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ISIS REPORT

Critique of Gregory Jones's Breakout Estimates at the Natanz Fuel Enrichment Plant (FEP) [1]

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At the problem-plagued Natanz Fuel Enrichment Plant, breakout in two months remains unrealistic.

In any discussion about Iran's nuclear weapons capability, a key estimate is the amount of time Iran would need to "breakout" and enrich to weapon-grade its stock of low-enriched uranium (LEU) that is currently under International Atomic Energy Agency (IAEA) safeguards. This estimate provides an indication of the amount of time the international community has to detect and respond to Iran, should it embark on a breakout scenario. If breakout times become a matter of several weeks, then even the ability of the IAEA to detect a breakout is at issue.

Most estimates of breakout time at the Natanz Fuel Enrichment Plant (FEP) exceed six months. A year ago, U.S. officials stated that breakout at the FEP would take about a year, while ISIS assessed that breakout would take six months. At least one other government assessed breakout time as between these two estimates.

Thus, it was interesting when Gregory S. Jones assessed that Iran could currently enrich a stock of 3.5 percent LEU and existing 19.75 percent LEU to enough weapon-grade material for one bomb's worth in 62 days at the FEP. His estimate appeared recently in *The Washington Post*, *The New Republic*, and a Bipartisan Policy Center publication.

Because Jones's estimate differs so radically from other breakout estimates, ISIS reviewed his calculation, enlisting the assistance of an experienced centrifuge expert who has performed many detailed centrifuge calculations of the Iranian program. The ISIS and government estimates are based on detailed calculations modeling the centrifuge cascades at the FEP. The ISIS calculation uses a "fixed plant" production model, which means that the existing cascades are not reconfigured as in the U.S. estimate. This difference accounts for much of the divergence in the ISIS and U.S breakout estimates.

ISIS's review of Jones's methodology concluded that his method of calculation is unreliable in predicting the production of weapon-grade uranium in a breakout at the FEP, even as a worst case.[2] In particular, his method would greatly understate the length of time needed to produce a significant amount of weapon-grade uranium at the FEP. Given the problems at the FEP during the past year, even while mitigated by Iran's modest success in producing 19.75 percent LEU, ISIS found on balance no justification to change its earlier breakout estimate of six months at the FEP. The following discusses problems in Jones's conclusions about breakout times.

[1]Greg Jones, "An In-Depth Examination of Iran's Centrifuge Enrichment Program and Its Efforts to Acquire Nuclear Weapons." Nonproliferation Policy Education Center, September 2011.

[2] ISIS did not evaluate the use of this method in approximating enriched uranium output in Iran's advanced centrifuges, which are reportedly slated for deployment at the Fordow enrichment plant, near the city of Qom.

Jones's Calculation

Jones's estimate uses two enrichment steps, taking a stockpile of 1,415 kg of 3.5 percent uranium to 120 kg (uranium (U) mass) of 19.75 percent in 46 days, and 153.2 kg (U mass) of 19.75 percent uranium to 20 kg (U mass) of 90 percent in 12 additional days (see Table 3 in Jones's August report). Jones incorporates 38.3 kg (U mass) of 19.75 percent uranium that had already been produced by June 2011 at the Pilot Fuel Enrichment Plant (PFEP) at Natanz. In both steps, the estimate uses 5,184 IR-1 machines enriching at the Fuel Enrichment Plant.

His result derives from the use of separative work calculations that assume an idealized cascade and a two-step "batch-recycling" enrichment process, one from 3.5 percent to 19.75 percent and a second one from 19.75 percent to 90 percent He assumes that Iran needs to produce 20 kilograms of weapon-grade uranium for its first weapon.

His calculation for the step from 3.5 percent to 19.75 percent reflects the actual production rate achieved by Iran in a cascade at the PFEP (but see below). His estimate for the step from 20 percent to 90 percent is not justified by data.

Separative Work Calculations are Unreliable at the FEP

As is well known, Iran's cascades at the FEP are not ideal. In addition, many years of experience in evaluating the FEP's performance has shown that separative work calculations are not accurate estimates of the actual situation at the FEP. The basic design of the cascades at the FEP involves 164 IR-1 centrifuges linked together in 15 stages (see figure 1). This cascade, according to an expert with years of experience with this type of centrifuge, is far from ideal because of the limited number of centrifuges in the cascade and weaknesses in the design of this type of centrifuge, which Iran bought from Pakistan.

To off-set this criticism, Jones claims that his calculation is accurate because of a well-known phenomenon of cascades. When the feed rate in a cascade is reduced, the separation factor, or ability of the individual centrifuge to enrich, increases. However, this increase has a cost, namely the decrease of the separative capacity, which is directly related to the production rate of the product. He concludes, however, that the separation factor can be increased without significantly affecting the separative capacity, i.e. product, and that the separative work calculation gives an accurate estimate of that product.

In IR-1 cascades at the FEP, the drop in separative capacity would be expected to be great when enriching from 20 percent to 90 percent. In fact, according to a former IAEA official with years of familiarity with the FEP, in practice, going from 20 percent to 90 percent in one step may not be possible in FEP cascades. Because the amount of uranium hexafluoride in a cascade significantly decreases as the concentration of U-235 increases, the gas pressure in the cascades decreases as a result. In the case of the FEP cascades, the gas pressure within the centrifuges can become so low at the top of the cascade that no product will emerge. This result is also reflected in at least one of the references Jones cites, where the referenced graph shows a sharp drop in separative capacity, or product, when the feed rate is reduced past a certain point.[3] This problem is why most use a two-step process, where 19.75 percent would be enriched to 60 percent and then the 60 percent is increased to 90 percent, or weapon-grade. The goal is to significantly increase the total number of stages that the uranium passes through. In practice, to increase output and efficiency, it is desirable to increase the

[3] *Safeguards Training Course: Nuclear Material Safeguards for Enrichment Plants, Part 4. Gas Centrifuge Enrichment Plant: Diversion Scenarios and IAEA Safeguards Activities*, K/ITP--156/P4/R1, Martin Marietta Energy Systems, Inc., Oak Ridge, Tennessee, October 1988, p.165. This paper does not contain any calculations for an actual centrifuge plant. It was intended to show the potential for the production of highly enriched uranium at gas centrifuge plants.

number of stages above the 15 stages in the current IR-1 cascade design. Doing so requires the reconfiguration of the cascades and contributes to a total reconfiguration time of at least 2-3 months. A reconfiguration time is reportedly included in the U.S. government estimates.

Moreover, the available data on the production of 19.75 percent LEU from 3.5 percent LEU at the PFEP in a single cascade is not consistent with such production in an ideal cascade. There is a reasonable match between the actual production of 19.75 percent LEU at the PFEP and Jones's estimate using a separative work calculation. However, the differences should have raised concern about extrapolating this method to the next step, namely enriching from 19.75 percent to 90 percent.

Jones's justification for using an ideal separative work calculation relies extensively on a 2008 article by Alexander Glaser but this article dates from the time when Iran was expected to operate its IR-1 centrifuge considerably better. For example, Glaser assumes that the separative capacity of each IR-1 centrifuge would be 2.5 separative work units (swu)/year/centrifuge. Jones assumes an average value of 0.89 swu/yr/centrifuge, which is based on Iran's operational experience. (For historical and current values, see the ISIS website, which reports on these values quarterly.) However, Jones does not discuss the implications of the disparate separative capacities on his estimate.

Other Problems

In addition to the problems of modeling the enrichment output with a separative work calculation, there are several other factors that lengthen the breakout time.

1) In the case of making 19.75 percent enriched uranium, Jones assumes that the performance in one or two cascades at the PFEP can be replicated in 31 cascades in the FEP. He further assumes that these same cascades can reliably make weapon-grade uranium from the 19.75 percent LEU. However, the centrifuges in the cascades at the FEP have encountered excessive breakage and erratic operation. For example, during the summer of 2011, the average separative output in the FEP fell to 0.74 swu/year/centrifuge, differing from the 0.89 swu/year/centrifuge value used by Jones. During much of 2010, Iran had achieved an average of about 0.9 swu/year/centrifuge, but as Iran expanded the number of centrifuges enriching from about 4,000 to near 6,000, this average decreased.[4] Thus, Jones's assumption that all cascades would work flawlessly during the period of breakout is highly questionable.

2) The performance of a centrifuge can vary in different stages. A cascade making LEU can be very efficient while the same cascade making highly enriched uranium would be less efficient. This factor can lower the output significantly. Glaser does not account for the inefficiencies at these higher enrichments.

3) After emptying cascades (and the modules) at the FEP and starting to feed higher-enriched uranium, such as when introducing 19.75 percent LEU to make weapon-grade uranium, it is possible that a significantly greater mass of feed is required than a separative work calculation would predict. When the cascades at FEP and PFEP started, they required much more feed than expected. Figure 2 shows the ratio of feed to product in the cascade(s) at PFEP producing 19.75 percent LEU from 3.5 percent LEU. Figure 3 shows a comparable figure during the start up period of the FEP. As is evident, large amounts of extra feed were needed in the initial phase of operation. The reasons for this phenomenon are not well understood. Partially, it is due to "hold-up," or the amount of uranium that is deposited in the pipes, cold traps, intermediate storage tanks, etc. when uranium is first introduced. But hold-up does not fully explain the measured feed to product ratios. Another phenomenon may also occur more during startup periods. Because of centrifuge breakage and other cascade

[4] The reason for this decrease is unknown. This decrease should not be confused with the oft reported increase in the monthly production of 3.5 percent LEU at the FEP. This increase was accomplished by compensating with more IR-1 centrifuges enriching.

problems, significant amounts of feed produce enriched uranium with a lower than desired enrichment level. This material is dumped into special tanks rather than being mixed with the product.

One would expect that additions to hold-up should be less in the case of operating cascades in a batch recycle approach. Nonetheless, after emptying the cascades prior to enriching with a new feed, the large FEP modules, each containing 18 cascades and auxiliary equipment and tanks, will likely add enriched uranium feed to their inventories of hold up. In addition, as mentioned above, a fraction of the feed will end up in enriched uranium sent to dump tanks. Thus, high feed-to-product ratios may still occur during batch recycle. How large are these ratios in the FEP in a batch recycle mode? They are hard to predict without more data, but Iran is unlikely to know. These ratios could be substantial and require significantly more 19.75 percent LEU feed to produce the goal quantity of weapon-grade uranium.

4) The IR-1 cascades at the FEP are experiencing larger amounts of inter-stage “mixing” than expected, which means that uranium flowing up the cascade into a particular stage is at a different enrichment than the uranium flowing down to this stage. The result is that when the two flows combine and enter this particular a stage the resulting enriched uranium has lost separative work and is at a lower enrichment level than designed. Some mixing losses are inevitable, but the losses in the case of the IR-1 cascades are significant. During the last few years, the concentration of the cascade product has gradually declined, while the cascade tails concentration has increased. So, in a breakout, the effect of inter-stage mixing could degrade significantly the final enrichment level of the product of the step(s) from 20 to 90 percent, ignoring any other problems with the IR-1 cascades. To get to 90 percent may require additional recycling.

Findings

Estimating the breakout time at the FEP remains a complicated issue that requires careful consideration. A separative work calculation is inadequate to predict breakout times at the FEP. Such calculations should be discounted even as worst-case estimates.

Jones likely underestimates the amount of 19.75 percent LEU feed Iran would need to produce a given quantity of weapon-grade uranium. His calculation also overestimates the amount of product and its enrichment level that would result. The result is a significant underestimate of the breakout time at the Fuel Enrichment Plant.

Jones is correct to incorporate the effect of a growing stock of near 20 percent enriched uranium into calculations estimating the time Iran would need to breakout at the Natanz Fuel Enrichment Plant. As it grows, this stock will shorten the times needed for breakout at the FEP.

Iran has a high motivation to study the production of highly enriched uranium. It could be seeking ways to produce 60 percent or even 90 percent enriched uranium under a civilian justification. To that end, it bears watching Iran’s recent decision to reinsert U.S. origin spent highly-enriched uranium fuel into the Tehran Research Reactor for research purposes. Could this be a precedent for an Iranian argument that it needs to make its own HEU fuel for this reactor?

Figure 1: FEP IR-1 Centrifuge Cascade

Stage	10E	9E	8E	7E	6E	5E	4E	3E	2E	1E	5S	4S	3S	2S	1S
No. of Centrifuges	2 (1+1)	2	4	6	8	10	12	16	20	24	20	16	12	8	4
	Product Stage									Feed Stage					Tails Stage

Notes and Comments:

1) Stage 10E, which is where the highest enrichment level is achieved, involves two centrifuges but this stage acts to all intents as 'one plus a spare."

2) The cascade shape is far from an ideal cascade for highly enriched uranium because of the limited number of centrifuges in this cascade.

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

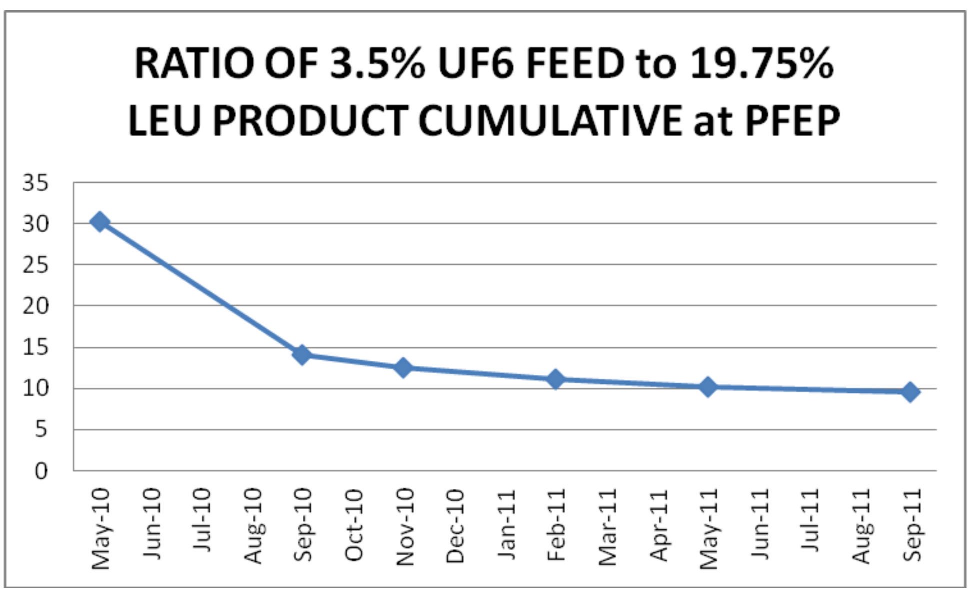

Figure 3: Ratio of the Cumulative 0.0711 Percent Natural Uranium Feed to the 3.5 Percent Enriched Product at the Natanz Fuel Enrichment Plant