Centrifuge Research and Development Limitations in Iran[1]

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Iran's centrifuge research and development (R&D) program poses several risks to the verifiability of a comprehensive solution under the Joint Plan of Action. Negotiations on a comprehensive solution should seek to place further limitations on this program and establish effective and expanded monitoring practices as part of an agreement on a mutually defined enrichment program with agreed parameters. Throughout the duration of a long-term comprehensive agreement, Iran's centrifuge R&D program should be limited to centrifuges with capabilities comparable to the current IR-2m centrifuge.

An open-ended Iranian centrifuge R&D program aimed at developing more sophisticated centrifuges than the IR-2m makes little economic sense. Iran will not be able to produce enriched uranium competitive with that produced by exporting countries such as Russia or URENCO during the next several decades, if ever. Therefore, Iran's investment in a large centrifuge R&D program would be a waste of time and resources. Moreover, the goal of a long-term agreement is to eventually integrate Iran into the international civilian nuclear order (even as a non-exporting producer of enriched uranium). This integration would render mute Iran's claims for self-sufficiency in enriched uranium production or for continuing the program out of national pride.

A long-term agreement should reinforce sound economic principles universally accepted in the world's nuclear programs, all of which are deeply interconnected through an international supply chain based on reactor suppliers and enriched uranium fuel requirements. Building an agreement catering to open-ended, economically unrealistic ambitions is both unnecessary and counterproductive, and also sets dangerous precedents for other potential proliferant states.

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[1] This technical discussion of limits on an Iranian centrifuge R&D program first appeared as appendices in another longer ISIS report critiquing a proposed negotiating offer.

Iran's development of more advanced centrifuges would also significantly complicate the verification of a long-term agreement. In a breakout or cheating scenario, Iran would need far fewer of these advanced centrifuges in a clandestine plant to make weapon-grade uranium than in one using IR-1 centrifuges. For example, Iran recently [claimed](#) it has done initial work on a centrifuge, called the IR-8, reportedly able to produce enriched uranium at a level 16 times greater than the IR-1 centrifuge. Such a centrifuge, if fully developed, would allow Iran to build a centrifuge plant with one sixteenth as many centrifuges. Currently, Iran has about 18,000 IR-1 centrifuges and in a breakout it could produce enough weapon-grade uranium for a nuclear weapon in about two months, according to both [U.S.](#) and [ISIS](#) estimates. So, instead of needing 18,000 IR-1 centrifuges to achieve this rapid production of weapon-grade uranium, it would need only 1,125 advanced ones to produce as much weapon-grade uranium in the same time. Thus, equipped with more advanced centrifuges Iran would need far fewer centrifuges than if it had to use IR-1 centrifuges, permitting a smaller, easier to hide centrifuge manufacturing complex and far fewer procurements of vital equipment overseas. If Iran made the decision to break out to nuclear weapons, the advanced centrifuges would greatly simplify its ability to build a covert centrifuge plant that would be much harder to detect in a timely manner allowing an international response able to stop Iran from succeeding in building nuclear weapons.

Advanced centrifuges bring with them significant verification challenges that complicate the development of an adequate verification system. Even with an intrusive system that goes beyond the Additional Protocol, International Atomic Energy Agency inspectors would be challenged to find such small centrifuge manufacturing sites, detect the relatively few secret procurements from abroad, or find a small, clandestine centrifuge plant outfitted with these advanced centrifuges. Moreover, with such a small plant needing to be built, Iran would also have a far easier time hiding it from Western intelligence agencies.

Discussions at ISIS workshops helped identify several limitations that should be placed on Iran's centrifuge R&D program:

- The speed of the rotor assembly of centrifuges under R&D 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 1 and 2). 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 1, 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 1: Background on Theoretical Maximum Centrifuge Capacity

Defining a SWU Limit Based on Physical Parameters

Separative Power Estimation:

Following the derivation in Appendix 2, 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 conservatively in order to over-estimate the 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 approximated for most models.

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.[2] 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

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[2] Interview of Gernot Zippe by David Albright. See also David Albright, Frans Berkhout and William Walker *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies* (Oxford: Oxford University Press, 1997).

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 2: Theoretical Maximum Separative Power

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

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

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 (given in units of kg/m-s)

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

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

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

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

$$e_C = \frac{m^2}{1 + m^2} \quad (8)$$

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

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

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