By Alexander Glaser,
Zia Mian, Hossein Mousavian,
and Frank von Hippel

Agreeing on Limits for Iran's Centrifuge Program: A Two-Stage Strategy

Iran is negotiating with a group of six states over the future of its nuclear program. In November 2013, Iran and the P5+1 (China, France, Germany, Russia, the United Kingdom, and the United States) agreed to a Joint Plan of Action that seeks to reach a "comprehensive solution" by July 20, 2014.

The goal is an agreement on a set of measures that can provide reasonable assurance that Iran's nuclear program will be used only for peaceful purposes and enable the lifting of international sanctions imposed on Iran over the past decade because of proliferation concerns.

A key challenge is to reach agreement on limiting Iran's uranium-enrichment program, which is based on gas centrifuges, in a way that would enable Iran to meet what it sees as its future needs for low-enriched uranium (LEU) fuel for nuclear research and power reactors while forestalling the possibility that this program could be adapted to quickly produce highly enriched uranium at levels and in amounts suitable for use in nuclear weapons.[1]

This article proposes a compromise based on a two-stage approach that involves Iran maintaining a capacity for enriching a small amount of uranium annually for research reactor fuel in the short term and developing a potential enrichment capacity in the longer term that would be appropriate to fuel power reactors. Iranian supply needs for its power reactors will develop in 2021 if Tehran decides to fuel the existing Bushehr power reactor domestically, in whole or in part, rather than renewing its fuel supply contract with Russia or buying fuel from another foreign supplier.

The proposed compromise also reflects Tehran's plan to shift from its current low-power, first-generation centrifuges to high-capacity machines that are still under development.

This article therefore suggests that, during the next five years, Iran should modernize its enrichment facilities and in doing so, keep its operating capacity at about the current level rather than begin to operate the many thousands of first-generation machines that it already has installed and continue setting up more. During this period, Iran could phase out its first-generation machines in favor of the second-generation centrifuges it already has installed but has not yet operated. At the same time, it could develop, produce, and store components for a future generation of centrifuges that would be suitable for commercial-scale deployment. These later-generation centrifuges would not need to be assembled, except for test machines, until at least 2019.

To maintain the confidence of the international community that there will be no diversion of centrifuge components to a secret enrichment plant, the current transparency measures that Iran has undertaken for its centrifuge program would continue. These transparency measures should become the standard for transparency for centrifuge production worldwide.

Finally, the article suggests that the

Alexander Glaser, **Zia Mian**, **Hossein Mousavian**, and **Frank von Hippel** are members of the Program on Science and Global Security at Princeton University.

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Representatives from Iran and the six world powers negotiating with Tehran over its nuclear program meet in Vienna on April 8. Iranian Foreign Minister Mohammad Javad Zarif (second from right) headed his country's delegation; EU foreign policy chief Catherine Ashton (third from right) led the six-country group.

five-year period created by this proposal be used as an opportunity by Iran, the P5+1, and other interested states to explore in a second stage of the negotiations a multinational uranium-enrichment arrangement that would see Iran deploy its advanced centrifuges in a new regional, multinational facility rather than a national enrichment plant. By committing to working on such multinational arrangements for the Middle East and, ultimately, around the world, Iran and the P5+1 could chart a path to greatly reduce the proliferation risks that stem from national control of enrichment plants, regardless of location.

Background

The dispute over Iran's enrichment activities is more than a decade old. In 2003, Iran offered to cooperate with France, Germany, and the UK to resolve international concerns, agreeing to suspend key parts of its enrichment program temporarily and make it more transparent to help build global confidence that Tehran was not developing nuclear weapons. In the United States, however, the George W. Bush administration adopted the view that Iran should not be allowed to operate even a single centrifuge. When diplomacy failed, Iran resumed its enrichment program and has built and installed large numbers of centrifuges—the first-generation IR-1 and the second-generation IR-2m—at its Natanz facility, developed designs and prototypes for more-powerful machines, and constructed a second, deeply buried enrichment plant at Fordow. The international community imposed sanctions on Iran to pressure it to suspend its nuclear program again and to bring it back to the negotiating table.

As part of the current talks on a comprehensive solution to proliferation concerns about Iran's nuclear program, as set out in the Joint Plan of Action, Iran and the P5+1 seek to agree on "a mutually defined enrichment programme with mutually agreed parameters consistent with practical needs, with agreed limits on scope and level of enrichment activities, capacity, where it is carried out, and stocks of enriched uranium, for a period to be agreed upon."[2]

Western negotiators are concerned that the total of about 19,000 centrifuges that Iran has installed at its enrichment plants at Natanz and Fordow is sufficient for producing, should it decide to do so, highly enriched uranium for nuclear weapons purposes (typically enriched to 90 percent uranium-235) in a time frame that may be too short for the international community to detect the effort and respond to it effectively. The negotiators currently appear to be discussing limits on Iran's centrifuge program that would translate into a potential "breakout" time of about six to 12 months to make enough material for a first bomb rather than the estimated two months that Iran probably would require today.[3] Additional time would be required to fabricate a nuclear explosive device that could be tested or a nuclear warhead that could be integrated with a delivery system such as a ballistic missile, turning Iran into a nuclear-armed state.

Estimates of Iran's breakout time are linked to the numbers of centrifuges that it has installed at its two plants. Put simply, the larger the available enrichment capacity, the more quickly it can enrich sufficient uranium for a first nuclear weapon. This has led to a debate over the number of centrifuges Iran should be able to operate as part of a deal on the future of its nuclear program. The West demands that Iran scrap many of its already installed centrifuges, and Iran responds by pointing out that such a requirement goes beyond the requirements of the nuclear Nonproliferation Treaty (NPT). Also, Iran cites its anticipated need for a large increase in the number of centrifuges to allow it to supply the Bushehr reactor after the present contract for Russian fuel ends in 2021.

> **Using IR-1 centrifuges to attain the enrichment capacity of 100,000 SWU per year needed to fuel the Bushehr reactor would be neither efficient nor economical.**

The Current Situation

Under the Joint Plan of Action, during the six-month period of talks on a comprehensive settlement, Iran committed to

- limit the number and type of operating centrifuges to those operating as of January 20;
- not enrich uranium to a level above 5 percent U-235; and
- convert the stockpile of uranium that it has enriched to almost 20 percent into oxide, which would have to be converted back to uranium hexafluoride to be further enriched, or blend it down to uranium enriched to less than 5 percent.

The International Atomic Energy Agency (IAEA) said in its May 23, 2014, report that its inspectors had found that as of mid-May, Iran had about 10,000 IR-1 centrifuges operating at its Natanz and Fordow enrichment plants.[4] These machines are linked together in 60 cascades of 164 or 174 machines each by an intricate network of pipes that carry the uranium hexafluoride gas in three streams: feed, enriched uranium product, and depleted uranium. Each cascade has machines linked together in parallel as stages, and the stages are linked together in series. The gas is enriched by a small amount in each centrifuge in each stage and then piped to a higher stage for further enrichment or collection while depleted uranium is returned to a lower stage for re-enrichment or discharge as waste.

Along with 10,000 operating machines, about another 8,000 IR-1 machines (48 cascades) are installed but not operating at Natanz and Fordow.[5] In addition, Iran had installed at Natanz but was not operating about 1,000 IR-2m centrifuges in six cascades. Finally, in the pilot plant at Natanz devoted to research and development, relatively small numbers of IR-1, IR-2m, IR-4, and IR-6 centrifuges were operating, and a single IR-5 was installed but not operating.

Based on the number of IR-1 centrifuges that Iran has had operating and the rate and levels of enrichment of the LEU that it has produced, the IR-1 centrifuge appears to have a very low enrichment capacity, between 0.7 and 1 separative work units (SWU) per year.[6] Therefore, the estimated combined capacity of Iran's operating IR-1 centrifuges is 7,000 to 10,000 SWU per year.

The IR-2m centrifuge probably has an enrichment capacity about five times larger than that of the IR-1.[7] If so, the collective capacity of the IR-2m centrifuges that are installed but not operating is about half that of the operating IR-1 centrifuges. There appears to be no published information about the enrichment capacities of the IR-4, IR-5, or IR-6 centrifuges, which presumably all have higher capacities than the IR-2m.

The May 23 IAEA report confirmed that Iran is observing the agreed enrichment limit of 5 percent and that the uranium is in fact enriched to about 3.4 percent U-235.[8] It would take about 1,500 SWU to produce a weapon-equivalent of 90 percent-enriched uranium from this enriched uranium.[9] The length of time that would be required do this with the currently operating 10,000 IR-1 centrifuges, with their combined capacity of 7,000 to 10,000 SWU per year, is three to four months.[10] By using the rest of its installed IR-1 centrifuges, Iran could reduce this time to about two months.

Iran's Enrichment Needs

Iran's primary use of the 3.4 percent-enriched uranium that it has been producing has been as feed material to make 19 percent-enriched uranium fuel for the five-megawatt thermal (MWt) Tehran Research Reactor. A small amount has been converted to uranium dioxide for irradiation tests in that reactor of fuel rods and assemblies of the type used in the 915-megawatt electric (MWe) Bushehr power reactor.[11]

Iran's near-term practical needs for enriched uranium and, therefore, for operational enrichment capacity are relatively modest. Iran has already stockpiled enough uranium dioxide enriched to almost 20 percent to fuel the Tehran reactor for at least a decade.

Iran has announced a plan to build a 10-MWt light-water research reactor near Shiraz for which it would need LEU fuel.[12] This reactor is still in the design stage.[13] It may be part of a reported plan for perhaps four or five research reactors that, like the Tehran reactor, would probably all use 20 percent-enriched uranium fuel.[14] If Iran went ahead with these ambitious plans, it would have more high-power research reactors than any other non-nuclear-weapon state.[15] Iran would need about 1,500 SWU per year for each 10-MWt light-water research reactor that it brought into service.[16]

Iran may be interested in converting its 40-MWt Arak heavy-water reactor to use 5 percent-enriched fuel instead of natural uranium and reducing its power to 10 or 20 MWt as a way to reduce the amount of plutonium the reactor would produce in its fuel, thereby lessening proliferation concerns, while retaining the reactor's utility for making radioisotopes for medical use and carrying out scientific experiments.[17] The enrichment capacity required to fuel a 10-, 20-, or 40-MWt heavy-water research reactor with 5 percent-enriched uranium would be about 750 SWU; 1,500 SWU; or 3,000 SWU per year, respectively.[18]

Another goal, however, for Iran's enrichment program is to provide domestic enriched-uranium fuel for the Bushehr reactor after Russia's existing 10-year fuel supply contract expires in 2021.[19] To produce the 27 metric tons per year of 3.5 percent-enriched uranium to fuel that reactor,[20] Iran's enrichment capacity would have to grow to about 100,000 SWU per year, increasing its currently operating enrichment capacity more than tenfold. Looking even further ahead, Iran has been negotiating with Russia over the purchase of two more 1,000-MWe reactors.[21] In 2005, Iran's parliament passed a nonbinding resolution setting a goal of a fuel production capacity sufficient to support 20,000 MWe of nuclear power.[22]

In principle, Iran could extend its fuel supply contract with Russia in whole or in part or could buy LEU from another foreign supplier and fabricate the enriched uranium into fuel assemblies in Iran. Domestic political constraints appear to weigh against such options.[23] Iranian policymakers believe Iran has paid a huge price for its right to enrichment—in direct costs, in the lives of some of its centrifuge experts,[24] and indirectly through the economic impact of sanctions, estimated at more than $100 billion.[25]

Phasing Out the IR-1

Using IR-1 centrifuges to attain the enrichment capacity of 100,000 SWU per year needed to fuel the Bushehr reactor would be neither efficient nor economical. The IR-1 design is based on Pakistan's P-1 centrifuge, which was itself based on a design that was used in a small Dutch pilot plant but not used commercially.[26] Pakistan used the P-1 briefly before abandoning it in the mid-1980s, about the same time that Abdul Qadeer Khan's network sold it to Iran.[27] The IR-1's separative capacity of about one SWU per year is much smaller than that of centrifuges deployed in modern commercial enrichment plants, which typically use machines with an enrichment capacity of at least 10 SWU per year. The most modern centrifuge deployed by the European enrichment consortium Urenco, the TC-21, has a capacity of about 100 SWU per year.[28]

In addition, the performance of the IR-1 does not fit well with Iran's enrichment infrastructure. Iran would require at least 100,000 IR-1 centrifuges to provide sufficient enrichment capacity to meet the fuel needs of the Bushehr reactor, whereas the two Natanz centrifuge halls can hold a total of only 50,000 machines. Continuing to rely on the IR-1 would require building a second Natanz-size facility. Making use of an advanced machine, for example, a centrifuge with a capacity to produce 10 SWU per year, would allow fuel production for the Bushehr reactor with only about 10,000 machines.

Iran has recognized the logic of replacing the IR-1 with more-advanced designs. It is developing more-powerful centrifuges, but expects the process to take at least a few years to complete the R&D on the designs and begin serial production. Ali Akbar Salehi, head of the Atomic Energy Organization of Iran, explained in an interview in February,

> We have a number of advanced centrifuges, which are under the IAEA supervision where they are being tested.... Once you test the first centrifuge you will have two centrifuges; test them together and then you will have 10, 20; then you can go up to 50 and then 164. And those centrifuges will have to be working together in a cascade for a while—for probably two years to make sure that those centrifuges that have been developed are performing well enough to then be able to produce them in mass production.[29]

Iran could satisfy the needs of its current and planned research reactors by phasing out use of the operating IR-1 centrifuges and replacing them with a smaller number of IR-2m centrifuges. Assuming that each IR-2m is equal to five IR-1 machines, bringing into operation the roughly 1,000 IR-2m centrifuges already installed would be more than sufficient to supply 5 percent-enriched LEU for fueling the Arak reactor after it had been converted to run on fuel of that enrichment level. Even if Iran were able to complete construction of its planned four 10-MWt light-water research reactors before 2019, it would not need to install more than an additional 1,000 IR-2m centrifuges to meet their fuel needs. Also, Iran should extend indefinitely its current commitment under the Joint Plan of Action to convert to oxide any newly enriched uranium hexafluoride

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Different types of centrifuges are displayed during a technology exhibition in Tehran in February.

product and commit to convert all its enriched uranium hexafluoride within two or three months of production.

Store Centrifuges as Parts

To meet the goal of having an enrichment capacity sufficient to fuel and to make and hang the cascade piping required to operate them. Even a large number of machine components in Iran would not significantly shorten the time to a first nuclear weapon below the breakout time determined by the machines already operating at Natanz.

advanced centrifuges and deploys them in numbers required to support a significant nuclear power program, then its breakout time would become very short. If Iran decided to produce weapons-grade uranium, even a plant with an enrichment capacity

Iran could begin to manufacture the required number of [next-generation] centrifuge components for the targeted SWU capacity and store them under IAEA supervision at a central location.

the Bushehr reactor by 2021, when the current fuel-supply contract with Russia ends, Iran could continue to develop and test next-generation centrifuges such as the IR-4, IR-5, or IR-6 in an R&D facility. As Salehi explained, it could take years to test a reasonable number of machines of the chosen design to ensure that the individual components and overall machine design and operation are reliable and that the centrifuge performance is well understood.

After selecting one or more advanced centrifuge models that meet the standards for commercial-scale operation in terms of separative performance and long-term reliability, Iran could begin to manufacture the required number of centrifuge components for the targeted SWU capacity and store them under IAEA supervision at a central location. The key components requiring monitoring would include centrifuge rotors and casings.

Iran could agree to refrain from making preparations for the installation of these centrifuges. This would include not assembling and balancing more centrifuges than required for testing and not making preparations for hanging cascade piping. The IAEA could verify these steps.

An inventory in Iran of components sufficient for perhaps 10,000 next-generation centrifuges need not be of great international concern. Because they would be under IAEA monitoring, removal of components from storage would be quickly detected. A reasonable estimate is that it would take at least six months thereafter to assemble and balance a thousand of these centrifuges

To build international confidence in this arrangement, Iran should ratify an additional protocol to its safeguards agreement with the IAEA, as envisioned in the Joint Plan of Action. This would elevate its safeguards system to the highest current standard under the international NPT safeguards regime.[30] Iran could commit to continue indefinitely with the transparency measures it has accepted under the Joint Plan of Action. These measures include managed access for the IAEA "to centrifuge assembly workshops, centrifuge rotor production workshops and storage facilities."[31] Iran accepted similar monitoring arrangements under Presidents Mohammad Khatami and Mahmoud Ahmadinejad from November 2003 until February 2006 when the IAEA Board of Governors referred Iran's case to the UN Security Council.[32] These transparency measures could become an international standard for centrifuge production worldwide.

Toward a Long-Term Solution

An approach that involves transparently phasing out the IR-1 centrifuges and replacing them with IR-2m centrifuges while conducting R&D on more-advanced, next-generation centrifuge designs and manufacturing them as needed could provide an interim solution for the negotiations on Iran's enrichment capacity. The United States and some of Iran's neighbors may remain concerned, however, that Iran's program to develop advanced centrifuges could exacerbate the proliferation risk in the longer run.

If Iran succeeds in developing

of 100,000 SWU per year, which is very small by commercial uranium-enrichment industry standards, could churn out tens of bomb equivalents per year after the centrifuge cascades had been reconnected for this purpose. In addition, the more efficient a centrifuge, the fewer that would be required to equip a clandestine facility that could produce weapons-grade uranium at a significant rate.

These problems are not specific to Iran. They represent the general challenge that national gas-centrifuge enrichment programs all over the world pose to the current international nonproliferation and disarmament regime.[33] At the same time that a solution to the confrontation over Iran's nuclear program is being developed, it would be wise to begin dealing with the underlying problem rather than continue to face crisis after crisis.

One option would be for the P5+1 and Iran to agree as part of the final comprehensive solution to embark immediately on designing a new, permanent transparency regime for centrifuge manufacturing and operation and a regime that includes a ban on reprocessing and effective multinational arrangements for enrichment in the Middle East, reducing the risk of future Middle Eastern nuclear crises.[34] Assuming that Iran and the P5+1 can sign the final deal to be operationalized by early 2015, they could immediately establish a working committee on multilateralization of enrichment in the Middle East. One requirement for such an arrangement could be that the same country cannot manufacture the centrifuges and host the centrifuge facility.

The idea that a multinational arrangement for uranium enrichment could be part of the resolution of the dispute with Iran is well established. In 2004, during the first cycle of negotiations over the future of Iran's nuclear program, IAEA Director-General Mohamed ElBaradei invited a group of experts, including one from Iran, to consider multinational alternatives to national enrichment and reprocessing programs. The expert group's report was published in February 2005.[35] In September 2005, at the UN General Assembly, Ahmadinejad stated that Iran was willing to participate in such an arrangement.[36]

Multilateralizing Iran's enrichment program would establish a new standard for managing the risks from uranium-enrichment plants worldwide. Such a step would be consistent with a larger international trend away from national enrichment plants. Today, only three non-nuclear-weapon states (Brazil, Iran, and Japan) operate autonomous enrichment plants. In 1971, Germany and the Netherlands folded their national plants into Urenco, the multinational European consortium that also includes the UK.

Among the nuclear-weapon states, France, the UK, and the United States no longer have fully national enrichment programs.[37] All have ended their enrichment of uranium for military purposes and have commercial plants equipped with centrifuge technology delivered on a "black box" basis—that is, without access to the technology. The centrifuges are produced by the Enrichment Technology Company, which is jointly owned by Urenco and France's Areva.

Devising arrangements for black-box multinational enrichment in the Middle East and globally would be challenging technically, legally, and politically. Yet, one lesson from the decade-long dispute over Iran's enrichment program is that national enrichment programs in Middle Eastern countries would be at least as challenging.

A strategy for matching Iran's separative capacity with its needs over the next five years while Tehran develops more-advanced centrifuges but does not deploy them until needed would not shorten Iran's breakout time, but would enable Iran to prepare in a timely way to meet its possible needs for enriched-uranium fuel for its nuclear research and power reactors. Such a strategy could create a window of time to devise a multinational arrangement that could provide a long-term solution to the proliferation concerns raised by national enrichment plants in the Middle East and elsewhere.

ENDNOTES

1. Steven Erlanger, "Nuclear Talks With Iran Fail to Yield Pact, Officials Say," *The New York Times*, May 16, 2014.

2. See International Atomic Energy Agency (IAEA), "Communication Dated 27 November 2013 Received From the EU High Representative to the Agency Concerning the Text of the Joint Plan of Action," INFCIRC/855, November 27, 2013 (contains the Joint Plan of Action as an attachment) (hereinafter Joint Plan of Action).

3. Jay Solomon and Laurence Norman, "Obama Administration Shows Optimism on Iran Nuclear Talks," *The Wall Street Journal*, April 7, 2014.

4. IAEA, "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions in the Islamic Republic of Iran," GOV/2014/28, May 23, 2014 (hereinafter May 2014 IAEA report on Iran).

5. Ibid.

6. Between November 5, 2013, and February 9, 2014 (96 days), Iran fed 8,345 kilograms of unenriched uranium hexafluoride into 9,400 IR-1 centrifuges at Natanz and produced 754 kilograms of uranium hexafluoride (510 kilograms uranium) enriched to less than 5 percent uranium-235. The ratio of input to output (11.1) is consistent with a product enrichment of 3.4 percent and a depleted uranium assay of 0.45 percent. Based on those assumptions, the amount of embedded enrichment would be 2,511 separative work units (SWU) or 0.267 SWU per centrifuge. For 365 days, that would be about 0.7 SWU per IR-1 centrifuge. Researchers at the Institute for Science and International Security (ISIS) calculated 0.74 SWU per year for the same reporting period based on the assumption that the assay of Iran's depleted uranium is 0.4 percent. The IR-1's range of performance for the production of almost 20 percent-enriched uranium is somewhat higher: 0.8-1.0 SWU per year. See David Albright, Christina Walrond, and Andrea Stricker, "ISIS Analysis of IAEA Iran Safeguards Report," ISIS, February 20, 2014, http://www.isisnucleariran.org/assets/pdf/ISIS_Analysis_IAEA_Safeguards_Report_20February2014-Final.pdf.

7. This assumes that the IR-2m centrifuge is based on Pakistan's P-2 centrifuge. See Alexander Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation (corrected)," *Science and Global Security*, Vol. 16, Nos. 1-2 (2008): table 1. See also David Albright and Christina Walrond, "Iran's Advanced Centrifuges," ISIS, October 18, 2011, http://isis-online.org/isis-reports/detail/irans-advanced-centrifuges.

8. The IAEA's discussions of Iran's uses of Iranian uranium enriched to less than 5 percent as a reactor fuel or as a feed to produce uranium enriched to almost 20 percent specify it as enriched to 3.4 or 3.5 percent. See, for example, IAEA, "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions in the Islamic Republic of Iran," GOV/2012/23, May 25, 2012, para. 24; IAEA, "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions in the Islamic Republic of Iran," GOV/2013/40, August 28, 2013, para. 64; May 2014 IAEA report on Iran, tables 2, 4.

9. As a weapon-equivalent—the amount of material required to make one nuclear weapon—this calculation uses the IAEA's "significant quantity": a quantity of uranium enriched to 20 percent or more (90 percent in this case) in U-235 containing 25 kilograms of chain-reacting U-235. The calculation assumes that the depleted uranium from the process of raising the enrichment level from 3.4 percent to 90 percent would contain 0.7 percent U-235.

10. This calculation assumes that two weeks would be required to connect the cascades to produce the highly enriched uranium. For a detailed discussion of various possible breakout scenarios, see Patrick Migliorini et al., "Iranian Breakout Estimates: Updated September 2013," ISIS, October 24, 2013, http://www.isisnucleariran.org/assets/pdf/Breakout_Study_24October2013.pdf. The calculations for the present article assume that no significant

amount of 19 percent-enriched uranium would be available for this breakout scenario.

11.As of May 23, 2014, Iran had produced 11,870 kilograms of uranium hexafluoride enriched to less than 5 percent. See May 2014 IAEA report on Iran, table 1. Of this amount, 3,437 kilograms had been used to produce uranium enriched up to 20 percent, and 24 kilograms had been converted to uranium dioxide for test fuel. Ibid., tables 1, 3.

12. Ibid., fn. 12.

13. "Iran Designing 10MW Nuclear Research Reactor," Fars News Agency, May 3, 2014.

14. IAEA, "Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions in the Islamic Republic of Iran," GOV/2011/29, May 24, 2011 (citing "Iran Will Not Stop Producing 20% Enriched Uranium," *Tehran Times*, April 11, 2011).

15. See IAEA Research Reactor database, http://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx?rf=1. "High power" is defined as reactors with power of 10 megawatts thermal (MWt) or more.

16. Ten MWt of light-water research-reactor capacity with 40 percent U-235 consumption ("burn-up") would require about 45 kilograms of 20 percent-enriched uranium, which would require about 1,500 SWU per year to produce, assuming 0.4 percent depleted uranium. The residence time of the fuel in the core would be about 1.2 years. Alexander Glaser, "On the Proliferation Potential of Uranium Fuel for Research Reactors at Various Enrichment Levels," *Science and Global Security*, Vol. 14, No. 1 (2006): table 4.

17. Ali Ahmad et al., "A Win-Win Solution for Iran's Arak Reactor," *Arms Control Today*, April 2014.

18. Assuming 300 days per year of operation, the Arak heavy-water reactor operated at 20 MWt would require about 200 kilograms of 5 percent-enriched uranium per year (about 1,500 SWU per year). The amounts for operation at 10 MWt and 40 MWt would be about half as much and twice as much, respectively. One-third of the core would be refueled each year. Ibid.

19. Bushehr-1 was first connected to the grid on September 3, 2011. Commercial operations did not begin until September 23, 2013. IAEA, Power Reactor Information System, June 14, 2014, http://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=IR.

20. Atomic Energy Organization of Iran, "Bushehr Power Plant Fuel Reserve Was Replaced," March 11, 2014.

21. "Tehran, Moscow Work Out Deal for Building 2 More N. Power Plants in Iran," Fars News Agency, March 12, 2014.

22. Neil MacFarquhar, "Iran Parliament Calls for Resuming Nuclear Fuel Development," *The New York Times*, May 16, 2005.

23. "A senior Iranian official asked: 'After all our investment in blood and treasure, the West now expects us to rely on them for our fuel needs?'" "Iran and the P5+1: Solving the Nuclear Rubik's Cube," *International Crisis Group Middle East Report*, No. 152 (May 9, 2014), n. 93.

24. On the assassination of Iranian scientists, see Alan Cowell and Rick Gladstone, "Iran Reports Killing of Nuclear Scientist in 'Terrorist' Blast," *The New York Times*, January 11, 2012.

25. Ali Vaez and Karim Sadjadpour, "Iran's Nuclear Odyssey: Costs and Risks," Carnegie Endowment for International Peace, 2013, http://carnegieendowment.org/files/iran_nuclear_odyssey.pdf.

26. Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation (corrected)."

27. On Iran's acquisition of the drawings and components for its first IR-1 centrifuges, see IAEA, "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran," GOV/2006/63, August 26, 2003, paras. 30, 31.

28. Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation (corrected)," table 1.

29. "Iran Has Scored Major Achievements in Peaceful Nuclear Development: Dr. Salehi (Part 1)," Press TV, February 5, 2014 (interview with Ali Akbar Salehi, head of the Atomic Energy Organization of Iran).

30. By ratifying an additional protocol, a country commits to report nuclear-related activities and sites even if they do not involve nuclear material. The production of centrifuges for uranium enrichment is a key example. The 1997 Model Additional Protocol was developed after the discovery of Iraq's clandestine uranium-enrichment program in 1991.

31. May 2014 IAEA report on Iran, para. 32.

32. See, for example, IAEA, "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran," GOV/2004/11, February 24, 2004, para. 68 ("Between November 2003 and mid-January, Iran continued to assemble centrifuges. During that time, Iran assembled some 120 centrifuges [in addition to the 800 centrifuges which had been produced prior to November 2003], which have been counted by the Agency. These, and any centrifuges assembled since mid-January 2004, will now be placed under Agency seal"); IAEA, "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran," GOV/2005/67, September 2, 2005, para. 54 ("Prior to 22 November 2004, the Agency had already established a baseline inventory of all UF_6, essential centrifuge components, key raw materials and equipment, and the assembled centrifuge rotors at declared workshops said by Iran to have been involved in the manufacturing of centrifuge components, and had applied containment and surveillance measures to these items").

33. Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation (corrected)."

34. Frank N. von Hippel et al., "Fissile Material Controls in the Middle East: Steps Toward a Middle East Zone Free of Nuclear Weapons and All Other Weapons of Mass Destruction," International Panel on Fissile Materials, October 2013, http://fissilematerials.org/library/rr11.pdf.

35. IAEA, "Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report Submitted to the Director General of the International Atomic Energy Agency," INFCIRC/640, February 22, 2005.

36. Islamic Republic of Iran Permanent Mission to the United Nations, "Address by H.E. Dr. Mahmood Ahmadinejad, President of the Islamic Republic of Iran Before the Sixtieth Session of the United Nations General Assembly," September 17, 2005, http://www.un.org/webcast/ga/60/statements/iran050917eng.pdf.

37. Two U.S. companies, USEC and General Electric, however, have been conducting research and development on centrifuge and laser enrichment, respectively.

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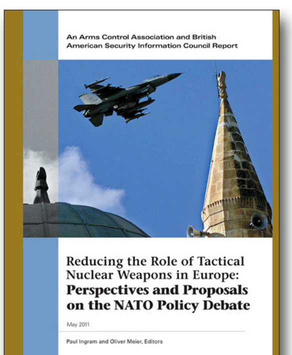

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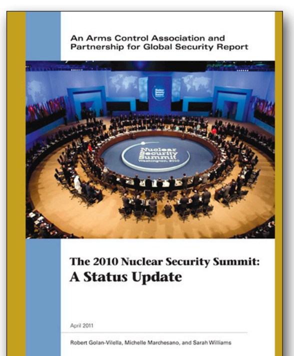

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