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Iran's Centrifuge Enrichment Program as a Source of Fissile Material for Nuclear Weapons

Executive Summary

A recent National Intelligence Estimate (NIE) concluded that though Iran had a nuclear weapons program until the fall of 2003, this program has been halted.[1] It also concluded that Iran could produce a weapon's worth of highly enriched uranium (HEU) "sometime during the 2010-2015 timeframe." However, the unclassified version of the NIE provides only "key judgments" without analysis. As a result, the unclassified version of the NIE does not describe the pathways whereby Iran could acquire this highly enriched uranium. An analysis of these pathways is important since it would allow one to determine the amount of warning the West might have that Iran was starting to produce highly enriched uranium. Also, the unclassified version of the NIE is silent on the implications of Iran's acquisition of a weapon's worth of highly enriched uranium. This is surprising since for any nuclear weapons program the most demanding requirement is the ability to produce the fissile material (plutonium or highly enriched uranium) required for the weapons.

Iran has been developing centrifuge enrichment (which could produce highly enriched uranium) using technology imported from Pakistan. Iran claims that its centrifuge enrichment program is for peaceful purposes and is intended to provide low enriched uranium fuel for its Russian supplied nuclear power reactor (a VVER-1000 PWR), located at Bushehr, which is due to start operation in 2008. Iran has defied several UN Security Council resolutions calling for a suspension of its enrichment program citing an "inalienable right" to peaceful nuclear energy. As of November 2007 Iran had nearly 3,000 centrifuges in operation at Natanz.[2]

The Natanz plant is under IAEA (International Atomic Energy Agency) safeguards and these safeguards have confirmed that thus far this plant has only produced low enriched uranium (LEU) which would be suitable for nuclear power reactor fuel but unusable for nuclear weapons. Indeed, the first ever physical inventory conducted at Natanz (on December 12, 2007) found only about 50 kilograms of uranium product with an enrichment of 3.8%.[3] As long as Natanz is under safeguards, it is likely that it could not be used to produce the highly enriched uranium needed for nuclear weapons. However, Iran could terminate the safeguards at any time and use its current enrichment program as a starting base for the production of highly enriched uranium. The enrichment plant at

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[1] National Intelligence Estimate, *Iran: Nuclear Intentions and Capabilities*, National Intelligence Council, November, 2007.
[2] *Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions 1737 (2006) and 1747 (2007) in the Islamic Republic of Iran*, IAEA, GOV/2007/58, November 15, 2007.
[3] *Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions 1737 (2006) and 1747 (2007) in the Islamic Republic of Iran*, IAEA, GOV/2008/4, February 22, 2008.

Natanz, as well as the stock of low enriched uranium that this plant would have produced by that time could be used for this weapons production effort. Since the reactor at Bushehr requires nearly fifteen metric tons of low enriched uranium for each annual reload, Iran's stockpile of this material could, in the future, be quite large.

The key question is how long will it take Iran to acquire the highly enriched uranium once it has terminated IAEA safeguards? Unfortunately, the technical characteristics of the centrifuge enrichment process allow for the relatively rapid production of highly enriched uranium. In March 2007, in light of the risk posed by the increasing number of installed centrifuges at Natanz, Iran and the IAEA agreed to monthly interim inspections, containment and surveillance measures and unannounced inspections.[4] In the twelve month period from March 2007 to February 2008, the IAEA conducted nine unannounced inspections.[5] Note that for three months no unannounced inspection took place between the regularly scheduled monthly inspections which means it could take the IAEA at least one month before any violation of safeguards could be detected.

Clearly then, for diversions of nuclear material that can occur in only a few weeks to a month, the IAEA may only find out about them after the fact. Even once the diversion is discovered, it may take some time for any counter-action to be taken given that the matter would have to be referred to the UN Security Council. Consequently, for the purposes of this paper we will consider that IAEA safeguards are not adequate in situations where Iran can produce a weapon's worth of highly enriched uranium in less than two months.

We examined two main classes of scenarios for an Iranian breakout from safeguards. The first class of scenarios involves Iran using a clandestine enrichment plant to produce highly enriched uranium from either its stock of low enriched uranium or from natural uranium. Our results are shown in Table A. As can be seen, if Iran breaks out of safeguards and uses a stockpile of 4.8% enriched uranium as feed, then a weapon's worth of highly enriched uranium (20 kilograms) can be produced in a few weeks to one month. This time is significantly less than the two months required for effective safeguards. If Iran were to feed natural uranium into the enrichment plant, the time would be much longer (100-200 days) but Iran would no longer have to break safeguards, since Iran's uranium mining operations are not under safeguards. The IAEA would be unlikely to detect this production absent Iran allowing the Additional Protocol to its safeguards agreement to be implemented, since otherwise the IAEA would have no authority to search Iran for a clandestine enrichment plant or monitor uranium mining.

[4] *Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions in the Islamic Republic of Iran, IAEA*, GOV/2007/22, May, 23, 2007.
[5] IAEA, GOV/2008/4, *op. cit.*

Table A

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

Centrifuge Type	Centrifuge Separative Capacity SWU/YR-Machine	Number of Centrifuges	Feed Enrichment and Amount	Time to Produce 20 kg of HEU* (Days)
P-1	2.5	3,000	4.8% enriched 700 kg	31**
P-1	2.5	6,000	4.8% enriched 700 kg	16**
P-2	5.0	3,000	4.8% enriched 700 kg	16**
P-1	2.5	3,000	Natural U 4,400 kg	~200***
P-1	2.5	6,000	Natural U 4,400 kg	~100***
P-2	5.0	3,000	Natural U 4,400 kg	~100***

*Includes one day to account for equilibrium time.
**Tails enrichment 2.26%
***Tails enrichment 0.287%

The second class of scenarios involves Iran producing highly enriched uranium by batch recycling at its enrichment plant at Natanz. We examined various future cases involving the current enrichment plant and an expanded enrichment plant. The results are shown in table B. As can be seen, as Iran carries out its planned expansion from the current 3,000 centrifuges at Natanz to 50,000 by 2012, (and it acquires a substantial stock of enriched uranium), the time required for Iran to produce a weapon's worth of uranium will drop from 95 days to less than a month. Indeed the time required is so short that with the full 50,000 centrifuges, even five weapons' worth of highly enriched uranium (100 kilograms) could be produced in little more than one month. And even in the extreme case that the centrifuge separative capacity is only 1.0 SWU/year-machine, instead of 2.5, a weapon's worth of highly enriched uranium could still be produced in less than one month. These times are significantly less than the two months required for safeguards to be effective. In this class of scenarios, the Additional Protocol would be of no help in preventing the rapid production of highly enriched uranium, since both the centrifuge plant at Natanz and the stockpile of enriched uranium would be permitted.

Table B

Time Required to Produce HEU by Batch Recycling in Centrifuge Enrichment Plant at Natanz

Number of P-1 Centrifuges	Centrifuge Separative Capacity SWU/YR-Machine	Amount of HEU Produced (kilograms)	Stockpile of 4.8% enriched uranium feed required (kilograms)	Time to Produce HEU* (Days)
3,000	2.5	20	1,780	95
10,000	2.5	20	2,250	37
20,000	2.5	20	2,940	24
50,000	2.5	20	5,000	17
50,000	2.5	100	11,200	36
50,000	1.0	20	2,940	24

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

Note that due to Iran's current small stockpile of low enriched uranium (50 kilograms of 3.8% enriched uranium) and its limited centrifuge production, neither of these classes of scenarios pose a current threat. However both of these classes of scenarios raise questions about the future adequacy of the IAEA's safeguards of Iran's enrichment program. If Iran begins producing tens of thousands of centrifuges and acquires a larger stockpile of low enriched uranium, then Iran's execution of any of these scenarios would provide a source of highly enriched uranium in the 2010-2012 timeframe. Though it may not have a formal nuclear weapons program, Iran's developing centrifuge enrichment program is inexorably improving its capability to quickly produce highly enriched uranium, which is a key component of a nuclear weapons program.

The bottom line is that if Iran maintains its planned expansion of its centrifuge enrichment capacity, then by 2010-2012, Iran will be able to produce a weapon's worth of highly enriched uranium in just a month or even a few weeks. The West will be unable to counter such a rapid effort. Indeed, in some circumstances, the IAEA will only detect the effort after the fact. Under these conditions, the Iranian enrichment program must be considered unsafeguardable. Furthermore this dire situation will exist even if the Additional Protocol to Iran's safeguard agreement is brought into force since Iran could still produce highly enriched uranium by batch recycling in its current enrichment plant at Natanz. Unless action is taken soon to bring Iran into compliance with UN Security Council resolutions 1737, 1747 and 1803, 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. Future NIEs on Iran's nuclear program need to reflect this serious reality.

Introduction

A recent National Intelligence Estimate (NIE) concluded that though Iran had a nuclear weapons program until the fall of 2003, this program has been halted.[6] It also concluded that Iran could produce a weapon's worth of highly enriched uranium (HEU) "sometime during the 2010-2015 timeframe." However, the unclassified version of the NIE provides only "key judgments" without analysis. As a result, the unclassified version of the NIE does not describe the pathways whereby Iran could acquire this highly enriched uranium. An analysis of these pathways is important since it would allow one to determine the amount of warning the West might have that Iran was starting to produce highly enriched uranium. Also, the unclassified version of the NIE is silent on the implications of Iran's acquisition of a weapon's worth of highly enriched uranium. This is surprising since for any nuclear weapons program the most demanding requirement is the ability to produce the fissile material (plutonium or highly enriched uranium) required for the weapons.

Iran is building a plutonium production reactor and also has been developing centrifuge enrichment (which could produce highly enriched uranium) using technology imported from Pakistan. Iran's centrifuge enrichment program had been clandestine until it was revealed in 2002 by Iranian opposition groups. Iran has never admitted to having a nuclear weapons program but in response to international pressure (and likely concerned by Coalition military action in neighboring Iraq) Iran suspended its enrichment program in 2003. However, in early 2006 (possibly emboldened by continuing U.S. trouble in Iraq), Iran restarted its program and soon reported that it had successfully enriched uranium.[7] Iran claims that its centrifuge enrichment program is for peaceful purposes and is intended to provide low enriched uranium fuel for its Russian supplied nuclear power reactor (a VVER-1000 PWR), located at Bushehr, which is due to start operation in 2008. Iran has defied several UN Security Council resolutions calling for a suspension of its enrichment program citing an "inalienable right" to peaceful nuclear energy. As of November 2007 Iran had nearly 3,000 centrifuges in operation at Natanz.[8]

The Natanz plant is under IAEA (International Atomic Energy Agency) safeguards and these safeguards have confirmed that thus far this plant has only produced low enriched uranium which would be suitable for nuclear power reactor fuel but unusable for nuclear weapons. Indeed, the first ever physical inventory conducted at Natanz (on December 12, 2007) found only about 50 kilograms of uranium product with an enrichment of 3.8%.[9] As long as Natanz is under safeguards, it is likely that it could not be used to produce the highly enriched uranium needed for nuclear weapons. However, Iran could terminate the safeguards at any time and use its current enrichment program as a starting base for the production of highly enriched uranium. The enrichment plant at Natanz, as

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[6] National Intelligence Estimate, *Iran: Nuclear Intentions and Capabilities*, National Intelligence Council, November, 2007.

[7] *Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, IAEA, GOV/2006/15, February 27, 2006.

[8] *Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions 1737 (2006) and 1747 (2007) in the Islamic Republic of Iran*, IAEA, GOV/2007/58, November 15, 2007.

[9] *Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions 1737 (2006) and 1747 (2007) in the Islamic Republic of Iran*, IAEA, GOV/2008/4, February 22, 2008.

well as the stock of low enriched uranium that this plant would have produced by that time could be used for this weapons production effort. Since the reactor at Bushehr requires nearly fifteen metric tons of low enriched uranium for each annual reload, Iran's stockpile of this material could, in the future, be quite large.

The key question is how long will it take Iran to acquire the highly enriched uranium once it has terminated IAEA safeguards? To take an extreme example, highly enriched uranium metal spheres could be under safeguards. Yet once the material was removed from safeguards it could be used in weapons in a matter of hours. Under these circumstances, safeguarding the material would have little value since no time would available for counter-action before the weapons could be used. At the other extreme, consider a uranium enrichment program based on the gaseous diffusion process. (For many decades this was the technology that provided most enriched uranium.) It would take at least six months using this technology to produce highly enriched uranium even starting with substantial stocks of low enriched uranium. Safeguards under these conditions could be quite effective.

Unfortunately, the technical characteristics of the centrifuge enrichment process allow the production of highly enriched uranium in a much shorter time than is required for the gaseous diffusion process. The IAEA is well aware of this problem and has proposed continuous remote monitoring of Iran's enrichment facility at Natanz but Iran has refused to discuss this proposal.[10] Instead, in March 2007, in light of the increasing number of installed centrifuges at Natanz, Iran and the IAEA agreed to monthly interim inspections, containment and surveillance measures and unannounced inspections.[11] In the twelve month period from March 2007 to February 2008, the IAEA conducted nine unannounced inspections.[12] Note that for three months no unannounced inspection took place between the regularly scheduled monthly inspections which means it could take the IAEA at least one month before any violation of safeguards could be detected.

Clearly then, for diversions of nuclear material that can occur in only a few weeks to a month, the IAEA may only find out about them after the fact. Even once the diversion is discovered, it may take some time for any counter-action to be taken given that the matter would have to be referred to the UN Security Council. Consequently, for the purposes of this paper we will consider that IAEA safeguards are not adequate in situations where Iran can produce a weapon's worth of highly enriched uranium in less than two months.

We will look at two main classes of scenarios for an Iranian breakout from safeguards. The first class of scenarios involves Iran using a clandestine enrichment plant to produce highly enriched uranium from either its stock of low enriched uranium or from natural uranium. As we will show, if this plant contains somewhere between 3,000 and 6,000 centrifuges and Iran has acquired a stockpile of 700 kilograms of 4.8% enriched uranium,

[10] *Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, IAEA, GOV/2006/64, November 14, 2006.
[11] *Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions in the Islamic Republic of Iran, IAEA*, GOV/2007/22, May, 23, 2007.
[12] IAEA, GOV/2008/4, *op. cit.*

then Iran will be able to produce a weapon's worth of highly enriched uranium (twenty kilograms of uranium with an enrichment of 90% or greater) in a few weeks to a month. If Iran were to feed natural uranium into the enrichment plant, the time would be much longer (100-200 days) but Iran would no longer have to break safeguards, since Iran's uranium mining operations are not under safeguards.

The second class of scenarios involves Iran producing highly enriched uranium by batch recycling at its enrichment plant at Natanz. We examine various future cases involving the current enrichment plant and an expanded enrichment plant. The main cases are summarized in table 1. The results show that as Iran expands the number of centrifuges at Natanz and acquires a substantial stock of enriched uranium, the time required for Iran to produce a weapon's worth of uranium will drop from 95 days to less than a month.

Both of these classes of scenarios raise questions about the future adequacy of the IAEA's safeguards of Iran's enrichment program. Note that due to Iran's current small stockpile of low enriched uranium (50 kilograms of 3.8% enriched uranium), none of these scenarios is a current threat. However, as will be discussed below, either of these scenarios could become a threat in the 2010-2012 timeframe.

Table 1

Time Required to Produce 20 kg of HEU by Batch Recycling at Centrifuge Enrichment Plant at Natanz

Number of P-1 Centrifuges	Time to Produce 20 kg of HEU (Days)	Stockpile of 4.8% enriched uranium feed required (kilograms)
3,000	95	1,780
10,000	37	2,250
20,000	24	2,940
50,000	17	5,000

Centrifuge Enrichment

In order to detail the Iranian breakout scenarios it is first necessary to describe the characteristics of centrifuge enrichment plants. (For those unfamiliar with uranium enrichment the Appendix provides an explanation for some of the main terms and concepts.) The technical specifications of Iran's centrifuges have not been published. However, it is known that Iran's machines are similar to Pakistan's P-1 centrifuges which in turn are based on early URENCO technology. It is therefore possible to make some reasonable assumptions about Iran's centrifuges. For our analysis we assume that Iran's centrifuges have an elementary separation factor of 1.2972.[13] Current estimates of the

[13] An elementary separation factor of 1.3 is quite consistent with early URENCO technology. We chose this particular value so that it would take exactly fifteen stages to enrich natural uranium to an enrichment of 4.8%.

annual separative capacity range from two to three SWU (separative work units) per machine per year.[14] For our analysis we will assume 2.5 SWU per machine per year.

Early PWR nuclear power reactors used a low enriched uranium fuel where the uranium enrichment was around 3%. Over time this enrichment has increased which has allowed for better fuel economy. Elemash, the Russian manufacturer of fuel for Russian PWRs has indicated that reactors of the VVER-1000 type (such as is being built at Bushehr) can use a fuel with an enrichment as high as 4.8%.[15] Indeed, Iran has stated that it has enriched uranium up to 4.8%. Therefore we will assume that any Iranian enrichment plant designed to produce low enriched uranium fuel for its PWR at Bushehr will be designed to produce uranium with an enrichment of 4.8%.[16]

Starting from natural uranium and using centrifuges with the characteristics we have assumed, it will take 15 enrichment stages (including the feed stage) to produce uranium with an enrichment of 4.8%. Using six stripping stages (excluding the feed stage) will produce tails with an enrichment of 0.287%. For a plant of this design, the production of one kilogram of 4.8% product will require 10.9 kilograms of natural uranium feed and 6.98 SWU. For the 3,000 centrifuges at Natanz, the assumption of 2.5 SWU per machine per year would mean that the total plant would produce 7,500 SWU per year. The plant would then produce 1,070 kilograms of 4.8% product per year requiring 11.7 metric tons of natural uranium feed. For this plant its equilibrium time would be less than four hours and its inventory in the enrichment stages themselves would only be about 5 kilograms of uranium.[17]

Since the annual fuel requirements for Iran's Bushehr PWR are 14.2 metric tons, the current plant is nowhere large enough to supply the fuel for this reactor. Iran has indicated that it plans to expand the Natanz plant to 50,000 centrifuges by 2012.[18] At 2.5 SWU per machine per year this larger plant would produce 125,000 SWU per year which would be able to produce 17.9 metric tons of 4.8% enriched fuel using 195 metric tons of natural uranium feed. Such a plant would be able to supply the fuel for Iran's single PWR. The equilibrium time for this plant would be less than four hours and the inventory in the enrichment stages would be about 75 kilograms of uranium.

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[14] David Albright & Corey Hinderstein, "The Centrifuge Connection", *Bulletin of the Atomic Scientists*, March/April 2004, pp. 61-66. An early description of the URENCO plant at Capenhurst implies a range of 2.7 to 3.1 SWU per year per machine. See: "Capenhurst centrifuge plant inaugurated", *Nuclear News*, Vol. 20, No. 14, November 1977.

[15] With an enrichment of 4.8%, a VVER-1000 reactor would require 14.2 metric tons of uranium as replacement fuel each year. See: http://www.elemash.ru/en/production/Products/NFCP/VVER/1000/

[16] Assuming that an Iranian enrichment plant produces a somewhat lower enrichment than the 4.8% that we use in our analysis would not change our main conclusions regarding the unsafeguardability of Iran's centrifuge enrichment plant.

[17] In order to calculate the plant equilibrium time and inventory it is necessary to know the "stage holdup time" which is the time it takes material to flow through one stage. The French have given information on the equilibrium time of centrifuge enrichment plants which allowed us to calculate this quantity as being 180 sec. See: C. Frejacques, et al., "Evolution Des Procedes De Separation Des Isotopes De L'Uranium En France", IAEA-CN-36/257, *Nuclear Power and its Fuel Cycle*, Vol. 3, IAEA, Vienna, 1977.

[18] "Iran aims for 50,000 centrifuges in 5 years", Reuters, December 11, 2007.

In order to build a plant that produces weapons usable highly enriched uranium from natural uranium, a much larger number of enriching stages are required. Using 58 enriching stages (including the feed stage) will produce uranium with an enrichment of 93.1%. Using 6 stripping stages (excluding the feed stage) will produce tails with an enrichment of 0.287%. To produce one kilogram of highly enriched product at a plant with these characteristics will require 219 kilograms of natural uranium feed and 204 SWU. Using centrifuges producing 2.5 SWU per machine per year, and assuming that 20 kilograms of highly enriched uranium are required to produce a nuclear weapon, then about 1,630 centrifuges would be required to produce one weapon's worth of highly enriched uranium in a year.

If 4.8% uranium is used as feed instead of natural uranium and the tails enrichment remains 0.287%, then 20.6 kilograms of feed would be required to produce one kilogram of 93.1% enriched uranium. This would require 60.5 SWU. Since 204 SWU are required to produce one kilogram of 93.1% enriched uranium starting from natural uranium, this means that the 4.8% enriched uranium already has 70% of the SWU required to go from natural uranium to 93.1% enrichment.[19] This result can seem surprising since 4.8% is only a small fraction of 93.1% but it can be explained by considering the enrichment process. The SWU requirements are closely related to the flows of material through the enrichment plant. At low levels of enrichment, large flows are required since the desired isotope is very dilute.

Many analyses of the production of highly enriched uranium from low enriched uranium focus only on the SWU requirements. But it is important to remember that though the 4.8% enriched uranium contains 70% of the SWU required to go from natural uranium to 93.1% enriched uranium, the 4.8% enriched uranium has only passed through 15 of the 58 (26%) of the enriching stages required to go from natural uranium to 93.1% enriched uranium. Therefore producing 93.1% enriched uranium from 4.8% enriched uranium will still require a large number of enriching stages even if the SWU requirements are greatly reduced.

Iranian Options for Breakout from IAEA Safeguards

Clandestine Enrichment Plant

Iran could quickly produce highly enriched uranium for nuclear weapons by building a supplementary clandestine centrifuge enrichment plant. This clandestine enrichment plant would be designed to produce highly enriched uranium using a stockpile of 4.8% enriched material as feed. If Iran had accumulated enough 4.8% uranium, it could abrogate its IAEA safeguards and this now unsafeguarded material could be fed into the clandestine enrichment plant.

[19] That low enriched uranium contains a substantial fraction of the separative work needed to produce highly enriched uranium was first noted in: V. Gilinsky and W. Hoehn, *The Military Significance of Small Uranium Enrichment Facilities Fed with Low-Enrichment Uranium*, RM-6123-ARPA, RAND, Santa Monica, CA, December 1969.

It is highly unlikely that the IAEA could find a clandestine enrichment plant as long as the Additional Protocol to Iran's safeguard agreement has not been implemented. The IAEA's original safeguards tended to focus "mainly on nuclear material and activities declared by the State. However, the discovery of Iraq's clandestine nuclear weapons programme (despite an existing comprehensive safeguards agreement between Iraq and the IAEA), as well as subsequent events in the DPRK, demonstrated that an effective verification regime must also focus on possible undeclared material and activities."[20] In May 1997 the IAEA Board of Governors approved the Model Additional Protocol to Safeguards. As with all safeguards, the Additional Protocol is a voluntary agreement between the State and the IAEA. States that add the Additional Protocol to their safeguards agreement with the IAEA are required "to provide the Agency with an expanded declaration that contains information covering all aspects of their nuclear and nuclear fuel cycle activities. The States must also grant the Agency broader rights of access and enable it to use the most advanced technologies." The additional protocol requires a State to provide "access to any place on a nuclear site and to other locations where nuclear material is, or may be present."

Since 1998, 75 countries have had the Additional Protocol to their safeguards agreement with the IAEA enter into force.[21] Iran is not one of these countries. Up until 2003 Iran did not have the Additional Protocol as part of its IAEA safeguards agreement. However, in the aftermath of the revelation of its clandestine centrifuge enrichment program and Iran's voluntary halt to this program, Iran signed the Additional Protocol in December 2003. Normally there would be a lag from the time of the signing until the Additional Protocol formally entered into force as Iran would first have to ratify this Protocol. However, Iran indicated that the IAEA could start enforcing the Additional Protocol immediately even before it had formally entered into force. But Iran never did ratify the Additional Protocol. Instead in February 2006, just as Iran resumed work on its centrifuge enrichment program, Iran informed the IAEA that it could no longer enforce the Additional Protocol.[22] Consequently, while the IAEA can monitor the Iranian centrifuge facility at Natanz, it can not conduct activities to find any clandestine enrichment facilities nor can it monitor Iran's centrifuge manufacturing facility to see if it is manufacturing additional centrifuges beyond what can be accounted for by Iran's safeguarded enrichment program. Furthermore even if somehow the IAEA found a clandestine centrifuge enrichment plant, under the current safeguards in Iran, this would not be a violation of safeguards as long as fissile material had not been fed into the plant.

In order to produce 93.1% product from 4.8% feed, Iran's clandestine centrifuge enrichment plant would require 43 enriching stages. If it had 21 stripping stages (excluding the feed stage), then the tails enrichment would be 0.287%--the same as we assumed for the plant at Natanz. However, such a large number of stripping stages is not necessary. In table 2 we have calculated how the number of stripping stages affects the

[20] This and the other quotations in this paragraph are from: *Non-Proliferation of Nuclear Weapons & Nuclear Security: IAEA Safeguards Agreements and Additional Protocols*, IAEA, May 2005.
[21] As of November 23, 2007, see: "Strengthened Safeguards Systems: Status of Additional Protocols", http://www.iaea.org/OurWork/SV/Safeguards/sg_protocol.html
[22] IAEA, GOV/2006/15/, *op.cit.*

SWU and feed requirements for producing the 20 kilograms of 93.1% enriched uranium required to produce a nuclear weapon. The table clearly indicates why enrichment facilities have stripping sections since with zero stripping stages the amount of feed required is quite high. Similarly, using 21 stripping stages greatly increases the SWU requirements. An intermediate number of stripping stages is clearly preferable since it balances both the feed and the SWU requirements. For our analysis we will assume that the clandestine Iranian enrichment plant uses five stripping stages and therefore has a tails enrichment of 2.26%. This clandestine enrichment plant would have an equilibrium time of about one day.

Table 2

SWU and Feed Required to Produce 20 kg of 93.1% Enriched Uranium From 4.8% Enriched Feed as a Function of the Number of Stripping Stages

Number of stripping Stages*	Tails Enrichment (%)	Feed (kg) per 20 kg of HEU	SWU per 20 kg of HEU
21	0.287	412	1,210
6	1.99	648	645
5	2.26	695	614
4	2.56	788	584
3	2.91	934	554
0	4.24	3,150	471

*Excluding the feed stage.

With the information from table 2, it is easy to calculate the time required to produce 20 kilograms of 93.1% enriched uranium as a function of the number of centrifuges in the clandestine enrichment plant. The results are shown in table 3. Assuming that the clandestine enrichment plant uses the P-1 type of centrifuge that is used at Natanz with an output of 2.5 SWU per machine per year, then if 3,000 machines were used in the clandestine enrichment plant, it would take just about one month to produce the 20 kilograms of highly enriched uranium required for a nuclear weapon. As indicated in table 2, this would require just under 700 kilograms of 4.8% enriched uranium feed. As was stated earlier, Iran currently only has a stockpile of about 50 kilograms of 3.8% enriched uranium. Additionally, Iran currently has only 3,000 centrifuges at Natanz. Thus, it unlikely that Iran has already been able to divert a similar number of centrifuges to build a clandestine enrichment plant. For these reasons, Iran is probably not currently capable of producing a weapon's worth of highly enriched uranium, under this scenario.

But when Iran is producing tens of thousands of centrifuges, such a diversion could be quite possible. Indeed, at such a time diverting even 6,000 centrifuges would be quite possible which would reduce the time required to produce 20 kilograms of highly enriched uranium to just sixteen days. (The amount of 4.8% enriched uranium required as feed would still be about 700 kilograms). These times are quite short and would be hard to counteract (or perhaps even discover) before a nuclear weapon's worth of highly enriched uranium were produced. If Iran keeps to its current plans, then its production of tens of thousands of centrifuges would be reached sometime during the period of 2010 to 2012. In this timeframe, it will also be likely that Iran would have a stockpile of low enriched uranium of at least the required 700 kilograms.

Table 3

Time Required to Produce 20 kg of 93.1% Enriched Uranium From 4.8% Enriched Feed as a Function of the Number of Centrifuges in a Clandestine Enrichment Plant*

Centrifuge Type	Number of Centrifuges	Time to Produce 20 kg of HEU** (Days)
P-1	3,000	31
P-1	6,000	16
P-2	3,000	16

*Tails enrichment 2.26%
**Includes one day to account for equilibrium time.

Though Iran is currently using P-1 type centrifuges at Natanz, it has also received information from Pakistan for an improved centrifuge known as the P-2.[23] The P-2 centrifuges are believed to have an output of 5 SWU per machine per year which is twice the output of the P-1 centrifuge.[24] In the future Iran could begin large-scale production of the P-2.[25] If Iran were to use the P-2 in a clandestine enrichment plant then just 3,000 P-2 centrifuges would be enough to produce a weapon's worth of highly enriched uranium in only sixteen days. (Again, 700 kilograms of 4.8% of enriched uranium feed would be required).

It should be noted that for all of these calculations, these times are only the time required for the first weapon's worth of highly enriched uranium. Additional weapons' worth of highly enriched uranium could be produced at successive time intervals. As noted above, Iran could in the future claim to have a legitimate reason to stockpile at least 15,000 kilograms of 4.8% enriched uranium feed. This amount of uranium feed is large enough to produce twenty or more weapons' worth of highly enriched uranium given enough time.

Iran may also acquire highly enriched uranium if it were to construct a clandestine enrichment plant designed to produce highly enriched uranium from natural uranium

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[23] IAEA, GOV/2007/58, *op.cit.*
[24] "Pakistan developed more powerful centrifuges", http://www.platts.com/Nuclear/highlights/2007/nucp_nf_012907.xml
[25] Recently, Iran has begun testing ten P-2 centrifuges with uranium hexafluoride. See: George Jahn, "Deplomats: Iran Processes Uranium Gas", February 13, 2008. http://www.washingtonpost.com/wp-dyn/content/article/2008/02/13/AR2008021302303_pf..html

feed. We described such a plant in a prior section, and found that if the product were 93.1% enriched and the tails 0.287% enriched then the production of 20 kilograms of product would require 4,080 SWU. Since this is about 6.6 times as much as the 614 SWU required to produce 20 kilograms of enriched uranium from 4.8% feed, the time required to produce the material will be 6.6 times as large as the numbers in table 3 for the same number of centrifuges. This would total approximately 100 to 200 days per weapon's worth of highly enriched uranium. Though this is a long time, this method has the advantage of not requiring Iran to overtly break safeguards since Iran's uranium mining operations are not under safeguards. It would require Iran to construct a clandestine uranium hexafluoride production facility but there is no reason to think this would be a problem. Though it would take years for Iran to produce a number of weapons' worth of highly enriched uranium using this sort of clandestine enrichment plant, the IAEA is not likely to be able to find this plant, nor detect the diversion of natural uranium, absent the Additional Protocol. Thus, Iran could produce a large stockpile of highly enriched uranium without an overt confrontation with the IAEA and the West.

Batch Recycling in Natanz Centrifuge Enrichment Plant

Including the Additional Protocol in Iran's safeguards with the IAEA would help to prevent the scenarios in the previous section in which Iran relied on a clandestine enrichment plant, but Iran has another option for producing highly enriched uranium for which even the Additional Protocol would not help to prevent. In this option, Iran would produce highly enriched uranium by taking a stockpile of 4.8% enriched uranium and using this material as feed to the Natanz enrichment plant. As was discussed earlier, we assume that this plant is designed to produce 4.8% enriched product from natural uranium feed with a tails enrichment of 0.287%. Since a plant designed to produce 4.8% enriched uranium from natural uranium feed has only 26% of the enriching stages required to enrich natural uranium to highly enriched uranium, the enriched uranium would have to be passed through the plant three additional times. Each pass would be in a batch mode, where the cycle produced the feed required for the next cycle. This feed would include not only the uranium required to produce the product but also the plant inventory required to fill the plant for the next cycle. Operating the plant in this fashion raises criticality concerns, especially for the last cycle. Criticality safe product withdrawal cylinders would have to be used but due to the small inventory of uranium in a centrifuge enrichment plant, only minor adjustments would have to be made to the operation of the plant itself. [26]

The current centrifuge enrichment plant at Natanz has about 3,000 centrifuges of the P-1 type. At 2.5 SWU per machine per year, the plant's output is 7,500 SWU per year. The plant inventory is about five kilograms of uranium. The feed, product and time required for each cycle is shown in table 4, where the objective it to produce 20 kilograms of

[26] "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.

highly enriched uranium. As can be seen from the table, the first pass has a product with an enrichment of 26.2%, the second a product with an enrichment of 71.4% and the third a product with an enrichment of 94.6%. These enrichments are determined by the 4.8% enrichment of the feed and the number of enriching stages in the plant.

Since the plant at Natanz is designed to produce 4.8% product from natural uranium, its cascade 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. For example, as was indicated above, the current 3,000 centrifuge plant at Natanz can produce 1,070 kilograms of product a year which is 2.93 kilograms of product per day. The third cycle in table 4 produces 20 kilograms so the amount of time required for the third cycle is 20/2.93 which equals 6.83 days (which we rounded to 7 days in the table). In addition, one must account for the equilibrium time of about four hours for each cycle and the cascade drain and fill time of about twelve hours for each cycle. For all three cycles, this adds about two full days. Therefore, the production of 20 kilograms of highly enriched uranium requires a total of about 95 days. This is a fairly long interval, which indicates that currently this method for production of highly enriched uranium may not be that attractive to Iran. Furthermore, as indicated in table 4, Iran would need to start this process using 1,780 kilograms of 4.8% uranium feed. However, as was stated before, Iran currently only has a stockpile of about 50 kilograms of 3.8% enriched uranium—far less than is required. At a production rate of 1,070 kilograms of 4.8% enriched uranium per year, it would take over a year and a half for the current plant at Natanz to produce the required 1,780 kilograms.

Table 4

Time, Product and Feed Requirements for the Production of 20 kg of HEU by Batch Recycling in a 7,500 SWU/yr Plant Designed to Produce LEU

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	26.2% 206 kg	4.8% 1,780 kg	70
Second	71.4% 47 kg	26.2% 201 kg	16
Third	94.6% 20 kg	71.4% 42 kg	7
Total			95*

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

As was indicated above, Iran plans to expand its centrifuge enrichment plant at Natanz to include 50,000 centrifuges by 2012. If these are all P-1 type centrifuges, then the plant would be able to produce 125,000 SWU per year.[27] The time, product and feed requirements for such a plant to produce 20 kg of highly enriched uranium by batch recycling is shown in table 5. Since this expanded plant has the same number of enriching stages as the current Natanz plant, the enrichment in each cycle is the same. However, the starting feed and total time required are significantly different. The flow through the plant is much higher than for the current plant, which results in the much shorter production time of only 17 days. The plant inventory is much higher, being around 75 kilograms of uranium. This causes the amount of 4.8% feed required to increase to 5,000 kilograms, compared to the 1,780 kilograms for the current 7,500 SWU per year plant. That it would take Iran only seventeen days to use this method to produce a weapon's worth of highly enriched uranium is an indication that a centrifuge enrichment plant with this capacity is essentially unsafeguardable. The 5,000 kilograms of 4.8% enriched feed required is smaller than the 15,000 kilograms or more that Iran might legitimately stockpile as fuel for its Bushehr power reactor and would represent only about three months production of the 125,000 SWU/yr plant. Note that the Additional Protocol would have no effect on this case, since both the enrichment plant at Natanz and the 4.8% feed would be permitted.

Table 5

Time, Product and Feed Requirements for the Production of 20 kg of HEU by Batch Recycling in a 125,000 SWU/yr Plant Designed to Produce LEU

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	26.2% 578 kg	4.8% 5,000 kg	11.8
Second	71.4% 117 kg	26.2% 503 kg	2.4
Third	94.6% 20 kg	71.4% 42 kg	0.4
Total			17*

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

Given the small amount of time required to produce twenty kilograms of highly enriched uranium with a 125,000 SWU per year centrifuge enrichment plant, we also calculated the time, product and feed required to produce one hundred kilograms of highly enriched uranium (five weapons' worth) in such an enrichment plant. The results are shown in table 6. Though the amount of product is five times that of the previous case, the time

[27] In this section we assume that all of the centrifuges at Natanz are of the P-1 type with a capacity of 2.5 SWU per machine per year. If some of them are P-2 type then the times given in this section would be reduced.

and feed required are only increased by little more than a factor of two. This is a result of having the same plant inventory for both cases so that once a cycle has produced the inventory for the next cycle, the enrichment plant can run to generate as much product as is required for each cycle. This case requires over eleven metric tons of 4.8% enriched feed, but this is still less than the 15 or more metric tons that Iran might legitimately stockpile. The 36 days required to produce five weapons' worth of highly enriched uranium is still too short a time for safeguards were to be effective.

Table 6

Time, Product and Feed Requirements for the Production of 100 kg of HEU by Batch Recycling in a 125,000 SWU/yr Plant Designed to Produce LEU

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	26.2% 1,300 kg	4.8% 11,200 kg	26
Second	71.4% 284 kg	26.2% 1220 kg	6
Third	94.6% 100 kg	71.4% 209 kg	2
Total			36*

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

Currently, the time required to produce 20 kilograms of highly enriched uranium using batch recycling in the 3,000 centrifuge plant at Natanz is fairly long (95 days). But how will this time decline as Iran expands the enrichment plant at Natanz even before it reaches its 50,000 centrifuge goal in 2012? To examine this question we calculated the time, product and feed requirements to produce 20 kilograms of highly enriched uranium using a 10,000 centrifuge (25,000 SWU per year) plant and a 20,000 centrifuge (50,000 SWU per year) plant. The results are shown in tables 7 and 8 respectively. Even for the 10,000 centrifuge case, the time required to produce a weapon's worth of highly enriched uranium is only 37 days and the amount of 4.8% enriched uranium feed is 2,250 kilograms. For a 20,000 centrifuge plant, the time is only 24 days and the feed required is 2,940 kilograms. Clearly Iran will not have to wait until it has the full 50,000 centrifuge plant before it will have the option to produce a weapon's worth of highly enriched uranium by batch recycling.

Given Iran's goal of having 50,000 centrifuges in 2012, it does not seem unreasonable to assume that it will have 10,000 centrifuges and will have also acquired the necessary stockpile of 4.8% enriched uranium by 2010. The effectiveness of safeguards even for plants with 10,000 or 20,000 centrifuges must therefore be considered highly doubtful. This is particularly so for the 20,000 centrifuge plant since the 24 days required for the production of a weapon's worth of highly enriched uranium could be performed between the IAEA's monthly inspections. As a result, the IAEA might well find out about the production of the highly enriched uranium only after it had occurred.

Iran's use of batch recycling at the enrichment plant at Natanz would enable it to produce one or more weapons' worth of highly enriched uranium in a month or even a few weeks sometime in the 2010 to 2012 timeframe. This is the same timeframe of concern for the scenarios in the prior section related to a clandestine enrichment plant. This congruence is no accident and just illustrates that once Iran has tens of thousands of centrifuges and a sufficient stock of low enriched uranium, it will have a number of options to quickly produce highly enriched uranium.

Table 7

Time, Product and Feed Requirements for the Production of 20 kg of HEU by Batch Recycling in a 25,000 SWU/yr Plant Designed to Produce LEU

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 8

Time, Product and Feed Requirements for the Production of 20 kg of HEU by Batch Recycling in a 50,000 SWU/yr Plant Designed to Produce LEU

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	26.2% 340 kg	4.8% 2,940 kg	17
Second	71.4% 72 kg	26.2% 310 kg	4
Third	94.6% 20 kg	71.4% 42 kg	1
Total			24*

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

Though our estimate of 2.5 SWU per machine per year is a reasonable one, how would these times change if we were to assume a less capable Iranian centrifuge? Assume only 1.0 SWU per machine per year (an extremely low estimate). Then the 50,000 centrifuge plant at Natanz would produce 50,000 SWU per year. For such a plant our calculations in table 8 would apply. Comparing these results with table 5, one can see that changing the assumption about the output of Iran's centrifuges from 2.5 SWU per machine per year to 1.0 SWU per machine per year only increases the time required to produce twenty kilograms of 94.6% enriched uranium from 17 to 24 days and actually reduces the amount of feed required from 5,000 kilograms to 2,250 kilograms. Changing our assumption about Iranian centrifuge SWU output will not change our basic conclusion that safeguarding Iran's centrifuge enrichment facility at Natanz once it has been significantly expanded will be very difficult.

Another Iranian Option for HEU Production

Another option other than using batch recycling to produce highly enriched uranium in the centrifuge enrichment plant at Natanz, would be to reconfigure the cascade by changing the piping.[28] Centrifuge enrichment plants utilize many parallel cascades to produce the desired output. By changing the plant flow, the cascades could be configured to produce highly enriched uranium by operating in series. Such a reconfigured plant could operate as if it had been designed from the beginning to produce highly enriched uranium. In the long run this would be a better option than batch recycling since it would allow continuous operation of the plant and fully utilize the SWU output of the plant. Fully reconfigured, a 125,000 SWU per year plant could produce 613 kilograms of 93.1% enriched uranium per year from natural uranium feed or 339 kilograms of 93.1% enriched uranium per month from 4.8% enriched uranium feed.[29] Such a reconfiguration of the plant would be detected by IAEA safeguards. However, the time available for safeguards to detect these violations is unclear since we can not calculate how long reconfiguring the plant would take without detailed knowledge of the current configuration of the plant at Natanz. We would also need extensive knowledge of the engineering of centrifuge enrichment plants.

Note that using batch recycling or reconfiguring the cascade are not necessarily mutually exclusive. Iran could quickly produce a small number of weapons' worth of highly enriched uranium by using batch recycling. Then, with the threat of this small arsenal of nuclear weapons to hold Western counteraction at bay, Iran could reconfigure the cascade for the production of highly enriched uranium on a more sustained basis.

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[28] Martin Marietta Energy Systems, K/ITP--156/P4/R1, *op.cit.*

[29] The tails enrichment for the natural uranium feed case is 0.287% and for the 4.8% enriched uranium feed case is 2.26%. For this latter case we give the highly enriched uranium output on a monthly rather than yearly basis because Iran is unlikely to have stockpiled the over 130 metric tons of 4.8% enriched feed which would be required for a year's operation.

Conclusions

"Our analysis of enrichment technologies so far has focused on the current or near-term state of the art. It shows that the transfers of some current technologies, and in particular the centrifuge, need to be restricted if highly enriched uranium for bombs is not to become easily accessible to many nonweapon states."[30] My colleagues Albert and Roberta Wohlstetter and I wrote those words nearly thirty years ago. Unfortunately we now have a vivid illustration of the consequences of ignoring this recommendation. Though it may not have a formal nuclear weapons program, Iran's developing centrifuge enrichment program is inexorably improving its capability to quickly produce highly enriched uranium, which is a key component of a nuclear weapons program.

Iran has a stockpile of low enriched uranium, facilities to manufacture centrifuges and a centrifuge enrichment facility with a significant capacity to produce low enriched uranium. These three components can be combined in various ways to produce highly enriched uranium. Currently the amounts and capacities of these components are small enough so that it would take Iran some time (six months or more) to produce the twenty kilograms of highly enriched uranium needed for a nuclear weapon. IAEA safeguards would likely detect this Iranian effort well before its completion and Iran would run the risk of Western counteraction.

However, this situation is changing rapidly as Iran expands its centrifuge enrichment effort. If Iran maintains its planned expansion, then by 2010-2012, Iran will be able to produce a weapon's worth of highly enriched uranium in just a month or even a few weeks. The West will be unable to counter such a rapid effort. Indeed, in some circumstances, the IAEA will only detect the effort after the fact. Under these conditions, the Iranian enrichment program must be considered unsafeguardable. Furthermore this dire situation will exist even if the Additional Protocol to Iran's safeguard agreement is brought into force since Iran could still produce highly enriched uranium by batch recycling in its current enrichment plant at Natanz. Unless action is taken soon to bring Iran into compliance with UN Security Council resolutions 1737, 1747and 1803, 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. Future NIEs on Iran's nuclear program need to reflect this serious reality.

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[30] Albert Wohlstetter, Gregory Jones, Roberta Wohlstetter, "Why the Rules Have Needed Changing", *Towards a New Consensus on Nuclear Technology*, Volume I, PH-78-04-832-33, Pan Heuristics, Prepared for U.S. Arms Control and Disarmament Agency, July 6, 1979.

Appendix

Basics of Uranium Isotope Separation

The purpose of this appendix is to provide a general overview of various concepts related to uranium isotope separation so as to make the text more understandable. For those who desire additional information, there are a number of more detailed sources.[31]

The majority of elements consist of two or more isotopes. These are atoms that have the same number of protons but differing numbers of neutrons. The different isotopes of an element all have approximately the same chemical properties but can have quite different nuclear properties. Natural uranium has two principal isotopes, U-235 and U-238. The isotope U-235 is the one that is desirable for processes involving nuclear fission reactions, including nuclear fuel and nuclear explosives. However, U-235 is only about 0.7% of natural uranium (usually taken to be 0.711 weight percent) with the rest being 99.3% U-238. For most purposes the percentage of U-235 must be increased (enriched). When uranium is referred to as being x% enriched the x always refers to the fraction of U-235.

In any centrifuge enrichment plant, uranium of a certain enrichment is fed into the plant and two streams are withdrawn from the plant. The product stream consists of uranium with a higher enrichment than the feed and the tails stream consists of uranium with a lower enrichment than the feed. For example, to produce one kilogram of 4.8% enriched product requires 6.98 kilograms of natural uranium feed and also produces 5.98 kilogram of tails if the tails enrichment is 0.287%. (Conservation of mass requires that the sum of the product and tails always equals the feed).

The smallest unit of an isotope separation plant that effects some separation of the process material is called a separating unit which in the case of Iran's enrichment effort is a centrifuge. The chemical form of the uranium fed to a centrifuge must have the physical characteristic of being gaseous at near room temperatures. The only uranium compound that has this property is uranium hexafluoride. The centrifuge separates an incoming feed stream of uranium hexafluoride into two outgoing streams: a product stream in which the uranium is enriched in U-235 compared to the feed and a tails stream which is somewhat depleted in U-235 compared to the feed. Since the flow through a single centrifuge is rather low, an enrichment plant consists of a number of centrifuges operating in parallel each being fed with feed with the same enrichment and producing product and tails with the same enrichment. This group of parallel-connected centrifuges is known as a stage. Since the degree of enrichment produced by a single stage is generally less than is desired for the product, an enrichment plant is composed of a

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[31] Manson Benedict, Thomas H. Pigford and Hans Wolfgang Levi, *Nuclear Chemical Engineering,* 2nd Edition, McGraw-Hill Book Company, New York, 1981; Stelio Villani, *Isotope Separation*, American Nuclear Society, 1976; Allan S. Krass, et al., *Uranium Enrichment and Nuclear Weapon Proliferation*, Stockholm International Peace Research Institute, Taylor & Francis Ltd, London 1983; and Karl Cohen, *The Theory of Isotope Separation as Applied to the Large-Scale Production of U-235*, McGraw-Hill Book Company, Inc. New York, 1951.

number of stages connected in series. Such a series-connected group of stages is known as a cascade.

The portion of the cascade between the feed point and the product end is known as the enriching section. Since uranium has significant economic value, stages are used to reduce the enrichment of the tails produced by the enrichment plant. These stages are known as the stripping section and are located between the feed point and the tails end. As was shown in table 2 in the text, the use of a stripping section allows the amount of feed required to be significantly reduced.

Let us call the enrichment of the feed, product and tails to a particular centrifuge N, N' and N" respectively. Let R = N/(1-N). Then R'/R" is the elementary separation factor for the enrichment process which as was stated in the text, we assume to be about 1.3 for Iran's centrifuges. The capacity of a separation element and an enrichment plant are measured in separative work units (SWU). There is no simple explanation of what a SWU is but it is related to the elementary separation factor and the flow rate of uranium through the cascade.

When a cascade is operating at equilibrium, there is a steady increase in the uranium enrichment from the feed stage, through the enriching section, to the product stage. However, when the plant first starts operation, the plant is filled entirely with uranium having the enrichment of the feed. The plant must operate for a while to create the internal enrichment gradient in the plant so that the product with desired enrichment can be produced. This time is the equilibrium time, which for many enrichment processes can be quite long but as was discussed in the text is short for a centrifuge enrichment plant.