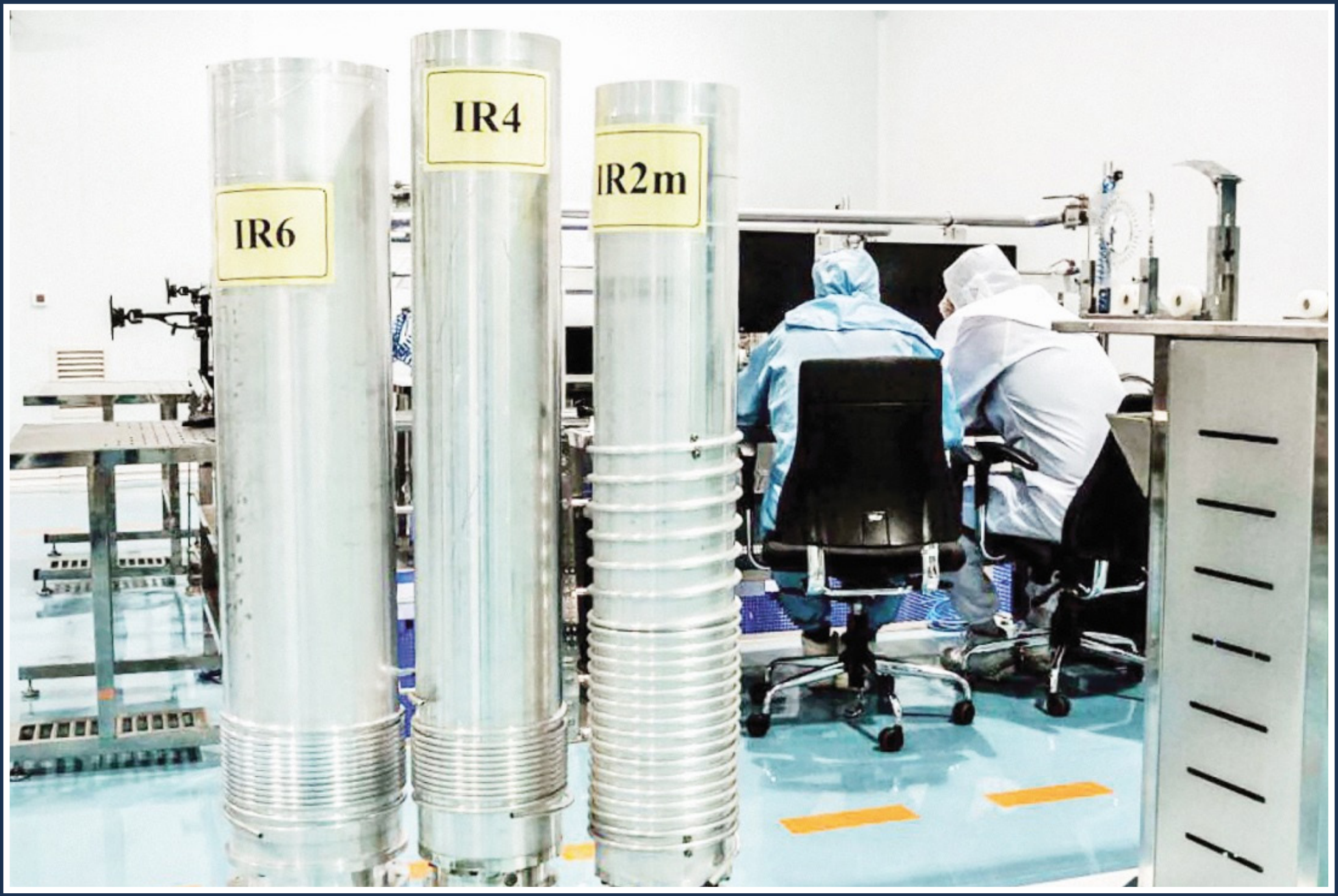
WISCONSIN PROJECT
ON NUCLEAR ARMS CONTROL

Beyond the IR-1

Iran's Advanced Centrifuges and their Lasting Implications



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Introduction

As a result of illicit imports and domestic development since the late 1980s, Iran now possesses thousands of gas centrifuges, which are the mainstay of its nuclear program. These rapidly spinning machines enable Iran to enrich uranium to a level suitable for nuclear reactor fuel, or to a higher level suitable for nuclear weapons. The number and capacity of these machines determine Iran's "breakout" time: how long it would take Iran—if it decided to do so—to produce the fuel for a small nuclear arsenal. The machines are also key to Iran's ability to accomplish a "sneakout": the production of nuclear weapon fuel at secret sites.

This report provides a technical description of Iran's centrifuges and estimates the contribution each is likely to make to Iran's ability to enrich uranium. It also reviews the testing and production history of centrifuge models, explores possible choke points in their continued development, and assesses the implications of Iran's growing mastery of centrifuge design and manufacturing. The report relies on information published in reports by the International Atomic Energy Agency (IAEA) and the United Nations, analysis of publicly available images of Iran's centrifuges, and studies of the centrifuges on which Iran's models are based.

The Importance of Advanced Centrifuges

To make fuel for nuclear weapons, Iran would need to produce weapon-grade uranium, which is usually defined as uranium enriched to at least 90 percent in the uranium isotope U-235.[1] Iran could do so using the centrifuges it is operating at the Fuel Enrichment Plant (FEP) and Pilot Fuel Enrichment Plant (PFEP) at Natanz and those it is operating at the Fordow Fuel Enrichment Plant (FFEP). Iran could also apply the technological proficiency it has acquired in its declared program to produce weapon-grade uranium at clandestine enrichment plants.

One of the most important variables in an evaluation of how quickly Iran could produce nuclear weapon fuel is Iran's ability to build and operate more powerful centrifuges. Such centrifuges would allow clandestine uranium enrichment sites to be smaller and easier to hide.

[1] Uranium enrichment is not the only path to obtaining fissile material for a nuclear weapon. Iran could also fuel a weapon with plutonium. The plutonium pathway, however, has been largely closed following the conversion of the Arak heavy water reactor. Some studies have also suggested that nuclear weapons could be fueled with uranium enriched to less than 90% U-235.

Iran's Centrifuges

Iran began its centrifuge effort with know-how from Pakistan, obtained from the notorious proliferation network led by the late Pakistani metallurgist A.Q. Khan. Khan stole centrifuge designs from the British-German-Dutch enrichment company Urenco during his work there in the 1970s and delivered them to Pakistan. In Pakistan, the designs were used to develop the P-1 type (based on the Dutch CNOR) and P-2 type (based on the German G-2) centrifuges. Khan also transferred incomplete P-1 designs and components to Iran in the late 1980s and in the mid-1990s sent Iran more complete P-1 and P-2 centrifuge designs and components.[2]

TABLE I: A COMPARISON OF IRAN'S CENTRIFUGE MODELS

MODEL	CAPACITY SWU/YR*	MATERIAL	FIRST TESTED	INSTALLED	IN PRODUCTION MODE**
IR-1	~0.8	Aluminum/ Maraging Steel	Late 1990s	6124	5963
IR-2m	~4-5	Maraging Steel/ Carbon Fiber	2009	1076	902
IR-4	~4-5	Carbon Fiber	2009	511	510
IR-6	10†	Carbon Fiber‡	2013	208	197
IR-8	20-24†	Carbon Fiber‡	2017	1	0
IR-9	40-50†	Carbon Fiber‡	2021	1	0

* The separative work unit (SWU) measures the amount of effort needed (by one machine, in one year) to separate uranium isotopes in the enrichment process. A higher SWU/year indicates a more capable centrifuge that can enrich greater quantities of uranium to higher levels in shorter periods of time.

** Centrifuges that are accumulating enriched uranium. Numbers based on centrifuges verified by the IAEA at Iran's declared sites in August 2021

† Iranian claim

‡ Assumed due to technical progression

[2] R. Scott Kemp, "The Nonproliferation Emperor Has No Clothes," International Security, Vol. 38, No. 4, 2014), pp. 67-70, available at https://dspace.mit.edu/handle/1721.1/89182; "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions 1737 (2006) and 1747 (2007) in the Islamic Republic of Iran," International Atomic Energy Agency, November 15, 2007, pp. 3-5, available at https://www.iaea.org/sites/default/files/gov2007-58.pdf.

The power of each centrifuge model is based on the efficiency with which it is able to separate isotopes of uranium – specifically the fissionable U-235 isotope from the heavier U-238 isotope, of which natural uranium is largely composed. The separative work unit, or SWU, is used to measure the amount of effort needed (by one machine, in one year) to separate these isotopes in the enrichment process. Uranium is considered enriched when, by separation, the concentration of the isotope U-235 is increased above the level found in nature. The efficiency depends on a number of factors, including the material of which the rotor is made.

Iran's workhorse centrifuge: The IR-1

Iran used the P-1 design from Pakistan to develop the IR-1 centrifuge. This is Iran's most widely deployed centrifuge. As of August 2021, Iran was operating approximately 6,000 IR-1 centrifuges,[3] with thousands more in storage.[4] Also as of this date, the machines at FEP were producing low-enriched uranium while the IR-1s at the Fordow plant were producing uranium enriched up to 20% U-235.[5]

The IR-1 uses rotors made with aluminum 7075 and bellows made with maraging steel.[6] The machine's rotor assembly is reportedly 180 cm long, its rotors are 10.5 cm in diameter, 40 cm in length, and the casing is 20 cm wide.[7] The whole machine stands about 210 cm tall, including the

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[3] "Verification and monitoring in the Islamic Republic of Iran in light of United Nations Security Council resolution 2231 (2015)," International Atomic Energy Agency, September 7, 2021, pp. 7-9, available at https://www.iaea.org/sites/default/files/21/09/gov2021-39.pdf.

[4] In November 2013, Iran had more than 18,000 IR-1 centrifuges installed at its nuclear sites. All but 5,060 of these machines were placed in storage following the implementation of the JCPOA in 2016, with Iran permitted to remove them from storage to replace failed or damaged machines. Expected attrition, as well damaged caused by sabotage at Natanz in April 2021 do not appear to have substantially diminished the total number of IR-1s.

[5] "Verification and monitoring in the Islamic Republic of Iran," IAEA, September 7, 2021, pp. 7-8.

[6] "Final Report of the Panel of Experts on Iran Established Pursuant to Resolution 1929 (2010)," U.N. Security Council, June 12, 2012, p. 17, available at https://www.iranwatch.org/sites/default/files/un-panelofexpertsreport-061212.pdf.

[7] Alexander Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation (Corrected)," *Science and Global Security*, 2008, p. 8, available at https://www.princeton.edu/~aglaser/2008aglaser_sgsvol16.pdf. The reported length must exclude the casing and base of the centrifuge, as shown in a photo in the 2014 U.N. Panel of Expert report (which gives the diameter and rotor length). See "Final Report of the Panel of Experts on Iran Established Pursuant to Resolution 1929 (2010)," U.N. Security Council, June 5, 2014, p. 16, available at https://www.iranwatch.org/library/multilateral-organizations/united-nations/un-panel-experts/final-report-panel-experts-iran-established-pursuant-resolution-1929-2010-0.

casing and mounting base.[8] Its separation performance in a cascade is estimated to be about 0.8 SWU/year, based on past performance reported by the IAEA.[9]

Research and design on the IR-1 began in earnest in the late 1990s, when Iran first successfully tested a centrifuge and made a decision to scale up its program.[10] Iranian engineers continued single-machine testing in the Kalaye Electric Workshop through 2003, after which the Pilot Fuel Enrichment Plant (PFEP) became the main testing site. Single machine testing, along with 10- and 20-machine cascade testing began in February 2006.[11] The first 164-machine IR-1 cascade was completed in March 2006, and it produced enriched uranium a month later.[12] By early 2007, two 164-machine cascades had been installed at the Fuel Enrichment Plant (FEP) at Natanz, with two more cascades in the final stages of installation.[13] By November 2007 Iran was producing enriched uranium with a fully installed 18-cascade unit there.[14] The IR-1 has historically produced most of Iran's low-enriched uranium stockpile.

The second-generation IR-2m and IR-4

Iran's second-generation centrifuges started with the IR-2 and IR-3 experimental designs, based on the Khan-supplied P-2 drawings and components.[15] The shorter IR-2 and IR-3 sub-critical centrifuges each deploy a single carbon-fiber rotor.[16] Sub-critical centrifuges operate at relatively

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[8] Based on photo-measurements performed by the authors. When measuring the casing length of a centrifuge, we include the whole casing, from where the mounting block touches the floor, but excluding any caps that are attached on top of it.

[9] Valerie Lincy and Gary Milhollin, "Iran's Nuclear Timetable: The Weapon Potential," *Iran Watch*, April 28, 2020, available at https://www.iranwatch.org/our-publications/articles-reports/irans-nuclear-timetable-weapon-potential#_ftn10.

[10] "Implementation of the NPT Safeguards Agreement," IAEA, November 15, 2007, p. 4.

[11] "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran," International Atomic Energy Agency, February 27, 2006, p. 9, available at https://www.iaea.org/sites/default/files/gov2006-15.pdf.

[12] "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran," International Atomic Energy Agency, April 28, 2006, p. 7, available at https://www.iaea.org/sites/default/files/gov2006-27.pdf.

[13] "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolution 1737 (2006) in the Islamic Republic of Iran," International Atomic Energy Agency, February 22, 2007, p. 2, available at https://www.iaea.org/sites/default/files/gov2007-08.pdf.

[14] "Implementation of the NPT Safeguards Agreement," IAEA, November 15, 2007, p. 6.

[15] The P-2 design is taken from the German G-2 model, a segmented machine with rotors and bellows both constructed from maraging steel. Alexander Glaser estimates its length at 1 m, based on reporting by Mark Hibbs. Glaser, "Characteristics of the Gas Centrifuge," *Science and Global Security*, 2008, p. 8.

[16] In a 2004 IAEA report, an AEOI contractor explains that limitations in domestic production capacities led him to simplify the P-2 design to a shorter, single carbon-fiber rotor, sub-critical machine ("Implementation of the NPT

(footnote continued)

low speeds and not pass through so-called critical velocities. The lower speeds make the centrifuges less effective at separating isotopes of uranium but also less likely to tear themselves apart during operation.

Shortly after these types were introduced for testing, Iran announced a modified version of the IR-2, the IR-2m, as well as the IR-4. The only discernible difference between the IR-2m and IR-4 is that the IR-2m uses two carbon fiber rotors connected by a maraging steel bellow, whereas the IR-4 uses a carbon fiber bellow.[17] The rotors for both centrifuges have a diameter of 17 cm, with an estimated rotor length of about 60 cm. The total machine length (height) of the IR-2m is estimated to be between 155-162 cm, while the length of the IR-4 is between 164-175 cm. The casings for both have a width of 25 cm.[18]

Iran has claimed these machines to have a nominal separation capacity of 6 SWU/year,[19] whereas the capacity of the P-2, upon which the IR-2 is modeled, is thought to have a capacity of 5-6 SWU/year.[20] Some experts have estimated the operational capacity of the IR-2m and IR-4 to be about four to five times that of the IR-1, or about 3-4 SWU/year.[21]

Safeguards Agreement in the Islamic Republic of Iran," International Atomic Energy Agency, November 15, 2004, p. 11, available at https://www.iaea.org/sites/default/files/gov2004-83.pdf); a 2008 IAEA report mentions two sub-critical designs shown during an Agency visit to Kalaye Electric Company ("Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions 1737 (2006) and 1747 (2007) in the Islamic Republic of Iran," International Atomic Energy Agency, February 22, 2008, p. 8, available at https://www.iaea.org/sites/default/files/gov2008-4.pdf); another 2008 IAEA report confirms the IR-3 to be a sub-critical machine ("Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions 1737 (2006), 1747 (2007) and 1803 (2008) in the Islamic Republic of Iran," International Atomic Energy Agency, May 26, 2008, p. 2, available at https://www.iaea.org/sites/default/files/gov2008-15.pdf).

[17] "Final Report of the Panel of Experts on Iran," U.N. Security Council, June 12, 2012, p. 17.

[18] "Final Report of the Panel of Experts on Iran," U.N. Security Council, June 5, 2014, p. 16. Estimate of rotor and machine length are based on visual measured comparison with other centrifuges by authors.

[19] "Iran: Dozens of nuclear tech achievements displayed in Tehran," Ruptly, April 10, 2019, https://www.youtube.com/watch?v=JC8iu0GXC1o&feature=youtu.be.

[20] Glaser, "Characteristics of the Gas Centrifuge," *Science and Global Security*, 2008, p. 8.

[21] "Final Report of the Panel of Experts Established Pursuant to Resolution 1929 (2010)," U.N. Security Council, June 5, 2013, p. 17, available at https://www.iranwatch.org/sites/default/files/un-panel-of-experts-report-june-2013.pdf.

Testing of the IR-2 and IR-3 at PFEP began between January and May 2008.[22] This test program has not progressed beyond the small (10 machine) cascade phase, with testing on the IR-2 apparently ceasing in 2010.[23] Iran resumed testing the IR-3 on a small scale at the PFEP in 2019.[24]

However, the testing program for the IR-2m and IR-4 has been ongoing since early 2009. Single machine testing of both designs was followed by small cascade testing, between January and May 2009.[25] Large cascade testing setups for these designs were announced by Iran in January 2011 and gradually installed, with a full 164-machine IR-2m bank installed in PFEP in October 2011.[26] By February 2013, Iran had begun to install these machines at FEP, the first time more advanced centrifuges had been placed there.[27] By August 2013, the installation of six large IR-2m cascades was completed at FEP (as well as preparatory work on twelve more). However, these

[22] "Implementation of the NPT Safeguards Agreement," IAEA, February 22, 2008, p. 8; "Implementation of the NPT Safeguards Agreement," IAEA, May 26, 2008, p. 2.

[23] The IAEA last reports on tests with the IR-3 in June 2009 and on tests with the IR-2 in February 2010; "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions 1737 (2006), 1747 (2007), 1803 (2008) and 1835 (2008) in the Islamic Republic of Iran," International Atomic Energy Agency, June 5, 2009, p. 2, available at https://www.iaea.org/sites/default/files/gov2009-35.pdf; "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions 1737 (2006), 1747 (2007), 1803 (2008) and 1835 (2008) in the Islamic Republic of Iran," International Atomic Energy Agency, February 18, 2010, p. 2, available at https://www.iaea.org/sites/default/files/gov2010-10.pdf.

[24] "Verification and Monitoring in the Islamic Republic of Iran in Light of United Nations Security Council Resolution 2231 (2015)," International Atomic Energy Agency, November 11, 2019, p. 5, available at https://www.iaea.org/sites/default/files/19/11/gov2019-55.pdf.

[25] "Implementation of the NPT Safeguards Agreement," IAEA, June 5, 2009, p. 2; "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions 1737 (2006), 1747 (2007), 1803 (2008), and 1835 (2008) in the Islamic Republic of Iran," International Atomic Energy Agency, August 28, 2009, p. 2, available at https://www.iaea.org/sites/default/files/gov2009-55.pdf.

[26] "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions in the Islamic Republic of Iran," International Atomic Energy Agency, May 24, 2011, p. 4, available at https://www.iaea.org/sites/default/files/gov2011-29.pdf; "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions in the Islamic Republic of Iran," International Atomic Energy Agency, November 8, 2011, p. 4, available at https://www.iaea.org/sites/default/files/gov2011-65.pdf.

[27] "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions in the Islamic Republic of Iran," International Atomic Energy Agency, February 21, 2013, p. 4, available at https://www.iaea.org/sites/default/files/gov2013-6.pdf.

cascades were not used to enrich uranium.[28] The IR-4 cascade at PFEP was more gradually installed, with the IAEA counting 164 installed centrifuges in November 2013.[29]

Until 2019, Iran pursued research and development with the IR-2m and IR-4, without using them to accumulate enriched uranium, as permitted by the Joint Comprehensive Plan of Action (JCPOA). However, Iran subsequently resumed and then scaled up uranium enrichment using both machines. By August 2021, Iran was operating 348 IR-4 centrifuges in two cascades at FEP, as well as enriching uranium to 60% U-235 with a cascade of 153 IR-4s at PFEP. It had also installed 1044 IR-2m centrifuges in six cascades at FEP and was enriching uranium to 5% U-235 using five of the cascades.[30]

The future workhorse? The third generation IR-6 centrifuge

A first version of the IR-6 was reportedly produced in 2009 and presented to the public on Iran's National Nuclear Technology Day in April 2010.[31] The standard model of the IR-6 that eventually emerged is an estimated 160-168 cm tall, with a casing width of 30 cm.[32] Iran claims it to have a separation capacity of 10 SWU/year.[33] Little has been disclosed about the IR-6 other than its outer dimensions. It probably employs dual rotors connected by a bellow,[34] with the rotors and

[28] "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions in the Islamic Republic of Iran," International Atomic Energy Agency, August 28, 2013, p. 5, available at https://www.iaea.org/sites/default/files/gov2013-40.pdf.

[29] "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions in the Islamic Republic of Iran," International Atomic Energy Agency, November 14, 2013, p. 6, available at https://www.iaea.org/sites/default/files/gov2013-56.pdf.

[30] "Verification and Monitoring in the Islamic Republic of Iran," IAEA, September 7, 2021, pp. 7-8; "Verification and Monitoring in the Islamic Republic of Iran in Light of United Nations Security Council Resolution 2231 (2015)," International Atomic Energy Agency, April 14, 2021, p. 1, available at https://www.iaea.org/sites/default/files/21/06/govinf2021-24.pdf.

[31] 'Iran starts injecting gas into advanced IR-6 centrifuges', Press TV, November 4, 2019, https://web.archive.org/web/20200304173649/https://www.presstv.com/Detail/2019/11/04/610371/Salehi-IR6-centrifuges-Natanz-enrichment; the centrifuge is also displayed next to a banner reading "The Fourth National Anniversary of Nuclear Technology 9 April 2010" in a photo analyzed by the authors.

[32] Based on photo-measurements performed by the authors.

[33] "Iran Starts Injecting Gas into Advanced IR-6 Centrifuges," Press TV, November 4, 2019; "Iran: Dozens of nuclear tech achievements displayed in Tehran," Ruptly, April 10, 2019.

[34] David Albright and Olli Heinonen, "Is Iran Mass Producing Advanced Gas Centrifuge Components?" Institute for Science and International Security, May 31, 2017, p. 7, available at https://isis-online.org/uploads/isis-reports/documents/Mass_Production_of_Centrifuges_30May2017_Final.pdf.

bellows made from carbon fiber.[35] The IR-6 also has a smaller, single-rotor variant, the IR-6s, which has been less widely deployed than the standard IR-6.[36]

In February 2012, Iran notified the IAEA of its intention to install single IR-6 and IR-6s machines at PFEP.[37] A year later, the IAEA confirmed this installation and the intermittent feeding of single IR-6 and IR-6s machines with uranium hexafluoride (UF6), the feedstock in uranium enrichment.[38] By August 2013, the Agency reported that Iran was testing the IR-6 in small cascades, alongside single machine testing.[39] Under the JCPOA, Iran was permitted to continue testing the IR-6 without accumulating enriched uranium. This testing phase continued until early 2020, when Iran began testing the IR-6 in a larger cascade of 72 machines using UF6.[40] By June 2020, that number had grown to 135 IR-6 machines.[41]

In 2021, Iran began using its cascade of IR-6 centrifuges at PFEP – consisting of 164 machines as of August 2021 – to produce uranium enriched up to 60% U-235. It also began installing two cascades of IR-6 machines at Fordow, where they will feed uranium enriched up to 5% U-235 directly into IR-1 machines dedicated to producing uranium enriched to 20% U-235. Iran also

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[35] Iran is unlikely to return to components made from inferior materials after having used carbon-fiber rotor tubes in the IR-2m and rotor tubes and bellows in the IR-4. In addition, Iran announced the completion of a new centrifuge rotor factory in July 2018, claiming a capacity to build rotors for up to 60 IR-6 centrifuges using "advanced materials" daily ("Iran is building advanced centrifuges: Salehi," Iranian Labor News Agency, September 10, 2018 , available at https://www.ilna.news/Section-politics-3/666696-iran-is-building-advanced-centrifuges-salehi). Furthermore, the IAEA reported Iran's use of carbon fiber in centrifuge production beginning in June 2017, and the use of unsafeguarded carbon fiber for this purpose beginning in September 2019 ("Verification and Monitoring in the Islamic Republic of Iran in Light of United Nations Security Council Resolution 2231 (2015)," International Atomic Energy Agency, June 2, 2017, p. 5, available at https://www.iaea.org/sites/default/files/gov2017-24.pdf; "Verification and Monitoring in the Islamic Republic of Iran in Light of United Nations Security Council Resolution 2231 (2015)," International Atomic Energy Agency, September 26, 2019, p. 2, available at https://www.iaea.org/sites/default/files/19/11/govinf2019-12.pdf.

[36] The model first reported on in 2009 was an IR-6s. Based on photo-measurements performed by the authors.

[37] "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions in the Islamic Republic of Iran," International Atomic Energy Agency, February 24, 2012, p. 5, available at https://www.iaea.org/sites/default/files/gov2012-9.pdf.

[38] "Implementation of the NPT Safeguards Agreement," IAEA, February 21, 2013, p. 5.

[39] "Implementation of the NPT Safeguards Agreement," IAEA, August 28, 2013, pp. 5-6.

[40] "Verification and Monitoring in the Islamic Republic of Iran in Light of United Nations Security Council Resolution 2231 (2015)," International Atomic Energy Agency, March 3, 2020, p. 5, available at https://www.iaea.org/sites/default/files/20/03/gov2020-5.pdf.

[41] "Verification and Monitoring in the Islamic Republic of Iran in Light of United Nations Security Council Resolution 2231 (2015)," International Atomic Energy Agency, June 5, 2020, p. 5, available at https://www.iaea.org/sites/default/files/20/06/gov2020-26.pdf.

announced plans for a single cascade of 174 IR-6 centrifuges at FEP, but installation had not begun as of August 2021.[42]

The IR-8 and IR-9: Still early days

Not much is known about the fourth-generation centrifuges that Iran is developing. Iran informed the IAEA of its intention to install the IR-8 in early December 2013, and had installed an empty casing for it at PFEP less than two weeks later.[43] By October 2014, IAEA inspectors verified that the casing contained a rotor, but was still missing connection components.[44] Iran's partial installation of the IR-8 may be explained by a desire to include the machine in a 2013 precursor agreement to the JCPOA, known as the Joint Plan of Action.

Based on an analysis of photographs, the IR-8 is estimated to be between 391 and 396 cm tall, with a casing width of 40 cm.[45] For the same reasons as the IR-6, we assume the IR-8 rotors and bellows to be made of carbon fiber.[46] The number of rotors and bellows is uncertain. The machine casing is wider, possible indicating a wider, and therefore longer rotor. Alternatively, it could indicate and account for the greater distortion effects of the rotor assembly during operation, requiring more room inside the casing. Assuming that the IR-8 has the same rotor-to-casing ratio as the IR-2m, IR-4, and IR-6, the rotor width would be 25 cm. Iranian officials have claimed the separation capacity of the IR-8 to be between 20 SWU/year and 24 SWU/year.[47]

Testing the IR-8 at PFEP began in January 2017, when engineers started feeding a single centrifuge with UF6.[48] Single machine testing, albeit with some interruption, has continued since

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[42] "Verification and Monitoring in the Islamic Republic of Iran," IAEA, September 7, 2021, pp. 7-9; "Verification and Monitoring in the Islamic Republic of Iran," IAEA, April 14, 2021, p. 1.

[43] "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions in the Islamic Republic of Iran," International Atomic Energy Agency, February 20, 2014, p. 7, available at https://www.iaea.org/sites/default/files/gov2014-10.pdf.

[44] "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions in the Islamic Republic of Iran," International Atomic Energy Agency, November 7, 2014, p. 6, available at https://www.iaea.org/sites/default/files/gov2014-58.pdf.

[45] Based on photo-measurements performed by the authors.

[46] See footnote 35.

[47] "Iran's [*sic*] to Increase IR-8 Centrifuge Enrichment Capacity 20-Fold," Taghrib News, February 15, 2017, available at http://www.taghribnews.com/en/news/260170/print/iran-s-to-increase-ir-8-centrifuge-enrichment-capacity-20-fold; "Nuclear Chief: Iran Ready to Launch New Generation of Centrifuges," Fars News Agency, August 27, 2014, available at https://www.farsnews.ir/en/news/13930605001187/Nclear-Chief-Iran-Ready-Lanch-New-Generain-f-Cenrifges.

[48] "Verification and Monitoring in the Islamic Republic of Iran in Light of United Nations Security Council Resolution 2231 (2015)," International Atomic Energy Agency, February 24, 2017, p. 5, available at https://www.iaea.org/sites/default/files/gov2017-10.pdf.

that time. Like the IR-6, the IR-8 also has a shorter (most likely single-rotor) version, the IR-8s, as well as an IR-8B variant about which little is publicly known.[49] These versions were also tested in the period following November 2019, shortly after Iran declared them to the IAEA.[50]

Recent tests have also included the IR-9, which may represent a fifth-generation Iranian centrifuge. In November 2019, a group of Iranian journalists visiting Natanz was shown the IR-9, which was reported to be 550 cm tall, and which Iranian officials claim has a separation capacity of 40 to 50 SWU/year.[51] One IR-9 machine was being tested with UF6 by February 2021.[52]

Centrifuge Development and Operation

Each generational category used to classify centrifuges above does not necessarily represent a substantial improvement in the quality and reliability of successor machines – though the Iranians are claiming major improvement in separation capacity in each new generation. The categories used in this report were established by considering statements by Iranian officials as well as the distinct technological progression of each centrifuge, such as the use of new materials and the construction of centrifuges of greater length and width.

Generally, Iranian officials have used a generational typology that makes technological sense. Iran calls the IR-2m is its second-generation machine; it uses a simplified design and new materials compared to the IR-1. Iran presented the IR-6 as the start of its third-generation line; it has a wider rotor and other innovations. Iran termed the IR-8 a fourth-generation machine; it is much longer (taller) and wider than any previous centrifuge. The IR-9, a claimed fifth generation centrifuge, is longer still. Over each generation, the separation capacity as claimed by Iran has

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[49] "Iran Nuclear Deal: Fordo Uranium Centrifuges to Be Injected with Gas," BBC News, November 5, 2019, available at https://www.bbc.com/news/world-middle-east-50300952.

[50] "Verification and Monitoring in the Islamic Republic of Iran," IAEA, November 11, 2019, p. 5.

[51] "Walking the S8," Iranian Students News Agency, November 12, 2019, available at https://www.isna.ir/news/98082113044/%D9%BE%DB%8C%D8%A7%D8%AF%D9%87-%D8%B1%D9%88%DB%8C-%D8%AF%D8%B1-S8 (in Persian);" Report: IR-9 Centrifuges to Increase Enrichment Capacity," Financial Tribune, October 20, 2019, available at https://financialtribune.com/articles/national/100406/report-ir-9-centrifuges-to-increase-enrichment-capacity#:~:text=The%20advanced%20IR%2D9%20centrifuges,Khorasan%20on%20condition%20of%20anonymity.

[52] "Verification and Monitoring in the Islamic Republic of Iran in Light of United Nations Security Council Resolution 2231 (2015)," International Atomic Energy Agency, February 23, 2021, p. 7, available at https://www.iaea.org/sites/default/files/21/03/gov2021-10.pdf.

roughly doubled, from 2-3 SWU/year (IR-1), 4-5 SWU/year (IR-2m), 10 SWU/year (IR-6), 20-24 SWU/year (IR-8), to 40-50 SWU/year (IR-9).[53] (See Table 1 on page 2.)

Developing centrifuges with higher SWU/year output presents several challenges. Machines that are longer and spin faster are more effective at separating isotopes of uranium, but they must be exactingly designed so as not to tear themselves apart at high rotational speeds. Each centrifuge needs a number of "bellows" between the rotors to form a rotor assembly that allows for flexibility when spinning at higher speeds. The rotor itself must be made with strong, lightweight material. For example, a carbon fiber rotor assembly may use fewer, longer, rotors because of the higher strength of the material, compared to metals like aluminum and steel.

Each rotating part of a centrifuge also needs to be engineered with extreme precision to ensure balance and durability. Once it reaches its optimal speed, a centrifuge must continue spinning. This requires a magnetic top bearing that keeps the rotor in place without touching it, and a pin or ball-pivot bearing at the bottom that causes the least amount of friction possible. The internal parts of the centrifuge must also resist the corrosive effects of uranium hexafluoride gas (UF6), which passes through.

Beginning with the IR-1 and continuing to the IR-9, Iran has experimented with centrifuge rotor size, number of rotors per machine, bellows, and the materials used to construct these components. This experimentation has proven fruitful over time. Whereas Iran's first-generation rotors were made of aluminum, these components in later machines appear to be made of carbon fiber. Similarly, later designs are longer (taller) than the IR-1, with the IR-8 and IR-9 estimated at 395 cm and 500 cm respectively, and have greater diameters.

Possible 'Bottlenecks'

Nuclear-related trade restrictions and sanctions have slowed Iran's centrifuge development, including Iran's ability to make more powerful centrifuges. However, the impact of these measures has declined as Iran's domestic capability grows.

During the early phase of its nuclear program, between 1985 and 2002, Iran procured "about 2,000 components and some sub-assemblies," both through the Khan network as well as by direct acquisition, according to the IAEA.[54] Imports during this early phase of the program

[53] These are the nominal separation capacities of these machines as claimed by Iran, with actual performance in a cascade depending on their efficiency while in production mode.
[54] "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran," International Atomic Energy Agency, November 10, 2003, Annex I, p. 8, available at https://www.iaea.org/sites/default/files/gov2003-75.pdf.

reportedly included high-strength aluminum, maraging steel, balancing machines, vacuum pumps, advanced (numerically-controlled) machine tools[55], and flow-forming machines.[56]

Following the exposure and dismantlement of the Khan network, procurement of finished components for centrifuges became more difficult. This change in international availability, combined with the increased scrutiny Iran found itself under after the public revelation of the Natanz and Arak sites in 2002, and the imposition of international sanctions beginning in 2006, may have contributed to Iran's decision to make centrifuge components and cascade equipment domestically.

However, Iran continued to seek items from "high-quality suppliers based in countries with well-developed export control systems," according to a 2011 report by the United Nations.[57] The report included a list of "choke point" items critical to Iran's centrifuge program that Iran could not produce indigenously at the time.[58] (See Table 2 on page 13.) Since then, Iran's indigenous manufacturing capability has improved. While there have been more recent publicly document efforts by Iran to procure these items from abroad, they likely no longer represent "choke points" in Iran's centrifuge development.

The items identified by the United Nations in 2011 can be divided in the three categories: centrifuge construction materials and technologies; electric power control systems; and equipment related to cascade construction and operation, including fluorine-related equipment.[59] (See Image 1 on page 17.)

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[55] Numerically-controlled machine tools are industrial tools used for cutting and shaping, such as grinders and lathes, whose processes and operation are controlled by a computer.
[56] Jack Boureston, "Fuel Cycle: Tracking the Technology," *Nuclear Engineering International*, September 30, 2004, available at https://www.neimagazine.com/features/featuretracking-the-technology/.
[57] "Final Report from Panel of Experts on Iran Established Pursuant to Resolution 1929 (2010)," U.N. Security Council, May 1, 2011, p. 22, available at https://www.iranwatch.org/library/international-organization/united-nations-un/un-security-council/final-report-panel-experts-established-pursuant-resolution-1929-2010-0.
[58] "Final Report from Panel of Experts on Iran," U.N. Security Council, May 1, 2011, pp. 20-21.
[59] M. D. Zentner, G. L. Coles, and R. J. Talbert, "Nuclear Proliferation Technology Trends Analysis," Pacific Northwest National Laboratory, September 2005, pp. 33-34, available at http://fissilematerials.org/library/zen05.pdf.

TABLE 2: CRITICAL ITEMS FOR GAS CENTRIFUGE ENRICHMENT

ITEM	FUNCTION
Flow-forming machines	These machines are essential for the production of metal rotor tubes for gas centrifuges.
Maraging steel	Maraging steel is used in the production of centrifuge rotor tubes, bellows, end caps and baffles. It is especially suited to the high performance demands of rapidly spinning centrifuges.
Fibrous or filamentary materials	Carbon fibre is used in more modern centrifuges; rotors made with carbon fibre, such as the ones Iran is currently developing, are able to spin faster than those made with maraging steel.
Filament winding machines	Iran's procurement of these machines would advance its ability to manufacture carbon fibre rotor tubes.
High strength aluminium alloys	High strength aluminium is used in the production of centrifuge rotor tubes, end caps and baffles.
Frequency changers or inverters	Inverters are necessary to regulate the supply of power to centrifuges.
Bellows-sealed valves	These valves are necessary for Iran's construction and operation of its gas centrifuge cascade piping systems.
Magnetic alloys in thin strip form	This magnetic material is used in construction of the gas centrifuge drive motor.
Perfluorinated lubricants	These lubricants, which are resistant to uranium hexafluoride (UF6) are necessary in gas centrifuge plant vacuum pumps and other equipment.
Ring magnets	Ring magnets are essential component parts of the upper bearing/suspension assembly in Iran's gas centrifuges.

"Final Report from Panel of Experts on Iran Established Pursuant to Resolution 1929 (2010)," U.N. Security Council, May 1, 2011, p. 21, available at https://www.iranwatch.org/library/international-organization/united-nations-un/un-security-council/final-report-panel-experts-established-pursuant-resolution-1929-2010-0.

Centrifuge Construction Materials and Technologies

While Iran's later-generation centrifuges use carbon fiber for centrifuge rotors, other important components, such as scoops, baffles and endcaps, will continue to be made from metals such as high-strength aluminum or maraging steel.[60] There have been numerous reported cases of Iran attempting to evade sanctions in order to procure these materials, including at below export control list threshold specifications.[61] In addition, several entities in Iran are running production lines for maraging steel and high-strength aluminum.

In 2011, Iran claimed to have a domestic carbon fiber production capability.[62] However, Iran continued to seek high-grade carbon fiber and related production equipment like filament winding machines until at least 2013.[63] Filament winding machines can construct carbon fiber components of different shapes using fibrous or filamentary materials as source material. The quality of the filamentary materials varies; only high-quality materials can produce components with the required strength and stiffness suitable for use in super-critical centrifuges.

Finally, technologies to manufacture centrifuge components from metals and carbon fiber include metallurgical techniques and high precision etching technology,[64] the ability to construct magnets for use in the top bearings of centrifuges,[65] and specialized equipment such as numerically-controlled machine tools.[66] Specialized oils, such as Fomblin oil, are used for lubrication of the bottom pin-bearing of the centrifuge. Iran has sought such machine tools,

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[60] Kolja Brockmann and Robert Kelley, "The Challenge of Emerging Technologies to Non-Proliferation Efforts: Controlling Additive Manufacturing and Intangible Transfers of Technology," Stockholm International Peace Research Institute, April 2018, p. 22, available at https://www.sipri.org/sites/default/files/2018-04/sipri1804_3d_printing_brockmann.pdf.

[61] "Final Report of the Panel of Experts on Iran Established Pursuant to Resolution 1929 (2010)," U.N. Security Council, June 2, 2015, p. 14, available at https://www.iranwatch.org/sites/default/files/un-panelofexpertsreport-060215_0.pdf.

[62] "Iran Inaugurates First Carbon Fiber Production Line," Mehr News Agency, August 27, 2011, available at https://en.mehrnews.com/news/47722/Iran-inaugurates-first-carbon-fiber-production-line.

[63] See for example: Sentencing Memorandum for Hamid Reza Hashemi, November 13, 2013, available at https://www.iranwatch.org/library/governments/united-states/executive-branch/department-justice/sentencing-memorandum-hamid-reza-hashemi; Austin Bodetti, "An Iranian Plot to Acquire Carbon Fiber," Iran Watch, November 15, 2019, available at https://www.iranwatch.org/our-publications/international-enforcement-actions/iranian-plot-acquire-carbon-fiber.

[64] Zentner et al., "Nuclear Proliferation Technology Trends Analysis," Pacific Northwest National Laboratory, September 2005, pp. 33.

[65] "Final Report of the Panel of Experts on Iran," U.N. Security Council, June 5, 2013, p. 19.

[66] "Final Report of the Panel of Experts on Iran," U.N. Security Council, June 5, 2014, p. 22.

magnets, and oils in the past and may still need such specialized equipment in order to advance its centrifuge program.[67]

Electric Power Control Systems

Operating a centrifuge requires a reliable, well-controlled electrical drive system, with variable-frequency drives controlled by frequency converters. Additionally, regulating the centrifuges and uranium gas flow in a cascade requires a SCADA (Supervisory Control and Data Acquisition) system, which is a process control system that can communicate with other devices such as programmable logic controllers (PLCs) and pressure transducers, or sensors.[68] Iran has sought to procure frequency converters and process control equipment, including equipment below the control list thresholds, up to at least 2013.[69] These systems have also been the target of cyberattacks, notably the 2010 Stuxnet attack on Natanz that targeted the SCADA system.

Equipment Related to Cascade Construction and Operation

The construction of gas centrifuge cascades requires large quantities of stainless steel piping and associated control valves, bellows, and connected equipment such as vacuum pumps, feed autoclaves, and desublimers, or cold traps.[70] The UF6 gas that flows through the piping and centrifuges is highly corrosive and reactive, so all equipment that is part of the flow system needs to be corrosion resistant (coated with aluminum or nickel alloys, for example). Additionally, measurement equipment such as helium gas detectors are required to detect leaks in the system, which must operate in a vacuum.

Iran told the IAEA in 2008 that it was developing an indigenous capacity to produce cascade equipment such as vacuum pumps.[71] Despite this claim, Iran attempted to procure foreign pressure transducers, which are used to regulate the vacuum systems of gas centrifuges, until at

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[67] "Final Report of the Panel of Experts on Iran," U.N. Security Council, June 5, 2013, pp. 19-20; "Final Report of the Panel of Experts on Iran," U.N. Security Council, June 5, 2014, pp. 15, 22.

[68] The 2010 Stuxnet cyberattack targeted the SCADA system in use at Natanz. Blaise Misztal, "Iran's Nuclear Program: Status and Breakout Timing", Bipartisan Policy Center, September 2011, p. 6, http://large.stanford.edu/courses/2014/ph241/alnoaimi1/docs/Iran-Nuclear-Program.pdf; Ralph Langner, "To Kill a Centrifuge: A Technical Analysis of What Stuxnet's Creators Tried to Achieve", The Langner Group, November 2013, pp. 8-9, https://www.langner.com/wp-content/uploads/2017/03/to-kill-a-centrifuge.pdf.

[69] See for example: "Final Report of the Panel of Experts on Iran," U.N. Security Council, June 5, 2013, pp. 18, 20.

[70] Desublimers (or cold traps) are used to remove gaseous streams of UF6 from cascades, where they are condensed prior to onward transfer into suitable containers for transportation or storage. There are temperature and pressure requirements for this equipment in a gas centrifuge plant.

[71] "Implementation of the NPT Safeguards Agreement," IAEA, February 22, 2008, p. 8.

least 2013.[72] Since 2019, the Fordow plant has housed Iran's National Center for Vacuum Technology, which reportedly produces pressure transducers in order to reduce Iran's dependence on foreign sources of supply.[73]

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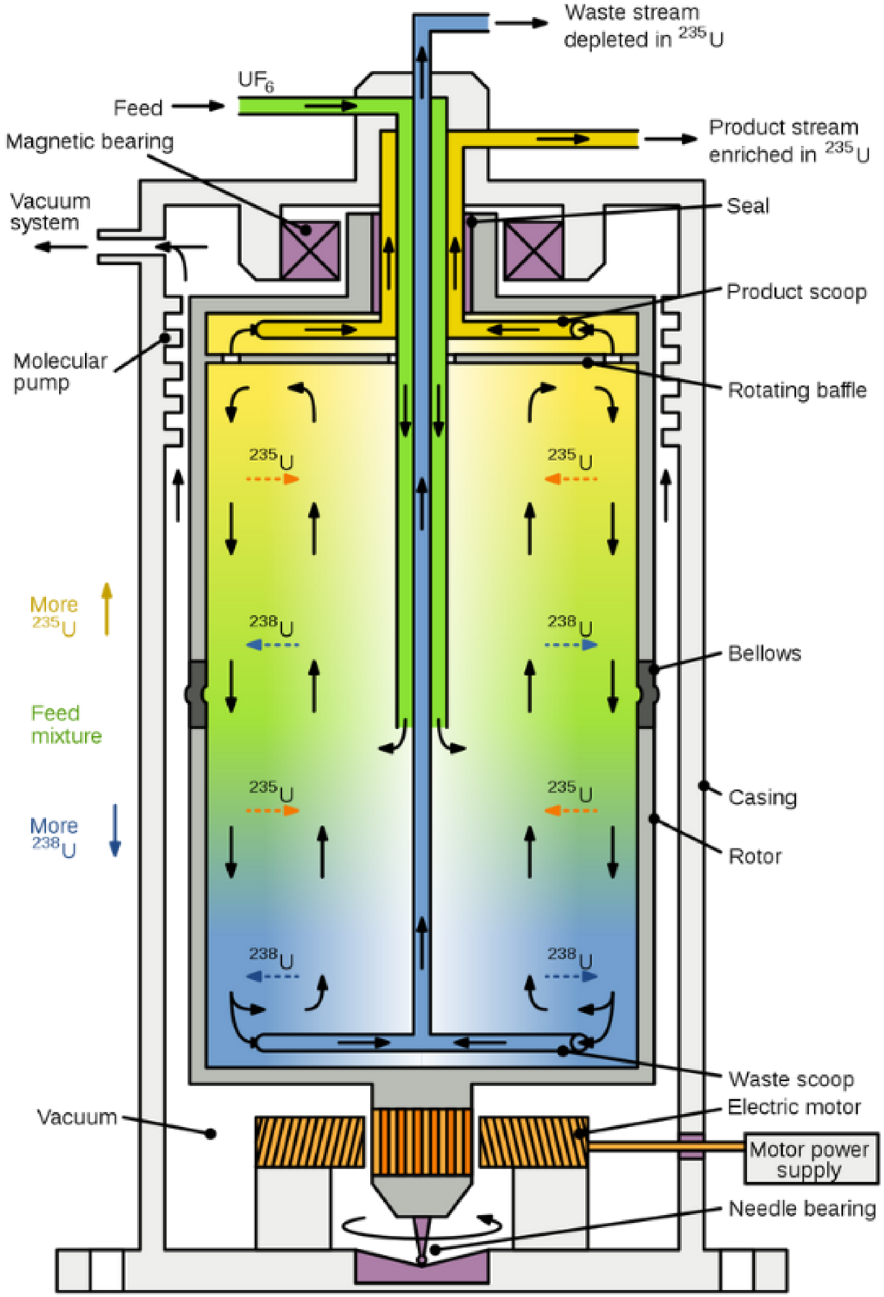
[72] "Summary of Major U.S. Export Enforcement, Economic Espionage, and Sanctions-Related Criminal Cases," U.S. Department of Justice, January 19, 2018, pp. 34-35, available at https://www.justice.gov/nsd/page/file/940591/download.

[73] "Conversion of Fordow: Another Unfulfilled Hope of the Iran Nuclear Deal," David Albright, Sarah Burkhard, Frank Pabian, and Jack Toole, Institute for Science and International Security, July 10, 2019, available at http://isis-online.org/uploads/isis-reports/documents/Conversion_of_Fordow_Another_Unfulfilled_Hope_of_the_Iran_Nuclear_Deal_July_10%2C2019.pdf.

IMAGE 1: SCHEMATIC DIAGRAM OF A GAS CENTRIFUGE



Inductiveload, "Countercurrent Gas Centrifuge," Wikimedia Commons, January 12, 2020, available at https://commons.wikimedia.org/wiki/File:Countercurrent_Gas_Centrifuge.svg

Implications for Weapons Production and Diplomacy

Iran is increasing the variety and number of the more powerful centrifuges it is operating in "production mode." That is, Iran is using these centrifuges to contribute to the enriched uranium stockpile, rather than in a research mode, where no enriched uranium is accumulated.

In November 2020 the IAEA reported that, for the first time, Iran had installed a cascade of IR-2m centrifuges in production mode at the FEP.[74] Several additional cascades of IR-2m centrifuges were subsequently installed, followed by two cascades of IR-4 machines by May 2021.[75] Iran has also shifted IR-4 and IR-6 centrifuges at PFEP to production mode, and has been using them since April 2021 to accumulate uranium enriched up to 60% U-235, which is close to weapon grade.[76] Altogether, these transfers mark an important change. They show that Iran appears confident that its advanced centrifuges can successfully enrich uranium at a production level.

If Iran continues to reject any limit on manufacturing or deploying these centrifuges, they may soon be fielded in quantity. Iran had more than 1,000 IR-2m machines installed as of August 2021, roughly 900 of which were in production mode, according to the IAEA. More than 500 IR-4 centrifuges were also installed, nearly all of which were in production mode.[77] Iran has produced only a few hundred of the other advanced models, but its decision to move the IR-6 into production mode suggests that Iran is confident in its ability to manufacture this and other more powerful models. It is also possible that internal political pressures and a desire to build leverage in the context of negotiations play a role in the deployment of new centrifuges.

Iran's increasing mastery of centrifuge design and manufacturing raises the risk of a "sneakout," in which Iran would use secret sites to produce nuclear weapon fuel. The reason is that more advanced centrifuges would permit such sites to be smaller and therefore easier to hide. For example, Iran's IR-2m centrifuge could enrich the same amount of uranium as the IR-1 centrifuge in approximately one-fifth the space. Iran could install 3,000 IR-2m or IR-6 centrifuges, which

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[74] "Verification and Monitoring in the Islamic Republic of Iran in Light of United Nations Security Council Resolution 2231 (2015)," International Atomic Energy Agency, November 17, 2020, p. 1, available at https://www.iaea.org/sites/default/files/20/11/govinf2020-16.pdf.

[75] "Verification and Monitoring in the Islamic Republic of Iran in Light of United Nations Security Council Resolution 2231 (2015)," International Atomic Energy Agency, May 31, 2021, p. 5, available at https://www.iaea.org/sites/default/files/21/06/gov2021-28.pdf.

[76] "Verification and Monitoring in the Islamic Republic of Iran in Light of United Nations Security Council Resolution 2231 (2015)," International Atomic Energy Agency, April 17, 2021, p. 2, available at https://www.iaea.org/sites/default/files/21/06/govinf2021-26.pdf.

[77] "Verification and Monitoring in the Islamic Republic of Iran," IAEA, September 7, 2021, pp. 7-8; "Verification and Monitoring in the Islamic Republic of Iran," IAEA, April 14, 2021, p. 1.

would require only about 32,000 square feet – equal to approximately twice the size of the ice surface of a professional hockey rink. Operating at 80% of their nominal capacity, the IR-2m and the IR-6 could produce enough fuel for a small arsenal of five warheads in 20 months and 10 months, respectively (starting with natural uranium). Alternatively, Iran could decide to split these 3,000 centrifuges equally among three smaller sites of approximately 11,000 square feet each. That would decrease the size of each site and therefore the likelihood of detection. Each site would be about two-thirds the size of the ice surface of a professional hockey rink.[78]

The concern about advanced centrifuges operating secretly has been reinforced by the declining level of access by the IAEA to Iran's centrifuge production and storage locations.[79] Iran removed four IAEA monitoring cameras from a centrifuge manufacturing plant in Karaj after an alleged sabotage attempt in June 2021. As of October 2021, Iran had refused to replace the cameras, leading the Agency's Director General to conclude that the IAEA's monitoring system was "no longer intact."[80]

The steps Iran has taken to advance its centrifuge program also have implications for nuclear diplomacy. The JCPOA had restricted Iran's ability to pursue research and development of more advanced centrifuges because such centrifuges, operating in cascades in production mode, decrease the time it would take Iran to produce fuel for a nuclear weapon. Iran's advances, insofar as they reflect the acquisition of knowledge and the mastery of technological processes, cannot be reversed by a return to the JCPOA or as part of a new agreement. Any diplomatic engagement with Iran over its nuclear program will thus need to take into account the fact that, as long as Iran's advanced centrifuge development progresses, some increase in the country's nuclear capability will be permanent.

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[78] Lincy and Milhollin, "Iran's Nuclear Timetable," *Iran Watch*, October 4, 2021.

[79] "Verification and Monitoring in the Islamic Republic of Iran," IAEA, September 7, 2021, p. 11.

[80] Katrina Manson, "IAEA Chief Warns Iran Nuclear Surveillance Is No Longer Intact," Financial Times, October 19, 2021, available at https://www.ft.com/content/ad8526f0-da73-48cc-ab90-4a3f146158d4.

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About the Wisconsin Project

The Wisconsin Project on Nuclear Arms Control is a non-profit, non-partisan organization based in Washington, D.C. that conducts research, advocacy, and public education designed to inhibit the spread of nuclear, chemical, and biological weapons and the missiles to deliver them. The organization was founded in 1986, in cooperation with the University of Wisconsin.

The Wisconsin Project's mission is to reduce the risk that exports will accelerate the proliferation of weapons of mass destruction. The Project helps governments comply with the export restrictions in international agreements, and helps them ensure that their national controls on strategic goods are enforced. The Project also publicizes clandestine transactions in these goods, and draws attention to weaknesses in trade agreements and national laws. Through its research, the Project has influenced the export policies of major supplier countries.

About Iran Watch

Iran Watch is a website published by the Wisconsin Project that monitors Iran's capability for building nuclear weapons and long-range missiles. The purpose of the website is to increase public awareness of the strategic situation in Iran and to make detailed knowledge of Iran's weapon potential available to policymakers, the media, scholars, and the general public.

Through Iran Watch, the Wisconsin Project provides an objective resource for monitoring and assessing U.S. sanctions that were re-imposed following the U.S. withdrawal from the Joint Comprehensive Plan of Action (JCPOA), as well as advances in Iran's nuclear program following Tehran's decision to stop complying with JCPOA requirements. The site contains thousands of primary source documents related to Iran, as well as reports on Iran's nuclear and missile programs, profiles of the entities involved in or supporting these programs, and analysis of the international effort halt them.