INSTITUTE FOR SCIENCE AND INTERNATIONAL SECURITY

Updated Highlights of Comprehensive Survey of Iran's Advanced Centrifuges[1]

By David Albright, Sarah Burkhard, and Spencer Faragasso

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Photo Credit: Iran's AFTAB News

[1] David Albright, Sarah Burkhard, and Spencer Faragasso, "A Comprehensive Survey of Iran's Advanced Centrifuges," *Institute for Science and International Security*, December 2, 2021, https://isis-online.org/isis-reports/detail/a-comprehensive-survey-of-irans-advanced-centrifuges/8.

Background

- This report summarizes and assesses information in the International Atomic Energy Agency's (IAEA) quarterly report for November 10, 2022, *Verification and monitoring in the Islamic Republic of Iran in light of United Nations Security Council resolution 2231 (2015),* including Iran's compliance with the Joint Comprehensive Plan of Action (JCPOA) and updates issued on November 22 and 29, 2022.
- Iran continues to deploy advanced centrifuges at its three enrichment facilities at Natanz and Fordow in violation of the limitations outlined in the JCPOA.
- Under a revived JCPOA, Iran would be permitted to mothball its advanced centrifuges, shortening Iran's breakout timeline and increasing its ability to build up its capability should the deal collapse or once enrichment capacity restrictions phase out starting in 2025.
- Iran continues to sideline the IAEA and has significantly reduced its ability to monitor Iran's complex and growing nuclear program, which notably has undeclared nuclear materials and activities. The IAEA's ability to detect diversion of nuclear materials, equipment, and other capabilities to undeclared facilities remains greatly diminished. In a recent press conference, as reported by the *Jerusalem Post*, IAEA Director General Grossi stated there is a "mass of activity about which we don't know anything."

Findings

- Since the last quarterly report in September, based on data in the most recent quarterly report, Iran installed 1740 advanced centrifuges, all at the Natanz Fuel Enrichment Plant (FEP). Of these, 1566 are IR-2m centrifuges, organized in nine cascades. The rest were IR-4 centrifuges, in one cascade. These deployments represent a huge jump in the number of installed advanced centrifuges.
- Iran's annual deployment rate of advanced centrifuges during this year (November 2021 - November 2022) has increased by over 50 percent compared to the last year (November 2020 - November 2021) and quadrupled from the two years prior combined (November 2018 - November 2020).
- The origin of the newly deployed IR-2m centrifuges could not be determined. They may have been produced since 2018 or produced prior to 2016. In the former case, Iran may have greatly expanded its advanced centrifuge production rate. In the latter case, Iran would have retrieved them from a secret storage location not declared under the rules of the Joint Comprehensive Plan of Action (JCPOA). The latter case would confirm a long-held suspicion that prior to the JCPOA, Iran had manufactured 3000 IR-2m centrifuges for installation at the FEP but only installed about 1,000 of them, hiding the rest.
- As of the November 2022 quarterly report, Iran had 4515 advanced centrifuges of all types installed at its three enrichment facilities at Natanz and Fordow as well as 7135 installed IR-1 centrifuges.

- At the Fordow Fuel Enrichment Plant Fordow (FFEP), Iran has announced the installation of 14 IR-6 centrifuge cascades, where six IR-6 cascades would replace six currently operating IR-1 centrifuge cascades, and result in a total of 16 IR-6 cascades, or 2656 centrifuges, present at Fordow.
- On November 20, Iran began at the FFEP to use IR-6 centrifuges to produce 60 percent enriched uranium from 5 percent feed. This suggests that Iran continues to experiment with a three-step process towards weapon-grade uranium. Traditionally, a four-step process is used to enrich natural uranium to weapon-grade levels. A three-step process enables Iran to produce weapon-grade uranium in a more compact and efficient manner, making a potential breakout to a nuclear weapon faster. It also suggests that the IR-6 emerged as Iran's centrifuge of choice for HEU production; a worrisome choice as compared to the IR-1, IR-2m, or IR-4. It is the type it would need fewest of for a secret enrichment plant of high capacity, the type for which few design details are available, and the number of which Iran has made is completely unknown.
- At its Natanz FEP, Iran intends to install another 18 cascades at the FEP, of which it specified six to be IR-4 centrifuge cascades and six to be IR-2m centrifuges; the remaining six cascades are of yet unspecified type. Installation of these centrifuges has not started as of November 20, 2022.
- As of November 2022, Iran has exceeded the Institute's September projection of advanced centrifuge deployments for late 2022, 4440 centrifuges, by 75 advanced centrifuges.
- Based on new Iranian plans reported by the IAEA on November 22, the Institute projects that Iran now plans on deploying about 4934 additional advanced centrifuges, reaching a total of 9449 advanced centrifuges. Iran did not provide a schedule of deployments and the Institute considers this at least a one or two year deployment plan, based on current understandings of Iran's ability to manufacture and assemble centrifuges.
- Iran currently has a total installed nominal enrichment capacity of approximately 24,500 SWU per year, where advanced centrifuges account for 18,000 SWU per year and IR-1 centrifuges account for about 6400 SWU per year. This exceeds for the first time any previously installed enrichment capacity, including before the JCPOA, with only one-quarter of the number of centrifuges.
- Iran's installed advanced centrifuge enrichment capacity has exceeded its installed capacity of its IR-1 centrifuges since February 2021 and advanced centrifuges currently account for almost 75 percent of the total installed enrichment capacity.
- As of November 20, 2022, Iran started to install the fourth of a set of six long-announced cascades of IR-4 centrifuges at Natanz FEP.

- A centrifuge assembly facility continues to be constructed underneath a mountain near the Natanz FEP, but its startup date remains uncertain, and is unlikely to be operational in 2022 or even 2023.[2]
- Since June 2022, the IAEA has had no ability to monitor Iran's centrifuge manufacturing or assembly rate, old or new centrifuge stocks, stocks of critical parts and material, or potential diversion of such stocks or manufacturing capabilities to unknown sites. The IAEA has reiterated its concerns about the completeness of the information it has from Iran and its ability to accurately verify Iran's declared centrifuges. With Iran accelerating its advanced centrifuge deployments, uncertainties will likely grow in the estimated number of advanced centrifuges produced in excess of those deployed, adding concern to the possibility that Iran will again seek to build a clandestine enrichment plant, using advanced centrifuges manufactured in secret.

Advanced Centrifuge Deployments

In the last three years, Iran has been deploying advanced centrifuges in violation of the limits in the Joint Comprehensive Plan of Action (JCPOA), following a lull of three years created by those limits. Starting in late 2020 or early 2021, it dramatically increased the number of deployed advanced centrifuges, with deployment rates skyrocketing after August 2022, when it deployed ten advanced centrifuge cascades at a rate of about one per week. Since then, Iran has made additional announcements, with its latest plans reported by the IAEA on November 22, 2022, calling for the installation of additional 29 advanced centrifuge cascades, or about 4934 centrifuges. Iran has clearly demonstrated its commitment to deploy advanced centrifuges, which can produce considerably more enriched uranium than the first-generation IR-1 centrifuge.

Iran has been deploying advanced centrifuges at three enrichment plants–the Natanz above-ground Pilot Fuel Enrichment Plant (PFEP), the much bigger, below-ground Natanz Fuel Enrichment Plant, and the deeply buried Fordow Fuel Enrichment Plant. Its recent jump in deployments means Iran is moving towards achieving its long-announced plan of having a total installed enrichment capacity of 125,000 SWU per year. Iran's deployments have focused on its three most successful advanced centrifuge types: the IR-2m, IR-4, and IR-6 centrifuges.

Figure H.1 shows the number of advanced centrifuges deployed from 2011 onwards through November 2022, with a new, greatly increased projection, based on Iran's most recent announcements.[3] With the visible jump in the number of deployed centrifuges following

[2] David Albright and Sarah Burkhard, "Imagery Update: Iran Adds Expected Fourth Tunnel Entrance to its Natanz Tunnel Complex," *Institute for Science and International Security,* November 9, 2022, https://isis-online.org/isis-reports/detail/imagery-update-iran-adds-fourth-tunnel-entrance-to-its-natanz-tunnel.

[3] David Albright, Sarah Burkhard, Spencer Faragasso, and Andrea Stricker, "Analysis of IAEA Iran Verification and Monitoring Report - November2022," *Institute for Science and International Security,* November 16, 2022, https://isis-online.org/isis-reports/detail/analysis-of-iaea-iran-verification-and-monitoring-report-november-2022 ; IAEA Director General, *Verification and monitoring in the Islamic Republic of Iran in light of United Nations Security Council resolution 2231 (2015)*, GOV/2022/24, November 22, 2022.

August 2022, as of November 2022, Iran had exceeded our earlier projection for the end of 2022, based on Iran's earlier plans, by 75 centrifuges. Our new projection, based on Iran's new plans announced to the IAEA on November 20, 2022, calls for the deployment of about 4934 new advanced centrifuges, bringing the projected total to 9449 advanced centrifuges.

The centrifuges installed since August 2022 are primarily IR-2m centrifuges, about 1566 centrifuges in number, meaning that Iran has now close to 2700 IR-2m centrifuges installed across its three enrichment plants Iran also completed installation of one IR-4 cascade at the FEP for an estimated total of 686 IR-4 centrifuges installed. As reported by the IAEA on November 22, 2022, it also started installation of another, its fourth IR-4 cascade at the FEP. No new IR-6 centrifuges had been or were being installed after the end of August 2022 and as of November 20, 2022, thus that number remains at 1018 centrifuges.

Because of unclear Iranian practices regarding the number of advanced centrifuges produced versus deployed, and less Iranian transparency at its centrifuge manufacturing and assembly sites since February 2021, it is difficult to estimate to what extent the recent advanced centrifuge deployments reflect increased manufacturing and assembly capacity or deployments of stored IR-2m centrifuges not disclosed earlier. But the deployments are substantial and suggest a large source of advanced centrifuges, whether newly made or taken from a secret storage location. Iran may have largely recovered from attacks on its advanced centrifuge manufacturing and assembly capabilities in 2020 and 2021 and in doing so expanded its manufacturing and assembly capability. The destroyed plants included the Natanz Iran Centrifuge Assembly Center (ICAC) and a key workshop at the centrifuge manufacturing plant at a site called TABA Karaj (also known as TESA), situated near Karaj. The ICAC was built to have a capacity to make an estimated 8000 advanced centrifuges per year. After the attacks, Iran's manufacturing and assembly capacity appears to have been substantially reduced, down to a level of several hundred advanced centrifuges per year. A temporary assembly facility was inaugurated at Natanz in April 2021, about nine months after the attack on the ICAC. Shortly afterwards, an attack occurred on Iran's centrifuge manufacturing capabilities at Karaj. Iran subsequently moved manufacturing capabilities to Natanz and to an unknown site at or near Esfahan. But it is unclear if these new capabilities provide Iran the ability to make thousands of centrifuges each year, complicating any explanation of the large deployment of IR-2m centrifuges since August 2022. Further, it remains unknown how Iran plans to make the nearly 5000 additional advanced centrifuges called for in its recent announcement.

With Iran accelerating its advanced centrifuge deployments, uncertainties will likely grow in the estimated number of advanced centrifuges produced in excess of those deployed, adding concern to the possibility that Iran will again seek to build a clandestine enrichment plant, using advanced centrifuges manufactured in secret.

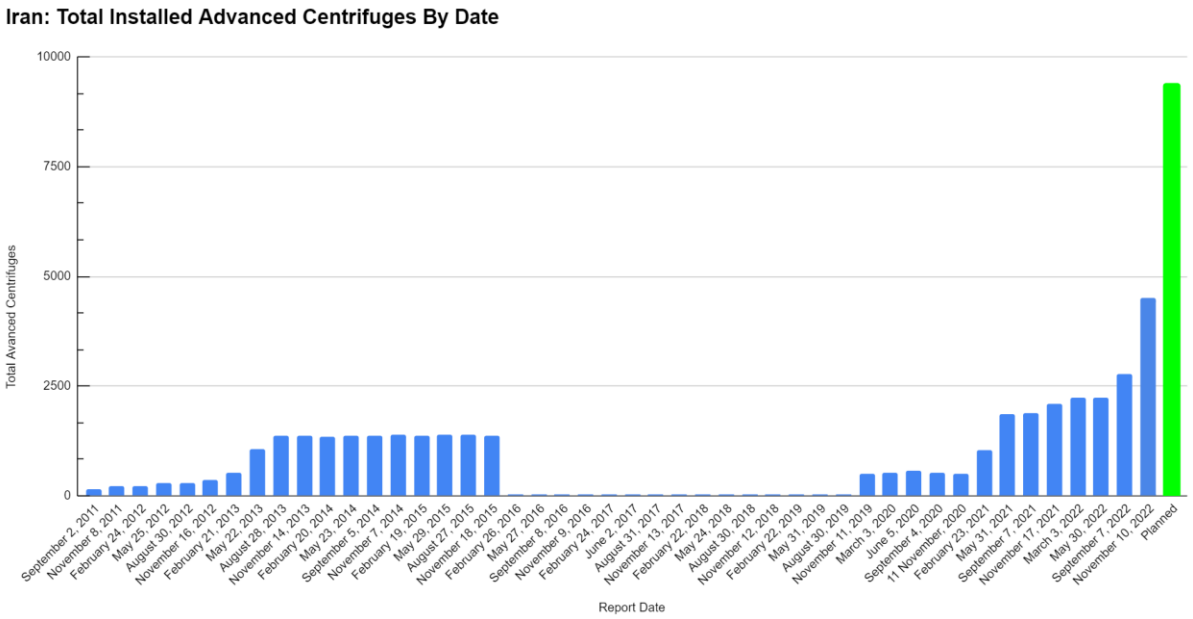


Figure H.1. Iran's quarterly number of installed advanced centrifuges at its three enrichment plants, with a projection without a specified schedule, but likely spanning more than one year, perhaps 2023 and 2024 (last vertical bar). (The number of IR-1 centrifuges are ignored in this graph but see Figure H.3 for a complete breakdown of the situation today.) Planned in the context of this graph means firmly announced plans filed with the IAEA; it does not reflect Iran's long-term plan to deploy sufficient centrifuges to have a total enrichment capacity of 125,000 SWU/year.

Closer Look at the Numbers

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 following the U.S. withdrawal from the deal, but at a faster rate than prior to the JCPOA, reaching unprecedented deployment levels in May 2021 after a sharp increase after late 2020. For a year and a half now, the number of deployed advanced centrifuges has exceeded the number deployed prior to the JCPOA. As of November 2021, Iran had approximately 2101 advanced centrifuges installed at its three enrichment plants. A year later, by the end of November 2022, the total number had more than doubled to 4515.

Table H.1 shows that since November 2018 (ignoring advanced centrifuges installed earlier), Iran has installed a total of 4474 advanced centrifuges, deploying multiple cascades of IR-2m, IR-4, and IR-6 centrifuges, some taken from storage, many newly made, and a variety of other advanced centrifuges in partial cascades. The first full cascades of advanced centrifuges were deployed after August 2019, followed by a lull in deployments for most of 2020, before almost 1600 advanced centrifuges were installed between November 2020 and November 2021. Over

half of the roughly 4500 currently installed advanced centrifuges–2414 advanced centrifuges–were installed over the last year, between November 2021 and November 2022, with 1740 advanced centrifuges installed within a couple of months between the end of August and the end of October.

Table H.1 Advanced Centrifuge Deployment, Year Over Year, and Monthly Average

Time Period (One Year)	Advanced Centrifuges Added Over One Year Period	Monthly Average
Nov 2018 - Nov 2019	454	38
Nov 2019 - Nov 2020	17	1.4
Nov 2020 - Nov 2021	1589	132
Nov 2021 - Nov 2022	2414	201

Table H.1. Yearly advanced centrifuge deployment numbers and monthly average across all three enrichment facilities.

Iran has continued to reiterate its determination to increase the number of deployed advanced centrifuges over the next several months. On November 19, 2022, Iran announced that it intends to deploy six additional cascades of IR-2m and six additional cascades of IR-4 centrifuges at Natanz FEP. Iran also intends to install another six cascades of yet unspecified type. The 12 specified cascades alone would represent an increase in advanced centrifuges at the FEP of 2088 to a new total of 6264 total advanced centrifuges at FEP.

At the Fordow Fuel Enrichment Plant no new advanced centrifuges have been installed since the last reporting period, but a dramatic announcement has been made: Iran intends to almost fully outfit the plant with IR-6 centrifuges only, replacing the six IR-1 cascades currently present and installing 14 IR-6 centrifuge cascades, for a total of 16 IR-6 cascades containing an estimated 2656 centrifuges at the FFEP. Another recent development is that Iran started enriching uranium to 60 percent HEU in the two IR-6 centrifuge cascades already installed at the FFEP.

On November 29, 2022, the IAEA reported that Iran announced plans to install additional IR-2m, IR-4, and IR-6 centrifuges in line 5 at the PFEP, however, no numbers were given publicly. Line 5 currently holds 18 IR-1 and 33 IR-2m centrifuges, although these numbers have been last reported in a quarterly IAEA report from November 2021. This line is designed to hold roughly 165-170.

IR-2m, IR-4, and IR-6 Centrifuges

The most important advanced centrifuges today are the IR-2m, IR-4, and IR-6 centrifuges. With the November 20, 2022 announcements, it is hard to identify a clear centrifuge type of choice, although the IR-4 has been deployed at a slower rate than the IR-2m and IR-6, and in total fewer IR-4 centrifuges are planned.

One way to see the importance of these three centrifuges is to consider that they can replace the IR-1 centrifuges while utilizing the same existing cascade piping and feed and withdrawal systems at the Natanz and Fordow sites. In fact, Iran has announced that it will do just that: replace six IR-1 cascades at Fordow with six IR-6 cascades. One other notable recent development is that Iran has managed to deploy more IR-2m centrifuges. In addition, Iran continues to be successful in evading national and international controls and sanctions with regards to materials needed for the IR-4 and IR-6 centrifuges.

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 the ones 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. Further, when choosing to install a cascade at Fordow with sub-headers easily modifiable for producing different levels of enrichment, Iran chose the IR-6 centrifuge. This modifiable cascade is one of two cascades that started to enrich uranium from near 5 percent LEU to up to 60 percent HEU on November 22, 2022.

However, based on the operational experience of the IR-6 in making 20 and 60 percent production, as reported by the IAEA, the IR-6 centrifuge does not work as well as thought, despite some design changes.[4] It appears the IR-6 needs more development to reach its nominal enrichment output.

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 in the main report (*A Comprehensive Survey of Iran's Advanced Centrifuges*, December 2021, available here) 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 for its average output in a production-scale cascade. In general, these

[4] David Albright and Sarah Burkhard, "The IR-6 Centrifuge Needs Further Development," *Institute for Science and International Security,* July 14, 2022, https://isis-online.org/isis-reports/detail/the-ir-6-centrifuge-needs-further-development/8.

more practical outputs are about 75 percent of their single machine theoretical values given in the main report.[5] In practice, lower average values result, due to centrifuge breakage, inefficient operation, or during the production of highly enriched uranium, such as production of 20 or 60 percent enriched uranium or weapon-grade uranium. The IR-6 centrifuge, as mentioned above, seems to be underperforming significantly. Nonetheless, the practical enrichment output of these three centrifuges is far higher than that of the IR-1 centrifuge, which has achieved average production-scale cascade values of 0.6-1.0 SWU per year per centrifuge.

Table H.2 Enrichment Output of Iran's Key Advanced Centrifuges

Type	**Average Enrichment Output in Production-Scale Cascade (SWU/year/machine)**
IR-2m	3.67
IR-4	3.3
IR-6	5.25 (actual so far for 20 and 60 percent production appears closer to 3.5)

Note: The enrichment output of the IR-6 centrifuge in production-scale cascades remains uncertain in general. However, in calculating total enrichment output in this report, which we identify as nominal, we are using the higher value of 5.25 SWU per year per centrifuge. The enrichment output unit in this table should not be confused with Iran's non-standard enrichment output unit (called in Institute reports the uranium hexafluoride unit). Iran's unit is significantly larger than the more conventional unit. An analogy would be using liters instead of gallons in front of a U.S. audience, perhaps with the intention to make a value appear larger than it is.

Advanced Centrifuge Development and Status

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 of the main centrifuge report, along with a more detailed discussion about the theoretical and achieved enrichment outputs of each centrifuge type.

Starting in November 2019, Iran demonstrated that it had accelerated its centrifuge research and development by installing seven types of advanced centrifuges in addition to the existing seven types allowed to be deployed under the JCPOA. These seven additional types were not

[5] As discussed in the main report, the associated single machine theoretical values for the IR-2m, IR-4, and IR-6 centrifuges are 4.4, 4.7, and 6.7 SWU/year/centrifuge, respectively. For comparison the single machine theoretical value for the IR-1 centrifuge is 1.4 SWU/year/centrifuge.

included in Iran's confidential JCPOA Enrichment and Enrichment R&D Plan, which projected the deployment of centrifuges up to about 2030.[6] The seven allowed ones are the IR-2m, IR-4, IR-5, IR-6, IR-6s, IR-7, and IR-8 centrifuges. The seven not allowed to be deployed under the JCPOA are the IR-3, IR-s, IR-6M, IR-6sm, IR-8B, IR-8s, and IR-9 centrifuges. Of these, all but the IR-3 centrifuge are new models.

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. For example, Iran changed the endcap design on some of the IR-6 centrifuge rotors from flat to domed. By early 2021, for testing purposes, Iran started to make maraging steel bellows for the IR-6 instead of carbon fiber, perhaps indicating ongoing problems in those bellows.[7]

Of the fifteen advanced centrifuge types in Figure H.2, based on the November 2022 quarterly IAEA report, the IR-2m, IR-4, IR-5, IR-6, and IR-6s centrifuges were accumulating enriched uranium. The ten IR-s centrifuges in R&D Lines 2 and 3 were removed. The IR-7, IR-8, IR-8B, and IR-9 centrifuges were being tested with natural uranium feed but not accumulating enriched uranium. As of November 2022, not a single IR-2, IR-3, IR-6M, IR-6sm, IR-s, or IR-8s centrifuge was listed as present in any of the three enrichment plants. The IR-2 and IR-3 centrifuges may have been retired. The others may have failed or served their research and development purpose. Figure H.3 shows the fraction of each type in a pie chart.

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

[7] "Analysis of IAEA Iran Verification and Monitoring Report - February 2021," *Institute for Science and International Security, February 25, 2021,* https://isis-online.org/isis-reports/detail/analysis-of-iaea-iran-verification-and-monitoring-report-February-2021/8.

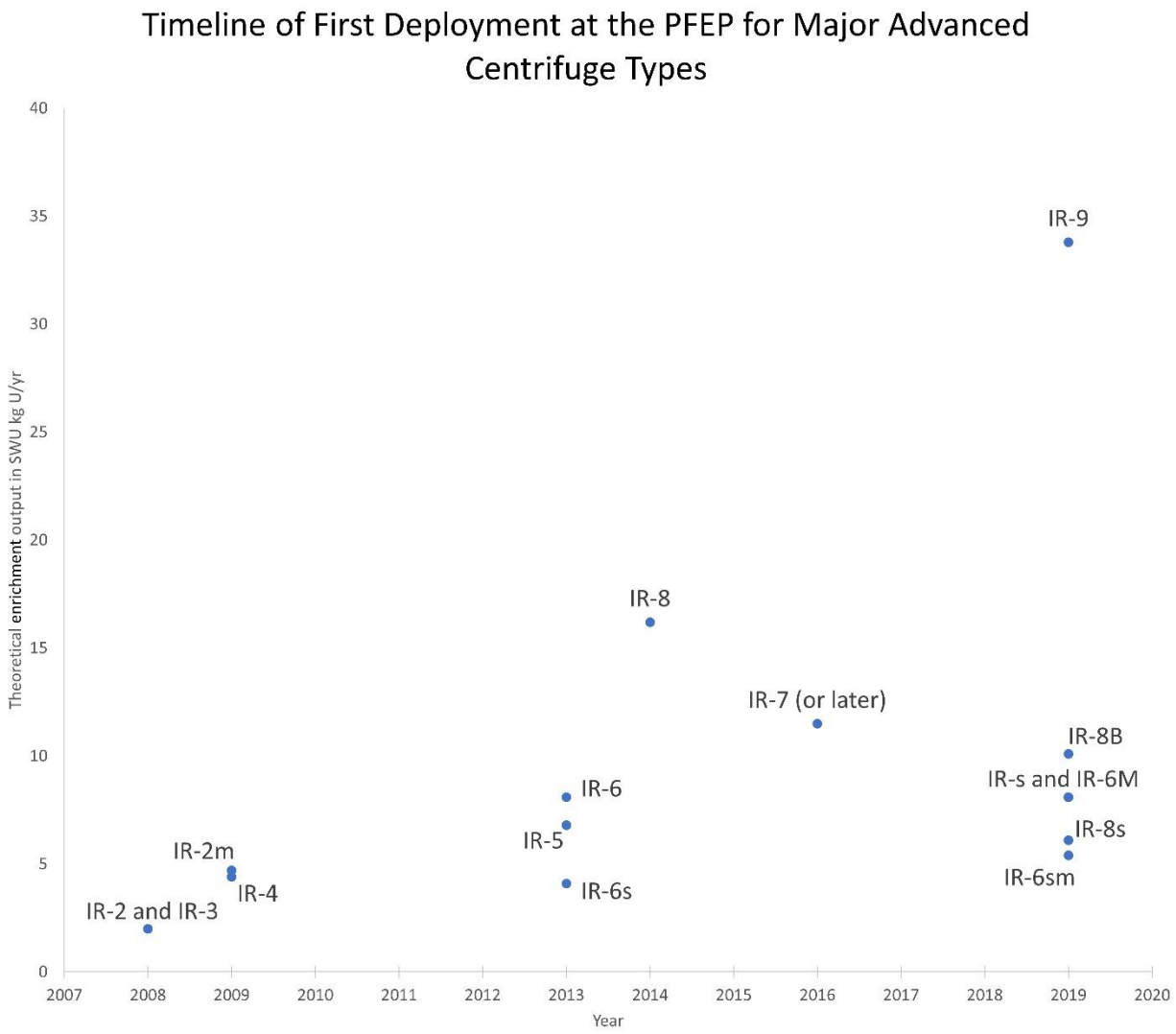


Figure H.2. Timeline of Iran's deployment of major advanced centrifuge types at the Natanz Pilot Fuel Enrichment Plant, in relation to their theoretical enrichment output, starting with the IR-2 and IR-3 in 2008. Where data exist, the theoretical output proved significantly greater than the practical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

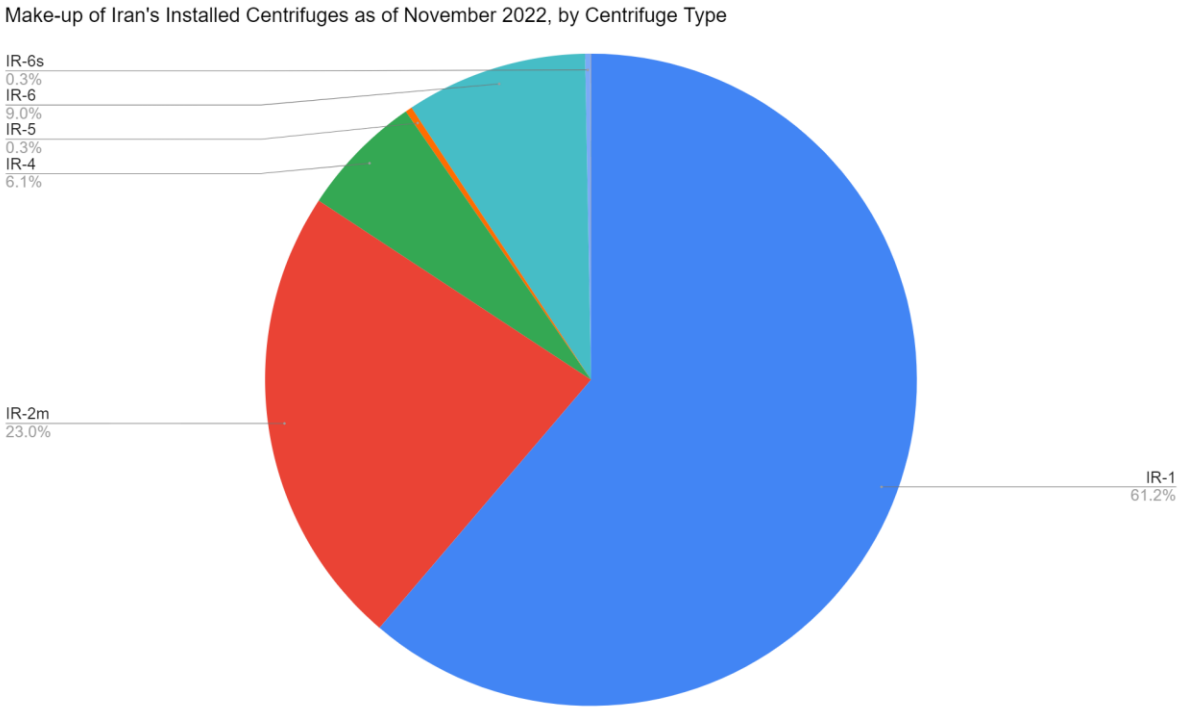


Figure H.3. The fraction by type and number of Iran's installed centrifuges at all facilities as of November 2022. The IR-7 (1 installed), IR-8 (1 installed), IR-8B (1 installed), IR-9 (1 installed) centrifuge types are represented on this graph, however, the respective counts are too few to be seen. In a new development, the 10 IR-s centrifuges were removed from the PFEP.

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 produce and deploy advanced centrifuges once Iran decided to stop abiding by the JCPOA limits (see Annex for their historical deployments). Iran has demonstrated its ability not only for a nuclear snapback but also for a snap nuclear buildup.

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 buildup of centrifuge capabilities. Those gains cannot be reversed or erased, presenting further challenges in seeking to reestablish JCPOA limits.

Figure H.4 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. For the first time, Iran's current nominal enrichment capacity has exceeded its total capacity prior to

the JCPOA's implementation, and the nature of that capacity is shifting predominately to advanced centrifuges.

Enrichment Output of 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 2022, the advanced centrifuges numbered about 4515, or about 63 percent of the number of deployed IR-1 centrifuges at Natanz and Fordow, and their nominal enrichment capacity is almost threefold the enrichment capacity of the 7134 deployed IR-1 centrifuges (see Figure H.5 for a breakdown of the total installed enrichment capacity by centrifuge type).

If Iran reaches the projected number of about 9449 advanced centrifuges, they will have more than six times the enrichment capacity of the currently deployed IR-1 centrifuges. This advanced centrifuge capacity will also be more than double that of all of Iran's estimated 16,000 IR-1 centrifuges—deployed *and* stored—with only 59 percent of the number of centrifuges. This comparison ignores any stored advanced centrifuges.

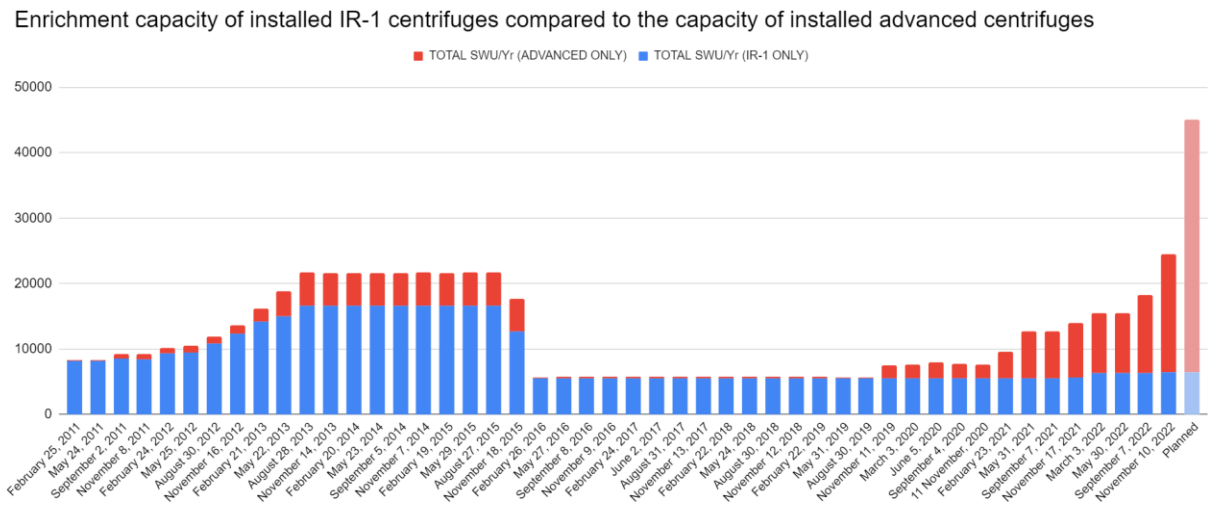


Figure H.4. Total enrichment capacity, by quarter, of the installed IR-1 and advanced centrifuges, with a projection on the far right of the graph. Planned in the context of this graph means firmly announced plans filed with the IAEA. It does not reflect Iran's long-term plan to deploy sufficient centrifuges to have a total enrichment capacity of 125,000 SWU/year.

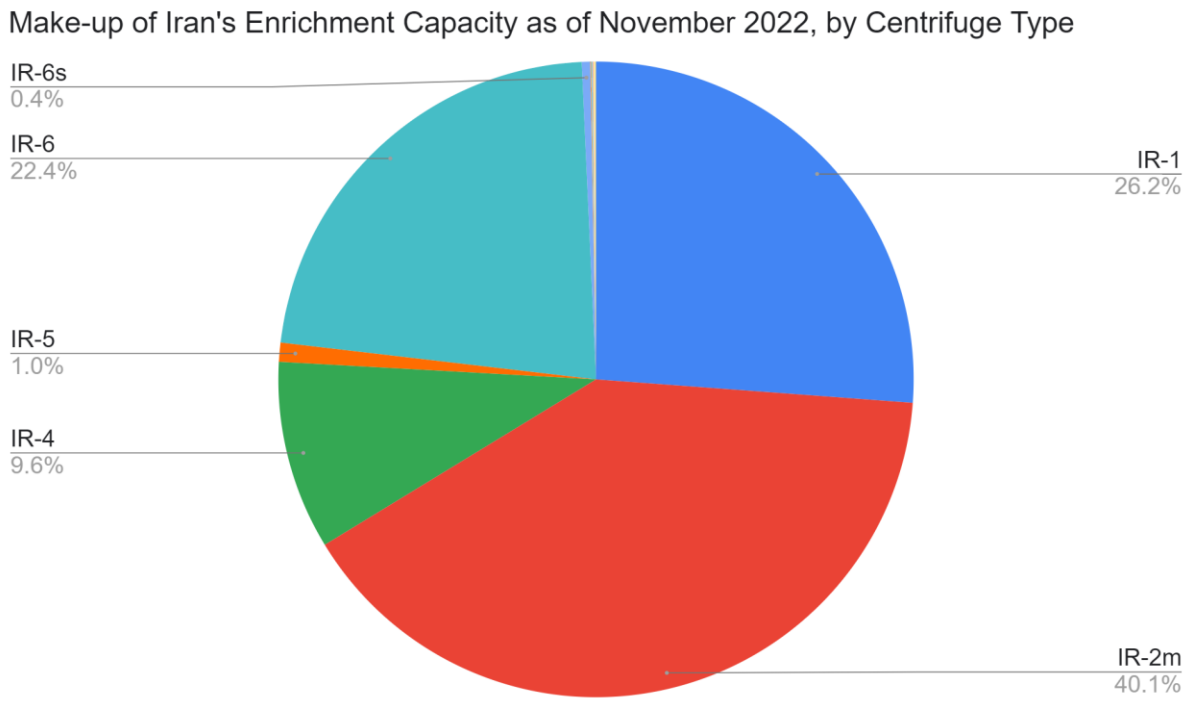


Figure H.5. The make-up of Iran's total installed enrichment capacity organized by centrifuge type. Despite the IR-1 accounting for 61 percent of the total installed centrifuges in terms of number (see Figure H.3), it only accounts for about 26 percent in terms of the installed enrichment capacity. The IR-2m, IR-4, and IR-6 make up about 72 percent, and the IR-5 and IR-6s about less than 2 percent of the installed capacity. The other installed advanced centrifuge types contribute only slightly to the total capacity and are not annotated in the pie chart.

Increasing Advanced Centrifuges' Enrichment Output

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 in the quantities and form it projected to need. 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 bellows, a centrifuge design easier to develop than one with two or more bellows. In addition, as mentioned above, Iran may be substituting maraging steel bellows for carbon fiber ones.

The IR-s centrifuge 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. In a new development, the ten IR-s installed at the PFEP were removed during the latest quarterly reporting period, raising the question whether they all failed.

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. Nonetheless, the strategic nature of Iran's centrifuge program cannot be ignored.

New, Large-Scale, Underground Centrifuge Assembly Facility

Construction of a new tunnel complex to house a replacement for the ICAC is progressing visibly.[8] Iran recently completed a fourth tunnel entrance; a second western entrance. The new tunnel complex will harbor halls more deeply buried than the Fordow uranium enrichment site, itself deeply buried, and features tunnel entrances that appear better protected as well. This site is expected to be large enough to produce centrifuges on the same scale as planned for the ICAC, namely thousands of advanced centrifuges per year. In fact, the estimated available floor space underneath the mountain ridge and between the visible tunnel entrances appears to significantly exceed that of the ICAC, leading to concerns that the site may have additional purposes, including housing a small enrichment facility containing advanced centrifuges.

[8] David Albright, Sarah Burkhard, and John Hannah, "Iran's Natanz Tunnel Complex: Deeper, Larger than Expected," *Institute for Science and International Security,* January 13, 2022, https://isis-online.org/isis-reports/detail/irans-natanz-tunnel-complex-deeper-larger-than-expected; and "Imagery Update: Iran Continues to Harden its New Natanz Tunnel Complex." ; and David Albright, Sarah Burkhard, "Imagery Update: Iran Adds Expected Fourth Tunnel Entrance to its Natanz Tunnel Complex," *Institute for Science and International Security,* November 9, 2022, https://isis-online.org/isis-reports/detail/imagery-update-iran-adds-fourth-tunnel-entrance-to-its-natanz-tunnel.

Sneak Out in a Clandestine Plant

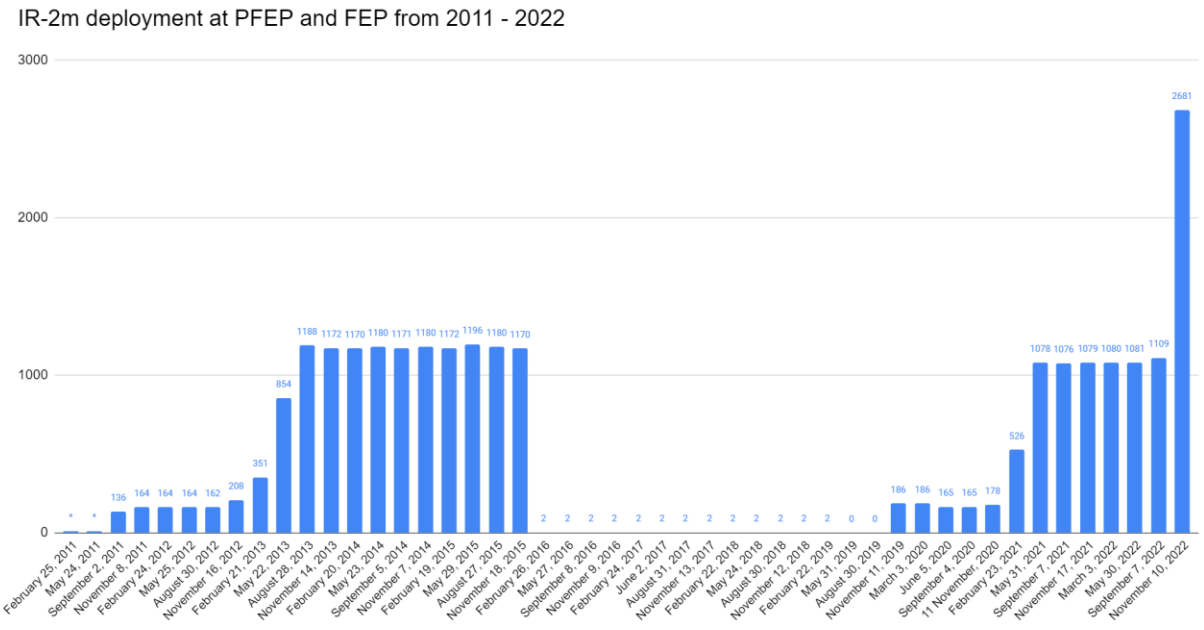
More powerful advanced centrifuges make it easier for Iran to set up a secret enrichment plant, which would be smaller and host only a fraction of the centrifuges Iran would have needed in 2009, when it was trying to finish up and install IR-1 centrifuges at its secret enrichment plant near Qom (now known as Fordow FEP), designed to produce weapon-grade uranium.[9]

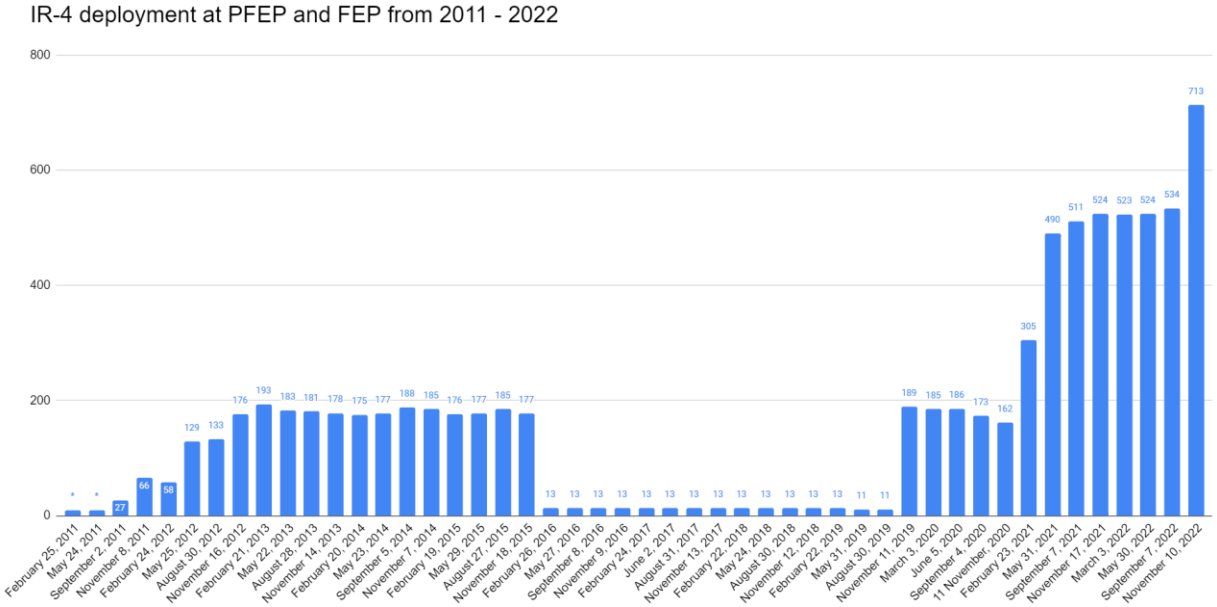
Since only a relatively small number of advanced centrifuges would be needed to set up a secret and relatively powerful enrichment plant, concern increases about unaccounted production of major parts for advanced centrifuges or whole rotor assemblies.

The concern about Iran building another secret enrichment plant will undoubtedly grow with time, absent negotiated limits and far more robust IAEA inspections than have functioned in Iran with or without the JCPOA. After all, the Natanz enrichment plant and the Fordow enrichment plant were built in secret until exposed, 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.[10] With advanced centrifuges, a secret plant could be smaller, more capable, and harder to discover, and this possibility should not be discounted.

[9] 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).
[10] *Iran's Perilous Pursuit of Nuclear Weapons.*

Annex. Numbers of IR-2m, 4, and 6 Centrifuges, historical deployments, by quarter





IR-6 deployment at the PFEP, FEP, and FFEP from 2013 - 2022