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Iran's Centrifuge Enrichment Program as a Source Of Fissile Material for Nuclear Weapons: An Update

Introduction

Iran's centrifuge enrichment program is nominally designed to produce low enriched uranium which is incapable of being used to produce nuclear weapons. However, three aspects of this program: its ability to produce centrifuges, its stockpile of low enriched uranium and its operating centrifuge plant producing low enriched uranium, can be used in various ways to produce the highly enriched uranium (HEU) needed for nuclear weapons. In the early stages of Iran's centrifuge enrichment program, its capabilities were clearly less than that needed to produce highly enriched uranium but as this program matures, Iran will inexorably gain the capability to be able to produce the highly enriched uranium needed for nuclear weapons as a by-product of this program. Further Iran will be able to carry out this production of highly enriched uranium in ways that IAEA (International Atomic Energy Agency) safeguards will be unable to prevent.[1]

Prior work by various analysts including this author have provided estimates of when Iran's enrichment program will reach this level of maturity. This author's prior work indicated that it was likely that sometime in 2010-2012, Iran's centrifuge enrichment program would be capable of providing the highly enriched uranium needed for nuclear weapons. This estimate was based on information current as of late 2007. At this time Iran had about 3,000 operating centrifuges and a low enriched uranium stockpile of only 50 kilograms (3.8% enriched). Recently the IAEA has released information current as of May 31, 2009.[2] (A further update as of August 28, 2009 is provided in the Appendix). At this time Iran had about 4,900 operating centrifuges with another 2,300 installed but not yet operational. Its low enriched uranium stockpile was 905 kilograms (in the form of 1,339 kilograms of uranium hexafluoride). The enrichment level of this stockpile was not specified but based on prior reporting its enrichment may be about 3.5%.

Given Iran's clear progress in developing its centrifuge enrichment program, it seems timely to perform an update of our prior work to see if our estimates are still valid. Additionally we will look at estimates of other analysts to see how closely they match our estimates and to examine why they might differ from ours. Though nominally some of these other estimates may seem rather different than ours, we will show that given the proper assumptions, all of the estimates are actually rather similar and indicate that by the

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[1] As was discussed in prior work, we consider any situation where Iran can produce a weapon's worth of highly enriched uranium in less than two months as one where IAEA safeguards can not be adequately applied. See: Gregory S. Jones, *Iran's Centrifuge Enrichment Program as a Source of Fissile Material for Nuclear Weapons*, April 8, 2008. http://www.npec-web.org/Essays/20081017-Jones-IranEnrichment.pdf

[2] *Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions 1737 (2006), 1747 (2007), 1803 (2008) and 1835 (2008) in the Islamic Republic of Iran*, IAEA, GOV/2009/35, June 5, 2009.

end of the next year, Iran's centrifuge enrichment program will provide it with the capability to produce highly enriched uranium for weapons any time it wants.

There are two main classes of scenarios whereby Iran might produce highly enriched uranium for nuclear weapons. First, it could construct a clandestine enrichment plant. Second, it could conduct batch recycling at its current enrichment plant at Natanz. We will examine each option in turn. For our analysis we will assume that all of Iran's centrifuges are similar to Pakistan's P-1 machines.[3] Iran has more advanced centrifuges under development and if it is capable of manufacturing these machines in large numbers it will only improve Iran's ability to produce highly enriched uranium.

Clandestine Enrichment Plant

As was discussed in our earlier analysis, Iran has not implemented the Additional Protocol to its IAEA safeguards agreement.[4] As a result there is no monitoring of Iran's centrifuge production facility and it is entirely unknown what the actual production rate of this facility is. Therefore Iran could easily be manufacturing additional centrifuges beyond those that it is installing at the safeguarded low enrichment production facility at Natanz. These additional centrifuges could be used to construct a clandestine enrichment plant whose location is unknown to the IAEA and the West. This clandestine enrichment plant could be designed to produce highly enriched uranium for nuclear weapons is one of two ways. First, this clandestine plant could be designed to produce highly enriched uranium starting from natural uranium. The time required to produce a weapon's worth of highly enriched uranium (20 kilograms) as a function of the number of centrifuges in the clandestine enrichment plant are shown in table 1. As can be seen, a weapon's worth of highly enriched uranium could be produced every three to six and a half months assuming that the clandestine enrichment plant contains a number of centrifuges similar to that at its low enrichment facility at Natanz. While this may seem like a long time, it should be noted that without the Additional Protocol to Iran's IAEA safeguards, Iran's uranium mining is also not being monitored. Therefore this effort could be ongoing right now without any detection by the IAEA.

[3] The standard assumptions for these machines are that each one produces 2.5 separative work units (SWU) per year and that the elementary separation factor is 1.3.
[4] Jones, *op.cit.*

Table 1

Time Required to Produce 20 Kilograms of 93.1 % Enriched Uranium as a Function of the Number of Centrifuges in the Clandestine Enrichment Plant

Number of Centrifuges	Feed Enrichment And Amount	Time to Produce 20 kg of HEU* (Days)
3,000	Natural U 4,500 kg	~200**
6,000	Natural U 4,500 kg	~100 **
3,000	3.5% enriched 920 kg	43***
6,000	3.5% enriched 920 kg	22***

*Includes one day to account for equilibrium time
** Tails enrichment 0.3%
*** Tails enrichment 1.5%

The second way that a clandestine enrichment plant could be used to produce highly enriched uranium is to enrich Iran's stockpile of low enriched uranium (nominally 3.5% enriched) to highly enriched uranium for weapons. This would require violating IAEA safeguards since the low enriched uranium stockpile would have to be diverted to the weapons production effort. However, as can be seen from table 1, the time required is short enough that there is little chance that any effective counteraction could be taken by the West before Iran produced the material needed for its first nuclear weapon. To produce 20 kilograms of highly enriched uranium would require a stockpile of about 900 kilograms of 3.5% enriched uranium but this is exactly the size of Iran's current low enriched uranium stockpile. Therefore the production of highly enriched uranium in a clandestine enrichment plant starting with either natural uranium or low enriched uranium are both current threats.

David Albright and colleagues have published a recent assessment of threat posed by a clandestine Iranian enrichment plant.[5] They state: "A clandestine plant with about 3,000 P1 centrifuges…would be able to produce the 20-25 kilograms of weapon-grade uranium from 3.5 percent material in 2.5-3.6 months at 2 SWU per year per machine, or 3.3-4.8 months at 1.5 SWU per year per machine." Even taking into account that we use 2.5 SWU per year per machine, Albright's estimates are about 60% longer than ours. Though Albright does not specify the tails enrichment he uses, it appears he uses a tails enrichment of about 0.4% instead of the 1.5% that we use. While using such a low tails enrichment would make sense in a long-term sustained program, it unnecessarily lengthens the effort to produce highly enriched uranium at a time when Iran would be

[5] David Albright, Paul Brannan, and Jacqueline Shire, "Nuclear Weapon Breakout Scenarios: Correcting the Record" Institute For Science and International Security, March 18, 2009. http://www.isisnucleariran.org/assets/pdf/Correcting_the_Record.pdf

trying to produce its first nuclear weapon before the West could undertake counteraction. If Albright had used our tails enrichment then his estimate would be shorten to 52-65 days for the 2.0 SWU per year per machine case and 70-87 days for the 1.5 SWU per year per machine case.

Batch Recycling At Natanz

Iran is currently operating a centrifuge enrichment facility at Natanz which is designed to produce low enriched uranium. By taking its stockpile of low enriched uranium and feeding it back into the Natanz facility multiple times, highly enriched uranium could be produced. The exact technical characteristics of this process depend of the enrichment levels at Natanz. Since this is unknown, we will examine two different possible designs for the plant at Natanz to show how the time and material required can vary.

In our earlier work we assumed that the plant at Natanz was producing a product with an enrichment of 4.8% and a tails enrichment of 0.287%. This design is consistent with statements by the IAEA that the plant is producing a product with an enrichment of less than 5%. The details of how the recycling process would work in a 10,000 centrifuge plant are shown in table 2. As can be seen, it takes three recycles through the plant to produce weapons grade uranium. Since the use of Iran's low enriched uranium stockpile in the manner would be a violation of safeguards, the time required is important. For this case it would take only 37 days which is fast enough that there is little chance that any effective counteraction could be taken by the West before Iran produced the material needed for its first weapon. Due to inefficiencies in the recycling process, in this case Iran would need to have a starting low enriched uranium stockpile of about 2 and one quarter metric tons.

Table 2

Time, Product and Feed Requirements for the Production of 20 kg of HEU by Batch Recycling in a 10,000 Centrifuge Enrichment Plant Designed to Produce LEU (4.8% Product)

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	26.2% 260 kg	4.8% 2,250 kg	27
Second	71.4% 57 kg	26.2% 245 kg	6
Third	94.6% 20 kg	71.4% 42 kg	2
Total			37*

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

Table 3 shows how the time and needed low enriched uranium stockpile vary with the number of centrifuges. As for table 2, these calculations apply to a plant producing 4.8% product and 0.287% tails. As can be seen, as the number of centrifuges increases, the time required decreases but the stockpile of required low enriched feed increases. Also if there are enough centrifuges, it will be possible to produce more than one weapon's worth of highly enriched uranium. It seems clear that the danger point will be reached when Iran acquires more than about 10,000 centrifuges. Given its rate of installation, this will likely occur in the second half of 2010. Iran will also need a stockpile of low enriched uranium on the order of 2 to 3 metric tons. If the plant operates at it design capacity, it could produce this stockpile in less than six months. However as will be discussed below, the current plant does not seem to be operating at anywhere close to its design capacity. Still even at its current operating efficiency, Iran will probably be able to produce this low enriched uranium stockpile sometime in the latter part of 2010,

Table 3

Time Required to Produce HEU by Batch Recycling in Centrifuge Enrichment Plant at Natanz (4.8% Product)

Number of Centrifuges	Amount of HEU Produced (kilograms)	Stockpile of 4.8% enriched uranium feed required (kilograms)	Time to Produce HEU* (Days)
3,000	20	1,780	95
10,000	20	2,250	37
20,000	20	2,940	24
50,000	20	5,000	17
50,000	100	11,200	36

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

Glaser has proposed a quite different design for the enrichment plant at Natanz.[6] He has suggested that there is a standard Pakistani cascade design. This consists of 164 centrifuges per cascade and that each cascade would produce a low enriched product with an enrichment of 3.5% and a tails enrichment of 0.4%. Further Glaser has suggested that Iran's installations at Natanz follow this Pakistani design without modification.

Such a design would perform poorly in the simple batch recycling that we illustrated above. It would require four batch recycles and require a large low enriched uranium stockpile. However, Glaser has done a more sophisticated analysis of batch recycling

[6] 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.

which obviates these problems. In particular in his second recycle Glaser proposes changing the operating parameters of the centrifuges in a way that allows the process enrichment to go all of the way to highly enriched uranium. An example of such a recycle is shown in table 4. We used 61 of Glaser's cascades which totals to 10,004 centrifuges. Compared with table 2, we can see that Glaser's proposed batch recycle takes less time than a less sophisticated recycle but that the amount of low enriched feed needed is still about the same i.e. around 1,900 kilograms. As we discussed previously, even at Iran's current low efficiency for the production of low enriched uranium, Iran would be able to produce this much low enriched uranium by sometime in the second half of next year.

Table 4

Time, Product and Feed Requirements for the Production of 20 kg of HEU by Batch Recycling in a 10,004 Centrifuge Enrichment Plant Designed to Produce LEU (3.5% Product-Glaser Design)

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	16.1% 197 kg	3.5% 1,880 kg	10.4
Second	91.1% 20 kg	16.1% 191 kg	3.2
Total			18*

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

Kemp and Glaser have produced estimates of when Iran might be able to produce a weapon's worth of highly enriched uranium via batch recycling at Natanz.[7] Some of these estimates are much longer than the ones we have discussed thus far. One key reason for these longer estimates is that Kemp and Glaser have noted that based on the amount of low enriched uranium that the current cascades at Natanz are actually producing; Iran's centrifuges seem to be operating at an efficiency far less than our standard assumption (2.5 SWU per year per machine) would indicate. Kemp and Glaser are not explicit but our calculations indicate that the current cascades may only be producing about 21% of the expected low enriched uranium. It is unclear whether this low efficiency is just a temporary teething problem at Natanz or fundamental to the design and operation of Iran's current generation of centrifuges.

For many of their estimates, Kemp and Glaser assume that the low efficiency of the current centrifuges at Natanz is inherent feature of these machines. They take as their

[7] R. Scott Kemp and Alexander Glaser, "Statement on Iran's ability to make a nuclear weapon and the significance of the 19 February 2009 IAEA report on Iran's uranium enrichment program.", March 2, 2009, http://www.princeton.edu/~aglaser/2009aglaser_iran.pdf

goal the production of 25 kilograms of highly enriched uranium. Though not entirely explicit, it seems that they believe that Iran would need to start with a 3.5% enriched uranium stockpile of around 2.2 metric tons total. Given that Iran had about 4,000 operating centrifuges on February 1, 2009, Kemp and Glaser assume that this is a constant number and indicated that it would take Iran 31 months to produce the additional low enriched uranium with just this number of centrifuges (Iran had 683 kilograms of 3.5% enriched uranium at the end of January 2009). After this time the 4,000 centrifuges would be operated in batch recycle mode and it would take an additional 4 to 6 months for the highly enriched uranium to be actually produced. This would make a total estimate of about three years which Kemp and Glaser term "a more realistic estimate" compared to some other estimates such as our own.

However, this estimate is highly misleading. It assumes that Iran would continue to operate only 4,000 centrifuges over this long period of time and is already obviously obsolete. Iran will soon have 7,200 centrifuges in operation. If one just makes this change as well as using a goal of producing 20 kilograms of highly enriched uranium, then it would take only about one year to produce the required uranium for batch recycling. Note that even at the 21% efficiency, 7,200 centrifuges will produce a little over 1,000 kilograms of 3.5% enriched uranium each year. And as we stated earlier, as of May 31, 2009, Iran already had 905 kilograms of 3.5% enriched uranium. Therefore Iran will clearly reach the needed goal of around 2,000 kilograms in little more than another year.

The possible lower efficiency of Iran's centrifuges would also affect the time required for batch recycle at Natanz. We have recalculated our results from table 4 to take this lower efficiency into account and the results are shown in table 5. As can be seen the required quantities of enriched uranium does not change but now the time required is just over the two month threshold required for effective safeguards.

Table 5

Time, Product and Feed Requirements for the Production of 20 kg of HEU by Batch Recycling in a 10,004 Centrifuge Enrichment Plant Designed to Produce LEU (3.5% Product-Glaser Design-21% efficient centrifuges)

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	16.1% 197 kg	3.5% 1,880 kg	50
Second	91.1% 20 kg	16.1% 191 kg	15
Total			69*

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

The times required for batch recycling now and in the near future are shown in tables 6 and 7. Table 6, uses the 4,920 centrifuges (30 Glaser cascades) that Iran had in operation on May 31, 2009. The batch recycling in this case would take 135 days. Table 7 uses the 7,052 centrifuges (43 Glaser cascades) that Iran will soon have in operation. For this case the batch recycling would take 96 days. For both cases the required 3.5% enriched uranium stockpile is still about 1,900 kilograms.

Table 6

Time, Product and Feed Requirements for the Production of 20 kg of HEU by Batch Recycling in a 4,920 Centrifuge Enrichment Plant Designed to Produce LEU (3.5% Product-Glaser Design-21% efficient centrifuges)

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	16.1% 194 kg	3.5% 1,850 kg	100
Second	91.1% 20 kg	16.1% 191 kg	31
Total			135*

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

Table 7

Time, Product and Feed Requirements for the Production of 20 kg of HEU by Batch Recycling in a 7,052 Centrifuge Enrichment Plant Designed to Produce LEU (3.5% Product-Glaser Design-21% efficient centrifuges)

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	16.1% 195 kg	3.5% 1,860 kg	70
Second	91.1% 20 kg	16.1% 191 kg	22
Total			96*

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

It is somewhat uncertain when Iran might achieve more than 10,000 operating centrifuges. Iran is installing the cascades in groups of 18 known as “units”. All 18 cascades have been installed in both Unit A24 and Unit A26. Eight of the 18 are already installed in Unit A28. When this unit is completed, Iran will have 8,856 centrifuges in operation. This will likely occur before the end of 2009.[8] Iran is already constructing two new units (Unit A25 and Unit A27). Given Iran's apparent ability to install 2 to 3 cascades a month, Iran will probably have these two additional units installed by the end of 2010 giving it a total of 14,760 operating centrifuges (90 Glaser cascades). Table 8 shows the time required for the batch recycling to take place in this larger centrifuge plant. The time is now less than 50 days and the 3.5% low enriched uranium stockpile is only slightly larger. Table 9 provides a summary of our results from tables 5 through 8. As the number of centrifuges at Natanz increases from 4,920 to 14,760 the time to produce 20 kilograms of highly enriched uranium by batch recycling will decrease from 135 days to 48 days. In all cases, the required low enriched uranium stockpile is about 1,900 kilograms.

Table 8

Time, Product and Feed Requirements for the Production of 20 kg of HEU by Batch Recycling in a 14,760 Centrifuge Enrichment Plant Designed to Produce LEU (3.5% Product-Glaser Design-21% efficient centrifuges)

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	16.1% 200 kg	3.5% 1,910 kg	34
Second	91.1% 20 kg	16.1% 191 kg	10
Total			48*

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

Table 9

Time Required to Produce HEU by Batch Recycling in Centrifuge Enrichment Plant at Natanz (3.5% Product-Glaser Design-21% efficient centrifuges)

Number of Centrifuges	Amount of HEU Produced (kilograms)	Stockpile of 3.5% enriched uranium feed required (kilograms)	Time to Produce HEU* (Days)
4,920	20	1,850	135
7,052	20	1,860	96
10,004	20	1,880	69
14,760	20	1,910	48

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

[8] Iran installed the first seven cascades in A28 as well as the final three cascades in A26 during the four months from the end of January 2009 to the end of May 2009.

The bottom line is that despite the possible low efficiency of Iran's centrifuges, sometime in the latter part of 2010, Iran will have enough centrifuges installed at Natanz as well as the required 3.5% enriched uranium stockpile (around 1,900 kilograms) so that it will be able to produce a weapon's worth of highly enriched uranium (20 kilograms) in less than the two months that would be required for IAEA safeguards to provide the West with adequate warning.

Conclusions

Iran's current centrifuge enrichment program provides it with two options for producing highly enriched uranium for nuclear weapons. First, it can build a clandestine enrichment plant which would be able to utilize either natural uranium feed or Iran's current stockpile of 3.5% enriched uranium. Given that there are no IAEA safeguards of Iran's centrifuge production facility and its uranium mining industry, a clandestine enrichment plant using natural uranium feed could operate for years without necessarily being detected. Such a plant could be in operation right now. Iran's stockpile of 3.5% enriched uranium is large enough (905 kilograms) to produce a weapon's worth of highly enriched uranium if it were processed in an appropriately designed clandestine enrichment plant.

However, some may argue that our current lack of detection of any Iranian clandestine enrichment plant indicates that such a plant does not exist. No similar argument can be made regarding the possibility of Iran producing highly enriched uranium at its centrifuge enrichment plant at Natanz. Our calculations have shown that even if Iran's centrifuges are as inefficient as they currently appear (only 21% of what is generally assumed), once Iran has a 3.5% uranium stockpile of around 1,900 kilograms and somewhat more than 10,000 operating centrifuges, Iran will be able to produce a weapon's worth of highly enriched uranium by batch recycling in less than two months. Iran will likely be able to achieve these goals before the end of 2010. Though batch recycling at Natanz would violate IAEA safeguards, it could easily take more than two months for the IAEA to sound the alarm and for the West to take effective counter action.

As we stated in our prior work, once Iran's centrifuge enrichment program reaches this stage of development, its centrifuge enrichment program must be considered unsafeguardable. Unless action is taken soon to bring Iran into compliance with UN Security Council resolutions 1737, 1747, 1803 and 1835, which call on Iran to suspend without further delay "all enrichment-related and reprocessing activities", Iran will have the ability to quickly produce one or more weapon's worth of highly enriched uranium and thereby have a latent nuclear weapons capability.

Appendix: IAEA August 28, 2009 Update

Since the text was written, the IAEA has issued a new update dated August 28, 2009.[9] This update shows that Iran remains on its trajectory of attaining the capability to produce a weapons worth of highly enriched uranium (20 kilograms) by batch recycling at its existing enrichment facility at Natanz sometime in 2010. As indicated in the text, this would require Iran to have about 10,000 operating centrifuges and to have a low enriched uranium stockpile of around 1,900 kilograms (see table 9).

Specifically, a key judgment in our assessment discussed in the text is that Iran would be able to continue to install centrifuges at the rate of 2 to 3 cascades a month (164 centrifuges in each cascade) as opposed to the only 1 cascade a month suggested by Kemp and Glazer. From May 31, 2009 to August 12, 2009 Iran increased its number of installed centrifuges from 7,221 to 8,308. This is an increase of 1,087 centrifuges which is an installation rate of about 2.8 cascades a month. In the text we estimated that Iran could have 8,856 centrifuges in operation by the end of 2009 and 14,760 centrifuges in operation by the end of 2010. Iran is on a pace to meet or even somewhat exceed these estimates.

With regard to Iran's low enriched uranium stockpile, it is now reported (as of July 31, 2009) to have 1,019 kilograms (in the form of 1,508 kilograms of uranium hexafluoride). This is an increase of 114 kilograms since May 31, 2009 or a production rate of 57 kilograms of low enriched uranium a month. At the current rate, Iran will reach 1,900 kilograms in fifteen and one half months from the end of July 2009 which would be mid-November 2010. Furthermore, Iran is currently only producing low enriched uranium with 4,592 centrifuges (the reasons for this are unclear).[10] If it were to start producing low enriched uranium with all 8,308 centrifuges that it has currently installed then Iran could have a stockpile of 1,900 kilograms in eight and one half months which would be mid-April 2010. If Iran brings more centrifuges online as they are installed, the time interval could be even shorter.

The bottom line is that Iran remains on course to have at least 10,000 operating centrifuges and a low enriched uranium stockpile of at least 1,900 kilograms sometime in 2010. These achievements will give Iran the ability to be able to produce a weapons worth of highly enriched uranium by batch recycling at its existing uranium enrichment facility at Natanz whenever it wishes.

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[9] *Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions 1737 (2006), 1747 (2007), 1803 (2008), and 1835 (2008) in the Islamic republic of Iran,* GOV/2009/55, August 28, 2009.

[10] Producing 57 kilograms of low enriched uranium a month with 4,592 centrifuges indicates that Iran's centrifuges are still operating at a 21% efficiency compared to a centrifuge capable of producing 2.5 SWU per year per machine. That is to say there is no evidence that Iran is improving the operating efficiency of its centrifuges.