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Recalibrating Tehran's Nuclear Breakout Capability:

A Response to ISIS's Critique of NPEC Calculations Regarding the Time Required for Iran to Produce a Weapon's Worth of HEU

Since 2008 I have written fifteen papers on Iran's centrifuge enrichment program describing how Iran is moving ever closer to a nuclear weapons capability. Recently, several analysts who claim Iran could not possibly acquire sufficient weapons-grade uranium to make its first bomb in less than 6 to 24 months, have taken strong exception to my analysis. My calculations indicate that if Tehran chose to, it could acquire this material in as little as 2 months using its declared enrichment plant at Natanz.[2] I have already reviewed analyses done by the International Institute of International Studies (IISS), which claimed Iran is at least two years from getting the material it needs for its first bomb.[3] For several reasons, I believe IISS's conclusions are unsound.

The Institute for Science and International Security (ISIS) and its President, David Albright, recently published a critique of my calculations.[4] Mr. Albright maintains that Iran could not acquire enough weapons uranium in just 2 months and argues instead that Iran needs at least 6 months. For most observers, 2 months versus 6 months may seem a bit of quibble – six months, after all, is still pretty close in. But diplomatically six months is an eternity (all things, including more negotiations, would still be possible); whereas 2 months is less than an instant. In an article that I wrote last month for *The New Republic*, I drove this point home by noting that an Iranian nuclear diversion that took just 2 months might not be caught right away by international nuclear inspectors and could well present the West with a diplomatic fait accompli. For this reason, Iran is already a virtual nuclear power.[5]

Mr. Albright, who only a year ago was making nuclear forecasts regarding Iran similar to my current forecasts, seems to have become uncomfortable with his own prior conclusions. His

[1] The author has multiple affiliations. This paper was produced for the Nonproliferation Policy Education Center. 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 RAND bears no responsibility for any of the analysis and views expressed in it.
[2] Gregory S. Jones, "An In-Depth Examination of Iran's Centrifuge Enrichment Program and Its Efforts to Acquire Nuclear Weapons", August 9, 2011, http://npolicy.org/article.php?aid=1092&rt=&key=Greg%20Jones&sec=article
[3] Gregory S. Jones, "Critique of IISS Estimates of the Time Required for Iran to Produce the HEU Metal Core Required for a Nuclear Weapon, Addendum: Time Required to Produce the Non-Nuclear Components Needed For a Nuclear Weapon," March 3, 2011, Revised April 6, 2011.
http://www.npolicy.org/article_file/Critique_of_IISS_Estimates_with_Addendum.pdf
[4] David Albright, Paul Brannan and Christa Walrond, "Critique of Gregory Jones's Breakout Estimates at the Natanz Fuel Enrichment Plant (FEP), September 20, 2011. Note that in their paper, my paper is incorrectly cited as having been published in September rather than in August.
[5] Greg 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

direct attack on my calculations seems to be one result of his change of course. Certainly, no one knows when Iran will decide to become an overt nuclear weapons power and it is unlikely that Iran will take this step anytime soon. However, just how much time we might have to head Iran off if they suddenly chose to acquire nuclear weapons is a matter of great significance. It is therefore is useful to take a look at Mr Albright's analysis as well as my own.

NPEC's Analysis, ISIS's Critique

A key element in many of my papers has been the calculation of the time required for Iran to produce a nuclear weapon's worth of Highly Enriched Uranium (HEU, 20 kilograms) should Iran decide to quickly do so. Iran could produce this HEU using a method known as batch recycling. These calculations are based on detailed information from inspections performed by the International Atomic Energy Agency (IAEA) regarding Iran's growing centrifuge enrichment capacity and its growing stockpiles of 3.5% and 19.7% enriched uranium. The IAEA publishes this information quarterly.[6] In 2008, I estimated that it might take Iran two to four years to produce the HEU needed for a nuclear weapon but by June 2011, this time had shrunk to only two months.[7] Further it appears that by the later part of 2012, this time may shrink to only two weeks.

My two month estimate was reproduced in a more comprehensive paper I published on August 9, 2011, covering many aspects of Iran's nuclear program (the relevant section of this paper is reproduced as appendix 1).[8] On September 20, 2011, David Albright and others (hereafter referred to as Albright *et al.*) from ISIS published a critique critical of the batch recycling calculations contained in this paper.[9] Albright *et al.* say that my calculations are "unreliable" and that I "greatly understate" the amount of time that it would take Iran to produce the HEU required for a nuclear weapon. They say: "…ISIS found on balance no justification to change its earlier breakout estimate of six months at the FEP."

Albright *et al.*'s paper is entirely qualitative. They present no calculations regarding how Iran might produce HEU. They say that they enlisted "the assistance of an experienced centrifuge expert who has performed many detailed centrifuge calculations of the Iranian program" but they present none of the calculations performed by this anonymous expert. For their own six month estimate, they again present no calculations and do not provide even a reference or link to where this "earlier" estimate might be found.

In this paper I will show that their criticisms involve factors that would produce only minor corrections to my calculations or are entirely irrelevant to them. Albright *et al.*'s criticisms are related to three areas: (1) problems with centrifuge operations at the Iran's Fuel Enrichment Plant

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6 The most recent IAEA report is: "*Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran*", GOV/2011/54, September 2, 2011.

7 Gregory S. Jones, "Out of the Spotlight Iran's Rate of Enriched Uranium Production Continues to Increase: Centrifuge Enrichment and the IAEA May 24, 2011 Update," June 2, 2011, http://npolicy.org/article.php?aid=1043

8 Gregory S. Jones, "An In-Depth Examination of Iran's Centrifuge Enrichment Program and Its Efforts to Acquire Nuclear Weapons", August 9, 2011, http://npolicy.org/article.php?aid=1092&rt=&key=Greg%20Jones&sec=article

9 David Albright, Paul Brannan and Christa Walrond, "Critique of Gregory Jones's Breakout Estimates at the Natanz Fuel Enrichment Plant (FEP), September 20, 2011.

(FEP, see appendix 1), (2) concerns that calculations by Alexander Glaser that form a key element of my calculations are invalid, and (3) concerns that historically when Iran has started its centrifuge enrichment facilities, they have required much more uranium feed than my calculations would predict. I will examine each of these issues in turn. Then I will review some of Albright's past predictions as to how long it would take Iran to produce HEU and how Albright might have calculated them. Finally I will show that Iran's growing stockpile of 19.7% enriched uranium opens up additional ways for Iran to quickly produce the HEU for a nuclear weapon. For ease of reference, I first summarize my conclusions.

Summary of Conclusions

The qualitative nature of Albright *et al.*'s critique of my batch recycling calculations masks the fact that their criticisms would either produce only minor changes to my calculations or in some cases are entirely irrelevant to them. The net result is that my calculations are essentially unchanged and my estimate that Iran could produce a weapon's worth of HEU by batch recycling at the FEP in two months remains the same. Significantly, certain of Albright *et al.* criticisms are based on assertions that contradict Albright's own previously published papers.

Albright *et al.* incorrectly claim that I assume "that all cascades would work flawlessly during the period of breakout…" In fact, I simply assume that Iran will be able to operate their centrifuge enrichment plant as it has in the past, producing the same separative capacity. Since my calculations depend *only* on the output of Iran's enrichment plant and not with the manner in which this output is produced, all of Albright *et al.*'s comments concerning how the plant might be designed or how efficient individual components might be are irrelevant. Note that Albright *et al.*'s concerns about problems at the FEP are a change from what Albright was saying just last year: "Iran is unlikely to face significant delays in making weapon-grade uranium at Natanz [the FEP] if it decides to build nuclear weapons."[10]

My calculations on how Iran could enrich 19.7% uranium to 90% enriched uranium in one step by batch recycling are an adaptation of calculations by Glaser published in 2008 in a peer-reviewed scientific journal.[11] Albright *et al.* say that "a former IAEA official" believes that "going from 20 percent to 90 percent in one step may not be possible." However, it is not clear that this former IAEA official has done any calculations on this matter and Albright *et al.* present none. In addition, Albright *et al.* claim that I have not taken into account the differences between Glaser's published calculations and my own but in fact these differences are irrelevant to my calculations. Albright *et al.* also point out that the reduction in cascade feed rate that is required to go from 19.7% to 90% enriched uranium in one step would lead to the loss of some separative capacity. Albright *et al.* claim this loss "would be expected to be great" but Glaser has calculated this loss as being only 3%. Furthermore, Iran's current production of 19.7% enriched uranium exceeds what one would calculate using a simple separative work model, a fact that provides a strong indication that Glaser's calculations are correct. Note that just last year Albright himself saw no problem for Iran to carry out this enrichment step saying: "…further

[10] David Albright and Christina Walrond, "Supplement to *Iran's Centrifuge Program:* Taking Stock," Institute for Science and International Security, March 3, 2010, p.1.
[11] Alexander Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation", *Science and Global Security*, Vol. 16, 2008.

enriching from 20 percent enriched uranium to 90 percent material is quick and involves relatively few centrifuges…”[12]

Albright *et al.* claim that when Iran began to produce enriched uranium at the FEP and the PFEP, Iran had to use “much more feed than expected.” The figure that they present to support this contention at the PFEP is seriously flawed since not only is a key data point incorrect but also it combines data from periods when the PFEP was operating with two different tails assays. Using data from the original IAEA safeguards reports, I calculated that Iran’s experience at the PFEP might lead to an increase in the feed required to produce the HEU for a nuclear weapon that would amount to an insignificant 3.2%. Further even Albright *et al.* admit that they do not know whether any increase in the feed required will actually occur should Iran perform batch recycling at the FEP.

In their critique of my paper, Albright *et al.* have said, “…ISIS found on balance no justification to change its earlier breakout estimate of six months at the FEP.” They provide no reference or link for this six-month estimate. After extensively reviewing Albright’s prior writings, I have concluded that no such estimate has been published that applies to Iran’s current situation where it has stockpiles of 2,690 kilograms of 3.5% enriched uranium plus 48 kilograms of 19.7% enriched uranium and the FEP has a separative capacity of 4,300-4,600 SWU per year.

In June 2011 Albright published an estimate that Iran could produce the HEU for a nuclear weapon in six months, based on a hypothetical in which Iran would have a large stockpile of 19.7% enriched uranium and also be able to deploy large numbers of advanced centrifuges.[13] Key to Albright’s calculation is his assumption that Iran would build six cascades to enrich between 20% enriched uranium and 90% using a total of 584 advanced centrifuges and that these cascades would be highly inefficient. Albright provides no explanation for this high inefficiency and his assumption is all the more puzzling since Glaser performed calculations that found this design to be highly efficient.[14] Whatever the problem might be, Iran could easily avoid it by arranging the 584 advanced centrifuges into one or more efficient cascades. Indeed in 2009 Albright was critical of an analysis by Kemp and Glaser for not considering “…a configuration that would produce weapon-grade uranium efficiently.”[15] With efficient cascades, and using other assumptions that Albright has used in his prior publications, Albright’s estimate would fall to between two and three months.

The closest previously published estimate by Albright that would seem to apply to Iran’s current situation was in March 2010.[16] Albright’s estimate related to a case where Iran would use the FEP (which at the time had a separative capacity of 3,400 SWU per year) to produce HEU from

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[12] David Albright, Paul Brannan, and Jacqueline Shire, “Taking Stock of the Production of 19.75 percent uranium at the PFEP,” Institute for Science and International Security, June 11, 2010, p.3.
[13] David Albright, Paul Brannan, and Andrea Stricker, *Iran in Brief*, “Moving 20 Percent Enrichment to Fordow: Slow Motion Breakout Continues?”, Institute for Science and International Security, June 8, 2011.
[14] Alexander Glaser, “Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation”, *Science and Global Security*, Vol. 16, 2008, pp.17-19.
[15] David Albright, Paul Brannan and Jacqueline Shire, “Nuclear Weapon Breakout Scenarios: Correcting the Record,” Institute for Science and International Security, March 18, 2009, p.1.
[16] David Albright and Christina Walrond, “Supplement to *Iran’s Gas Centrifuge Program: Taking Stock*,” Institute for Science and International Security, March 3, 2010.

3.5% enriched uranium. Albright assumes what he calls “a worst-case scenario” where Iran could quickly modify the FEP to function as an ideal cascade enriching 3.5% to 90%. He said that Iran “could currently produce enough weapon-grade uranium for a weapon in six months or less,” which elsewhere in this paper he characterizes as “several months.” Using the actual HEU production rate he calculated, the estimate would have been 1.5 to 3.5 months. Albright apparently used separative work calculations to produce these estimates even though Albright *et al.* now say “separative work calculations are not accurate estimates of the actual situation at the FEP.”

However, Albright’s has performed his separative work calculations incorrectly and his calculated HEU production rates are in error. Using the proper HEU production rate changes his estimate to two to five months. Note that my June 2011 estimate of two months is fairly comparable to Albright’s worst-case estimate of two to five months and certainly comparable to his incorrectly calculated 1.5 to 3.5 month estimate.[17] Indeed since the separative capacity at the FEP is now 4,300-4,600 SWU per year and Iran now has a sizable stockpile of 19.7% enriched uranium, one would think that if Albright were to update his March 2010 estimate it would be even shorter, making it even more comparable to my two month estimate. None of this is consistent with Albright *et al.*’s current critique of my 2 month calculation which is termed “unreliable…even as a worst case.”

Also it is not clear how Albright *et al.*’s current six-month estimate is related to these past estimates, particularly since they say that for their current estimate they use “…a ‘fixed plant’ production model, which means that the existing cascades are not reconfigured…” Is their current six-month estimate also a “worst-case?” Since Albright *et al.* provide no reference or link to what they say is their “earlier breakout estimate of six months at the FEP,” there is no way to clarify their statements until they are more explicit.

As can be seen from my Table 2 (appendix 1), using batch recycling at the FEP Iran would produce HEU by a two-step process. The 3.5% uranium is enriched to 19.7% uranium and this uranium is then enriched to 90.0% uranium. The first step requires 79% of the total two month period. Iran has already been carrying out this first step and as of August 2011, it had produced 48 kilograms of 19.7% enriched uranium. In addition, Iran is taking concrete steps to triple its production of 19.7% enriched uranium. Further, the method for producing 19.7% enriched uranium at the Pilot Fuel Enrichment Plant (PFEP, see appendix 1) between February and July 2010 was identical to what would be used for batch recycling to produce 19.7% enriched uranium at the FEP, providing a clear demonstration of the feasibility of the process. Indeed Albright *et al.* have had to concede that this is true. Given that the second step, enriching from 19.7% to 90.0% is a small part of the total effort needed to produce HEU, Iran has various options to perform this final production step.

As I have previously published (see appendix 1, Table 2), once Iran has a large enough stockpile of 19.7% enriched uranium, it can skip the first batch recycling step and just use the second batch recycling step at the FEP to produce the HEU for a nuclear weapon in just two weeks. This process, though fast, uses the 19.7% enriched uranium relatively inefficiently. As a result

[17] Note, however, my calculations are intended to be “best-estimate” rather than “worst-case.”

Iran would require a stockpile of 158 kilograms of 19.7% enriched uranium and Iran will probably not have a stockpile this large until the latter part of 2012.

Iran could also use a relatively small clandestine enrichment plant to convert its growing stockpile of 19.7% enriched uranium into HEU. Such a plant need only contain 1,400-2,100 centrifuges of the type Iran currently uses. Once Iran obtains a stockpile of 94-106 kilograms of 19.7% enriched uranium then this small clandestine centrifuge enrichment plant could produce a weapon's worth of HEU in just two months. Iran will likely have the required 19.7% enriched uranium stockpile by the first part of 2012.

An option that allows Iran to utilize its stockpiles of enriched uranium more efficiently and could be started today (assuming that a clandestine enrichment plant already exists), would be to combine batch recycle at the FEP to produce 19.7% enriched uranium while at the same time using a small enrichment plant to convert the 19.7% uranium into HEU. Using its current (October 2011) stockpiles of enriched uranium, this arrangement would enable Iran to produce enough HEU for three nuclear weapons. Iran could produce this HEU at a rate of one weapon's worth every two months.

Regardless of whether Iran has any clandestine centrifuge enrichment plants, Iran can use its current stockpiles of 3.5% and 19.7% enriched uranium and batch recycling at the FEP to produce a weapon's worth of HEU in just two months. However, by using a small clandestine enrichment plant, Iran could use its stockpiles of enriched uranium more efficiently and currently produce three nuclear weapons worth of HEU, well on its way to a full-fledged arsenal. As I have written elsewhere, Iran is unlikely to move to an overt nuclear weapons status any time soon, but by being able to acquire nuclear weapons quickly, Iran must be treated as a defacto nuclear weapon state.[18]

Below is a more detailed analysis of the specific points over which my calculations and that of ISIS disagree

How Quickly Iran Could Produce HEU: Albright et al.'s Criticisms

In my work, I have analyzed all of the methods whereby Iran might be able to produce HEU. The method that has attracted the most attention is called "batch recycling." If Iran were to use this method, I calculated that Iran could produce the HEU required for a nuclear weapon in just two months. Albright *et al.* have criticized my calculations related to batch recycling.

One should note that there are other ways that Iran could produce HEU. For example, Iran could produce HEU in a clandestine facility, a threat that has been growing more serious and which will be discussed below. Also note that since I published my August 9, 2011 paper, the IAEA has published another safeguards update. I, in turn, have updated my calculations in a report

[18] Greg 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 and Gregory S. Jones, "An In-Depth Examination of Iran's Centrifuge Enrichment Program and Its Efforts to Acquire Nuclear Weapons", August 9, 2011, http://npolicy.org/article.php?aid=1092&rt=&key=Greg%20Jones&sec=article

which was published on September 14, 2011.[19] Iran's stockpiles of enriched uranium have continued to grow and my calculation of the time needed for Iran to produce the HEU for a nuclear weapon by batch recycling has decreased from 62 days to 58 days.

Albright *et al.*'s criticisms fall into three general categories. First, they note that the centrifuge operation at the FEP appears to be non-optimal which they believe will slow Iran's production of HEU by batch recycling. Second, they raise concerns about the second step of my batch recycling calculations, which depend on published results by Glaser, showing an enhanced separation factor when the feed rate is reduced to the centrifuge cascade. Third, they note that when Iran first began the production of 3.5% enriched uranium at the FEP and 19.7% enriched uranium at the PFEP, Iran had to use higher than expected amounts of feed. They contend that this could lead to the need for "much more feed than expected" during batch recycling to produce the HEU for a nuclear weapon.

Non-Optimal Operation of the FEP

Albright *et al.* mention several factors that may cause the enrichment operations at the FEP to be less than optimal. They say that there has been excessive breakage and erratic operation of the centrifuges. They say that the basic 164 centrifuge cascade is non-ideal and that separative capacity is lost due to inter-stage mixing. They also note that the separative capacity per centrifuge may be declining from the 0.89 SWU per centrifuge-year that I use in my calculations to only 0.74 SWU per centrifuge-year. Since Albright *et al.* present no calculations of their own it is difficult to determine how important they think any of these factors are individually.

Note that Albright *et al.*'s concerns about problems at the FEP are a change from what Albright was saying just last year: "Iran is unlikely to face significant delays in making weapon-grade uranium at Natanz [the FEP] if it decides to build nuclear weapons."[20] Indeed, the inherent properties of centrifuge enrichment plants are such that they are highly resistant to reliability problems. The FEP centrifuge enrichment plant consists of 35 cascades each operating independently. If one cascade were to break down, only 3% of the enrichment capacity would be lost. Further, the equilibrium time for centrifuge cascades is quite short, ranging from a few hours to at most a day or two. Any cascade that had failed could quickly be returned to service once it was repaired.

The key point, however, is that all of these factors are irrelevant to my calculations. Albright *et al.* claim that I assume "that all cascades would work flawlessly during the period of breakout…" This statement is incorrect. In my calculations I assume *only* that the cascades continue to operate in the manner that they have been operating. This means that the cascade has a total separative capacity of 4,600 SWU per year and that the cascade is designed to produce 3.5% enriched uranium product and 0.4% depleted uranium tails from natural uranium. The details of how the cascade produces this separative capacity do not matter. For example, the cascade could

[19] Gregory S. Jones, "Iran Continues to Move Closer to Nuclear Weapons: Centrifuge Enrichment and the IAEA September 2, 2011 Update," September 14, 2011
http://npolicy.org/article.php?aid=1099&rt=&key=Greg%20Jones&sec=article

[20] David Albright and Christina Walrond, "Supplement to *Iran's Centrifuge Program:* Taking Stock," Institute for Science and International Security, March 3, 2010, p.1.

consist of 5,200 centrifuges with a separative capacity of 0.89 SWU per centrifuge-year (5,200 x 0.89 = 4,600) or 5,750 centrifuges with a separative capacity of 0.80 SWU per centrifuge-year (5,750 x 0.80 = 4,600). Regardless of which of these choices maybe correct, the result is the same. Similarly the cascade might operate as an ideal cascade with each centrifuge having a separative capacity of 0.89 SWU per centrifuge-year or each centrifuge might have a separative capacity of 1.0 SWU per centrifuge-year which is effectively reduced to 0.89 SWU per centrifuge-year by the non-ideal operation of the cascade. Again, the specific details do not matter. It is unclear why Albright *et al.* suggest otherwise.

Note that Albright was well aware that as of May 2011 the separative capacity of the FEP was 4,600 SWU per year.[21] It is true that in the latest IAEA update (September 2, 2011) the separative capacity at the FEP has fallen to 4,300 SWU per year. The separative capacity at the FEP has had ups and downs before but the overall trend has clearly been upward and there is no reason to believe that this latest downturn is at all significant.[22] Even if I were to redo my calculations in Table 2 (see appendix 1) using only 4,300 SWU per year as the separative capacity at the FEP, due to the increase in Iran's stockpile of 19.7% enriched uranium (38.3 kilograms in May, 47.9 kilograms in August), the time required for Iran to produce a weapon's worth of HEU would be exactly the same, 62 days i.e. two months. This outcome illustrates that as long as Iran continues to produce 19.7% enriched uranium (and is moving to triple its production rate), the hope that somehow Iran will not be able to quickly produce HEU is illusory. Another illustration of this fact will be shown below when I discuss the threat posed by clandestine enrichment plants.

Enriching From 19.7% to 90% in One Step Using Reduced Cascade Feed Rate

If 19.7% enriched uranium were to be batch recycled into the cascades at the FEP and these cascades were to be operated in the same manner as when they were producing 3.5% enriched uranium, two steps would be required to produce the HEU required for a nuclear weapon. In the first step the 19.7% enriched uranium would be enriched to 55.4% and in the second step the 55.4% uranium would be enriched to 86.3%.[23] This process would be slower than what I calculated for enriching from 19.7% to 90% (see appendix 1 Table 2) and might double my two week estimate. This increase in time would not be that significant. Iran's real problem would be that the amount of 19.7% enriched uranium feed required would increase from about 160 kilograms to about 360 kilograms. As of August 2011, Iran only had 47.9 kilograms of 19.7% enriched uranium and was producing it at a rate of 3.2 kilograms per month. Iran is taking steps to triple its production rate to 9.6 kilograms per month and may achieve this production rate before the end of the year. This increase would put Iran on track to reach the total of 160

[21] David Albright, Andrea Stricker and Christina Walrond, "IAEA Iran Safeguards Report: LEU Monthly Production Dramatically Higher but Centrifuges less Efficient than Optimal; Deployment of Advanced Centrifuges Delayed; IAEA's Knowledge about Iran Enrichment Activities Continues of Diminish," Institute for Science and International Security, May 24, 2011, revised May 25, 2011, p.9.

[22] The separative capacity at the FEP is directly proportional to the production of 3.5% enriched uranium. As my Table 1 shows (see appendix 1), since late 2008, the production of 3.5% of enriched uranium and therefore the separative capacity at the FEP, has doubled.

[23] As is discussed in the Appendix 1, though 90% enriched uranium is generally thought to be the required level of enrichment to produce a nuclear weapon, the South Africans produced their first nuclear weapon with just 80% enriched uranium and it is known that the Hiroshima weapon used uranium with an enrichment of less than 89%.

kilograms by the latter part of 2012 but to produce a total of 360 kilograms would take until the middle of 2014, assuming that Iran did not further increase its production of 19.7% enriched uranium.

As is discussed in appendix 1, Glaser has shown that if the feed rate to the cascade were to be reduced, 19.7% enriched uranium can be enriched to 90% enriched uranium in one step.[24] Glaser's calculations are a key element in my own calculations and form the basis for the numbers presented in appendix 1 (Tables 2 and 3) for the second step of the process using batch recycling to produce HEU starting from 3.5% enriched uranium.

Albright *et al*. have raised a number of objections to these calculations. Sometimes these objections seemed to be based on the way I have used Glaser's calculations and sometimes they seem to object to Glaser's calculations themselves. As with the rest of their paper, Albright *et al.*'s discussion is completely qualitative, so it is not possible to determine how significant their objections would be even if they were true. They say that a "former IAEA official" believes that "going from 20 percent to 90 percent in one step may not be possible." However, it is not clear that this former IAEA official has performed any calculations relevant to this issue and Albright *et al.* present none. Again as was noted in the previous section, Albright's current views are quite different that the ones he held just last year when he said "…further enriching from 20 percent enriched uranium to 90 percent material is quick and involves relatively few centrifuges…"[25]

That reducing the cascade feed rate will increase the separation factor of a centrifuge cascade is a well-known phenomenon and was illustrated generically by a graph in the 1988 Martin Marietta document cited in my earlier papers (appendix 2).[26] This increase in separation factor comes with the cost that the separative capacity of the centrifuge declines. As the Martin Marietta graph shows, the separation factor increases immediately with the reduction of the feed rate but the reduction in separative capacity is at first very gradual. As the feed rate is further reduced at some point the loss of separative capacity becomes great and indeed can drop to zero—a point that Albright *et al.* make. The question then becomes what is the magnitude of the loss of separative capacity that applies to my calculations? Albright *et al.* qualitatively claim that the loss "would be expected to be great."

Glaser built a computer model to address this issue. He calculated that with reduced cascade feed rate, one pass through a cascade of the design at the FEP could enrich uranium from 16.3% to 91.0% with only a 3% loss of separative capacity.[27] Glaser's results were published in a peer-reviewed scientific journal. In the case I calculate, I enrich 19.7% uranium to 90.0% uranium. Therefore the loss in separative capacity would be even less than for Glaser's case and is small

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[24] Alexander Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation", *Science and Global Security*, Vol. 16, 2008.
[25] David Albright, Paul Brannan, and Jacqueline Shire, "Taking Stock of the Production of 19.75 percent uranium at the PFEP," Institute for Science and International Security, June 11, 2010, p.3.
[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, p.165.
[27] Alexander Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation", *Science and Global Security*, Vol. 16, 2008, p.16.

enough that I ignore it. If I were to take it into account, it would change my calculated times by about one-third of a day.

Albright *et al.* point out that Glaser's calculations assume that each Iranian centrifuge has a separative capacity of 2.5 SWU per year whereas the more up-to-date estimate that I use is 0.89 SWU per year. Albright *et al.* say that I ignored this fact but as was discussed in the prior section, this fact is irrelevant. The key input to my calculations is not the separative capacity of the individual centrifuges but rather the total separative capacity of the FEP, which is 4,600 SWU per year.

Nor is this issue simply an academic one. Iran has already been using the technique of reducing the feed rate to a cascade to produce 19.7% enriched uranium at the PFEP. On February 9, 2010, Iran began to enrich 3.5% feed in a standard 164 centrifuge cascade composed of IR-1 type centrifuges (this is the exact setup as at the FEP). As I discussed in my August 9, 2011 paper, using 3.5% enriched feed with this cascade in its standard operating mode, would have produced only 15.5% enriched uranium (see appendix 1). Yet on February 11, Iran was producing 19.7% enriched uranium. This result implies that Iran indeed altered the cascade feed rate to achieve the higher level of enrichment. The short time the cascade needed to operate before the production of 19.7% enriched uranium commenced indicates that Iran encountered little difficulty in carrying out this batch recycling step and is consistent with the short equilibrium time associated with the centrifuge enrichment process.

Since Iran began producing 19.7% enriched uranium at the PFEP, its rate of production has been at least 80% of the value that would be predicted by a simple separative work calculation. With its current setup, Iran is using two interconnected 164 centrifuge cascades to produce 19.7% enriched uranium from 3.5% enriched uranium feed with 0.7% uranium (equivalent to natural uranium) tails. Having tails with this U-235 concentration allows this uranium to be fed back into the cascades at the FEP to produce more 3.5% enriched uranium. If one assumes that each centrifuge has a separative capacity of 0.89 SWU per year and the Iranian plant is operating as an ideal cascade then Iran should be able to produce 3.0 kilograms of 19.7% enriched uranium per month at the PFEP.[28]

Albright *et al.* believe that since the PFEP was producing less than 100% of the amount of 19.7% enriched uranium that might be expected by a simple separative work calculation, this shortfall indicates that an even larger deficit might occur when Iran attempted to enrich from 19.7% to 90.0%. They do not mention that data from the latest IAEA safeguards report (September 2, 2011) indicates that Iran is now producing 3.2 kilograms of 19.7% enriched uranium per month i.e. 107% of the amount that a simple separative work calculation would predict. Though Albright *et al.* believe that my calculations overstate Iran's potential production rate and are not worthy of even being considered as a "worst-case," the latest IAEA data supports my calculations and prove Albright *et al.* wrong.

Another point to consider is that, as in all uranium enrichment operations, the lower stages where the enrichment is the lowest require the most time and effort. My own calculations in Table 2 (see appendix 1), demonstrate that the first step of batch recycling, going from 3.5% enriched

[28] An ideal cascade is one that is designed to maximize separative capacity.

uranium to 19.7% enriched uranium, takes 79% of the total time and the second step of batch recycling, going from 19.7% enriched uranium to 90.0% enriched uranium, takes only 21% of the time required. Albright *et al.* concede that my calculations related to the first step accurately represent what Iran has already achieved at the PFEP in producing 19.7% enriched uranium. Consequently, even if my calculations related to time required for the second step are underestimates, my overall estimates would not be greatly changed. For example, even if one doubles the time required for the second step, the overall time would only increase by 12 days, from 62 days to 74 days i.e. two and one half months. In other words, my overall time calculations are not very sensitive to how long it would take Iran to carry out the second step.

Further as will be discussed below in the section on clandestine enrichment plants, the fact that Iran can quickly produce large quantities of 19.7% enriched uranium by batch recycling at the FEP means that Iran would have other options to carry out the last remaining step to produce 90.0% enriched uranium.

Higher Than Expected Feed Requirements at Cascade Startup

Albright *et al.* say that when both the FEP and the PFEP began their production of highly enriched uranium, each plant required "much more feed" than the standard material balance equation would indicate. In keeping with the qualitative nature of their paper, they neither specify how much extra feed was needed nor do they attempt to calculate the impact of this difference on the amount of time it would take Iran to produce the HEU required for a nuclear weapon. They do, however, provide figures showing the cumulative ratio of feed to product for the startup periods of both the FEP and PFEP given at quarterly intervals corresponding to the IAEA reports.[29]

I have focused my attention on their Figure 2 (appendix 3) which relates to the operation of the PFEP since Iran's production of 19.7% enriched uranium at this facility has involved batch recycling identical to that used in my calculations. Albright *et al.*'s data point on the far right of this figure (labeled Sept-11 i.e. September 2011, even though the IAEA has only provided data through August 20, 2011) shows that the feed to product ratio is about 10. Their data point on the far left for May 2010 shows a value of about 31. This would imply that the increase in feed during the early operation of the PFEP was about a factor of 3.1 (31/10) but Albright *et al.* provide no discussion of how this figure should be interpreted or the numerical significance of the data. Also note that their May 2010 data point is incorrect and should actually be 17, not 31.[30]

However, it is impossible to tell from their Figure 2 whether the PFEP has required any extra feed or not since it uses a flawed comparison. From its start on February 9, 2010 to July 13,

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[29] David Albright, Paul Brannan and Christa Walrond, "Critique of Gregory Jones's Breakout Estimates at the Natanz Fuel Enrichment Plant (FEP)," September 20, 2011, Figure 2 and Figure 3, pp.5-6.

[30] *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/2010/28, May 31, 2010, p.3. The IAEA says that between February 9, and May 21, 2010, the uranium hexafluoride feed at the PFEP was 172 kilograms and between February 9 and April 7, 2010, the uranium hexafluoride product was 5.7 kilograms. Extrapolating the product production rate to May 21 gives 10.1 kilograms of uranium hexafluoride product. The feed to product ratio between February 9 and May 21 is 172/10.1 = 17.

2010, the PFEP produced 19.7% enriched uranium from 3.5% enriched uranium feed with tails of 2.0%. Using the standard material balance equation it is easy to calculate that the expected feed to product ratio should be about 12.[31] After July 13, 2010 to the present, the PFEP began to use a second cascade to lower the tails, so that it was producing 19.7% enriched uranium from 3.5% feed with 0.7% tails. The expected feed to product ratio during this interval should be about 7. Albright *et al.* cumulate data from both these periods so that the expected feed to product ratio is some weighted average of 12 and 7 that would decrease with time. Even if no extra feed were required, such a graph would show a downward curve to the right. Though the data point on Albright *et al.*'s Figure 2 for "September 2011" is about 10 there is no way to tell if this number is higher than expected without doing detailed calculations to disaggregate the data. In addition, by using the correct data point for May 2010, the downward slope would be far less than shown on Albright *et al.*'s Figure 2.

I examined the original IAEA safeguard reports and found that the feed to product ratio at the PFEP between May 22, 2011 and August 20, 2011 is indeed 7.[32] Also the average of the feed to product ratio at the PFEP for the period from September 19, 2010 to August 20, 2011 is also 7, indicating that whatever problems might have affected the PFEP, they all occurred before September 18, 2010.

During the interval between February 9, 2010 and September 18, 2010, the PFEP used 352 kilograms of 3.5% enriched uranium hexafluoride feed to produce 25.1 kilograms of 19.7% enriched uranium hexafluoride product.[33] Assuming that the production rate was constant during this interval, and taking the expected feed to product ratio as 12 between February 9 and July 13 and 7 between July 14 and September 18, one can calculate the expect feed to be about 263 kilograms of uranium hexafluoride. Since 352 kilograms of uranium hexafluoride was required instead, this is an increase of about 60 kilograms of uranium feed (89 kilograms of uranium hexafluoride) over what one would calculate using the standard mass balance equation.

As can be seen by my Table 3 (appendix 1), Iran needs to use a total of 1,870 kilograms of 3.5% enriched uranium feed in order to be able to produce the 20 kilograms of HEU required for a nuclear weapon by batch recycling. An increased requirement of 60 kilograms is only a 3.2% increase in the total feed required. This calculated result is quite different from Albright *et al.*'s claim that "much more feed" would be required. Since Iran has already produced 3,100 kilograms of 3.5% enriched uranium and is producing 100 kilograms of 3.5% enriched uranium per month, the increase in feed required is insignificant.

Note also that Albright *et al.* say that they do not know what caused this increase in the feed required when the PFEP started operation and admit that in a batch recycling case, the increase

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[31] The feed to product ratio is calculated by the equation: $F/P = (N_P – N_W)/(N_F – N_W)$, where N_P, N_F, and N_W are the enrichment of the product, feed and tails respectively.

[32] See: "*Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran*", GOV/2011/54, September 2, 2011 and *Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran*, GOV/2011/29, May 24, 2011.

[33] *Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran*, GOV/2010/62, November 23, 2010, p.3.

in feed requirements might be less than what has occurred in the past or might not even occur at all.

Albright et al.'s Six Month Estimate

In their critique of my work, Albright *et al.* have said, "…ISIS found on balance no justification to change its earlier breakout estimate of six months at the FEP." They provide no reference or link to this six month estimate. Consequently, I spent many hours reviewing ISIS's previous papers and as best I can tell, ISIS has published no estimate of the time it would take Iran to produce a weapon's worth of HEU that is applicable to Iran's current situation where Iran has a separative capacity of 4,300-4,600 SWU per year at the FEP and has stockpiles of 2,690 kilograms of 3.5% enriched uranium and 47.9 kilograms of 19.7% enriched uranium. I did find two prior estimates of the time it would take Iran to produce the HEU required for a nuclear weapon by Albright that warrant further discussion.

In June 2011, Albright presented an estimate of how long it would take Iran to produce the HEU for a nuclear weapon that applies to some future time when Iran has accumulated enough 19.7% enriched uranium so that it can be directly enriched to HEU.[34] Albright posits that Iran will also have significant numbers of centrifuges more advanced than the current IR-1 centrifuges that Iran is using at the FEP. These more advanced centrifuges would each have a separative capacity of 2.9 SWU per year rather than the 0.9 SWU per year of the IR-1 centrifuges.

Albright assumes that Iran arranges 584 of these advanced centrifuges in six cascades. Four of the cascades (114 centrifuges each) enrich 20% enriched uranium to 60% and the other two cascades (64 centrifuges each) enrich 60% to 90%. The tails for the 20% to 60% step are 4.5% and for the 60% to 90% step are 20%. This arrangement is meant to replicate the design of a centrifuge enrichment plant reportedly sold by Pakistan to Libya.[35] The Pakistani design is a four step arrangement where the first step enriches from natural uranium to 3.5% enriched uranium and the second step takes the 3.5% enriched uranium and further enriches it to 20%. Iran is already carrying out these first two steps. The third and fourth steps are as indicated by Albright.

Albright says that this arrangement would allow the production of 31 kilograms of HEU in just six months, requiring 192 kilograms of 20% enriched uranium feed. He also says that if Iran were to have 1,200 such centrifuges then Iran could produce this much HEU in just three months and if it had 2,400 such centrifuges then the HEU could be produced in just one and one half months. Albright makes no estimate as to when Iran might be able to deploy such numbers of advanced centrifuges.

[34] David Albright, Paul Brannan, and Andrea Stricker, *Iran in Brief*, "Moving 20 Percent Enrichment to Fordow: Slow Motion Breakout Continues?", Institute for Science and International Security, June 8, 2011.
[35] Alexander Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation", *Science and Global Security*, Vol. 16, 2008, pp.17-19. Note, however, that Glaser has calculated that the tails for these two steps should be 0.72% and not the values used by Albright.

In prior work Albright has assumed that between 16.5 and 30 kilograms of HEU is needed to produce a nuclear weapon.[36] In his June 2011 publication Albright does not say how much HEU he now assumes is needed for a nuclear weapon but if he had used the 16.5-30 kilogram range, then for his 584 advanced centrifuge case, Iran could produce a weapon's worth of HEU in just 3-6 months. Increasing the number of advanced centrifuges used by Iran would decrease these times proportionally.

However, key to Albright's time estimates is his assumption that these two enrichment steps are highly inefficient with the cascades enriching to 60% achieving only 35% of their design separative capacity and the cascades enriching to 90% achieving only 40% of their design separative capacity. Albright offers no explanation for this high level of inefficiency. In contrast, Glaser who has performed calculations on this same cascade design, found that to replicate the performance of what has been reported for the Pakistani design, the efficiency needed to be 100%.[37] On September 19, 2011, I sent Albright an email asking him how he calculated his efficiency numbers but my inquiry has gone unanswered.

At any rate, Iran could avoid whatever inefficiency might exist in the Pakistani cascade design by simply constructing all 584 centrifuges in one or more ideal cascades designed to produce 90% enriched uranium from 19.7% enriched uranium feed and having tails of 0.711%. Indeed in 2009, Albright was critical of an analysis by Kemp and Glaser for not considering "…a configuration that would produce weapon-grade uranium efficiently."[38] The 584 efficiently arranged centrifuges could produce 16.5-30 kilograms of HEU in just two to three months, requiring 77-141 kilograms of 19.7% enriched feed.[39] With 1,200 advanced centrifuges, these times would drop to between one month and one and one half months. With 2,400 advanced centrifuges the time required would be between two and three weeks. These results clearly show that when Iran can deploy large numbers of advance centrifuges, Iran will be able to produce HEU very quickly from 19.7% enriched uranium feed.

Albright's other estimate of interest is included in a March 2010 paper.[40] In this paper he said: "In a breakout scenario using low enriched uranium, Natanz [FEP] could currently produce enough weapon-grade uranium for a weapon in six months or less."[41] From the IAEA

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[36] David Albright, Christina Walrond, "Iran's Gas Centrifuge Program: Taking Stock," Institute for Science and International Security, February 11, 2010, p.16. The amount of HEU needed for a nuclear weapon is taken as being between 15 and 25 kilograms with the rest "representing losses in manufacturing the weapon." These manufacturing losses range between 10% and 20%. As I have written elsewhere, such large manufacturing losses well exceed those experienced by the U.S. during the manufacture of the Hiroshima nuclear weapon. See: Gregory S. Jones, "Critique of IISS Estimates of the Time Required for Iran to Produce the HEU Metal Core Required for a Nuclear Weapon, Addendum: Time Required to Produce the Non-Nuclear Components Needed For a Nuclear Weapon," March 3, 2011, Revised April 6, 2011, p.5. http://www.npolicy.org/article_file/Critique_of_IISS_Estimates_with_Addendum.pdf

[37] Alexander Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation", *Science and Global Security*, Vol. 16, 2008, pp.17-19.

[38] David Albright, Paul Brannan and Jacqueline Shire, "Nuclear Weapon Breakout Scenarios: Correcting the Record," Institute for Science and International Security, March 18, 2009, p.1.

[39] The time required to be reduced to one to two months if the tails were increased to 3.5% though this would increase the required 19.7% feed to 88-160 kilograms.

[40] David Albright and Christina Walrond, "Supplement to *Iran's Gas Centrifuge Program: Taking Stock*," Institute for Science and International Security, March 3, 2010.

[41] *Ibid.*, p.1.

safeguards update that was issued on February 18, 2010, Albright estimated that the separative capacity of the FEP was 3,400 SWU per year. He hypothesizes what he calls "a worst case scenario" where Iran could, in a very short time, modify the cascades at the FEP to perform as an ideal cascade. His analysis seems to assume that this conversion could take place virtually instantly though he is not wholly clear about this is a very important assumption. Albright apparently used separative work calculations even though Albright *et al.* now say "separative work calculations are not accurate estimates of the actual situation at the FEP."

Albright says that with natural uranium feed, 3,400 SWU per year could produce 22 kilograms of HEU per year with a 0.5% tails.[42] Such a result is consistent with a separative work calculation and the FEP being configured as an ideal cascade. He also says that using 3.5% enriched uranium feed, 3,400 SWU per year could produce 105 to 130 kilograms of HEU per year with a tails of 1.0% and 1.7% respectively. Given his assessment that one nuclear weapon's worth of HEU ranges from 16.5 to 30 kilograms, this estimate would imply that Iran could produce enough HEU for a nuclear weapon in 1.5 to 3.5 months (Albright says "several months"). In fact, Albright's calculations are incorrect. Even if configured as an ideal cascade, I calculate that the 3,400 SWU per year would only produce 71 to 88 kilograms per year with a tails of 1.0% and 1.7% respectively. This corrected calculation would imply that Iran could produce enough HEU for a nuclear weapon in about 2 to 5 months.

Similarly Albright estimates that at a future time when Iran has enough 19.75% feed, the 3,400 SWU per year when configured as an ideal cascade could produce 350 to 680 kilograms of HEU per year given a tails of 1% and 10% respectively. These calculations would imply that Iran could produce enough HEU for a nuclear weapon in one week to one month (Albright says "a month or less"). As in the case with 3.5% enriched uranium feed, Albright's calculations are incorrect. I have calculated that in these cases, Iran could produce 233 to 456 kilograms of HEU respectively which would imply that Iran could produce enough HEU for a nuclear weapon in two to seven weeks.

Albright recognized that it would be some time before Iran would have enough 19.75% enriched uranium to produce HEU in one step since Iran had only just begun to produce 19.75% enriched uranium as of March 2010. Clearly, his estimate starting from 3.5% enriched uranium was the one that was applicable to the situation in March 2010 and his statement that Iran could produce enough HEU for a nuclear weapon in "six months or less" is consistent with the two to five months that his worst-case calculations imply. Note that at this time, my own "best-estimate" calculation of how long it would take Iran to produce a weapon's worth of HEU, if it decided to do so, was about 8.5 months.[43]

My June 2011 estimate of two months is fairly comparable to Albright's March 2010 worst-case estimate of two to five months and certainly comparable to his incorrectly calculated 1.5 to 3.5

[42] *Ibid.*, p.4.

[43] Gregory S. Jones, "Iran's Increasing Progress towards a Nuclear Weapons Capability: Centrifuge Enrichment and the IAEA February 18, 2010 Update," February 23, 2010 http://128.177.28.81/files/20100223-Jones_Iran_Enrichment_Update.pdf I estimated that it would take Iran another 5 months before its stockpile of 3.5% enriched uranium would be large enough (about 1,900 kilograms) to permit batch recycling and that the batch recycling itself to produce a weapon's worth of HEU would take about 3.5 months.

month estimate.[44] By May 2011, Iran had a stockpile of 19.7% enriched uranium of 38.3 kilograms, increased its stockpile of 3.5% enriched uranium from about 1,400 kilograms to about 2,460 kilograms and had increased the separative capacity of the FEP from 3,400 SWU per year to 4,600 SWU per year. These factors resulted in my estimate falling from 8.5 months to the current two months.

One would think that these factors would have caused a similar decline in Albright's March 2010 "worst-case" estimates. Instead, Albright *et al.* inexplicably states that my June 2011 estimate of two months is "unreliable…even as a worst case" when my estimate is comparable to estimates Albright made in March 2010. It is not clear how Albright *et al.*'s current estimate is related to these past estimates particularly since they say that for their current six month estimate they use "…a 'fixed plant' production model, which means that the existing cascades are not reconfigured…" Is their current six-month estimate also a "worst-case?" Since Albright *et al.* provide no reference or link to what they say is their "earlier breakout estimate of six months at the FEP," there is no way to clarify their statements until they are more explicit.

The Growing Threat of Clandestine Centrifuge Enrichment Plants

Batch recycling is not the only method for Iran to quickly produce the HEU for a nuclear weapon. Iran's growing stockpile of 19.7% enriched uranium is making clandestine centrifuge enrichment plants containing 1,400-2,100 IR-1 type centrifuges an increasingly attractive option for Iran. As I said in my August 9, 2011 paper[45]:

> Since Iran can produce its own centrifuges and also can transfer centrifuges from safeguarded facilities to unknown locations (IAEA safeguards do not apply to the centrifuges once they leave a safeguarded facility), Iran has the option to produce HEU at a clandestine enrichment plant. Since Iran continues to refuse to implement the Additional Protocol to its safeguards agreement, the IAEA would find it very difficult to locate a clandestine enrichment plant—a fact that the IAEA has continued to confirm.[46] 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).

Iran had originally suggested to the IAEA that the FFEP might eventually contain somewhere between 2,600 and 3,000 IR-1 type centrifuges.[47] Iran has changed its plans several times and

[44] Note, however, that my calculations are intended to be "best-estimate" rather than "worst case."

[45] Gregory S. Jones, "An In-Depth Examination of Iran's Centrifuge Enrichment Program and Its Efforts to Acquire Nuclear Weapons", August 9, 2011, p.12 http://npolicy.org/article.php?aid=1092&rt=&key=Greg%20Jones&sec=article

[46] "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/2011/29, May 24, 2011, p.9.

[47] "*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/2009/74, November 16, 2009, p.3.

now says that it plans to install four cascades of IR-1 centrifuges (two sets of two interconnected cascades) containing a total of about 700 centrifuges in order to triple its production of 19.7% enriched uranium. Though the FFEP is no longer clandestine, Iran has announced that it plans to build ten new enrichment facilities and has made statements that imply that one such plant may already be under construction.[48] Iran has not revealed the locations for any of these ten plants and the IAEA's efforts to obtain more information from Iran have been unsuccessful.

In my past work I have focused on Iran using either natural uranium or 3.5% enriched uranium as feed to a clandestine enrichment plant but Iran's growing stockpile of 19.7% enriched uranium now provides Iran with additional options to quickly produce the HEU required for a nuclear weapon. If configured as one or more efficient cascades, a clandestine Iranian enrichment plant with only about 1,400 IR-1 type centrifuges could produce a weapon's worth of HEU in only two months. In this case, the tails would be 3.5% enriched uranium and the total amount of 19.7% required would be 107 kilograms. The tails could then be fed back into the PFEP in order to produce more 19.7% enriched uranium. The 107 kilograms of 19.7% enriched uranium required as feed is significantly less than the 158 kilograms that would be required if the HEU were to be produced by batch recycling. Given that Iran already had 47.9 kilograms in August 2011 and may well triple its production rate of 19.7% enriched uranium by the end of the year, Iran could have 107 kilograms of 19.7% enriched uranium by the first part of 2012. If the tails were reduced to 0.711% then the amount of 19.7% enriched uranium required as feed would be only 94 kilograms though the number of required centrifuges would increase to about 2,100. These results are shown in Table 4.[49] Of course, doubling the number of centrifuges in these cases would reduce the time required to just one month.

Table 4

Enriched Uranium Feed (19.7%) and The Number of Centrifuges (IR-1 type, 0.89 SWU per year) Required by a Clandestine Enrichment Plant to Produce 20 Kilograms of HEU in Two Months

Number of Centrifuges	Kilograms of 19.7% Feed	Tails Assay
1,430	107	3.5%
2,130	94	0.711%

Nor would Iran have to wait until 2012 to start this operation if it had such a clandestine enrichment plant. Iran already has a sufficient stockpile of 19.7% enriched uranium to run the clandestine enrichment plants in Table 4 for about one month. In the meantime batch recycling at the FEP could be used to convert Iran's current stockpile of 3.5% enriched uranium into 19.7% enriched uranium to provide additional 19.7% feed. The batch recycling produces the 19.7% enriched uranium at a pace that is more than enough to meet the feed requirements of

[48] "*Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran*", GOV/2011/54, September 2, 2011, p.5.
[49] Tables 1, 2 and 3 are in appendix 1.

these clandestine enrichment plants and Iran's entire stockpile of 3.5% enriched uranium could be converted into 19.7% feed.

In August 2011 Iran had a stockpile of 2,690 kilograms of 3.5% enriched uranium and was producing this enriched uranium at a rate of about 100 kilograms per month. By mid-October this would give Iran a stockpile of about 2,900 kilograms of 3.5% enriched uranium, which could produce about 246 kilograms of 19.7% enriched uranium if batch recycled at the FEP. In August 2011 Iran had a stockpile of 47.9 kilograms of 19.7% enriched uranium and was producing this enriched uranium at a rate of 3.2 kilograms per month which by mid-October would give Iran a total of about 54 kilograms of 19.7% enriched uranium. Adding these two quantities would give Iran a total of about 300 kilograms of 19.7% enriched uranium.

With 3.5% tails, this amount of 19.7% enriched uranium could be converted into 56 kilograms of HEU and with 0.711% tails it could be converted into 64 kilograms of HEU. This would be enough HEU for about three nuclear weapons. Since the clandestine enrichment plants in Table 4 are sized to produce 10 kilograms of HEU per month, this entire process would take about six months with enough HEU for a nuclear weapon being produced every two months. These results are shown in Table 5.[50] At Iran's current productions rates of 3.5% and 19.7% enriched uranium, these totals will increase by about 2 kilograms every month.

Table 5

Amount of HEU That Iran Could Produce at a Clandestine Centrifuge Enrichment Plant If Iran Concurrently Converted Its Stockpile of 3.5% Enriched Uranium To 19.7% Enriched Uranium by Batch Recycling at the FEP

Number of Centrifuges* Required by a Clandestine Enrichment Plant Sized to Produce 10 Kg HEU per Month**	Tails Assay at the Clandestine Enrichment Plant	Total HEU Production*** (Kilograms)
1,430	3.5%	56
2,130	0.711%	64

*IR-1 type, 0.89 SWU per year
**Using 19.7% enriched uranium feed
***Using a total of 300 kilograms of 19.7% enriched uranium feed. In mid-October 2011, Iran is estimated to have stockpiles of 54 kilograms of 19.7% enriched uranium and 2,900 kilograms of 3.5% enriched uranium. If the 3.5% enriched uranium were to be batch recycled at the FEP this would produce 246 kilograms of 19.7% enriched uranium.

These results demonstrate that while the production of HEU by batch recycling at the FEP remains a serious concern, Iran's sizable stockpile of 19.7% enriched uranium gives Iran the

[50] Tables 1, 2 and 3 are in appendix 1.

capability to quickly produce HEU by the use of a clandestine centrifuge enrichment plant. If such a plant were equipped with about 1,400-2,100 centrifuges of the type Iran currently has in use, Iran could use its current stockpiles of enriched uranium more efficiently than with just batch recycling alone. If Iran were to convert its entire stockpile of 3.5% enriched uranium into 19.7% enriched uranium by batch recycling at the FEP and concurrently convert the 19.7% enriched uranium into HEU at a clandestine enrichment plant, Iran already has enough 3.5% enriched uranium to produce enough HEU for three nuclear weapons. I have sized the clandestine enrichment plant so that Iran could produce one nuclear weapon every two months but if the clandestine enrichment plant were to use more centrifuges, this time could be reduced.

Appendix 1

Excerpt From "An In-Depth Examination of Iran's Centrifuge Enrichment Program and Its Efforts to Acquire Nuclear Weapons," August 9, 2011
Batch Recycling Calculations Related to How Quickly Iran Could Produce HEU for Nuclear Weapons

Information Provided by the IAEA

In the past, when analysts have evaluated various countries' nuclear programs and addressed the issue of how they might be used to provide fissile material for nuclear weapons, often little specific technical information was available. As a result, calculations would have to be parametric in nature, with reasonable assumptions used to provide a range of possible fissile material production rates. The situation for Iran is quite different. Since Iran is subject to IAEA safeguards and since the IAEA publishes the results of its inspections, much more technical information about Iran's centrifuge enrichment program is available so that far more detailed calculations of fissile material production rates are possible.[51]

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 consists of 164 centrifuges, though Iran has begun to modify some cascades by increasing the number of centrifuges to 174. All centrifuges installed 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 May 14, 2011, Iran had installed 53 cascades containing approximately 8,000 centrifuges at the FEP. Of these 53 cascades, only 35 (containing 5,860 centrifuges) were being fed with uranium hexafluoride and therefore producing 3.5% enriched uranium.[52]

Also at Natanz, Iran has the Pilot Fuel Enrichment Plant (PFEP) which is used to test a number of more advanced centrifuge designs. These are usually configured as single centrifuges or small ten or twenty centrifuge test cascades. However, Iran has indicated that it plans to install two full cascades containing more advanced centrifuges (one cascade using IR-4 centrifuges and one cascade using IR-2m centrifuges) which could significantly increase the rate of Iran's production of 3.5% enriched uranium. 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.

Finally Iran is constructing an enrichment facility near Qom. Known as the Fordow Fuel Enrichment Plant (FFEP), this plant's construction was started clandestinely in violation of its IAEA safeguards. Its existence was only revealed by Iran in September 2009 after Iran believed that the plant had been discovered by the West. No centrifuges have yet been installed at FFEP.

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[51] The most recent such report is: *Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran*, GOV/2011/29, May 24, 2011.

[52] The IAEA's description of the number of centrifuges being fed with uranium hexafluoride is rather ambiguous: "The 35 cascades being fed with UF_6 on that date contained a total of 5860 centrifuges, some of which were possibly not being fed with UF_6." *Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran*, GOV/2011/29, May 24, 2011, p.2.

Iran has been producing 3.5% enriched uranium at the FEP since February 2007. As of May 14, 2011 it had produced a total of 2,775 kilograms (in the form of 4,105 kilograms of uranium hexafluoride[53]). Based on the IAEA's safeguards reports, I have calculated the average Iranian monthly production rate of 3.5% enriched uranium starting from near the end of 2008. The results are shown in Table 1. As can be seen, while being steady at around 55 kilograms per month for much of 2009, the production rate has now almost doubled to around 105 kilograms per month.

Table 1
Average Iranian Production Rate of 3.5% Enriched Uranium
Late 2008 to Mid-2010

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

Iran began producing 19.7% enriched uranium at the PFEP in February 2010. Since production began, the rate of 19.7% enriched uranium production has been fairly steady and as of the last IAEA safeguards report, the rate was 2.6 kilograms per month. As of May 21, 2011, Iran had accumulated about 38.3 kilograms of 19.7% enriched uranium (in the form of 56.7 kilograms of uranium hexafluoride). As of the May 21, 2011, date, about 320 kilograms of 3.5% enriched uranium would have been processed into 19.7% enriched uranium, leaving Iran with about 2,455 kilograms of 3.5% enriched uranium. Though Iran claims that it is producing this enriched uranium for peaceful uses, all of the 3.5% enriched uranium and the 19.7% enriched uranium is just being stockpiled.

From the Iranian production rate of 105 kilograms per month of 3.5% enriched uranium at the FEP, it can be easily calculated that this plant's current enrichment production capacity is about 4,600 separative work units (SWU, see Appendix 2) per year.[54] Given that in the past Iran's centrifuges were each producing about 0.89 SWU per year, 4,600 SWU per year would indicate

[53] The IAEA reports Iran's enriched uranium production in terms of uranium hexafluoride. However, since the production of nuclear weapons involves the use of metallic uranium, we report the uranium content of the uranium hexafluoride, which can be found by multiplying by 0.676. Note that the failure to make this distinction can lead to confusion since the IAEA's uranium hexafluoride figures are sometimes erroneously reported as uranium alone.
[54] Assuming 0.4% tails.

that the equivalent of about 31 cascades (5,184 centrifuges) were in operation. Note that Iran had 31 cascades in operation at the end of the last IAEA reporting period on February 20, 2011. Since the IAEA has indicated that on May 14, 2011, Iran had 35 cascades producing 3.5% enriched uranium, this implies that either some cascades are not operating at full effectiveness or that the new cascades only came online near the end of the current IAEA reporting period. In any event, what is important is Iran's current enrichment capacity (4,600 SWU per year) and not the exact number of centrifuges Iran has in operation.

How Could Iran Produce the HEU Required for a Nuclear Weapon?

Iran's stockpiles of 3.5% and 19.7% enriched uranium, its enrichment capacity of 4,600 SWU at the FEP, it ability to manufacture new centrifuges as well as its ability to transfer centrifuges from one facility to the other, all give Iran a number of options for producing the 20 kilograms of HEU required for a nuclear weapon.[55] Two distinct possibilities involve either Iran using its existing enrichment facility at the FEP or Iran using a specially constructed clandestine enrichment facility. We will examine each possibility in turn.

Using the FEP to produce enriched uranium

It has long been known that the technical properties of centrifuges allow for the fairly easy production of HEU from a centrifuge enrichment facility even if the facility was not designed to produce HEU. Writing as long ago as 1979 with my colleagues Albert and Roberta Wohlstetter, we said: "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."[56]

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) confirms this point: "…there are several characteristics of the gas centrifuge enrichment process that enable a centrifuge facility designed for produce LEU [low enriched uranium, i.e. uranium enriched to 3% to 5%] to be used for the undeclared production of HEU. Specifically, these features include a high separation factor, a small in-process inventory, and a short equilibrium time."[57] The course materials also state that the production of HEU can be carried out either by "batch recycling operations" or by "reconfiguring the process piping."[58] These processes are discussed below.

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[55] Iran's stockpiles of enriched uranium are important since, in separative work terms, 3.5% enriched uranium is over 60% of the way to 90% enriched uranium and 19.7% enriched uranium is about 90% of the way to 90% enriched uranium.

[56] 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, p.73. http://www.npolicy.org/files/19790706-TowardsANewConsensus-Vol01.pdf

[57] "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.

[58] *Ibid.*, p.187.

Batch Recycling

According to Martin Marietta, "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."[59] "...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. However, precautions must be taken in product-collecting areas where the gas is returned to the solid phase."[60] In other words, due to the higher enrichment of the product in batch recycling, criticality safe containers must be used when the gas is converted back to a solid.

Batch recycling is the process of greatest concern since it allows Iran to produce the HEU needed for a nuclear weapon in the least amount of time. Iran's cascades at the FEP produce 3.5% enriched uranium from natural uranium (usually considered to have an enrichment of 0.711%). Without modification these cascades could produce HEU in a three step process, starting from 3.5% enriched uranium. In the first step, 15.5% enriched uranium would be produced from 3.5% enriched uranium, in the second step, 48.2% enriched uranium would be produced from the 15.5% enriched uranium and in the third step 82.5% enriched uranium would be produced from the 48.2% enriched uranium.[61]

But a simple modification to the cascades can improve this process. As Martin Marietta points out, it is possible to increase the enrichment in each step by reducing the flow through the cascade.[62] As long as the flow is not reduced too severely, the separative capacity is not greatly reduced. It is not possible to use this method alone to produce 90% enriched uranium from 3.5% enriched uranium but Glaser has shown that reduced cascade flow can be used to improve the batch recycling process by reducing the number of cycles from three to two.[63] In the two step process, the first step would produce 19.7% enriched uranium from 3.5% enriched uranium and then the second step would take the 19.7% enriched uranium and further enrich it to the 90% level for use in a nuclear weapon.[64] I have performed calculations based on the two-step process, taking into account Iran's current stockpile of 19.7% enriched uranium. The results are shown in Table 2.

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[59] *Ibid.*, p.178.
[60] *Ibid.*, p.148.
[61] Though weapon states have generally used HEU with an enrichment of at least 90%, it is known that HEU with an enrichment of at least 80% can be used for nuclear weapons. For example, the first South African nuclear weapon used HEU with an enrichment of 80%. See: David Albright, "South Africa and the Affordable Bomb", *Bulletin of the Atomic Scientists*, July/August 1994, pp.37-47.
[62] "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.165.
[63] Alexander Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation", *Science and Global Security*, Vol. 16, 2008, p.16.
[64] In his analysis, Glaser also uses two steps. In his first step, 3.5% enriched uranium is enriched to 16.3% and then in his second step the 16.3% enriched uranium is enriched to 91.0%. While obviously differing in detail, the principle is the same.

Table 2

Time, Product and Feed Requirements for the Production of 20 kg of HEU by Batch Recycling at the FEP (4,600 SWU per year, 31 Equivalent Operating Cascades, 5,184 Centrifuges, 0.89 SWU per Centrifuge-Year)

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	19.7% 119.9 kg	3.5% 1,415 kg	46
Second	90.0% 20 kg	19.7% 153.2 kg*	12
Total			62**

* Includes 38.3 kilograms of 19.7% enriched uranium that Iran has already stockpiled.
**Includes four days to account for equilibrium and cascade fill time.

As can be seen, Iran can now produce the 20 kilograms of HEU needed for a nuclear weapon in about two months should it decide to do so. Most of this time is taken by the first step, where 3.5% enriched uranium is enriched to 19.7% enriched uranium. This first step in this batch recycling process is more than a theoretical possibility, since Iran is already producing 19.7% enriched uranium from 3.5% enriched uranium. Iran used one of its standard 164 centrifuge cascades to start this process. Since as was stated above, if the flow through the cascade were unaltered, only 15.5% enriched uranium would be produced, it is apparent that Iran has reduced the flow though the cascade, so that 19.7% enriched uranium is being produced instead.

Also, since Iran has already established the principle that it can enrich 3.5% enriched uranium to 19.7% enriched uranium, it is not clear that the first step in the batch recycle process would be considered a safeguards violation. Only the second step of batch recycling might be considered a violation of safeguards but by then Iran would need only about two weeks to produce the HEU required for a nuclear weapon.

That Iran can produce the 20 kilograms of HEU required for a nuclear weapon in just two months is a dramatic reduction in the time that would have been required only a few years ago. In the first part of 2008 when I made my first calculations, I estimated that it would take Iran two to four years to be able to produce the HEU required for a nuclear weapon.

Further, as Iran's stockpile of 19.7% enriched uranium continues to grow, the time required for Iran to produce HEU will continue to decline. When Iran has a stockpile of about 160 kilograms of 19.7% enriched uranium, it will be possible to skip the first step entirely and Iran will be able to produce 20 kilograms of HEU in only about 2 weeks. At Iran's current rate of production of 19.7% enriched uranium, the time when Iran will have a stockpile of 160 kilograms of 19.7% enriched uranium is still about four years away. However, Iran has recently announced that it plans to triple its rate of production of 19.7% enriched uranium.[65] Not everything that Iran has been announced about its enrichment program has come to pass but if Iran can carry through on this proposal reasonably soon, then it might have the required 160 kilograms of 19.7% enriched uranium by the end of 2012.

One disadvantage of the batch recycling process is that it requires relatively large amounts of 3.5% enriched uranium to produce the required 20 kilograms of HEU needed for a nuclear weapon. Starting from 3.5% enriched uranium and having no intermediate stockpile of 19.7% enriched uranium, it takes about 1,900 kilograms of 3.5% enriched uranium to produce 20 kilograms of 90% enriched uranium by batch recycling. In contrast, if one uses an enrichment plant designed specifically to produce 90% enriched uranium from 3.5% enriched uranium, then it would only take about 600 kilograms of 3.5% enriched uranium to produce 20 kilograms of 90% enriched uranium. The reason for this difference is that the tails in the latter case would be only 0.4% enriched uranium meaning that most of the U-235 contained in the 3.5% enriched uranium would end up in the 90% enriched product. However, in the first batch recycle step the tails are 2.0% enriched uranium and in the second step 9.2% enriched uranium, so that much of the U-235 in the original 3.5% enriched uranium is "lost" to the tails. In reality, Iran could eventually extract the U-235 from these tails but in the short term 1,900 kilograms of 3.5% enriched uranium would be needed to produce the required 20 kilograms of 90% enriched uranium.

With Iran's current setup it can produce 20 kilograms of HEU from somewhat less than 1,900 kilograms of 3.5% enriched uranium. In February 2010 Iran started producing 19.7% enriched uranium from 3.5% enriched uranium using one of its standard 164 centrifuge cascades. As stated above the tails from this process would have had an enrichment of 2.0%. To utilize its 3.5% enriched uranium more efficiently, in July 2010 it added a second of its standard 164 centrifuge cascades to this process but rather than increase its output of 19.7% enriched uranium, this second cascade was used to reduce the tails enrichment from 2.0% to 0.7%. This reduction increases the amount of 19.7% enriched uranium that can be produced from a given amount of 3.5% enriched uranium by about 73%. The effect of this improvement can be seen from Table 2. Currently it would take about 1415 kilograms of 3.5% enriched uranium when used with Iran's existing stockpile of 38.3 kilograms of 19.7% enriched uranium to produce 20 kilograms of HEU. Since it took about 320 kilograms of 3.5% enriched uranium to produce the 38.3 kilograms of 19.7% enriched uranium, this means that Iran could produce 20 kilograms of 90% enriched uranium from about 1,735 kilograms of 3.5% enriched uranium. Since Iran has already produced 2,775 kilograms of 3.5% enriched uranium it has more than enough to produce this much HEU.

Further as noted above, if Iran wanted to produce a second 20 kilogram batch of 90% enriched uranium (so that it would have a total of 40 kilograms, enough for two nuclear weapons), then it would require 1,900 kilograms of 3.5% enriched uranium. Added to the 1,735 kilograms required for the first 20 kilogram batch of 90% enriched uranium, Iran would need to produce just over 3,600 kilograms of 3.5% enriched uranium in total. Given that Iran has already produced 2,775 kilograms of 3.5% enrich uranium and is producing about 105 kilograms, by the

[65] David E. Sanger and William J. Broad, "Iran Says It Will Speed Up Uranium Enrichment", *New York Times*, June 8, 2011.

beginning of next year Iran will be in a position to produce two nuclear weapons worth of HEU. Table 3 shows how this process would be carried out.

Since Iran would have already consumed its stockpile of 19.7% enriched uranium by producing the first batch of 20 kilograms of HEU, this case would take about two and one half months. The production of the HEU for two weapons would have to be carried out sequentially with the production of the HEU for the first weapon taking about two months (Table 2) and the production of the HEU for the second weapon taking about two and one half months (Table 3) for a total of about four and one half months. These times should be considered the maximum since by the beginning of 2012, Iran will have produced more 19.7% enriched uranium and likely will have added even more enrichment capacity which will shorten the time required.

Table 3

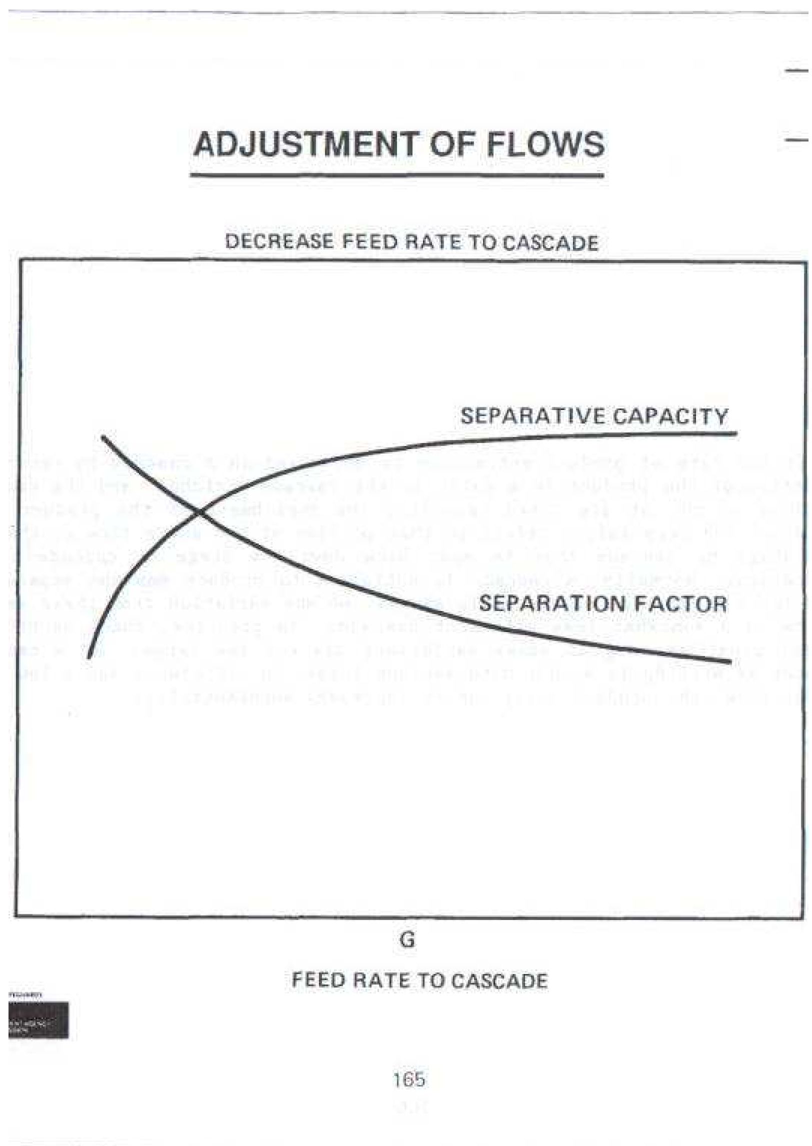
Time, Product and Feed Requirements for the Production of a Second Batch of 20 kg of HEU by Batch Recycling at the FEP (4,600 SWU per year, 31 Equivalent Operating Cascades, 5,184 Centrifuges, 0.89 SWU per Centrifuge-Year)

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	19.7% 158.2 kg	3.5% 1,872 kg	61
Second	90.0% 20 kg	19.7% 153.2 kg	12
Total			77*

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

Appendix 2

Martin Marietta Chart Showing an Increase in Separation Factor with Decreased Cascade Feed Rate



Appendix 3

Albright *et al.*'s Figure 2

Figure 2: Ratio of the Cumulative 3.5 Percent Enriched Feed to 19.75 Percent Enriched Uranium Hexafluoride at the Pilot Fuel Enrichment Plant