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Calculating the Capacity of Fordow

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SUMMARY:
This brief serves as a technical appendix to our November 23 article in the Bulletin of the Atomic Scientists, which premised that Iran's Fordow enrichment plant is well-sized neither for a commercial nor military program. We concluded that Fordow may be one of several facilities planned. Our estimates of the plant's capacity are based on current performance of IR-1 centrifuges at Natanz. Underlying our assessment is a calculation of the effective separative capacity per machine of 0.44 kg-SWU/year. This result is based on IAEA data, which we consider as the most credible open-source information on Iran's nuclear program. Our estimate for the IR-1 performance is significantly lower than values published in the literature, which cannot account for the current performance of Natanz. We argue that, despite Iranian rhetoric, Tehran's strategic planning for Fordow is based on actual enrichment performance rather than on desired results.

The 16 November 2009 report of the International Atomic Energy Agency (IAEA) was its first account of the initial inspection of Iran's recently declared Fordow Fuel Enrichment Plant (FFEP), located just north of Qom. On November 23, we published in the *Bulletin of the Atomic Scientists*[1] a short technical analysis of what the new plant reveals about Iran's nuclear weapons potential and its implications for international policy.

In summary, we concluded that the timing of the construction and announcement of the facility did not *prove* an Iranian intention to deceive the agency, although it certainly poses many troubling questions. The facility is far too small for commercial-scale enrichment, raising concerns that it might have been intended to covertly produce highly enriched uranium (HEU) for weapons. But we also argued that the facility, by itself, is actually too small to be of great use to a weapons program. A quite plausible explanation is that FFEP was meant to be one of several covert enrichment plants and was simply the only one to be discovered. We believe, however, that it is significant that the Iranians assured the agency that they "did not have any other nuclear facilities that were currently under construction or in operation that had not yet been declared to the Agency"[2] because any additional enrichment plants uncovered in the future will be almost impossible to explain innocently. This statement, however, does not preclude Iran from making a decision to construct new enrichment facilities in the future.

Our *Bulletin* publication was based primarily on information available in the press and in IAEA reports. Much of our discussion of the legality and political significance of the FFEP hinged on the timing of the construction, specifically – did Iranian actions violate even Iran's narrow interpretation of their obligations to declare new facilities to the IAEA? We argued that the plant is too small to be useful to enrich fuel for nuclear reactors. Contrary to most analyses, we also argued that the FFEP was too small even to make much sense as a source of nuclear weapon material. These statements are based on a technical analysis of Fordow's capabilities and specifically 3 main time estimates: (1) it will take about 90 years for the 3,000 IR-1 centrifuges, as declared by Iran in the design information submitted to the IAEA, to enrich enough natural uranium to fuel a typical 1000-megawatt reactor for

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[1] Ivan Oelrich and Ivanka Barzashka, "A Technical Evaluation of the Fordow Fuel Enrichment Plant", 23 November 2009, <http://www.thebulletin.org/web-edition/features/technical-evaluation-of-the-fordow-fuel-enrichment-plant>

[2] GOV/2009/74, Art. 16, 16 November 2009, <http://www.iaea.org/Publications/Documents/Board/2009/gov2009-74.pdf>

a year, (2) it will take about four years for those same machines to enrich enough natural uranium to a "significant quantity" (SQ), or a bomb's worth, of HEU, and (3) it will take about one year to enrich enough LEU to a SQ of HEU for a bomb. All three calculations, based on estimates of the performance of the IR-1, were not included in the *Bulletin* article but are presented here.

In this *Issue Brief*, we show in detail our calculations and state explicitly our assumptions and assertions. We believe it is important to go into some detail about how we arrived at these results because our estimate of the effective capacity of Iran's centrifuges is smaller, by a factor of three, four, or more, than values typically cited in the literature. Simple rules of thumb sometimes used to estimate Iran's nuclear weapon breakout capability can seriously overestimate the threat and are not useful in analyzing Iranian intentions. In addition, we have used the IAEA value of a SQ of uranium, the amount that is required to make a crude gun-assembled type nuclear weapon. We explain the rationale behind this decision.

1 Estimating the Separative Capacity of the IR-1

Most analyses that have addressed the question of estimating the enrichment capacity of Iran's facilities, either at Natanz or Fordow, estimate the capacity of an individual centrifuge of the type installed in the facility (or in the case of Fordow, expected to be installed) and then multiply by the number of centrifuges, which should yield the total capacity of machines working together. There are two problems with this approach. First, the capacity of the individual centrifuges is unknown and, second, linking centrifuges together in cascades is more complicated than can be represented by simple multiplication. We shall deal with each problem in turn.

The performance of the IR-1, Iranian centrifuge now in operation at the Fuel Enrichment Plant (FEP) in Natanz, is not known, although several estimates have been made. The Iranians have never formally published technical details or performance characteristics of their centrifuges (except for few Farsi media accounts quoting Iranian officials). The IAEA recognizes centrifuge separative capacity as legitimate proprietary data and does not collect values directly nor publish estimates. Nevertheless, some information can be gleaned from a wide range of sources. Estimates of IR-1 performance in the literature are based on some combination of: (1) calculated performance based, in turn, on estimates of the physical characteristics of the machine, such as size and rotation speed obtained from sources or from author's estimates, (2) assumed analogs with known European machines that have imperfectly known performance or even less well known Pakistani machines, (3) unnamed sources of unascertainable credibility with supposed access to non-public data that cannot be verified, (4) calculated performance based on Iranian statements, primarily a television interview with Gholamreza Aqazadeh, the head of Iran's Atomic Energy Organization, or (5) selective data contained in IAEA reports.

We have calculated the capacity of the IR-1 using a significantly different approach than has been previously published. Our results yield the effective separative power per machine based entirely on performance data from the IAEA reports, which we consider to be the most credible open-source of information on the Iranian nuclear program.

1.1 IR-1 Performance in Open Source Literature

In *Table 1*, prepared by FAS researcher Richard Abott, we show what we believe are the sources of the most commonly cited values for the IR-1. None of the sources listed can be considered to have reliability that could be called scientific; such data are simply not publically available.

Table 1. Separative Power[3] of P-1 and IR-1[4] Centrifuges in Open Source Literature

Separative Power [kg-SWU/yr]	Source Year	Source Author	Source Name	Reference
1-3	2004	Gilinsky, *et al*	*A Fresh Examination of the Proliferation Dangers of Light Water Reactors*. Victor Gilinsky, Marvin Miller, Harmon Hubbard. October 22, 2004. The Nonproliferation Policy Education Center. P. 37&38.	"unclassified sources (and educated guesses)"
>1	2004	Boureston	"Fuel Cycle: Tracking the technology," August 31 2004, Jack Boureston. *Nuclear Engineering International.*	"sources told Nuclear Fuel"
0.5-2	2005	Zentner	*Nuclear Proliferation Technology Trends Analysis*. M.D. Zentner, G.L. Coles, R.J. Talbert, September 2005. Pacific Northwest National Laboratory, PNNL-14480, p. 22	None, assumed Urenco CNOR, SNOR values
1-2	2005	Zentner	*Nuclear Proliferation Technology Trends Analysis*. M.D. Zentner, G.L. Coles, R.J. Talbert, September 2005. Pacific Northwest National Laboratory, PNNL-14480, p. 22	None, assumed Urenco G-1 values.
2	2005	Glaser	*Life in a Nuclear Powered Crowd (The Problem of Uranium Enrichment),* Alexander Glaser, Program on Science and Global Security, Princeton University, New Approaches to Cooperative Security Workshop: Powerpoint presentation, slide 21.	None
3	2006	Albright & Hinderstein	*The Clock is Ticking, But How Fast?,* David Albright and Corey Hinderstein*, ISIS Report,* March 27, 2006.	"senior IAEA officials"
2.5-3	2006	Albright	"When Could Iran get the Bomb? What we know and what we don't know about Iran's nuclear program." David Albright*, Bulletin of the Atomic Scientists,* July/August 2006	None
2-3	2006	Lewis	"Collected Thoughts On Iranian LEU." *Arms Control Wonk,* Jeffrey Lewis. April 15, 2006.	Reverse engineer calculations from Steve Rademaker estimates.
1.4	2006	Albright	*Iran's Political/Nuclear Ambitions and U.S. Policy Options. A compilation of statements by witnesses before the Committee on Foreign Relations, 109th Congress, Second Session, May 17 & 18 2006.*	Based on calculations using Aqazadeh statement of 164-machine cascade
2.3	2006	Albright	*Iran's Political/Nuclear Ambitions and U.S. Policy Options. A compilation of statements by Witnesses before the Committee on Foreign Relations, 109th Congress, Second Session, May 17 & 18 2006.*	Based on calculations using Aqazadeh's public statements about Natanz' eventual 48,000 centrifuges

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[3] In the literature, separative power is synonymously referred to as separative capacity, separative performance, or separative output.

[4] Specifically noted Iranian machines have SWUs in bold.

Separative Power [kg-SWU/yr]	Source Year	Source Author	Source Name	Reference
2.3	2006	Lewis	“More Fun With SWU,” Jeffrey Lewis, *Arms Control Wonk,* April 18, 2006	Own calculations from Aqazadeh statements
1.46	2006	Lewis	“Iranian Centrifuge Developments.” Jeffrey Lewis, *Arms Control Wonk.* Friday, May 12, 2006.	Commenter named "Richard Feynman" calculations
<1	2007	Hibbs	*Pakistan developed more powerful centrifuges. Inside NRC*, A Platts.com Product and Services Highlight, Mark Hibbs, January 29, 2007.	"Western government intelligence"[5]
2	2007	Albright	“A Witches' Brew? Evaluating Iran's Uranium-Enrichment Progress.” David Albright and Jacqueline Shire. *Arms Control Today*. November, 2007	"level Pakistan is said to have achieved"
3	2007	Albright	“A Witches' Brew? Evaluating Iran's Uranium-Enrichment Progress.” David Albright and Jacqueline Shire. *Arms Control Today*. November, 2007	"According to a former Urenco official…realistic maximum output"
about 2	2008	Albright & Shire	*Iran Installing More Advanced Centrifuges at Natanz Pilot Enrichment Plant: Factsheet on the P-2/IR-2 Centrifuge*, David Albright and Jacqueline Shire, ISIS, February 7, 2008	None
1.362	2008	Garwin	“When could Iran deliver a nuclear weapon?” Richard L. Garwin, *Bulletin of the Atomic Scientists*. January 17 2008	Calculations based on Aqazadeh 2006 interview
2.5	2008	Lewis	*IR2 and IR3 Scoops,* ArmsControlWonk, May 27, 2008.	Scott Kemp calculations, based on 42% observed efficiency
2.5	2008	Jones	*Iran's Centrifuge Enrichment Program as a Source of Fissile Material for Nuclear Weapons*, Gregory S. Jones, April 8, 2008.	Albright & Hindernstein,*”*The Centrifuge Connection,*” Bulletin of Atomic Scientists,* March/April 2004 pp. 61-66
1-2	2008	ISIS	*ISIS NuclearIran FAQ, What is a SWU?*	None[6]
about 2.2	2009	Presbo	*Progress at Natanz (reposted). Verification, Implementation and Compliance (armscontrolverification.org),* February 27, 2009	None,” based on a model with a separative factor of…”
2.1	2009	Salehi	*Iran Building New Generation of Centrifuges*. Fars News Agency, September 22, 2009.	Ali Akbar Salehi, head of the Atomic Energy Organization of Iran (AEOI)

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[5] Individual segment on the P-1

[6] “Iran’s P-1 centrifuges are estimated to have a maximum SWU of 3, and appear to be working at a level of between 1 and 2 SWU per year.”

The danger arises only when repeated citation makes us forget just how wobbly the foundations of our estimates really are.

The Aqazadeh interview[7] is an important source of technical information. The interview, in Farsi but with English transcripts available, provides a surprising amount of quantitative data – enough, in fact, to calculate the separative power of the IR-1. (There are a couple of apparent inconsistencies in the numbers, but we believe these are easily resolved if references to flow in some cases refer to uranium and in other cases to uranium hexafluoride.) Calculation of the IR-1 performance based on this interview has been done by us (to be published soon) and others, including Richard Garwin.[8] While analysis of the Aqazadeh interview is significant, Garwin points out that the numbers are a useful measure of potential capacity and can be used as a benchmark for comparison, writing, "[...] the above analysis shows how far from a nominal performance Iran's centrifuges must fall, to fail to produce HEU for nuclear weapons within a year after the action is taken to rearrange the plumbing [...]"

We suspect that separative power estimates based on the Aqazadeh interview describe more closely what the Iranians *hope* to achieve with the IR-1 than actual performance. The purpose of our article in the *Bulletin* was to glean Iranian intentions from the technical specifications of Fordow. Is it better to consider Iranian hopes or Iran's knowledge of the actual operations of its centrifuges? We believe Tehran's strategic planning is based on data from actual operation of IR-1s at Natanz, despite what Iranian rhetoric may be, and the best way to determine what Iran knows about its own machines is to look closely at the IAEA data.

1.2 Diminished IR-1 Performance

The IAEA reports that, at least early on, "The throughput of the facility has been well below its declared design capacity."[9] There are a variety of reasons that the IR-1 might perform less well than calculation and analogy with known machines might suggest. Most citations of its performance are actually references to the Pakistani P-1. That the IR-1 is basically a copy of the P-1 is fairly well established, but the performance of the P-1 is estimated primarily by trying to find an analog with some better characterized European machine. However, there is not even a complete consensus on what that analog ought to be and the performance even of older European machines is not always available (centrifuge capacity is considered a proprietary and competition-sensitive value). Moreover, there is no guarantee that the Pakistanis, even with detailed technical data stolen by A. Q. Khan, were able to achieve the performance of the European models (the Pakistanis, not being parties to the Nonproliferation Treaty, are not subject to IAEA inspections, so the outside world has almost no public information on the performance of the their centrifuges). In addition, there is no guarantee that the Iranians were able to reproduce the performance of the Pakistani machines even with the Khan network's technical help. Thus, there are several links in the chain connecting half-century old European technology to the IR-1 of today and we believe that knowledge of every link is uncertain.

Actual performance of the IR-1 may also fall short of expectations because, for example, more easily available but weaker rotor materials may have been substituted. Poor quality control in the manufacture of the rotors or bearings may cause a wide distribution of maximum sustainable speeds and, to keep the number of machine failures to tolerable levels, all the machines may be operated at

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[7] "Iran's Nuclear Chief Explains Nuclear Fuel Cycle, Comments on US Concerns Interview with Gholamreza Aqazadeh, the head of Iran's Atomic Energy Organization – live" ,*Vision of the Islamic Republic of Iran Network 2* , Friday, April 14, 2006

[8] Richard Garwin, "When could Iran deliver a nuclear weapon?" *Bulletin of the Atomic Scientists*, 17 January 2008, <http://www.thebulletin.org/web-edition/features/when-could-iran-deliver-a-nuclear-weapon>

[9] GOV/2008/4, Art.43, 22 February 2008, <http://www.iaea.org/Publications/Documents/Board/2008/gov2008-4.pdf>

lower speeds. Slight changes in rotor structure can change the flexural vibrational harmonics and reduce the critical frequency. In addition, details of the design and manufacture of small components, such as the product scoops, can have large effects on the efficiency of a machine.
The centrifuges may not be operated at their most efficient throughput or the cuts (the ratio of product to feed) may not be optimal. Indeed, the IAEA reports indicate that the Iranians are not able to even *measure* their flow rates to within better than about a third,[10] making it highly unlikely that they are able to *optimize* their flow rates.

1.3 Performance of IR-1s in Cascades

Estimates of the overall capability of Natanz are usually calculated by multiplying the enrichment performance of the IR-1 (which we have shown to be highly uncertain) and the number of centrifuges (a value well established by IAEA inspection). But even if the performance of the machines were well established, such a simple calculation is inadequate; linking centrifuges together is more complex than that.

One centrifuge can process only a tiny fraction of the uranium needed by a nuclear power plant. Therefore, many machines are operated in parallel to increase throughput. Such an arrangement is called a stage. Nor can one stage enrich uranium to fuel-grade level in one step, so the output of one stage provides the input for a next higher stage for further enrichment. Such an arrangement of stages is called a cascade. We have described cascades in detail on the FAS website.[11]

The output of an ideal cascade is the output of a single machine multiplied by the number of machines, but ideal output is never achieved in practice for a variety of reasons. Machines in different stages are not identical in operation because different throughputs result in different separative performance, unless optimized precisely. So the output of the machines will not be the same yet all the outputs will be mixed, losing some separative work effort. The enriched output from one stage is passed up to the next higher stage for further enrichment. But, to conserve material, the waste, or relatively depleted output, from a stage is recycled back to a lower stage. Thus, each stage (except the bottom and top stages) has two input streams, from higher and lower stages (and the input stage, where natural uranium is fed into the cascade has three input streams). If these inputs are not perfectly balanced, material of different concentrations will be mixed and separative work already done will be wasted. When solving the equations for an ideal cascade, the number of centrifuges required in each stage will not necessarily be integer. The ideal cascade might contain a stage of, say, 5.4 centrifuges. Obviously, one cannot have 0.4 centrifuges so the stage will in fact contain either 5 or 6 machines and either the flow rates appropriate for the cascade will not be optimal for the machines or the optimal flow rates for the machines will not be optimal for the cascade.

Because of the complexity of linking centrifuges into cascades, the most common approach to estimating the capability of the Iranian facility should be modified. Rather than calculate a simple product by multiplying a highly uncertain machine capacity by the number of machines, that product should also be multiplied by an additional efficiency factor for the cascade, which we believe is also highly uncertain. The weakest aspect of this approach is that all of the uncertainties that create errors between estimated and actual performance point in the same direction, toward overestimating Iranian capacity.

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[10] Ivan Oelrich and Ivanka Barzashka, "Iran's Uranium: Don't Panic Yet." *FAS Strategic Security Blog*, 23 February 2009, <http://www.fas.org/blog/ssp/2009/02/irans-uranium-dont-panic-yet.php>

[11] Ivanka Barzashka and Ivan Oelrich, "Enrichment Cascades," <http://www.fas.org/programs/ssp/nukes/fuelcycle/centrifuges/cascades.html>

1.4 Calculating Effective IR-1 Capacity

We describe here the approach we used to produce the numbers we use in the *Bulletin* article quantifying the enrichment capacity of the newly discovered Fordow facility near Qom, which will reportedly use the same IR-1 machines that are currently being used in Natanz. We use well-documented, publicly available data from official IAEA reports and one assertion: The best estimate of the near term capacity of the Fordow facility is the most recent capacity of the Nantanz facility, scaled by size. We calculate the performance assuming a facility with 3000 centrifuges like those in Natanz (the IR-1) and a critical mass of enriched uranium of 25 kg. (Advanced bomb designs could definitely use less uranium; this is the IAEA "significant quantity.")

Recent IAEA reports contain enough information to calculate the total enrichment capacity and efficiency of the entire Natanz facility, including the number of centrifuges in operation, the total throughput of the facility, the enrichment levels, and the amount of product.

Table 2 shows the key input parameters needed to calculate the Natanz capacity. The process quantities reported by the IAEA are for uranium hexafluoride; we converted to quantities of uranium, so those are listed also. (The molecular weight of uranium hexafluoride is 352 and of uranium 238, so one can convert from hexafluoride to uranium by multiplying by 238/352 or 0.676.)

Table 2. Iranian enrichment and throughput between 18 November 2008 and 30 October 2009[12]

Stream	**UF6** [kg]	**Uranium** [kg]	**Concentration** [% U235]
Feed	**10412**	*7039*	*0.711*
Hold Up	**518**	*350*	*0.711*
Effective Feed		*6688*	**3.49**
Product	**814**	*550*	
Waste	**9080**	*6138*	*0.46*

We do make one correction to the feed. Since material is neither created nor destroyed and, we hope, not escaping into the environment, the total output should equal the total input. If fact, it does not because some material is held up in cold traps. (The rotors are spinning at very high speed so it is impossible to get a good seal between the rotor cap and the tubes running into the center of the rotor. Because of the strong radial g-forces toward the outside of the rotor, the density of material along the axis of the rotor is low and the leakage is small but there is nevertheless some leakage into the vacuum between the rotor and the outside container and the leaked material must be pumped out of that volume and sequestered in cold traps.) We assume that the material leaks out from each machine equally, so the average U-235 concentration of the leaked material will equal the weighted average concentration of the material in the cascade, which should, in turn, equal the concentration of the feed material, which in this case in natural uranium.

Eventually, the trapped material will be recovered and could be recycled. If an enrichment facility operator trapped material separately from each stage in the cascades, the material leaking from the enriching stages would be slightly enriched in U-235 and the material from the depleted, or stripping,

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[12] Values in bold are taken from IAEA reports GOV/2009/74 and GOV/2009/8; values in italics are calculated or assumed.

stages would be depleted in U-235. Technically, the recovered material could be reintroduced at the appropriate point in the cascade to salvage some of the invested separative work, if the precise concentration of that hold up is known. We suspect the Iranian operation is not so sophisticated and the recovered material will simply be reintroduced as feed later and the separative work will be lost. In this case, it is reasonable to simply use an *effective* feed rate, which would be equal to the actual feed minus the hold up and that is what we have done in these calculations.

The effectiveness of a centrifuge, cascade, or entire enrichment plant is described by the "separative work" it can do. The separative work is defined as the increase in the "value" of the material. The value function depends on the concentration of U-235 in the uranium and is defined in such a way that the work done by the centrifuge is independent of the concentration of the feed material. The value function, V, is a dimensionless quantity defined as:

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

where x is the relative concentration of U-235. The value of a certain amount of material at a certain concentration is simply the value function times the mass of the material. The separative work done by any enrichment process is the net increase in the value, that is the difference between the value of the input and the combined values of the two output streams, one enriched, one depleted in U-235. That is,

$$\Delta V = PV(x_p) + W\,V(x_w) - F\,V(x_f)\ . \qquad [2]$$

where F, P, and W are the masses and the x_p, x_w and x_f are the concentrations of U-235 in the product, waste and feed, respectively.

Note that the quantities have units of mass so ΔV has the units of mass. ΔV is measured in mass "separative work units" or SWUs, typically kg-SWUs. The output of an entire enrichment plant is sometimes quoted in ton-SWUs. The amount of separative work performed in a certain amount of time is a separative power, typically kg-SWU/year. We have described elsewhere separative work and how it is calculated[13] and have developed a useful online separative work calculator.[14]

The IAEA report does not include a measurement of the waste concentration but that is easy to calculate, assuming that no U-235 is created or destroyed. The total amount of U-235 in the feed will show up in either the product or the waste. That is,

$$Feed\ U235 = Product\ U235 + Waste\ U235 \qquad [3]$$

or

$$F\,x_f = P\,x_p + W\,x_w\ . \qquad [4]$$

The concentration of the waste is simply:

$$x_w = \frac{(Fx_f - P\,x_p)}{W}\ . \qquad [5]$$

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[13] Ivanka Barzashka and Ivan Oelrich, "Separation Theory", <http://www.fas.org/programs/ssp/nukes/fuelcycle/centrifuges/separation_theory.html>

[14] "Uranium Enrichment Calculator", <http://www.fas.org/programs/ssp/nukes/nuclearcalculators/nuclear_cal.html>

All of the variables on the right hand side of the equation are given in the most recent IAEA report.

Table 3 shows the operating dates, quantities, concentrations, value functions, and total value for two cases. Based on the last physical inventory, the IAEA reported that up until November 2008, Iran was enriching its uranium to 3.49 percent and that is the first case. We also do a second case using a product concentration of 4.9 percent because elsewhere the IAEA reports that it has never detected any enriched material more concentrated than that. This serves as a worst case (in the sense that it provides a maximum estimate of capacity).

Table 3. Separative work of FEP between 18 November 2008 and 30 October 2009

Feed Amount F [kg U]	**Feed Concentration** xf [% U235]	**Product Amount** P [kg U]	**Product Concentration** xp [% U235]	**Waste Amount** W [kg U]	**Waste Concentration** xw [% U235]	**Separative Work** [kg SWU]
6688	0.0071	550	0.0349	6138	0.0046	1809
6688	0.0071	550	0.049	6138	0.0034	3620

Note that between 18 November 2008 and 30 October 2009, the Natanz facility generated 1836 kg-SWUs, assuming the lower product enrichment concentration, and 3613 kg-SWUs, using the higher concentration.

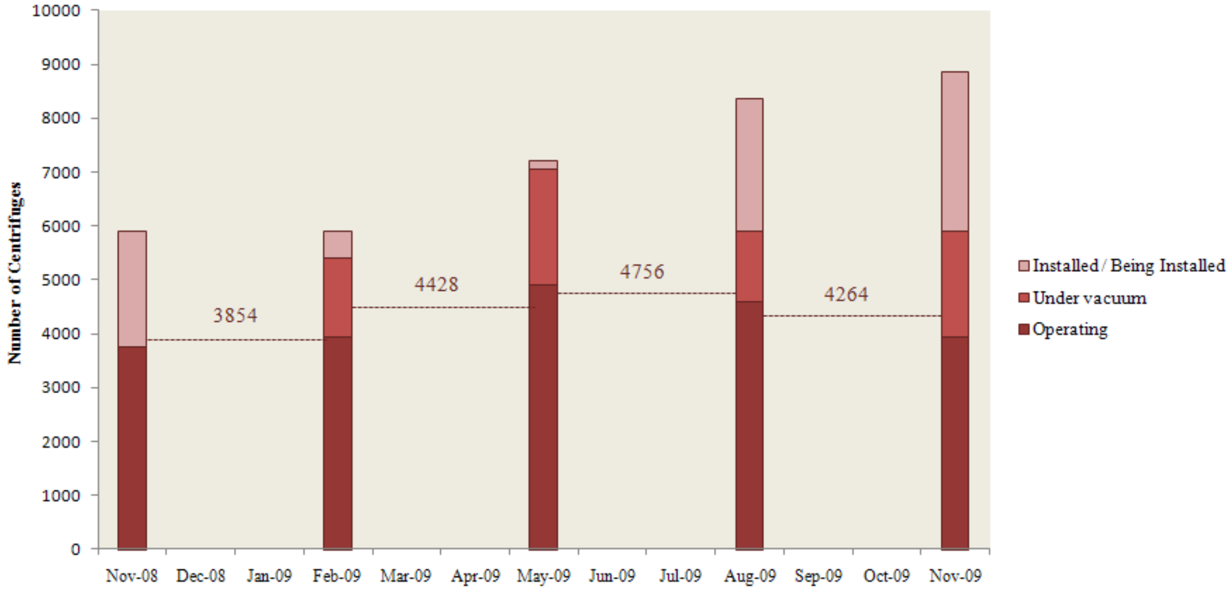
Now we need to develop a scaling factor, for which we will use an *effective* centrifuge capacity. Note that this may not be the actual centrifuge capacity. For example, the centrifuges may have significantly higher actual capacity but, due to technical issues discussed, the overall performance of the cascade could be low and the inferred performance of individual centrifuges would, therefore, appear low. We cannot say where inefficiencies appear and do not try to guess, but using an effective centrifuge capacity allows an easy metric for comparison to other published values.

Table 4. Centrifuge Machine-Days at Natanz

Period From	**Period To**	**Days Per Period**	**Average Number of Operating Machines**	**Machine-Days**
12-Aug-09	30-Oct-09	79	4264	336856
31-May-09	12-Aug-09	73	4756	347188
1-Feb-09	31-May-09	119	4428	526932
18-Nov-08	1-Feb-09	75	3854	289050
18-Nov-08	**30-Oct-09**	**346**		**1500026**

To develop an effective centrifuge capacity, we need the total capacity divided by the number of centrifuges. Unfortunately, that number has been changing over time. *Table 4* shows the number of centrifuges reported by the IAEA at various times during the period of interest and *Graph 1* illustrates these data.

Graph 1. Number of Centrifuges Operational at FEP between November 2008 and November 2009[15]



We make the simple approximation that the average number of centrifuges operating in the interval between two inspections is simply the arithmetic mean of the number at the beginning and the end of the interval. With this simple assumption, we are able to calculate the number of centrifuge-days for each interval and sum them for the entire period to arrive at a bit over one and a half million centrifuge-days. Next, we take the total separative work of the Natanz facility and divide by the total number of centrifuge-days and then multiply by 365 to convert to kg-SWU/year per centrifuge. The results are shown in *Table 5*.

Table 5. Recent Effective Centrifuge Separative Capacity for Natanz, 1 November 2008 to 30 October 2009

Product Enrichment [% U235]	**Separative Work** [kg SWU]	**Machine-Days** [days · number of machines]	**Separative Work/ Machine** [kg SWU/day per centrifuge]	**Separative Work per Machine** [kg SWU/yr per centrifuge]
3.49	1809	1500026	0.001205979	**0.44**
4.9	3620	1500026	0.002413292	**0.88**

The effective separative capacity of an IR-1 is 0.44 kg-SWU/year. This is the basis for the 0.5 kg-SWU/year that we used in our quick calculation in the *Bulletin* article and is about a quarter or fifth of the value typically used to estimate Iranian enrichment potential. If we take as a worst case that the total amount of enriched material has a U-235 concentration of 0.49 percent, a case that we consider highly unlikely, then the answer doubles to 0.88 kg-SWU/year. Note that the concentration of the product for the period discussed will become available with the results of the next physical inventory verification of the agency.

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[15] Data based on IAEA reports GOV/2009/74, GOV/2009/55, GOV/2009/35, GOV/2009/8, GOV/2008/59

2 Amount of Uranium Required for a Nuclear Weapon

Iranian enrichment capacity is of interest because the potential rate of HEU production divided by the HEU required per bomb should yield the rate at which Iran could build nuclear bombs. Both of those values are uncertain. In addition, HEU production estimates include time required to produce the material for a nuclear weapon and do not include weaponization, or physically constructing the bomb and testing it.

A nuclear explosion is fundamentally different from a conventional explosion because it depends on sustaining a nuclear chain reaction in a mass of material. One can make a firecracker by using tiny amounts of conventional explosive but, below a certain threshold, nuclear material produces no explosion at all. This is called a critical mass, which is the minimum amount of material that will maintain a chain reaction. (The point at which a chain reaction is sustainable is called criticality.) The IAEA uses the term "significant quantity" (SQ) to mean much the same thing, that is, the amount of material that a beginning nuclear power would need for its first bomb design. The IAEA uses values of 8 kg for plutonium and 25 kg of U235 in HEU.

The problem with defining a critical mass is that criticality is a function of both the mass *and* the density; as density goes up, the required mass goes down. A gun-assembled uranium bomb, which brings two masses together at constant density to form a mass greater than the critical mass, is considered simple enough and well enough understood to not need testing (the first such bomb was "tested" over Hiroshima). And, because it does not compress the uranium, the density is set at the normal density of uranium. For such a weapon, 25 kg is a reasonable threshold. Plutonium bombs *must* use implosion designs, which compress a given mass of nuclear material to a higher density to bring the mass above criticality. Implosion designs can use uranium as well, and the compressed uranium will go critical at much less than 25 kg.

There is another complication. The IAEA's definition assumes that a beginning nuclear power will be aiming for a Hiroshima-like yield but lower compression of a given material or the same compression of smaller materials will produce some nuclear yield, simply less. A nation might *want* a higher yield weapon but accept a lower yield if severely constrained by limits on nuclear material. For example, North Korea's first nuclear test was of such a low yield (near 0.4 kilotons), that most observers believed it to be a failed test. Richard Garwin and Frank von Hippel[16] speculate that it might have been more of an experiment than a test. Perhaps the Koreans built the biggest bomb that would fit on their missile and then simply tested it to discover what the yield is. The result might have been disappointing, but 0.4 kilotons is still a huge bomb by any conventional weapon standard. Similarly, if Iran were willing to accept lower yields, it could further reduce the amount of material required in a weapon. Thomas Cochran and Christopher Paine[17] argue that the IAEA SQs should be reduced by a factor of eight because sophisticated nuclear designers going for lower yields could make do with that little material. Even if limiting ourselves only to beginner nuclear designers, the amounts of uranium needed in implosion devices should be half of the current SQ.

In our calculations, we have used the IAEA SQ as a "bomb's worth" of HEU and clearly this could be lower. There are two cautions, however. First, as the amount of material used goes down, the designer accepts a lower yield. However, an unsophisticated designer, unable to draw upon a body of

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[16] Richard Garwin and Frank von Hippel, "A Technical Analysis: Deconstructing North Korea's October 9 Nuclear Test," *Arms Control Today*, November 2006, pp 14-16, <http://www.princeton.edu/sgs/faculty-staff/frank-von-hippel/The_Clocks_Ticking-Iran.pdf>

[17] Thomas Cochran and Christopher Paine, "The Amount of Plutonium and Highly-Enriched Uranium Needed in Pure Fission Nuclear Weapons," Natural Resources Defense Council, 13 April 1995, <http://www.nrdc.org/nuclear/fissionw/fissionweapons.pdf>

past testing and design information, runs a greater risk of producing weapons that will not produce *any* yield at all rather than a low yield. In terms familiar to the U.S. debate about the reliability of its weapons, lower yield weapons have lower design margins, meaning that smaller variations due to manufacturing or individual weapon operation are tolerated before the weapon fails to explode at all. Thus, a factor of eight reduction is the SQ might be appropriate for sophisticated designers but not novices. Second, whereas a gun-assembled bomb is so simple that a designer could have near perfect confidence that an untested weapon would work, the same is not true of implosion weapons. Implosion weapons are more complex and subtle. When allowing the Iranians the opportunity to get to a "bomb's worth" of material faster by assuming less material is needed, one is also assuming a more sophisticated bomb design that will require a longer design phase and will almost certainly require testing, which will be unambiguous. In effect, cutting down on the material production time will result in a longer time to develop a weapon.

3 Calculating Commercial and Breakout Scenarios

In the introduction, we said that this paper was meant to show the calculation behind three quantitative statements in our *Bulletin* article: that Fordow would take (1) ninety years to produce one year's worth of fuel for a large commercial reactor, (2) four years to produce a SQ of HEU starting with natural uranium, and (3) a year to produce a SQ starting with LEU.

While we have data on enrichment levels and amounts of uranium production at Natanz from IAEA reports, we do not have information on what the Iranians are *going* to do at Fordow, so a few assumptions are needed. In addition, for our *Bulletin* article, we used an approximation of the effective centrifuge capacity of 0.5 kg-SWU/yr, rather than the 0.44 kg-SWU/yr derived here and for the current calculation, we will use more precise numbers.

According to design information submitted by Iran to the IAEA[18] and US intelligence data[19], the Fordow facility is planned to be set up for 3,000 centrifuges (actually 2952, which is 18 of the 164 centrifuge cascades, similar to those already operating in Natanz). This suggests a total facility capacity of 0.44 times 2952 or 1300 kg-SWU/year.

3.1 Producing LEU for a Commercial Reactor from Natural Uranium

In estimating the time required to produce a year's worth of fuel for a commercial reactor, we assumed a 1000-gigawatt electric reactor. How much fuel such a reactor uses depends on the design (and keep in mind, the Iranian enriched uranium is not intended for Bushehr but for future plants). Some new reactor designs use more highly enriched fuel and burn the fuel longer. We assumed the reactor is comparable to current pressure water types and would burn about 27,300 kg of 3.3 percent uranium a year, assuming a thermal efficiency of 0.325, capacity factor of 0.8 and a burnup of 33,000 MWd/MT[20].

Another uncertainty is the amount of uranium-235 left in the enrichment waste. The world commercial standard seems to be 0.2-0.25 percent. The Iranians seem to leave much more U235 in their waste, with concentrations closer to 0.4 percent. This makes sense if, as we argue, Iranian enrichment is highly inefficient and, therefore, costly. If uranium cost is of greatest concern, an

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[18] GOV/2009/74, Art. 9, 16 November 2009, <http://www.iaea.org/Publications/Documents/Board/2009/gov2009-74.pdf>

[19] "Background Breifing by Senior Administration Officials on Iranian Nuclear Facility", 25 September 2009, <http://www.whitehouse.gov/the_press_office/Background-Briefing-By-Senior-Administration-Officials-On-Iranian-Nuclear-Facility/>

[20] Benedict, Manson, Thomas H. Pigford, and Hans W. Levi. *Nuclear Chemical Engineering*. 2nd ed. New York: McGraw-Hill, 1981. Print.

operator will try to extract as much U-235 as possible from every kilogram, meaning the amount left in the waste will be small. If the enrichment cost is more important, the operator will try to get as much enriched uranium as possible out of every available SWU, meaning more uranium will be fed into the machines and more U-235 will be sacrificed in the waste. Presumably, if Iran could achieve higher levels of enrichment performance, they would adopt more typical waste concentrations and their higher waste concentration is a tacit admission of low performance.

Producing 27,300 kg of 3.3 percent uranium starting with natural uranium and waste of 0.2 percent requires 136 ton-SWUs; if the waste is 0.46 percent, then 82 ton-SWUs are required. We are using an effective centrifuge capacity of 1300 kg-SWU/yr for 18 IR-1 cascades. So in the first case, Fordow would produce a year's worth of fuel in 105 years and the second case 63 years. (Using 3,000 machines and 0.5 kg-SWU/yr per machine and 0.2 percent tails, yields 90 years.)

3.2 Producing a Bomb's Worth of HEU from Natural Uranium

We have similar questions when calculating production of a SQ of HEU. Taking SQ as 25 kg of U-235, that is 27.8 kg of 90 percent HEU, then with waste concentration of 0.2 percent, 6320 SWUs are required, which would take our Fordow plant 4.9 years. If the waste were 0.46 percent, then 3.4 years would be required. (Using a rough calculation of 3,000 machines and 0.5 kg-SWU/yr per machine and 0.2 percent tails, yields 4.2 years.)

Of course, if we do not use the IAEA definition of "significant quantity," these numbers could be lower. The production times are simply proportional to the quantity of HEU enriched so, for example, if the SQ were reduced by half, all the above times would be cut in half. However, reducing the SQ effectively means choosing a more sophisticated weapon design, which requires testing, in turn extending the time to a deployable weapon.

3.3 Producing a Bomb's Worth of HEU from LEU

Finally, we consider a breakout scenario of starting with LEU to produce HEU. In this case, the Iranians have far more discretion in the concentration of the waste. By setting the waste concentration higher, they can get HEU faster with a given enrichment capacity (while, of course, starting with more LEU). Indeed, the U-235 concentration of the "waste" could easily be higher than that of natural uranium. If we start with Iran's current LEU stock of 3.49 percent and use a waste concentration of 1 percent, then the Fordow facility will need to generate 1330 kg-SWUs, just a shade over a year's production. This time can be reduced by using more LEU and setting the waste concentration higher. For example a waste of 2 percent corresponds to 9 months. We believe that this was the scenario that the White House may have been referring to when they said that the facility not large enough to "make sense from any commercial standpoint, […] enough for a bomb or two a year, it's the right size."[21]

We believe, based on this analysis, that Iran's enrichment capacity is frequently seriously over represented. The data from the IAEA indicates that the Iranians have not yet become adept at enriching uranium, although most likely separative performance will improve with the newer generation centrifuges that Iran is producing.

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[21] "Background Breifing by Senior Administration Officials on Iranian Nuclear Facility", 25 September 2009, <http://www.whitehouse.gov/the_press_office/Background-Briefing-By-Senior-Administration-Officials-On-Iranian-Nuclear-Facility/>

4 Conclusion

In our *Bulletin* article, we attempted to reverse engineer the history and expected capability of the Fordow facility to see what this reveals about Iranian nuclear intentions. Probably the most important questions revolve around the timing of the decision to build the facility and when construction actually started. Iran recognizes a much less rigorous requirement for declaring facilities than the IAEA believes they are committed to. However, the Iranians might be in violation even of their own more narrowly defined requirements, as US officials have suggested. If that were not the case, we must accept their claim to the IAEA that work on construction on the tunnel that now houses Fordow began as a generic project or “contingency center” against military attacks before 2007 without a centrifuge facility in mind.

The capacity of Fordow also figures prominently when trying to unravel Iran’s intentions. Fordow is unambiguously too small to be a commercial enrichment facility, which immediately raises suspicions that it is part of a weapons program. However, our assessment went further to consider how exactly the new enrichment plant would be used to manufacture weapons’ material and argued that Fordow is too small even as a weapons facility. (We speculated in the *Bulletin* article that Fordow could be one of several similar facilities that Tehran might have hoped to keep secret.)

Our estimate of the capacity of Fordow was based on recent performance of Natanz, as revealed by quantitative data measured during IAEA on-site inspections. We calculated an *effective capacity* for the only commercially operating Iranian centrifuge, the IR-1, that is significantly lower (by a factor of three or so) than the most widely accepted and cited values in the literature. Unfortunately, all of the estimates of IR-1capability are inconsistent with the IAEA data measured on site; the estimated IR-1 capabilities are too high. We pursue an entirely different approach for calculating Fordow’s capacity based on measured data on the production of the *entire* Natanz facility. This *Issue Brief* explains how our numbers were derived and gives the details of the data and assumptions that we applied.

We believe that it is more reliable and reasonable to estimate the near term future performance of Fordow on the recent performance of Natanz rather than to base an estimate on published values that cannot account for the current performance of the enrichment plant, as recorded by the agency. In addition, despite Iranian rhetoric, we believe that Tehran’s strategic planning would be based on actual enrichment performance rather than on desired results.

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