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Iran's Enriched Uranium Stocks Can Produce Enough HEU for 3 to 5 Nuclear Weapons
The World's Commitment to Nonproliferation is in Doubt
Centrifuge Enrichment and the IAEA August 28, 2013 Safeguards Update

In various papers since 2008, this author has outlined how Iran's growing centrifuge enrichment program could provide it with the ability to produce Highly Enriched Uranium (HEU) and thereby the ability to manufacture nuclear weapons.[2] On August 28, 2013, the International Atomic Energy Agency (IAEA) published its latest safeguards update which shows that Iran is continuing to expand its enrichment program.

Iran with its current enrichment capacity and its enriched uranium stockpiles, can use two different methods to quickly produce the HEU required for nuclear weapons should it decide to do so. I have analyzed this issue in detail in Appendix 1 and summarize the results here in Table 1.[3]

Table 1

Time Required For Iran to Produce Various Amounts of HEU For Nuclear Weapons Should Iran Decide to Do So Quickly

Number of Nuclear Weapons (HEU)	Batch Recycling at Known Enrichment Facilities	Clandestine Enrichment Plant
One (20 kg)	6 weeks	3 weeks
Three (60 kg)	4 months	2 months
Five (100 kg)	N/A*	3 ½ months

*Iran's current enriched uranium stockpiles are only large enough to allow it to produce 64 kilograms of HEU by batch recycling.

[1] The author has multiple affiliations. I am a Senior Researcher for the Nonproliferation Policy Education Center (NPEC) and this paper was produced for NPEC. Though the author is also a part-time adjunct staff member at the RAND Corporation, this paper is not related to any RAND project and therefore RAND should not be mentioned in relation to this paper.
[2] My most recent report is: Gregory S. Jones, "Iran's Rapid Expansion of its Enrichment Facilities Continues as the Entire Nonproliferation System Threatens to Unravel: Centrifuge Enrichment and the IAEA May 22, 2013 Safeguards Update," May 30, 2013, http://nuclearpolicy101.org/wp-content/uploads/2013/05/Iran-Enrichment-Update-05-2013.pdf
[3] My analysis assumes that 20 kilograms of HEU are required per weapon.

Iran can produce the HEU for nuclear weapons by using batch recycling at Iran's known enrichment facilities. In this process the enriched uranium is run through Iran's enrichment facilities multiple times until it reaches the required enrichment level. This process has the advantage of requiring only slight modifications to Iran's enrichment facilities and is entirely permitted by the IAEA as long as Iran notifies it in advance. Iran can produce enough HEU for a nuclear weapon in just six weeks and its entire stockpile of enriched uranium can be used to produce enough HEU for three weapons in four months. These results are a significant change from what I had calculated just last May. Then I had indicated that Iran could only produce a total of two nuclear weapons (instead of three) and that the time required to produce the HEU for its first nuclear weapon was 2 months (instead of six weeks). This change is the result of new analysis that has indicated that batch recycling can produce HEU more quickly and utilize Iran's uranium stocks more efficiently than was previously thought. (See Appendix 3).

Iran can also produce the HEU for nuclear weapons by building a clandestine enrichment facility specifically designed to enrich uranium from 20% to 90%. A small facility could produce enough HEU for a nuclear weapon in just three weeks. A major advantage of such a facility would be that it would use Iran's stockpile of enriched uranium more efficiently than would batch recycling and Iran could produce enough HEU for five nuclear weapons (i.e. a small arsenal) with one nuclear weapon's worth of HEU being produced every three weeks. A disadvantage of using a clandestine enrichment facility is that this process would require violating IAEA safeguards, though the time needed for Iran to produce HEU by this method is so short as to make it very doubtful that any effective counteraction could be taken before Iran obtained a nuclear weapon.

Since batch recycling would require six weeks before enough HEU is produced to manufacture a nuclear weapon one might imagine that there could be enough time to prevent Iran from acquiring nuclear weapons but this is not the case. As I have pointed out in the past, IAEA safeguards are so lax that they permit nonnuclear weapon states, including Iran, to produce HEU as long as the country notifies the IAEA in advance. This advance notice could be as short a one day.[4] Therefore Iran need not violate IAEA safeguards. Some have suggested that the U.S. might try to stop Iran from producing HEU but would the U.S. really militarily strike Iran's centrifuge facilities if they were still under IAEA safeguards? And if the U.S. did, this would open up the IAEA to accusations of spying for the U.S. and would jeopardize the existence of the entire IAEA safeguard system.

If Iran were to produce HEU in the form of uranium hexafluoride under IAEA safeguards, then perhaps it would only need to violate these safeguards when it wanted to produce the HEU metal components required for a weapon. Analysts consistently overestimate the time required for this process. Graham Allison recently stated that "at least another month [would be required] to fabricate this material [HEU hexafluoride] into a weapon."[5] However, as I have pointed out, such estimates fly in the face of U.S. World War II experience where these steps were carried out in just eleven days.[6]

[4] When Iran started producing 20% enriched uranium in February 2010 it gave the IAEA only one day notice.
[5] Graham Allison, "Will Iran Get a Bomb—or Be Bombed Itself—This Year?," *The Atlantic*, August 2013.
[6] Gregory S. Jones, "Recalibrating Tehran's Nuclear Breakout Capability II: A Response to Mark Fitzpatrick's (IISS) critique of NPEC Calculations Regarding the Time Required for Iran to Produce a Weapon's Worth of HEU",

It is not clear that even the first of these final steps, i.e. the production of HEU metal, would involve the violation of IAEA safeguards since Iran could claim that it was producing the material for research reactor fuel or to conduct some other nominally "peaceful" nuclear research. If so, IAEA safeguards would only be violated when the metal was machined into a sphere and placed into a weapon, operations that could be performed in a day or two.

As I have pointed out in a number of my previous writings, Iran could, prior to or simultaneously with the production of the HEU, produce the non-nuclear components of a nuclear weapon.[7] In this way there would be very little time between the production of the HEU metal weapon components and Iran's possession of a completed nuclear weapon.

The election in Iran of the "moderate" Hasan Rowhani, has once again raised hopes that somehow there might be a way for negotiations to solve the problem of Iran's nuclear program. But this is just wishful thinking. No one has suggested a realistic settlement that could effectively prevent Iran from being in a position to quickly produce sufficient nuclear material for a nuclear weapon should it decide to do so. Some have proposed having Iran send its stockpile of 20% enriched uranium out of the country. However, Iran's centrifuge enrichment capabilities are now so extensive that even if this were to occur, Iran could still produce enough HEU for a nuclear weapon in just eight weeks compared to the six weeks that are currently required (compare Tables 4 and 5). In order to prevent Iran from having the ability to quickly produce the HEU required for nuclear weapons, it would be necessary to shut down and eliminate Iran's entire enrichment program. This is not a likely negotiated outcome.

Further, as Iran's nuclear reactor at Arak gets closer to completion, there is a growing threat that in a few years Iran will be able to use this reactor to produce plutonium for nuclear weapons. The P5+1 proposals to Iran have thus far not included any restrictions on this reactor.[8]

However, this does not mean that I think Iran will become an overt nuclear weapons state in the near future. As I stated in September 2011:

> That is not to say that I expect Iran to divert nuclear material from IAEA safeguards anytime soon. After all, why should it? It can continue to move ever closer to the HEU required for a nuclear weapon with the blessing of the IAEA. Iran would only need to divert nuclear material from safeguards when it would want to test or use a nuclear weapon. Recall that the U.S. was unable to certify that Pakistan did not have nuclear weapons in 1990, but it was only in 1998 that it actually tested a bomb. Similarly, though it could be many years before Iran

Appendix: U.S. Production of the Hiroshima Nuclear Weapon, Implications for an Iranian Nuclear Weapon, November 4, 2011. http://npolicy.org/article_file/IISS-NPEC_Exchange.pdf

[7] Gregory S. Jones, "Facing the Reality of Iran as a De Facto Nuclear State: Centrifuge Enrichment and the IAEA February 24, 2012 Safeguards Update," March 22, 2012, pp.2-3.
http://www.npolicy.org/article_file/Facing_the_Reality_of_Iran_as_a_De_Facto_Nuclear_State.pdf

[8] The P5+1 is China, France, Germany, Russia, the UK and the U.S.

becomes an overt nuclear power, it needs to be treated as a de facto nuclear power simply by virtue of being so close to having a weapon.[9]

As bad as the Iranian situation is, an even worse problem is the potential unraveling of that the entire nonproliferation system. On August 21, 2013, Syria conducted large scale chemical weapon attacks against rebel held areas using the nerve agent sarin, exposing many thousands and killing at least many hundreds. This attack was the first time in 25 years that a nation has employed chemical weapons on such a large scale.

The world's reaction to this serious breach of nonproliferation norms has been underwhelming. Though France has come out strongly in favor of taking military action against Syria, the UK has gone "wobbly," as the late Margaret Thatcher would have said, with the British parliament voting against taking any military action against Syria. The U.S. is taking a very deliberate approach and President Obama is trying to get the support of Congress before taking any military action. But the statements of some U.S. lawmakers indicate that they do not see any value in taking military action to punish Syria for its use of chemical weapons and to deter Syria from any further use. Such statements indicate that these lawmakers see no value in maintaining nonproliferation norms, which is a rather disturbing development.

Even before Syria's large-scale use of chemical weapons and the world's tepid response, the accumulation of decades of neglect and short-term "fixes" has put the nuclear nonproliferation regime under considerable stress. During this interval both Pakistan and North Korea have acquired nuclear arsenals and Iran has made steady progress toward nuclear weapons.

One result of the most recent North Korean nuclear test was to increase pressures in both Japan and South Korea to acquire their own nuclear weapons.[10] Influential political figures in South Korea have suggested that now might be the time for South Korea to develop its own nuclear weapons or that at least the U.S. should return tactical nuclear weapons to South Korea.[11] South Korea has strongly pressed the U.S. to allow it to extract the plutonium from its nuclear reactor spent fuel. This step would provide South Korea easy access to nuclear weapons.

Japan already has a plutonium stockpile of 44 metric tons produced as a result of its civil nuclear power program. About 35 metric tons are stored overseas but about 9 metric tons (enough to produce thousands of nuclear weapons) are stored in Japan.[12] Recently a number of Japanese political figures have openly argued that Japan should continue its plutonium program as a nuclear weapon hedge and Japan's parliament has amended its atomic energy act to explicitly include "national security" as one of the prime missions of Japan's civilian nuclear energy program.

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[9] Gregory S. Jones, "No More Hypotheticals: Iran Already Is a Nuclear State, *The New Republic*, September 9, 2011, http://www.tnr.com/article/environment-and-energy/94715/jones-nuclear-iran-ahmadinejad

[10] Henry Sokolski, "After North Korea's Nuclear Test," *The National Review Online*, February 12, 2013.

[11] Martin Fackler and Choe Sang-Han, "South Korea Flirts With Nuclear Ideas as North Blusters," *The New York Times*, March 10, 2013.

[12] *Global Fissile Material Report 2011: Nuclear Weapon and Fissile Material Stockpiles and Production*, Sixth Annual report of the International Panel on Fissile Materials, January 2012, p.23.

These developments in East Asia provide a preview of how events in the Middle East may play out. Though countries such as Egypt and Saudi Arabia currently lack the necessary nuclear technology to be able to produce nuclear weapons any time soon, this may be changing. Saudi Arabia has said it plans to build 16 nuclear power reactors by 2030 and wants to have the first two in operation by 2023.[13] With such a large nuclear power program, Saudi Arabia could easily say that it also requires a large centrifuge enrichment program to provide fuel for these reactors, which would provide it with easy access to the HEU needed for nuclear weapons (See Appendix 2).

Though these stresses on the nuclear nonproliferation system already existed, Syria's large-scale use of chemical weapons and the weak international response has only increased the pressure on these other countries to acquire their own nuclear weapons by sending the signal that it is every country for itself. Though an effective military strike against Syria would help undo some of this damage, it is too late for a single military strike to stop Iran from acquiring nuclear weapons. Though a large sustained military campaign could destroy Iran's centrifuge enrichment program, I have always considered such a campaign ill-advised as I believe that the U.S. is too war-weary and financially exhausted to undertake such an effort. Certainly recent statements by U.S. lawmakers regarding even a limited effort in Syria show that there would be little supported for extended combat in Iran.

The U.S. needs to examine how it can strengthen the nuclear nonproliferation system as a whole. Key to this effort will be to stop countries from using nominally peaceful nuclear activities to acquire the HEU or plutonium needed for nuclear weapons. A negotiated agreement with Iran that legitimizes its centrifuge enrichment program would be a step in the wrong direction. It will also be important for the U.S. to continue to prohibit South Korea from producing separated plutonium and to help Japan find a way to dispose of its huge plutonium stockpile.

Additionally, the IAEA must stop being complicit in this problem. The IAEA must stop pretending that it can effectively safeguard such dangerous material and activities. Nuclear safeguards are supposed to be more than an accounting system. Rather the purpose of IAEA safeguards "…is the timely detection of diversion of significant quantities of *nuclear material* from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection."[14] [Emphasis in original]

For safeguards to be effective, non-nuclear weapon countries must be prohibited from possessing any materials or facilities that can quickly provide fissile material for nuclear weapons. This includes prohibiting not only enrichment and reprocessing facilities but also separated HEU, plutonium or U-233; and HEU, plutonium or U-233 that is contained in unirradiated reactor fuel (such as HEU fuel for research reactors or mixed oxide fuel for power reactors).[15] Such

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[13] "Saudi Arabia to have 16 nuclear reactors by 2030," *The Times of India*, August 27, 2013.
[14] "The Structure and Content of Agreements Between The Agency and States Required in Connection With The Treaty on the Non-Proliferation of Nuclear Weapons," International Atomic Energy Agency, INFCIRC/153 (Corrected), June 1972, p.9.
[15] U-233, like plutonium and HEU, can be used to manufacture nuclear weapons. It is produced by the irradiation of thorium. Mixed oxide power reactor fuel is a mixture of uranium and plutonium oxides.

restrictions would require shutting down enrichment facilities not only in Iran but also in Germany, the Netherlands, Brazil and Japan, as well as reprocessing facilities in Japan. Such restrictions would also require the removal of Japan's massive plutonium stockpile.[16]

The large-scale use of chemical weapons in Syria has further strained an already taxed nonproliferation system. Unless Syria is made to pay a significant price for its actions, additional use of chemical weapons should be expected. Further, if the prevention of the acquisition and use of chemical weapons is devalued, one should expect a similar devaluing of nuclear nonproliferation values and norms. This would send a signal to countries such as South Korea, Japan, and Saudi Arabia that they are on their own and that there is little consequence for acquiring nuclear weapons. The U.S. needs to take the lead to strengthen the nonproliferation system by taking strong action against Syria and heading off possible nuclear weapons programs in South Korea, Japan and Saudi Arabia.

[16] Victor Gilinsky and Henry Sokolski, "Serious Rules for Nuclear Power without Proliferation," Nonproliferation Policy Education Center, Working Paper No. 1302, February 2013. http://nuclearpolicy101.org/wp-content/uploads/2013/02/1302-Serious-Rules.pdf

Appendix 1

Detailed Analysis of the IAEA August 28, 2013 Safeguards Report and Methods Whereby Iran Could Produce HEU and/or Plutonium for Nuclear Weapons

Iranian Centrifuge Enrichment of Uranium

Iran has three known centrifuge enrichment facilities. Iran's main facility is the Fuel Enrichment Plant (FEP) at Natanz. The basic unit of Iran's centrifuge enrichment effort is a cascade which originally consisted of 164 centrifuges but Iran has now modified the majority of the cascades by increasing the number of centrifuges to 174. (All centrifuges operated up to now have been of the IR-1 type.) Each cascade is designed to enrich natural uranium to 3.5% enriched uranium. As of August 24, 2013, Iran had installed a total of 89 cascades of IR-1 type centrifuges and had partially installed one additional cascade. Of these 89 cascades, 54 were declared by Iran as being fed with uranium hexafluoride and therefore were producing 3.5% enriched uranium. In addition Iran has begun to install some of the more advanced IR-2m centrifuges at the FEP. Iran has installed six cascades of IR-2m type centrifuges. Thus far no IR-2m cascade has begun to enrich uranium. In March 2013, Iran stated that it would install 3,000 of these more advanced centrifuges.[17]

Iran began producing 3.5% enriched uranium at the FEP in February 2007 and as of August 10, 2013 Iran had produced a total of 6,560 kilograms (in the form of 9,704 kilograms of uranium hexafluoride). Since 1,945 kilograms of this enriched uranium has already been processed into 19.7% enriched uranium (see the PFEP and FFEP below) and a further 36 kilograms was used in the conversion process to produce uranium dioxide for use as fuel in the TRR, Iran's current stockpile of 3.5% enriched uranium is 4,579 kilograms. Iran's current production rate of 3.5% enriched uranium is about 156 kilograms per month.[18] This production rate has held roughly steady since early 2012 (see Table 2). From the production rate of 3.5% enriched uranium, it is easy to calculate that the FEP has a separative capacity of about 6,820 separative work units (SWU) per year.[19]

Iran also has the Pilot Fuel Enrichment Plant (PFEP) at Natanz, which is used to test a number of more advanced centrifuge designs. These are usually configured as either single centrifuges or test cascades containing various numbers of centrifuges. Two of these test cascades are complete cascades. One contains 164 IR-4 centrifuges and one contains 162 IR-2m centrifuges. Up to now no enriched uranium has been produced by these test cascades. Iran had said that it planned to start producing enriched uranium with these two complete test cascades but more recently indicated that these plans had been delayed. Since each of these cascades will be equivalent to multiple IR-1 cascades, the enriched uranium output will be significant.

[17] Yeganeh Torbati, "Iran says building 3,000 advanced centrifuges," *Reuters*, March 3, 2013.
[18] To avoid problems with the fact that the length of a month is variable, I have adopted a uniform month length of 30.44 days.
[19] Assuming 0.4% tails. A Separative Work Unit is a measure of the amount of enrichment a facility can perform. The SWU needed to produce a given amount of enriched uranium product can be calculated if the U-235 concentration in the product, feed and tails are known.

In addition, there are two full cascades each with 164 IR-1 type centrifuges at the PFEP. These two cascades are interconnected and are being used to process 3.5% enriched uranium into 19.7% enriched uranium. In February 2010, Iran began producing 19.7% enriched uranium at the PFEP using one cascade. It added the second cascade in July 2010. As of August 16, 2013, Iran had produced 120.2 kilograms of 19.7% enriched uranium (in the form of 177.8 kilograms of uranium hexafluoride) at this facility. Iran's production rate of 19.7% enriched uranium at the PFEP has been fairly steady over the past two years and is currently about 3.15 kilograms per month. The centrifuges at this facility are each producing about 0.94 SWU per centrifuge-year.

Table 2
Average Iranian Production Rate of 3.5% Enriched Uranium
November 2008 to August 2013

IAEA Reporting Interval	Average 3.5% Enriched Uranium Production Rate (Kilograms Uranium per Month)
11/17/08-1/31/09	52
2/1/09-5/31/09	53
6/1/09-7/31/09	57
8/1/09-10/31/09	57
11/22/09-1/29/10	78
1/30/10-5/1/10	81
5/2/10-8/6/10	80
8/7/10-10/17/10	95
10/18/10-2/5/11	88
2/6/11-5/14/11	105
5/15/11-8/13/11	99
8/14/11-11/1/11	97
11/2/11-2/4/12	115
2/5/12-5/11/12	158
5/12/12-8/6/12	161
8/7/12-11/11/12	156
11/12/12-2/3/13	162
2/4/13-5/4/13	158
5/5/13-8/10/13	156

Finally, Iran has constructed an enrichment facility near Qom. Known as the Fordow Fuel Enrichment Plant (FFEP), Iran clandestinely started to construct this plant in violation of IAEA safeguards. Iran only revealed the existence of this plant in September 2009, after Iran believed that the West had discovered the plant.

The FFEP is designed to hold a total of 16 cascades (each cascade holds 174 IR-1 type centrifuges for a total of 2,784 centrifuges). Fifteen of the sixteen cascades have been vacuum tested and could operate at any time. The sixteenth cascade had been fully installed in

November 2012 but for some reason, some of the centrifuges in this cascade have since been removed.

Only four of the fifteen cascades are producing enriched uranium. They are configured as two sets of two interconnected cascades so as to produce 19.7% enriched uranium from 3.5% enriched uranium as is being done at the PFEP. The first of these two sets began production on December 14, 2011 and the second set began operation on January 25, 2012. As of August 16, 2013, Iran had produced 131.6 kilograms of 19.7% enriched uranium (in the form of 194.7 kg of uranium hexafluoride) at this facility. This facility is currently producing 19.7% enriched uranium at the rate of 6.95 kilograms per month. These centrifuges are each producing about 0.98 SWU per centrifuge-year.

Currently Iran is producing a total of about 10.1 kilograms of 19.7% enriched uranium per month (see Table 3). As of August 2013, Iran had produced a total of about 252 kilograms of 19.7% enriched uranium. Since Iran has converted about 125 kilograms of this uranium (50 percent) into a uranium oxide compound for use as fuel in the TRR, and further blended down about 1 kilogram to lower enrichments, Iran's current stockpile of 19.7% enriched uranium that is being kept as uranium hexafluoride is about 126 kilograms of uranium.

Regarding the twelve other cascades at the FFEP that have yet begun operation, the IAEA has asked Iran whether these new cascades are to be interconnected to produce yet more 19.7% enriched uranium or only 3.5% enriched uranium. However, Iran says that the installation of these new cascades is not yet complete and that it will only inform the IAEA prior to the start of their operation. This development opens the possibility that Iran could further increase its rate of 19.7% enriched uranium. Using these cascades Iran could put a six more sets of two interconnected cascades into operation and increase its production of 19.7% enriched uranium to as much as 31 kilograms a month.[20] Given Iran's current rate of production rate of 3.5% enriched uranium at the FEP, the current size of Iran's its stockpile of 3.5% enriched uranium and the capacity expansion occurring at the FEP, Iran could maintain this high rate of 19.7% enriched uranium production indefinitely.

[20] Assuming the performance of these additional cascades matches that of the four already in operation at the FFEP.

Table 3

Iranian Production of 19.7% Enriched Uranium
April 2010 to August 2013

IAEA Reporting Interval	Average Monthly* Production at PFEP (kg U)	Average Monthly* Production at FFEP (kg U)	Total Average Monthly* Production (kg U)	Cumulative Production (kg U)	Cumulative Total 20% U Converted From UF_6 (kg U)	Total Net Production 20% U in Form of UF_6 (kg U)
2/9/10-4/7/10	2.0	0	2.0	3.9	0	3.9
4/8/10-8/20/10	2.5	0	2.5	14.9	0	14.9
8/21/10-11/19/10	2.5	0	2.5	22.3	0	22.3
11/20/10-2/11/11	2.6	0	2.6	29.5	0	29.5
2/12/11-5/21/11	2.7	0	2.7	38.3	0	38.3
5/22/11-8/20/11	3.2	0	3.2	47.9	0	47.9
8/21/11-10/28/11	2.7	0	2.7	53.9	0	53.9
End 10/11-Mid 2/12**	3.1	6.5***	9.6	73.8	7	66.8
Mid 2/12-Mid 5/12	3.1	5.2	8.3	98.4	30.2	68.2
Mid 5/12-Mid 8/12	3.0	6.7	9.7	128.0	49.3	78.7
Mid 8/12-Mid 11/12	3.3	6.9	10.2	157.4	57.0	100.4
Mid 11/12-Mid 2/13	2.8	7.7	10.5	189.1	76.1	113.0
Mid 2/13-Mid 5/13	3.1	7.3	10.4	219.3	96.3	123.0
Mid 5/13-Mid 8/13	3.1	7.0	10.1	251.8	126.2	125.6

*In order to avoid the problem of the variable length of a month I use a uniform 30.44 day month
**IAEA inspections are carried out at the PFEP and the FFEP on slightly different dates
***The first set of interconnected cascades began operation on 12/14/11. The second set began operation on 1/25/12.

Iranian Options for Producing HEU

Given that Iran currently has in operation a total enrichment capacity of about 8,000 SWU per year at the FEP, FFEP, and PFEP and stockpiles of 4,579 kilograms of 3.5% enriched uranium and 126 kilograms of 19.7% enriched uranium, Iran has a number of options for producing the 20 kilograms of HEU required for a nuclear weapon.

The most straightforward method Iran could use to produce HEU would be batch recycling. In this process, no major modifications are made to Iran's enrichment facilities but rather enriched uranium is successively run though the various enrichment facilities in batches until the desired enrichment is achieved. Iran could use a two-step process to produce HEU. This process is illustrated in Table 4.

Table 4

Time, Product and Feed Requirements for the Production of HEU by Batch Recycling at the FEP, PFEP and FFEP
Cycles Carried out Simultaneously

Enrichment Plant	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
FEP	19.7% 34.8 kg	3.5% 411 kg	11***
PFEP and FFEP*	90.0% 20 kg	19.7% 160 kg**	42***
Total			42****

* The combined plant inventory at the PFEP and FFEP is 0.8 kilogram.
** Includes 126 kilograms of 19.7% enriched uranium that Iran has already stockpiled.
*** Includes two days to account for equilibrium and cascade fill time.
**** Cycle times *not* additive since cycles are simultaneous.

This batch recycling process is somewhat different than what I have used in prior papers (See Appendix 3). The tandem cascades at the PFEP and FFEP can be adjusted so as to produce 90% enriched uranium from 19.7% enriched feed. It takes 160 kilograms of 19.7% enriched uranium to produce the 20 kilograms of 90% enriched uranium needed for a nuclear weapon. The 160 kilograms required is greater than Iran's current stockpile of 19.7% enriched uranium (counting only the 126 kilograms which is in the form of 186 kilograms of uranium hexafluoride.) However, Iran can produce additional 19.7% enriched uranium by using 3.5% enriched uranium as feed to the cascades at the FEP. Iran produced 19.7% enriched uranium at the PFEP using a cascade identical to the ones at the FEP between February and July 2010.

Nor would Iran need to stop at producing only one nuclear weapon's worth of HEU. After using 411 kilograms of 3.5% enriched uranium required to produce 20 kilograms of HEU, Iran would still have 4,168 kilograms of 3.5% enriched uranium left over. This material could be enriched to produce an additional 353 kilograms of 19.7% enriched uranium. This could be used at the PFEP and FFEP to produce an additional 44 kilograms of 90% enriched uranium. The FEP could produce the 19.7% enriched uranium at a rate sufficient so that the PFEP and FFEP could produce 60 kilograms of enriched uranium (enough for three nuclear weapons) in a total of about four months.

Though much attention has been focused on Iran's growing stockpile of 19.7% enriched uranium, most of the reason why Iran can produce the HEU for a nuclear weapon as quickly as it can is because of its growing enrichment capacity and not its growing 19.7% enriched uranium stockpile. As is shown in Table 5, even if Iran did not have a stockpile of 19.7% enriched uranium, it could still produce a weapon's worth of HEU in just eight weeks which is only somewhat longer than the six weeks that would be required given Iran's current stockpile of 19.7% enriched uranium (Table 4). As is shown in Appendix 2, continued growth of Iran's centrifuge enrichment capacity, even if Iran does not stockpile 19.7% enriched uranium, means that the time required for Iran to produce the HEU for a nuclear weapon will become quite short. This is not to say that Iran's growing stockpile of 19.7% enriched uranium is unimportant, but rather focusing only on the 19.7% enriched uranium and not Iran's growing enrichment capacity as well will not provide a solution to the problem of Iran's ability to quickly produce the HEU required for a nuclear weapon.

Table 5

Time, Product and Feed Requirements for the Production of HEU by Batch Recycling at the FEP, PFEP and FFEP
Iran's Current Stockpile of 19.7% Enriched Uranium Removed From Iran

Enrichment Plant	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
FEP	19.7% 160.8 kg	3.5% 1897 kg	44***
PFEP and FFEP*	90.0% 20 kg	19.7% 160 kg**	42***
Total			54****

* The combined plant inventory at the PFEP and FFEP is 0.8 kilogram.
** Includes 126 kilograms of 19.7% enriched uranium that Iran has already stockpiled.
*** Includes two days to account for equilibrium and cascade fill time.
**** Cycle times *not* additive. The FEP starts producing 19.7% enriched uranium 10 days in advance of the start of HEU production at the PFEP and FFEP.

Currently the fastest way for Iran to produce the HEU for a number of nuclear weapons is by using batch recycling at the FEP combined with a clandestine "topping" enrichment plant. This method would allow Iran to produce a weapon's worth of HEU in just three weeks. Since Iran continues to refuse to implement the Additional Protocol to its safeguards agreement, as well as the Modified Code 3.1, the IAEA would find it very difficult to locate a clandestine enrichment plant—a fact that the IAEA has continued to confirm.[21] While this has been a theoretical possibility since 2007, its salience increased with the discovery in September 2009 that Iran was actually building such a clandestine enrichment plant (the FFEP near Qom).

In this case, the enrichment plant could be designed as an ideal cascade to enrich 19.7% enriched uranium to the 90% enriched uranium needed for a nuclear weapon. By starting from 19.7% enriched uranium, this clandestine enrichment plant need only contain 3,000 centrifuges (2,000 IR-1 centrifuges and 1,000 IR-2m centrifuges). The time (see Table 6) required to produce a weapon's worth of HEU (20 kilograms) would be 21 days (three weeks).[22]

Table 6

Time, Product and Feed Requirements for the Production of HEU at a 3,000 Centrifuge Clandestine Plant (2,000 IR-1 and 1,000 IR-2m Centrifuges)

Enrichment Plant	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
Clandestine	90.0% 20 kg	19.7% 93.8 kg*	21**
Total			21

* There is additional processing of the tails of the clandestine plant at the PFEP and FFEP.
** Includes two days to account for equilibrium and cascade fill time.

Iran already has sufficient 19.7% enriched uranium to produce more than enough HEU for one nuclear weapon. By using the FEP to produce additional 19.7% enriched uranium, Iran could produce additional HEU. Given its current stockpile of 3.5% enriched uranium Iran could produce a total of 109 kilograms of HEU which would be enough for five or perhaps even six nuclear weapons. Since the FEP can produce 19.7% enriched uranium at about the same rate as the clandestine plant would use it, each weapon's worth of HEU would be produced at three week intervals and Iran could have a five weapon arsenal in about three and one half months.

Nor is a multi-step enrichment process the only pathway for Iran to produce the fissile material required for nuclear weapons, though it is the process that allows Iran to produce HEU most quickly. Iran could produce HEU at a clandestine enrichment plant designed to produce 90% enriched uranium from natural uranium feed.

[21] "While the Agency continues to verify the non-diversion of declared nuclear material at the nuclear facilities and LOFs declared by Iran under its Safeguards Agreement, as Iran is not providing the necessary cooperation, including by not implementing its Additional Protocol, the Agency is unable to provide credible assurance about the absence of undeclared nuclear material and activities in Iran, and therefore to conclude that all nuclear material in Iran is in peaceful activities." *Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran*, GOV/2013/27, May 22, 2013, p.13.

[22] I assume that the IR-2m centrifuges have twice the enriching capacity of the IR-1 centrifuges. This is probably a conservative estimate.

A clandestine enrichment plant containing 3,400 IR-1 centrifuges (1.0 SWU per centrifuge-year) could produce around 20 kilograms of HEU (the amount required for one nuclear weapon) each year using natural uranium as feed. Since this option does not require any overt actions, the relatively slow rate of HEU production would not necessarily be of any concern to Iran. Such production could be going on right now and the West might well not know. A clandestine enrichment plant would need a source of uranium but Iran is producing uranium at a mine near Bandar Abbas.[23] Since Iran has refused to implement the Additional Protocol to its IAEA safeguards, this uranium mining is unsafeguarded and the whereabouts of the uranium that Iran has produced there is unknown.

Iran then, has a number of methods whereby it could produce the HEU required for a nuclear weapon. By batch recycling at the FEP, PFEP and the FFEP (Table 4), Iran could produce enough HEU for a nuclear weapon in about six weeks. Using its current stockpiles of 3.5% and 19.7% enriched uranium, Iran could produce enough HEU for three nuclear weapons in about four months. Even if Iran were to give up its current stockpile of 19.7% enriched uranium (Table 5), the time required for Iran to produce the HEU for a nuclear weapon would be eight weeks.

If Iran were to produce 19.7% enriched uranium at the FEP and simultaneously enrich 19.7% enriched uranium to HEU at a clandestine enrichment plant (Table 8), then it could produce a weapon's worth of HEU in just three weeks and enough HEU for five weapons in three and one half months. Alternatively, Iran might build a stand-alone clandestine plant to enrich natural uranium to HEU. Such a plant would only produce enough HEU for one weapon a year but since the plant could go undetected for many years, Iran could produce a sizable stockpile before detection.

Iranian Production of Plutonium

The IAEA has also reported that Iran has continues to make progress on its construction of its plutonium production reactor (the IR-40 at Arak). Iran has installed the reactor vessel but a number of key items have yet to be installed. Iran has produced a test fuel assembly for this reactor that it is irradiating in the Tehran Research Reactor. Iran has also produced over 15 metric tons of uranium dioxide (using natural uranium) which is probably enough for the first core of this reactor. Iran has transferred over nine metric tons of this material to its Fuel Manufacturing Plant and has completed the fabrication of the first ten fuel assemblies for the IR-40.

One issue on which the IAEA has provided new information is the heavy water needed to operate this reactor. Iran has said that it has produced 90 metric tons of heavy water and expects to have the 100 metric tons it says that it needs for this reactor. Note that 100 metric tons is a large amount for this type of reactor which typically would require only 70 to 80 metric tons.[24]

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[23] *Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran*, GOV/2011/7, February 25, 2011, p.9.

[24] The IR-40 will have a power output of 40 MW. The Canadian NPD had a power output of 88 MW yet required only 75 metric tons of heavy water. L.W. Woodhead and W.M. Brown, "Performance and problems of NPD,"

Iran has said that its heavy water production plant can produce 16 metric tons per year which would be more than enough to provide the makeup heavy water needed for this reactor once it is in operation. Neither the IAEA nor any other public source has discussed where Iran might have gotten the technology needed for this plant. The plant seems to rely on the widely used water-hydrogen sulfide chemical exchange process, but as the Indians found out in the 1970s, the engineering needed to successfully run such a plant is non-trivial. In particular the long equilibrium time of this process puts a high premium on the ability to operate the plant without interruption for many months at a time. Pakistan may have sold Iran the needed technology but this only raises the question of where did Pakistan acquire the technology.

Iran had stated that it had planned to begin to operate this reactor in the third quarter of 2014 but has more recently indicated that it now cannot meet this schedule. This development is not really surprising and the schedule may slip even more. Once the reactor starts operation it will still take about another year before Iran would be able to produce and separate enough plutonium for a nuclear weapon. Still Iran's steady progress on this reactor shows that in a few years it will have the ability to produce plutonium as well as HEU for nuclear weapons.

Proceedings of the Third International Conference of the Peaceful Uses of Atomic Energy, August 31-September 9, 1964, Volume 5, Nuclear Reactors—I. Gas-cooled and Water-cooled Reactors, United Nations, New York, 1965. Similarly, Dhruva, India's 100 MW plutonium production reactor is reported to have required only 78 metric tons of heavy water. Gary Milhollin, "Dateline New Delhi: India's Nuclear Cover-up," *Foreign Policy*, Fall 1986.

Appendix 2

Limiting Iran to Producing and Stockpiling Less Than 5% Enriched Uranium Does Not Prevent Easy Access to HEU

As was discussed in the text, many who propose a diplomatic solution with Iran have suggested that Iran should be allowed to continue to enrich uranium as long as this activity is subject to "proper" controls. In particular, they propose that Iran should not enrich uranium to more than 5% and that Iran's current stockpile of near 20% enriched uranium should be removed from Iran. Further, they propose that the size of Iran's enrichment effort be determined by the needs of Iran's peaceful nuclear program.

But as was shown in Appendix 1 (Table 5), even if Iran were to give up its current stockpile of 19.7% enriched uranium, Iran could still produce the HEU required for a nuclear weapon in just eight weeks. The problem is Iran's growing enrichment capacity. Furthermore, Iran's current enrichment effort is quite small compared to that needed for most peaceful nuclear activities such as providing fuel for a single nuclear power reactor. A diplomatic solution could provide Iran with the justification for greatly expanding its current enrichment facilities as well as removing sanctions. Under these circumstances, Iran might receive assistance to expand its enrichment facilities (from say China or Pakistan) as part of normal nuclear commerce. These greatly expanded facilities would provide Iran easy access to the HEU needed for nuclear weapons.

For example, even if Iran produced only 4.1% enriched uranium[25] and expanded its current enrichment capacity by about a factor of 12 (100,000 SWU/yr), it would only produce about 15 metric tons of enriched uranium per year. This amount would still be less than that needed to fuel a single large power reactor yet, using batch recycling, these enrichment facilities could produce enough HEU for a nuclear weapon in just two weeks. This process is shown in Table 7.

In the first step, 4.1% enriched uranium is processed into 20.2% enriched uranium. In the second step, this uranium is processed into 60.2% enriched uranium and the third step completes the process by producing the 20 kilograms of 90% enriched uranium needed for a nuclear weapon. Each step produces not only the material needed to be processed in the next step but the material needed for the plant inventory which in this case is 30 kilograms per step.

Instead of just producing enough HEU for one nuclear weapon, Iran could produce enough HEU for five nuclear weapons (100 kilograms) in a single batch recycling campaign. This process would take about five weeks and is shown in Table 8. This process would require starting with 6,090 kilograms of 4.1% enriched uranium but since the plant will be producing about 15,000 kilograms per year, it would not be hard for Iran to stockpile this quantity of enriched uranium.

Though Iran's expansion of its 19.7% enriched uranium stockpile contributes to the shrinking time required for Iran to produce the HEU needed for a nuclear weapon, unless restrictions are placed on the size of Iran's overall enrichment effort, Iran's growing centrifuge enrichment capacity will allow Iran to quickly produce the HEU required for a nuclear weapon.

[25] With tails of 0.2%.

Table 7

Time, Product and Feed Requirements for the Production of 20 kg of HEU by Batch Recycling at a Centrifuge Enrichment Plant Designed to Produce 4.1% Enriched Uranium (100,000 SWU per year total)

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	20.2% 304 kg	4.1% 1,990 kg	7.5
Second	60.2% 69.5 kg	20.2% 274 kg	1.7
Third	90.0% 20 kg	60.2% 39.5 kg	0.5
Total			16*

*Includes six days to account for equilibrium and cascade fill time.

Table 8

Time, Product and Feed Requirements for the Production of 100 kg of HEU by Batch Recycling at a Centrifuge Enrichment Plant Designed to Produce 4.1% Enriched Uranium (100,000 SWU per year total)

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	20.2% 929 kg	4.1% 6,090 kg	23
Second	60.2% 228 kg	20.2% 899 kg	5.6
Third	90.0% 100 kg	60.2% 198 kg	2.5
Total			37*

*Includes six days to account for equilibrium and cascade fill time.

Appendix 3

Iran Can Increase the Efficiency of Batch Recycling by Enriching 20% Enriched Uranium to 90% Enriched Uranium in One Step

In a paper published in April 2008, I analyzed how Iran might use its centrifuge enrichment program to produce the HEU needed for nuclear weapons.[26] In that paper, I showed that Iran could produce HEU by a process known as batch recycling. Using this process Iran would not have to significantly modify its centrifuge enrichment plant producing low enriched uranium but rather could run the low enriched uranium product back through the plant three times. In the first pass the uranium would be enriched from low enrichment to about 20% enriched, in the second pass the uranium would be enriched from 20% enriched to about 60% enriched and in the final pass the uranium would be enriched from 60% to around 90% which would then be suitable for use in a nuclear weapon.[27] (This process is illustrated in Appendix 2).

I was not the first person to suggest that using batch recycling at a centrifuge enrichment plant was a viable means of producing HEU for nuclear weapons. For example, a 1988 training course for the IAEA, conducted by Martin Marietta Energy Systems (which at that time was operating the Oak Ridge enrichment plant for the U.S. Department of Energy) stated: "In batch recycle, the approach involves recycling cascade product on a batch basis using one or more unit cascades. In this method, physical modifications to the process and support systems are not necessarily required to produce HEU successfully. ...batch recycling is a viable option for a small centrifuge facility. Reflux and criticality problems do not arise in the cascade because of the use of low-pressure UF_6 gas."[28]

I pointed out in my 2008 paper that there were certain inefficiencies in this process since a cascade that was designed to produce low enriched uranium "is more tapered than is optimal for the upper stages of an enrichment plant designed to produce highly enriched uranium. As a result some of the SWU output of the plant can not be utilized especially during the latter cycles of the batch production process. The plant is restricted by the flow at the product end of the cascade. The time required per cycle is then determined by the amount of product required and the amount of product the plant can produce per day and not by a SWU calculation."[29]

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[26] Gregory S. Jones, "Iran's Centrifuge Enrichment Program as a Source of Fissile Material for Nuclear Weapons," April 8, 2008, http://www.npolicy.org/files/20081017-Jones-IranEnrichment.pdf

[27] In 2008 there was no public information as to the enrichment of the uranium Iran was producing and I assumed it was to 4.8%. In 2010 it became known that Iran was only enriching to the 3.5% level and I changed my calculations to reflect this fact. While this change altered the specifics of my calculations it did not alter the overall result, namely using batch recycling three times would allow Iran to produce the HEU for weapons.

[28] "Safeguards Training Course: Nuclear Material Safeguards for Enrichment Plants, Part 4. Gas Centrifuge Enrichment Plant: Diversion Scenarios and IAEA Safeguards Activities", K/ITP--156/P4/R1, Martin Marietta Energy Systems, Inc., Oak Ridge, Tennessee, October 1988, p.148. Note that when this document refers to "a small centrifuge facility," it has in mind a small commercial centrifuge enrichment facility which would be 10 to 20 times larger than Iran's current FEP.

[29] Gregory S. Jones, "Iran's Centrifuge Enrichment Program as a Source of Fissile Material for Nuclear Weapons," April 8, 2008, p. 14. http://www.npolicy.org/files/20081017-Jones-IranEnrichment.pdf

In August 2009 I published an updated version of my April 2008 paper.[30] In my August 2009 paper, I noted that in 2008, Alexander Glaser of Princeton had published a paper which showed that Iran could produce HEU by a more efficient method of batch recycling.[31] In particular, Iran could enrich the 3.5% enriched uranium it was producing to 16.3% in the first step and then by significantly reducing the cascade feed rate, enrich the 16.3% enriched uranium to 91.1% in only one additional step (i.e. two steps total instead of three). Glaser calculated that operating in this reduced feed mode, the enrichment plant's enrichment capacity would still be 97% of what it was when enriching natural uranium to 3.5% enrichment. This two-step process would allow Iran to produce enough HEU for a nuclear weapon in a shorter time compared to the three-step batch recycling process and would also allow Iran to produce a greater quantity of HEU from a given amount of 3.5% enriched uranium. In 2010 Iran began producing 20% enriched uranium from 3.5% enriched uranium and I adapted Glaser's calculations to reflect this fact.

On September 20, 2011 David Albright of the Institute for Science and International Security published a critique of my estimates of how quickly Iran could produce the HEU required for a nuclear weapon.[32] Since a key part of my calculations depended on Glaser's work, Albright attacked Glaser as well. In contrast to Glaser's paper which had been published in a peer reviewed scientific journal, Albright relied on unpublished statements by parties that he refused to name, stating:

> In IR-1 cascades at the FEP, the drop in separative capacity would be expected to be great when enriching from 20 percent to 90 percent. In fact according to a former IAEA official with years of familiarity with the FEP, in practice, going from 20 percent to 90 percent in one step may not be possible in FEP cascades.

In his follow up note of October 27, 2011, Albright continued his attack on Glaser.

> But Jones's analysis has a bigger problem. Jones's justification depends on calculations made by Glaser that are not applicable to the estimation of the production of highly enriched uranium (HEU) at the FEP. Moreover, Glaser is aware of this problem.[33]

In light of Albright's criticisms I decided to make the conservative choice and revert to using three-step batch recycling for my calculations regarding how quickly Iran could produce HEU for nuclear weapons. I pointed out at the time that since most of the enrichment effort is required to go from 3.5% to 20% enriched uranium, this change would not buy that much time. Indeed Iran's progress in expanding its enrichment program has been so rapid that in May 2013 I calculated that Iran, using a three-step enrichment process, could produce enough HEU for a

[30] Gregory S. Jones, "Iran's Centrifuge Enrichment Program as a Source of Fissile Material for Nuclear Weapons," August 17, 2009, Appendix added August 31, 2009, http://www.npolicy.org/article_file/20090817-Iran_Enrichment_Update_290111_0621.pdf
[31] Alexander Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation", *Science and Global Security*, 2008, Vol. 16, pp. 1-25.
[32] David Albright, Paul Brannan, and Christina Walrond, "Critique of Gregory Jones's Breakout Estimates at the Natanz Fuel Enrichment Plant (FEP), Institute for Science and International Security, September 20, 2011.
[33] David Albright and Christina Walrond, "Debunking Gregory Jones Again," October 27, 2011.

nuclear weapon in just two months, which is what I had calculated Iran could do in fall of 2011 using a two-step enrichment process.[34]

Given Albright's statements in 2011, I was surprised when Albright published a paper[35] on July 31, 2013 showing that one step enrichment from 20% to 90% enriched uranium was possible, meaning that Iran could produce HEU using two-step batch recycling. As I demonstrate in the main text, by being able use two-step batch recycling Iran can produce the HEU for a nuclear weapon more quickly and utilize its stocks of 3.5% and 20% enriched uranium more effectively to produce a greater amount of HEU.

There is one significant difference between the Glaser's calculations and those in Albright's July 31, 2013 paper. Whereas Glaser calculated that a plant enriching from 20% to 90% would operate at 97% of its normal enrichment capacity, the paper of which Albright is a coauthor indicates that the enrichment capacity would only be about 63%.[36] While this is a significant difference, it is a far cry from Albright's 2011 assertion that "going from 20 percent to 90 percent in one step may not be possible." The important point is that Glaser's basic calculations have been affirmed and Iran can produce HEU via two-step batch recycling.

Though Albright's July 31, 2013 paper affirmed Glaser's 2008 results, Albright's paper does not acknowledge this fact and indeed makes no mention of Glaser's 2008 paper at all. Given Albright's criticisms of Glaser's work in 2011, one would have thought that Albright would want to acknowledge that Glaser was basically correct. Additionally, one of Albright's coauthors, Houston Wood of the University of Virginia, provided comments to Glaser on his 2008 paper and therefore should have been well aware of Glaser's paper and its priority in demonstrating that two-step batch recycling is possible.

One clear lesson of this episode is that relying on unpublished comments by anonymous individuals is prone to error. The false claims that the two-step production of HEU was infeasible allowed the seriousness of the threat of Iran's enrichment program to be significantly underestimated between the fall of 2011 and August 2013. At least now, the true dangers of Iran's centrifuge enrichment program can be seen.

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[34] Gregory S. Jones, "Iran's Rapid Expansion of its Enrichment Facilities Continues as the Entire Nonproliferation System Threatens to Unravel: Centrifuge Enrichment and the IAEA May 22, 2013 Safeguards Update," May 30, 2013, http://nuclearpolicy101.org/wp-content/uploads/2013/05/Iran-Enrichment-Update-05-2013.pdf

[35] William C. Witt, Patrick Migliorini, David Albright, and Houston Wood, "Modeling Iran's Tandem Cascade Configuration for Uranium Enrichment by Gas Centrifuge," Paper presented at INMM 54th Annual Meeting, July 14-18, 2013.

[36] Another difference is that Albright's July 31, 2013 paper provides an analysis of Iran's tandem cascades. Since Iran's first tandem cascade was not built until mid-2010, Glaser's 2008 paper did not discuss them.