Analysis of IAEA Iran Verification and Monitoring Report - May 2021

by David Albright, Sarah Burkhard, and Andrea Stricker[1]

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This report assesses information in the International Atomic Energy Agency's (IAEA's) quarterly safeguards report for May 31, 2021, *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).

The IAEA report is also the first update on the status of Iran's uranium enrichment program since an attack on the Natanz Fuel Enrichment Plant (FEP) on April 11, which caused major damage to the underground enrichment hall's electricity supply and emergency backup power.[2] The IAEA report reflects apparent significant post-explosion damage to about half of the enriching cascades operating at the time of the power outage. Enriched uranium output also decreased by over half post-explosion.

Highlights and Worst-Case Breakout Estimate

- On April 17, 2021, Iran started to produce near 60 percent enriched uranium at the Pilot Fuel Enrichment Plant (PFEP) and as of May 22, 2021, has produced 2.4 kg of near 60 percent enriched uranium (in uranium mass).
- Iran continued to grow its near 20 percent enriched uranium stock and as of May 22, 2021, has produced a stock of 62.8 kg (in uranium mass), or 92.9 kg (in uranium hex mass, or hex mass for short).
- Iran experimented with skipping typical enrichment steps as it enriched up to 60 percent uranium 235, going from a level below 5 percent low enriched uranium (LEU) directly to near 60 percent in one cascade, rather than using two steps, a slower process entailing the intermediate production of 20 percent enriched uranium. As such, Iran is experimenting with multi-step enrichment while seeking to shortcut the process, and is likely learning important lessons, all useful if Iran decides to break out and produce weapon-grade uranium.
- Iran continued to produce uranium metal and has increased its yield of uranium metal significantly from when it first converted uranium tetrafluoride to uranium metal in February 2021.

[1] Andrea Stricker is a research fellow at the Foundation for the Defense of Democracies (FDD).
[2] Kim Zetter, "Israel May Have Destroyed Iranian Centrifuges Simply by Cutting Power," *The Intercept*, April 13, 2021, https://theintercept.com/2021/04/13/iran-nuclear-natanz-israel/.

- Half of the IR-1 and IR-2m cascades (translating to 15 cascades and 3 cascades, respectively) installed at the Natanz Fuel Enrichment Plant (FEP) appear to have been destroyed by the April 11 attack, based on consideration of which cascades the IAEA reports are now being fed with uranium.
- Iran's production of low enriched uranium at the FEP likewise slowed after the explosion, its rate dropping by at least one half.
- Iran's usable stock of below 5 percent LEU did not grow this reporting period, because of slower production and use of it as feed into cascades to produce 20 and 60 percent enriched uranium.
- Iran has enough LEU, in the form of 2 to 3 percent LEU and near 20 percent enriched uranium, to produce weapon-grade uranium (WGU) for three nuclear weapons without using any natural uranium as feedstock, a fact that reduces breakout timelines.
- Iran started using an existing workshop at Natanz to conduct mechanical testing of centrifuges, a workshop noted by the IAEA noted as not listed under the JCPOA. This likely means that this work is not subject to IAEA video surveillance and suggests that any work done at this workshop will not be included in the set of data and recordings being held by Iran under the temporary monitoring agreement.
- The report does not discuss Iran's construction of a new advanced centrifuge assembly facility in a tunnel near the main Natanz complex.
- A worst-case breakout estimate, which is defined as the time to produce enough WGU for one nuclear weapon, is as short as 2.3 months. Iran could produce a second significant quantity of WGU early in the fifth month after breakout commences, and a third quantity could be produced early in the seventh month. For comparison, if no explosion had occurred at the FEP, the minimum breakout timeline would have been 1.75 months, reflecting a longer breakout by one month. However, it should be noted that the post-explosion breakout estimate has additional uncertainties that suggest that it may be lengthier.
- Iran's suspension of the Additional Protocol (AP) and JCPOA monitoring arrangements has severely limited the IAEA's ability to verify the peacefulness of Iran's nuclear program. Iran's threat to destroy IAEA monitoring data underscores the recent dramatic reduction in its transparency, at a time when it is carrying out many activities related to nuclear weapons applications.
- As noted in a companion report,[3] and independent of the problems caused by Iran's suspension of the AP and JCPOA monitoring, Iran has failed to cooperate with the IAEA regarding the IAEA's findings of undeclared uranium at least three sites, leading Director General Grossi to state, "The lack of progress in clarifying the Agency's questions concerning the correctness and completeness of Iran's safeguards declarations seriously affects the ability of the Agency to provide assurance of the peaceful nature of Iran's nuclear program."

[3] 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.

Temporary Suspension of Additional Protocol and JCPOA Monitoring Arrangements

The quarterly report is the first since Iran stopped implementing the AP to its comprehensive safeguards agreement (CSA) and the JCPOA's additional monitoring arrangements on February 23, 2021. Iran also stopped implementing modified Code 3.1 to the CSA.

While Iran is legally free to suspend the AP and JCPOA, its renunciation of modified Code 3.1 is a violation of its legal obligations under the CSA. The IAEA reminded Iran that implementation of modified Code 3.1 is a legal obligation under the Subsidiary Arrangements to its CSA, which cannot be modified unilaterally, and iterated that there is no mechanism in the Safeguards Agreement for the suspension of provisions.

In February 2021, the IAEA obtained an agreement whereby Iran agreed to continue implementing for three months a limited number of IAEA surveillance and monitoring activities which record and collect data at sites, preserving during the life of the agreement the data and video monitoring records. Iran also agreed to continue abiding by its CSA, the fundamental IAEA inspection arrangement. It is worth noting that under the CSA, the IAEA is still empowered to access any location in Iran relevant to determining the correctness and completeness of Iran's safeguards declaration. It is unclear from the report whether the IAEA intends to invoke this authority.

The three months mark expired last week, but Iran agreed to extend the bilateral agreement for another month, until June 24, 2021. Iran threatens to erase the IAEA's surveillance and electronic data if it does not receive sanctions relief by this date.

In this quarterly report, the IAEA for the first time provides more clarity regarding the verification and monitoring provisions it lacks in Iran as of February. The IAEA can no longer carry out daily visits to Iran's enrichment facilities, receive updated declarations, or conduct "complementary access" to sites. It can also no longer reconcile Iran's declarations of the production of centrifuge rotor tubes and bellows prior to February 23 with the current inventory. It no longer receives the data and recordings collected by surveillance equipment at locations where Iran conducts mechanical testing of centrifuges. It no longer receives data and recordings of test stands for conducting quality control tests of advanced centrifuge rotor assemblies, prior to their installation at Natanz and Fordow enrichment plants.

An annex to the IAEA report describes these and other reduced provisions, many of which fall under the JCPOA's enhanced monitoring. At a press conference on May 24, IAEA Director General Rafael Grossi stated that the agency requires this added insight due to recent advances in Iran's nuclear program. The Director General characterized the temporary agreement as a "stop gap measure" to enable the agency to reconstruct what occurred at Iran's nuclear sites and reconcile its estimates with actual data collected in Iran and avoid losing "essential information."

Iran has also augmented activities in violation of the JCPOA. It has started using an existing workshop at Natanz to conduct mechanical testing of centrifuges, a location the IAEA noted was not listed in the JCPOA. This work is likely not subject to IAEA video surveillance.

The IAEA told Iran in February that "stopping or limiting the Agency's verification and monitoring activities would have a serious impact on the Agency's ability to report on the implementation of Iran's commitments and undermine the critical confidence in the peaceful nature of Iran's nuclear program." It added, "Without the measures currently provided by the Additional Protocol and the JCPOA being implemented, the Agency may be unable to continue to provide factual reports on Iran's nuclear program or to recover the knowledge necessary to resume such a verification role in future."

Combined with outstanding safeguards issues in Iran, discussed in the companion Institute analysis on Iran's non-compliance with its NPT safeguards commitments, the IAEA is sounding clear warning bells about its reduced ability to monitor Iran's complex and growing nuclear program, which notably has unresolved nuclear weapons dimensions. If Iran does destroy the verification and monitoring records, the verification process would face a serious gap, breaking the continuity of inspections, and seriously complicating and likely delaying any re-implementation of the JCPOA.

Part 1: Low Enriched Uranium Stocks

The IAEA report provides more detail about LEU stocks than previous reports, at least since the implementation of the JCPOA in early 2016.

At the Natanz FEP, according to the report, Iran produced approximately 335.7 kg of UF_6 enriched up to 5 percent U-235 during this recent reporting period, which spans 94 days from February 16 to May 21, 2021. The report discusses this amount as kilograms of uranium hexafluoride, creating confusion over whether the values represent the uranium mass of the uranium hexafluoride or the mass of both the uranium and hexafluoride, which we refer to as hex mass. However, other language in the report indicates that 335.7 kg of UF_6 enriched up to 5 percent U-235 is in units of hex mass.[4] Its uranium mass would be 226.9 kilograms.

At the Fordow Fuel Enrichment Plant (FFEP), from February 16 to May 3, 2021, Iran produced 61 kg of UF_6 enriched up to 20 percent enriched uranium, or 41.3 kg U mass.

At the Pilot Fuel Enrichment Plant, Iran produced all its up to 2 percent enriched uranium stockpile and all its up to 60 percent enriched uranium stock. It also produced small amounts

[4] For example, in paragraph 36, the report states, "The quantity of 300 kg of UF_6 corresponds to 202.8 kg of uranium." Further, in paragraph 38, the IAEA refers to the kilograms of uranium in the form of UF_6 rather than "kg of UF_6," as is written in paragraph 37. An additional indicator is that according to paragraph 37, 3.6 kg of UF_6 enriched to near 60 percent U-235 were produced, but the stockpile in paragraph 38 is 2.4 kg, where the ratio of the two numbers indicates that the former number is the hex mass and the latter is the uranium mass.

of uranium enriched up to 5 percent and up to 20 percent in R&D lines 1, 4, and 6. During this reporting period, the PFEP produced 3.6 kg hex mass of near 60 percent enriched uranium, or the equivalent of 2.4 kg Uranium mass; 5.9 kg of near 20 percent enriched uranium (hex mass), or 4 kg U mass; 24.6 kg hex mass of up to 5 percent LEU (16.6 kg U mass); and 160.6 kg hex mass of uranium enriched to up to 2 percent U-235 (108.6 kg U mass).

Of the 2 percent enriched uranium, Iran produced 68.4 kg hex mass (46.2 kg U mass) in R&D lines 1, 2, 3, and 5, and 92.2 kilograms of UF_6 (62.3 kg U mass) enriched up to 2 percent U-235 as tails in lines 4 and 6. Another 44.7 kg of UF_6 enriched up to 2 percent U-235 in tails was not included in the IAEA's tally in this section, since this quantity was still in process and remained unmeasured, but had an enrichment level only slightly above natural.

The language in this IAEA report appears less exact than in previous reports due to several factors. For example, due to the reduced monitoring measures, the IAEA can only verify the amount of LEU removed from the process as a product and not the amount that is still in the process, but it is able to reliably estimate the total amount. For estimates of additional amounts of LEU in oxides and intermediate products, fuel assemblies and rods, and in scrap, which add up to about 34.7 kg, the IAEA is using the same numbers from the previous reporting period. The IAEA was last able to verify enriched uranium products on May 3, 2021 and uses estimates to report the total stockpile as of May 22, 2021. The latter are used in this report.

Newly reported, at least for the first time in many years, are the masses of enriched uranium feed used to produce the higher enriched uranium stockpiles. The IAEA provides the amount of LEU used to make near 20 percent and near 60 percent enriched uranium, which allows for a more realistic estimate of production capability compared to using differences in total stockpiles alone.

Of its near 5 percent LEU stock, Iran fed 382.4 kg hex mass (or 258.5 kg U mass) into the tandem cascades at Fordow, for a feed rate of about 4 kg per day hex mass, or 2.75 kg U mass. It also fed 157.9 kg hex mass (109.7 kg U mass) into PFEP R&D lines 4 and 6. In total, Iran used 540.3 kg hex mass (365.2 kg U mass) as feed to produce 20 and 60 percent enriched uranium.

Based on this information, the new stockpile of near 5 percent LEU in uranium mass should be the sum of 1890 kg U mass from the last reporting period, 226.9 kg from the FEP, 16.6 kg from the PFEP, with the feed of 365.2 kg subtracted, resulting in 1768.3 kg. This is close, but not exactly equal to the 1773.2 kg U mass of near 5 percent LEU that the IAEA reported.

The net overall enriched uranium stock, including all levels of enrichment and all chemical forms, grew by 273.2 kg from 2967.8 kg to 3241 kg U mass (see Table 1). The near 5 percent LEU stock decreased by 116.8 kg to 1773.2 kg, signifying its lower level of production and use as feedstock. The near 2 percent LEU stock increased by 342.4 kg to 1367.9, the near 20 percent enriched uranium stock increased by 45.2, from 17.6 to 62.8 kg (U mass), and the newly added near 60 percent enriched uranium stock comprised 2.4 kilograms (U mass).

During the previous reporting period, which spanned 106 days, the net increase in near 5 percent LEU stock was 354.9 kg (U mass). There was no mention of the stock enriched to 3.67 percent, so it is assumed that this stock was used to feed the tandem cascades producing near 20 percent enriched uranium at Fordow. However, in reality, it is likely that less was used to feed the cascades at Fordow, and the remainder may have been added to the 2 to 5 percent LEU stockpile. This can be seen by considering the following calculation. At the daily average feed rate observed during this reporting period, namely 2.75 kg per day, the value for the previous reporting period, where cascades at Fordow enriched uranium from near 5 percent to near 20 percent for 43 days, would have amounted to 118.25 kg and not the full 215 kg.

This means that the amount of near 5 percent LEU produced was 354.9 kg *or less* over the previous reporting period, which equals a daily average of 3.35 kg or less (U mass). It should be noted that during this previous reporting period, six IR-1 cascades at Fordow were reconfigured to produce the near 20 percent enriched uranium, and it is not clear how long they were used to produce near 5 percent LEU before that. In addition to using its 5060 IR-1 centrifuges at the Natanz FEP, Iran enriched uranium to near 5 percent LEU in one IR-2m cascade since November 17, 2020, for 92 days, and in a second cascade since February 1, 2021, for 16 days. It also accumulated enriched uranium, likely below 5 percent LEU, in two cascades of advanced centrifuges in lines 4 and 6 in the PFEP, then containing 119 IR-4 centrifuges and 133 IR-6 centrifuges and having an estimated enrichment output equivalent to that of about 1340 IR-1 centrifuges.

The near 5 percent LEU production during this recent period, which spanned 94 days at the Natanz FEP, equaled 226.9 kg U mass, or a daily average of 2.4 kg (U mass), about 72 percent of the previous daily production rate. This translates to a monthly rate of 72.4 kg (U mass). Prior to the Natanz incident on April 11, Iran was enriching natural uranium at the FEP to near 5 percent LEU for 53 days in 30 cascades of IR-1 centrifuges and two cascades of IR-2m centrifuges; for 34 days in an additional IR-2m cascade; for 27 days in an additional IR-4 cascade; and for 11 days in yet an additional IR-2m cascade. After the explosion, the number of enriching cascades appears to have dropped by half, reducing accordingly the enriched uranium output, as reflected in the lower average production rate. Further, after the explosion, two cascades of advanced centrifuges in PFEP Line 4 and 6, previously dedicated to making below 5 percent LEU, were modified to enrich uranium to 60 percent and 20 percent, as discussed below.

The near 20 percent enriched uranium production rate during the previous reporting period was 17.6 kg over 43 days, equaling 0.41 kg per day. The production rate during this recent period was 41.2 kg (U mass) over 94 days (at Fordow only) for a very similar daily production rate of 0.44 kg per day. At this rate, Iran could produce 13.1 kg of near 20 percent enriched uranium per month (U mass), or 19.4 kg of near 20 percent enriched uranium per month (hex mass). Yearly, Iran could produce 157.8 kg per year (U mass) or 233 kg per year (hex mass).

Table 1. Enriched Uranium Quantities,* less than 5 % and less than 20 % enriched (all quantities in uranium mass)

Chemical Form	November 2, 2020	February 16, 2021	May 22, 2021
UF_6 (kg)	2408.5	2933.1	3206.3
Uranium oxides and their intermediate products (kg)	15.5	13.3	13.3
Uranium in fuel assemblies and rods (kg)	8.2	10.5	10.5
Uranium in liquid and solid scrap (kg)	10.7	10.9	10.9
Enrichment Level Subtotals			
Uranium enriched to 3.67 percent (kg)	215.1	0	0
Uranium enriched up to 5 percent (kg) but more than 2 percent	1535.1	1890	1773.2
Uranium enriched up to 2 percent (kg)	692.7	1025.5	1367.9
Uranium enriched up to 20 percent (kg)	0	17.6	62.8
Uranium enriched up to 60 percent (kg)			2.4
Uranium in chemical forms other than UF_6 with unspecified enrichment level (kg)		34.7	34.7
Totals of Enriched Uranium in UF_6, <5 % (kg)		2915.5	3141.1
Totals of Enriched Uranium in UF_6, including near 20 % and near 60 % (kg)		2933.1	3206.3
Totals of Enriched Uranium in all chemical forms, <5 % <20 % and <60 % enriched	**2442.9**	**2967.8**	**3241**

Part 2: Enrichment capacity

Natanz Fuel Enrichment Plant

As of May 24, 2021, 15 IR-1 cascades, three IR-2m cascades, and two IR-4 cascades were being fed with natural uranium hexafluoride. The report also states that in total, 30 cascades of IR-1 centrifuges, six cascades of IR-2m centrifuges, and two cascades of IR-4 centrifuges were installed to enrich natural uranium hexafluoride up to 5 percent. Notably, only half of the IR-1 cascades that were operating prior to the April 11 attack appear to be operating currently. Likewise, only three of the six IR-2m cascades were being fed with uranium, perhaps indicating that the other three cascades were destroyed or seriously damaged by the disruption in power supply.

Overall, this suggests that about half of the enriching cascades at the FEP were destroyed in the April attack, namely 15 IR-1 cascades and three IR-2m cascades. In addition, many individual centrifuges in the remaining cascades may have also been destroyed and either replaced or left in place but with their valves closed, the latter meaning that some of the remaining cascades could be operating with significantly fewer centrifuges than normal, reducing their output or enrichment level.

The IAEA also reported that Iran had not started installing a number of planned cascades: four IR-4 cascades, one IR-6 cascade, and six IR-1 cascades.

The number of IR-1 centrifuges Iran withdrew from storage is not available for this reporting period because of Iran's refusal since February to provide the IAEA with access to the data and recordings collected by its equipment. This quantity would provide concrete evidence of the total number of centrifuges destroyed in the April attack.

A question is also whether a cascade of IR-6 centrifuges was destroyed in the attack. Per the February report, Iran "was still installing the cascade of IR-6 centrifuges" at the FEP, and media reported that on Iran's Nuclear Technology Day, one day before the attack, the IR-6 cascade was to be inaugurated.[5] However, the report states that the planned IR-6 cascade has yet to be installed. It could be that the cascade was never moved to the FEP but instead remained at PFEP Line 6, where it was completed to contain 164 centrifuges and started up on April 10. One further indication for this would be the fact that the IAEA does not list an IR-6 centrifuge cascade as being newly fed with uranium on April 10, which should have been listed if it had happened at the FEP, even if it had operated only for a day.

[5] "On its 'National Nuclear Technology Day,' Iran starts up advanced centrifuges," *The Times of Israel*, April 10, 2021, https://www.timesofisrael.com/iran-starts-up-advanced-centrifuges-in-new-nuclear-deal-breach/

Fordow Fuel Enrichment Plant

Since January 2021, Iran has been using three sets of two interconnected IR-1 cascades to produce 20 percent enriched uranium from up to 5 percent enriched uranium. Iran announced that it would install two IR-6 cascades to produce the 5 percent feed for the tandem IR-1 cascades. Iran had installed 10 IR-6 centrifuges as of May 26, 2021, a fraction of the roughly 328 centrifuges in two full IR-6 cascades planned for installation.

Iran's plan is to use the two cascades of IR-6 centrifuges to enrich natural uranium to 5 percent and then directly feed that enriched material into the three sets of IR-1 cascades for further enrichment up to 20 percent enriched uranium. This plan would bypass the need for condensing the enriched uranium from the IR-6 cascades into tanks, moving the tanks to autoclaves of the IR-1 cascades, where they would be heated to again produce uranium hexafluoride gas for feeding into the IR-1 cascades, an arrangement which would reduce the time needed to produce 20 percent enriched uranium from natural uranium.

Pilot Fuel Enrichment Plant

For several months, Iran has been transferring its enrichment research and development activities to a segregated area of Building A1000 at the FEP. Iran has completed the installation of sub-headers for 18 cascades in this new area, an increase of three-fold from the six lines in the above ground PFEP. The IAEA report does not provide a start date for this new area. Given its three-fold greater size, one has to ask if this area could be devoted to production-scale enrichment in case of a surge in enriched uranium production or of a breakout.

Iran continued to enrich uranium up to 2 percent in lines 2 and 3 at the above ground PFEP, feeding natural uranium into a whole host of centrifuge types and cascades: ten IR-4 centrifuges; five IR-5 centrifuges; five IR-6 centrifuges, ten IR-6 centrifuges and another cascade of 18 IR-6 centrifuges; nine IR-6s centrifuges; and ten IR-s centrifuges.

The following single centrifuges were being tested in lines 2 and 3 with natural uranium but not accumulating enriched uranium: one IR-1 centrifuge; two IR-2m centrifuges; two IR-4 centrifuges; two IR-5 centrifuges; two IR-6 centrifuges; one IR-6s centrifuge; one IR-7 centrifuge; one IR-8 centrifuge; one IR-8B centrifuge; and one IR-9 centrifuge.

Iran was using line 5, which earlier held a production-scale IR-2m cascade, to enrich uranium in a cascade of 18-IR-1 centrifuges and 32 IR-2m centrifuges, producing uranium enriched below 2 percent.

Lines 1, 4, and 6 were used for the production of 60 percent enriched uranium and re-enrichment of tails, principally in a variety of cascade arrangements of IR-4 and IR-6 centrifuges (see next section for further discussion). Line 4 contained 130 IR-4 centrifuges, resulting in an estimated enrichment output of about 430 separative work units per year (SWU/year). Line 6 contained 164 IR-6 centrifuges, for a total estimated enrichment output of about 1000

SWU/year. The two lines together have an estimated output of 1430 SWU/year, or the equivalent of about 1600 IR-1 centrifuges.

Table 2 lists the estimated enrichment capacity by facility, leading to a current total of 8297 SWU/year, or the equivalent of 9218 IR-1 centrifuges. This total number is similar to that from the previous reporting period; without the attack on the Natanz FEP, this number would be higher. The currently unused 15 IR-1 centrifuges and three IR-2m centrifuges, likely destroyed, constitute an estimated enrichment capacity of about 4140 SWU/year. It must also be noted that the total enrichment capacity should not be used in breakout calculations, as many of the advanced centrifuges in the PFEP likely could not contribute meaningfully to the quick production of enough WGU for a nuclear explosive. Therefore, taking down cascades of proven IR-1 and IR-2m centrifuges at the FEP had a greater effect on actual breakout capabilities than destroying single or small cascades of various advanced centrifuges at the PFEP. Detailed breakout scenarios and timelines are discussed below.

Table 2. Number of enriching centrifuges and enrichment capacity

	Number of centrifuges	**Enrichment capacity in SWU/yr**	**IR-1 equivalent**
Natanz	3362	5224	5805
Fordow	1031	928	1031
Natanz PFEP*	470	2144	2383
Lines 2 & 3	See text		
Lines 4, 5, 6	See text		
Total enriching	**4863**	**8296.5**	**9218**

*The value for lines 2, 3, and 5 of the PFEP is a rough estimate based on the use of estimated and measured values for the separative output of these centrifuges in cascades, drawn from IAEA information. The values for lines 4 and 6 of the PFEP are given in the text. All values used to make these estimates reflect historical enrichment output values obtained by Iran prior to the nuclear deal and do not reflect current values, which are not included in the IAEA's quarterly reports.

Practicing Breakout by Producing 60 Percent Enriched Uranium

During this reporting period, Iran took the unprecedented step of producing 60 percent enriched uranium, breaking a new barrier by producing highly enriched uranium (HEU) for the first time. This level of enrichment is associated with a key step in the traditional four-step process of climbing from natural uranium to 90 percent enriched uranium, or WGU. Sixty percent enriched uranium can be used directly in nuclear weapons, although the amount needed is almost double the amount required if 90 percent enriched material were used. Iran's accumulation of 60 percent enriched uranium is a highly provocative, dangerous step.

Moreover, the manner in which Iran has proceeded to enrich to 60 percent, starting from near 5 percent enriched material, is innovative, suggesting Iran is gaining valuable experience in producing HEU, and by extension even WGU, practicing breakout under a civilian cover, and also learning to reduce the number of steps that it would need to go from natural to WGU.

Initially, Iran enriched up to 60 percent uranium at the PFEP by feeding near 5 percent enriched uranium simultaneously into two cascades of IR-4 and IR-6 cascades in lines 4 and 6, respectively. Soon afterwards, Iran changed the mode of operation twice, as it sought to learn more and use its enriched uranium more efficiently. It settled, by the end of May, on a sequential process:

A. Feeding near 5 percent enriched uranium into a cascade of 164 IR-6 centrifuges in line 6 to produce HEU enriched up to 60 percent;
B. Feeding the tails from the IR-6 cascade, which would be enriched to an estimated 2 to 3 percent, into a cascade of 130 IR-4 centrifuges in line 4 at the PFEP to produce up to 20 percent enriched uranium;
C. Feeding the tails from the IR-4 cascade into a cascade of 30 IR-5 centrifuges and 29 IR-6s centrifuges in line 1 to produce uranium enriched up to 5 percent.

The enrichment process in step A jumps a conventional step by going from near 5 percent to 60 percent. It bypasses the step of first going from 5 percent to 20 percent, in the four-step process to reach WGU pioneered by A.Q. Khan in Pakistan, who provided this method to Iran in the late 1980s or 1990s. To the extent that the enrichment process was successful, Iran is advancing its centrifuge cascade skills, all useful in a breakout.

The IAEA reported on the total amount of 60 percent enriched uranium Iran produced. The IAEA divided this production into two periods.

During the first period, from April 17 to May 3, where the IAEA verified the quantities, Iran fed 100.2 kg of UF_6 enriched up to 5 percent (hex mass) into cascades installed in PFEP lines 4 and 6, where Iran produced:

- 92.2 kg of UF_6 enriched up to 2 percent (hex mass), evidently in tails, although this may not be all the tails;
- 3.5 kg of UF_6 enriched up to about 20 percent (maximum 20.3 percent); and
- 2.0 kg of UF_6 enriched up to 60 percent

(The reason that these three numbers do not add up to 100.2 is not explained).

During the second period, from May 3 to May 21, where Iran provided estimates to the IAEA and evidently used the process described in steps A, B, and C above for most of this period, Iran fed 57.7 kg of UF_6 enriched up to five percent into the cascade in line 6 (IR-6 cascade), followed by enriching tails in additional cascades, as detailed in steps B and C above. The result was:

- 1.6 kg of UF_6 (hex mass) enriched up to and over 60 percent (with maximum of up to 63 percent);
- 2.4 kg of UF_6 enriched up to 20 percent;
- 9 kg of UF_6 enriched up to 5 percent; and
- 44.7 kg of UF_6 (tails from line 1) with an average enrichment slightly above the level of natural uranium.

The values add up to 57.7 kg, as would be expected from a mass balance of the feed, product, and tails.

Comparing the results to that of a separative work calculator, where the initial feed is 57.7 kg of UF_6 enriched up to 5 percent (taken as all 4.5 percent), and the tails are at the level of natural uranium, the calculator predicts production of 3.7 kg of UF_6 enriched to 60 percent (hex mass). Iran's multi-step process is far from ideal, leading to the production of less than half that amount in a single, ideal cascade approximating the Iranian process. Nonetheless, the Iranian process has certain advantages, including being within its technical reach, recycling the tails down to the level of natural uranium, while producing 5, 20, and 60 percent enriched uranium, and more importantly, practicing multi-step enrichment arrangements. Moreover, the Iranians are experimenting with transferring enriched uranium hexafluoride as a gas from one step to the next. All this experimentation is bound to lead the Iranians to be more capable of breaking out to produce 90 percent enriched uranium, if the leadership orders its production or moves toward the construction of nuclear weapons.

Part 3: Current Breakout Estimates

The Institute's breakout calculator is used to estimate a current worst-case breakout time, based on Iranian low enriched uranium stocks and installed enrichment capacity, post explosion. In this case, a major impact can be seen from the April 11 explosion.
In the breakout estimate, the following conditions are assumed:

- Enrichment capacity at both the Natanz and Fordow Fuel Enrichment Plants, as drawn from the latest IAEA report. The total enrichment contribution from advanced centrifuges installed at the PFEP is not included, as their use in a breakout would be complicated and likely not contribute to reducing breakout timelines. However, as the breakout continues, advanced centrifuge cascades at the PFEP may be used to reach the highest enrichment levels and recycle the tails.
- Only LEU stocks above 2 percent enriched uranium are used. Stocks of less than 2 percent enriched uranium are not used, since to do so would require additional modifications of the cascades to handle the lower enrichments, likely significantly slowing or contributing only slightly, rather than speeding up breakout timelines; and

- Iran redeploys or installs additional centrifuges during a breakout. During the first four months of the breakout, this estimate considers only the additional deployment of seven centrifuge cascades already slated for deployment, including four IR-4 cascades and three IR-6 cascades. This calculation applies an additional inefficiency coefficient of 50 percent to the IR-6 cascade and of 10 percent to the IR-4 cascade, reflecting operational inexperience and breakage.[6] During this period, Iran would also be adding IR-1 centrifuge cascades, at a rate of two per month. Iran may deploy additional IR-2m, IR-4, and IR-6 centrifuges during subsequent months as it ramps up centrifuge production. Iran may also deploy additional types of advanced centrifuges, but this effect is not included in the estimate, as none of the dozen advanced centrifuge types Iran is testing at the PFEP stands out as Iran's clear centrifuge of choice, and many are assessed as performing poorly.

Because of uncertainties, only one case is considered in this report, a worst case, which likely represents the shortest time to breakout, with longer timelines being probable. The uncertainties include ongoing ones, such as the exact enrichment level of the enriched uranium stock enriched between 2 and 5 percent. Additional uncertainties concern the operational efficiencies of the advanced centrifuges, particularly the IR-4 and IR-6 cascades. Further, there may be a number of damaged centrifuges in cascades listed as being fed natural uranium at the FEP.

In this worst-case assessment, Iran's stock of uranium enriched between 2 and 5 percent (2,623 kg (hex mass)) is assumed to be all enriched to 4.5 percent.[7] In addition, Iran has a stock of 93 kg of near 20 percent enriched uranium (hex mass). Iran's small stock of 60 percent enriched uranium is ignored here. Under these additional assumptions, Iran's current stock of enriched uranium has grown sufficiently to support the production of enough WGU for over three nuclear weapons. In this new situation, breakout for one nuclear weapon could be accomplished in as little as 2.3 months, including a two-week setup time. If breakout continued, a second significant quantity of WGU would be produced early in the fifth month after breakout commences, and a third quantity would be produced early in the seventh month. The second and third quantities would be produced more slowly due to an absence of additional 20 percent enriched uranium, which plays a key role in speeding up the production of the first significant quantity. This effect is compensated to a certain extent by the addition of more advanced centrifuges. Nonetheless, enough WGU could be produced for three nuclear weapons in just over six months.

[6] This essentially leads the estimated enrichment output of the IR-6 and IR-4 to be similar to that of the IR-2m , facilitating the calculation, where the IR-6, IR-4, and IR-2m centrifuges can be treated as equivalent. This also explains the particular values in the text.

[7] In its report, the IAEA refers to uranium enriched up to 5 percent rather than 4.5 percent, as was done earlier. However, there is no evidence that Iran systematically increased the level of enrichment in its product. We continue to use 4.5 percent as the upper bound of this category of enriched uranium in breakout calculations.

For comparison, if no explosion had occurred at the FEP, the minimum breakout timeline would have been 1.75 months. So, the explosion lengthened the breakout timeline by at least half a month, if not longer.

With a feedstock of 4.5 percent enriched uranium, the production of 25 kilograms of WGU requires less LEU than if it were enriched to 3.5 percent; 900 kilograms of 4.5 percent LEU compared to 1,250 kilograms of 3.5 percent LEU in hexafluoride mass. These amounts of LEU are sufficient to reach the requisite amount of weapon-grade uranium without the need to also use natural uranium to make a portion of the needed WGU. As a result, the process is strictly a three-step one instead of a three-step process followed by a four-step one, if natural uranium were required. The ability to use only three steps to reach weapon-grade, instead of four, is why the media often discusses a key threshold of about 1,000 kg of LEU as significant.

Part 4: Other Information - Heavy water & Arak reactor, Uranium metal production, Scrap fuel recovery & Target production, Additional Protocol, JCPOA monitoring

Heavy water & Arak reactor

The IAEA reports that since February, it has not been able to ascertain the status of Iran's Heavy Water Production Plant (HWPP), but based on analysis of commercial satellite imagery, assesses that it continues to operate. Iran has "neither informed the Agency about the inventory of heavy water in Iran...nor allowed the Agency to monitor the quantities of Iran's heavy water stocks and the amount of heavy water produced at the HWPP." The IAEA's monitoring equipment at the HWPP continues to operate, but it has not had access to the data and recordings collected by its equipment.

The IAEA reports that Iran has not pursued construction of the Arak heavy water research reactor based on its original design. However, the Arak reactor working group established under the JCPOA may have permitted technical allowances, such as the installation of a secondary cooling circuit, that suit the reactor's original design.[8] The IAEA also wrote in its previous report that Iran had installed a refuelling machine based on the reactor's original design. The IAEA has apparently still not questioned Iran about statements by the head of Iran's Atomic Energy Organization that Iran illicitly imported spare pressure tubes during JCPOA negotiations to permit it to make a new calandria for the reactor, if needed.

Uranium metal production

In December 2020, Iran informed the IAEA that it would begin producing uranium metal, including uranium metal enriched up to 20 percent, in violation of its JCPOA commitments. Iran claims the uranium metal will be used in fuel rods for the Tehran Research Reactor (TRR). On

[8] Andrea Stricker, "Biden Administration Should Ascertain the Status of Iran's Arak Reactor," *Foundation for Defense of Democracies,* May 5, 2021, https://www.fdd.org/analysis/2021/05/05/status-of-irans-arak-reactor/

February 2, Iran began producing uranium metal using natural uranium in a laboratory experiment at the Esfahan Fuel Plate Fabrication Plant (FPFP). As of May 14, the IAEA verified that Iran had produced 2.42 kg of natural uranium metal from 3.1 kg of natural uranium in the form of uranium tetrafluoride.

The yield indicates an improvement in the process from the first experiment. During the first experiment on February 8, 2021, Iran gained 3.6 grams metal out of 9.85 grams uranium metal contained in 13 g of UF_4, a yield of less than 40 percent. During this most recent reporting period, Iran gained 2.42 kg out of 3.1 kg uranium in the form of UF_4, a yield of 78 percent.

Further, "From the 2.42 kg of natural uranium metal, 0.85 kg were used to produce 0.54 kg of uranium in the form of uranium silicide, from which two uranium silicide fuel plates were manufactured."

Iran also told the IAEA in December 2020 that it would install equipment for a full uranium metal process line over the next four to five months. On April 1, Iran provided the IAEA with an updated design information questionnaire (DIQ) for the Esfahan Uranium Conversion Facility to indicate "it was starting to install equipment for the production of uranium metal." The IAEA verified on May 14 that installation of equipment for the first stage of the process, production of uranium tetrafluoride from uranium hexafluoride, was ongoing. On May 23, the IAEA verified Iran had completed installation of equipment and that it was "ready to operate with either natural uranium or depleted uranium, although nuclear material had yet to be introduced into the production area."

Iran's production of uranium metal could assist it in furthering knowledge relevant to making nuclear weapons under the guise of a peaceful use. Prior to 2003, under the Amad Plan, Iran was constructing both pilot and large-scale uranium metallurgy facilities to make nuclear cores and practicing with surrogate materials for weapon-grade uranium.[9]

Scrap fuel recovery & Target production

On April 7, the IAEA "verified at the FPFP that Iran had dissolved six unirradiated, scrap fuel plates for the TRR containing 0.43 kg of uranium enriched up to 20% U-235, from which a uranyl nitrate solution was extracted and converted into ammonium uranyl carbonate (AUC)."

Under the JCPOA, Iran is prohibited from having this type of 20 percent enriched uranium even if it is in scrap fuel plates. However, this scrap was included in material exempted by the JCPOA Joint Commission in 2016, which deemed this 20 percent enriched material "unrecoverable." Iran proved the Joint Commission was mistaken in its assessment, making the exemption an

[9] David Albright with Sarah Burkhard and the Good ISIS Team, *Iran's Perilous Pursuit of Nuclear Weapons* (Washington, D.C.: Institute for Science and International Security Press, 2021); David Albright, Sarah Burkhard, and Frank Pabian, "Shahid Mahallati: 'Temporary' Plant for Manufacturing Nuclear Weapon Cores," *Institute for Science and International Security,* April 8, 2020, https://isis-online.org/isis-reports/detail/shahid-mahallati-temporary-plant-for-manufacturing-nuclear-weapon-cores/8

unwise decision. The Institute both revealed the exemption and pointed out its unsound reasoning in September 2016.[10] Likewise, the processing of scrap could have occurred in hot cells at the Molybdenum, Iodine, and Xenon Radioisotope Production Facility (MIX), which were larger than allowed under the JCPOA, but the Joint Commission also exempted them from the JCPOA limits.[11]

On May 15, Iran dissolved another unirradiated, scrap fuel plate containing 0.8 kg of 20 percent enriched uranium and extracted a uranyl nitrate solution. The IAEA report did not explain the scrap fuel plate's origin, and whether it had also been exempted from the limits.

Iran converted the solution from both fuel plates into a U_3O_8 powder. Iran claims it will use the powder to produce enriched uranium targets for irradiation at the TRR to produce molybdenum at the MIX facility. Iran provided the IAEA with an updated DIQ for the MIX facility, informing the IAEA of its intention to extract cesium from irradiated targets. On April 18, the IAEA verified the presence of 28 targets containing up to 20 percent enriched uranium, 26 of which were at the MIX facility. On May 18, the IAEA verified the presence of additional 22 targets. The 50 total targets contained 330 grams of uranium enriched up to 20 percent. Iran is also forbidden from producing enriched uranium targets under the JCPOA. The processing of the irradiated targets may also exploit the Joint Commission exemption on hot cells.[12]

Moreover, other proliferant states, such as Taiwan in the 1980s, also used molybdenum production as a cover story to practice sensitive nuclear weapons-relevant processes.

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[10] David Albright and Andrea Stricker, "JCPOA Exemptions Revealed," *Institute for Science and International Security,* September 1, 2016, https://isis-online.org/uploads/isis-reports/documents/JCPOA_Exemptions_Revealed_1Sept2016_Final1.pdf. Several months after the publication of this study, the full set of exemptions were published (see INFCIRC/907).
[11] Ibid.
[12] Ibid.