Comments on the Princeton Group's Proposal on Iran

ISIS

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At the core of a recent set of proposals by Alexander Glaser, Zia Mian, Hossein Mousavian, and Frank von Hippel of Princeton University, titled "Agreeing on Limits for Iran's Centrifuge Program: A Two-Stage Strategy," published by the Arms Control Association, is an acceptance that Iran should be able to build, while negotiating a second phase to a long term agreement in the next five to seven years, enough newer-generation advanced centrifuges so that by 2021 it could produce sufficient enriched uranium to fuel a commercial nuclear power reactor. This is a massive enrichment capacity. Enabling the creation of such a capacity during the period of a long term agreement may be consistent with Iran's negotiating position, but it is way outside the bounds of the positions of the United States and its allies.

This proposal is a variation of Iran's oft-stated demand that an agreement must not interfere with its ability to establish a large enrichment program capable of providing enough low enriched uranium (LEU) to fuel the Bushehr power reactor. This reactor was supplied by Russia and has a capacity of 1,000 megawatts-electrical or a power 100 times larger than that of the Arak heavy water reactor. But the P5+1 have consistently rejected this Iranian demand as unjustified since Russia or another supplier can reliably supply this fuel for the life of this reactor. In fact, Russia may insist on providing fuel for the reactor out of liability concerns. In addition, such a rapidly growing enrichment capability would significantly worsen the threat posed by Iran's nuclear programs long before confidence could be restored that Iran will not misuse this program to build nuclear weapons. An enrichment plant this size would allow Iran to break out using low enriched uranium and produce enough weapon-grade uranium for a bomb in a matter of days. This breakout time is far shorter than the roughly 12 month timeframe sought by the United States. Thus, the fundamental goal of the Princeton proposal—namely, laying the basis for a large enrichment program during the period of the agreement—is at odds with the positions of the United States and its allies.

The Princeton Group does caveat its commercial-scale enrichment proposal by suggesting the creation of a multilateral, regional enrichment facility in the Middle East which would be negotiated after a first phase final agreement, or during the next five to seven years. Among many issues making this part of the proposal unlikely, which we will not discuss here, is the central issue of what happens if such a multilateral arrangement is never created? Iran would be left with a stock of more advanced centrifuges and a greatly reduced breakout timeline, with no follow-on agreement to limit their deployment in Iran.

The proposal, which appears heavily influenced by the Iranian government's point of view, does have some intriguing aspects. One element is to phase out Iran's more than 18,000 IR-1 centrifuges and replace a fraction of their total enrichment capacity with the more advanced IR-2m centrifuges. About 1,000 of the IR-2m centrifuges in six cascades are already installed at the Natanz Fuel Enrichment Plant, although they have never enriched uranium. To be consistent with the U.S. position, it would be necessary to limit the total enrichment capacity of the installed IR-2m centrifuges to below 3,000-4,000 separative work units (swu) per year, where the IR-2m centrifuge is estimated by ISIS to have an average capacity of 3-5 swu per year, but tending toward the middle and lower bound of this estimate. Under this cap, Iran would install a total of no more than 600-1,300 IR-2m centrifuges, where the range reflects uncertainties about the actual enrichment output of the IR-2m centrifuges, which after all have not yet been fully developed. (One question is whether the authors, one of whom is a former Iranian official, have queried the Iranian atomic establishment over whether the IR-2m centrifuges are yet ready to replace the IR-1 centrifuges.) Nonetheless, an advantage of this approach is that there would be no need to keep the old IR-1 centrifuges, and they could be scrapped. This would eliminate the need to store them, a thorny issue in the negotiations.[1] If this switch in centrifuge types were done at the start of the implementation of the comprehensive solution, it could provide Iran a face saving way to make the cuts in its enrichment program that are essential if there is to be an agreement. But if the switch cannot happen for a few years, or the success of the IR-2m centrifuge is in doubt, the value of this element diminishes greatly. The negotiators would still need to obtain a sharp, initial reduction in the numbers of IR-1 centrifuges and decide on the immediate fate of the excess ones.

The Princeton paper serves to highlight the difficult issue of the nature of limiting Iran's centrifuge research and development (R&D) program during the duration of a second phase comprehensive agreement. As discussed above, the authors prefer a somewhat open-ended program aimed at developing more sophisticated centrifuges than the IR-2m. But again, these more advanced centrifuges are unlikely to be commercially viable compared to those built by Russia and URENCO, the European enrichment consortium. (As the authors note, URENCO's TC-21 centrifuge, by comparison to the 3-5 swu per year IR-2m, has a capacity of 100 swu per year.)[2] From that point of view, Iran's investment in a large centrifuge R&D program makes little economic sense. In addition, Iran's development of more advanced centrifuges, albeit of

[1] See David Albright, Olli Heinonen, and Andrea Stricker, *Five Compromises to Avoid in a Comprehensive Agreement with Iran*, ISIS Report, June 3, 2014.

[2] Although Russia's enrichment program uses centrifuges with separative capacities far less than Urenco machines, it has over decades built millions of them and absorbed their development and deployment costs during the Cold War, when their purpose was to make highly enriched uranium for nuclear weapons and cost was not much of an issue.

order of 10 swu per year, could complicate verification of a comprehensive agreement significantly. On balance, ISIS has recommended more stringent limitations on Iranian centrifuge R&D activities during the duration of the comprehensive solution (the appendices contain a technical discussion of these recommended limits).[3]

Acceptance of Large Enrichment Capacity has Negative Implications

Without providing a justification, the authors appear to accept that a long term agreement must accommodate the establishment of this large Iranian enrichment capability by 2021, when Russia's first ten year contract to provide LEU fuel to the Bushehr reactor ends. However, other than quoting official Iranian justifications, based heavily on national pride, that they have invested too much money and costs from sanctions into their enrichment program, the authors offer no credible reason for Iran not to renew its contract with Russia. In addition, by accepting this artificial deadline, the Princeton proposal seems to accept the idea that if a final deal is achieved, the limits on enrichment capacity would last only five to seven years, which is again in sharp contrast to the duration that the Unites States and its allies are seeking.

The United States wants the duration of the deal to be much longer, and during this period, Iran would be limited to a minimal enrichment program--certainly not one sized to make components for thousands of centrifuges. Iran needs to prove its compliance with the Nuclear Non-Proliferation Treaty and its intentions to have only a peaceful nuclear program. It has been in non-compliance with its safeguards obligations for twenty years and it must demonstrate its compliance over an extended period of time. As underlined by Olli Heinonen, former Deputy Director General of Safeguards at the International Atomic Energy Agency (IAEA), "Due to the fact that Iran has been running parts of its nuclear [program] first clandestinely and then without satisfactorily fulfilling its reporting obligations to the IAEA and disregarding UN Security Council resolutions, the onus of proof bears heavily on Iran to show that its nuclear program is entirely peaceful."[4] The United States wants Iran to establish and demonstrate this compliance in an agreement that lasts twenty years or longer, so seven years is woefully inadequate to do so. The authors offer no rationale for such a short period for an agreement other than stating that it is what Iran wants.

The proposal would also enormously complicate verification aimed at ensuring the absence of undeclared centrifuge plants. It would enshrine Iran having a large centrifuge manufacturing complex, which would be, in the best of circumstances, difficult to monitor in order to provide assurance that centrifuges are not being made in secret. Undermining the proposal further, the

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[3] For the originally proposed limits on centrifuge R&D, see *Defining Iranian Nuclear Programs in a Comprehensive Solution under the Joint Plan of Action*, Institute for Science and International Security, January 15, 2014. http://www.isisnucleariran.org/assets/pdf/Elements_of_a_Comprehensive_Solution_20Jan2014_1.pdf

[4] Testimony of Olli Heinonen, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, on 10 June 2014, before the House Committee on Foreign Affairs. http://belfercenter.ksg.harvard.edu/publication/24303/olli_heinonens_testimony_on_verifying_irans_nuclear_compliance.html?breadcrumb=%2Fpublication%2F22658%2Fcritical_monitoring_and_verification_issues_in_northeast_asia

verification arrangements recommended by the authors—the current ones in place under the Joint Plan of Action—are minimal, and contrary to what they state, far less strict than the ones existing during the enrichment suspension from 2003-2006. These minimal verification conditions reflect again Iranian views about verification that are seen as inadequate.[5]

The authors recognize that Iran is unlikely to be able to deploy enough IR-1 centrifuges to establish a capability to provide LEU fuel for the Bushehr reactor. Iran planned originally that it would need 50,000 IR-1 centrifuges to produce enough LEU for the Bushehr reactor but the centrifuges have not worked well. Today, based on the operating history of these centrifuges, Iran would need over 100,000 IR-1 centrifuges to provide the minimal amount of LEU needed to fuel Bushehr. Iran would need to make almost 15,000 IR-1 centrifuges a year to establish this large plant by 2021.[6] Their proposal appears motivated to provide Iran a more practical way to achieve its goal by 2021.

The authors would clearly prefer that if Iran were to expand its enrichment capacity greatly, it would use a more advanced and reliable centrifuge than the IR-2m centrifuge, one that would have an enrichment output of 10 separative work units (swu) a year. But in any case, if Iran succeeds in building this more advanced centrifuge, the risks would not diminish. In fact, as the authors do acknowledge and hence their recommendation that the centrifuges be used in a multinational enrichment plant, Iran would need far fewer of these centrifuges in a clandestine plant to make weapon-grade uranium than in one using IR-1 centrifuges. A similarly sized plant to one with IR-1 centrifuges would need ten times fewer centrifuges. Thus, armed with more advanced centrifuges Iran would have an easier time hiding a covert plant than if it had to use IR-1 centrifuges. This fact would place additional strains on the verification system.

Moreover, nothing in the proposal appears to prevent Iran from building thousands more IR-2m centrifuges instead of a more advanced machine, if it were to choose that route to having a plant able to meet the needs of Bushehr by 2021. The authors envision Iran using no more than 2,000 IR-2m machines to produce fuel for a modified Arak reactor and perhaps up to four research reactors during a first phase of the proposal (research reactors which are, in any case, highly unlikely to be built soon). But Iran may in fact be far more motivated to use the IR-2m centrifuges in lieu of the more advanced centrifuge to meet the goal of commercial-scale deployment by 2021. Iran could take many years to develop a reliable 10 swu per year centrifuge and fail to meet the deadline as a result. Whether Iran could manufacture reliably such advanced centrifuges on a mass scale also remains unknown. However, as mentioned above, Iran has installed about 1,000 IR-2m centrifuges underground in the Natanz Fuel

[5] For a discussion of the verification required, see Testimony of Olli Heinonen, op. cit.

[6] Although in practical terms, Iran would be severely challenged to build so many centrifuges, the economics of choosing this route versus choosing an advanced centrifuge route is a difficult question not addressed in this report. On the surface, it appears not to be economic, as the authors assert; but it may be economic to go with the IR-1 centrifuges after including all the development costs of more advanced centrifuges and the risks that the investment may not pay off in terms of a suitably advanced machine. These considerations may also favor the deployment of the IR-2m rather than a more advanced centrifuge, if the goal is a large plant by 2021.

Enrichment Plant (although they are not enriching per the interim agreement of the Joint Plan of Action). Thus, Iran already has experience manufacturing IR-2m centrifuges, so ramping up production could be more straightforward, particularly if sanctions on Iran's importation of key raw materials are loosened or removed. Since the proposal appears to allow the components to be pre-produced, starting as soon as Iran wants, Iran would be further motivated to build IR-2ms centrifuges as its main production model while still developing more advanced ones.

How many IR-2m centrifuges would be needed to reach the equivalent production capability of the IR-1? As mentioned above, at ISIS we assign an IR-2m centrifuge a separative work capacity of 3-5 separative work units per year. The Princeton group assigns five times the swu capability of the IR-1; they did not give a specific value. Here we will use the 5 swu/year value, but the use of this value may underestimate the number that would need to be built. With that caveat in mind, Iran would need to deploy 20,000 IR-2m centrifuges by 2021 to achieve the equivalent capability of 100,000 IR-1 centrifuges to meet the goal of fueling the Bushehr reactor. For a more advanced centrifuge with a capacity of 10 swu per year, the number would fall to 10,000 centrifuges. The decrease in numbers also shows the advantages of more advanced centrifuges in building a clandestine centrifuge plant, and without adequate verification the possibility of a fast, covert breakout would be real.

These numbers, in any case, would imply a large yearly centrifuge component production rate. Under this proposal, over the next five to seven years, Iran would gain a green light to make on average annually 3,000-4,000 IR-2m centrifuges (if there were no cap on their production) or annually 1,500-2,000 more advanced centrifuges each with a capacity of up to twice that of the IR-2m centrifuge. The authors propose that this massive manufacturing capability and rate be endorsed by the P5+1, despite the lack of economic need and the enormous risks to U.S. and international security.

If this proposal stated that after a more reasonable amount of time, perhaps 15-20 years, Iran could start making more centrifuges at the end of the agreement, then this proposal would be valuable. It would also add value if it had proposed capping the number of IR-2m centrifuges at 600-1,300 and 3,000-4,000 swu per year, in a switch out of the IR-1 machines. But as it is presented, the proposal has many holes that could be exploited by Iran to maintain a large, difficult to monitor breakout capability. And while the advantages to Iran are clear, namely maintaining a large breakout capability under the justification of a large enrichment program, the advantages of this proposal for the United States and its allies are absent in the negotiation of a sound, long term agreement.

Appendix 1 Centrifuge R&D Limitations

Based on discussions at ISIS workshops, several limitations on centrifuge research and development (R&D) were identified that should be placed on an Iranian centrifuge R&D program.

- The speed of the rotor assembly should be limited to no more than 500 m/s
- The total effective rotor assembly length should be no more than 1.2 meters
- The limit on total separative work for a centrifuge is difficult to define in an unambiguous manner. It could also involve data that Iran may view as sensitive or proprietary, complicating a comparison. As an alternative, or a supplement to the approach in the first two bullets, it is possible to define a limit via a theoretical maximum separative capacity, or power, calculation (see appendices 2 and 3). These values would fundamentally depend on rotor speed and length and provide a method of comparison. However, it must be kept in mind that the actual separative capacity could be significantly less, as is the case of the IR-1 centrifuges deployed at Natanz and Fordow. Based on the formula in appendix 2, and the values in the first two bullets, the cap under this approach would be 6.8 swu per year.
- The size of test cascades would be limited; the allowed maximum number of centrifuges in a test cascade would be a small fraction of the number of centrifuge in a cascade designed to produce 5 percent low enriched uranium (LEU). This fraction would account for more advanced machines possibly needing fewer enrichment stages, and thus fewer centrifuges, to produce 3.5-5 percent LEU. In the case of the IR-1 centrifuges, Iran produces 3.5-5 percent LEU in production-scale cascades containing 164-174 centrifuges organized in 15-17 stages, respectively. Test IR-1 cascades typically have involved about 20 or fewer IR-1 centrifuges. The ratio of centrifuges in test cascades (20 IR-1's) to the number is a production-scale cascade (164-174) is about 0.11-0.12. A similar ratio would be developed for advanced centrifuges and would serve to define the maximum number of centrifuges in test cascades.
- The agreement on centrifuge R&D would include a review and adjustment condition that could modify the limits, subject to mutual agreement.
- Iran would declare all nuclear-related centrifuge R&D facilities, including those not using nuclear material, and subject those facilities and activities to additional, agreed upon monitoring.

Appendix 2: Background on Theoretical Maximum Centrifuge Capacity

Defining a SWU Limit Based on Physical Parameters

Separative Power Estimation:

Following the derivation in appendix 3, a maximum separative power of a counter-current gas centrifuge can be estimated by

$$\delta U = \frac{HV^2}{43882}\ (swu/yr) \tag{1}$$

where *H* is the separative length, or effective length, of the centrifuge in meters and *V* is the wall speed in meters per second.

This equation is of course an estimate and may not be exactly correct (in fact, parameters have been chosen to predict a greater separative power), but allows for a simple way of setting a swu limit based on physical parameters. Table 1 shows the estimated separative power for a few selected centrifuges, where length and wall speed are for most models only approximated.

Table 1: Approximate Estimated Separative Power of Selected Gas Centrifuges

Centrifuge	Length (m)	Wall Speed (m/s)	Separative Power (swu/yr)
Zippe	0.30	360	0.886
P1	2.00	350	5.580
IR-1	2.00	330	4.930
IR-2m	1.25	480	6.563
TC-10 type	3.20	500	18.23

The actual, achieved separative power will be lower reflecting additional inefficiencies in the centrifuges when running as individual machines and in cascades. For example, The Zippe centrifuge achieved a maximum of 0.6 swu/year, according to Zippe. The IR-1 centrifuge achieves an average separative power in cascades of less than one swu/year, significantly less than its theoretical maximum separative power of 4.9 swu/year. Although its value when run individually is greater, it is still far below the theoretical value, even accounting for the fact that the separative length of the IR-1 centrifuge is somewhat less than given in the table. Not only do additional inefficiencies in this model reduce its actual separative power but it also experiences a relatively high breakage rate, which accounts for much of the additional reduction of its separative power when run in production cascades.

Appendix 3: Theoretical Maximum Separative Power

The theoretical maximum separative power that a gas centrifuge can achieve is calculated by

$$\delta U = \frac{\pi \rho D H}{2}\left[\frac{\Delta M V^2}{2R_u T_0}\right]^2 \tag{2}$$

where *H* is the separative length of the centrifuge, *ΔM* is the mass difference between U_{235} and U_{238}, *V* is the wall speed, R_u is the universal gas constant, T_0 is the average gas temperature, and *ρD* is the product of the gas density and self-diffusion coefficient. For UF_6 this product is a function of temperature alone

$$\rho D(T_0) = \left(2.756 \cdot 10^{-6}\right) + (6.349 \cdot 10^{-8})T_0 + (1.33 \cdot 10^{-11})T_0^2 + (-1.725 \cdot 10^{-14})T_0^3 \tag{3}$$

The maximum separative power is never achievable and the actual separative power is determined by the centrifuge efficiency

$$\delta U_{act} = E \cdot \delta U_{max} \tag{4}$$

The separative efficiency of a countercurrent gas centrifuge is the product of four factors: the flow pattern efficiency (e_F), the circulation efficiency (e_C), the ideality efficiency (e_I), and the experimental efficiency (e_E)

$$E = e_F \cdot e_C \cdot e_I \cdot e_E \tag{5}$$

The flow pattern efficiency depends on the shape of the axial velocity profile. For a flow driven by a linear temperature gradient along the wall, the flow pattern efficiency can be determined by

$$e_F = \frac{7.2}{A^2} \tag{6}$$

where A^2 is the stratification parameter (or speed parameter) of the centrifuge, defined as

$$A^2 = \frac{MV^2}{2R_u T_0} \tag{7}$$

where *M* is the mass of UF_6.

The circulation efficiency represents the loss of separative capacity due to axial diffusion working against axial convection and is defined as

$$e_C = \frac{m^2}{1 + m^2} \tag{8}$$

where m is the circulation rate.

The ideality efficiency represents the difference between the shape of the square cascade representation of the centrifuge and an ideal cascade. It accounts for mixing of concentrations and suboptimal operation of the centrifuge. It can be shown that the maximum value for this efficiency is 0.8145.

The experimental efficiency includes phenomena not captured in the flow model, diffusion model, or other efficiencies. Here it is taken to be 1.

Assuming an average gas temperature of T_0 = 300 K and a circulation rate of $m = \infty$, the separative power of a gas centrifuge can be estimated as

$$\delta U = \frac{HV^2}{43882} \ (swu/yr) \tag{9}$$

where H is in meters and V is meters per second.