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Using Enrichment Capacity to Estimate Iran's Breakout Potential

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Iran is developing fuel cycle technology as part of what it asserts is a purely civilian nuclear program. Since 2007, it has been enriching uranium using gas centrifuges at Natanz. The greatest challenge for a potential nuclear weapons proliferator is acquiring the fissile material[2] and any civilian fuel cycle program has the potential to power both nuclear reactors and nuclear bombs. Specifically, the same centrifuges that produce low-enriched uranium (LEU) for reactors could make highly-enriched uranium (HEU) for a bomb. There is, therefore, no question that Tehran has the technical capability to produce a nuclear weapon,[3] if it chooses to do so, but there is still ambiguity regarding Iran's intentions. Tehran could, at minimum, be interested in maintaining the option of developing nuclear weapons in the indefinite future.

How concerned should we be about the possibility of a nuclear Iran? When could Iran produce a bomb, if it decided to do so? How do we know when we are running out of time?

Iran's breakout potential, the time required to make a bomb, is an important measure of the Iranian threat and, as such, plays a significant factor in weighing policy options toward Tehran. Such estimates create a baseline for Iranian latent weapons capabilities, which provide a tangible measure of the relative imminence of the threat and are a touchstone for policy. For example, on January 10, 2011 U.S. Secretary of State Hillary Clinton said that according to Washington's "best estimate" Iran's enrichment program "has been slowed down," crediting international sanctions against the Islamic Republic adopted over the past year.[4] Iran's breakout potential is used as a surrogate measure of the time that the international community has for diplomacy versus military action. On January 7, 2011 Israel's outgoing intelligence chief Meir Dagan said that

[1] I would like to thank Dr. Ivan Oelrich for the valuable insights and review of calculations in the course of this report. I would also like to acknowledge Dr. Charles Ferguson for his useful comments on an earlier draft of this paper.
[2] Both plutonium and highly enriched uranium can be used for nuclear weapons. Iran's Arak heavy water reactor, currently still under construction, is ideally suited for producing weapons grade plutonium. In theory, the Bushehr nuclear reactor, which will go online early this year, could also be used as a source of plutonium. However, the uranium path to a bomb is of greater concern because Iran already has the capabilities to produce HEU.
[3] Iran, at minimum, will be able to produce a crude nuclear weapon, such as a gun-assembled bomb.
[4] Jay Solomon, "Clinton Says Curbs Slow Iran Program," *Wall Street Journal,* 11 January 2011, <http://online.wsj.com/article/SB10001424052748703779704576073201667479450.html>

Iran will not be able to produce a weapon until 2015, prolonging previous Israeli estimates.[5] He added that "Israel should not hasten to attack Iran, doing so only when the sword is upon its neck."[6] Perhaps most importantly, Iranian breakout estimates are significant because such numbers are widely used in the public debate, especially as justification for political or potential military decisions. At the same time, the uncertainties in these numbers are often underappreciated and the assumptions and methods used to arrive at such conclusions are typically left unstated.

An important factor in estimating how long it would take Iran to build a bomb is the time it needs to produce enough HEU. Therefore, a key factor in estimating Iran's breakout potential is assessing its uranium enrichment capabilities, specifically the performance of its gas centrifuges. The goal of this paper is to estimate the current effective separative power of Iran's IR-1 centrifuge using IAEA physical inventory verification (PIV) data, which FAS considers to be the most credible open-source information available on Iran's enrichment activities. Calculations are shown in detail and all assumptions are explicitly stated. The annual performance of Iran's centrifuges is compared to assess whether enrichment capacity has changed over the past year. The most recent estimates of the centrifuge's separative power are used in notional breakout scenarios at Natanz and at the Fordow Fuel Enrichment Plant.

Calculations using IAEA data show that the total enrichment capacity at Iran's commercial-scale enrichment facility at Natanz has grown during 2010 relative to previous years. The boost in capacity is due to an apparent increase in centrifuge performance. The effective separative power of the IR-1 during 2010 is estimated to be 0.77 kg-SWU/yr – a 60 percent increase from 2009. The observed increase in performance could be partially due to salvaged separative work lost as hold up, but a technological improvement in Iran's centrifuges would not be surprising. Data from Iran's pilot plant appear to corroborate an increase in centrifuge performance. An increase in IR-1 enrichment capacity would reduce Iran's time to produce bomb-grade material. We cannot definitively conclude what caused the measured jump in performance, but only that such an increase is observed. Contrary to statements by U.S. officials and many experts, Iran clearly does not appear to be slowing down its nuclear drive.

1 OVERVIEW OF IRAN'S URANIUM ENRICHMENT CAPABILITIES

Estimates of Iran's breakout potential hinge on assessing its enrichment capabilities at Natanz, specifically the performance of its gas centrifuges. Since the beginning of enrichment operations in February 2007, Iran has been running IR-1 centrifuges for large-scale uranium enrichment at the Fuel Enrichment Plant (FEP). The IR-1 is based on blueprints of Pakistan's P-1 model, which Iran admits it obtained from A.Q. Khan's illicit procurement network. The Islamic Republic is also developing several new centrifuge models at its testing facility, the Pilot Fuel Enrichment Plant (PFEP), but those are apparently not yet ready for mass production.

Individual centrifuges do not have the capability to enrich large amounts of uranium to a high enough degree, so machines are piped together in cascades. Iran operates cascades of 164 machines and most

[5] Yossi Melman, "Outgoing Mossad chief: Iran won't have nuclear capability before 2015," *Ha'aretz,* 7 January 2011, <http://www.haaretz.com/print-edition/news/outgoing-mossad-chief-iran-won-t-have-nuclear-capability-before-2015-1.335656?localLinksEnabled=false>
[6] Dan Williams, "Israel: No Iran bomb before 2015," *Reuters,* 7 January 2011, <http://www.reuters.com/article/idUSTRE70612X20110107>

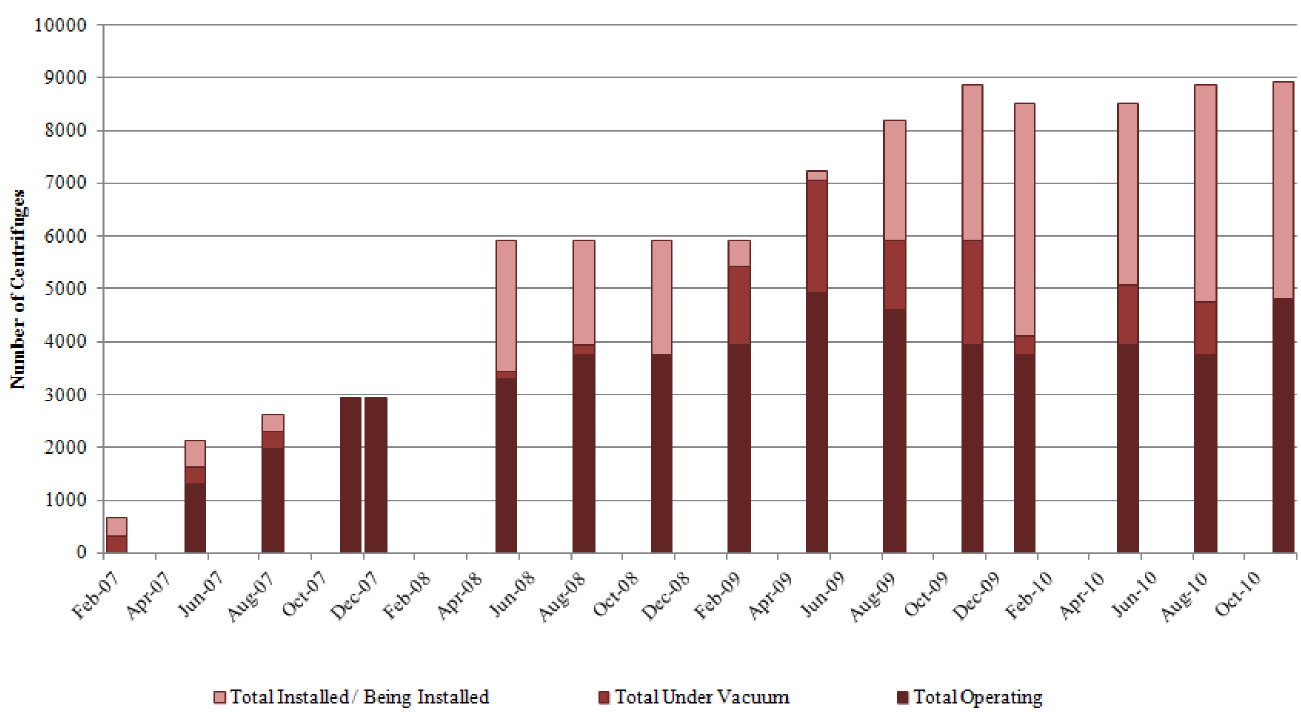
recently "modified six of its cascades to contain 174 centrifuges each."[7] (The modification is discussed later in this report.)

At FEP, Iran uses natural uranium, which has a concentration of about 0.7 percent U-235, to produce low-enriched uranium (LEU) containing approximately 3.5 percent U-235. LEU produced at FEP is suitable for manufacturing fuel for the most common types of light water reactors, such as Bushehr. Because of a stalemate on a deal to purchase the fuel from abroad, Iranian officials began higher-level enrichment to make its own fuel for the Tehran Research Reactor (TRR), which is largely used to produce medical isotopes. Thus, in February 2009 Iran began enriching to 19.75 percent at PFEP by feeding LEU, instead of natural uranium, into IR-1 cascades.

Centrifuge Numbers

As of 22 November 2010, Iran was operating 28 cascades or about 4592 machines at FEP, according to the IAEA.[8] The ultimate capacity of Iran's main enrichment plant is 50,000 centrifuges, so Tehran obviously has the goal of adding more machines. However, in August 2009 FAS staff started seeing a drop in the total operating centrifuges and the number of machines has fluctuated over the past year and a half, but since August 2010, the machine numbers have been steadily increasing. According to the latest report by the IAEA, only about half of the total of 54 cascades or 8426 installed centrifuges were operating. But this new total means that Iran has clearly added new machines since August 2009.

Figure 1: Number of IR-1 centrifuges at FEP from 2007 to 2010



Since the net centrifuge count does not reveal which centrifuges are operating, Iran is either installing new machines, which it is not running, or it is replacing its older centrifuges. In the first case, Iran could be experiencing a shortage of uranium hexafluoride (UF6) and operating fewer machines until more material is available or it could be installing machines that are flawed and not using them until some problem is fixed. However, if all the installed machines at FEP are in good condition, then Iran

[7] GOV/2010/62, Section 4
[8] GOV/2010/62

has the potential to suddenly double its enrichment capacity, which is significant in breakout scenarios. In the second case, Iran may simply be replacing centrifuges reaching the end of their lifecycle[9] or it could be weeding out a technical problem, such as an infection by the Stuxnet computer worm. On November 23, 2010, Ali Akbar Salehi, the head of Iran's nuclear program, admitted, "One year and several months ago, Westerners sent a virus to [our] country's nuclear sites."[10] The timing is consistent with the drop in centrifuge numbers.

In addition, Iran was not feeding material into any centrifuges on 16 November 2010, according to the IAEA. The reason for the shutdown is not stated, but likely points to some technical problem or a routine test. Some experts speculate that the shutdown was an indication that Iran's centrifuges were attacked by Stuxnet,[11] while some government officials have claimed that a shutdown was not out of the ordinary and Iran had experienced those before.[12] While the reasons behind fluctuations in machine numbers at FEP are unknown, it is clear that Iran continues to operate centrifuges and overall to add new machines.

IAEA Data

IAEA data are the most credible publicly available source of information on Iran's centrifuges. Agency reports provide data on the total amount of uranium fed into the cascades and the amount of uranium produced per given period. The total number of operational machines is also recorded on given dates. Safeguards inspectors collect this information for material accountancy purposes – to ensure that no nuclear material is diverted from the facility to, for example, a clandestine enrichment plant. In addition, data are used to verify that the facility is operating consistent with its design plans, so that a nuclear operator is not producing HEU at a plant that is said to be making only reactor fuel.

The most reliable and detailed data that the IAEA publishes are the results of the annual physical inventory verification (PIV). A physical inventory is taken by the Iranian operator to account for all nuclear material at the end of a specified period. During the PIV, the IAEA performs independent measurements of the inventory to confirm that all nuclear material is present. Between PIVs, inspectors report estimates of enrichment recorded by the Iranian operators, in this report also refers to as "logbook data." Ideally, annual production as measured in the PIV should correspond to the sum of short term Iranian production estimates in their logbooks. In practice, there have been discrepancies in the past between the results of the annual PIV data and the higher frequency Iranian logbook data, which reflect errors in accounting.[13] As a result, since 2009, IAEA reports have contained independently calibrated operator load cell readings, which include information on waste and hold up, in addition to logbook data.

[9] Centrifuges spin very quickly over extended periods of time, which results in material fatigue. As a result, the machines do not have very long lifecycles.

[10] http://news.yahoo.com/s/ap/20101123/ap_on_re_mi_ea/iran_nuclear

[11] David Albright, Paul Brannan, and Christina Walrond, "Did Stuxnet Take Out 1,000 Centrifuges at the Natanz Enrichment Plant?" 22 December 2010, <http://isis-online.org/isis-reports/detail/did-stuxnet-take-out-1000-centrifuges-at-the-natanz-enrichment-plant/>

[12] Fredrik Dahl and Sylvia Westall, "Iran temporarily halted enrichment in mid-November: IAEA," *Reuters,* 23 November 2010, <http://www.reuters.com/article/idUSTRE6AM4I420101123>

[13] For further reading on Iranian accountancy problems, please see: "Iran's Uranium: Don't Panic Yet," FAS Strategic Security Blog, http://www.fas.org/blog/ssp/2009/02/irans-uranium-dont-panic-yet.php

2 Calculating the Effective Separative Power of the IR-1

The purpose of the information recorded by the agency is to detect any illicit activity and ensure that all nuclear material is involved only in peaceful activities. However, the PIV data can also be used to calculate the *effective separative power*[14] of Iran's IR-1 centrifuge, which is a measure of overall centrifuge/cascade performance -- taking into account inefficiencies in both individual centrifuges and inefficiencies due to the cascade arrangements. The approach on calculating the effective separative power is described below.

Iran's enrichment capability at Natanz cannot be calculated simply by multiplying the number of operating machines by the separative power of a notional IR-1 centrifuge, as most analyses that address the issue do, for two main reasons. First, as we have shown in earlier reports,[15] any independently assessed estimate of the separative power of the IR-1 is highly uncertain. Second, IR-1s do not operate in ideal cascades, so some separative work is lost when streams of material of different concentrations mix. In addition, because actual cascades have integer number of stages and stages have an integer number of centrifuges, centrifuges are forced to operate at off-optimum flow-rates, which again result in inefficiencies.[16] The IAEA data only allow calculation of the overall efficiency of the cascades. They do not tell us whether inefficiencies occur in the centrifuges individually or in the cascade as a whole. But by taking the separative power of the cascade and dividing by the number of centrifuges, we can determine the *effective* centrifuge separative power, which is useful if for no other reason than to allow comparison to other analysts' estimate of the separative power of the IR-1.

Estimating IR-1 Performance at FEP

The IAEA has published PIV data for FEP since the beginning of operations in 2007. Results from the 2010 PIV are available in the most recent IAEA report of 23 November 2010. PIV data are cumulative, so for example, the 2010 PIV reflects uranium production from 17 February 2007, when Iran began enrichment activities, to 17 October 2010. Consequently, to obtain process quantities for 2010, 2009 PIV numbers, which cover activities at FEP from 17 February 2007 to 22 November 2009, have to be subtracted from the results of the 2010 PIV. In *Table 1*, annual process quantities are obtained by taking these differences.

PIV data contains the amount of material fed into the cascades – F, the amount of enriched product – P, and the average isotopic concentration of the product – x_p. From this information, it is easy to calculate the waste amount and concentration using the principle of conservation of mass, which assumes that no material is created or destroyed during the enrichment process. (We will, for now, neglect small amounts of *hold up* material that leaks during centrifuge operation. This problem is addressed in detail later in this report.)

The amount of waste – W, or the "tails" is the difference between the feed and the product, so the waste concentration – x_w is given by:

$$x_w = \frac{F\,x_f - P\,x_p}{F - P} \qquad [1]$$

[14] Throughout this paper, separative capacity and separative performance are used synonymously with separative power.
[15] Ivan Oelrich and Ivanka Barzashka, "Calculating the Capacity of Fordow," Issue Brief, FAS, 7 December 2009, <http://www.fas.org/policy/_docs/12-08-09-fordowissuebrief.pdf>
[16] A more detailed explanation is available in the 7 Dec 2009 FAS issue brief and in the section on cascades on the FAS website <http://www.fas.org/programs/ssp/nukes/fuelcycle/centrifuges/cascades.html>

The capacity of a single centrifuge, a cascade of centrifuges, or an entire enrichment plant is measured by *separative work*, which describes the increase in concentration of a given amount of material. The separative work is defined as the change in value ΔV of the material

$$\Delta V = PV(x_p) + WV(x_w) - FV(x_f) \qquad [2]$$

where the value is the amount of material multiplied by a value function *V(x)*, which is dependent on the isotopic concentration of the material:

$$V(x) = (2x - 1)\ln\left(\frac{x}{1-x}\right) \qquad [3]$$

The value function is dimensionless and is defined such that the separative work is independent of the concentration of the material.[17]

The separative work has mass separative work units, usually kg-SWU. The *separative power* is simply the separative work, as given in equation [2], per unit time. For gas centrifuges, it is typically measured in kg-SWU per year; sometimes the separative power of an entire plant will be reported in ton-SWU.

Table 1 contains the annual separative work from 2007 to 2010 at FEP, along with key input parameters based on PIV data from IAEA reports. IAEA reports note process quantities in UF_6 mass, but quantities are converted to uranium mass to calculate separative properties. (The uranium is 67.6 percent of the UF_6.)

PIV data provides the net product concentration measured by inspectors, so the product concentration for individual years needs to be recalculated. This is done again using the mass conservation principle. For example, according to the 2010 PIV, the total amount of uranium produced from 2007 to 2010 was 2119 kg U and the overall product enrichment was 3.37 percent. The 2009 PIV tells us that from 2007 to 2009 Iran produced 1 222 kg U at 3.47 percent. This means that the average product enrichment during 2010 was 3.23 percent.

Table 1: Annual separative work at FEP from 2007 to 2010

Year	**Feed Amount** [kg U]	**Feed Concentration** [% U235]	**Product Amount** [kg U]	**Product Concentration** [% U235]	**Waste Amount** [kg U]	**Waste Concentration** [% U235]	**Separative Work** [kg SWU]
2007	1 129	0.71	51	3.8	1 595	0.56	167
2008	5 601	0.71	516	3.46	5 085	0.43	1 756
2009	7 560	0.71	655	3.45	6 905	0.45	2 156
2010	9 192	0.71	897	3.23	8 295	0.44	2 718

To estimate the effective separative *power* of the IR-1, the annual separative work needs to be scaled by the number of operating centrifuges. (A more accurate and perhaps more meaningful measure would be the separative power per cascade, but the separative work per machines is useful because it can be compared to other published values for the IR-1 or other centrifuge models.) However, the number of centrifuges at Natanz is not constant over time. (Machine quantities are discussed in detail in the

[17] For more information, please see: Ivanka Barzashka and Ivan Oelrich, "Separation Theory," FAS.org, <http://www.fas.org/programs/ssp/nukes/fuelcycle/centrifuges/separation_theory.html>

previous section of this paper.) Fortunately, IAEA inspectors regularly record the number of operating centrifuges at Natanz. Therefore, we can estimate the average number of operational machines per given period by taking the arithmetic mean of the number of centrifuges at the beginning and at the end of each period. Using this information, we can calculate the number of centrifuge-days for the time periods corresponding to the annualized separative work from 2007 to 2010. The results are displayed in the *Table 2*.

To quantify the uncertainties in the centrifuge count, we can look at extreme cases, which are, of course, unlikely but useful in providing a limit on the range of possible values. First, let us suppose that during each time interval, Iran operates the minimum number of machines. This yields a maximum separative work per machine value.

Table 2: Average machine-days per PIV period from 2007 to 2010

Year	Period Start Date	Period End Date	Days per Period	Minimum Machine Days	Average Machine Days	Maximum Machine Days
2007	17 Feb 2007	12 Dec 2007	298	393 272 (-24%)	**518 568**	643 864 (+24%)
2008	12 Dec 2007	17 Nov 2008	341	1 109 132 (-4.6%)	**1 162 350**	1 215 568 (+4.6%)
2009	17 Nov 2008	22 Nov 2009	370	1 488 464 (-6.6%)	**1 593 752**	1 699 040 (+6.6%)
2010	22 Nov 2009	17 Oct 2010	329	1 240 988 (-3.8%)	**1 289 966**	1 338 944 (+3.8)

Alternatively, we can assume that Iran has consistently operated the maximum recorded number of machines during each time period. This yields the minimum separative work per machine. The range of possible estimates based on these extrema is less than ± 10 percent from the arithmetic mean for centrifuge performance from 2008 to 2010. The range for 2007 is much greater; however, this is not significant because, at the time, IR-1s were significantly underperforming, as the IAEA noted in its reports. This error analysis shows that the actual number of centrifuges operating between 2008 and 2010 could not be more than 10 percent off the average centrifuge count for each period, which is therefore a good approximation.

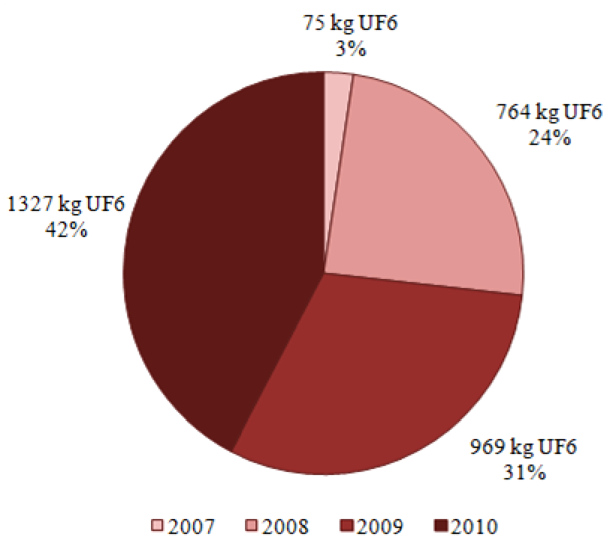
To obtain the effective separative power per centrifuge for each period, we divide the total separative work from *Table 1* by the number of centrifuge days from *Table 2* and multiply by 365 to convert to units of kg-SWU per year per machine. The results are displayed in *Table 3.*

Table 3: Effective separative power of the IR-1 centrifuge from 2007 to 2010

Year	Separative Work [kg SWU]	Average Machine Days	Separative Power per Machine [kg SWU/yr]
2007	167	518 568	**0.12**
2008	1 756	1 162 350	**0.54**
2009	2 156	1 593 752	**0.49**
2010	2 718	1 289 966	**0.77**

The trends in total uranium enrichment capacity at the main plant at Natanz and the reasons for those trends are important for estimating Iran's breakout potential. It is essential to understand whether any changes in overall capacity can be explained by quantitative or qualitative changes in Iran's centrifuges.

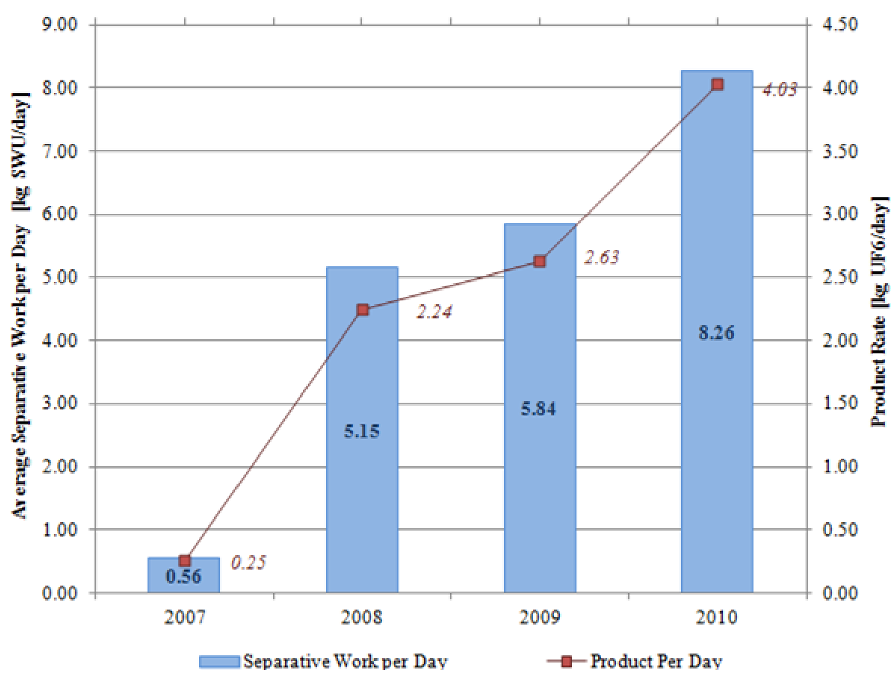
Figure 2: Total LEU production at FEP(2007-2010)



Calculations using IAEA PIV data, displayed in *Table 1* show that the total separative work per year at FEP has been increasing each year since Iran began enrichment operations in 2007[18], despite alleged problems with Iran's centrifuges. This is also true of the total amount of LEU produced at the facility. A breakdown of Iran's LEU stockpile by year shows that the biggest share of Iran's stockpile was added during the 2010 period[19] as *Figure 2* shows.

It is intuitive to compare industrial plant production in terms of total amount of product manufactured, but separative work is a more appropriate measure of capacity in the case of uranium enrichment facilities. As equation [2] shows, separative work factors in parameters such as enrichment levels that a value for net product neglects. Both quantities are used here.

Figure 3: Average separative work per day and amount of LEU produced per day at FEP from 2007 to 2010



The enrichment capacity at FEP grew more during 2010 than it did during 2009: the growth in separative work done per day increased from 13 percent for 2009 to 41 percent for 2010, relative to immediately preceding years. In terms of final product, Iran's daily LEU production rate jumped by 53 percent last year[20], whereas it grew by only 17 percent in during 2009. The increase in production during 2009 can be explained by the fact that Iran was operating more centrifuges than before. However, in 2010 the average number of centrifuge days dropped significantly relative to the previous year, as is

[18] Results for 2007 are not compared to other years, since, as it has been noted in several IAEA reports, the facility was operating considerably below its design specification. It is, therefore, not a useful point for comparison.
[19] Note that this refers to the difference between the 2010 and 2009 PIV (from 22 Nov 2009 to 17 Oct 2010) reporting periods and does not completely correspond to the 2010 calendar year.
[20] Note that the average isotopic concentration during 2010 was lower than in 2009.

evident in *Table 2*. The increase in separative work, as well as LEU produced, seems to be due to increased machine performance rather than machine quantity.

These conclusions are supported by calculations of the annual effective separative power per IR-1 centrifuge shown in *Table 3*. Average centrifuge performance in 2007 was very low. Iran was beginning industrial scale operations and was having documented problems with its machines. It appears that centrifuge performance remained largely the same during 2008 and 2009, at 0.54 kg-SWU/yr and 0.49 kg-SWU/yr, respectively.[21] The IR-1 performance for 2009 based on PIV data is consistent with FAS's estimates published in December 2009 using calibrated operator data.[22]

However, separative capacity increased by nearly 60 percent in 2010 to 0.77 kg-SWU/yr, which cannot be explained by the uncertainties in centrifuge numbers during reporting periods. These estimated values for machine performance are still below the values most widely cited for the IR-1 in the open-source literature, although it is not certain what the effective separative power of Iran's centrifuge ought to be, so there is no credible baseline for comparison. This jump in performance is very significant because of its effect on estimates of Iran's breakout potential, which is discussed later in this report.

Estimating IR-1 Performance at PFEP

Iran's enrichment activities at its pilot plant PFEP are an additional way to gauge the performance of its gas centrifuges. There, Iran is using cascades of 164 IR-1 machines to enrich LEU to concentrations just below 20 percent U-235. Those are likely the same type of machines and cascades that operate at FEP, although they may be more finely tuned and monitored than those on the production floor. Twenty percent enrichment is done using 2 cascades. The first uses LEU from FEP as feed, likely with an isotopic concentration of 3.45 percent (the average product enrichment of the 2009 PIV) and has a product stream close to 20 percent concentration. The tails assay of the first cascade is relatively high – about 2 percent U-235, according to IAEA reports. The waste is recycled in an identical second cascade. The second cascade uses the 2 percent uranium as feed and produces a waste of about 0.7 percent – the concentration of natural uranium, which could be used as feedstock for the cascades at FEP. The second cascade has a product stream of about 10 percent uranium, which is either fed back into the appropriate stage of the first cascade or used in some other way.

The IAEA published PIV data from PFEP from the beginning of enrichment activity on February 9 to September 18, 2010. Although Iran has designated space for 6 cascades, enrichment is currently done using one two-cascade system. Unlike at FEP, there is no uncertainty in the number of operating machines during the period. Iran added a second cascade on July 13 and has, consequently, operated a single cascade for 70 percent of the time of the PIV.

Table #: Separative work at PFEP from 8 February to18 September 2010

Feed Amount [kg U]	**Feed Concentration** [% U235]	**Product Amount** [kg U]	**Product Concentration** [% U235]	**Waste Amount** [kg U]	**Waste Concentration** [% U235]	**Total Separative Work** [kg SWU]
238	3.45	17	19.94	221	2.18	80

[21] The slight drop in performance in 2009 is within the uncertainties in machine count described previously.
[22] These numbers were the basis of the claim by FAS staff that the Fordow centrifuge plant was too small for both civilian and military purposes, which has been widely cited as contradicting U.S. government's statements of the day.

The two cascades form a separating element, so, in principle, the same approach described in the previous section can be used to calculate the total separative work. The amount of waste and its concentration are calculated using equation [1], whereas all other parameters are provided in the IAEA data. If the product of the second cascade is not fed back into the first cascade, the PIV measurements are characteristic of the first cascade. In this case, the calculated tails assay should be close to 2 percent, as is the case here. Consequently, we take the total number of operating centrifuges to be 164. The average separative power per machine is 0.80 kg-SWU/yr. This appears to be consistent with the effective centrifuge capacity of the IR-1 at FEP during 2010, which is expected.

Table 4: Effective Separative Power at PFEP from February 8 to September 18, 2010

Year	**Separative Work** [kg SWU]	**Average Machine Days**	**Separative Power per Machine** [kg SWU/yr]
2010	80	36 244	**0.80**

There is an important caveat. If the product of the second cascade is re-fed into the first cascade, this will increase the total separative work of the system. The calculated tails assay in this case should be close to 0.7 percent. However, since the two cascades have operated a relatively short period of time together, it may be difficult to tell based on the PIV data if the 10 percent product is fed back into the system, but we should nevertheless observe some decrease in the calculated waste concentration, which does not seem to be the case. However, factoring hold up may change these estimates.

3 Explaining Increased Performance

PIV data from FEP and PFEP corroborate that IR-1 centrifuge performance appears to have increased in 2010 relative to previous years. It is clear that the jump in capacity is not due to an increase in machine numbers, which implies that Iran may have improved the performance of its IR-1 centrifuge. However, other factors, such as recycling hold up material, could affect the effective separative power. It should be noted that the *cause* of the increase does not change the fact that a boost in performance is *observed*, but understanding the reason behind the hike is important for forecasting whether this new performance will be long-term, which is important for estimates of Iran's breakout potential.

Hold Up

Centrifuges spin at very high speeds, which result in strong radial centrifugal forces. This means that most of the uranium hexafluoride gas is along the walls of the centrifuge rotor and there is little material close to the center axis. The stationary extraction tubes enter the centrifuge along the axis. Creating high speed rotating seals is a difficult engineering task; so, although the rotor shaft is sealed, small amounts of gas can escape. Maintaining a vacuum in the centrifuge casing is important, so a molecular pump collects the escaped molecules and sends them into cold traps, which condense and solidify the UF6.

This means that the amount of material fed into a cascade does not equal the amount of material in the product and waste because some small fraction is collected as hold up. The amount of material that leaks is proportional to the material that is fed into the centrifuge; therefore, we can assume that an equal amount of hold up will leak out of every centrifuge in a cascade (if all machines are optimized for similar flow rates and the average flow per machine is the same). But the material leaking out of every machine will not have the same concentration – that depends on which stage in the cascade the centrifuge is in. If hold up is collected separately from each stage, it could later be re-fed at the right point in the cascade and the separative work done on that material could be salvaged. If the hold up storage is not that sophisticated, all hold up material could be mixed and collected in one tank. On average, we have higher stage product flow rates for the enriching section of the cascade than for the stripping section, therefore, we would expect the net concentration of the hold up to be slightly higher than the concentration of the feed for the cascade.

In 2009 Iran started reporting independently calibrated data, which contained hold up amount as part of material inventories. Although only small amounts of uranium escape during operation, many machines over large periods of time can accumulate large quantities of hold up material. Accounting for hold up is important for ensuring that no nuclear material is being diverted. For the period of the 2009 PIV, Iran had accumulated over two tons of UF6 as hold up with an average concentration of 0.97 percent.[23] In addition, the FEP had collected nearly half a ton of material in the feed purification cylinder at an average concentration very close to that of natural uranium. The hold up amounts to approximately 10 percent of the material that was fed during the whole period.

One possible explanation for the spike in centrifuge performance during 2010 could be that Iran started re-feeding the enriched hold up back into the cascades at FEP. There is circumstantial evidence that this could have been the case. First, IAEA inspectors had complained to the Iranians that the facility was accumulating large quantities of hold up. Second, higher frequency calibrated data shows a net loss in hold up for certain periods, such as 29 Jan to 1 May 2010, which indicates that hold up material may have been re-fed to the cascades. Third, there is a net decrease in overall product enrichment from 3.45 to 3.23 percent U-235. If additional material enters the cascade, this could result in increased flow rates, which in turn would mean more product, enriched to a lesser degree. Fourth, after nearly 3 years of operations, Iran decided to increase the number of centrifuges per cascade from 164 to 174. The 10 additional centrifuges could mean the addition of an entire cascade stage. Alternatively, single machines could have been added to increase stage width, which would decrease the average flow per machine, thus restoring the average cascade flow rate closer to optimum. In either case, additional centrifuges mean that Iran is most likely interested in increasing the isotopic concentration of its product.

Let us look at the extreme case that Iran re-fed all 2026 kg UF6 of hold up and 516 kg UF6 from the feed purification trap back into its cascades during 2010. Neglecting the design of the cascade, we can simply calculate the value for each new stream. If a cascade leaks enriched material, then the effective separative work appears to be decreased. To get the "real" separative work for the 2009 PIV, if hold up were simply re-fed back into the machines, we need to add the value of the two new streams to the separative work for the period. This yields an average separative power per machine of 0.53 kg-SWU/yr.

To estimate the "real" separative power for 2009, we need to figure out how much of the total feed escaped that year. Since the amount of hold up is proportional to the amount of feed, we can divide the total hold up by the feed for the 2009 PIV and we get that about 9.5 percent of the material fed into the cascades escapes as 0.96 percent enriched hold up and about 2.4 percent is lost in the feed purification cylinder. This means that during 2009, approximately 724 kg U at 0.97 percent were lost and 185 kg U at 0.72 percent were lost. This results in a "real" separative work per machine of 0.58 kg SWU/yr for 2009, compared to 0.49 without factoring holdup.

[23] In the Dec 2009 FAS Issue Brief, we did not have hold up concentration data, so we assumed it was the same as the feed material, or 0.7%, which will make a very small difference in the calculated performance.

If all hold up accumulated until November 2009 was re-fed into the machines during 2010 this will create the appearance of an increase in separative power. Subtracting the value of the two streams from the total separative work for 2010 and dividing by the number of centrifuge days and multiplying by 365 gives us a separative work per machine of 0.63 kg SWU/yr, compared to 0.77 if Iran did not re-feed all of its hold up. In this extreme case, we assume that any hold up produced during 2010 was re-fed into the cascades as well.

If all hold up was re-fed, is there an increase in centrifuge performance during 2010 relative to 2009? Under this scenario, there is still an increase in separative power from 2009 to 2010, but that is not significant because it falls within the uncertainty in the number of machines that were operating during that period. So, in theory, it is possible that hold up could account for the performance hike. In practice, it is unlikely that Iran re-fed all of the hold up back into the machines, which amounts to close to 20 percent of the amount of uranium fed that year.

Note that the average capacity from Feb 2007 to Nov 2009 factoring hold up is 0.53 kg SWU/yr. The average capacity from Feb 2007 to Nov 2010 without factoring hold up, meaning that whatever was lost was fed back in, is 0.54 kg SWU/yr. We would expect those two values to be similar, except that we would expect an even higher average for the 2010 PIV, since the 2007 PIV centrifuge performance values are exceptionally low.

It is possible that the jump in IR-1 performance is, at least in part, due to re-feeding separative work in the form of hold up or, in the case of PFEP, enriched material from a second cascade. However, we believe that explaining the *entire* increase in performance by those factors in unlikely. The entire hold up accumulated until the end of 2009 constitutes 20 percent of all material fed into the cascades during 2010. If all hold up was re-fed back into the machines,[24] this would be a significant increase in cascade flow rates, which would seem unacceptable to the plant operator.

Real Increase in Performance

Although it is possible to, at least in part, explain the increase in performance by salvaging separative work lost as hold up, the option remains that the observed increase of effective centrifuge separative power at both FEP and PFEP is due to technological improvements in Iran's machines. This would imply that the boost in performance is long-term and that we should expect similar IR-1 performance at other facilities, such as Fordow.

Iran has been known to have poor accountancy, which implies poor measurement of flow rates. However, in 2009 Iran started independently calibrating its data. If Iran has improved its accuracy in measuring flow rates then, by making simple adjustments, it could improve the performance of its centrifuges by operating them closer to the flow rates for which the design was optimized. Note that the average feed per centrifuge increased by more than 60 percent from 2009 to 2010. In this context, drop in centrifuge numbers during 2010 could be explained by Iran replacing old IR-1 machines with better performing ones.

We cannot know for sure what combination of technical factors increased Iran's centrifuge performance, but an improvement in Iran's centrifuges would not be surprising. Public statements by Iranian officials show that they were aware that their machines were underperforming. Moreover, the Iranians have been testing single IR-1 machines at PFEP, which could imply that they hoped to improve its capabilities.

[24] This assumes that all hold up produced during 2010 was also re-fed back into the cascades.

4 Estimating Iran's Breakout Potential

Assessments of Iran's breakout potential play an important role in justifying policy decisions. There are several steps in making a nuclear weapon: designing the bomb, producing enough weapons usable fissile material (HEU or plutonium) and "weaponizing" the material, that is, physically assembling the bomb and testing it.

There are many uncertainties in estimating Iran's breakout potential. This estimate of Iran's breakout time assumes that the weapons design work has already been done, that the non-nuclear components of the bomb have been manufactured and are assembled and all that remains is for the fissile material, in this case the HEU, to be produced and weaponized. A key time-limiting factor is how quickly Iran can enrich enough HEU for a bomb. After HEU is produced at an enrichment facility, it would have to be converted from UF6 to uranium metal, the metal would be machined and the bomb will be assembled. Iran would have to test any weapon before considering it to be reliable, unless it is building a simple gun-assembled uranium bomb, which requires more HEU compared to more sophisticated designs. It is uncertain what kind of weapons design Iran may try to use and, consequently, how much HEU it would require. In the following calculations, an IAEA significant quantity (SQ) of 25 kg of U235 in HEU is used to measure the amount of material that is required for a single weapon. This is an upper limit of a bomb's worth of material, but the reasoning behind choosing this number are explained in detail in section 2 of the December 2009 FAS issue brief.

Iran has a couple of breakout options. It could expel IAEA inspectors and use existing enrichment facilities such as FEP and soon the Fordow enrichment plant. Alternatively, it could use a clandestine enrichment plant of unknown capacity. A reasonable assumption is that the secret facility will be smaller than its main enrichment plant at Natanz, which is therefore likely the quickest option for producing HEU. The Iranian government's poor track record of keeping enrichment facilities secret may weigh in if it considering viable breakout options.

The time required to produce bomb-grade uranium is determined by the uranium enrichment capacity available, which is affected by a number of factors: (1) the effective performance of individual centrifuges, (2) the number of machines available, and (3) the amount and degree of enrichment of the uranium used as feedstock.

Centrifuge Performance for Breakout Scenarios

This paper shows that over the past year, Iran's uranium enrichment capacity has increased due to a jump in the effective separative power of the IR-1 centrifuge, which appears to be 0.77 kg SWU/yr based on calculations from IAEA data -- a 60 percent increase relative to 2009. This implies that Iran could have been quicker in making a bomb in 2010 than in 2009. The key question is whether this boost in performance is long-term and can be applied to future breakout scenarios.

We have shown that separative work can be lost as hold up and this can drive centrifuge performance up or down. IAEA data shows that about 10 percent of all material fed into the cascades escapes as hold up. Unless hold up is automatically re-fed into the cascades, which did not seem to be the case in 2009, separative work lost as hold up could be factored simply as an inefficiency in the cascade in the short-term. Thus, in calculating a *rapid* breakout option,[25] it does not seem likely that Iran would be concerned about calibrating flow rates to salvage separative work lost as hold up, unless this provides a

[25] If breakout time was in the order of years, not months, Iran could afford to re-feed holdup, in which case there will be zero net losses to performance.

significant advantage. Therefore, an Iranian planner calculating a realistic breakout scenario may want to use the effective separative work per machine with hold up lost, the best estimate of which is the 2009 value of about 0.49 kg-SWU/yr.[26]

On the other hand, the possibility that Iranian centrifuge performance improved during 2010 cannot be ignored. What if Iran chose to break out during a period when it "appears" to be performing better? This could shorten its breakout time by 60 percent, for a given number of centrifuges. Therefore, policy planners concerned about an Iranian bomb may want to use the effective separative work per machine for 2010 of 0.77 kg-SWU/yr in calculating breakout scenarios in the immediate future. Although, in such cases, worst case approaches are preferable, one should also be careful not to overestimate Iran's capabilities as this could interfere with strategic assessments of Iranian nuclear intentions, such as the Fordow enrichment plant.[27]

Effective separative performance based on IAEA data is the most reliable method in estimating breakout scenarios in the *short term*. If, for some reason, we are interested in knowing how long it would take Iran to make a bomb in 2013, then additional assumptions need to be made. For example, Iran is planning on mass producing a next generation centrifuge over the next years, so current estimates of IR-1 performance may be entirely irrelevant for long term enrichment capacity forecasts.

Amount and Enrichment Level of Feedstock

Iran could substantially shorten its time to a bomb if it uses higher enriched material as feedstock instead of natural uranium. Currently, Iran has enough stockpiled enough LEU to be used as feed for a weapon. The amount of feed needed depends on how much material losses (waste) Iranian engineers are willing to accept, which in turn, is affected by the amount of UF6 available. If more material is wasted, the time to produce the HEU will be shortened. It takes about 1 300 kg UF6 enriched to 3.5 percent as feedstock to produce a SQ of HEU at 90 percent, with a tails assay of 0.7 percent, the concentration of natural uranium. About 1 200 kg UF6 would be required if the tails assay was 0.45 percent or the current estimated waste concentration at FEP. According to the most recent PIV data, Iran has accumulated over 3 tons UF6 of LEU, which would be enough to produce 2 crude nuclear weapons.

Once Iran has enough LEU for one bomb, the amount of LEU stops being a limiting factor on the timing -- given a certain number of centrifuges, it would take exactly the same amount of time for Iran to enrich to HEU if it had enough stockpiled feedstock material for 1, 2 or 3 bombs. The amount of LEU is important for how many bombs Iran can make, not how quickly it can produce them. If LEU is shipped out of the country, as was the plan under the recent deal to refuel the Tehran Research Reactor, unless Iran is left below one bomb's worth of LEU, this would not add time to the clock for the production of the first bomb.

Similarly, if Iran started with 20 percent enriched uranium as feedstock, this would substantially reduce its time to a bomb. Currently, Iran has produced about 40 kg UF6 (27 kg U)[28] or roughly 20 percent of the amount needed to produce a SQ of HEU. At its current enrichment pace, it would take Iran about

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[26] Data shows that Iran may have been re-feeding at least some hold up during 2010, although the possibility that there was a net loss in separative work loss due to hold up during that year cannot be excluded.
[27] In November 2009, using capacity estimates, we were able to accurately predict that Fordow was likely one of many similar plants. See Ivan Oelrich and Ivanka Barzashka, "A technical evaluation of the Fordow fuel enrichment plant, *Bulletin of the Atomic Scientists*, 23 November 2009, <http://www.thebulletin.org/web-edition/features/technical-evaluation-of-the-fordow-fuel-enrichment-plant>.
[28] "Iran has produced 40kg of 20-percent fuel: Soltanieh," *ISNA,* 17 January 2011, <http://www.isna.ir/ISNA/NewsView.aspx?ID=News-1696920&Lang=E>.

3.5 years to produce the necessary 20 percent uranium. However, Iran could install more cascades for 20 percent enrichment (there is allocated space for a total of 6 cascades at PFEP). If all 6 cascades or 3 cascade systems are running, Iran could produce enough 20 percent material for bomb feedstock in about a year.

Breakout at FEP

The quickest way for Iran to break out is to expel safeguards inspectors and use the entire enrichment capacity at current facilities to produce HEU. The approach considered below is simplified and assumes that Iran could repipe cascades to enrich from LEU concentrations to HEU and the IR-1 will maintain the same effective performance regardless of the cascade shape. The batch recycling option, or running the product through existing 164 machine cascades, would require more time and is not considered here.

The total enrichment capacity of FEP can be estimated by simply multiplying the *effective* separative power per machine times the number of operational centrifuges. As of November 2010, Iran was running 4592 centrifuges. This would suggest a separative power of 3536 kg SWU/yr, if we use the effective separative power of the IR-1 for 2010.

It takes 1510 kg SWU to enrich enough LEU (concentration 3.5 percent) to a significant quantity (27.8 kg U) of HEU (concentration 90 percent), with a tails at concentrations of natural uranium, 0.71 percent. If Iran used its entire capacity at Natanz, it would take about 5 months to produce enough HEU for a bomb.

If Iran started from 20 percent enriched uranium, it would take less than a month to enrich enough HEU for a bomb, if the tails are set at 3.5 percent U235. This would need about 146 kg U as feedstock. Alternatively, if material is scarce, Iran could set the tails to 0.7 percent. This scenario would require 129 kg U, and it would take a month and a half to produce the HEU.

Breakout at Fordow

The Fordow enrichment plant is a well-protected facility, located in a tunnel in the mountains near Qom and in close proximity to an Iranian military base equipped with air defenses. These characteristics make it less susceptible to an air strike and, therefore, a more convenient location for breakout than FEP, despite its smaller capacity. Iran had announced plans to install 3,000 IR-1 centrifuges at Fordow.[29] This implies that the plant would have an annual enrichment capacity of 2 310 kg SWU. It would take Iran close to 8 months to produce enough HEU for a bomb at Fordow. However, if it started with 20 percent enriched uranium, it would take Iran about a month and a half to produce a SQ of HEU with a tails assay of 3.5 percent, if it had enough 20 percent enriched material as feedstock.

Breakout Potential Conclusions

Increased centrifuge performance during 2010 could shorten Iran's time to a bomb by as much as 60 percent relative to 2009. Iran has enough LEU to serve as feedstock for the production of enough HEU for a crude nuclear weapon. Even if its stockpile of LEU is substantially reduced, as long as Iran continues operating centrifuges, it could produce bomb-grade material starting from natural uranium, but this would take longer compared to LEU. Potential breakout scenarios at FEP using Iran's current capabilities show that it would take about half a year to *overtly* produce enough material for a single

[29] In September 2010, Iran notified the IAEA that it planned to have only 12 cascades for production and 4 cascades for R&D purposes (GOV/2010/62).

bomb. This does not seem like a reliable breakout scenario. However, in the near future, Iran could accumulate enough 20 percent material to be further enriched to a bomb's worth of HEU. This would dangerously cut its time to producing bomb-grade material to as little as a month at its main enrichment plant or a month and half at Fordow, which could be a viable breakout scenario.

5 Conclusions

There is an observed increase in the enrichment performance of the IR-1 centrifuge at FEP during 2010 relative to the previous year based on calculations from IAEA data, which is the most credible information on Iran's nuclear program. Despite a drop in centrifuge numbers during 2010, the total enrichment capacity of Iran's main facility has increased relative to previous years. The growth in enrichment capacity from 2009 to 2010 is greater than from 2008 to 2009. Contrary to statements by U.S. officials and many experts, Iran clearly does not appear to be slowing down its nuclear drive. On the contrary, it has a greater enrichment capacity and seems to be more efficient at enrichment. The measured increase in IR-1 performance could be explained, at least in part, by salvaging separative work lost as hold up. However, an actual improvement in centrifuge performance would not be surprising and cannot be ruled out.

Currently, the quickest breakout scenarios assume Iran would further enrich its stockpiled LEU to produce bomb-grade uranium. According to these estimates, it would take Iran anywhere from 5 months to almost a year to produce enough HEU for a single crude bomb, which does not seem like a viable breakout option. We are still in a stage where the numbers of new centrifuges Iran installs and their effective performance have significant effect on its time to a bomb. As total enrichment capacity at FEP grows and especially as Iran continues to stockpile 20-percent uranium, we are entering a phase in which Iran's enrichment capacity will no longer be the important rate-limiting step in producing a bomb because breakout time will be in the order of weeks, not months.

About the Author

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About FAS

The mission of the Federation of American Scientists (FAS) is to promote a safer and more secure world by developing and advancing solutions to important science and technology security policy problems. FAS was founded in 1945 by scientists who worked on the Manhattan Project to develop the first atomic bombs. The founders believed that scientists had a unique responsibility to both warn the public and policy leaders of potential dangers from scientific and technical advances and to show how good policy could assure the benefits of new scientific knowledge.