



A Comprehensive Survey of Iran's Advanced Centrifuges

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Table of Contents

Preface

Highlights

Chapter 1 Technical Parameters of Individual Centrifuge Types

Chapter 2 Iran's Historical Deployment of Centrifuges

Chapter 3 Findings and Discussion

Annexes

- 1. Centrifuge Specifications and Comparisons**
- 2. The Centrifuge Bellows**
- 3. Upper Limit Theoretical Enrichment Output**
- 4. Major Components of Centrifuges and Material Properties**
- 5. Feed to Product Ratios for Enriched Uranium**

Preface

Iran's development of gas centrifuges to enrich uranium has been long-standing and seemingly haphazard but in general encompasses a program seeking longer, faster centrifuges, while struggling with reliability. Cost does not seem to be a constraining factor, making the program more strategic than commercial.

Iran's first centrifuge deployed on an industrial scale is the IR-1, and like the Pakistani model it copied, itself derived from Dutch designs stolen in the 1970s, the IR-1 centrifuge has been rife with problems. Although Iran acquired both designs and several hundred complete centrifuges from Pakistan's A.Q. Khan network in the late 1980s and early 1990s, it took years to master and deploy the IR-1 centrifuges by the thousands. Ever since the IR-1 centrifuge was first deployed on a development scale in the 1990s and an industrial scale in the 2000s, it has suffered from very low outputs and high failure rates often exceeding 20 percent per year. An Iranian priority has been replacing the IR-1 centrifuge with a more reliable, powerful one. In the 1990s, Iranian centrifuge experts set out to develop a variant of another Pakistani type, the P2 centrifuge, this time a German design also stolen by Pakistan in the 1970s and provided to Iran in the 1990s.

Over the course of the last twenty years, based on modifications to the P2 designs, Iran has worked on upwards of 20 different advanced centrifuge types, abandoning many, and never, during this period, fielding a robust replacement for the IR-1 centrifuge, until perhaps today. Since Iran started its major violations of the 2015 Joint Comprehensive Plan of Action (JCPOA) in 2019, it emphasized centrifuge research and development, leading to the accelerated development and deployment of three centrifuge types: the IR-2m, IR-4, and IR-6 centrifuges. In addition, Iran continues working on many other advanced centrifuge types.

Because the advanced centrifuges are significantly more powerful than the IR-1 centrifuge, they pose a greater threat from their use in a breakout to nuclear weapons or deployment in a clandestine enrichment plant. As a result, they were a special concern in negotiations of the JCPOA, leading to severe, albeit temporary limits on their testing and development.

Much about Iran's different types of advanced centrifuges remains publicly unknown, due to Iranian secrecy. This report presents information gathered by the Institute over the last fifteen years on the individual types and the families of centrifuge types, as many individual types are closely related. It is a comprehensive public survey of Iran's advanced centrifuges.

This report is organized into a highlights chapter followed by three comprehensive chapters. Chapter 1 is a detailed discussion of each of the centrifuge types that Iran has deployed, including technical details about their size and capabilities. Chapter 2 discusses trends in their deployment and includes tables detailing Iran's historical deployment of advanced centrifuges at Natanz and Fordow enrichment plants, starting in 2011, carrying through the period of the JCPOA, up to November 2021, the date of the most recent International Atomic Energy Agency

(IAEA) quarterly report on Iran at the time of the publication of this study. Chapter 3 contains findings and assessments about Iran’s gas centrifuges. Annexes provide a variety of technical background information on centrifuges and their operation.

A Word on Sources

This survey relies on several sources of information both publicly available and collected independently by the Institute. One of the most important sources for technical details about Iran’s centrifuges is its official declarations as part of bringing the JCPOA into force. In this report, these data are referred to generally as some variant of Iran’s declaration under the JCPOA. This information is supplemented by information in IAEA reports on Iran’s nuclear program, information on Iranian government websites or in official handouts of the Atomic Energy Organization of Iran (AEOI), interviews of knowledgeable officials, and a variety of data about centrifuges in general. In addition, the Institute has collected other information on Iran’s centrifuges, part published on its website, and all held in an Institute archive.

Two related recent sources are Iranian tables released during 2021 purporting to contain official data about the centrifuges. On July 12, 2021, two Farsi-language tables were circulated online and tweeted by an Iranian journalist.¹ The table of main interest here, published by Etemadonline, an Iranian news website, contains technical information on each of sixteen different Iranian centrifuge models. The table’s title is translated as “Specification Table of 16 Iranian Centrifuges.” Figure A1.1 in Annex 1 contains the original Farsi table and the translation by the Institute. This table is undated, but it may reflect the period from the end of 2019 to the first part of 2021, based on information in the table. In this report, it is often referenced as the “Iranian table.” Annex 1 also includes a comparison between the enrichment output data in this table and the earlier declared values from 2015.

The other Farsi table is stated to be from a report “to the people” by then Foreign Minister Mohammad Javad Zarif. The table contains information on the official status of different parts of Iran’s nuclear program prior to the JCPOA and “currently.” It is titled “Pre-JCPOA and Current Nuclear Status Comparison Table.” The table is undated and has information from different periods of 2021, some as recent as July 2021. In this survey, this table is referred to as Zarif’s table.

Moreover, Iran’s enrichment and enrichment research and development (R&D) plan that was negotiated as part of the JCPOA is compared to Iran’s recent testing and operation of advanced centrifuges in violation of the JCPOA, allowing for a closer examination in a few cases of the successes and failures in its centrifuge program.²

¹ Tweet by @SaraMassoumi, July 12, 2021, <https://twitter.com/saramassoumi/status/1414468113886760960?s=21>.

² “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>.

A Note on Technical Units

In Iran's public discussions, it has adopted a non-standard unit to discuss the output of a centrifuge. For example, Iranian leaders have often discussed Iran's desire to build a centrifuge plant with an enrichment output of "190,000 SWU."³ This statement must be interpreted and converted into standardized units. The units used by Iran are technically kilograms (kg) uranium hexafluoride (UF₆) separative work units (SWU) per year, or kg UF₆ SWU per year for short. The more standard units are technically kg uranium (U) SWU per year, typically shortened by the Institute to "SWU per year." Converting the "190,000 SWU" to the more standard units results in a value of about 128,000 SWU per year.⁴ Iran also uses this non-standard unit to discuss the enrichment output of its advanced centrifuges, causing further confusion. In this report, we will favor the more standard unit, but we will sometimes use the unit favored by Iran, when indicated. In a few cases, we will also refer to one as the uranium unit and the other as the uranium hexafluoride unit. (A similar distinction is also made in Institute reports between uranium mass and uranium hexafluoride mass.)

³ ShiaTV, "Salehi: Iran needs 190000 SWU for nuclear power, research plants – English," *Press TV*, July 8, 2014, http://www.shiatv.net/view_video.php?viewkey=440288591.

⁴ The conversion factor is 0.676.

Highlights

In the last two years, Iran has accelerated its deployment of advanced centrifuges, following a lull of three years created by limits in the Joint Comprehensive Plan of Action. Iran has demonstrated its commitment to replace the IR-1 centrifuge with advanced centrifuges, which can produce considerably more enriched uranium.

Figure H.1 shows the number of advanced centrifuges deployed from 2011 onwards through today, with a projection for early to mid-2022 based on Iran’s announced plans. The three enrichment plants where advanced centrifuges have been deployed are the Natanz above-ground Pilot Fuel Enrichment Plant (PFEP), and the much bigger, below-ground Fuel Enrichment Plant (FEP), and the deeply buried Fordow Fuel Enrichment Plant (FFEP). The total number of installed advanced centrifuges has been increasing rapidly as Iran continues to violate the terms of the JCPOA. Iran’s plans and declarations to the IAEA show that it intends to install many more advanced centrifuges in the coming months, further increasing its enrichment capacity.

Iran: Total Installed Advanced Centrifuges By Date

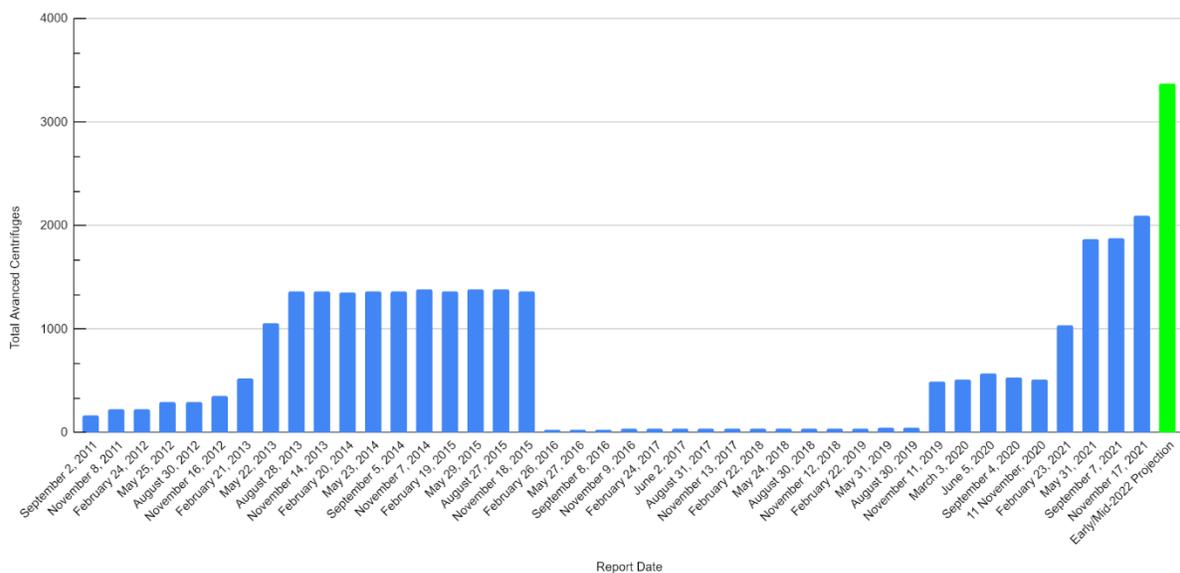


Figure H.1. Iran’s quarterly number of installed advanced centrifuges at its three enrichment plants, with a multi-quarter projection for early to mid-2022 (last vertical bar). (The number of IR-1 centrifuges are ignored in this graph; see Chapter 1.) In April 2021, the Natanz FEP was attacked, affecting half of the IR-2m and IR-1 cascades. The total number of installed cascades remained the same but many of the centrifuges could have been destroyed. Since the attack, Iran likely replaced the broken centrifuges in those cascades, although the IAEA does not report how many centrifuges were replaced.

Figure H.1 shows a steady increase in the number of advanced centrifuges until 2013, followed by a steady level, and then a sharp drop in 2016, when the JCPOA was implemented with a focus on limiting advanced centrifuge research and development, at least temporarily. That

number started to increase again in the fall of 2019, after Iran began to violate the JCPOA, but at a faster rate than prior to the JCPOA, reaching unprecedented deployment levels in May 2021. In recent months, the number of deployed advanced centrifuges has exceeded the number deployed prior to the JCPOA. As of September 2021, Iran had approximately 1889 advanced centrifuges installed at its three enrichment plants, almost all in violation of the JCPOA. By mid-November 2021, this number increased to 2101. During the next several months, based on Iran's announcements to the IAEA and an Iranian nuclear law passed in December 2020, the Atomic Energy Organization of Iran (AEOI) is projected to install up to another 1280 advanced centrifuges, bringing the projected total to 3381 installed advanced centrifuges.

Due to difficulties in manufacturing centrifuges, caused mainly by two sabotage events in 2020 and 2021 at its centrifuge production plants, Iran may have trouble achieving the projected number by mid-2022. However, Iran appears to be recovering from these attacks and is stepping up its centrifuge production rates. As a result, the country may be able to deploy the projected number, although further delays would be unsurprising.

The most important advanced centrifuges today are the IR-2m, IR-4, and IR-6 centrifuges. The recent deployments represent a *build-back* for the IR-2m centrifuge, in contrast to a *build-up* for the IR-4 and the IR-6 centrifuges.

One way to see the importance of these three centrifuges is to consider that they can replace the IR-1 centrifuges while utilizing the existing cascade piping and feed and withdrawal systems at the Natanz and Fordow sites. In terms of wide-scale deployments, the IR-4 and IR-6 centrifuges appear more important than the IR-2m centrifuge. Iran may have encountered obstacles procuring needed and tightly controlled materials from overseas for the IR-2m centrifuge, limiting its ability to produce it in larger numbers. In contrast, Iran has been more successful evading national and international controls and sanctions with regards to materials needed for the IR-4 and IR-6 centrifuges.

Notably, when Iran started production of 60 percent highly enriched uranium in April 2021, the IR-4 and IR-6 centrifuges were chosen for this task, rather than using one with which Iran had more operational experience, such as the IR-1 or IR-2m centrifuge. The IR-1 centrifuge has already been used for the production of 20 percent enriched uranium, and the IR-2m centrifuge has been operated in cascades for several years.

In terms of understanding the impact of these three centrifuges, a key value is their estimated average enrichment output when arranged into cascades of about 160-170 centrifuges, called production-scale cascades, the workhorse for enrichment in Iran. These estimated average outputs are less than theoretical values or single centrifuge measured values because of inefficiencies experienced during larger-scale cascade operation. The enrichment output of the IR-2m centrifuge when operating in a production-scale cascade is estimated at 3.67 SWU per year; the estimated value for the IR-4 centrifuge in a production-scale cascade is 3.3 SWU per year. The equivalent value for the IR-6 centrifuge is harder to discern from the available

information, but an estimated value of approximately 5.25 SWU per year appears justified and reasonable. In practice, lower average values may result, due to centrifuge breakage or during the production of highly enriched uranium, such as production of 60 percent enriched uranium or weapon-grade uranium. Nonetheless, the practical enrichment output of these three centrifuges is far higher than that of the IR-1 centrifuge, which achieves production-scale cascade values of 0.5-1.0 SWU per year.

Figure H.2 is a timeline of the deployment of major advanced centrifuge types; the horizontal axis gives the year in which each type was deployed for the first time at the pilot plant at Natanz, starting with the IR-2 and IR-3 centrifuges in 2008. For comparison purposes, the vertical axis lists each centrifuge's theoretical enrichment output. It should be noted that, when data exist, the output in practice has proven to be significantly less than predicted by these theoretical values. Some centrifuge types are not included in Figure H.2; these centrifuges are included in Chapter 1.

Starting in November 2019, Iran demonstrated that it had accelerated its centrifuge research and development by installing seven types of centrifuges in addition to the existing seven types allowed to be deployed under the JCPOA. These seven additional types were not included in Iran's confidential JCPOA enrichment plan, which projected the deployment of centrifuges up to about 2030. Iran's rapid deployment of many advanced centrifuges in 2019, including many new models, suggests that centrifuge development work continued during the period when the JCPOA was in force and accelerated secretly at least as soon as the United States ended its participation in the JCPOA in May 2018.

Of the fifteen advanced centrifuge types in Figure H.2, based on the November 2021 quarterly IAEA report, the IR-2m, IR-4, IR-5, IR-6, IR-6s, and IR-s centrifuges were accumulating enriched uranium. The IR-7, IR-8, IR-8B, and IR-9 centrifuges were being tested with natural uranium feed but not accumulating enriched uranium. The IR-2, IR-3, IR-6m, IR-6sm, and IR-8s centrifuges were not listed as present in an enrichment plant. The IR-2 and IR-3 centrifuges may have been retired. An additional new centrifuge type, the IR9-1B, is discussed in Chapter 1, but it has not been deployed at the PFEP to this date and is not included in Figure H.2.

Timeline of First Deployment at the PFEP for Major Advanced Centrifuge Types

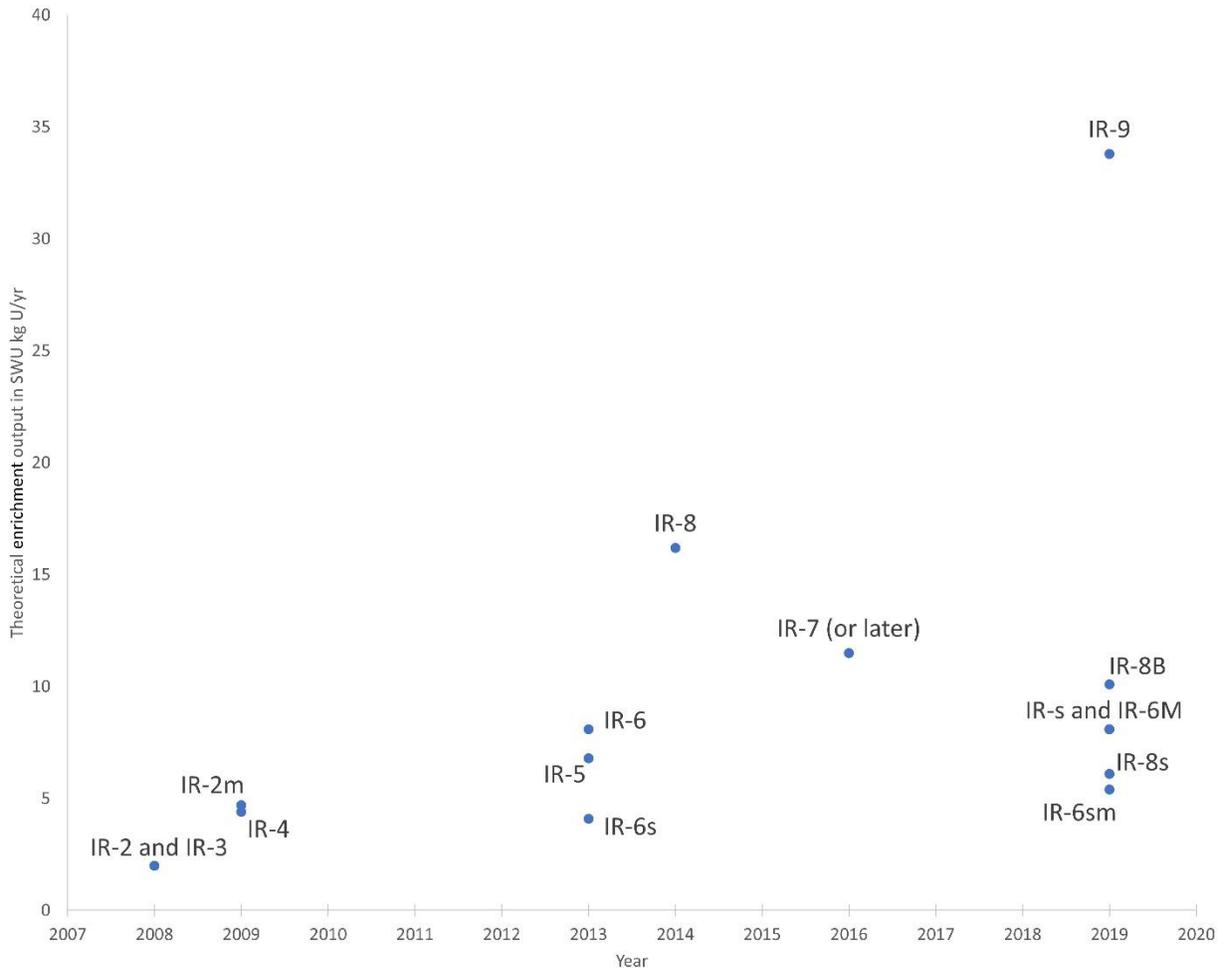


Figure H.2. Timeline of Iran’s deployment of major advanced centrifuge types at the Natanz Pilot Fuel Enrichment Plant, in relation to their theoretical enrichment output, starting with the IR-2 and IR-3 in 2008. Where data exist, the theoretical output proved significantly greater than the practical values Iran achieved when the centrifuges enriched uranium either alone or in cascades.

The JCPOA reduced the number of installed IR-2m and IR-4 centrifuges temporarily, but despite limitations, it only reduced the number of IR-6 centrifuges for a relatively short period of time, and it did not slow Iran’s ability to rapidly produce and deploy advanced centrifuges once Iran decided to stop abiding by the JCPOA limits. Iran has demonstrated its ability not only for a nuclear snap-back but also for a snap nuclear build-up.

In reviewing Iran’s work on advanced centrifuges, the step from single machine tests to small cascade testing appears critical. However, under the JCPOA, this step was allowed from year one of the JCPOA’s implementation for the IR-6 and IR-8 centrifuges, and not enforced sufficiently for the IR-6 centrifuge.

Iran has gained valuable technical knowhow, experience, and advancements in the designing and building of its advanced centrifuges, further enabling a rapid build-back or build-up of centrifuge capabilities. These gains cannot be reversed or erased, presenting further challenges for the international community and the IAEA, as they seek to reestablish the JCPOA. A sobering finding is that the only way to truly limit centrifuge research and development is to stop it completely, or at least establish a moratorium on it.

Figure H.3 provides Iran’s total historical theoretical enrichment capacity at Natanz and Fordow, where the IR-1 capacity is in blue and advanced centrifuge capacity is in red. So far, Iran’s current enrichment capacity has not exceeded its total capacity prior to the JCPOA’s implementation but the nature of that capacity is shifting predominately to advanced centrifuges.

Because of their far greater enrichment outputs, the installed advanced centrifuges, although many fewer in number, began in May 2021 to exceed the enrichment capacity of the several thousands of installed IR-1 centrifuges. As of November 2021, the advanced centrifuges numbered about 2100, or about 34 percent of the number of deployed IR-1 centrifuges at Natanz and Fordow, and they out-produced the 6290 deployed IR-1 centrifuges in enrichment output by about 48 percent. If Iran reaches the projected number of 3381 advanced centrifuges, they will have almost two and half times the enrichment capacity of the currently deployed IR-1 centrifuges. This advanced centrifuge capacity will also rival all of Iran’s estimated 16,000 IR-1 centrifuges—deployed *and* stored—with only 21 percent of the number of centrifuges. This comparison ignores any stored advanced centrifuges.

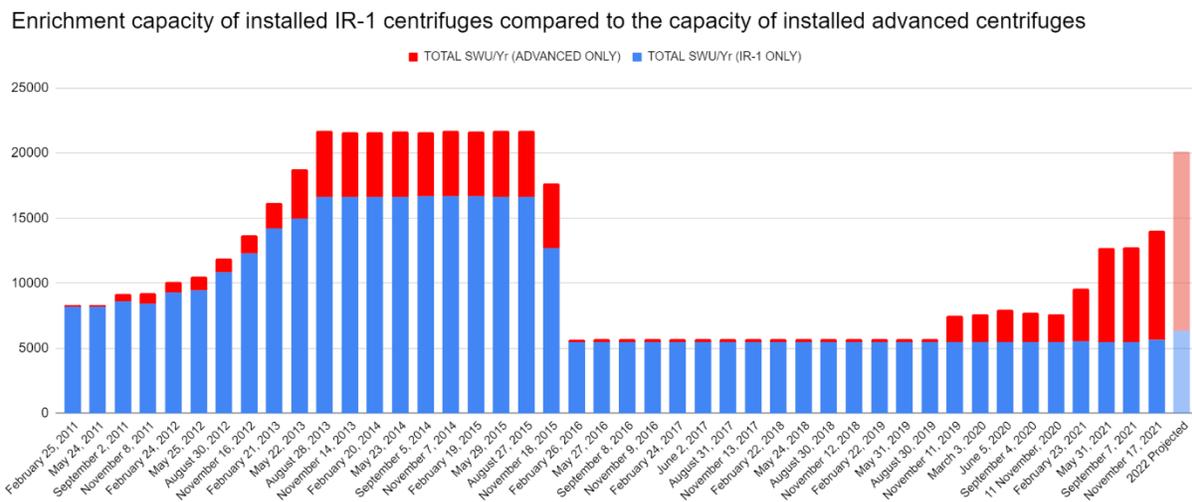


Figure H.3. Total enrichment capacity, by quarter, of the IR-1 and advanced centrifuges, with a projection on the far right of the graph.

In its development of advanced centrifuges, Iran has lengthened their centrifuge rotor assemblies, boosted their wall speed marginally by increasing the diameter, and changed the

rotor tube material to carbon fiber. Carbon fiber allows for higher rotor speeds than the high strength aluminum used in Iran's IR-1 centrifuge. Iran could have also achieved higher speeds by opting for high strength maraging steel rotor assemblies, as Pakistan did, but Iran appears to have encountered difficulties procuring this material. However, excluding the IR-1 centrifuge, Iran's enrichment output appears to have increased mostly with length, indicating Iran has had difficulties operating its centrifuges at the higher speeds offered by carbon fiber rotors.

Difficulties with high strength maraging steel appear to have also motivated Iran to develop the bellows, an important component of Iran's longer centrifuges, from carbon fiber, although carbon fiber bellows are much more difficult to make than ones made from maraging steel. Not unexpectedly, Iran appears to have ongoing difficulties making carbon fiber bellows, continuing to deploy shorter centrifuge models that do not need a bellows in parallel to developing the longer centrifuges. It is also concentrating on deploying advanced centrifuges with only one carbon fiber bellows, a centrifuge design easier to develop than one with two or more bellows.

The IR-s centrifuge bears watching. It is an outlier among the shorter centrifuges, with a relatively high theoretical enrichment output, implying a wall speed more consistent with the potential of carbon fiber rotors. Typically, Iran's advanced centrifuges have achieved speeds less than optimal for carbon fiber rotors. However, the IR-s may be testing at these higher speeds, say of the order of 700 meters per second. Achieving these higher speeds is difficult but would allow significant increases in enrichment output.

Recent attacks on the Natanz Iran Centrifuge Assembly Center (ICAC) and a centrifuge manufacturing plant at a site called TABA (also known as TESA), situated near Karaj, have likely limited or slowed Iran's ability to install advanced centrifuges. The numbers installed over the last year in the three centrifuge plants support that supposition.

The ICAC was built to have a capacity to make a few to several thousand advanced centrifuges per year. Iran's subsequent manufacturing and assembly capacity appears to have been substantially reduced, down to a level of several hundred advanced centrifuges per year. However, Iran has been rebuilding its centrifuge manufacturing capacity, so increases should be expected, absent more attacks or negotiated limits.

Nonetheless, advanced centrifuge production rates are hard to predict, because of unclear Iranian policies on the number produced versus deployed, and less Iranian transparency at its centrifuge manufacturing sites since February 2021, including the refusal to allow the re-installation of IAEA monitors at the Karaj facility after the attack. In addition, the sabotage events at Natanz and Karaj have limited the production of centrifuges to an unknown extent. While the November 2021 IAEA report contains no information on the operational status of the Karaj site, the *Wall Street Journal* reported that the site resumed centrifuge production on a

limited scale in August 2021 and accelerated production subsequently, producing “parts for at least 170 advanced centrifuges” by mid-November.⁵

Further, it is unclear where Iran has been assembling its advanced centrifuges with the ICAC’s destruction. The large, and sudden deployment of various types of advanced centrifuges, however, raises questions as to how, where, and when those centrifuges were produced.⁶ In an April 2021 MEMRI TV interview, then AEOI-head Ali-Akbar Salehi indicated that a temporary replacement was built. In English subtitles, he is quoted as stating: “Today it was announced that we he had managed to build a hall instead of the one that was lost. This is temporary of course.”⁷ The subtitles did not identify the location, although it is supposedly at the Natanz site. The Natanz site offers several possible locations for assembling advanced centrifuges on a temporary basis.

In the longer term, Iran plans to assemble centrifuges in a deeply buried underground replacement facility near Natanz, although its construction progress is unclear. This site is expected to be large enough to produce centrifuges on the same scale as planned for the ICAC, namely several thousand advanced centrifuges per year.

In general, the AEOI has tried to develop many types of centrifuges, far too many for a commercial or economic program. Some of the developments, such as the proudly proclaimed very long centrifuges, appear aimed at impressing a domestic audience and not at large scale deployments in a reasonable time frame. The strategic nature of Iran’s centrifuge program cannot be ignored.

These more powerful advanced centrifuges make it easier for Iran to set up a secret enrichment plant, which would be smaller and host only a fraction of the centrifuges Iran would have needed in 2009, when it was trying to finish up and install IR-1 centrifuges at its secret enrichment plant at Qom, designed to produce highly enriched uranium.

Since only a relatively small number of advanced centrifuges would be needed to set up a secret and powerful enrichment plant, concern increases about unaccounted production of

⁵ Laurence Norman, “Iran Resumes Production of Advanced Nuclear-Program Parts, Diplomats Say,” *The Wall Street Journal*, November 16, 2021, <https://www.wsj.com/articles/iran-resumes-production-of-advanced-nuclear-program-parts-diplomats-say-11637079334>.

⁶ There is no concrete evidence that Iran has resumed production of IR-1 centrifuges, but recent AEOI statements about deploying six cascades of more powerful IR-1 centrifuges at the FEP raise at least the question whether production of IR-1 components has resumed.

⁷ MEMRI, “Iranian Nuclear Chief Day Before Natanz Nuclear Facility Blast: We Activated IR-6 Centrifuge Chain,” MEMRI TV Videos, Interview with Ali-Akbar Salehi that aired on channel 1 (Iran) on April 10, 2021, <https://www.youtube.com/watch?v=qLmQJOHsUsE>. Note: In several cases Iranian media mistranslates cascade, calling it a “chain” in English. An Institute translator confirmed the accuracy of the subtitles. In a description accompanying the video clip attributed also to MEMRI TV, a mistranslation appears to occur. According to this description, Salehi said that a hall in the ICAC had been restored where centrifuges are again assembled. He in fact did not make this statement in the video. Moreover, a November 2021 commercial satellite imagery of the ICAC shows its near destruction and no signs of restoration.

major parts for advanced centrifuges or whole rotor assemblies. With stocks of near 20 percent and 60 percent enriched uranium as of November 2021, about 650 IR-6 centrifuges would be enough to breakout at a clandestine enrichment site and produce enough weapon-grade uranium for a nuclear explosive in about one month.

The concern about Iran building another secret enrichment plant will undoubtedly grow with time, absent negotiated limits or far more robust IAEA inspections than exist today. After all, the Natanz enrichment plant and the Fordow enrichment plant were started in secret, the latter as part of a covert military program to produce weapon-grade uranium, a facility that went undiscovered for upwards of six or seven years.⁸ With advanced centrifuges, a secret plant could be smaller, more capable, and harder to discover, and this possibility should not be discounted.

Unless compensatory steps are taken, such as destroying rather than mothballing advanced centrifuges, a renewed JCPOA will not maintain a 12-month breakout timeline to produce enough weapon-grade uranium for a nuclear weapon. If Iran mothballs its advanced centrifuges, timelines of only five to six months are likely.

Because of the risk that Iran has accumulated a stock of undeclared assembled centrifuges as well as sensitive centrifuge components, breakout timelines could be further reduced, absent some compensatory action, such as the IAEA's verification of Iran's declaration of major components of advanced centrifuges, ensuring it is both complete and correct. So far, Iran has shown no interest in providing such cooperation. Nonetheless, the IAEA would be expected to attempt to verify Iran's declaration, complicating the implementation of a deal but ultimately providing more assurance of any breakout estimate.

Institute breakout calculations also ignore Iran's demonstrated capability to rapidly build and deploy additional advanced centrifuges, as well as its practice of skipping steps in the Khan four-step method of producing weapon-grade uranium, both allowing a quicker breakout to a first nuclear weapon, and in latter months a quicker increase of its centrifuge capabilities, enabling the speedier production of enough WGU for the second, third, and fourth nuclear weapons.

Seeking a moratorium on centrifuge research and development and the construction and operation of centrifuge manufacturing sites would help alleviate these challenges to the integrity and viability of the JCPOA.

⁸ David Albright with Sarah Burkhard and the Good ISIS Team, *Iran's Perilous Pursuit of Nuclear Weapons*, (Washington, DC: Institute for Science and International Security, 2021).

Chapter 1 Technical Parameters of Individual Centrifuge Types

Detailing the characteristics of Iran’s advanced centrifuges is challenging. Over the years, the Institute has collected a wide variety of data about Iran’s centrifuges from various sources. In addition, the Iranian media and government have published or provided handouts with useful information or images.

Figures 1.1-1.3 are images featuring models of several of Iran’s centrifuges, from the IR-1 to the IR-8 centrifuges, as presented at Iranian conferences open to the media. These models as well as others are discussed in detail below. All the models are based on a Zippe-type centrifuge, a design developed in Russia after World War II and brought to the West by one of its developers, Gernot Zippe. It features a collection of rotor tubes connected by bellows. Figure 1.4 shows a common version of such a centrifuge, with two rotor tubes connected by one bellows. A discussion of bellows can be found in Annex 2.



Figure 1.1. A variety of centrifuge types at a nuclear fair in Tehran, along with technical specifications for a few of them on posters behind them. The centrifuges on the right appear to be IR-1 centrifuges connected in a small cascade, showing the distinctive piping of the IR-1 cascade, where each centrifuge is linked via three small pipes to overhead piping, called headers. A cutaway of the IR-1 is also visible. Source: IRNA



Figure 1.2. From left to right: IR-2m, IR-4, IR-5, IR-6, and IR-8 centrifuge models. Source: Ali Hashem, @alhashem_tv



Figure 1.3. A variety of centrifuge types with posters behind them showing key technical parameters. Source: Iran Press

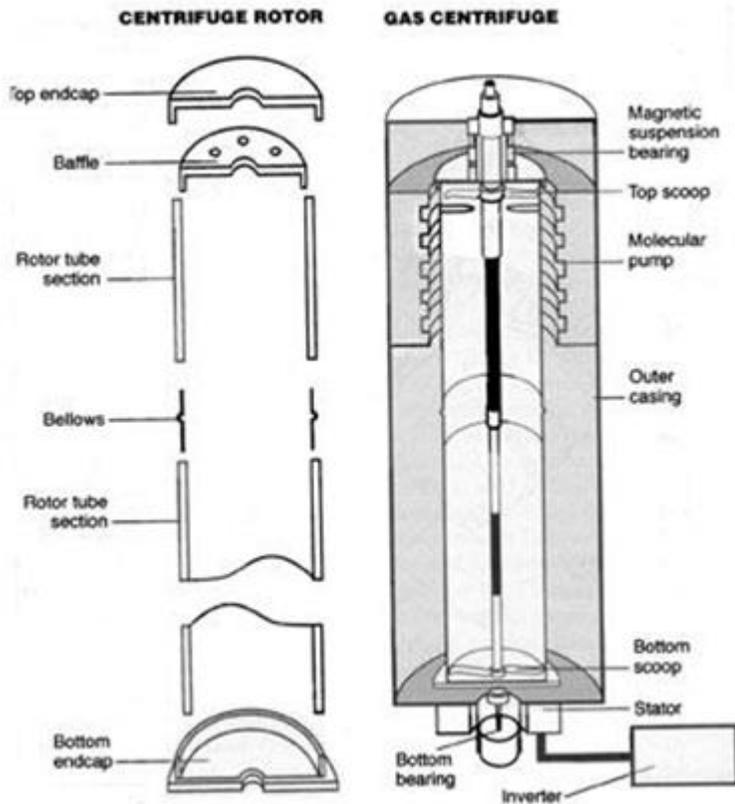


Figure 1.4. Schematics showing a supercritical Zippe-type centrifuge with two-rotor tubes and one bellows (see Annex 2: The Bellows). The schematic on the left is a disassembled rotor assembly. The type of bellows in the schematic, with an outward-pointing convolution, is not the same as found in Iranian bellows, which have an inward-pointing bellows. Source: Albright, D. and Hibbs, M., "Iraq's Shop-Till-You-Drop Nuclear Program," *Bulletin of the Atomic Scientists*, vol. 48, no. 3 (April 1992), pp. 32 and 33.

Table 1.1, Parts 1 and 2, and Table 1.2, all located at the end of this chapter, summarize the Institute's collection effort for the key technical parameters of Iran's major centrifuges deployed at the Natanz and Fordow enrichment facilities. These parameters are discussed in the following sections focused on individual centrifuge types. However, not all the key parameters could be identified, and those cells in the tables are left blank. In addition, the tables do not include at least one centrifuge deployed at an unknown military site (see below) and a range of models deployed as part of earlier centrifuge development programs in the 1990s and early 2000s.

Figure 1.5 is a timeline of the initial deployment of the advanced centrifuge types, where the horizontal axis gives the year in which each type was first deployed at the pilot plant at Natanz, starting with the IR-2 and IR-3 in 2008. On the vertical axis, the theoretical, single centrifuge enrichment output is given. The graph shows that in general, theoretical enrichment output of

Iran’s advanced centrifuge models increased over time, but Iran continued to develop lower-output single-rotor machines in parallel. Further, the IR-7 is an outlier as it was not deployed before the IR-8. It is not clear when the IR-7 was deployed for the first time, as the JCPOA allowed deployment of single IR-7 machines and the IAEA did not report any details. It is possible that it was not deployed until November 2019, when the IAEA specifically listed the IR-7 present at the PFEP for the first time.

Timeline of First Deployment at the PFEP for Major Advanced Centrifuge Types

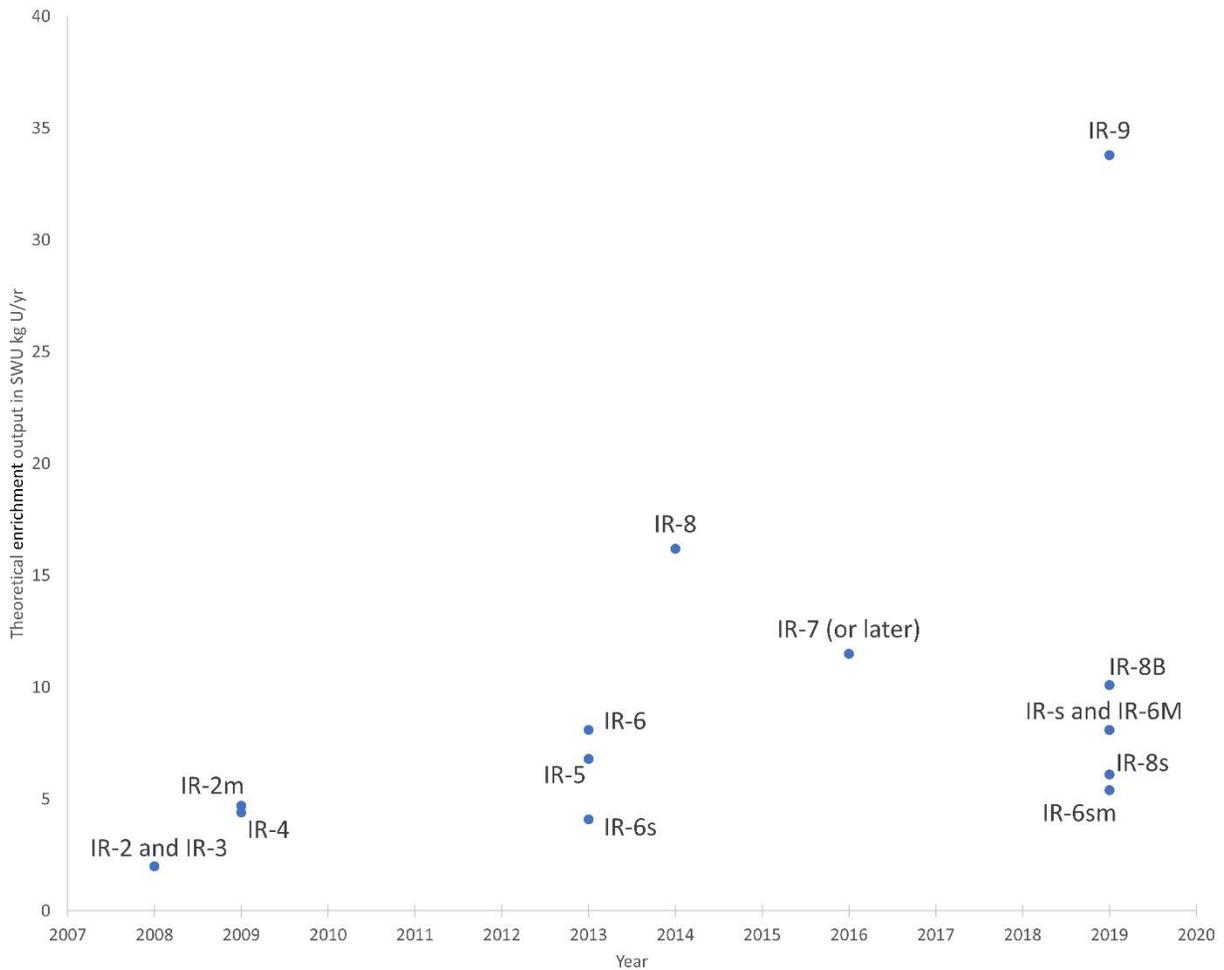


Figure 1.5. Timeline of Iran’s deployment of major advanced centrifuge types at the Natanz Pilot Fuel Enrichment Plant, in relation to their single centrifuge theoretical enrichment output, starting with the IR-2 and IR-3 in 2008. The theoretical output is significantly greater than the values Iran achieved when the centrifuges enriched uranium either alone or in cascades.

IR-1 Centrifuge

The IR-1 is Iran’s first deployed centrifuge at Natanz, a copy of Pakistan’s P1 centrifuge, a centrifuge developed from stolen Dutch Urenco centrifuge designs, called the CNOR. The

Atomic Energy Organization of Iran tested it with uranium hexafluoride in the 1990s, with first deployment on a large scale in 2007, although mass production started in 2002, utilizing a series of military manufacturing sites.⁹ Its rotor tube assembly has a length of 1800 millimeters, a diameter of 100 millimeters, and a rotational frequency of 1050 Hertz (Hz). The rotor assembly is composed of four tubes of high strength aluminum connected by three maraging steel bellows, with aluminum end caps. Each upper bearing contains two ferrite magnets with exacting specifications. Figure 1.6 shows a centrifuge rotor assembly; a cutaway of the IR-1 centrifuge can be seen in Figure 1.1. Typically, IR-1 centrifuges are combined via piping into cascades of either 164 or 174 of them (see Figure 1.7).

The above frequency and diameter convert to a wall speed of 330 meters per second, which largely determines the enrichment output of a centrifuge, where output is linearly proportional to length and to the square of speed (See Annex 3: Upper Limit Theoretical Enrichment Output). This speed is typical for high strength aluminum rotors. Although aluminum rotors can reach a speed of almost 450 meters per second (see Annex 3), aluminum tends to “creep,” or deform, at such high speeds, causing structural failures. As a result, the rotor speed is usually kept to the lower speed seen in the IR-1 centrifuge.

According to Iranian sources, the IR-1 has a theoretical enrichment output of about 1.4 SWU per year per machine (see Table 1.1, Part 1). Historically, it has rarely achieved over 1 SWU/yr, experiencing a range of operational difficulties. The Institute typically assigns the IR-1 centrifuge a value of 0.9 SWU per year when operating in a production-scale cascade, although lower values are also used, particularly in breakout calculations.¹⁰ (See the Iranian table in Annex 1, where a value of 0.68 SWU per year (after conversion) is given.) The IR-1 centrifuge has experienced breakage rates exceeding 20 percent per year. Cascade operation has often been disrupted by the need to rapidly shut down the cascade and evacuate the cascade, or “dump” the uranium hexafluoride in the cascade into tanks connected to the centrifuges via an emergency system.¹¹ This emergency measure is initiated automatically when there is a heightened risk that the centrifuges in the cascade could break or “crash.” Pakistan provided Iran with the design of this emergency system, described as a “fast acting valve system for cascade protection during centrifuge failure.”¹² A. Q. Khan obtained this system illegally from

⁹ Iran’s early pre-2003/2004 IR-1 centrifuge manufacturing complex is discussed in: David Albright, Paul Brannan, and Jacqueline Shire, “Can military strikes destroy Iran’s gas centrifuge program? Probably not.,” *Institute for Science and International Security*, August 7, 2008, https://www.isis-online.org/publications/iran/Centrifuge_Manufacturing_7August2008.pdf.

¹⁰ For example, in Institute breakout calculations, i.e., the time needed by Iran to produce 25 kilograms of weapon-grade uranium, after accounting for inefficiencies, an average value of about 0.5 SWU per year is utilized.

¹¹ Dumping still occurs today with the IR-1, where over one recent quarter, Iran had to dump 170 kg 2 percent enriched uranium feed material at the FEP, and 34.3 kg 5 percent enriched uranium at the FFEP, both representing about 8 percent of the overall feed in the reporting period May to August 2021. See, Report by the Director General, *Verification and monitoring in the Islamic Republic of Iran in light of United Nations Security Council resolution 2231 (2015)*, GOV/2021/29, September 7, 2021, <https://isis-online.org/uploads/iaea-reports/documents/gov2021-39.pdf>.

¹² David Albright, *Peddling Peril* (Washington, DC: Institute for Science and International Security, 2010).

Urenco through a leak in the late 1970s, engineered by the Swiss national Fredrich Tinner, a key member of the Khan network.¹³

Prior to 2016, Iran deployed over 18,000 IR-1 centrifuges at its declared centrifuge plants, almost 15,420 of them in the Natanz Fuel Enrichment Plant (see Figure 1.8). Of the latter, up to 6300 had not been fed with uranium hexafluoride prior to the implementation of the JCPOA in early 2016.¹⁴ The Iranian table (Figure A1.1 in Annex 1) states: “Currently, more than 16,000 of these machines are available in enrichment centers or warehouses in Iran.” This implies that about 2000 IR-1 centrifuges have broken or otherwise become unusable since the implementation of the JCPOA in early 2016. Currently, Iran is not known to be making additional IR-1 centrifuges.

As of late August 2021, the Natanz Fuel Enrichment Plant had a total of 30 cascades of IR-1 centrifuges, comprising 5060 centrifuges; this number increased to 31 cascades by mid-November 2021, or about 5234 centrifuges. The Fordow Fuel Enrichment Plant was enriching in six IR-1 centrifuge cascades, or up to 1044 centrifuges, in three sets of two interconnected IR-1 cascades to produce 20 percent enriched uranium from up to 5 percent enriched uranium. One additional IR-1 centrifuge was installed at Fordow as of November 2021. Further, as of November, there are 18 IR-1 centrifuges at the Natanz Pilot Fuel Enrichment Plant (PFEP). In mid-November, the quantity of IR-1 centrifuges in the 37 production-scale cascades was 6278, for a total of 6297 including the 19 additional centrifuges used in research and development activities at the PFEP and Fordow.

With reportedly 16,000 IR-1 centrifuges available as of 2021, and about 6300 in use at Natanz and Fordow, Iran has almost 10,000 IR-1 centrifuges in storage. According to Zarif’s table mentioned in the Preface, Natanz has 4000 in storage; thus, an additional 6000 are stored elsewhere, if the information in this table is true.

Recent media reports claim that IR-1 centrifuges have in recent years increased their enrichment output by 50 percent.¹⁵ This new value does not approach the output of the advanced centrifuges, but it would place the performance of these IR-1 centrifuges closer to their theoretical enrichment output value. The claims would also help explain why Iran has maintained IR-1 centrifuges at the PFEP and is planning to deploy five more cascades of IR-1 centrifuges at Natanz, which would bring the total of IR-1 centrifuges to about 42 production-

¹³ *Peddling Peril*.

¹⁴ Fifty-four out of 90 cascades of IR-1 centrifuges at the FEP were enriching before the JCPOA, which translates to 9156 out of 15,420 IR-1 enriching, which means 6264 were installed but not fed with uranium hexafluoride. See: David Albright, Serena Kelleher-Vergantini, Andrea Stricker, and Daniel Schnur, "ISIS Analysis of IAEA Iran Safeguards Report," *Institute for Science and International Security*, May 29, 2015, https://isis-online.org/uploads/isis-reports/documents/ISIS_Analysis_IAEA_Report_May_29_2015_Final.pdf.

¹⁵ “60 Percent Enrichment Operation to Begin Tonight: Kamalvandi,” April 13, 2021, Tasnim News (Google translation).

scale cascades or 7056 IR-1 centrifuges.¹⁶ Based on data available in the IAEA's quarterly verification reports on Iran, this improvement in the IR-1 enrichment output is not visible in the IR-1 cascades operating at the Fordow plant to make near-20 percent enriched uranium.



Figure 1.6. An IR-1 centrifuge rotor assembly, showing three bellows, four rotor tubes, and an end cap. The image was taken in Libya, where the rotor assembly was supplied by Pakistan.

¹⁶ Based on available information, it is unclear if these IR-1 centrifuges will be taken from storage or include newly produced components.



Figure 1.7. IR-1 centrifuge cascades in the Pilot Fuel Enrichment Plant in 2008 during a visit by then President Mahmoud Ahmadinejad.

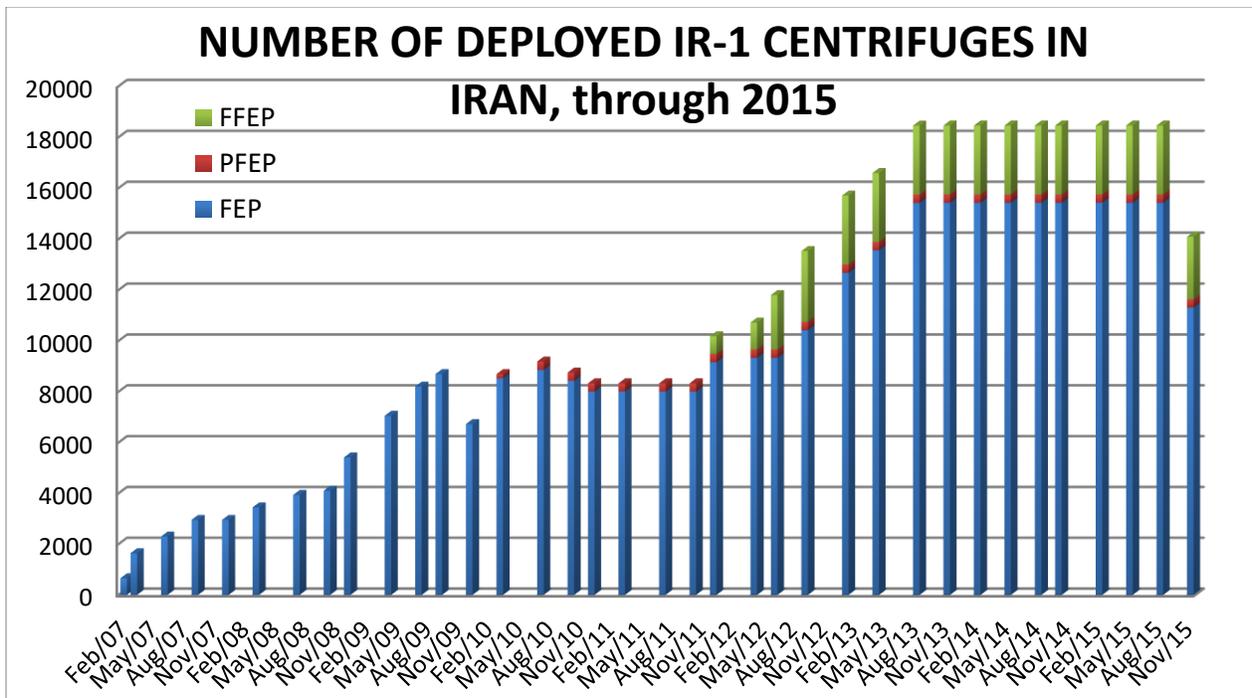


Figure 1.8. Historical tabulation of numbers of IR-1 centrifuges installed at the Fordow Fuel Enrichment Plant (FFEP), the Natanz Fuel Enrichment Plant (FEP), and the Pilot Fuel Enrichment Plant (PFEP), drawn from IAEA quarterly reporting, prior to the implementation of the JCPOA in January 2016. The sharp dip in February 2010 is attributed to destruction wrought by the Stuxnet malware. The one in November 2015 is due to the start of the implementation of limits in the JCPOA. This graph does not include the approximately 1000 IR-2m centrifuges installed at the FEP and the roughly 300 additional advanced centrifuges installed at the PFEP. Out of the 18,000 IR-1 centrifuges, over 6000 were not fed with uranium hexafluoride prior to the implementation of the JCPOA. Source: ISIS reports based on IAEA quarterly Iran reports

Amad Plan Centrifuge(s): The Industrial Model

In parallel to the AEOL’s development of the IR-1 centrifuge in the 1990s, Iran’s nuclear weapons program was developing other centrifuges. Little information is available about this effort.

One of the rare pieces of information on this centrifuge effort was an early Amad Plan table in Iran’s Nuclear Archive, which lists a centrifuge project starting on October 2, 1999, with plans to finish building all necessary facilities and associated activities by March 18, 2004.¹⁷ This table lists that work on the “industrial model” started on October 3, 1999, and was to be finished on March 18, 2002, the end date corresponding to the end of a Persian year. At the time when the table was prepared, sometime during early 2002, the industrial model was listed as 70 percent finished, although expectations were that it would be 91 percent finished by that time.

¹⁷ *Iran’s Perilous Pursuit of Nuclear Weapons*, Chapter 2, Figure 2.2, and Chapter 8.

The Nuclear Archive also has an undated video that may show this industrial model being developed by the Amad Plan, or its predecessor, the Physics Research Center (PHRC). Figure 1.9 shows a freeze-frame from this video of a line of five centrifuge housings, absent rotor assemblies, in an unidentified building. The entire video shows two lines of centrifuge housings in this room (not visible in the freeze frame).

The centrifuges in the video may have been at a military facility, either under the PHRC or subsequently under the Amad Plan, in parallel to the AEOI centrifuge program. Based on IAEA reporting, the tiled, relatively small room does not appear to be at the AEOI's known centrifuge research and development facilities. IAEA reporting makes clear that its inspectors had been unsuccessful in identifying where any military centrifuge work happened.

Moreover, the centrifuges shown do not match the IR-1 centrifuge, and their diameter appears narrower than those typically associated with IR-2-type centrifuges (see below).

As far as can be discerned, the industrial model was never built in large, industrial-scale numbers. The Amad Plan instead decided it would opt for the procurement of IR-1 centrifuges in its secret enrichment plant, which would later be built in secret, until its exposure in 2009.¹⁸ The enrichment plant is now under the AEOI and is called the Fordow Fuel Enrichment Plant (FFEP).

The rotor material is unknown, and it likely changed as the program developed, finally settling on carbon fiber. During the IAEA's investigation of Iran's secret centrifuge program in 2003/2004, according to a senior person involved in the investigation,¹⁹ inspectors discovered non-IR-1 rotor tubes, located away from AEOI sites, manufactured with high strength aluminum and others made from Kevlar fibers, a strong synthetic material that can be used in centrifuges. Both materials may have represented intermediate steps leading finally to carbon fiber.

¹⁸ *Iran's Perilous Pursuit of Nuclear Weapons*, Chapter 12.

¹⁹ June 2018 interview.



Figure 1.9. A photo, captured from an Iranian video in the Nuclear Archive, of individual centrifuge outer casings on stands in an unknown facility. The outer casings do not appear to contain centrifuge rotors.

Other Amad Plan Designs

The military is also believed to have overseen the development of other centrifuge types. During the second half of the 1990s, an Iranian engineer called “Fard” (not his real name), oversaw the exploitation of a Pakistani P2 centrifuge design acquired from the A.Q. Khan network in 1996, concentrating his work at his own workshop.²⁰ (The Institute could not determine whether the room in Figure 1.9 was at Fard’s workshop.) Fard modified the P2 design to use carbon fiber rather than maraging steel rotors, judging that Iran could not make either material domestically, but could procure abroad sufficient high strength, controlled carbon fiber. According to Fard’s account, his work on the P2 centrifuge started in 1997 and the carbon fiber rotors were wound at a military factory near the PHRC’s main site in north Tehran.²¹ He stated that he did this work as part of fulfilling his mandatory military service. Although Iran’s official declaration to the IAEA was that Fard was part of the AEOI centrifuge program, that assertion may not have been the case. Adding to that view, Iran initially hid its P2 centrifuge work from the IAEA, only admitting in February 2004 to having undertaken it, several months after then-National Security Council head Hassan Rouhani stated to the IAEA that Iran’s declaration was complete.²² A more believable possibility is that Fard was working

²⁰ *Peddling Peril*, p. 97.

²¹ *Peddling Peril*.

²² Rouhani admitted to the IAEA the existence of the P2 program during a dinner in February 2004, four months after stating Iran had fully declared its centrifuge program, according to a witness who was present, interviewed by an author of this report.

for the military centrifuge program, and the AEOI was concentrating on the IR-1 design at the Kalaye Electric plant, its main centrifuge research and development facility in the late 1990s.

IR-2 Centrifuge

The IR-2 centrifuge was an early advanced centrifuge. There is little public information about the history or operation of this centrifuge, except that it was also based on the Pakistani P2 centrifuge design, which in turn was a stolen German Urenco design called the G2. The IR-2 had a rotor assembly length of 650 millimeters, a diameter of 146 millimeters, and no bellows, making it a subcritical centrifuge with a single carbon fiber rotor tube. Such a centrifuge avoids damage or destruction at the first flexural critical speed, or resonance, during the centrifuge's runup and rundown. According to Iranian declarations, its theoretical output was 2.0 SWU per year per centrifuge. Its measured, single machine output was 1.8 SWU/year.

There remain questions about the IR-2 centrifuge's connection to centrifuges being developed in the Amad Plan. This centrifuge may have originally been developed by the military program and transferred to the AEOI after the downsizing and reorientation of the Amad Plan in 2003/2004. It corresponds with the centrifuges being developed by Fard, who was unable to develop a carbon fiber bellows by the time he stopped his work in 2003, when the centrifuge program was frozen under a deal negotiated between Iran and European powers.

Deployment of a small number of IR-2 centrifuges started in 2008 at the Natanz PFEP. Iran at that time installed it as a single machine and in a small, 10 machine cascade (see Figure 1.10).²³ These centrifuges were still operating in mid-2009.²⁴ It is unclear from public records when this centrifuge type was phased out.

²³ David Albright, Jacqueline Shire, and Paul Brannan, "May 26, 2008 IAEA Safeguards Report on Iran: Centrifuge Operation Improving and Cooperation Lacking on Weaponization Issues," *Institute for Science and International Security*, May 29, 2008, https://isis-online.org/uploads/isis-reports/documents/ISIS_Iran_IAEA_Report_29May2008.pdf.

²⁴ David Albright and Jacqueline Shire, "IAEA Report on Iran Centrifuge and LEU increases; access to Arak reactor denied; no progress on outstanding issues," *Institute for Science and International Security*, https://isis-online.org/uploads/isis-reports/documents/Iran_IAEA_Report_Analysis_5June2009.pdf.

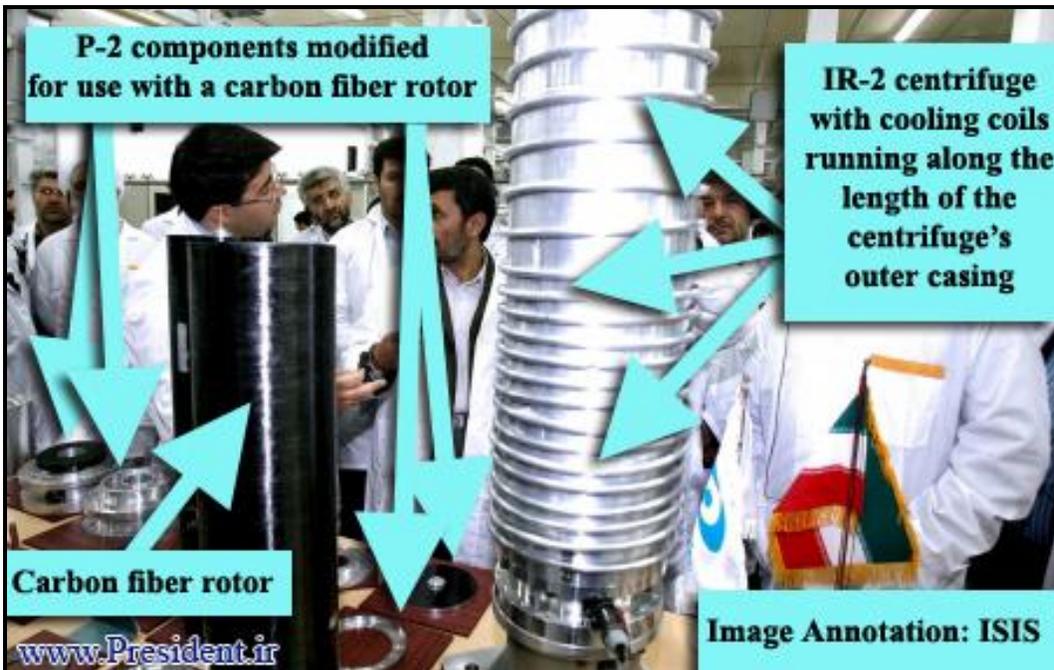


Figure 1.10. The IR-2 centrifuge has cooling coils running along the entire length of the centrifuge's outer casing. Off to the left on the lower image are P2 centrifuge components that have been adapted for use with a carbon fiber rotor tube. Images from then President Mahmoud Ahmadinejad's visit in 2008.

IR-2m Centrifuge

This centrifuge was also modeled on Pakistan's P2 centrifuge, but Iran made extensive changes in the design, shifting from maraging steel rotor tubes to carbon fiber rotor tubes while keeping the maraging steel bellows. This design also used high-specification ferrite magnets in the top bearing, as opposed to a more advanced type of ring magnet the P2 was using.

The rotor assembly has a length of 1050 millimeters and a diameter of 146 millimeters and is composed of two rotor tubes and one bellows, making it a supercritical centrifuge. According to Iranian statements prior to the JCPOA's implementation, it utilized aluminum end caps and baffles, which is not ideal for this type of centrifuge and may be another sign of Iran's shortage of high-grade maraging steel.

According to these Iranian statements, the centrifuge's frequency was 1050 Hz which, together with its diameter, translates into a wall speed of 482 meters per second, typical of the maraging steel rotors in the P2 centrifuge but much slower than speeds achievable with carbon fiber rotors. In 2008, the AEOI intended to seek a wall speed of 700 meters per second, a speed more typical of carbon fiber, but has had difficulty achieving that.²⁵

According to the pre-2016 information provided to the IAEA, the IR-2m centrifuge has a theoretical single machine output of 4.7 SWU/year and a single machine measured output of 4.1 SWU per year. Prior to the implementation of the JCPOA, its measured output in a production-scale cascade of 164 IR-2m centrifuges in the Natanz pilot plant was 3.67 SWU per year. According to the Iranian table, the enrichment output is 3.7 SWU per year (after conversion), close to the production-scale value declared in 2015.

At the target speed of 700 meters per second, the theoretical maximum enrichment output would have been up to 11.7 SWU per year (see Annex 3: Upper Limit Theoretical Enrichment Output for the formula used to calculate this value). The maximum at 482 meters per second is 5.6 SWU per year, making Iran's estimated theoretical single machine value of 4.7 SWU per year about 16 percent less than the calculated maximum value. Applying this percentage to the maximum value for the IR-2m centrifuge spinning at 700 meters per second results in a corresponding theoretical single machine value of 9.8 SWU per year.

This centrifuge design was likely based on Fard's work as part of the military centrifuge program. However, by 2002/2003 Fard still had considerable work to do on the rotor and bellows before this centrifuge would have been ready for mass production.

The Iranian table states that Iran was manufacturing the IR-2m centrifuge in Persian year 1385, or 2006/2007. It deployed its first production-scale cascade of IR-2m centrifuges in 2011 in the PFEP, a cascade which continued to operate until it was disassembled as part of the implementation of the JCPOA in 2015.

²⁵ Private communication to one of the authors.

By January 2013, Iran had decided to move beyond testing of IR-2m centrifuges in the PFEP and announced that it would install a total of 3000 IR-2m centrifuges in the Fuel Enrichment Plant. By February 21, 2013, it had installed 180 IR-2m centrifuges at the FEP, followed by an additional 509 centrifuges by May 22, 2013. It halted after having installed six cascades, or 1008 of them, by August 28, 2013, although preparatory installation work had been completed for the additional 12 IR-2m cascades. Under the JCPOA it stored the six IR-2m cascades installed in the FEP and the one in the PFEP. The total number of IR-2m centrifuges that Iran had actually built was never settled as part of the JCPOA implementation process.

Nuclear legislation approved in December 2020 mandates that the AEOI install 1000 IR-2m centrifuges within three months. It did not revert to the 3000, implying that whatever quantity Iran possesses, it did not want to reveal that in the legislation. Iran did install the 1000 IR-2m in six cascades at the FEP, over the course of six months, from October 2020 to April 2021, increasing the installation speed over time, installing the last two cascades in less than two months. Iran also maintains a relatively small number of about 30 IR-2m centrifuges at the PFEP.

According to the Iranian table, the production stage of the IR-2m is “semi-industrial production.” However, there remain questions as to whether Iran has sufficient supplies of high-grade maraging steel to build IR-2m centrifuges in mass quantities.

Figure 1.11 shows the IR-2m centrifuge outer casing side-by-side with IR-6 and IR-4 casings. Figure 1.12 shows a cascade of IR-2m centrifuges in the Natanz pilot plant.



Figure 1.11. IR-2m centrifuge outer casing on right, compared to the IR-6 and IR-4 centrifuge casings.
Source: Iran Press News Agency



Figure 1.12. A cascade of IR-2m centrifuges at Natanz. Source: AEOI

IR-3 Centrifuge

The IR-3 centrifuge is subcritical, i.e., without bellows, and with a rotor assembly length of 720 millimeters and a diameter of 160 millimeters. It was calculated to have a single machine output of 2 SWU/year, and a measured single machine output of 1.8 SWU/year. The rotor tube is made from carbon fiber. These enrichment output values are the same as the ones for the IR-2 centrifuge, implying that the IR-3 had a slower wall speed, given their differing lengths.

This centrifuge represents Iran's first experiments with widening the diameter of the advanced centrifuge, a way to allow for a longer rotor assembly and potentially a faster wall speed, resulting in a greater enrichment output while preserving it being subcritical (see Annex 3: Upper Limit Theoretical Enrichment Output). As explained in Annex 2 on the bellows, the rule of thumb is that the ratio of the length to diameter should be less than five to ensure the centrifuge remains subcritical. In this case the ratio is 4.5.

The IR-3 centrifuge was first installed in the Natanz pilot plant in 2008, and single machine tests ensued (see Figure 1.13). As of mid-2009, a small, 10-machine cascade of IR-3 centrifuges was

operating at the PFEP.²⁶ According to the Iranian table, a total of ten IR-3 centrifuges enriched uranium in a small cascade and another one was run in a single test stand. Like the IR-2 centrifuge, it was phased out after a few years of operation, but at least one was deployed at the PFEP after Iran started major violations of its JCPOA commitments in 2019. However, its deployment only lasted for about a year until November 2020, and since then, not a single IR-3 has been listed as installed at the PFEP. Also like the IR-2, its origin and history, including any past connections to the military program, are unclear.



Figure 1.13. An image of an IR-3 centrifuge being tested. Images from then-President Mahmoud Ahmadinejad's visit to Natanz in 2008.

²⁶ David Albright and Jacqueline Shire, "IAEA Report on Iran Centrifuge and LEU increases; access to Arak reactor denied; no progress on outstanding issues," *Institute for Science and International Security*, June 5, 2009, https://isis-online.org/uploads/isis-reports/documents/Iran_IAEA_Report_Analysis_5June2009.pdf.

IR-4 Centrifuge

The IR-4 centrifuge is derived from the IR-2m centrifuge. It may be easier for Iran to build, or at least Iran was planning to build it by the thousands each year. It has a slightly longer rotor assembly of 1110 millimeters, compared to the IR-2m's length of 1050 millimeters, and a wider diameter of 160 millimeters, first seen in the IR-3 (see Figure 1.11). According to Iranian declarations prior to the implementation of the JCPOA, it had flat carbon fiber end caps.

More significantly, the IR-4 has a single carbon fiber bellows rather than one made from maraging steel. This change likely reflects the relative difficulty of illegally procuring maraging steel versus carbon fiber. However, carbon fiber bellows are extremely difficult to make, since a carbon fiber bellows is not as flexible as a maraging steel bellows, flexibility being a key criterion of a bellows. The Iranian table also notes that a "special characteristic" of the IR-4 is being the "first Composite Bellows machine," apparently a reference to the carbon fiber bellows.

According to the Iranian table, the AEOI and associated industries were manufacturing the IR-4 centrifuges in the Persian year 1387, or in 2008/2009. Iran was not manufacturing the centrifuge on an industrial scale at this time as the IR-4 centrifuge remained in the developmental stage for several more years.

Iran installed single machine IR-4 centrifuges at the Natanz pilot plant by mid-2009.²⁷ Afterwards, the numbers of IR-4 centrifuges installed there increased. Starting in 2011, Iran increased the numbers being installed to 27, reaching 164 centrifuges in a production-scale centrifuge by February 2013. However, this increase was not without mishaps. During this period, the number of installed centrifuges dropped twice, once by eight, and once by six centrifuges, before continuing to increase, possibly indicating breakage issues. Iran announced its plan to install two 164-centrifuge cascades, but did not reach that goal by the time of the JCPOA's implementation in early 2016. The total number of IR-4 centrifuges that Iran had built was never confirmed as part of the JCPOA implementation process.

The AEOI is known via pre-JCPOA declarations to have tested this centrifuge at rotational frequencies of 900, 950, and 1050 Hz with corresponding wall speeds of 452, 478, and 528 meters per second, respectively. These three wall speeds correspond to a theoretical output of 4.4, 4.9, and 6.0 SWU/year, respectively. A measured single machine value was 3.8 SWU/year, although the rotational frequency is not given in the available Iranian declarations.

A more recent data point from the Iranian table gives an enrichment output of 3.7 SWU per year per centrifuge, the same as for the IR-2m. A poster behind a model of the IR-4 at a recent nuclear conference in Tehran gives an IR-4 rotor wall speed of 446 meters per second and an

²⁷ "IAEA Report on Iran Centrifuge and LEU increases; access to Arak reactor denied; no progress on outstanding issues," *Institute for Science and International Security*, June 5, 2009.

enrichment output of 3.7 SWU per year per centrifuge. These data are also partially visible in Figure 1.3.

There is little information about this centrifuge's performance in a production-scale cascade, but the single machine values suggest that, while Iran may find making an IR-4 centrifuge easier than making an IR-2m, the IR-4 centrifuge does not perform better than the IR-2m and in fact may perform more poorly. Overall, it is reasonable to assign an average production-scale enrichment output of 3.3 SWU per year to this centrifuge, slightly below that of the IR-2m centrifuge.²⁸

In line with this assessment, Iran prioritized installing and using its IR-2m centrifuges at the FEP over its IR-4 centrifuges during its centrifuge build-back in 2019. By February 2021, it had two IR-2m cascades enriching uranium at the FEP, while one IR-4 centrifuge cascade was being installed (a photo of the cascade can be seen in Figure 1.14). By April 2021, Iran had all six IR-2m cascades but only two IR-4 cascades installed, which, according to the November 2021 IAEA report, has not changed since, despite a declaration dated April 17, 2021, that Iran intended to install four additional IR-4 cascades at the FEP. In the meantime, the number of IR-4 centrifuges at the PFEP dropped from 186 in June 2020 to 131 by February 23, 2021, before increasing again to 176 by November 2021.

Since April 2021, Iran has been using the IR-4 cascade at the PFEP to enrich to higher levels than five percent enriched uranium. For about one day, on April 17, 2021, Iran was using the IR-4 cascade to enrich near 5 percent enriched uranium to near 60 percent highly enriched uranium (HEU). For about three months, Iran used the IR-4 cascade to produce near 20 percent enriched uranium by enriching the tails discharged from an IR-6 centrifuge cascade that was in parallel enriching to 60 percent HEU. On August 15, Iran re-started enriching near 5 percent enriched uranium to near 60 percent highly enriched uranium in the IR-4 cascade and has been using this cascade for this purpose since. Further, between August and November 2021, Iran temporarily fed a small number of IR-4 centrifuges at the PFEP with 20 percent enriched uranium, resulting in additional Iranian experience in using this centrifuge type for the production of highly enriched uranium.

The choice of the IR-4 centrifuge to enrich to higher levels of enriched uranium could be an indication of Iranian confidence in the centrifuge type, despite possible problems between April and August.

Outside of Fordow and Natanz, according to the 2021 Iranian table, three IR-4 centrifuges are being mechanically tested at the new Iran Research and Development Center in Tehran.

²⁸ This value assumes the value given on the poster, 3.7 SWU/year, is a measured single machine value. A ratio of 0.89 is applied, where the ratio is that between the single measured and the cascade value for the IR-2m centrifuge in Table 1.1 Part 1.



Figure 1.14. A cascade of IR-4 centrifuges at the PFEP. Source: AEOI, see <https://aeoi.org.ir/en/portal/home/?news/45799/69280/294523/dr.-salehi-describes-advanced-nuclear-industry-achievements>

IR-5 Centrifuge

This centrifuge was first installed as a single machine in the first half of 2013 in the Natanz pilot plant. It is the first Iranian centrifuge type known to have three bellows, making it the longest centrifuge at the time.

It has the same width as the IR-4 centrifuge but it is double the length, at 2200 millimeters. Its three bellows are made from carbon fiber. Its theoretical single machine output is 6.8 SWU per year, and its measured output is 6.1 SWU per year. In the Iranian table, its capacity is also listed as 6.8 SWU per year (converted to uranium mass). In addition, according to that table, the IR-5 “belongs to the IR-4 generation.”

It was first fed with uranium hexafluoride sometime near November 2014. This took place after the beginning of the November 2013 U.S./Iran Joint Plan of Action, which froze all of Iran's advanced centrifuge work, effectively banning any feeding of uranium hexafluoride into this centrifuge.²⁹ Following protests by the United States, Iran stopped feeding this centrifuge with uranium hexafluoride and disconnected it from the piping.³⁰

Figures 1.15 and 1.16 show a number of IR-5 centrifuge models at an Iranian nuclear conference in a mock cascade arrangement.

Iran increased the number of IR-5 centrifuges at the Natanz pilot plant in the fall of 2019 at the PFEP, installing 9 more than allowed by the JCPOA, for a total of 11. Figure 1.17 shows a cascade of 10 IR-5 centrifuges installed at the Natanz pilot plant.

The number of installed IR-5 centrifuges dropped to five by February 2021, but subsequently increased. By mid-April, Iran was using an additional cascade of 30 IR-5 centrifuges in line 1, as well as testing two such centrifuges without collecting enriched uranium, for a total of 37, all being fed with uranium hexafluoride. This number is assumed to have remained subsequently the same, absent any indication to the contrary in the quarterly IAEA reports. According to the Iranian table, there are only 11 IR-5 centrifuges. This indicates that the Iranian table was compiled in the early part of 2021 or earlier and underreports the number of centrifuges in Iran as of November 2021.

²⁹ David Albright, Serena Kelleher-Vergantini, Andrea Stricker, Paulina Izewicz, and Daniel Schnur, "ISIS Analysis of IAEA Iran Safeguards Report," February 19, 2015, *Institute for Science and International Security*, https://isis-online.org/uploads/isis-reports/documents/ISIS_Analysis_IAEA_Report_19February2015_Final_1.pdf.

³⁰ David Albright and Andrea Stricker, "Update on IR-5 Centrifuge Issue: Taking Stock," *Institute for Science and International Security*, December 16, 2014, <https://isis-online.org/isis-reports/detail/update-on-ir-5-centrifuge-issue-taking-stock/8>.



Figure 1.15. IR-5 centrifuges displayed at an Iranian National Nuclear Technology Day. Source: AFTAB News, Iran



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Figure 1.16. IR-5 centrifuges next to much shorter IR-6s and IR-6 centrifuges. These centrifuges appear to be the same ones as in Figure 1.15 but from a different angle. Source: <https://president.ir/en/120598>



Figure 1.17. Ten IR-5 centrifuges in a small cascade in the Natanz pilot plant. Lines 2 and 3 at the PFEP contained IR-5 centrifuges and other advanced centrifuges, which are visible in the left line of centrifuges, one of which is likely an IR-2m centrifuge. The reason for the blurring of the image is unknown. Source: AEOI

IR-6 Centrifuge and its Variants

This important centrifuge is supercritical, with two carbon fiber rotor tubes and a carbon fiber bellows. Prior to the JCPOA, Iran stated that it had flat carbon fiber end caps. According to the Iranian table, it is “fully indigenous.” However, this statement belies both its origin and the need for imported raw materials and parts.

It has a diameter of 200 millimeters, wider than the IR-4, and a length of 1100 millimeters. Its nominal frequency is unknown publicly but in the declaration prior to the JCPOA it is listed as having a single machine theoretical output of 8.1 SWU per year, and a measured single machine output of 6.8 SWU per year. A poster featuring the IR-6 at a recent nuclear conference in Tehran lists the wall speed as 565 meters per second, and an enrichment output of 10 kg UF₆

SWU per year per machine, or 6.7 SWU per year per machine, lower than the value from about 2015. The same lower value is given in the Iranian table in Annex 1 and in Table 1.1 Part 1. Based on a review of the available information, the value of 6.7 SWU per year is assessed as a theoretical value, a more realistic one than the value given in the 2015 data, particularly when considering the wall speed listed on the poster. (The 2015 theoretical value of 8.1 SWU per year leads to a wall speed of over 600 meters per second.) A corresponding value for a production-scale cascade is assessed as 5.25 SWU per year, after applying a ratio derived by using relevant IR-2m centrifuge data in Table 1.1 Part 1.

The IR-6 centrifuge was first announced in 2010, when the AEOI revealed it at that year's National Nuclear Technology Day, although at the time its name was not provided publicly.³¹ At that time, the IR-6 prototype had not yet operated with any uranium hexafluoride and was not deployed at the PFEP. Further, Iran announced that it had undergone mechanical testing but that "we may need a year of time before we can arrange a cascade for testing."³²

By early 2013, Iran had installed six IR-6 centrifuges at the Natanz pilot plant, increasing the number installed during the next few years to about 10-20 machines, operating alone or in small cascades. The JCPOA initially limited the number to two, gradually allowing a defined increase in that number from year 1 to 8.5 of the JCPOA, where the first year started in October 2015.³³

Despite the JCPOA limitations, Iran had more IR-6 centrifuges than allowed. It ran 13-15 IR-6 centrifuges in a cascade that was supposed to be limited to "roughly 10" centrifuges.³⁴ (In

³¹ David Albright, Jacqueline Shire, and Paul Brannan, "Iran's new centrifuge: What do we know about it?" *Institute for Science and International Security*, April 13, 2010, <https://isis-online.org/isis-reports/detail/irans-new-centrifuge-what-do-we-know-about-it/8>. Although unknown at the time, the centrifuge featured in this report appears to have been the IR-6 centrifuge, based on its declared enrichment output and appearance.

³² "Iran to Mass-Produce 2nd Generation of Centrifuges," Fars News Agency, April 11, 2010.

³³ "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>; David Albright, "Update on Iran's Compliance with the JCPOA Nuclear Limits- Iran's Centrifuge Breakage Problem: Accidental Compliance," *Institute for Science and International Security*, September 21, 2017, <https://isis-online.org/isis-reports/detail/update-on-irans-compliance-with-the-jcpoa-nuclear-limits/#fn1>.

³⁴ Iran's long-term enrichment R&D plan provides the following limits on its operation of IR-6 and IR-8 centrifuges: Opening sentence of section 2: "Between years 1 to 8 and a half, in addition to continue the abovementioned activities:" Section 2.1 "Will continue the testing of the IR-6 on single centrifuges and intermediate cascades (testing with uranium of roughly 10 centrifuges and then roughly 20 centrifuges, with each of these groups being tested with uranium for approximately equal time periods)." Section 2.2: "Will start, upon implementation of the JCPOA, testing of the IR-8 centrifuge on single centrifuges and its intermediate cascades (completion of mechanical testing of single centrifuges in 1 year, testing with uranium of a single centrifuge, 3 centrifuges, roughly 10 centrifuges, and roughly 20 centrifuges sequentially with each of these groups being tested for approximately equal time periods)." It is worth noting that the phrase "approximately equal time periods" indicates that between years 1 through 8 of the JCPOA, each of the allowed activities must take place equally at intervals between the eight years. Thus, Iran should only be testing with uranium "roughly 10" IR-6 centrifuges up until year 4. It should be testing only one IR-8 centrifuge until year 3 begins. The plan does not specify that Iran can keep a stock of IR-6 or IR-8 centrifuges. See also "Iran's Long-Term Centrifuge Enrichment Plan: Providing Needed

subsequent tables in Chapter 2, the upper bound of 15 is used and combined with the two single centrifuges for a total of 17.)

After the breakdown of the JCPOA, Iran made IR-6 deployment a priority at the PFEP. Before even installing any IR-2m centrifuges, Iran had installed 30 IR-6 centrifuges at the PFEP by the fall of 2019, followed by another 30 by November 11, 2019, increasing that number to 168 centrifuges by June 5, 2020, and to 227 centrifuges by the end of the latest IAEA reporting period in November 2021. Figure 1.18 shows a cascade of 30 IR-6 centrifuges at the Natanz pilot plant. Since April 17, 2021, Iran has been using a cascade of about 164 IR-6 centrifuges at the PFEP to enrich uranium from near 5 percent enriched uranium to near 60 percent HEU. Further, between August and November 2021, it was, together with the IR-4 centrifuge, one of two centrifuge types Iran chose for temporary feeding with 20 percent enriched uranium and production (albeit not accumulation) of highly enriched uranium.

Iran has been increasing the number of IR-6 centrifuges also at the FFEP. Nuclear legislation passed in December 2020 mandates that the AEOI install 1000 IR-6 centrifuges by December 2021. In February 2021, Iran announced its plans to install two cascades of IR-6 centrifuges at the FFEP. While preparations for one cascade were almost completed by August 2021, only 10 IR-6 centrifuges had been installed by that time. However, by mid-November, Iran had installed 166 IR-6 centrifuges in a production-scale cascade at the FFEP, and another 23 IR-6 centrifuges were installed in the second cascade. On April 14, 2021, the IAEA also reported Iran's plans to install a cascade of 174 IR-6 centrifuges at the Natanz FEP, but as of November 2021, the installation of centrifuges had yet to begin.

As of mid-November 2021, Iran had a total of 416 IR-6 centrifuges installed across its three enrichment plants and therefore still needs to install almost 600 IR-6 centrifuges to reach the number stipulated in the nuclear legislation.

Despite limited progress in the installation of the centrifuges and the absence of any additional declaration to the IAEA, Iran may have been producing components for these centrifuges for many months. It may also indicate unexpected production problems, such as the June 23, 2021, attack on the Karaj centrifuge production plant.

There are several variants of the IR-6: the IR-6s, IR-6m, IR-6sm, and IR-6smo centrifuges. Details about them are scarce. The one exception is the IR-6s, which appears to be the IR-6 with only one rotor tube, making it a subcritical variant that is less prone to breakage since it does not have a carbon fiber bellows. Based on Iran's declaration in 2015, it has a rotor length of 630 millimeters, a diameter of 200 millimeters, with a theoretical output of 4.1 SWU per year and a measured, single machine output of 3.5 SWU per year. These 2015 values may be based on wall speeds assumed to be achievable in 2015 but subsequently lowered after 2015. The IR-

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>.

6s was first installed in the Natanz pilot plant in 2013, at the same time as the IR-6 centrifuge. During the last two years, from November 2019 to November 2021, the numbers installed have remained low compared to the number of installed IR-6 centrifuges, ranging from 20 to 40 machines, consistent with the variants being intermediate machines and steppingstones to the full-length centrifuge model. Figure 1.19 shows several outer casings with stands of the IR-6s at a Tehran conference.

The Iranian table lists the output of the IR-6m and IR-6sm (after conversion) as 8.1 SWU/year and 5.4 SWU/year, respectively. They are both listed as being single machines, apparently experimental centrifuges. Based on the information in the Iranian table, the IR-6smo is difficult to interpret, but it appears to be a 12 IR-6s centrifuges in a new modular configuration or cascade, and not a new IR-6 centrifuge variant.



Figure 1.18. IR-6 centrifuges in a cascade at the Natanz pilot plant. Source: AEOI, <https://aeoi.org.ir/en/portal/home/?news/45799/69280/294523/dr.-salehi-describes-advanced-nuclear-industry-achievements>



Figure 1.19. Images of the IR-6s centrifuge displayed in Iranian media, with IR-6 centrifuges in the background. Source: AFTAB News

IR-7 Centrifuge

The IR-7 centrifuge rotor assembly has a length of 2100 millimeters, with four carbon fiber rotor tubes and three carbon fiber bellows, similar to the IR-5 centrifuge. It differs in being wider, with a diameter of 200 millimeters, the same diameter as the IR-6 centrifuge. It has flat carbon fiber endcaps, like the IR-4 and IR-6.

Its theoretical single machine output is 11.5 SWU/year, according to Iran's declarations prior to the JCPOA. In terms of equivalent units used by Iran, it is 17.0 kg UF₆ SWU per year. A recent Iranian table lists the output as 20 kg UF₆ SWU per year (or 13.5 SWU per year) with manufacturing having started in Persian year 1398 (March 21, 2019 – March 20, 2020). This table also provides a taller rotor assembly of 3000 millimeters, although this may be the height of the outer casing and stand rather than the contained rotor assembly or possibly reflect design changes. If it is the height of the casing, the rotor may have also been lengthened.

The JCPOA allowed Iran to conduct mechanical testing of the IR-7, although the extent of such testing is unknown. In late 2019, Iran had two IR-7 centrifuges installed at the Natanz pilot plant. In late February 2020, the two centrifuges were being tested with uranium hexafluoride but not accumulating enriched uranium.³⁵ As of early November 2021, the IAEA quarterly report stated that one IR-7 centrifuge was being tested in lines 2 and 3 at the PFEP with natural uranium but was not accumulating enriched uranium.

Figure 1.20 shows the IR-7 centrifuge side-by-side with the IR-9 and IR-5 centrifuges, apparently at the Natanz pilot plant.

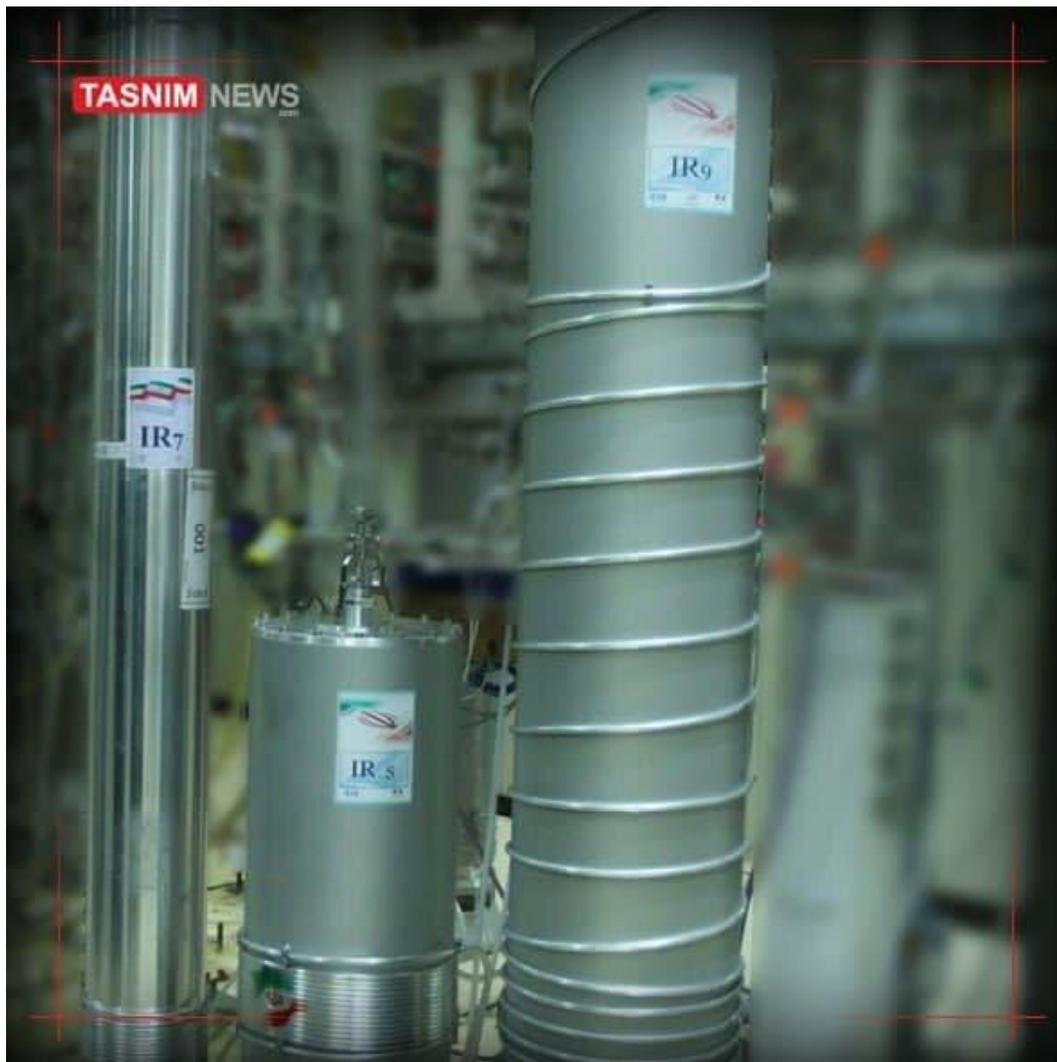


Figure 1.20. Image of the IR-7 displayed in Iranian media, along with later models.

³⁵ Report by the IAEA Director General, *Verification and monitoring in the Islamic Republic of Iran in light of United Nations Security Council resolution 2231 (2015)*, GOV/2020/5, March 3, 2020, https://isis-online.org/uploads/iaea-reports/documents/IAEA_quarterly_Iran_report_February_2020.pdf.

IR-8 Centrifuge and its Variants

Iran rolled out the IR-8 centrifuge in August 2014 with Iranian nuclear officials claiming that this long machine was 16 times more capable than the current generation IR-1 centrifuge.³⁶ However, this claim appears in hindsight to have been greatly exaggerated, given the subsequent large number of machine failures and difficulties in getting the machine to work.

Iran's declaration prior to the JCPOA implementation lists the rotor assembly as 3000 millimeters in length with a diameter of 250 millimeters, wider than the IR-6 centrifuge. It has four carbon fiber rotor tubes and three carbon fiber bellows. It has domed carbon fiber end caps with a flat metal disc in the bottom end cap. Its casing is apparently 3300 millimeters or about ten percent longer than the rotor assembly.

The length of the IR-8 centrifuge is listed as 3500 millimeters in the Iranian table. The reason for the discrepancy is unknown. However, the length in the table may also include the stand of the centrifuge below the bottom of the outer casing.

Its declared single machine theoretical enrichment output is 16.2 SWU per year or 24 kg UF₆ SWU per year.

As of November 2015, the IAEA verified the existence of the first prototype IR-8 centrifuge at the Natanz pilot plant. A prototype had been installed there in 2014 but without connections, which typically means without feed and withdrawal piping being connected. As of the implementation of the JCPOA, this prototype had not been tested with uranium hexafluoride.

Although the JCPOA initially allowed mechanical testing in only two IR-8 centrifuges, Iran had continued building and in effect mechanically testing many more at its Kalaye Electric site in Tehran. Iran exploited a JCPOA loophole to conduct mechanical testing at Kalaye Electric under the guise of quality control. According to a senior official close to the IAEA, it built eight IR-8 centrifuges and all but one broke. Subsequently, by about early 2018, it built about seven more IR-8 centrifuges, but their fate was likely the same as the earlier ones. This model has been plagued with air leakage problems in its rotor assembly, making operation under vacuum difficult and causing machine failures during operation with or without uranium hexafluoride. In general, outside observers judged this centrifuge model a failure.

In 2019, the AEOI head Ali-Akbar Salehi helped explain the troubles in this centrifuge model, stating that at the time Iran's experience in centrifuge machine industry design was "highly

³⁶ David Albright, "Technical Note: Making Sense out of the IR-8 Centrifuge," *Institute for Science and International Security*, September 23, 2014, <https://isis-online.org/isis-reports/detail/technical-note-making-sense-out-of-the-ir-8-centrifuge/8>.

experimental.” In designing the IR-8, he added, “we still did not possess proper software possibilities.”³⁷

The AEOI started injecting uranium hexafluoride into a single IR-8 centrifuge in early 2017, as permitted by the JCPOA. As a sign of the problems in this centrifuge, however, Iran has not scaled up the number operating as envisioned in Iran’s secret long-term enrichment plan created as part of the JCPOA. According to that plan, during years one to eight and a half of the deal, Iran “will start, upon implementation of the JCPOA, testing of the IR-8 centrifuge on single centrifuges and its intermediate cascades (completion of mechanical testing of single centrifuges in 1 year, testing with uranium of a single centrifuge, 3 centrifuges, roughly 10 centrifuges, and roughly 20 centrifuges) sequentially with each of these groups being tested for approximately equal time periods.”³⁸ As of November 2021, Iran was still testing only one IR-8 centrifuge using natural uranium but not accumulating enriched uranium. It had not connected three or more of them into a cascade, something Iran’s enrichment plan expected to start a few years ago.

Figure 1.21 shows a model of an IR-8 centrifuge. Next to it may be an IR-1 centrifuge model, based on the cooling coils reaching to the top of the centrifuge’s outer casing.

In recent years, Iran has produced a few variants of the IR-8, called the IR-8s and IR-8B, where publicly available images show that the IR-8B is shorter than the IR-8 and the IR-8s is the shortest model of this type (see Figure 1.22). The Iranian table list their outputs as 6.1 SWU per year and 10. 1 SWU per year, respectively. As of early November 2021, Iran was testing one IR-8B in the pilot plant, using natural uranium but not accumulating enriched uranium.

³⁷ “Dr. Salehi, describes advanced nuclear industry achievements,” AEOI, November 25, 2019, <https://aeoi.org.ir/en/portal/home/?news/45799/69280/294523/dr.-salehi-describes-advanced-nuclear-industry-achievements>.

³⁸ “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>.



Figure 1.21. An IR-8 outer casing, with feed and withdrawal tubes on top, can be seen in the background, next to an unidentified centrifuge, possibly an IR-1. Source: Screen capture from Simanews.ir/IRIB



Figure 1.22. From left to right: IR-8, IR-8B, and IR-8s centrifuges. Source: AEOI, <https://aeoi.org.ir/en/portal/home/?news/45799/69280/294523/dr.-salehi-describes-advanced-nuclear-industry-achievements>

IR-s Centrifuge

An Iranian table lists the IR-s as a subcritical centrifuge with a single machine theoretical output of about 8 SWU per year (12 SWU per year (hexafluoride units)) that Iran started to manufacture in 1398 (2019/2020). Figure 1.23 shows several models of the IR-s centrifuge; these models were displayed at a Tehran nuclear conference. The IR-s centrifuge's diameter and length are unknown publicly, but its diameter appears in AEOI photographic handouts as somewhat less than the IR-9 centrifuge and significantly wider than the IR-6 and IR-5 centrifuges (see Figure 1.20 and Figure 1.24). The Institute estimates it to be roughly 650 millimeters long and at least 250 millimeters wide.

The theoretical output of the IR-s is twice that of the subcritical IR-6s centrifuge, despite their similarities in length. If the reports about the IR-s centrifuge's output being about 8 SWU per

year are correct, this doubling of output suggests an increase due to operating at significantly faster tangential wall speeds.

Typically, Iran's advanced centrifuges have achieved speeds less than optimal, considering the potential of carbon fiber rotor tubes. However, the IR-s may be testing at these higher speeds. Achieving these higher speeds is difficult but would allow significant increases in the enrichment output of an Iranian centrifuge.

An estimate of the speed of the IR-s centrifuge, at least theoretically, can be derived from the formula in Annex 3, where its length is taken as 650 millimeters. An enrichment output of 8 SWU per year would imply a wall speed of up to 735 meters per second, a speed faster than Iran's late 2000s goal of 700 meters per second for the IR-2m.

The IR-s was first deployed as a single machine at the Natanz pilot plant in November 2019, and a total of 12 centrifuges were installed by June 2020. As of early November 2021, Iran was enriching uranium up to 2 percent in 10 IR-s centrifuges.



Figure 1.23. Image of the IR-s centrifuges displayed in Iranian media. Source: IRNA



Figure 1.24. Display on Iran's National Nuclear Technology Day in Tehran, April 10, 2021. From left to right: IR-s, IR-6s (front), IR-6 (back), and IR-5 centrifuges, during Iran's National Nuclear Technology Day in Tehran, Iran April 10, 2021. Source: Iranian President's web site, <https://president.ir/en/120598>

IR-9 Centrifuge and its Variants

In the Persian year 1398 (2019/2020) Iran revealed its plan to develop the IR-9 centrifuge over the next ten years. It reportedly has a length of 5500 millimeters. Here, this is taken as the length of the IR-9 rotor assembly, although it is possible it could be the length of its casing and stand. It claims this centrifuge has a theoretical single machine capacity of about 34 SWU per year. Figure 1.25 shows the outer casing of the centrifuge laying on its side. Little information is available about this centrifuge; however, in a television interview that aired in April 2021, Salehi, then head of the AEOI, stated that it has five bellows, implying six rotor tubes.³⁹ As a result, each rotor tube would have an average length of 917 millimeters, assuming a rotor assembly length of 5500. The Iranian table claims that 200,000 lines of code have been written for this centrifuge, and it is purely an Iranian creation. Salehi also told television viewers that it is an indigenous centrifuge, the first not requiring reverse engineering. An image shows that the IR-9 centrifuge is considerably wider than the IR-7 centrifuge, which is 200 millimeters (see Figure 1.20).

³⁹ "Iranian Nuclear Chief Day Before Natanz Nuclear Facility Blast: We Activated IR-6 Centrifuge Chain."

Given the acknowledged computer software issues that Iran had with the IR-8 just before the negotiation of the JCPOA, the IR-9 (and other) centrifuges may exemplify Iran's continued work on computer software and other more theoretical aspects of centrifuge development in the period between the JCPOA's implementation in January 2016 and the United States ending its participation in the deal in May 2018.

Public images show the existence of variants of the IR-9, called the IR9-1B and IR-9s, the latter having just one rotor tube and being subcritical (see Figure 1.26). According to Salehi, the IR-9 centrifuge is being developed, one rotor tube at a time.⁴⁰ He said the IR-9s is first being developed, followed in a roughly ten-year development effort, by a two-rotor variant, a three-rotor variant, etc.

As of early November 2021, one IR-9 centrifuge was deployed at the Natanz pilot plant. It was listed as operational, being fed with uranium hexafluoride, but not accumulating enriched uranium. No IR-9s centrifuges had been deployed at the PFEP.

⁴⁰ "Iranian Nuclear Chief Day Before Natanz Nuclear Facility Blast: We Activated IR-6 Centrifuge Chain."



Figure 1.25. IR-9 centrifuge outer casing. The IR-9 centrifuge is still in an early development stage.
Source: AEOI, <https://aeoi.org.ir/en/portal/home/?news/45799/69280/316331/the-basis-of-this-national-industry-are-meticulously-preserved6>



ISNA PHOTO
Mona Hoobehfekr

Figure 1.26. Variants of the IR-9 centrifuge (IR-9s and IR9-1B) showing their outer casings. Source: ISNA Photo.

Table 1.1, Part 1, Iranian Centrifuge Parameters

	IR-1	IR-2	IR-2M	IR-3	IR-4	IR-5	IR-6	IR-6s
Length of rotor assembly (mm)	1800	650	1050	720	1110	2200	1100	630
Diameter (mm)	100	146	146	160	160	160	200	200
Frequency (Hz)	1050		1050		900/950/1050		565?	
Tangential speed (m/s)	330		482		452/478/528			
Separative work, theoretical	1.4	2.0	4.7	2.0	4.4/4.9/6.0	6.8	6.7?	4.1
Separative work, single machine, measured		1.8	4.1	1.8	3.8	6.1		3.5
Separative work, in large cascade, meas.	0.9**		3.67					
Bellows, number, type	3, maraging steel	?	1, maraging steel	0	1, carbon fiber	3, carbon fiber	1, carbon fiber	0

Comments for Parts 1 and 2

* For those types of centrifuges that did not exist at the time of Iran's declaration in 2015 (see Part 2), the separative work values are taken from the Iranian Table in Annex 1. The values in parentheses are in units used by Iran, namely kg UF₆ SWU per year. The one exception is the IR-6, where the value in the Iranian table (and on an official poster discussed in the text) is used for its theoretical value instead of the 2015 value. This choice could also mean that the actual wall speeds of the IR-6 variants have also been reduced after 2015.

**This value varies greatly, usually lower, based on IAEA reporting over many years.

Table 1.1, Part 2, Iranian Centrifuge Parameters

	IR-6m	IR-6sm	IR-7	IR-8	IR-8s	IR-8B	IR-s	IR-9
Length of rotor tube (mm)			2100	3000				5000
Diameter (mm)	200?	200?	200	250			>250	>250
Frequency (Hz)								
Tangential speed (m/s)								
Separative work, theoretical	8.1 (12)*	5.4 (8)*	11.5	16.2	6.1 (9)*	10.1 (15)*	8.1 (12)*	33.8 (50)*
Separative work, single machine, meas.								
Separative work, in large cascade.								
Bellows, number, type			3, carbon fiber	3, carbon fiber		?	0	5

Comments: See above

Table 1.2 Major Components of IR-1, IR-2m, IR-4, IR-6, and IR-8 Centrifuges, circa 2015

	IR-1	IR-2M	IR-4	IR-6	IR-8
Bellows	Maraging steel	Maraging steel	Carbon fiber	Carbon fiber	Carbon fiber
Rotor tubes	High strength aluminum	Carbon fiber	Carbon fiber	Carbon fiber	Carbon fiber
End caps	High strength aluminum	High strength aluminum	Carbon fiber	Carbon fiber	Top end cap: carbon fiber; bottom end cap, carbon fiber with a metal central disk

Chapter 2 Iran’s Historical Deployment of Centrifuges

The IAEA’s detailed safeguards reports on Iran, which stretch back to about 2003, have carefully recorded Iran’s installation of advanced centrifuges. Based on this information, Figure 2.1 shows the numbers of advanced centrifuges deployed quarterly from 2011—when deployment of IR-2m and IR-4 centrifuges began to increase— onwards through November 2021, with a projection for 2022 based on Iran’s announced plans.

Figure 2.1 shows a steady increase in the number of deployed advanced centrifuges from 2011 until 2013, followed by a consistent level for a couple of years, and then a sharp drop in 2016, when the JCPOA was implemented. That number started to increase again in the fall of 2019, after Iran began to violate the JCPOA, deploying advanced centrifuges at a faster rate than prior to the JCPOA, reaching unprecedented deployment levels in May 2021. As of November 2021, Iran had installed at these three sites 2101 advanced centrifuges, almost all in violation of the JCPOA. During late 2021 and early 2022, the AEOI is projected to install many more advanced centrifuges, for an estimated total of up to 3381 installed advanced centrifuges, based on reporting to the IAEA and the nuclear law approved in December 2020. The pie chart in Figure 2.2 shows that the overwhelming number of centrifuges at Iran’s three centrifuge plants remain IR-1 centrifuges. However, when representing enrichment output, the pie chart looks considerably different, with a much smaller slice for the IR-1 centrifuges (see Chapter 3).

Iran: Total Installed Advanced Centrifuges By Date

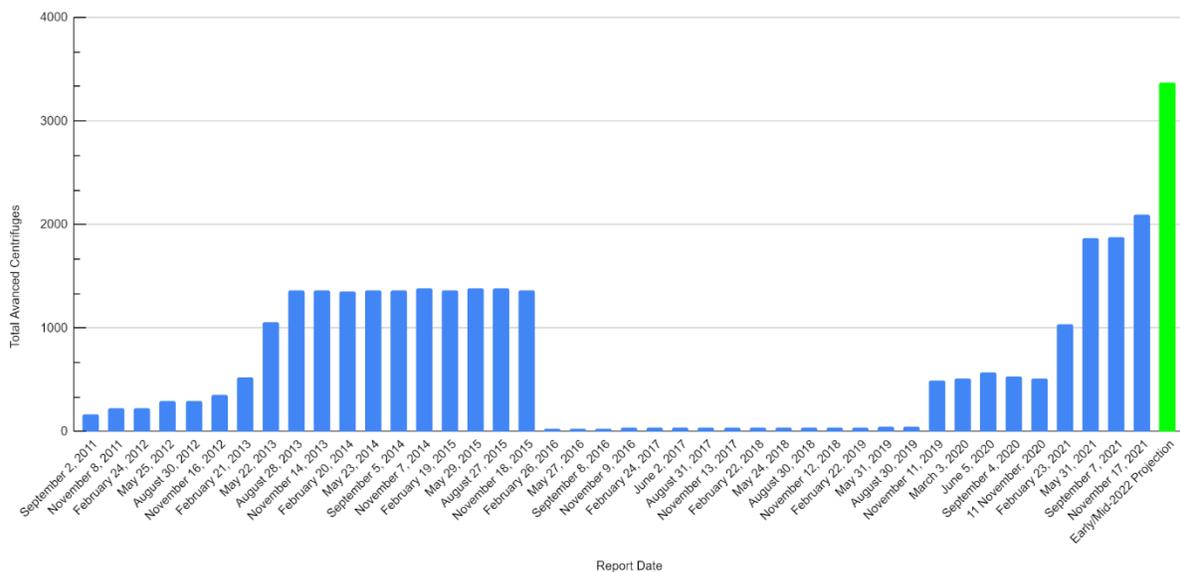


Figure 2.1. Iran’s quarterly number of advanced centrifuges installed at its three enrichment plants, with a multi-quarter projection for early to mid-2022 (last vertical bar). In April 2021, the Natanz FEP was attacked, affecting half of the IR-2m and IR-1 cascades. The total number of installed cascades remained the same but many of the centrifuges could have been destroyed. Since the attack, Iran likely

replaced any broken centrifuges in those cascades, although the IAEA does not report how many centrifuges were replaced.

Make-up of Iran's Installed Centrifuges as of November 2021, by Centrifuge Type

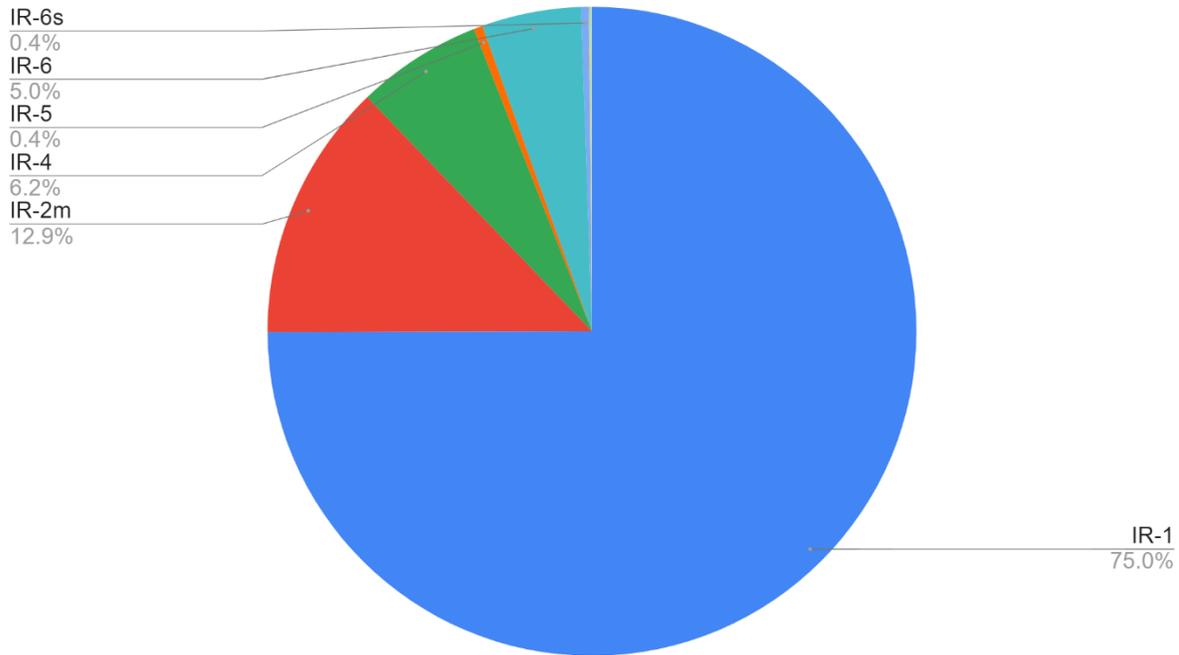


Figure 2.2. Fraction of installed centrifuges by centrifuge type at the three Iranian centrifuge plants as of November 2021. By number, the IR-1 centrifuges make up about three-quarters of all installed centrifuges.

Figure 2.1 is derived from data in a series of detailed tables derived from IAEA quarterly safeguards reports. The tables, presented in the last part of this chapter, document the following:

- Table 2.1 documents the build-up of centrifuges at the Natanz pilot plant from early 2011 up to November 2015, the time of the implementation of the JCPOA. The emphasis during this period is the testing of the IR-2m and IR-4 centrifuges, including the deployment of production-scale cascades. Relatively few deployments of the IR-6 centrifuge took place.
- Table 2.2 shows advanced centrifuges deployed at the Natanz Fuel Enrichment Plant prior to the implementation of the JCPOA. For reference, it includes the number of IR-1 centrifuges. The main feature is the deployment of 1008, or six cascades of, IR-2m centrifuges.
- Table 2.3 shows the advanced centrifuge deployments at the PFEP under the parameters of the JCPOA after Implementation Day in January 2016 until August 2019.
- Table 2.4 shows Iran's rapid buildup of advanced centrifuges at the PFEP after Iran openly violated the JCPOA in the second half of 2019.

- Table 2.5 shows the situation about one year later, when Iran began to install advanced centrifuges in the underground FEP as well. This table spans from the fall of 2020 until November 2021.
- Table 2.6 shows the advanced centrifuge deployments at the Fordow enrichment plant from the fall of 2020 until November 2021.

Deployments at the PFEP

Figure 2.3 displays patterns in advanced centrifuge deployment after the JCPOA of all the different types Iran has announced by November 2021, showing which advanced centrifuge types Iran has been focusing on. The figure tracks the quarterly changes in the number of deployed centrifuges at the PFEP from September 2019 to November 2021. The top graph shows the quarterly changes in the number of centrifuges for those advanced centrifuge types where the most changes occurred: the IR-2m, IR-4, IR-5, IR-6, IR-6s, and IR-s. The bottom graph shows the quarterly changes for the remaining types present at the PFEP: IR-1, IR-3, IR-6m, IR-6smo, IR-6sm, IR-7, IR-8, IR-8s, IR-8B, and IR-9. For a particular centrifuge type along the X-axis, there are nine bars associated with it, representing the difference in the number of installed centrifuges of that type from one quarter to the next, where the first bar in blue represents the change in the number of centrifuges from August to November 2019, when Iran started to deploy advanced centrifuges in larger numbers than allowed by the JCPOA.

Starting from the left with the IR-2m, the first bar in the top graph shows that Iran deployed a large number of IR-2m centrifuges immediately, between August and November 2019. Over the next quarter, November 2019 to March 2020, nothing changed, so the difference is zero. Then, Iran removed 21 centrifuges between March and June 2020, for a difference of negative 21, followed by no change from June to September 2020. Between September 2020 and November 2020, Iran removed 161 centrifuges from the PFEP (they were moved to the FEP), followed again by no change between November 2020 and February 2021. Iran then installed 30 IR-2m centrifuges between February and May 2021, followed by the removal of two centrifuges between May and September 2021, and the addition of three between September and November 2021.

The graph also shows that Iran installed a large number of IR-4 centrifuges immediately, but unlike the case with the IR-2m, upon deployment of two IR-4 centrifuge cascades at the FEP, the number at the PFEP decreased less and more slowly, indicating that rather than moving centrifuges from one facility to the next, Iran produced the additional ones needed. The number of IR-5 centrifuges increased by 10 during the first quarter, but it took over a year for the next increase of 25.

The number of IR-6 centrifuges increased steadily during the first three quarters, but dropped between June 2020 and November 2020, before increasing again.

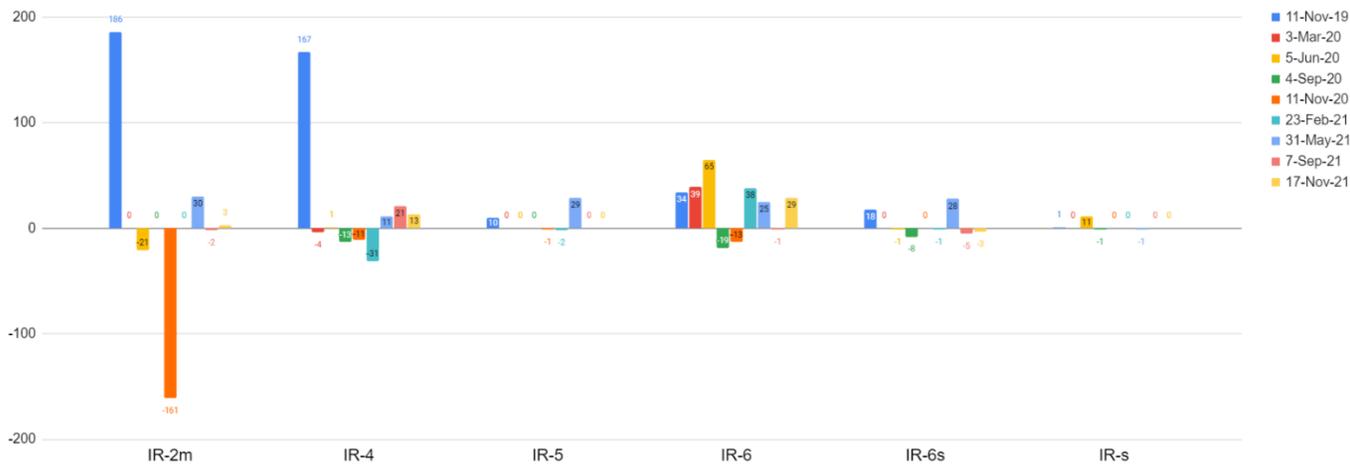
The IR-6s was also deployed early on, but, very similar to the IR-5, the next increase did not occur until early 2021. Unlike the IR-5, eight IR-6s centrifuges were removed between June 2020 and September 2020, likely indicating a relatively large number of IR-6s centrifuges breaking and not being replaced.

The IR-s is a new centrifuge type that did not exist prior to the JCPOA and was not listed in Iran's R&D plan. Accordingly, the number of centrifuges was not increased right away, but one centrifuge was installed by November 2019, and the number increased to twelve by June 2020.

It appears that almost all of the major centrifuge types go through a cycle—an increase, decrease, and increase in numbers of deployed centrifuges, possibly indicating that at the beginning, in September 2019, those centrifuges stored under the JCPOA were deployed, then during most of 2020 some broke while new ones were still being made, resulting in the “downward” movement, followed by newly installed centrifuges resulting in an “upward” movement again.

The pattern of deployments indicates that production of IR-4, IR-5, IR-6, and IR-6s centrifuges may have been a focus during that time, as they all experienced a second “up” movement, compared to those, where the “down” movement is *not* followed by another “up” movement. The latter is the case for all of the advanced centrifuge types in the bottom chart, and the IR-s from the top chart. Most of the centrifuge types in the bottom chart experienced changes between plus or minus one centrifuge between September 2019 and November 2021: the IR-3, IR-6m, IR-6sm, IR-7, IR-8s, IR-8B, and IR-9. The IR-6smo and the IR-8 both experienced a deployment followed by an equally large removal, likely indicating relatively quick breakage or possibly a lack of confidence in the design.

Quarterly changes in major advanced centrifuge types at PFEP from September 2019 to November 2021



Quarterly changes in other centrifuge types at PFEP from September 2019 to November 2021

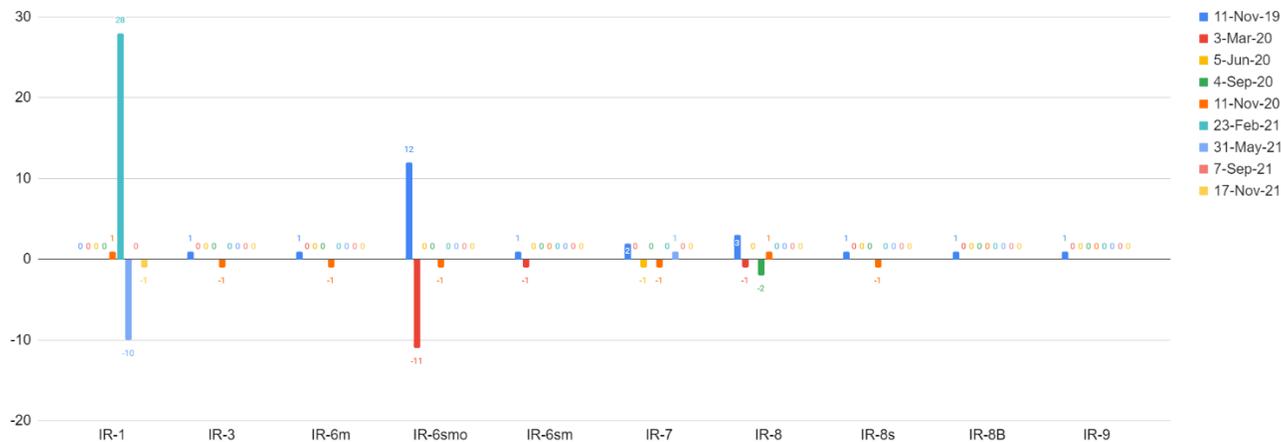


Figure 2.3. Each centrifuge type’s changes in deployment at the PFEP from September 2019 to November 2021. The horizontal axis lists each centrifuge type, starting with the IR-2m. The vertical axis gives the change in the number of that type of centrifuge deployed in each quarter, where the first bar on the left in the top chart represents the change in the number of IR-2m centrifuges from September 2019 to November 2019, and so on. The relatively large number of centrifuge types requires two graphs.

Deployment Patterns of IR-2m, IR-4, and IR-6 in the PFEP and FEP

Figures 2.4-2.9 take a closer look at the deployment patterns of IR-2m, IR-4, and IR-6 centrifuges at the PFEP and FEP going back to 2011, as these types were all deployed before and after the JCPOA, although on different scales.

IR-2m Centrifuge Deployment Patterns

Figure 2.4 shows IR-2m deployment over time, showing its build-up during 2011, reaching 164 by the fall of 2011. The number doubled by February 2013, again by May 2013, reaching over 1000 by August 2013. The number fluctuates between 1196 and 1170 between August 2013 and November 2015, averaging 1178 with a standard deviation of 8.7. The number of deployed IR-2m centrifuges dropped to only two centrifuges during the first ten years of the JCPOA, indicating that it was not Iran’s priority to maintain R&D on the IR-2m centrifuge, compared to the IR-4 or IR-6 models, which both could be deployed in quantities of ten or more during the first ten years. The post-JCPOA build-back looks similar to the original build-up but appears to have occurred slightly faster.

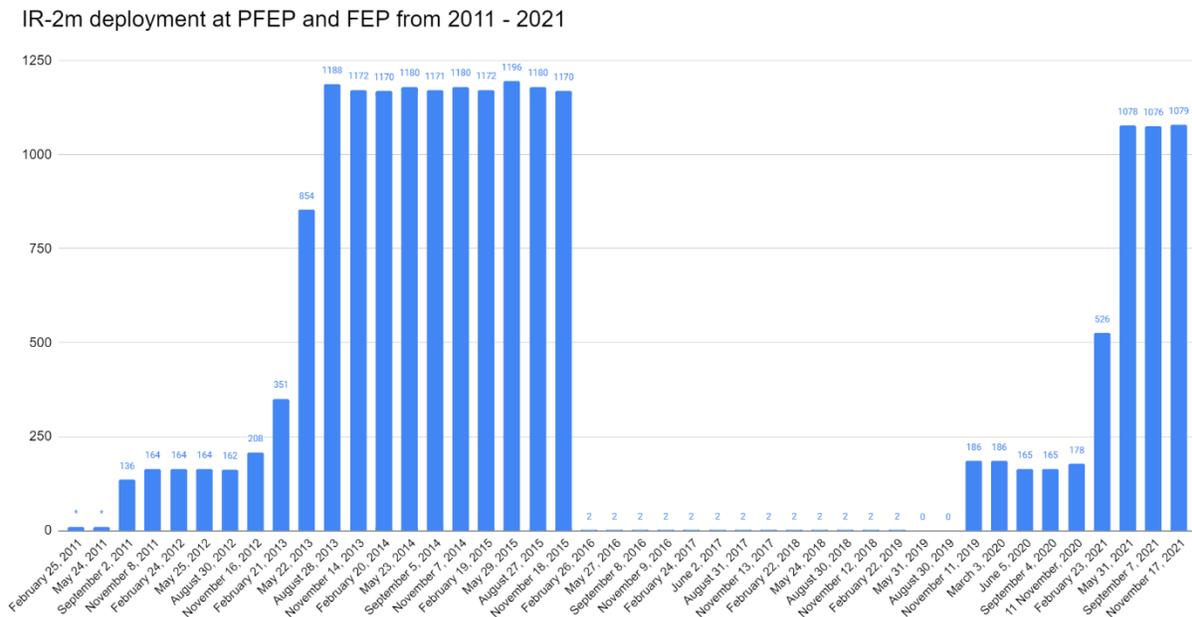


Figure 2.4. IR-2m deployment at the PFEP and FEP over time, starting in 2011. For the period between Feb 2016 - Feb 2019, where no specific numbers were given in the IAEA report, the JCPOA limit was used. The asterisk indicates that the exact number of IR-2m centrifuges is not reported, but some are present, likely between 10 and 30.

Figure 2.5 focuses on the IR-2m deployment during the last two years, September 2019 to November 2021, where the stacked bars show the number of IR-2m centrifuges at the FEP (red) and PFEP (blue). For the first year, about one cascade was installed at the PFEP. Then, as the number of IR-2m centrifuges at the FEP increased, the number at the PFEP decreased dramatically, indicating that those centrifuges were moved to the FEP. The graph further shows

that Iran quickly installed in a matter of months the six cascades of IR-2m centrifuges it announced at the end of 2020. The number of centrifuges announced but not yet installed at the FEP at a given time are shown in light red. At the same time, the number of IR-2m centrifuges at the PFEP recovered slightly to 34. All this is consistent with what Figure 2.4 shows; Iran having almost 1200 IR-2m centrifuges prior to the JCPOA that were stored and re-deployed from 2019 to 2021, except for roughly 140 centrifuges that may have been used to replace broken ones or are kept in storage for that purpose.

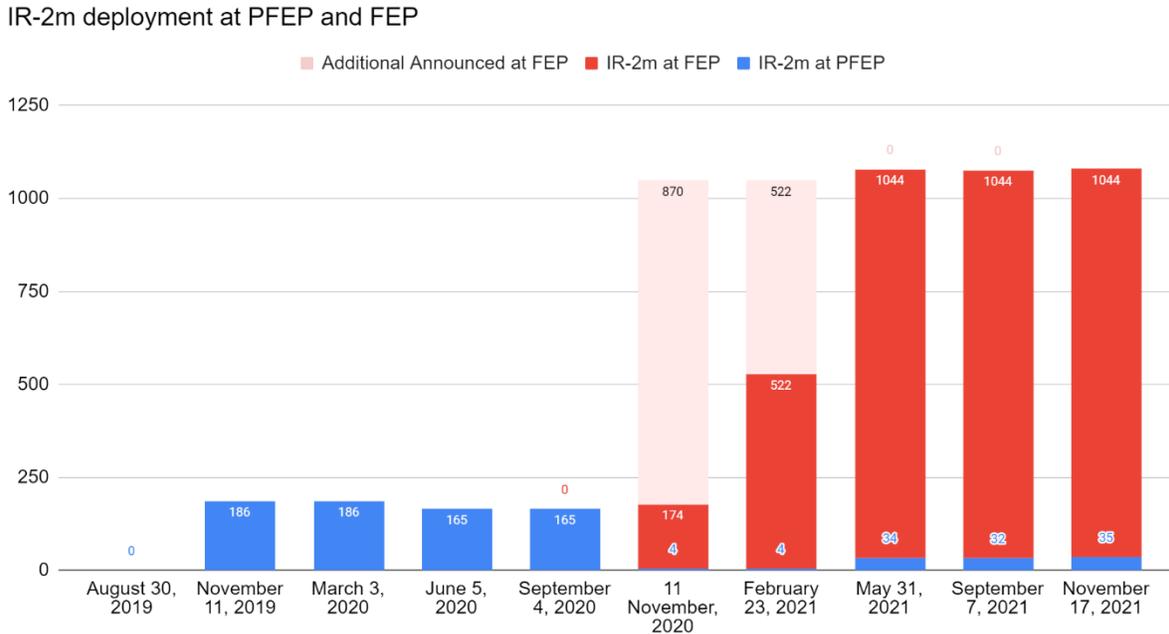


Figure 2.5. IR-2m deployments and deployment plans over the last two years at the PFEP and FEP.

IR-4 Centrifuge Deployment Patterns

The case with the IR-4 centrifuges is different, as Iran never had more than 193 IR-4 centrifuges installed prior to the JCPOA. Figure 2.6 below shows the IR-4 deployment over time, going back to 2011. The initial build-up is visible from September 2011 to February 2013. Fluctuation between February 2013 and November 2015 is visible, where the average deployment is 181 and the standard deviation is 5.6, representing three percent of the average, likely reflecting breakage and replacement rates. The largest drop in centrifuges from one quarter to the next is 10, from February 2013 to May 2013.

IR-4 deployment at PFEP and FEP from 2011 - 2021

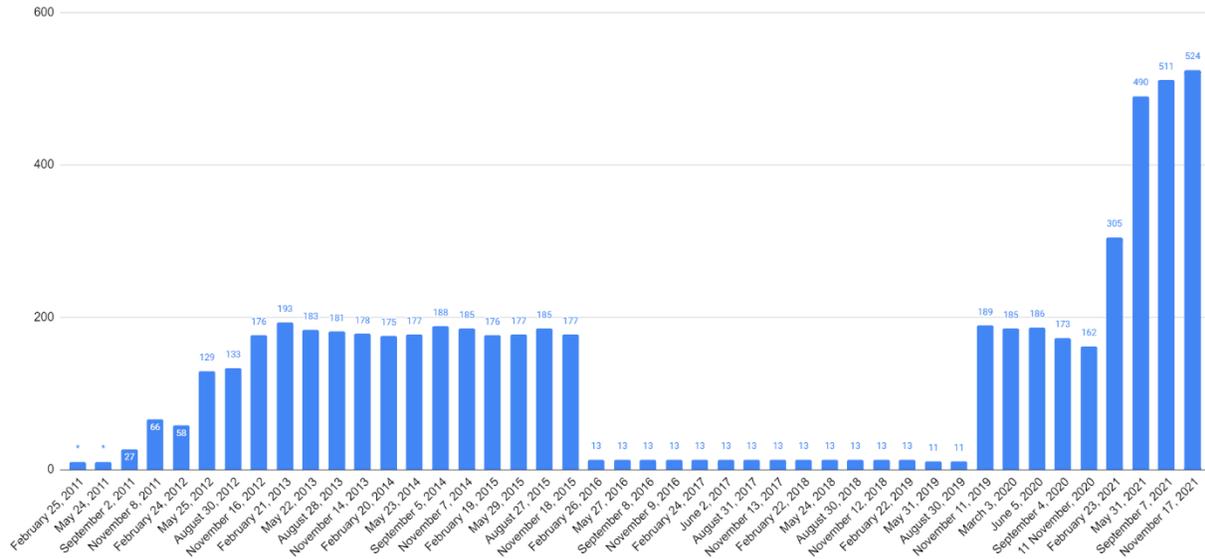


Figure 2.6. Deployment of IR-4 centrifuges over time. The asterisk indicates that the exact number of IR-4 centrifuges is not reported, but some are present, likely between ten and thirty. The drop in November 2020 in the total number stems from a drop at the PFEP and coincides with the installation of a new cascade at the FEP.

By November 2019, within about six months of Iran’s open violation of the JCPOA, it had 189 IR-4 centrifuges installed, but it took over a year until February 2021 to have an additional cascade at the FEP (Figure 2.7). By May 2021, it had 500 installed in total and plans for another 700. These plans are consistent with the pre-JCPOA plans to make thousands, but the lack of progress to meet the reported number (shown in light red in Figure 2.7) is not consistent with a current ability to produce and deploy the machines quickly. The destruction of the Iran Centrifuge Assembly Center in the summer of 2020 and the explosion in the Karaj centrifuge manufacturing plant in June 2021 may explain Iran’s current apparent slowdown in the implementation of its announced deployment plans. However, compared to the deployment of other centrifuge types it would have to produce, it may show a focus on IR-4 production. If Iran only had roughly 200 centrifuges prior to the JCPOA, it produced an additional 300 as of mid-November 2021.

IR-4 deployment at PFEP and FEP

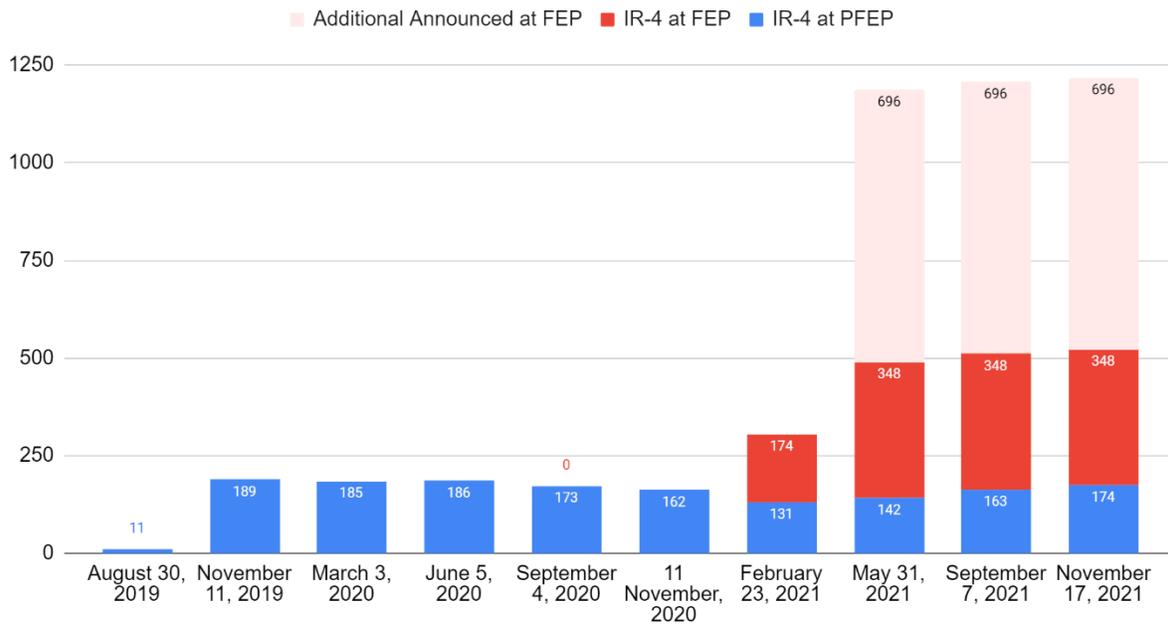


Figure 2.7. Deployment of IR-4 centrifuges at the PFEP and FEP during the last two years.

IR-6 Deployment Patterns

For the IR-6, prior to the JCPOA, the largest number of deployed centrifuges was 19 at the PFEP, on November 7, 2014. This number was quickly surpassed in May 2019, when Iran had 33 IR-6 centrifuges installed. Figure 2.8 shows the initial deployment starting in 2013 and significant fluctuation in the deployment between February 2013 and November 2015, with an average of 11.6 deployed centrifuges and a standard deviation of 3.8, representing 32 percent of the average. The number of IR-6 centrifuges stayed in the teens for almost three years, until the JCPOA came into effect, which led to a decrease in deployed centrifuges for a relatively short time. Following the JCPOA’s implementation, the number dropped to two centrifuges used in single machine mechanical testing. By late 2017, the number increased to up to 17, as Iran installed a cascade of “roughly 10” IR-6 centrifuges, defined by Iran as 13-15.

IR-6 deployment at the PFEP and FFEP from 2013 - 2021

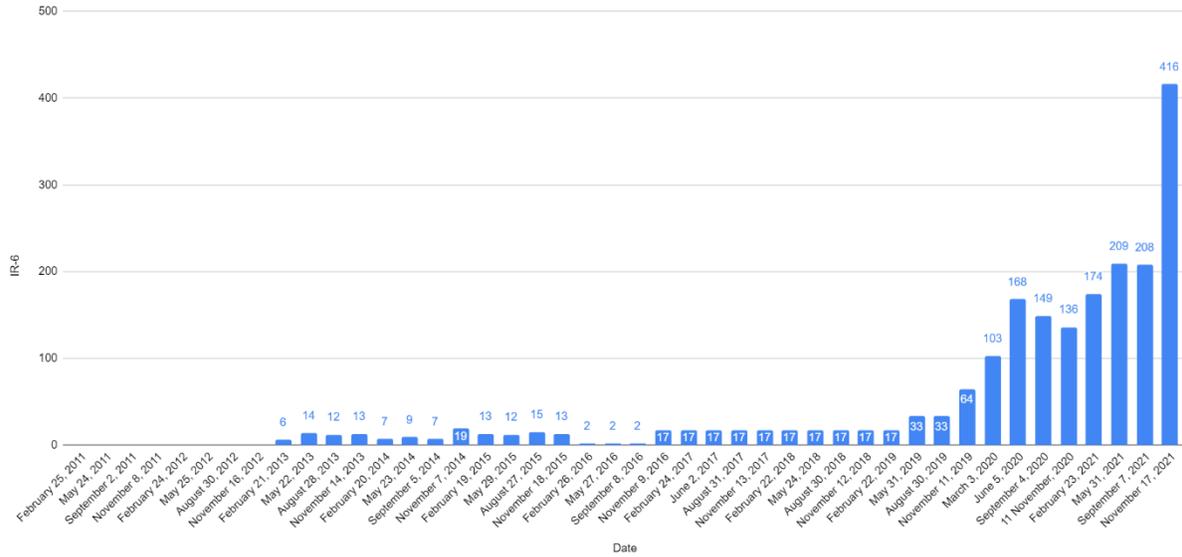


Figure 2.8. Deployment of IR-6 centrifuges at the PFEP and FFEP over time, starting in 2013. The values for 2016, 2017, and early 2019 are estimated.

Figure 2.9 shows that the post-JCPOA number of IR-6 deployed increased steadily from one quarter to the next, by about 30, by about 40, and then by about 60 between August 2019 to November 2019, November 2019 to March 2020, and March 2020 to June 2020 respectively. After June, the number declines for the subsequent two quarters before recovering to 174 by February 2021, increasing further to 209 by May 2021, and doubling to 416 between August and November 2021. Iran has made further progress towards its announced goal to deploy two cascades at the FFEP, but no reported progress towards deploying one cascade at the FEP. At the FFEP, Iran installed 179 IR-6 centrifuges between August and November 2021, bringing the total number of installed IR-6 centrifuges at the FFEP to 189.

If the rate of newly installed centrifuges is proportional to production levels, production was increasing from August 2019 to June 2020, but came to a low between June and November 2020. The temporary decrease may reflect the impact of the destruction of the Iran Centrifuge Assembly Center at Natanz in the summer of 2020. Production may have recovered afterwards.

If Iran only had about 20 IR-6 centrifuges prior to May 2019, it has produced about 400 since. One question is: where did the additional centrifuges come from in May 2019? The IAEA still reported in May and August 2019 that “the declared equipment has been used for the production of rotor tubes and bellows to manufacture centrifuges only for the activities

specified in the JCPOA”,⁴¹ yet, the 33 IR-6 centrifuges installed in May were about three times the amount expected during 2019 according to Iran’s enrichment R&D plan.⁴²

IR-6 deployment at PFEP, FFEP, and FEP

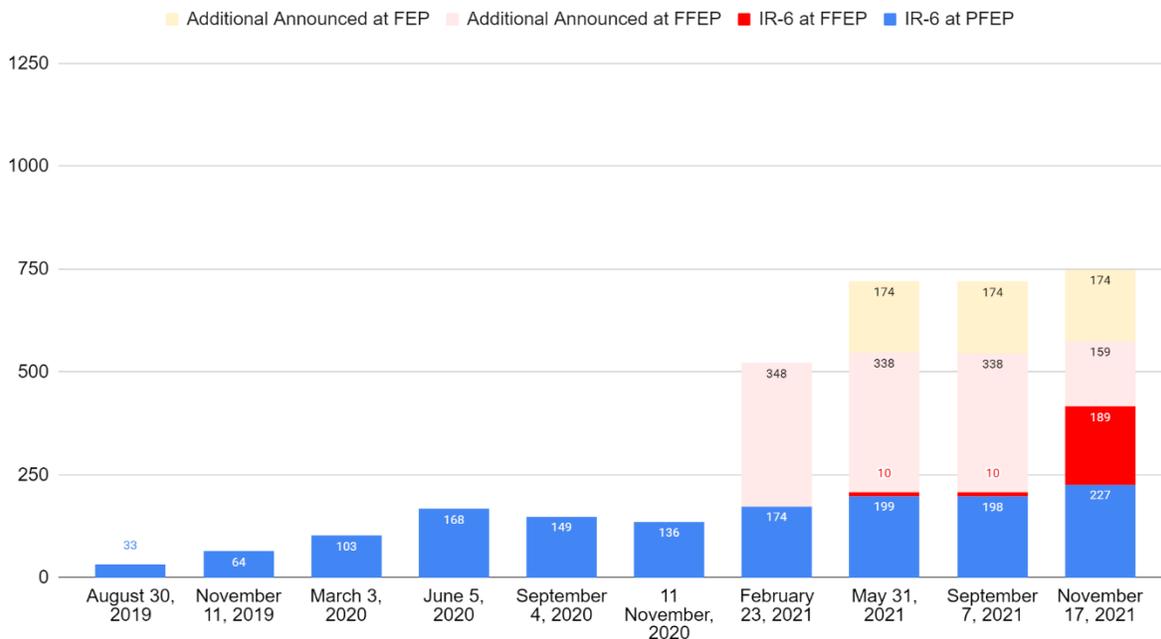


Figure 2.9. Deployment of IR-6 centrifuges during the last two years. It shows additional deployments announced to the IAEA. Per the December 2020 nuclear legislation, the AEOI is directed to install 1000 IR-6 centrifuges, but the law does not specify the location.

⁴¹ Report by the Director General, *Verification and monitoring in the Islamic Republic of Iran in light of United Nations Security Council resolution 2231 (2015)*, GOV/2019/21, May 31, 2019, <https://www.iaea.org/sites/default/files/19/06/gov2019-21.pdf>; and Report by the Director General, *Verification and monitoring in the Islamic Republic of Iran in light of United Nations Security Council resolution 2231 (2015)*, GOV/2019/32, August 30, 2019, <https://www.iaea.org/sites/default/files/19/09/gov2019-32.pdf>.

⁴² According to Iran’s enrichment R&D plan, Section 2.1, roughly ten centrifuges would have been expected. See: “Iran’s Long-Term Centrifuge Enrichment Plan: Providing Needed Transparency.”

Table 2.1 Pre-JCPOA Deployment of Centrifuges, including IR-1 centrifuges, at PFEP, February 2013 to November 2015

PFEP	2011				2012				2013				2014				2015			
Centrifuge Type	25-Feb-11	24-May-11	2-Sep-11	8-Nov-11	24-Feb-12	25-May-12	30-Aug-12	16-Nov-12	21-Feb-13	22-May-13	28-Aug-13	14-Nov-13	20-Feb-14	23-May-14	5-Sep-14	7-Nov-14	19-Feb-15	29-May-15	27-Aug-15	18-Nov-15
Cascade 2																				
IR-1	----	----	----	----	----	----	----	----	----	----	----	----	----	1	3	14	2	2	2	1
IR-2m	----	----	----	----	----	----	----	----	----	----	----	----	----	----	1	----	----	----	----	----
IR-4	*	*	*	*	*	*	10	32	29	19	17	14	11	13	14	13	12	11	11	13
IR-5	----	----	----	----	----	----	----	----	1	1	1	1	1	1	1	1	1	1	1	1
IR-6	----	----	----	----	----	----	----	----	6	14	12	13	7	9	7	19	13	12	8	4
IR-6s	----	----	----	----	----	----	----	----	2	3	8	1	1	----	----	----	----	----	1	2
IR-8	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	1	1	1	1	1
Cascade 3																				
IR-1	*	*	*	*	*	*	----	*	2	19	14	14	14	14	14	14	15	8	8	24
IR-2m	*	*	*	*	*	*	----	14	9	3	18*	2	----	10	----	10	2	26	10	----
IR-4	----	----	----	----	----	----	----	----	----	----	----	----	----	----	10	----	----	2	10	----
IR-6	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	7	9
Cascade 4																				
IR-4	----	----	27	66	58	129	123	144	164	164	164	164	164	164	164	164	164	164	164	164
Cascade 5																				
IR-2m	----	----	136	164	164	164	162	162	162	162	162	162	162	162	162	162	162	162	162	162
Total	*	*	163**	230**	222**	293**	295	352**	374	385	364**	371	360	374	376	398	372	389	385	381
Total Advanced Centrifuges	*	*	163**	230**	222**	293**	295	352	372	366	355**	357	346	359	359	374	355	379	375	356
Cascade 1 (IR-1)	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164
Cascade 6 (IR-1)	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164	164
Comments	* Centrifuges present but no breakdown by centrifuge type available in the reports. ** Tally does not include the unspecified centrifuge breakdown counts.																			

Table 2.2 Pre-JCPOA deployment at Natanz FEP

Natanz (FEP)	2013				2014				2015			
	Report Date	21-Feb-13	22-May-13	28-Aug-13	14-Nov-13	20-Feb-14	23-May-14	5-Sep-14	7-Nov-14	19-Feb-15	29-May-15	27-Aug-15
Number of Cascades	74 (74 IR-1)	83 (79 IR-1, 4 IR-2m)	95 (89 IR-1, 6 (IR-2m)	96 (90 IR-1, 6 IR-2m)								
Cascades Being Fed UF6	53 (IR-1)	53 (IR-1)	54 (IR-1)	52 (IR-1)	54 (IR-1)							
Centrifuge Type												
IR-1	12669	13555	15416	15420	15420	15420	15420	15420	15420	15420	15420	15420
IR-2m	180	689	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008
Total Advanced Centrifuges	180	689	1008	1008	1008	1008	1008	1008	1008	1008	1008	1008
Total Centrifuges	12849	14244	16424	16428	16428	16428	16428	16428	16428	16428	16428	16428
Change	----	1395	2180	4	0	0	0	0	0	0	0	0
Comments	No advanced centrifuges installed in FEP prior to reporting period that preceded the February 2013 report's reporting period.											

Table 2.3 Centrifuge deployment at PFEP post Implementation Day of the JCPOA, January 2016 until August 2019

PFEP	2016				2017				2018				2019		
Centrifuge Type															
Report Date	26-Feb-16	27-May-16	8-Sep-16	9-Nov-16	24-Feb-17	2-Jun-17	31-Aug-17	13-Nov-17	22-Feb-18	24-May-18	30-Aug-18	12-Nov-18	22-Feb-19	31-May-19	30-Aug-19
Mechanical Testing															
IR-2m	2	2	2	2	2	2	2	2	2	2	2	2	2	*	*
IR-4	2	2	2	2	2	2	2	2	2	2	2	2	2	*	*
IR-5	2	2	2	2	2	2	2	2	2	2	2	2	2	*	*
IR-6	2	2	2	2	2	2	2	2	2	2	2	2	2	*	*
IR-6s	2	2	2	2	2	2	2	2	2	2	2	2	2	*	*
IR-7	2	2	2	2	2	2	2	2	2	2	2	2	2	*	*
IR-8	2	2	2	2	2	2	2	2	2	2	2	2	2	*	*
Centrifuge Testing															
IR-4	1	1	1	1	1	1	1	1	1	1	1	1	1	11	11
IR-5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
IR-6	0	0	0	15	15	15	15	15	15	15	15	15	15	33	33
IR-8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IR-4 Cascade															
IR-4	10	10	10	10	10	10	10	10	10	10	10	10	10	*	*
Total	26	26	26	41	45**	45**									
Comments	For the period between Feb 2016 - Feb 2019, where no specific numbers were given in the IAEA report, the JCPOA limit was used.														
	* Centrifuges present but no breakdown by centrifuge type available in the reports.														
	** Tally does not include the unspecified centrifuge breakdown counts.														

Table 2.4 PFEP Post-JCPOA Centrifuge Deployment

PFEP	2019			2020			2021			
Centrifuge Type	8-Sep-19	11-Nov-19	3-Mar-20	5-Jun-20	4-Sep-20	11 November, 2020	23-Feb-21	31-May-21	7-Sep-21	17-Nov-21
R&D Line 1										
IR-5	----	----	----	----	----	----	----	30	30	30
IR-6s	----	----	----	----	----	----	----	29	29	29
R&D Line 2 and 3										
IR-2m	----	22	20	----	----	----	----	----	----	----
IR-3	----	1	----	----	----	----	----	----	----	----
IR-4	22	22	20	20	15	9	11	10	9	11
IR-5	1	11	10	10	10	8	5	5	5	5
IR-6	30	34	30	30	29	26	39	33	33	62
IR-6s	3	21	20	20	10	10	9	9	3	----
IR-6smo	----	12	----	----	----	----	----	----	----	----
IR-6m	----	1	----	----	----	----	----	----	----	----
IR-6sm	----	1	----	----	----	----	----	----	----	----
IR-7	----	2	----	----	----	----	----	----	----	----
IR-8	----	3	----	----	----	----	----	----	----	----
IR-8s	----	1	----	----	----	----	----	----	----	----
IR-8B	----	1	----	----	----	----	----	----	----	----
IR-s	----	1	----	10	10	10	10	10	10	10
IR-9	----	1	----	----	----	----	----	----	----	----
R&D Line 4										
IR-4	----	164	164	164	156	152	119	130	153	164
R&D Line 5										
IR-1	----	----	----	----	----	----	28	18	18	18
IR-2m	----	164	164	164	164	----	----	32	32	33
R&D Line 6										
IR-6	----	30	72	135	120	110	133	164	164	164
Single machine testing in lines 2 and 3, fed but not accumulating										
IR-1	----	----	----	----	----	1	1	1	1	----
IR-2m	----	----	2	1	1	4	4	2	----	2
IR-3	----	----	1	1	1	----	----	----	----	----
IR-4	----	3	1	2	2	1	1	2	1	1
IR-5	----	----	1	1	1	2	3	2	2	2
IR-6	----	----	1	3	----	----	2	2	1	1
IR-6m	----	----	1	1	1	----	----	----	----	----
IR-6s	----	----	1	----	2	2	2	1	2	2
IR-6sm	----	----	1	1	1	----	----	----	----	----
IR-7	----	----	2	1	1	----	----	1	1	1
IR-8	----	----	2	2	----	1	1	1	1	1
IR-8s	----	----	1	1	1	----	----	----	----	----
IR-8B	----	----	1	1	1	1	1	1	1	1
IR-s	----	----	1	2	1	1	1	----	----	----
IR-9	----	----	1	1	1	1	1	1	1	1
Total	56	495	517	571	528	339	371	484	497	538**
Total Advanced Centrifuge	56	495	517	571	528	338	342	465	479	520**
Comments:	* Centrifuges present but no breakdown by centrifuge type available in the reports.									

Table 2.5 Natanz FEP Post-JCPOA Centrifuge Deployment.

Natanz (FEP)		2021			
Report Date	11-Nov-20	23-Feb-21	31-May-21	7-Sep-21	17-Nov-21
Cascades Being Fed UF6	30 IR-1	30 IR-1 and 2 IR-2m	15 IR 1, 3 IR-2m, 2 IR-4	29 IR-1, 5 IR-2m, 2 IR-4	28 IR-1, 6 IR-2m, 2 IR-4
Number Installed by Centrifuge Type					
IR-1	5060	5060	Up to 5060	Up to 5060	5228
IR-2m	174	522	Up to 1044 IR-2m	Up to 1044 IR-2m	Up to 1044 IR-2m
IR-4	Begun installation	174	Up to 348 IR-4	Up to 348 IR-4	Up to 348 IR-4
IR-6	----	----	----	----	----
Total Advanced Centrifuges	174	696	1392	1392	1392
Total Centrifuges	5234	5756	6452	6452	6620
Change	0	522	696	0	168
Comments	Under JCPOA only IR-1 centrifuges installed, until October 2020				

Table 2.6 Fordow FEP Post-JCPOA Centrifuge Deployment.

Fordow (FFEP)		2021			
Report Date	11-Nov-20	23-Feb-21	31-May-21	7-Sep-21	17-Nov-21
Cascades Being Fed UF6	6	3 sets of 2 IR-1 cascades			
Number Installed by Centrifuge Type					
IR-1	1057	1045	1032	1045	1045
IR-2m	----	----	----	----	----
IR-4	----	----	----	----	----
IR-6	----	----	10	10	189
Total Advanced Centrifuges	0	0	10	10	189
Total Centrifuges	1057	1045	1042	1055	1234
Change	0	-12	-3	13	179
Comments	Only IR-1 were installed at FFEP until May 2021.				

Chapter 3 Findings and Discussion

Historical

Iran's gas centrifuge program has depended extensively on foreign procurements. Without initial and extensive assistance from Pakistan, Iran likely would not have been able to develop an industrial-scale centrifuge program.

From the late 1980s until about 2003/2004, there were two parallel, but interconnected, centrifuge programs in Iran. A highly secret one run by the military aimed at the production of weapon-grade uranium, and a less secret one run by the Atomic Energy Organization of Iran (AEOI) focused on achieving large-scale production of enriched uranium.⁴³ During this period, the military, through its industries, controlled the production of the centrifuges.

Based on information from the Nuclear Archive and the IAEA, the AEOI program during the 1980s and 1990s developed the IR-1 centrifuge and laid the groundwork for its large-scale deployment. The military program appears to have also worked on the IR-1 and related centrifuges, but it also did the initial development work on what have become known as advanced gas centrifuges. Despite the extensive information in the Nuclear Archive, the findings at Turqz Abad,⁴⁴ and years of IAEA investigations, much remains unclear about these early programs, particularly the specific centrifuge types and the military centrifuge program, including its relationship with the AEOI. Progress is often thwarted by Iran's unwillingness to cooperate with the IAEA in its investigations into ensuring that Iran's nuclear declaration is complete, a requirement of Iran's comprehensive safeguards agreement (CSA).

After 2003/2004, these programs were merged, with the AEOI taking over responsibility for developing and operating centrifuges. The AEOI, with military involvement, also took over responsibility for the building of a site to produce weapon-grade uranium at a secret enrichment plant under a mountain near Qom, called the Al Ghadir project under the Amad Plan, and now known as the Fordow Fuel Enrichment Plant, a name it acquired after the site was revealed by Western powers in 2009.⁴⁵ After being discovered, the AEOI modified the plant to produce low enriched uranium and subjected it to IAEA safeguards.

⁴³ *Iran's Perilous Pursuit of Nuclear Weapons*.

⁴⁴ David Albright, Sarah Burkhard, Olli Heinonen, and Frank Pabian, "Presence of Undeclared Natural Uranium at the Turqz-Abad Nuclear Weaponization Storage Location," *Institute for Science and International Security*, November 20, 2019, <https://isis-online.org/isis-reports/detail/presence-of-undeclared-natural-uranium-at-the-turqz-abad-nuclear-weaponiza/8>; David Albright, Sarah Burkhard, and Andrea Stricker, "The IAEA's Latest Iran NPT Safeguards Report: No Progress, No Accountability?" *Institute for Science and International Security*, June 4, 2021, <https://isis-online.org/isis-reports/detail/the-iaeas-latest-iran-npt-safeguards-report-no-progress-no-accountability>.

⁴⁵ *Iran's Perilous Pursuit of Nuclear Weapons*.

Program Today

Today, it is believed that the AEOI controls all major aspects of centrifuge development, production, and operation. However, if ordered by the Iranian leadership, the AEOI could rapidly switch to the production of weapon-grade uranium. As of late November 2021, Iran could produce enough weapon-grade uranium for a nuclear weapon in as little as three weeks.⁴⁶ Subsequently, it could rapidly grow its stock of weapon-grade uranium, having enough for three nuclear weapons within four months after initiating breakout.

Its enriched uranium stocks combined with advanced centrifuges offer Iran a more practical way to produce weapon-grade uranium in a clandestine site rather than at its declared enrichment sites. With stocks of near 20 and 60 percent enriched uranium as of November 2021, about 650 IR-6 centrifuges would be enough to breakout in a secret site and produce enough weapon-grade uranium for a nuclear explosive in about one month.

The AEOI has maintained a long-term goal of building a centrifuge plant with an enrichment output of at least “190,000 SWU,” which converts in a more standard unit to about 128,000 SWU per year (see Preface for a discussion of Iran’s non-standard unit). This value corresponds to an enrichment plant able to supply the enriched uranium needs of a nuclear power reactor like Iran’s Bushehr reactor.

A goal of “190,000 SWU” is relatively modest from a commercial vantage point, when large Russian and European centrifuge programs are considered. However, such a program from a nuclear weapons vantage is huge for a country like Iran. Merely installing one tenth of that capacity of 128,000 SWU per year is sufficient to produce enough weapon-grade uranium for more than one bomb per year. With a sufficient stock of low enriched uranium, Iran could produce enough weapon-grade uranium for over five weapons per year.

The AEOI has tried to develop many types of centrifuges, far too many for a commercial or economic program. Some of the developments, such as those proudly proclaiming very long centrifuges, such as the IR-8 and IR-9 centrifuges, appear aimed at impressing a domestic audience, not at deploying them on a large scale in a reasonable time frame.

However, other centrifuge types show a logical progression with a clear-eyed intention to replace the IR-1 centrifuges, relying on imported and domestic goods and technologies available to Iran. One way to identify these centrifuges is to consider those that can replace the IR-1 centrifuges while utilizing the existing cascade piping and feed and withdrawal systems at the Natanz and Fordow sites. The most important of these are the IR-4 and IR-6 centrifuges. The IR-2m centrifuge is also important, but Iran may have encountered obstacles procuring needed and tightly controlled materials from overseas, limiting its ability to produce it in larger

⁴⁶ David Albright, Sarah Burkhard, and Andrea Stricker, “Analysis of IAEA Iran Verification and Monitoring Report – November 2021,” *Institute for Science and International Security*, November 19, 2021, <https://isis-online.org/isis-reports/detail/analysis-of-iaea-iran-verification-and-monitoring-report-november-2021>.

numbers. In contrast, Iran has been more successful evading national and international controls and sanctions with regards to goods needed to make IR-4 and IR-6 centrifuges.

All three of these centrifuge types (the IR-2m, IR-4, and IR-6) have a rotor assembly composed of two rotor tubes and one flexible connecting bellows (see Chapter 1). Their single-machine measured enrichment output varies between 3.8 to over 6.8 separative work units (SWU) per year per centrifuge, a hefty increase from the IR-1 centrifuge's 0.6-0.9 SWU per year per centrifuge. The IR-2m and IR-4 centrifuges both have an estimated production-scale value of 3.67 and 3.3 SWU per year, respectively, and the IR-6 has an estimated production-scale value of 5.25 SWU per year, all three many times more powerful than the IR-1 centrifuge.

Iran's advanced centrifuge program has invested heavily into using carbon fiber for its centrifuge rotors and bellows. The use of carbon fiber in rotors, instead of maraging steel for example, has precedents. Iraq's centrifuge program of the late 1980s struggled with making maraging steel rotor tubes but had more success with making carbon fiber ones, particularly after receiving aid from an experienced German centrifuge expert, named Karl Heinz Schaab.⁴⁷ In addition, high-grade maraging steel of the type used in advanced centrifuges can be difficult to acquire internationally, and Iran seems to have been unable to make it domestically. However, bellows are far more difficult to make with carbon fiber than with maraging steel. So, the switch from the use of maraging steel bellows in the IR-2m centrifuges to carbon fiber bellows in every subsequent advanced centrifuge again suggests a problem in obtaining sufficient high-grade maraging steel either domestically or abroad. On the other hand, high strength carbon fiber has turned out to be far easier to acquire illicitly and to smuggle into Iran due to plentiful worldwide supplies, weak export controls in several countries, particularly China, and Iran's sophisticated procurement networks.⁴⁸ Nonetheless, making a reliable carbon fiber bellows appears to remain a central challenge for Iran.

To boost the centrifuge's enrichment output, Iran has primarily lengthened its advanced centrifuge rotor assembly and boosted its wall speed by using carbon fiber instead of the high strength aluminum used in its IR-1 centrifuge. As discussed above, maraging steel rotors of the type found in the P2 appear to have been viewed as unachievable. Iran's initial advanced centrifuges, deployed in the 2000s, had rotor assemblies made from carbon fiber just over one-half meter tall. By 2010, the length had doubled. Iran's carbon fiber rotor assemblies achieved wall speeds exceeding 500 meters per second compared to the 350 meters per second achieved in the IR-1 centrifuge.

⁴⁷ During interviews conducted by the Institute with Schaab in the late 1990s, he maintained he did not assist Iran's centrifuge program in any way. For his assistance to Iraq's centrifuge program in the late 1980s and early 1990s, see Karl Heinz Schaab, "Personal Reflections on Cooperation with Iraq in the 1980s," April 6, 2001, <http://exportcontrols.info/schaab.html>; and Institute for Science and International Security, "Iraq's Acquisition of Gas Centrifuge Technology, Part II: Recruitment of Karl Heinz Schaab," <http://exportcontrols.info/centpart2.html>.

⁴⁸ David Albright, Sarah Burkhard, Spencer Faragasso, Linda Keenan, and Andrea Stricker, *Illicit Trade Networks - Connecting the Dots*, Volume 1 (Washington, D.C.: Institute for Science and International Security, 2020), <https://isis-online.org/books/detail/illicit-trade-networks-connecting-the-dots-volume-1>.

Increasing wall speed of a rotor assembly is an attractive option since it has a much larger effect on improving enrichment output than increasing its length. Nonetheless, Iran has not fully exploited the increase in wall speed offered by carbon fiber. Its wall speeds are more typical of that of maraging steel and Pakistan's P2 centrifuge. Despite using carbon fiber rotors, the wall speed of Iran's centrifuges appears to have encountered a cap of approximately 560 meters per second. This speed remains below Iran's target speed of 700 meters per second, a target declared to the IAEA in the late 2000s for its advanced centrifuges. This higher speed is attractive, since at this target speed, the enrichment output would be almost 60 percent greater than the output at a speed of 560 meters per seconds, or double that at 500 meters per second. However, the achievement of this higher wall speed using carbon fiber rotors would require the redesign of many P2 parts, parts Iran carried over from the P2 design into its advanced centrifuges. The additional heat generated by these higher speeds creates special material and operational challenges that Iran still appears to be struggling with. However, a recently deployed centrifuge, called the IR-s centrifuge, may be experimenting with operating at speeds reaching or exceeding Iran's target speed of 700 meters per second.

Trend Toward Wider Centrifuge Rotor Assemblies

Over the course of developing many advanced centrifuge types, Iran has widened the diameter of its rotor assemblies. Starting with the diameter of the P2, namely 146 millimeters (IR-2 and IR-2m centrifuges), Iran has gradually widened its rotor assembly to 160 millimeters (IR-3, IR-4, and IR-5 centrifuges); then to 200 millimeters (IR-6 and IR-7 centrifuges); and finally, to 250 millimeters or wider (IR-8, IR-s, and IR-9 centrifuges). These diameters can serve to define groups, or families, of centrifuges.

This widening may also be an attempt to increase rotor wall speeds, which for a fixed rotational frequency increases linearly with the increase in the radius. However, this effect is mitigated by problems in Iran's centrifuges and their ability to survive significantly higher wall speeds. These problems likely have led to somewhat lower rotational frequencies that allow marginal increases in wall speeds at these wider diameters, without resulting in excessive damage to the centrifuge's other components of the type that would be encountered at the much higher speeds possible for carbon fiber rotors.⁴⁹

Advanced Centrifuge Trends

Figure 3.1 is a scatter plot of all major centrifuge types under development where the length was available, showing the relationship between the length of the rotor assembly and the theoretical enrichment output in SWU per year. Excluding the IR-1 centrifuge, the graph's linear trend for different centrifuge types with the same diameter supports that most of the improvements in enrichment output are resulting from increased length and not increased speed.

⁴⁹ Comparing the IR-2m and IR-6 centrifuge, using their tangential speeds and diameters in Table 1.1, Part 1, their rotational frequencies would be 1050 Hz and 911 Hz, respectively.

The general shift to higher separative work for those types with wider diameters may reflect a marginally higher wall speed associated with the larger radius. Examples include the IR-6 centrifuge, which appears to have a higher wall speed compared to the similarly tall IR-2m and IR-4, the IR-s compared to the IR-6s, and the IR-7 compared to the IR-5.

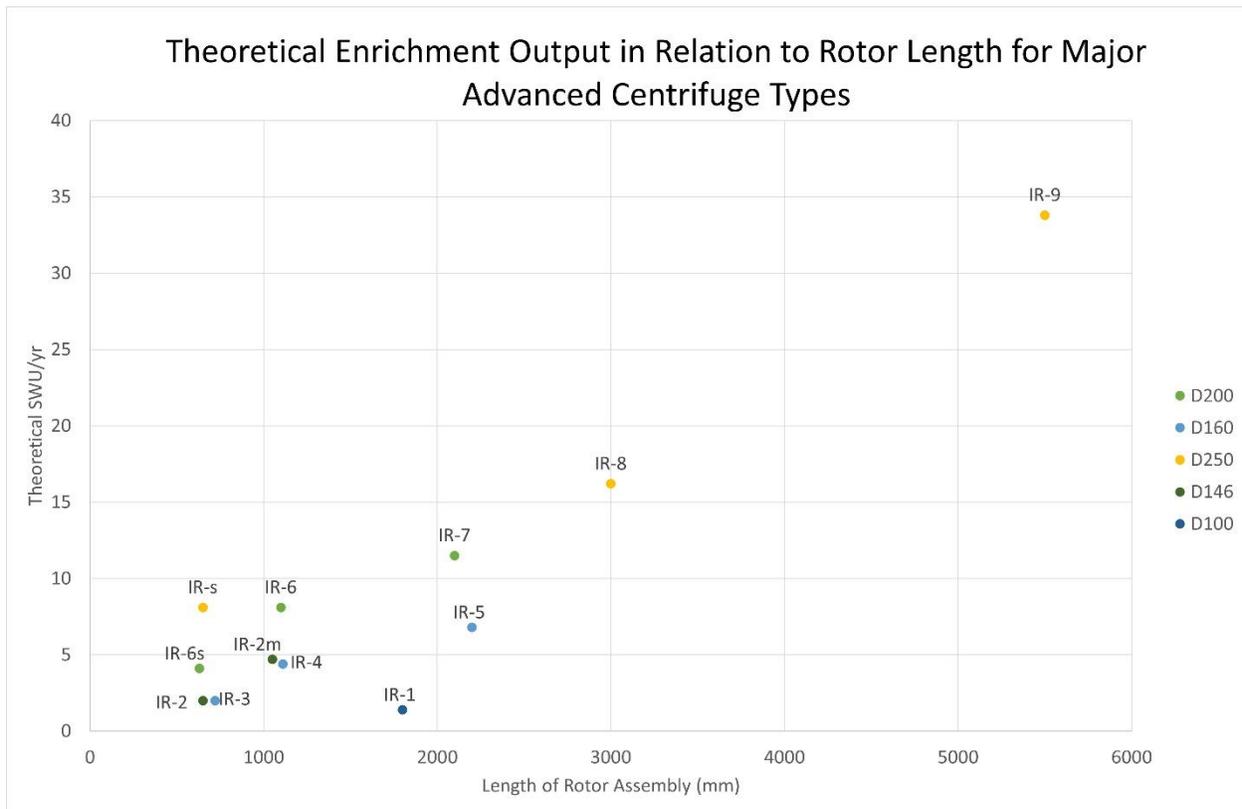


Figure 3.1. The length of rotor assemblies in relation to the theoretical enrichment output for 12 of Iran’s major centrifuge types, color-coded by their diameter, where yellow is the largest and dark blue is the smallest. (See the key on the right side of the graph.) The diameter of the IR-9 is estimated and may in fact be wider, based on visual comparisons with the IR-7 in available photos. The IR-s centrifuge’s diameter and length are unknown publicly, but its diameter appears in AEOI photographic handouts as significantly wider than the IR-6 and IR-5 centrifuges, but somewhat less than the IR-9 centrifuge.

Disorganized Program

When Iran develops a particular centrifuge, it increasingly also develops in parallel related centrifuges. For example, there is the IR-6 but also the related IR-6s (a single rotor tube model), the IR-6m, IR-6sm, and the IR-6smo. There is the IR-8 and the related IR-8S, and the IR-8B. The variants are shorter, either having no bellows or fewer bellows, representing developmental models on a path to a full-size model. This strategy reflects in part the difficulty Iran has experienced in mastering carbon fiber bellows. However, there is little evidence,

demonstrated at the PFEP, that Iran first deploys the shorter versions on a path to the full-length model, further contributing to a perception of a disorganized program.

In 2019, Iran quickly deployed many new advanced centrifuge types at the Natanz Pilot Fuel Enrichment Plant, an activity which had been banned from deployment under the JCPOA. Under the JCPOA, Iran's centrifuge R&D was constrained to limited work on IR-2m, IR-4, IR-5, IR-6, IR-6s, IR-7, and IR-8 centrifuges. Starting in November 2019, it accelerated work on several of these centrifuges and deployed seven additional models, the IR-3, IR-6m, IR-6sm, IR-8s, IR-8B, IR-s, and IR-9 centrifuges, all of which were not included in Iran's JCPOA enrichment plan.

Iran's rapid deployment of many advanced centrifuges, including many new models, in 2019 suggests that centrifuge development work may have continued during the period when the JCPOA was in force and accelerated secretly as soon as the United States ended its participation in the JCPOA in May 2018. The development of so many new models from May 2018 to their initial deployment at Natanz in the fall of 2019 seems beyond Iran's capabilities, let alone from early 2019 when Iran stated it would no longer abide by the JCPOA's limitations.

Frankly, it is unclear why Iran deploys so many centrifuge types. Is it seeking to let a "thousand flowers bloom" or is it throwing things against a wall and hoping something sticks? Legislation passed by Iran's parliament in December 2020 appeared in part to be an effort to focus the AEOI centrifuge program on deploying more successful centrifuges, in this case 1000 IR-6 and 1000 IR-2m centrifuges. These along with the IR-4 centrifuge are its more dangerous centrifuges, from a nuclear weapons production vantage point.

Advanced Centrifuge Enrichment Capacity

Figure 2.1 charts the total number of advanced centrifuges deployed at the FEP, PFEP, and FFEP over the last ten years. These centrifuges as of November 2021 have a combined theoretical enrichment output of about 8360 SWU per year.⁵⁰ By comparison, the theoretical enrichment capacity of the deployed IR-1 centrifuges is 5661 SWU per year.

Figure 2.1 does not include the large reservoir of deployed and stored IR-1 centrifuges in Iran, a number that, according to the Iranian table is more than 16,000. This quantity of IR-1 centrifuges has an estimated practical enrichment output of up to 14,400 SWU per year.

⁵⁰ Despite the precise number, this is only a rough estimate. The number is derived from the number of installed centrifuges reported by the IAEA as of November 2021, where all centrifuges are included at FEP, FFEP, and PFEP, including those installed as single machines. The enrichment output value used for the individual centrifuge types depended on the availability of data; for those where data on measured single machine enrichment output were available, they were used, for those where only a theoretical value was available, the latter was used (see Table 1.1). In the case where the theoretical value was used, the number of centrifuges is relatively low compared to the case where measured values were available. In addition, a value of 0.9 SWU/year was used for the IR-1 estimate.

However, because the advanced centrifuges have far greater nominal enrichment outputs, the advanced centrifuges deployed as of November 2021, numbering about 2101, or about 34 percent of the number of currently deployed IR-1 centrifuges at the three enrichment plants, outstrip in enrichment output by about 48 percent all of these IR-1 centrifuges. If Iran reaches the projected value of 3381 advanced centrifuges, it will have almost two and half times the nominal enrichment capacity in these centrifuges than in its currently deployed IR-1 centrifuges. This advanced centrifuge capacity will also rival all of Iran's estimated 16,000 IR-1 *deployed and stored* centrifuges with only 21 percent of the number of centrifuges. This comparison ignores any stored advanced centrifuges.

Figure 3.2 shows separately Iran's enrichment capacity, by quarter, from 2011 onwards of IR-1 centrifuges (blue) versus advanced centrifuges (red). The light blue and red bars on the far right of the graph are projections, discussed earlier. As can be seen, the installed enrichment capacity of the advanced centrifuges exceeded for the first time the capacity of the installed IR-1 centrifuges by May 2021. That capacity, however, remains lower than the theoretical capacity of the IR-1 centrifuges at their peak prior to 2016.

Figure 3.3 simply stacks the two blue and red bars, providing the total theoretical enrichment capacity by quarter. So far, Iran's current enrichment capacity has not exceeded its total capacity prior to the JCPOA but the nature of that capacity is shifting predominately to advanced centrifuges. Figure 3.4 shows that phenomenon as of November 2021, highlighting the relatively small number of advanced centrifuges but their relatively large share of the total enrichment capacity. Most of the advanced centrifuge capacity is from the IR-2m, IR-4, and IR-6 centrifuges, respectively.

Based on the projection for installed centrifuges in early to mid-2022, this phenomenon will strengthen. Figure 3.5 shows that under this projection, less than one third of the total enrichment capacity will result from IR-1 centrifuges. Of the advanced centrifuges, the IR-6 centrifuges are projected to make the largest contribution to enrichment capacity.

Enrichment capacity of installed IR-1 centrifuges compared to the capacity of installed advanced centrifuges

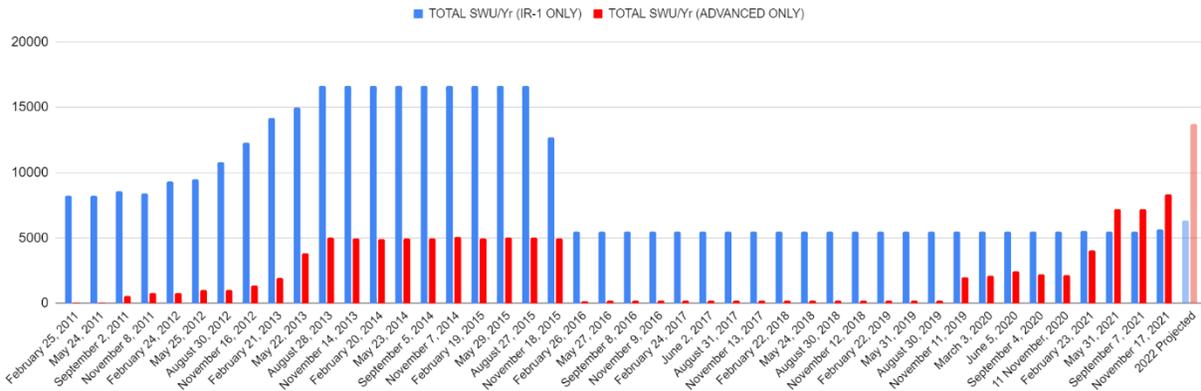


Figure 3.2. Iran’s enrichment capacity, by quarter, from 2011 onwards, where the capacity of the IR-1 centrifuges is shown in blue, and the capacity of the advanced centrifuges is shown in red. The light blue and red bars on the far right of the graph are projections, discussed earlier.

Enrichment capacity of installed IR-1 centrifuges compared to the capacity of installed advanced centrifuges

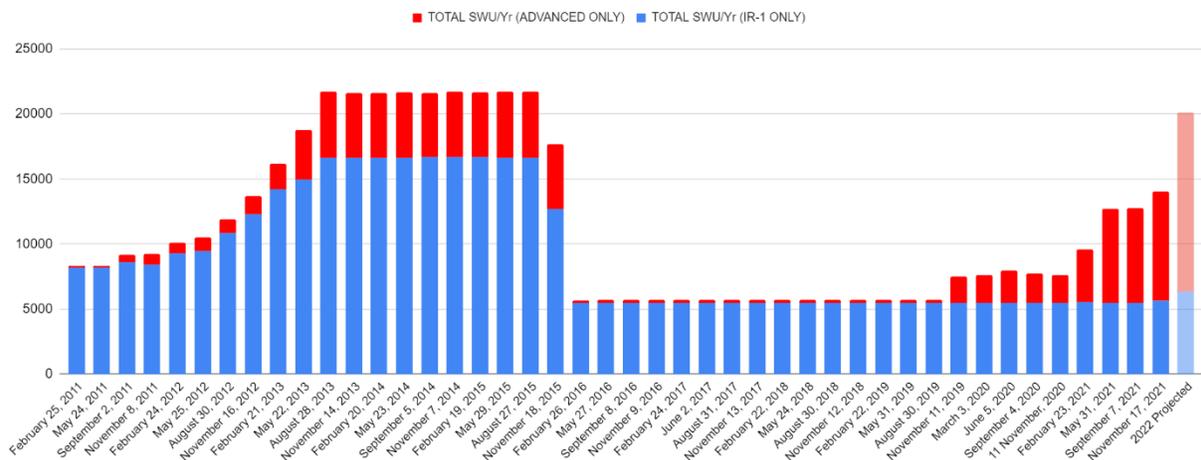


Figure 3.3. Total enrichment capacity, by quarter, of the IR-1 and advanced centrifuges, with a projection on the far right of the graph.

Figure 3.4 (A)

Make-up of Iran's Installed Centrifuges as of November 2021, by Centrifuge Type

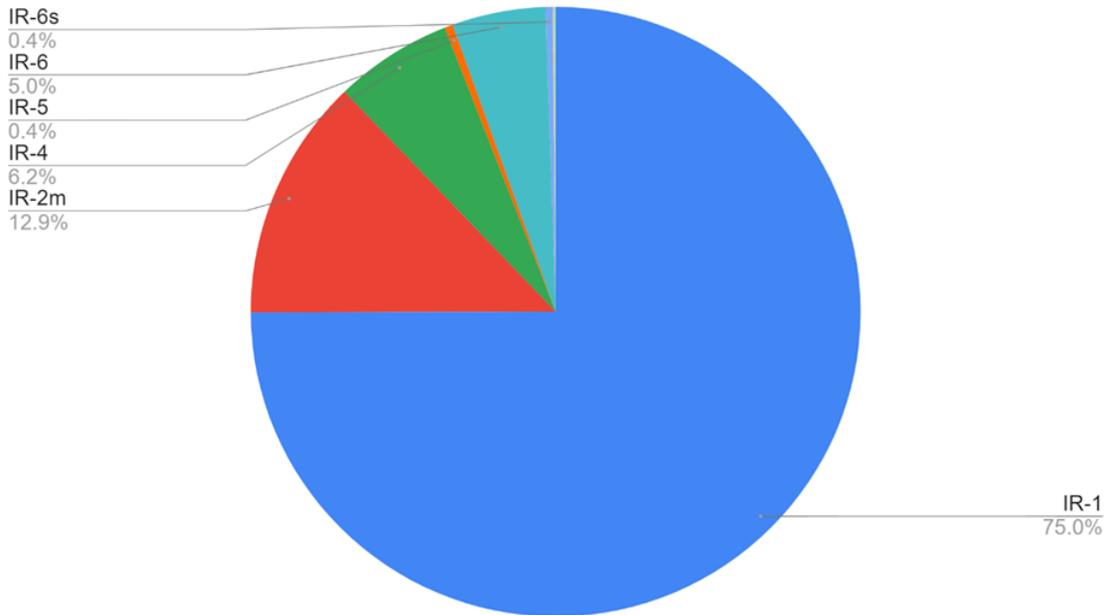


Figure 3.4 (B)

Make-up of Iran's Enrichment Capacity as of November 2021, by Centrifuge Type

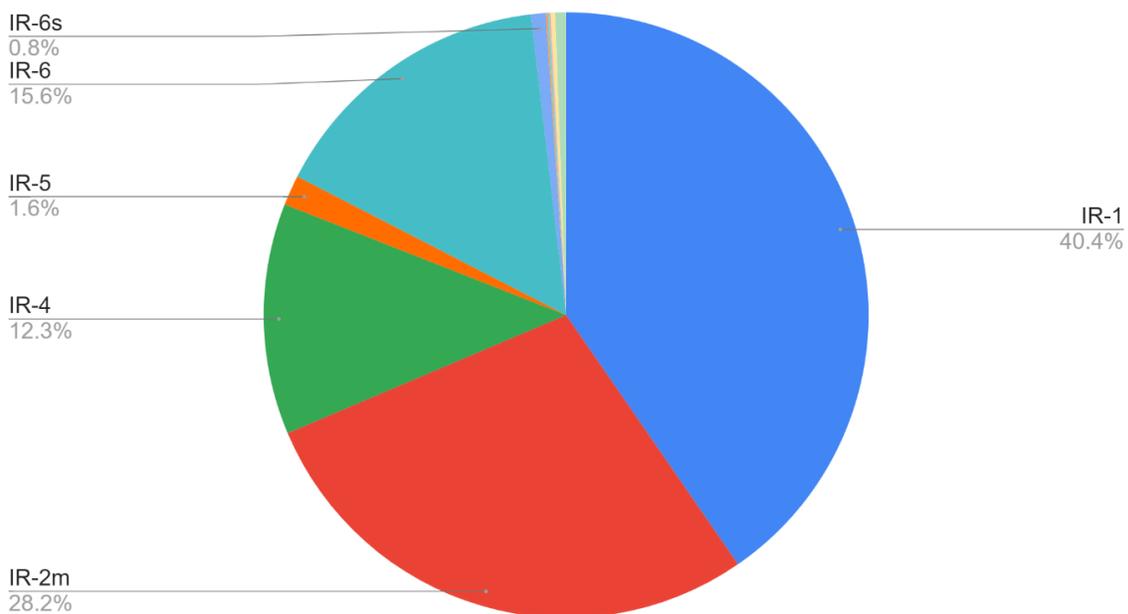


Figure 3.4 A and B. Comparison between the fraction of total installed centrifuges by number (top) versus the fraction each centrifuge type contributes to the total enrichment output (bottom). While the IR-1 centrifuge still dominates in number, its importance decreases in overall capacity.

Enrichment Capacity by Centrifuge Type Projected for Early/Mid 2022

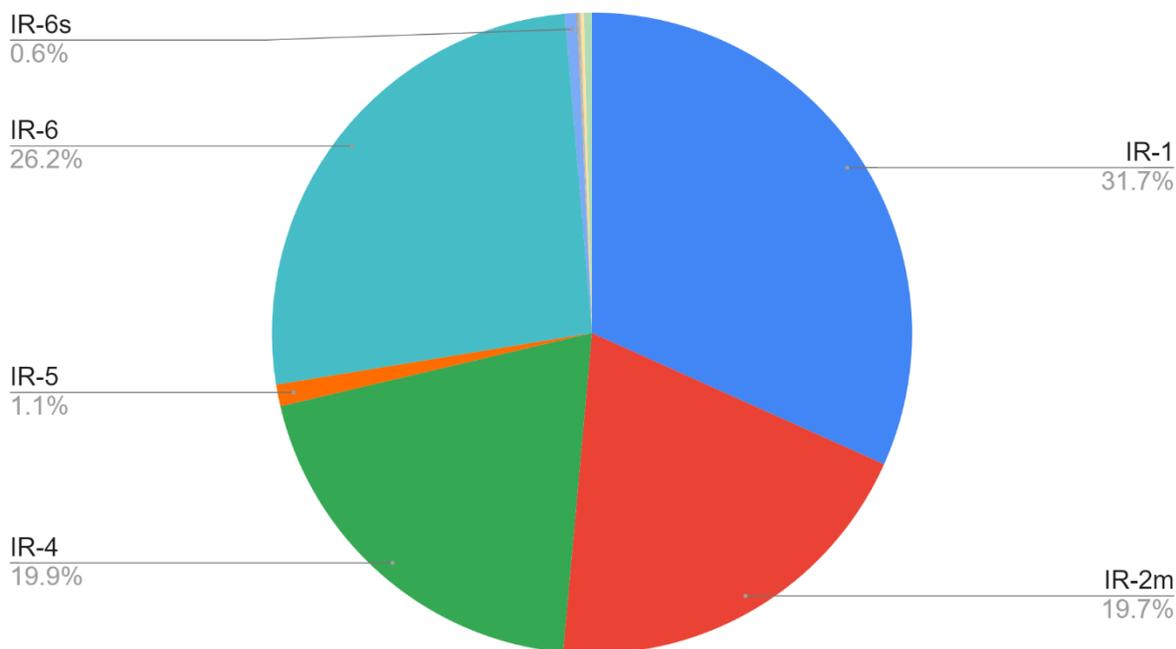


Figure 3.5. Projected distribution of enrichment capacity by centrifuge type for early to mid-2022, based on the AEOL’s announcements and domestic legal obligations, where the IR-1 centrifuges contribute only about 32 percent to the total.

Uncertainties About the Number of Advanced Centrifuges Produced

The data summarized in Figure 2.1 and provided in detail in Chapter 2 come from IAEA reports, which have proven accurate for what they represent. However, it should be borne in mind that the IAEA reports do not list the number of each type of advanced centrifuge that Iran possesses at other sites, stored or awaiting installation at the declared enrichment sites, or the number of centrifuges partially assembled. Thus, the IAEA figures underestimate the total number of advanced centrifuges in Iran’s possession. How much they underestimate is difficult to determine, using only publicly available information.

In general, Iran produces far more centrifuges than it deploys at any one time. Some of this overproduction reflects natural breakage or defects. However, for advanced centrifuges such as the IR-8, and IR-6 centrifuges, Iran had produced more than allowed under the JCPOA. According to one senior official close to the IAEA, in 2015, Iran was making three times more centrifuges than it would be allowed to have installed once the JCPOA was implemented, in essence overproducing before the deal came into force and centrifuge manufacturing was severely limited. Under the JCPOA, Iran’s total number of advanced centrifuges should have matched those allowed to be installed at Natanz for testing and should not have exceeded that

number severalfold. This discrepancy was reduced during 2016 to 2018 because of machine breakage, but the issue was never fully resolved.

One consequence was Iran's rapid deployment of IR-6 centrifuges in May 2019, when Iran immediately doubled the number of IR-6 centrifuges deployed during the JCPOA. Before even deploying the IR-2m or IR-4 centrifuges from its stock, it had 33 IR-6 centrifuges deployed, more than the up to 19 IR-6 centrifuges it had deployed at one point before the JCPOA. The question remains, were these additional centrifuges made right before JCPOA implementation? The IAEA still reported in May and August 2019 that "the declared equipment has been used for the production of rotor tubes and bellows to manufacture centrifuges only for the activities specified in the JCPOA."⁵¹ Only in November 2019 did the IAEA start to change the language to: "the declared equipment has been used for the production of rotor tubes and bellows to manufacture centrifuges not only for the activities specified in the JCPOA but also for activities beyond those specified in the JCPOA, such as the installation of the new cascades described in the previous paragraphs."⁵²

The number of deployed IR-6 centrifuges has steadily increased from August 2019 to June 2020, but dropped between June and November 2020, before increasing again. Thus, while Iran's recent deployments represent a build-back for the IR-2m centrifuge, for the IR-4 and the IR-6 centrifuges, it is a build-up.

Of the types allowed under the JCPOA, in addition to the IR-4 and IR-6, the IR-5 and IR-6s centrifuges were also a focus of production, based on deployments over the last two years. The IR-8 appears to continue to pose problems, and the IR-7 does not appear to be a current priority. Of the types not allowed under the JCPOA, the IR-s is the priority

Today, centrifuge production rates are hard to predict, because of unclear Iranian policies on the number produced versus deployed, less Iranian transparency at its centrifuge manufacturing sites, and sabotage events at some of these production facilities that have limited production. Lastly, it is unclear exactly where Iran has been assembling its advanced centrifuges after the newly inaugurated assembly facility at Natanz was destroyed, and the status of its underground replacement facility is also unclear, although it is not expected to be operational yet. Iran has stated that it had constructed a temporary assembly facility although its location and capacity are unclear from Iran's announcement.⁵³ The large, and sudden

⁵¹ Report by the Director General, *Verification and monitoring in the Islamic Republic of Iran in light of United Nations Security Council resolution 2231 (2015)*, GOV/2019/21, May 31, 2019, <https://www.iaea.org/sites/default/files/19/06/gov2019-21.pdf>; and Report by the Director General, *Verification and monitoring in the Islamic Republic of Iran in light of United Nations Security Council resolution 2231 (2015)*, GOV/2019/32, August 30, 2019, <https://www.iaea.org/sites/default/files/19/09/gov2019-32.pdf>.

⁵² Report by the Director General, *Verification and monitoring in the Islamic Republic of Iran in light of United Nations Security Council resolution 2231 (2015)*, GOV/2019/55, November 11, 2019, <https://www.iaea.org/sites/default/files/19/11/gov2019-55.pdf>.

⁵³ "Iranian Nuclear Chief Day Before Natanz Nuclear Facility Blast: We Activated IR-6 Chain [cascade]."

deployment of various types of advanced centrifuges raises questions as to how, where, and when those centrifuges were produced. These questions require answers.

Production of 60 Percent Enriched Uranium

Since April 2021, Iran has been using its advanced centrifuges at the PFEP to make 60 percent enriched uranium, a short step from weapon-grade uranium. As of early November 2021, Iran has produced a total of 17.7 kg (U mass) near 60 percent HEU. In terms of enrichment output, 60 percent enriched uranium is 99 percent of the way to weapon-grade uranium.

In addition, 60 percent enriched uranium is classified as highly enriched uranium and usable directly in nuclear weapons. The amount needed for an implosion-type nuclear explosive is no more than about 40 kg (U mass), compared to the 25 kg (U mass) of 90 percent enriched material that is often cited as more than sufficient for an Iranian nuclear weapon.

Iran has made this 60 percent by feeding two cascades of advanced centrifuges (one cascade of IR-6 centrifuges and one of IR-4 centrifuges) with near 5 percent enriched uranium and then using other cascades to re-enrich the tails to near 5 percent uranium. The penalty of this approach is that to achieve a given amount of 60 percent enriched uranium, Iran is feeding into the cascade considerably more than 5 percent enriched uranium, therefore wasting large amounts of feed compared to an “ideal cascade” where the set-up would have maximum efficiency. During the most recent IAEA reporting period spanning August to November 2021, Iran required an amount of near 5 percent LEU feed material 46 times greater than the amount it acquired as 60 percent HEU product (see Annex 5) where a feed to product ratio in an ideal cascade scenario predicts a feed amount about 16 times greater than the product.

Implications for Breakout

The JCPOA attempted to develop a list of nuclear limitations ensuring that Iran would need 12 months to breakout and produce enough weapon-grade uranium for a nuclear weapon. The Institute challenged this assertion, estimating that the true value could be as short as seven to eight months, based on the deal’s acceptance that Iran would not destroy any centrifuges, storing them under IAEA monitoring instead. (The U.S. government, when arriving at the 12-month breakout, took the position that Iran would not deploy the roughly 1000 stored IR-2m centrifuges in a breakout, preferring the redeployment of the IR-1 centrifuges only. However, time has shown that Iran did redeploy its IR-2m centrifuges preferentially, after moving to openly violate the JCPOA in 2019.)

This concession in the JCPOA means that Iran can build back its centrifuge capability by redeploying stored centrifuges. If there is a renewal of the JCPOA in 2022, the large number of advanced centrifuges in Iran’s possession—counting only those currently deployed at the three declared enrichment sites and ignoring the real possibility of additional ones in storage—

undercuts both earlier breakout estimates, resulting in a breakout time of about five to six months.

For reference, as mentioned above, Iran's breakout timeline as of November 2021 was as short as three weeks, reflecting mainly Iran's stocks of near 5 percent, 20 percent, and in particular 60 percent enriched uranium.⁵⁴ However, its stocks of advanced centrifuges would play a key role in accelerating the production of successive quantities of weapon-grade uranium for nuclear weapons. In a return to the JCPOA, these enriched uranium stocks would be expected to be eliminated or sent outside Iran, leaving the number and enrichment capacity of the stored centrifuges as the main driver of breakout timelines.

Because of the risk that Iran has accumulated a secret stock of assembled centrifuges and of undeclared sensitive centrifuge components, breakout timelines could be further reduced, absent some compensatory action, such as the IAEA's verification of Iran's declaration of advanced centrifuges, ensuring it is both complete and correct. This verification will inevitably require Iran's full cooperation, such as providing information about its activities at all locations involved in making and assembling centrifuges and the types and quantities of raw materials and equipment relevant to centrifuge production and assembly. A thorough check of Iran's relevant illicit and licit procurements for its nuclear programs since January 2016 would also contribute importantly to determining the completeness of Iran's declaration of advanced centrifuges, or at least the quantity of rotor tubes and bellows.

Potential breakout timelines in a revived JCPOA, with the acceptance of mothballing rather than destroying existing centrifuges, will be shorter than 12 months, or even the Institute's seven-to-eight-month estimate. How much shorter? To help answer that question, two scenarios are presented, a best case and a worst case, where the bounds are set by the number of advanced centrifuges Iran has deployed at the time of a negotiated deal, which is taken as the number of advanced centrifuges Iran has deployed at that time.

- **Best Case Estimates.** These estimates are based on assuming that Iran will mothball its advanced centrifuge production-scale cascades deployed as of November 2021, and it does not possess significant numbers of undeclared advanced centrifuges. Smaller cascades are ignored here. The existing production-scale cascades include six IR-2m cascades, three IR-4 cascades, and two IR-6 cascades. At the start of a breakout, Iran's stock of enriched uranium is assumed to be 300 kilograms of 3.5 percent enriched uranium, an enrichment level lower than its current level of 4.5 percent enriched uranium. During breakout, the average enrichment output of these advanced centrifuges is estimated as lower than their production-scale values discussed earlier,

⁵⁴ David Albright, Sarah Burkhard, and Andrea Stricker, "Analysis of IAEA Iran Verification and Monitoring Report – November 2021," *Institute for Science and International Security*, November 19, 2021, <https://isis-online.org/isis-reports/detail/analysis-of-iaea-iran-verification-and-monitoring-report-november-2021>; and Albright, Burkhard, and Stricker, "Analysis of IAEA Iran Verification and Monitoring Report - September 2021," *Institute for Science and International Security*, September 13, 2021, <https://isis-online.org/isis-reports/detail/analysis-of-iaea-iran-verification-and-monitoring-report-september-2021>.

significantly lower in the case of the IR-6 centrifuge cascades, reflecting breakage and other factors encountered in enriching to weapon-grade uranium. Iran is assessed as capable of re-deploying four advanced centrifuge cascades a month at its multiple enrichment sites. In this case, the breakout estimate is 6.3 months. If instead Iran possesses a stock of 300 kilograms of 4.5 percent enriched uranium, the breakout timeline drops to 5.85 months

- **Worst Case Estimates.** These estimates are based on assuming that Iran will mothball its advanced centrifuge production-scale cascades existing as of November 2021 and those solidly planned for deployment as of that date. The latter cascades are assumed completed prior to any negotiated nuclear deal. Again, smaller cascades are ignored here, and the other assumptions in the best estimates are also applied here. In this case, Iran would mothball six IR-2m cascades, seven IR-4 cascades, and six IR-6 cascades. In this case, the breakout estimate is 5.7 months, starting with 3.5 percent enriched uranium, or 5.3 months, starting with 4.5 percent enriched uranium. If Iran installs six advanced centrifuge cascades per month, two per enrichment plant, the breakout estimate is 5.1 months, starting with 3.5 percent enriched uranium, or 4.8 months, starting with 4.5 percent enriched uranium.

These calculations ignore Iran's demonstrated capability to rapidly build and deploy additional advanced centrifuge cascades, as well as its practice in skipping steps in the Khan four-step method of producing weapon-grade uranium, both allowing a quicker breakout to a first nuclear weapon and speeding up the subsequent production of enough WGU for a second, third, and fourth nuclear weapon.

Add-on measures to JCPOA mothballing procedures, such as supplementing the cascade disassembly with the removal of additional equipment, for example, electronic or power equipment, would be unlikely to significantly shift the breakout timeline, given Iran's capability to duplicate equipment at sites outside the IAEA and JCPOA verification arrangements.

Annex 1: Centrifuge Specifications and Comparisons

On July 12, 2021, a Farsi-language table circulated online, tweeted by an Iranian journalist.⁵⁵ The table, published by Etemadonline, an Iranian news website, entails information on each of sixteen different Iranian centrifuge models. The table is titled “Specification Table of 16 Iranian Centrifuges.” Figure A1.1 contains the original Farsi table and the translation by the Institute. In this report, it is often referenced as the “Iranian table.”

This table is undated, but it may be from the end of 2019 to the first part of 2021, based on information in the table. In addition, the information in the table is sometimes incomplete or inaccurate, as is discussed in the body of the report.

The table dedicates one row each to 16 different Iranian centrifuge models, beginning with Iran’s oldest model, the IR-1. After the IR-2m follow the IR-3, IR-4, IR-5, five different IR-6 models, IR-7, three different IR-8 models, the IR-s, and the IR-9. The IR-2 centrifuge is not included in the table. For most of these centrifuge models, the year of manufacturing is given as Persian year 1398, which represents the timespan between March 21, 2019, to March 20, 2020. For the IR-5, the year is given as six years earlier, the IR-8 eight years earlier, the IR-6 ten, IR-4 eleven, IR-2m thirteen, and for the IR-1 as eighteen years earlier, March 21, 2001, to March 20, 2002. For the IR-3, the year is missing. The accuracy of the manufacturing data is in several cases difficult to reconcile with publicly available information.

Table A1.2 compares the values from the more official 2015 declared Iranian values and those in Table A1.1. Blank cells in this table represent missing data.

The enrichment output data in Table A1.1 is a mixture of theoretical and measured values, with no identification of which is which. However, a comparison to the 2015 declared data helps to distinguish between theoretical and measured values in Table A1.1. The values for the IR-2m and IR-4 centrifuges in Table A1.1 appear to be measured values, possibly in production-scale cascades, while the IR-6 and IR-3 centrifuge values appear to be single machine measured ones. The IR-5, IR-6s, IR-7, and IR-8 centrifuges appear to have theoretical values and by implication the IR-6m, IR-6sm, IR-8s, IR-8B, IR-s, and IR-9 centrifuges also likely have theoretical values.

Based on comparing values in Table A1.2, the enrichment output of the IR-2m and IR-4 centrifuges is assessed as 3.67 and 3.3 SWU per year, respectively, in the important case of production-scale cascades. Iran uses this type of cascade to produce significant amounts of enriched uranium. The equivalent value for the IR-6 centrifuge is harder to discern, but a value of approximately 5.25 SWU per year is assessed and appears reasonable. More details of these estimates are in the main text of the report.

⁵⁵ Tweet by @SaraMassoumi, July 12, 2021, <https://twitter.com/saramassoumi/status/1414468113886760960?s=21>.

جدول مشخصات ۱۶ سانتریفیوژ ایرانی

ردیف	نام سانتریفیوژ	میزان حدودی ظرفیت فنی ستری (سو) بر اساس UF6	سال ساخت	مرحله ساخت	ویژگی خاص	توضیحات
۱	IR-1	۱	۱۳۸۰	تولید انبوه	اولین ماشین غنی سازی ایران	هم اکنون بیش از ۱۶ هزار عدد از این ماشین در مراکز غنی سازی یا انبارهای ایران موجود است
۲	IR-2M	۵٫۵	۱۳۸۵	تولید نیمه صنعتی	اولین ماشین پیشرفته ایران که هزار عدد از آن ساخته شده است	
۳	IR-3	۲٫۵		تحقیقات	یک سانتریفیوژ به صورت تک ماشین و یک زنجیره ۱۰ تایی آزمایش شده است	
۴	IR-4	۵٫۵	۱۳۸۷	آماده تولید انبوه است	اولین ماشین بیلوز کامپوزیتی	سه عدد از این ماشین هادر مرکز جدید تحقیق و توسعه ایران در تهران مشغول آزمایش مکانیکی هستند سه بیلوز دارد و از خانواده IR-4 به حساب می آید کاملاً بومی
۵	IR-5	۱۰	۱۳۹۲	زنجیره ۱۰ تایی در سالن ۸۸ در حال تحقیق است	۱۱ عدد از این ماشین موجود است	
۶	IR-6	۱۰	۱۳۸۸	زنجیره های ۱۰ تایی، ۲۰ تایی و ۳۰ تایی در حال تحقیق هستند	این ماشین با ارتفاع کم خود می تواند در آینده نزدیک جایگزین خوبی برای ماشین های نسل اول باشد	
۷	IR-6M	۱۲	۱۳۹۸	تک ماشین		
۸	IR-6SM	۸	۱۳۹۸	تک ماشین		
۹	IR-6SMO	۱۲ عدد در مجموع ۷۰ سو	۱۳۹۸	از زنجیره ۱۲ تایی IR-6S تشکیل شده		
۱۰	IR-6S	۶	۱۳۹۸	زنجیره ۲۰ تایی و تک ماشین	بدون بیلوز است	از خانواده IR-6 به یکی از آن ها گاز دهی شده است. کاملاً بومی بوده و از خانواده IR-6 به شمار می رود
۱۱	IR7	۲۰	۱۳۹۸	دو عدد به صورت تک ماشین	سه بیلوز و سه متر طول دارد	
۱۲	IRS	۲۴	۱۳۹۰	سه ماشین تک	۳٫۵ متر ارتفاع دارد	
۱۳	IRSS	۹	۱۳۹۸	تک ماشین تحقیقاتی		از خانواده IR-8
۱۴	IRSB	۱۵	۱۳۹۸	تک ماشین تحقیقاتی		از خانواده IR-8
۱۵	IRS	۱۲	۱۳۹۸	تک ماشین نمونه	ماشین تحت بحرانی	
۱۶	IR9	۵۰	۱۳۹۸	تک ماشین نمونه	۵٫۵ متر ارتفاع دارد و جدیدترین ماشین ایرانی است	۲۰۰ هزار خط برای نرم افزارش نوشته شده و صرفاً ۱۰۰ آن ایرانی است

میزان سو بر اساس هگزافلوراید اورانیوم (UF6) غنی شده حساب شده و برای تبدیل به اورانیوم غنی شده باید بر ۱٫۴۷ تقسیم کرد.

Specification Table of 16 Iranian Centrifuges

Comments	Special Characteristic	Production Stage	Year of Manufacturing **	Approximate Amount of Enrichment Capacity (SWU) Based on UF6 %	Centrifuge Name	No.
Currently, more than 16,000 of these machines are available in enrichment centers or warehouses in Iran	Iran's first enrichment machine	Mass production	1380	1	IR-1	1
	Iran's first advanced machine, which a thousand of it have been made	Semi-industrial production	1385	5.5	IR-2M	2
	A centrifuge has been tested as a single machine, and a cascade of 10	Researches		2.5	IR-3	3
Three of these machines are being mechanically tested at the new Iran Research and Development Center in Tehran	The first Composite Bellows machine	Ready for mass production	1387	5.5	IR-4	4
It has three Bellows and belongs to the IR-4 generation	There are 11 of these machines	A cascade of 10 is being researched in S8 Hall	1392	10	IR-5	5
Fully indigenous	This machine, with its low height, can be a suitable replacement for first-generation machines in the near future	Cascades of 10, 20, and 30 are being researched	1388	10	IR-6	6
		Single machine	1398	12	IR-6M	7
		Single machine	1398	8	IR-6SM	8
From the IR-6 generation	It is without Bellows	Includes a cascade of twelve IR-6S	1398	12, overall 70 SWU	IR-6SMO	9
		A cascade of 20 single machines	1398	6	IR-6S	10
One of them has been injected with gas. It is fully indigenous and belongs to the IR-6 generation	It has three Bellows and three meters (9.84 feet) in length	Two as a single machine	1398	20	IR7	11
	It is 3.5 meters (11.48 feet) high	Three single machines	1390	24	IRS	12
From the IR-8 generation		Single research machine	1398	9	IRSS	13
From the IR-8 generation		Single research machine	1398	15	IRSB	14
	Subcritical machine	Single sample machine	1398	12	IRS	15
100,000 lines have been written for its software, and zero to 100 of it is Iranian ***	It is 5.5 meters (18 feet) high and is the newest Iranian machine	Single sample machine	1398	50	IR9	16

* The amount of SWU is calculated based on enriched Uranium Hexafluoride (UF6) and to convert to enriched Uranium must be divided by 1.47.

** "Year of Manufacturing" Conversion:

Persian Year [1380] = The Gregorian Calendar Year [March 21, 2001 - March 20, 2002]
 Persian Year [1385] = The Gregorian Calendar Year [March 21, 2006 - March 20, 2007]
 Persian Year [1387] = The Gregorian Calendar Year [March 21, 2008 - March 20, 2009]
 Persian Year [1388] = The Gregorian Calendar Year [March 21, 2009 - March 20, 2010]
 Persian Year [1390] = The Gregorian Calendar Year [March 21, 2011 - March 20, 2012]

Table A1.1. Top: The table in Farsi. Bottom: Institute translation into English. (Translator's note: Chain is often used in Farsi translations instead of cascade.)

Table A1.2 Comparison of Enrichment Output of Iran’s Major Centrifuges—Values in Iran’s 2015 Declaration vs. More Recent Iranian Table

(Units are kg U SWU/year; units in parentheses are equivalent kg UF₆ SWU/year)

	IR-1	IR-2	IR-2M	IR-3	IR-4	IR-5	IR-6	IR-6s	IR-6m	IR-6sm
Separative Work Theoretical-2015 declaration	1.4	2.0	4.7	2.0	4.4/4.9/6.0	6.8	8.1	4.1		
Separative Work, Single machine, measured (2015)		1.8	4.1	1.8	3.8	6.1	6.8	3.5		
Separative Work, in large cascade, meas. (2015)	0.9		3.67							
Separative Work-Iranian Table	0.68 (1)		3.7 (5.5)	1.7 (2.5)	3.7 (5.5)	6.8 (10)	6.8 (10)	4.1 (6)	8.1 (12)	5.4 (8)

	IR-7	IR-8	IR-8s	IR-8B	IR-s	IR-9
Separative Work Theoretical-2015 declaration	11.5	16.2				
Separative Work-Iranian Table	13.5 (20)	16.2 (24)	6.1 (9)	10.1 (15)	8.1 (12)	33.8 (50)

Comments:

The units in the table are SWU per year, with those in parentheses kg UF₆ SWU per year. The conversion factor from hexafluoride units to uranium units is 0.676. The values in parenthesis are taken directly from the Iranian table and converted to units of SWU per year. For clarity, the values from the Iranian table are highlighted in yellow.

Blank cells in the data from 2015 represent unavailable data or represent centrifuge types that either Iran did not declare, or it developed after the implementation of the JCPOA in January 2016

Annex 2: The Centrifuge Bellows

The bellows is the name of an important part in a Zippe-type centrifuge, allowing the rotor assembly to bend slightly as it speeds up to its operational speed or slows down during a shutdown. This bending is caused by resonances produced in a solid rotating tube, similar in principle to a vibrating string, that reaches its flexural critical speeds. These rotor speeds are defined by the rotor's length, diameter, and material properties. At each flexural critical speed or frequency, a solid tube will start to bend, first into a banana shape, then at a higher speed into a figure eight shape, and so on. Given that the rotor assembly is solid, if it does not bend or otherwise compensate for the distortion caused by the resonance, it will break. The bellows in a Zippe-type centrifuge is what allows for that important bending, avoiding the rotor tube's destruction. U.S. and South African centrifuges addressed this problem differently.

There are other resonances encountered by a centrifuge rotor assembly after it starts spinning, alleviated by using flexible bearings and careful straightening and balancing of rotor assemblies, for example. Centrifuges are typically designed to encounter these types of resonances at lower rotational frequencies, i.e. lower wall speeds, say at less than 100 Hertz (Hz), where rotor straightening, and careful balancing combined with the centrifuge's damping systems reduce the amplitude of the resonance.

The bellows, essentially a convolution either in a separate component or in the rotor tube itself, provides a mechanism for bending and avoiding the damage at flexural critical speeds. Figure A2.1 shows a bellows where the convolution is in a separate piece. The bellows of a Pakistani P2 centrifuge has the convolution integral to the rotor tube; this method was also used in the case of Indian maraging steel centrifuges of the 2000s.

There are three basic types of Zippe-type centrifuge rotor assemblies:

- Subcritical rotor assembly—a single tube that operates below the first flexural resonance. A rule of thumb is that the ratio of the length to diameter should be less than five to ensure the centrifuge remains subcritical.
- Homogeneous supercritical rotor assembly—a single tube that traverses flexural resonances to reach operational speed. South Africa was developing a Zippe-type centrifuge of this type; Iran has apparently not done so.
- Non-homogeneous supercritical rotor assembly—a stack of subcritical tubes joined by a flexible bellows.

Iran's IR-1 and advanced centrifuges are in the first and third bullets.



Figure A2.1. A bellows from a Pakistani P1 centrifuge, which is the same as, or similar to, an IR-1 bellows.

Annex 3: Upper Limit Theoretical Enrichment Output

Theoretical centrifuge models remain complex, particularly in predicting the enrichment output of centrifuges, or more precisely their rate of separative work or separative power. Older theories, such as those proposed by Paul Dirac and Karl Cohen predict that the maximum separative output of a gas centrifuge is proportional to two key variables: length and the rotor wall velocity raised to the fourth power.⁵⁶ (The enrichment output does not depend directly on a centrifuge’s diameter, although it can depend indirectly on it, as discussed in the text.)

However, in practice at the wall speeds encountered in centrifuge programs, the output is proportional to velocity squared rather than the fourth power of velocity. An approximation of output involving the square of the velocity can be derived, giving upper bound values of the enrichment output. Without data from the use of uranium hexafluoride and more data about the centrifuges, however, estimates are upper bounds of enrichment outputs.

The following formula was developed at the request of the Institute by Dr. Patrick Migliorini, an engineer and former consultant to the Institute when he was at the University of Virginia, for the upper limit on predicted separative power of a counter-current gas centrifuge, δU :⁵⁷

$$\delta U = \frac{HV^2}{43882} \text{ (kg U SWU/yr)} \quad (1)$$

where H is the separative length, or effective length, of the centrifuge in meters, V is the rotor wall speed in meters per second, and the centrifuge operates at an average temperature of 300 K.⁵⁸ Table A3.1 lists several results, for differing effective lengths and rotor wall speeds of Iran’s advanced centrifuges.

⁵⁶ Karl Cohen, edited by George M. Murphy, *The Theory of Isotope Separation as Applied to the Large Scale Production of U235* (New York: McGraw Hill Books, 1951), republished in 2015 by ISHI Books International, available at Amazon, <https://www.amazon.com/Theory-Isotope-Separation-Applied-Production/dp/487187706X>.

⁵⁷ The derivation of this formula can be found in: Institute for Science and International Security, “Centrifuge Research and Development Limitations in Iran,” August 29, 2014, <http://isis-online.org/isis-reports/detail/centrifuge-research-and-development-limitations-in-iran/8>.

⁵⁸ A later, more rigorous derivation of a similar formula can be found in: Sergey Bogovalov and Vladimir Borman, “Separative Power of an Optimised Concurrent Gas Centrifuge,” *Nuclear Engineering and Technology* 48 (2016), 719-726. At 300 K, the equation is the same, except the coefficient is 38,583.

Table A3.1: Approximate Upper Limit on Predicted Separative Power of Selected Gas Centrifuges

Centrifuge	Effective Length (m)	Rotor Wall Speed (m/s)	Separative Power (kg U SWU/yr)
IR-2m ("target")	1.05	700	11.7
IR-2m	1.05	482	5.6
IR-4	1.11	446	5.0
IR-6	1.10	565	8.0
IR-8	3.0	500?	17.1
IR-s	0.65	735?	8.0

Note: It should be noted that the effective length, which is shorter than the total rotor length, is given roughly in this table; actual values are not publicly known and may differ somewhat from these values. But the results are not substantially affected.

Annex 4: Major Components of Centrifuges and Material Properties

The maximum peripheral velocity of a thin-walled cylinder is given as the square root of the ratio of the tensile stress of the rotor material to its density. The table below lists the values for several common centrifuge rotor materials. More typical operational speeds are also given, representing the practice of often picking an operational speed significantly below the maximum. One exception is maraging steel.

Table A4.1: Rotor Material Properties Define Wall Speed

Rotor Material	Tensile Strength (M Pa)	Density (Kg/m³)	Max. Peripheral Velocity (m/sec)	Rotor Operational Velocity (m/sec)
Aluminium alloy	550	2800	445	~350
Titanium alloy	980	4550	464	~ 400
Maraging steel	2100	8080	510	~ 480
Glass composite	1100	2130	718	~ 550
Kevlar composite	1000	1340	865	~ 600
Carbon composite	1630	1530	1000	~700?

Annex 5: Feed to Product Ratios of Enriched Uranium

Since its May 2021 quarterly report, the International Atomic Energy Agency has been reporting the amounts of enriched uranium feed used to enrich uranium to higher levels at the three enrichment plants. With the amount of feed, product, and tails given separately, one can in principle verify the mass balance and gain additional insight, particularly into discrepancies in the mass balance and the feed to product ratio for different enrichment levels and different types of centrifuges. Comparing these numbers over time may be indicative of the efficiency of enriched uranium production—especially highly enriched uranium production—as well as the efficiency of different types of centrifuges.

At the Natanz Fuel Enrichment Plant, Iran usually uses natural uranium feed, for which the amounts are not reported by the IAEA. However, during one recent reporting period, between May 22, and August 27, 2021, Iran used 2 percent enriched uranium as feed material to produce up to 5 percent enriched uranium at the FEP. Specifically, the IAEA reported that it fed 2090 kg (hex mass) of 2 percent enriched uranium and produced 746.9 kg (hex mass) 5 percent enriched uranium. Since an unreported amount of natural uranium was also used as feed material, the feed to product ratio was *at best* 2.8. The IAEA also reported that 170 kg of near 2 percent enriched uranium were dumped from the cascade due to emergency shutdowns, a quantity representing 8 percent of the enriched uranium feed. With the inability to separate the feed among the IR-1, IR-2m, and IR-4 centrifuges at the FEP, one cannot draw any conclusions about either of these types of centrifuges.

The situation with respect to near 20 and 60 percent enriched uranium is clearer. At the Fordow Fuel Enrichment Plant, Iran has used 382.4 kg (hex mass) of near 5 percent enriched uranium to produce 61 kg (hex mass) near 20 percent enriched uranium between February 16 and May 21, 2021, and 444.3 kg (hex mass) of near 5 percent enriched uranium to produce 61.5 kg (hex mass) of near 20 percent enriched uranium between May 22 and August 29, 2021. During the latest reporting period, from August 30 to November 5, 2021, Iran fed 310.8 kg (hex mass) of near 5 percent enriched uranium into the cascades and produced 43.7 kg (hex mass) of near 20 percent enriched uranium. The amounts of feed and product for the three production periods result in feed to product ratios of 6.3, 7.2., and 7.1 respectively. The higher numbers during the last two periods reflect decreased efficiency. Indeed, between May and August, the relevant IAEA report lists that 34.3 kg of near 5 percent LEU were dumped, representing 7.7 percent of the feed material. Between August and November, a smaller amount of 4.5 kg were dumped, representing 1.4 percent of the feed material, and indicating that dumped material is not the only explanation for decreased efficiency.

At the PFEP, the feed amount is only reported for those R&D lines that produce 60 percent HEU, as the remaining lines use the tails resulting from the production of 60 percent enriched uranium or natural uranium as their feed. On April 17, 2021, lines 4 and 6, hosting one cascade of IR-4 and one cascade of IR-6 centrifuges respectively, were both fed with near 5 percent enriched uranium to produce 60 percent HEU. This was changed after only one day to produce

60 percent only in the IR-6 cascade in line 6. During the time period from April 17 to May 3, 2021, Iran used a total of 100.2 kg near 5 percent enriched uranium (hex mass) to produce just 2 kg near 60 percent HEU (hex mass). This represents a feed to product ratio of 50. A 2.5 kg discrepancy (hex mass) in the mass balance (the mass of the product and tails combined should equal that of the feed) was also noted, possibly indicating that 2.5 kg ended up in the dump tank, which in this time period would represent 5 percent of the feed.

The feed to product ratio improved significantly for the period between May 4 and May 21, 2021, where 57.7 kg (hex mass) near 5 percent enriched uranium were used to produce 1.6 kg (hex mass) near 60 percent HEU, for a ratio of 36. This ratio increased only slightly between May 22, 2021, and August 29, 2021, where it was 37.8, as Iran used 427.2 kg near 5 percent enriched uranium (hex mass) to produce 11.3 kg near 60 percent HEU (hex mass). Towards the end of the time period, on August 15, 2021, Iran re-started the use of the IR-4 centrifuge cascade in line 4 to also produce 60 percent HEU, which it continued to do during the most recent reporting period of August 30 to November 5, 2021. During this period, the feed to product ratio increased again to 46, as Iran used 526.3 kg near 5 percent enriched uranium (hex mass) to produce 11.4 kg near 60 percent HEU (hex mass), raising the question whether the IR-4 cascade is the reason for the higher feed to product ratio.