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REPORT

The IR-6 Centrifuge Needs Further Development

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A thorough look at Iran's deployment and operation of IR-6 centrifuges indicates that this advanced centrifuge, widely assumed to be Iran's most promising and successful model, represents hidden challenges and inefficiencies in the Iranian enrichment program. There are several indicators that Iran's IR-6 centrifuge is less reliable, either due to design issues or lack of high quality components, and less efficient in its enrichment output than publicly assumed. It is achieving about half of its single machine theoretical value and about two thirds of its expected production-scale value. This is in contrast to the image Iran is promoting by making deployments of IR-6 centrifuges a priority and using the IR-6 for 60 percent highly enriched uranium (HEU) production. These problems undermine the commercial viability of today's IR-6 centrifuge in a civilian enrichment program but they do not reduce its proven capabilities in a nuclear weapons breakout, able to rely on inefficient centrifuges.

A revived Joint Comprehensive Plan of Action (JCPOA) would not prevent Iran from further developing the IR-6 centrifuge and its existing conditions would allow Iran to better prepare this centrifuge for subsequent mass production and deployment, measured in up to a few thousand per year, when key nuclear limitations on centrifuge deployment end in 2028-2030. This is another sign that Iran's advances have made the JCPOA archaic. With Iran's nuclear advances future-oriented, a nuclear deal should be, too. Iran's nuclear capabilities continue to become stronger, broader, and longer-lasting, and a nuclear deal should aim for the same.

Figure 1. On left, an IR-6 centrifuge rotor assembly. On right, three IR-6 outer casings. Source: 2021 Atomic Energy Organization of Iran (AEOI) video of Iran's temporary centrifuge assembly facility.

The IR-6 centrifuge has often been hailed as slated for mass production in Iran's gas centrifuge plants. It is a 200 millimeters wide and 1100 millimeters long centrifuge, composed of two carbon fiber rotor tubes connected by a bellows. While its single machine theoretical enrichment output is reportedly about 6.7 SWU per year per centrifuge, its average value in a production-scale cascade is estimated at 5.25 SWU per year per centrifuge.[1] The need to lower the theoretical value, particularly among Iranian centrifuge types, reflects difficulties and inefficiencies in operating large numbers of centrifuges in a production-scale cascade, typically in Iran involving 164-174 centrifuges. Nonetheless, the value of 5.25 SWU per year is what the average IR-6 centrifuge is expected to achieve in a production-scale cascade. This expectation is bolstered by the experience of the IR-2m and IR-4 centrifuges, the two other centrifuges at the foci of Iran's advanced centrifuge development.

This reduction also signifies that Iran's cascades are not "ideal," a technical term referring to an idealized cascade of centrifuges achieving the most efficient arrangement of centrifuges, something rarely achieved in countries such as Iran operating first or second-generation centrifuges in a relatively small cascade. Treating all cascades as ideal, however, remains appealing, since it involves a simplified calculation of the amount of separative work and enriched uranium product, despite the inaccuracy of the calculation when applied to centrifuge cascades that are far from ideal like in Iran. Nonetheless, a modified ideal cascade calculation can suffice for certain purposes, if the basic variables are reduced by efficiency factors modeled from actual production values. The reduction above from 6.7 to 5.25 SWU per year per IR-6 centrifuge represents one such reduction, leading to an efficiency factor of 0.78. This paper will explore additional efficiency factors for the IR-6 centrifuge as this centrifuge's operational experience is explored using data published by the International Atomic Energy Agency (IAEA) in its quarterly Iran reports.

Accelerated Deployments of the IR-6 Centrifuge

Iran's political leadership, particularly in its parliament, or the Majles, has pushed for faster installation of IR-6 centrifuges than the Atomic Energy Organization of Iran (AEOI). Parliament's December 2020 law mandated the installation of 1000 IR-6 centrifuges by the end of 2021, despite there being less than 200 in January 2021 and only one production-scale cascade installed.

Needless to say, the AEOI did not meet this deadline and in fact has yet to do so. As of May 2022, the last date when data were available, Iran had installed 538 IR-6 centrifuges in two cascades at Fordow and one cascade at the Natanz pilot plant, little over half of the mandated amount, and at that time, not all of these were being fed with uranium hexafluoride.

[1] David Albright, Sarah Burkhard, and Spencer Faragasso, "A Comprehensive Survey of Iran's Advanced Centrifuges," *Institute for Science and International Security*, December 2, 2021, https://isis-online.org/uploads/isis-reports/documents/A_Comprehensive_Survey_of_Irans_Advanced_Centrifuges_2021.pdf. The value of 6.7 SWU is from an AEOI poster at one of Iran's Nuclear Technology Day exhibitions.

The AEOI announced plans in June 2022 to install two more IR-6 cascades in the Natanz Fuel Enrichment Plant (FEP), in addition to one already planned for installation there.[2] Once these three are installed, although the date remains uncertain, the AEOI would have reached the mandated 1000 IR-6 centrifuges under the December 2020 law.

On July 9, 2022, Iran started to feed the second IR-6 production-scale cascade at the Fordow Fuel Enrichment Plant (FFEP) with near five percent enriched uranium, announcing that the cascade was producing near 20 percent enriched uranium.[3] Adding to concern, this cascade has been modified to be able to more easily change the enrichment level of the product, a modification designed more to facilitate breakout to the production of weapon-grade uranium than a justifiable civilian purpose.

The IR-6 cascades produce a variety of enrichments. A production-scale cascade at the Pilot Fuel Enrichment Plant (PFEP) produces 60 percent enriched uranium from near five percent enriched uranium feed. The two cascades at the FFEP produce near 20 percent from near five percent feed. The FEP cascades, when operational, are expected to produce near five percent enriched uranium.

The slow deployment of the IR-6 centrifuges reflects operational issues and possibly design challenges in the bellows. An attack on the Karaj centrifuge manufacturing site in June 2021 also contributed to a slowdown in the manufacture of IR-6 centrifuge parts. There is evidence that in Iran's rush to bring back its centrifuge manufacturing capability, the IR-6 components produced after the attack may be of lesser quality than those manufactured prior to the attack.

Deriving a Realistic IR-6 Enrichment Output Value

Operational IR-6 data can provide important insight into the achieved versus expected separative power of the IR-6 centrifuge when operating in a production-scale cascade. Two cases are considered, 1) production of near 20 percent enriched uranium at the FFEP and 2) production of 60 percent highly enriched uranium at the PFEP. As will be shown at the end of this report, Cases 1 and 2 demonstrate that the expected enrichment output of the IR-6 centrifuge needs to be further corrected, i.e. lowered by another efficiency factor of 0.6-0.7, resulting in separative power values of about 3.2-3.6 SWU per year per centrifuge. Compared to the original reported theoretical value of 6.7 SWU per year per centrifuge, the final values are about half. Based on the available operational data, the IR-6 centrifuge is not performing much better than the IR-2m and IR-4 centrifuges.

[2] Francois Murphy, "Exclusive: Iran expands advanced centrifuge work underground, IAEA report shows," June 8, 2022, Reuters, https://www.reuters.com/world/middle-east/iran-expands-advanced-centrifuge-workunderground-plant-iaea-says-2022-06-08/.
[3] Nasser Karimi, "Iran enriches to 20% with new centrifuges at fortified site," Associated Press, July 10, 2022, https://apnews.com/article/middle-east-iran-nuclear-united-nations-51cb62796ace2c64ba9278197d9b5464.

Why the Large Inefficiencies in the IR-6 Centrifuge?

There are multiple possible explanations for the relatively large observed inefficiency in the IR-6 centrifuge. In addition, it cannot be excluded that Iran is deliberately operating the IR-6 centrifuges at less-than-optimal levels, possibly to avoid centrifuge breakage, although this possibility applies more to the IR-6 cascade at Fordow than the PFEP. Moreover, other factors cannot be ignored and appear more likely.

The acceleration in the deployment of production scale IR-6 cascades is likely a factor. In April 2019, the AEOI was operating only a small IR-6 cascade of 20-30 centrifuges. Subsequently, it moved relatively quickly to deploying its first production-scale cascade, while facing pressure to deploy several more such cascades.

Another factor is the attack of the Karaj centrifuge manufacturing site, which may have reduced the number of components available and contributed to the subsequent, rushed production of lower quality parts. These parts were installed at the FFEP, possibly helping explain the poorer performance there.

Lastly, the IR-6 centrifuge may not be fully developed. The PFEP continues to include the operation of several small IR-6 cascades. Moreover, a 2021 AEOI video indicates that Iran may be continuing development of the IR-6 bellows, declared originally as made from carbon fiber. The video shows metal bellows for the IR-6, perhaps indicating on-going problems in the carbon fiber bellows and a desire to replace them with the more traditional metal bellows.[4] This is partially confirmed by IAEA reporting. On January 23, 2021, the IAEA verified that Iran had started manufacturing metal bellows for IR-6 centrifuges for testing, which Iran plans to reinforce with carbon fiber.[5] Large-scale deployment of a design in flux can foreshadow operational problems.

Implications

The inefficiencies in the operation of the IR-6 centrifuge highlight the fundamental weakness of Iran's civilian centrifuge program, namely its inability to develop a commercially viable centrifuge despite years of development. Despite this failure, Iran has demonstrated the adequacy of the IR-6 centrifuge to produce highly enriched uranium for nuclear weapons.

A revived Joint Comprehensive Plan of Action (JCPOA) will not stop Iran's further development of this centrifuge. If the original nuclear limitations are applied, requiring Iran to dismantle, but not destroy, all but a few tens of IR-6 centrifuges, it could still make progress on identifying

[4] David Albright and Sarah Burkhard, "Video Walk-Through of Iran's New Interim Centrifuge Assembly Center," *Institute for Science and International Security*, June 29, 2022, https://isis-online.org/isis-reports/detail/video-walk-through-of-irans-new-interim-centrifuge-assembly-center.
[5] "Analysis of IAEA Iran Verification and Monitoring Report - February 2021," *Institute for Science and International Security*, February 25, 2021, https://isis-online.org/isis-reports/detail/analysis-of-iaea-iran-verification-and-monitoring-report-February-2021/8.

problems and improving these machines, getting them ready for large-scale deployment (measured in thousands a year) in the years 2028-2030 when key nuclear limitations on centrifuge deployment end. If a revived deal reinstates Iran's original enrichment plan submitted as part of the original JCPOA, redeployment of a production-scale IR-6 cascade would be delayed for several years since Iran agreed not to deploy a production-scale cascade (taken in 2015 as 150 centrifuges) until the second half of year 12 of the deal, or in the second half of 2027.[6] However, it is unknown if the original conditions will still apply in a revived deal.

Iran's voluntary enrichment plan looks increasingly out-of-date, leading to questions of what modifications have been made to this plan in a draft revived JCPOA. For example, the plan emphasizes the IR-8 centrifuge; however, this centrifuge is today widely recognized as a failure with only a few deployed.[7] Iran very well may have demanded a revised, accelerated enrichment plan.

In summary, with a revived deal, Iran could continue working to solve the operational inefficiencies in the IR-6 centrifuge, utilizing smaller cascades, but it would be delayed in deploying larger numbers of these centrifuges under the original plan. But if Iran's voluntary enrichment plan has changed, it could accelerate its efforts, with an accelerated redeployment of cascades with greater numbers of IR-6 centrifuges and of more of these cascades in total.

Centrifuge research and development is one example of irreversible advances where implementation of restrictions negotiated seven years ago would lead to less meaningful outcomes today. The advances in Iran's enrichment program can only be offset by new, proportional restrictions, with a focus on the prevention of Iran advancing its enrichment program further or growing its ability to produce weapons-grade uranium openly or in secret, now or in the future. Areas that have progressed significantly may warrant drastic measures; a freeze or a ban. The only viable diplomatic way to limit further development of the IR-6 centrifuge, for example, appears via a freeze in centrifuge R&D. As many of Iran's nuclear advances appear future-oriented, a nuclear deal should be, too. Iran's nuclear capabilities continue to become stronger, broader, and long-lasting, and a nuclear deal should aim for the same.

[6] "Iran's Long-Term Centrifuge Enrichment Plan: Providing Needed Transparency," *Institute for Science and International Security*, Re-released April 25, 2019; Originally issued August 2, 2016, https://isis-online.org/isis-reports/detail/irans-long-term-centrifuge-enrichment-plan-providing-needed-transparency/8.

[7] "A Comprehensive Survey of Iran's Advanced Centrifuges" and subsequent quarterly IAEA reports on Iran.

Annex

Case 1: IR-6 Production of 20 Percent

The following calculations are based on 20 percent enriched uranium production by one IR-6 cascade deployed at the Fordow Fuel Enrichment Plant, extrapolated from information available on 20 percent enriched uranium production at Fordow in quarterly IAEA reports. All uranium amounts are given in uranium hexafluoride mass (hex mass) which includes the weight of the six fluorine atoms in a uranium hexafluoride compound. This is done because the IAEA reports the quantity of feed and product in uranium hexafluoride mass.

As discussed above, we calculate an effective separative power for the IR-6 centrifuge in a production-scale cascade, using as our basis modified ideal calculations. The expected average enrichment value is estimated as 5.25 SWU per year per centrifuge. In a cascade with 166 centrifuges at the FFEP, the total output, or separative work is 872 SWU per year.

Based on IAEA data in the period from November 2021 to February 2022, the IR-6 cascade is estimated to have produced 33.6 kg of nearly 20 percent enriched uranium over a period of 104 days, using 186 kg of less than five percent enriched uranium (hex mass) as feed. Again, assuming an ideal cascade, Iran would need 150 SWU and 170 kg enriched uranium feed (hex mass) to produce 33.6 kg 20 percent enriched uranium (hex mass), where the tails are taken as at the level of natural uranium, or a tails assay of 0.7 percent and the feed is 4.5 percent enriched uranium.[8] This output corresponds to an annualized average rate of 3.17 SWU per year per centrifuge in the production-scale cascade. Compared to the expected average separative power of 5.25 SWU per year per centrifuge, the cascade is achieving only 60 percent of its expected enrichment output, or an efficiency of 0.6.

At the same time, Iran used a higher than ideal feed of 186 kg (hex mass). A larger feed for the same product suggests a higher than natural tails assay, as the amount of material in feed, product, and tails has to balance. Here, the feed to product ratio was 5.5. In an ideal cascade, a higher tails assay means that less separative power is needed to achieve the same product. With a tails assay of 0.9 rather than 0.7, for example, Iran would have needed 135 SWU and 178 kg 4.5 percent enriched uranium feed if its cascade operated at ideal efficiency. This would leave an average value of 2.85 SWU per year per centrifuge, or an efficiency of 0.54.

Another way to gauge the efficiency of the IR-6 cascade is a direct comparison with the six IR-1 tandem cascades that produced 20 percent enriched uranium simultaneously. The IR-6 cascade produced an estimated 33.6 kg, or about half of the IR-1 cascades' estimated 67.6 kg (hex mass). Therefore, the 166 IR-6 centrifuges produced as much as half of the amount produced

[8] The IAEA only reports the amount of 20 percent enriched uranium produced by the IR-6 cascade and the tandem IR-1 cascades combined, but the amount produced by the IR-1 cascades can be estimated based on past daily production averages and subtracted from the total, resulting in 33.6 kg 20 percent enriched uranium (hex mass) assumed to have been produced by the IR-6 cascade. The same extraction can be done for the feed amount.

by the 1044 IR-1 centrifuges, or 522 IR-1 centrifuges. In other words, one IR-6 centrifuge produced on average as much near 20 percent enriched uranium as 3.14 IR-1 centrifuges. Assuming a separative power of 1 SWU per year for the IR-1[9] results in an effective separative power of 3.14 SWU per year for the IR-6. To get to 3.14 SWU per year from 5.25 SWU per year, one also arrives at an efficiency factor of 0.6.

Case 2: Production of 60 Percent Highly Enriched Uranium

The following calculations are based on 60 percent HEU production at the Natanz pilot plant, using information available in quarterly IAEA reports. However, 60 percent production occurs in two advanced centrifuge cascades, one IR-4 and one IR-6 cascade, and the amounts of feed and product the IAEA reports are not separated by cascade. Therefore, the following calculations apply to both the IR-4 and IR-6 cascade, and only general observations can be made about the IR-6 centrifuge. However, the IR-4 centrifuge is considered more developed than the IR-6 centrifuge, so this estimate may overstate the IR-6 centrifuge's performance.

Between February to May 2022, or over 84 days, Iran produced 17.8 kg near 60 percent highly enriched uranium using 164 IR-6 centrifuges with an expected estimated separative power of 5.25 SWU per year per machine when operated in a cascade and using 164 IR-4 centrifuges with an estimated separative power of 3.3 SWU per year per machine, resulting in the total estimated separative work of 323 SWU during the timeframe. Assuming an ideal cascade, Iran would need 223 SWU and 413 kg 4.5 enriched uranium feed (hex mass) to produce 17.8 kg 60 percent HEU (hex mass), where the tails are estimated to be above the level of natural uranium, estimated here as containing 2 percent uranium 235. In this case, the ratio between the achieved and expected separative work is 0.69. In terms of separative power, the average separative power is 3.6 SWU per year per centrifuge, better than in Case 1 at Fordow but still below expectations.

There are two factors that justify the use of a tails assay significantly greater than 0.7 percent, or natural uranium. The first one is that Iran uses less than a full cascade (30 IR-5 and 29 IR-6s centrifuges) in line 1 of the PFEP to recycle the tails back to near 5 percent enriched uranium. The second is the large amount of feed reported by the IAEA, 722.5 kg hex mass, during the latest reporting period. A caveat here is that the overall feed is reported as feed for lines 1, 4, and 6, however, counting some of the tails from line 4 and 6 also as feed for line 1 would in a sense lead to double counting.

[9] David Albright, Christina Walrond, and Andrea Stricker, "ISIS Analysis of IAEA Iran Safeguards Report," Table 3, November 14, 2013, *Institute for Science and International Security,* https://isis-online.org/uploads/isis-reports/documents/ISIS_Analysis_IAEA_Safeguards_Report_14November2013-final.pdf.