fission process, commonly known as a "chain reaction," or b), hit a nucleus of another form (called "isotope") of uranium – uranium-238. If this happens, the uranium-238 nucleus will eventually turn into a completely new nucleus – the nucleus of plutonium-239. This material is also a fissile material, like uranium-235, from which a plutonium bomb can be produced. If emitted in a controlled process, the product can serve as a reliable source of energy, e.g., electricity. If uncontrolled, an explosion can occur. The fission products nuclei are mostly radioactive and are commonly designated as "radioactive waste."

The uranium found in nature is composed mainly of uranium-238 (~99.3 percent) and uranium-235 (~0.7 percent). Most nuclear power reactors are fueled by uranium enriched in its 235 component (with the respective reduction in its 238 component). Natural uranium is the preferred fuel for nuclear reactors designed for plutonium production. Because of certain traits, natural uranium reactors must be built with either heavy water or graphite as moderators – the materials needed to slow down the neutrons in the reactors so that the chain reaction can be maintained. In contrast, when enriched uranium is used, e.g., in power reactors, light water (regular water) can be – and usually is – used as the moderator.

> Once the reactor has "gone critical," it enters a "zone of immunity," after which it is practically immune from attacks. Iran has the option of hastening the advent of the zone of immunity, and while this would contradict its obligations to the IAEA, the profit in doing so would be considerable.

Plutonium-239 is the preferred component for nuclear weapons production. Throughout the reactor's operation during its production, however, other forms (isotopes) of plutonium are produced, first and foremost plutonium-240. This isotope is an undesirable one since in nuclear weapons it can cause premature explosions, resulting in a much lower or even negligible yield. The production of this isotope is proportional to the duration of the irradiation of the uranium in the reactor where it is produced. Thus, the production regime becomes a balance between the desire to produce more plutonium and the aim to have as low a proportion of plutonium-240 as practicable.

Stage 2: The Separation of Plutonium from the Reactor Irradiated Fuel

Upon completion of the fuel irradiation according to the pre-planned schedule, the fuel must be removed from the reactor and chemically processed to separate the plutonium from its other components. Since this irradiated fuel is highly radioactive, in order to be able to handle it with relative safety it must be "cooled." Because of the characteristics of radioactivity this can only be done by waiting – giving the radioactivity time to "decay," i.e., to reduce its levels of activity. Thus, the irradiated fuel is stored after it has been removed from the reactor for a long period of time in a cooled pool of water until its radioactivity reaches the preset level, whereupon it can be processed relatively safely.

Because of the high residual level of radioactivity, the "reprocessing" activity takes place in a separate facility, with appropriate shielding against radiation and with remote controls and handling capabilities. The process stages are as follows: removal of the fuel cladding; removal of the radioactive waste; and separation of the plutonium from the uranium.

Stage 3: The Processing of the Plutonium into a Nuclear Weapons Core

Plutonium is a highly toxic metal that is also pyrophoric (prone to spontaneous combustion) in air. Therefore, special safety precautions must be taken when dealing with it: it must be handled in special glove boxes with inert gas atmosphere, to prevent both outside contamination and combustion. The liquid plutonium solution produced by the reprocessing procedure is turned into metal, melted, and machined to turn it into the sphere (the "core") that can then be inserted into the explosive mechanism, which turns it into a nuclear explosive device. Special care must also be taken during the processing of the plutonium to prevent "criticality." If the amount of the fissile element is too large, an uncontrolled spontaneous fission chain reaction can occur, which is a hazard when handling fissile materials – plutonium and enriched uranium. The history of fissile materials production is replete with careless criticality accidents, some of which resulted in deaths of personnel and the destruction of process facilities.

The Iranian IR-40 Reactor

Less than a year following the release of the information concerning the construction of the heavy water production plant, Iran informed the International Atomic Energy Agency (IAEA) that it was planning to construct a heavy water natural uranium reactor at Arak. Designated IR-40, it was to be a 40 megawatt reactor and dedicated to research and the production of commercial isotopes.[3] From the details of this reactor, both confirmed and assessed, it appears that its design is distinctive, employing some characteristics of known, mainly Russian, reactor designs, with some additional features unique to this reactor.[4]

From Iranian photographs of the nuclear fuel intended for use in the IR-40 and from additional information supplied by the Iranians, it was deduced that the basic nuclear fuel structure resembles the fuel of the Soviet-produced RBMK nuclear power reactors (one of which exploded in the Chernobyl accident in 1986).[5] The fuel itself is composed of uranium dioxide cylindrical pellets inserted into Zircaloy tubes, 18 of which are gathered into a fuel assembly.[6] It is estimated that some 150 fuel assemblies will comprise the reactor's core. Since this fuel design is not a natural choice for a heavy water reactor, the Russian design was likely copied as a matter of convenience, and the choice of uranium dioxide for the pellets was made because of its similarity to the Bushehr reactor fuel (even though the Bushehr fuel consists of low enriched uranium) so as not to need additional fuel designs and processes in Iran. Some of these choices make the reactor design less than optimal for the production of plutonium, and seem to have been made for the sake of easier construction.

When operational, what could this reactor produce? As a rule of thumb, one can estimate that a heavy water natural uranium reactor will produce about 1 gram of plutonium in one day for every megawatt (MW) of power. Thus, if we have a 40 MW reactor it will produce 8 kilograms of plutonium in 200 days.[7] When planning the reactor irradiation regime, additional considerations come into play: the 240 to 239 plutonium ratios, the considerable waste of uranium when a lower 240 to 239 plutonium ratio is desired, and the additional time given the frequent unloading of irradiated fuel and loading of fresh fuel.

A ratio of 2 percent plutonium 240 to 239 is considered to be super weapons grade. This is achieved when the nuclear fuel is irradiated for some three months and then removed from the reactor core. For the production of the 6 percent 240 to 239 plutonium, considered to be weapons grade, some nine months of irradiation would be needed, which reduces the load/unload times but increases the chances of premature nuclear explosions when the plutonium is used in an explosive device. In the case of extended irradiation much uranium can be saved, which could be a consideration for Iran, a country with limited uranium reserves.

Additional Facilities

In order to use the plutonium produced by the IR-40 reactor, both a reprocessing plant and metallurgical facilities would be needed. So far, based on open source information, nothing is known about additional facilities that would be needed in Iran for the production of the cores for plutonium-based nuclear explosive devices. Following the irradiation and removal of fuel from the reactor, the next stage of the process is the interim cooling storage of the fuel. This can take place at the reactor facility itself, thereby reducing the need for moving a highly radioactive fuel until necessary. Should the authorities consider the moving of this fuel to be necessary, it would take a heavy radiation shield and many trips of the shielded material to transport a full reactor load of irradiated fuel to another site. This interim storage could take place at the reprocessing plant or at an independent site, thereby requiring another transport once the fuel is ready for reprocessing.

Reprocessing is a messy activity. If reprocessed too soon, the radioactive waste includes many gaseous components, which would probably be released into the atmosphere and become a hazard to the environment. The longer the reprocessing is delayed, the smaller this hazard becomes. A reprocessing plant is a relatively large facility. Therefore, if a reprocessing plant is to be constructed in Iran it would be rather hard to conceal, and its operation would be easier to discover than that of a uranium enrichment facility.

The final stage in the production of the plutonium-based nuclear explosive core will take place at metallurgical facilities, very specialized but much smaller in scale than the two previous facilities. These laboratories do not have to be in close proximity to the reprocessing plant and can be constructed in parallel with the reprocessing plant.

Possible Iranian Timelines for the Production of a Plutonium Nuclear Explosive Core

The IAEA May 2013 periodic report to its Board of Governors and to the Security Council stated that Iran confirmed the following commissioning schedule for the IR-40 Reactor: "Phase 1 – pre-commissioning (using dummy fuel assemblies and light water) in the fourth quarter of 2013; Phase 2 – commissioning (using real fuel assemblies and heavy water) in the first quarter of 2014; expected to become operational during the third quarter of 2014."[8] If the above Iranian information is taken at face value, and if all goes well for Iran in the commissioning and operation of the reactor, the earliest that Iran could expect the completion of the first plutonium production is sometime in the spring of 2015. If Iran wants to retain a plutonium ratio of 2 percent, it would need three complete irradiation cycles of 90 days for each cycle; the load/unload time that could take a few weeks extends the time for the production of plutonium for one nuclear explosive core to around a year. One also should take into account a prolonged first operation of the reactor following its commissioning, since one has to test the reactor at all stages of its power increases, up to full power operation. This would bring the completion of the first production of plutonium in the reactor to late 2015. Note that the IAEA report of late August 2013 included a notification by Iran regarding a possible delay in the timetable for inaugurating the reactor.[9]

If we consider a minimal cooling period of 180 days before the irradiated fuel can be reprocessed, we have to calculate the beginning of reprocessing from either the completion of the first 90 days of irradiation, in the case of the 2 percent ratio, or from the completion of the 200 days of the first 8 kilogram production, a difference of more than three months.

We should assume an optimized plan for both the irradiation and the reprocessing operation, so that the time length of reprocessing should be on the order of the irradiation time, in order that the time length of one process should not be significantly different from the other, negating the possibility of the formation of a bottleneck. This would bring the estimate of the reprocessing time to about 200 days for the first eight kilograms.

It is difficult to simulate the processing of plutonium into a nuclear core for an explosive device. High enriched uranium (HEU) is similar to natural uranium in all mechanical, chemical, and metallurgical properties. As such, all preparations for manufacturing an HEU nuclear warhead, including the manufacturing of "dummy" warheads, can be simulated with natural uranium. Therefore, when one has a sufficient quantity of HEU at hand and all preparations have been made, one can produce a nuclear warhead without any delay in a very short time. This, however, is not the case for plutonium. It is difficult to simulate this highly toxic and flammable material. Iran will have to wait for a sufficient first quantity of plutonium before it can master the processing into a first nuclear core for an explosive device. Although arguable, one should assume at least six months for this to be completed.[10]

Table 1 summarizes the time estimates for the completion of one plutonium core for a nuclear explosive device under different scenarios.

Table 1: Estimating the Timelines for the Plutonium Route

The Product Activities	**2% Pu-240/239**	**8 Kilogram Pu Production**	**6% Pu-240/239**
Start of irradiation	End of 2014	End of 2014	End of 2014
Completion of first irradiation batch	90 days	200 days	270 days
Cooling period	180 days	180 days	180 days
Reprocessing of the 1st irradiation batch*	90 days	200 days	270 days
Completion of 1st 8 kilograms**	180 days	No extra time	No extra time
End of metallurgical processing	180 days	180 days	180 days
Estimated date of completion of 1st plutonium core	Late 2017	Early 2017	End of 2016

* Assuming the readiness of the reprocessing plant
** From the end of the 1st cooling period

The Bushehr Nuclear Power Reactor

Nuclear power reactors, fueled by uranium, produce plutonium, even if enriched to a low enrichment level. A characteristic of these reactors is that the fuel is irradiated for a very long period of time and to high irradiation levels for the sake of power production efficiency. In these reactors the ratio of plutonium-240 to 239 (denoted as "reactor grade plutonium") is much higher than is applicable for nuclear weapons production. Therefore, on the face of it, the Bushehr power reactor does not pose a proliferation threat. However, there is a caveat to this statement. If so desired, the Bushehr power reactor could be operated for a short period (weeks or very few months), possibly at low levels, and then its full or partial load of fuel removed and reprocessed. In this way, the 240 to 239 ratio would remain at weapons grade levels. An additional benefit would be that the amount of plutonium so produced in one batch would be considerable, because of the large amount of irradiated uranium. Admittedly, this is an awkward choice of procedure, not least because the fuel belongs to Russia, and Tehran has committed to return it to Russia – but can Iran be trusted to abide by its commitments under all circumstances?

The Rationale of Pursuing the Plutonium Route

Most of the states that embarked on a military nuclear weapons program did so at first in one way, either HEU or plutonium, and later went on to achieve a military nuclear capability in both routes. Such was the case for the five nuclear weapons states, as well as for India, Pakistan, Iraq, and North Korea. Although much more difficult to produce, plutonium has certain advantages, mainly the smaller quantity of plutonium needed to produce the same nuclear explosion yield, and consequently the smaller size of the warhead. This is immediately reflected in the size of, e.g., a missile payload, and the distance it can reach with a plutonium warhead, as compared with an HEU warhead.

Besides being more difficult to achieve, plutonium has several other drawbacks. Plutonium emits more radiation than HEU, it is more difficult to contain the process and thus the emission of radioactive materials to the environment makes the activity easier to discover, and the extensive stages of operation make this route more vulnerable to external intelligence surveillance.

Discussion and Conclusions

A program for the indigenous development and production of nuclear explosives is never short term. The UN Security Council did well when it consistently took note of the fact that Iran was developing not only its uranium enrichment route toward the potential nuclear weapons development, but also embarked on the plutonium potential development route. Although Iran insists that its IR-40 is part of its peaceful nuclear program, the choice of a natural uranium, heavy water reactor is not the natural one. Iran declares the intended use of this reactor to be radioisotope production. Iran's Tehran Nuclear Research Reactor (TNRC), partially fueled with its indigenously produced 20 percent enriched uranium nuclear fuel, produces medical isotopes. Thus looking at the IR-40 reactor on its own, there is some logic to its construction, yet within the overall picture of Iran's nuclear project, one cannot dismiss the horrifying potential of this reactor. Most nations of the world do not see the need for, and do not produce the medical and industrial radioisotopes for their needs but purchase them freely on the world market.

An issue that cannot be answered unequivocally is that of the length of time needed for the construction of a nuclear reprocessing plant. There are many answers to this question. A 1978 US GAO report brings several different estimates by several institutes, ranging from several months to two years.[11] Many of the estimates in the case of Iran depend on the availability of materials and equipment. Much could also depend on the availability of a detailed design of this installation. The time estimates about the Iranian project in the present paper are very rough ones. There are many unknowns at present that could tip the scales one way or the other. Still, these estimates serve as guidelines for neither pessimistic nor optimistic scenarios, and should be seen as midpoint estimates that offer useful information for the decision makers.

There can be no doubt that should Iran produce its first plutonium core, this would not be sufficient for any practical matter. While there can be arguments considering the minimal number of warheads (cores) that Iran would want, it is only reasonable to assume that once Iran would have the capability, it would attempt to accumulate as many warheads as possible in the shortest time. One factor to consider is the quantity of plutonium needed for a fission weapon. It is assessed that for a 10 kiloton TNT equivalent yield, a quantity of 3-5 kilograms would be needed, depending on the technical capabilities of the weapons developers.[12] Thus, following its first core, Iran could produce 2-3 cores per year.

One cannot ignore the history of military action against nuclear reactors. It is usually accepted that once the reactor has "gone critical," it enters a "zone of immunity," after which it is practically immune from attacks. This results from the possible environmental consequences of the release of radioactive matter, as exhibited by the Chernobyl and

Fukushima accidents. No doubt, a much smaller reactor and a very short irradiation time would cause much reduced damage, but still the "zone of immunity" is an internationally accepted benchmark. Iran has the option of hastening the advent of the zone of immunity by foregoing the first phase of commissioning, introducing uranium fuel and heavy water, and starting up the reactor. Although this would contradict its obligations to the IAEA, the profit in doing so would be considerable.

In conclusion, Iran is proceeding slowly but surely toward acquiring a plutonium production capability suitable for military purposes, although some important components have not yet been detected. There should be no doubt that Iran is capable of obtaining these components. In any agreement with Iran concerning the nuclear project, the plutonium route must be adequately covered.

Glossary

Enrichment – the process by which the natural composition of an element is changed to give preference to one or more isotopes. In the case of uranium, enrichment refers to higher concentrations of uranium-235.

Explosive device – the combination of a nuclear fissile core and the explosive mechanism that surrounds it.

Fission products – the atoms produced by the fission process; the vast majority of these are radioactive.

Fission – the process by which a heavy nucleus (e.g. uranium or plutonium) is split into two or more atoms, emitting neutrons and energy.

Fuel – nuclear material inserted into a reactor, which can undergo fission and carry out a controlled chain reaction.

Glove boxes – large boxes, with transparent walls, through which protective gloves can be inserted, facilitating safe work on equipment and materials inside the boxes. The atmosphere inside the boxes can be air or, in the case of sensitive materials, inert gases (e.g., argon).

Heavy water – water enriched with "deuterium" or heavy hydrogen. For utilization in a reactor a purity of 99.75 percent is required.

Irradiation – a process by which materials are "bombarded" by radiation or by particles. In a reactor, the fuel is irradiated by bombarding it with neutrons.

Isotopes – different forms of the same element, differing by weight and possibly some physical properties, such as radioactivity.

Metallurgy – the science and technologies dealing with metals.

Moderator – in most reactors, the neutrons involved in the fission process have to be slowed down in order to sustain the reactor. This is carried out by a moderator, usually composed of water, heavy water, or graphite.

Plutonium (Pu) – a heavy, man-made, highly toxic metal, produced in reactors. Of the many Pu isotopes, the high-purity Pu-239 is the important one for use in nuclear explosive devices. For this purpose a low (below 6 percent) concentration of Pu-240 is essential.

Reactor – the facility where a controlled fission process takes place. A reactor, which is a complicated technical facility, utilizes nuclear fuel composed of fissile materials. Power reactors, research reactors, and marine propulsion reactors are the most important among the many types of reactors.

Reprocessing – the process by which the plutonium is separated from the irradiated fuel.

Uranium (U) – the heaviest naturally-occurring element, composed of several isotopes. It is a heavy metal of relatively low radioactivity. The important isotopes for the present purpose are the fissile uranium-235 and the most abundant uranium-238.

Weapons-grade – materials suited for the production of cores for nuclear weapons. For uranium-based weapons, uranium-235 should be enriched to about 90 percent. For plutonium-based materials, composed mainly of plutonium-239, the concentration of plutonium-240 should be kept to below 6 percent.

Notes

1 See, e.g., Jay Solomon, "Iran Seen Trying New Path to a Bomb," *Wall Street Journal*, August 5, 2013, and Amos Yadlin and Avner Golov, "Iran's Plan B for the Bomb," *New York Times*, August 8, 2013.

2 See, e.g., Security Council resolution 1803 of March 2008, which denotes the "heavy-water related projects" that require full and sustained suspension, http://www.iaea.org/newscenter/focus/iaeairan/unsc_res1803-2008.pdf.

3 The energy released during the operation of a reactor is measured in thermal megawatts (MW(th)) – the heat energy released by the fission process. The output of power reactors is usually measured in electric megawatts (MW(e)) – the electric energy produced. The value of the MW(e) output of a power reactor is usually around a third of its MW(th) value.

4 Many of the descriptive portions of the IR-40 reactor and calculated characteristics come from the extensive work by Thomas Mo Willig,

"Feasibility and Benefits of Converting the Iranian Heavy Water Research Reactor IR-40 to a more Proliferation-Resistant Reactor," Norwegian University of Life Sciences, December 2011, http://brage.bibsys.no/umb/bitstream/URN:NBN:no-bibsys_brage_29337/1/master.pdf.

5 "Update on the Arak Reactor in Iran," Institute for Science and International Security, September 25, 2009, http://www.isisnucleariran.org/assets/pdf/Arak_Update_25_August2009.pdf; and David Albright, Paul Brannan, and Robert Kelley, "Mysteries Deepen Over Status of Arak Reactor Project," August 11, 2009, http://www.isisnucleariran.org/assets/pdf/ArakFuelElement.pdf.

6 Zircaloy is a zirconium metal alloy, used in nuclear reactor fuel cladding because of its advantageous mechanical, nuclear, and thermal characteristics.

7 The IAEA defines a "significant quantity" of plutonium as 8 kilograms, i.e., the quantity assessed to be necessary for the production of one nuclear explosive device. However, since some of this quantity will be retained as melting and machining waste, and may be recycled for the next device, this quantity could be true for the first device, but for the subsequent ones a lower quantity would be needed. See also note 12 below.

8 Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran; IAEA report GOV/2013/27, May 22, 2012, http://www.isisnucleariran.org/assets/pdf/IAEA_Iran_Safeguards_report_–_22May2013.pdf.

9 IAEA report on Iran of August 2013, http://www.iaea.org/Publications/Documents/Board/2013/gov2013-40.pdf.

10 It should be recalled, however, that the Soviet Union, in its crash program and in the rush to carry out its first nuclear test, accomplished the feat in a month. They had, however, the technical information gathered by its espionage system in the US.

11 "Quick and Secret Construction of Plutonium Reprocessing Plants: A Way to Nuclear Weapons Proliferation?" Report by the Comptroller General of the United States, 1978, http://archive.gao.gov/f0902c/107377.pdf.

12 Thomas B. Cochrane and Christopher E. Paine, "The Amount of Plutonium and Highly Enriched Uranium Needed for Pure Fission Nuclear Weapons," (Washington, DC, Natural Resources Defense Council, 1995), http://www.nrdc.org/nuclear/fissionw/fissionweapons.pdf.