feature article

The gas centrifuge and nuclear weapons proliferation

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Uranium enrichment by centrifugation is the basis for the quick and efficient production of nuclear fuel—or nuclear weapons.

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The most difficult step in building a nuclear weapon is the production of fissile material. One can either make plutonium-239 in a nuclear reactor or enrich uranium to increase the abundance of its fissile isotope uranium-235. Historically, enrichment has been the more obscure of the two routes, but the recent spread of one technology—the gas centrifuge—from the Netherlands to Pakistan and on to Libya, Iran, and North Korea has brought enrichment to the forefront of proliferation. That development is challenging old ideas about how to ensure the peaceful use of nuclear technology and prevent the further spread of nuclear weapons.

The gas centrifuge is particularly well suited for acquiring a first nuclear weapon. It is also the most economically efficient way to enrich uranium for peaceful power-reactor fuel, and therefore essentially impossible to abandon and difficult to control by political means. Combined, those aspects lead to a new kind of control problem that has not been experienced with other technologies. This article outlines the problem, showing how technical aspects affect policy options, and discusses some of the solutions currently under consideration.

The gas centrifuge

The gas centrifuge works much like a classic centrifuge: It is a hollow cylindrical tube that is spun at very high speeds about its axis.[1] The centrifugal force is able to separate chemically identical isotopes because of the variation in isotopic weight. For the separation of uranium isotopes, the gas fed into the centrifuge is uranium hexafluoride. Figure 1a shows the feed stream and two withdrawal streams: the product stream enriched in the desired isotope, ^{235}U, and the tails or waste stream depleted in ^{235}U. Technical details are presented in box 1.

Centrifuges have been fabricated from a variety of materials, with varying lengths, diameters, and operating speeds. Figure 1b shows the relative lengths of a number of centrifuges. The first and second Pakistani centrifuges were based on early designs by Urenco Ltd, a consortium involving the UK, Germany, and the Netherlands. Also shown are the more modern Urenco centrifuges. The largest centrifuge was developed in the US and is now called the American Centrifuge. Centrifuges of that design will be used by USEC Inc at a plant in Ohio.

A single centrifuge cannot simultaneously produce useful enrichment levels and product flow rates. To achieve those, centrifuges are connected in cascades. By connecting the centrifuges in series, the enrichment level is increased, and by connecting in parallel, the product flow rate is increased. A cascade schematic is presented in figure 1c. Each row represents a stage, and the number of stages in the cascade is determined by the performance of each centrifuge and by the desired enrichment level.

From Charlottesville to Natanz

The separation of isotopes by gas centrifugation was first suggested by Frederick Lindemann and Francis Aston in 1919, immediately after the existence of isotopes had been experimentally confirmed.[2] Robert Mulliken in the US, William Harkins in Germany, and Sydney Chapman in the UK tried unsuccessful experiments for more than a decade. It wasn't until 1934 that Jesse Beams of the University of Virginia first reported the successful separation by centrifuge with the isotopes of chlorine. His insight was to place the centrifuge rotor in a vacuum to thermally isolate it from the environment and thereby minimize the convective mixing that had foiled earlier attempts. Figure 2 shows a timeline of the centrifuge's history.

During World War II, Beams and others at the University of Virginia became involved with the Manhattan Project with the goal of producing enriched uranium for a nuclear weapon. However, the technology was not successful during that time because mechanically reliable ultrahigh-speed bearings had not been perfected. Nonetheless, development of the gas centrifuge continued after the war, especially in the USSR, where Austrian prisoner of war Gernot Zippe introduced a reliable pivot–magnetic bearing combination. In the summer of 1956, Zippe was released and intercepted by US intelligence agents. Ultimately, he was persuaded to come to the University of Virginia and repeat what he had done in the USSR. That work led to a new generation of advanced centrifuges in the US and the Urenco states. Over time, gas-centrifuge enrichment plants were built in each of those countries, and eventually the process became the workhorse of the international enrichment industry. Today, centrifuges are the primary method of uranium enrichment, and they will soon replace the two surviving plants based on the older gaseous-diffusion technology, located in the US and France.

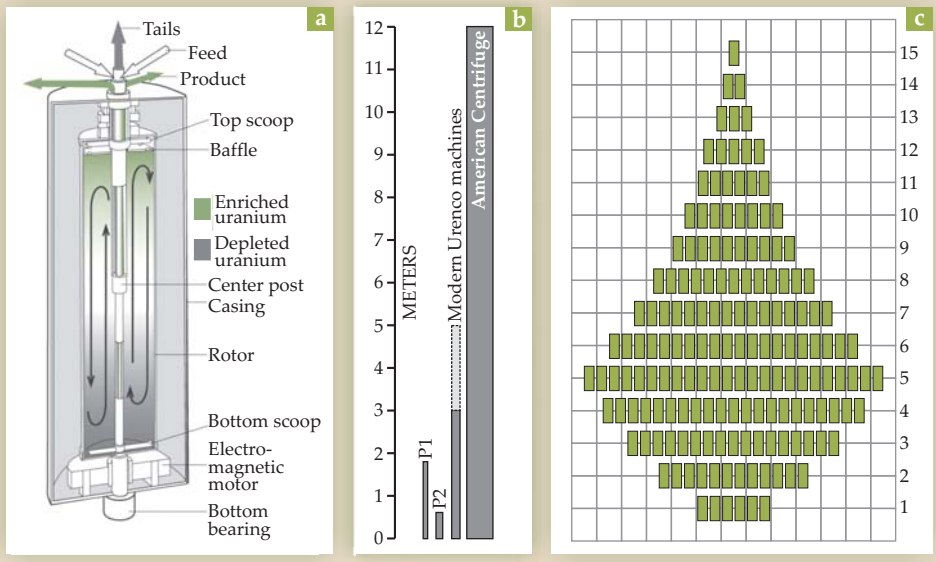


Figure 1. (a) Schematic of the flows into and out of a gas centrifuge plus the countercurrent flow in the separation chamber. (Adapted from *Sci. Am.*, August 1978, p. 39.) **(b)** Comparison of lengths of the first two Pakistani centrifuges P1 and P2, the range of modern Urenco centrifuges, and the current US centrifuge design. **(c)** Arrangement of gas centrifuges in a 15-stage ideal cascade.

In 1974 India exploded a nuclear device, which it called a peaceful explosion. That event spurred the development of Pakistan's nuclear weapons program. It also incited Pakistani metallurgist Abdul Qadeer Khan, who was working for Urenco in the Netherlands, to assist Pakistan by making copies of blueprints for centrifuge designs. He later returned to Pakistan, where he used the design information and his contacts in Europe to build an enrichment plant to produce the fuel for Pakistan's first nuclear bomb.

Once Pakistan had demonstrated that a developing country could make fissile material for nuclear weapons with centrifuges, others followed. In the summer of 1987, Iraq initiated its own covert centrifuge program. It floundered at first, but with the help of several disaffected German engineers, Iraq managed to build a modified version of an old Urenco design and test it in the days just prior to the invasion in January 1991.

In parallel to Iraq's effort, Khan began to sell old Pakistani centrifuge parts and blueprints on the black market. Fearing a sting operation, Iraq declined Khan's offer, but Iran and Libya decided to buy. In 2002 there were reports that North Korea had also been in contact with Khan and was developing a gas centrifuge of its own. As of July 2008, traces of highly enriched uranium were reportedly found on North Korean documents, but no evidence of an enrichment plant has emerged. The UK and US were successful in convincing Muammar Qaddafi to dismantle Libya's program, and most of the equipment was shipped to the US. Iran, however, has continued with its centrifuge program, including the recent installation of machines in an underground facility at Natanz. Iran insists that its program is peaceful and has defied international appeals to suspend the program and fully open it to inspection.

The Iran story

The controversy sparked by Iran's nuclear program has done more than any other event in the 60-year history of nuclear nonproliferation to underscore the challenges related to centrifuge proliferation. Iran's program was first revealed by non-government sources in August 2002, and Iran confirmed in February 2003 that it was constructing two centrifuge plants. By that time the program had been secretly under way for more than 15 years, according to information provided by Iran to the International Atomic Energy Agency, with the first centrifuge blueprints and components received from a foreign source in 1987.[3] Eventually, investigations revealed that source to be Khan and his network of suppliers. (The IAEA Board of Governors has released more than 20 reports on the status of the Iranian nuclear program since June 2003.)

In the months following the revelation of the Natanz site, the IAEA carried out several inspections there and made some surprising discoveries. Iran had not declared past enrichment experiments—activities that they were required to report to the IAEA. The agency also found documents related to the production of nuclear weapons and traces of highly enriched uranium, which suggested a foreign origin for some of the equipment.

Initially, a resolution looked workable. In November 2003 Iran suspended its enrichment program after it acknowledged that it had indeed carried out "a limited number of tests, using small amounts of UF_6" in the years 1999 and 2002. Shortly thereafter, Iran also signed (but did not ratify) the Additional Protocol and voluntarily complied with its terms, which give the IAEA broader access to Iran's facilities.

Diplomatic efforts pursued during the suspension period included attempts to persuade Iran to abandon its program in return for an incentive package that included fuel-supply assurances and reactor technology. Eventually, all those efforts collapsed. Iran resumed centrifuge production in June 2004 and enrichment activities in January 2006. In the meantime, Mahmoud Ahmadinejad was elected president, and the centrifuge program became a platform for winning domestic political support. In April 2006 Iran began testing the first complete 164-machine cascade, shown in figure 3, and reported the successful production of minute quantities of low-enriched uranium.

By then, the IAEA board of governors had referred Iran's case to the United Nations Security Council, which passed Resolution 1696 in July 2006, demanding "that Iran shall suspend all enrichment-related . . . activities, including research and development" to build confidence in the exclusively peaceful purpose of its nuclear program. Iran continues to defy those resolutions, and it appears increasingly unlikely that the country will roll back its enrichment project any time soon, given the project's broad domestic support. Various international efforts are being made to accommodate the

Box 1. How the gas centrifuge works

The gas in the centrifuge settles into a dynamic equilibrium, balancing the centrifugal force that presses the gas against the wall of the rotor and the diffusive force that seeks to distribute the gas equally throughout the volume of the rotor. For a binary mixture and no internal flow, the resulting distribution holds independently for each species. An equilibrium separation factor α_0 representing the difference in the concentrations of the species at the wall of the rotor is given by

$$\alpha_0 = \exp[(M_2 - M_1)v_a^2/2RT], \quad (1)$$

where v_a is the peripheral speed of the rotor, M_1 and M_2 are the molecular weights of the two species, R is the universal gas constant, and T is the gas temperature. Normally, a countercurrent flow is established as depicted in figure 1, and that convective flow carries the lighter isotope to the top of the centrifuge and the heavier isotope to the bottom. That results in an axial separation factor that tends to be much larger than the radial separation factor given by equation 1. The overall separation factor for the centrifuge is defined as

$$\alpha = \frac{x_P}{1 - x_P} \Big/ \frac{x_W}{1 - x_W}, \quad (2)$$

where x_P and x_W are the concentrations of uranium-235 in the product and waste streams, respectively.

The performance of a gas centrifuge is measured in separative work units per unit time, which has units of kgU/yr. The separative work ΔU is not a measure of energy, but it is nonetheless a measure of the effort expended by the centrifuge. A function of flows into and out of the centrifuge and the concentrations of the streams, it is calculated by the formula

$$\Delta U = PV(x_P) + WV(x_W) - FV(x_F), \quad (3)$$

where P, W, and F are product, waste, and feed mass flows, respectively, x_F is the concentration of ^{235}U in the feed, and $V(x)$ is the value function derived by Paul Dirac and is given by

$$V(x) = (2x - 1)\ln[x/(1 - x)]. \quad (4)$$

The expression for the maximum theoretical performance of a gas centrifuge was also derived by Dirac and given by

$$\Delta U(\max) = \frac{\pi}{2} L \rho D \left(\frac{\Delta M\, v_a^2}{2RT} \right)^2. \quad (5)$$

Dirac's work was published as part of a book by Karl Cohen.[4]

In equation 5, L is the length of the centrifuge, ρD is the binary diffusion coefficient, and ΔM is the difference in molecular weights. The actual, or achievable, performance has some efficiency factors related to the shape of the flow profile and the strength of the countercurrent flow. Equation 5 shows that the performance has a fourth-power dependence on the peripheral speed of the rotor v_a and is directly proportional to the length. In practice, the dependence on speed is closer to v_a^2, but that is still a strong dependence and emphasizes the importance of rotor speed.

Controlling the countercurrent flow optimizes both the flow profile efficiency and the separative work produced by a single gas centrifuge. Solving the fluid-dynamics equations of motion allows the flow pattern to be optimized. That has been done by directly solving the equations numerically and by obtaining exact solutions. In the US program, a theory group led by Lars Onsager addressed the problem in the 1960s. Onsager used a minimum principle to obtain a single sixth-order partial differential equation, which he solved by eigenfunction methods. An analysis of the mathematical details can be found in reference 5.

Making long centrifuges spin at high speeds requires consideration of the materials of construction and dynamics of the rotor. To first order, the maximum peripheral speed is given by $v_a = \sqrt{\sigma/\rho}$, where σ is the tensile strength and ρ is the density of the rotor. There is thus a need for strong, lightweight materials.

Long rotors spinning at high speeds have natural bending frequencies, which should not coincide with the operating frequency. A centrifuge operating above the lowest bending frequency is called a supercritical centrifuge, otherwise subcritical. One way to traverse the resonant speeds is to connect a number of shorter rotor segments together with flexible bellows, which provide damping to help the rotor accelerate past the resonances.

Iranian technology in a multinational enrichment plant, supplemented by arrangements and features that would make military use of such a facility more difficult. See box 2 for more about Iran's program.

A new kind of challenge

Since early in the nuclear age, the IAEA has been charged with safeguarding nuclear technology to ensure that it is not used for the production of nuclear weapons. The operating premise of those safeguards is deterrence through timely detection. Thus it is not the role of safeguards to prevent proliferation. Rather, safeguards are meant to detect nonpeaceful activities sufficiently early that they can be stopped by political intervention. The centrifuge, however, has properties that make timely detection difficult. One of those properties is the speed with which any peaceful-use plant can be converted to nonpeaceful purposes. That so-called rapid breakout enables the proliferating country to produce nuclear weapons before there is time for a political response and thus renders safeguards largely ineffective. A second problem is the potential for clandestine plants. Compared with nuclear reactors and large gaseous-diffusion plants, a centrifuge plant uses little electricity and produces little detectable signal, so it is much easier to hide the plant and evade safeguards altogether.

The rapid-breakout problem. The inventory of UF_6 in a centrifuge is limited by the condensation pressure at the wall; the UF_6 must remain in gas form, or the rotor will become unbalanced and crash. For normal operating temperatures, the maximum pressure is on the order of 0.001 atmosphere, and the corresponding gas inventory is only a few grams. Typical throughput is on the order of milligrams per second, so an individual machine (or cascade stage) can be flushed of its UF_6 inventory in less than an hour.

In addition, centrifuges typically achieve separation factors (defined in box 1) of 1.2 to 1.5. That is high compared with the earlier gaseous-diffusion process, which is characterized by a separation factor of no more than 1.004. Because

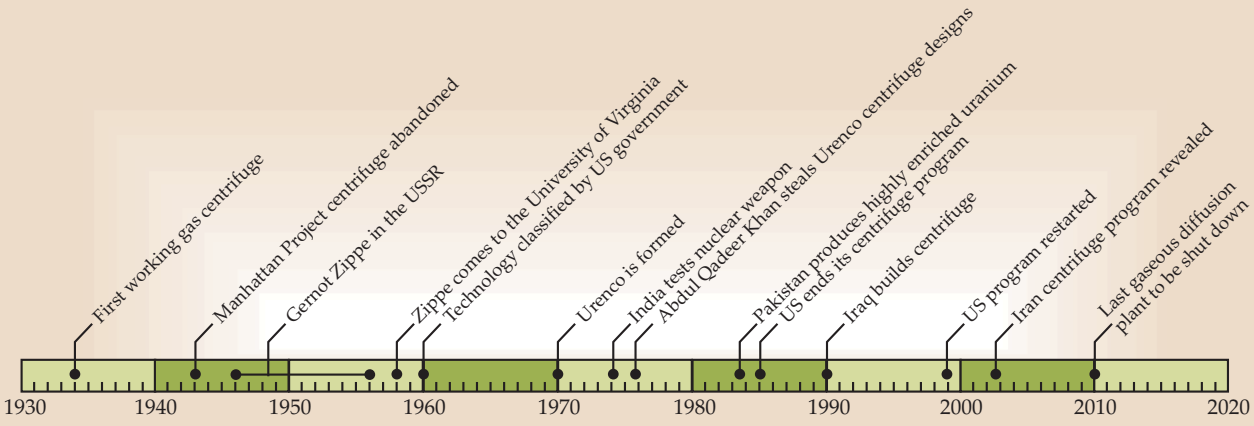


Figure 2. Timeline of centrifuge-related events.

of the larger separation factor, a plant based on centrifuges requires fewer total stages to achieve a given level of enrichment. Even for a first-generation centrifuge, the gas needs only to pass through a series of 30–40 stages to reach the high enrichment levels used in nuclear weapons. The combination of few total stages with the short equilibrium time per stage means the overall cascade equilibrium time is also small. Thus a cascade designed to produce low-enriched uranium for fuel can be re-fed its low-enriched product and begin converting it to highly enriched uranium suitable for weapons use in a matter of days—a procedure called batch recycling. Alternatively, the machines can be reconfigured into a narrower but longer cascade with more stages, a process that requires additional time before production of highly enriched uranium can begin but is more efficient than batch recycling. If the available enrichment capacity is sufficient, the options give a country the ability to produce weapon quantities of material before there is time to respond politically. For an example of a breakout scenario based on Iran's current technology, see box 3.

The clandestine problem. A country could try to build a clandestine plant in the hope of escaping detection altogether. A clandestine centrifuge plant could be difficult to detect. Centrifuges can be placed in buildings indistinguishable in appearance from other industrial facilities. A typical plant uses about 160 W/m^2, comparable to an average food services facility; that low consumption makes the centrifuge plant impossible to detect by IR imaging. (In contrast, the older gaseous-diffusion plants, which use hundreds or thousands of large compressors, require 10 000 W/m^2.) Furthermore, most of the pipes in a centrifuge plant operate below atmospheric pressure, so little of the process gas leaks into the atmosphere. Those effluents provide a method of detecting centrifuge plants, but their exceedingly low level makes detection impossible at distances of more than a few kilometers, so it is impractical to detect a covert plant whose location is not already known.

Problems of control

The inability of safeguards to adequately deal with centrifuge plants went largely unnoticed when the technology was held exclusively by states that already possessed nuclear weapons and by their close allies. Today, increasing numbers of states possess centrifuges, including states that are not supporters of the nonproliferation regime and might willingly transfer the technology to like-minded nations. In addition to concerns about state-to-state transfer, residual black-market elements are left over from the Khan network, and qualified technical people are available for hire. UN Resolution 1540 has been important in addressing some of those latter problems by requiring states to put in place stringent export controls and to criminalize private-party proliferation, but the solutions are neither perfect nor easily implemented, especially in resource-starved nations.

Some have argued that if controlling the technology per se is not possible, then it might be possible to set rules on who can own centrifuges and when.

Figure 3. The first publicly released picture of the 164-machine cascade installed at Iran's aboveground Pilot Fuel Enrichment Plant. The photo was used in a presentation by Mohammad Saeidi of the Atomic Energy Organization of Iran in September 2005.

Box 2. Is Iran pursuing a nuclear weapon?

Many questions relating to the scope and nature of Iran's nuclear program have been addressed over the past few years. However, as of May 2008, the International Atomic Energy Agency remains unable to certify that Iran's program is for entirely peaceful purposes. From other states, the IAEA obtained evidence that points to weaponization efforts: alleged studies on converting uranium to UF_4 (a precursor of uranium metal), testing of special firing equipment and detonators used in nuclear weapons, and the design of a special missile reentry vehicle suitable for nuclear warheads. Iran maintains that those allegations are baseless and all related documents fabricated.

In addition, early in the investigation, a 15-page document was found in Iran describing the process of converting uranium into metal form and machining it into hemispheres, a step related to the production of weapons. Iran has reiterated that it obtained the document through the Abdul Qadeer Khan network in 1987 along with centrifuge documentation, but that it had not requested that information. To date, the IAEA still seeks to confirm with contacts in Pakistan the circumstances of the delivery of that document.

All the documents suggesting weapons-related activities date to before the year 2004. That is consistent with the November 2007 US National Intelligence Estimate, which judged "with high confidence that in fall 2003, Teheran halted its nuclear weapons program," primarily in response to international pressure. Iran maintains that it never pursued a nuclear weapons option or program.

Even if Iran has terminated specific weapons-related activities for the time being, the remaining centrifuge plant represents the most significant step in acquiring weapons; it can be readily converted to weapons purposes and the other details worked out quickly. It is that fact, combined with the lack of transparency, past infractions, and the possible sublimated interest in nuclear weapons, that continues to fuel tensions between the West and Iran.

The problems with that strategy are twofold. First, peaceful-use nuclear energy provides a legitimate reason to possess centrifuges. States with reactors, or even plans for reactors, can argue that they need to build a national centrifuge enrichment plant to ensure the uninterrupted supply of nuclear fuel for those facilities. Yet a centrifuge plant built to fuel just one commercial-sized reactor is adequate to produce highly enriched uranium for dozens of nuclear weapons per year.

Efforts have been made to counter the energy-security argument by pointing out that it is often cheaper to purchase enrichment services on the international market than to build a national plant at home. Although that is technically true, the economic penalty is not severe. Even if the cost of national enrichment were triple the market price, it results in less than a 10% increase in the final cost of nuclear power—a small insurance premium for energy security. Others have argued that existing market mechanisms have yet to fail. However, the past shows mainly that the market works when the enriching and client states are friends; we have yet to see a state supplying nuclear fuel to one of its enemies. Still others have proposed various kinds of internationalized fuel-supply assurances. Paradoxically, those proposals have not received much traction, because most countries are satisfied with their existing arrangements—and it is difficult to create a new international system without their support.

The second major problem with attempts to set rules limiting the acquisition of centrifuge plants is that many states have grown weary of giving up sovereign rights in the name of nonproliferation. The current nonproliferation regime was based on a bargain between the nuclear haves and have-nots: Those without weapons would forgo the right to possess them and subject themselves to perpetual inspections in exchange for assistance with peaceful-use nuclear technology and eventual disarmament by the nuclear weapons states. So far, none of the original nuclear weapons states has disarmed, cooperative assistance has been less than forthcoming, and nuclear energy has not been the panacea it was once thought to be. As a result, many states oppose nuclear weapons but also oppose what they see as an inherently unfair nuclear control regime. Some states have even cast their acquisition of centrifuge technology as a political protest against efforts to cement a permanent state of inequity among nations.

Other incentives to acquire centrifuge technology are also increasing. Because of the Iranian nuclear program and the international attention it attracted, centrifuges are now seen as a mark of power and prestige in the Middle East. Although in reality it may be more technically impressive to build any number of other peaceful-use technologies, the connection to nuclear weapons, combined with the efforts to prevent the acquisition of the technology, has rendered the centrifuge a symbol of power. Governments like those of Pakistan and Iran have successfully parlayed that symbolism into widespread domestic support for their centrifuge programs and brought considerable resistance to international efforts to place those programs into abeyance. What is more worrisome is that their enthusiasm might be contagious. It is perhaps not mere coincidence that many Persian Gulf states announced their interest in nuclear power shortly after Iran's centrifuge program became popular.

Looking ahead

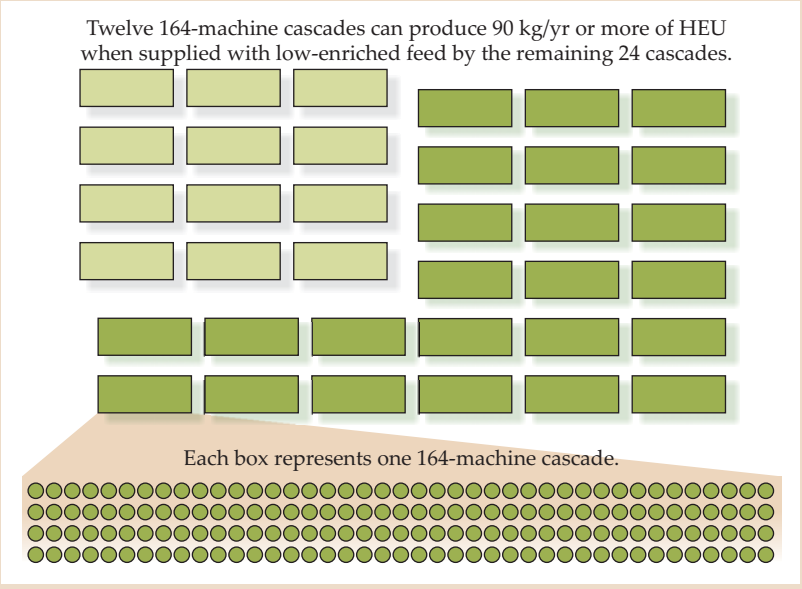
As we have seen, safeguards cannot prevent proliferation, especially in the case of centrifuges. However, safeguards can be extended to nuclear materials so as to make the breakout and clandestine loopholes less attractive. In a breakout scenario, speed is the critical factor, and breakout can be made about three times faster if the state uses preenriched UF_6 instead of natural uranium to feed its cascades. Thus it would be sensible to require that all enriched uranium be stored offsite and in a chemical form, such as uranium oxide, that is not suitable for direct reenrichment. That requirement would minimize the amount of low-enriched uranium that can be readily fed back into the centrifuge cascade, extend the breakout timeline, and allow more time for political intervention. However, the solution works only for small-scale facilities; large facilities could enrich uranium fast enough to break out using unenriched uranium feed.

Safeguards might also address the covert-facility problem by safeguarding flows of unenriched UF_6, starting at the facilities where the UF_6 is produced. Traditionally, that material has received relatively little attention. Monitoring unenriched UF_6 more carefully can make its diversion to a covert plant more difficult. Thus, although direct detection of covert plants may not be possible, safeguards can make it more difficult to operate those plants with undeclared feed.

With material controls helping to close the loopholes, the application of safeguards to the overall centrifuge complex becomes important again, with a focus especially on uranium flows in the plant. Existing safeguards do not adequately address many of the strategies for centrifuge misuse. Upgrades directed toward better monitoring of enrichment levels and

Box 3. How credible and fast is a breakout scenario?

Represented in the figure are two plants, one with 12 and one with 36 164-machine cascades (1968 and 5904 machines, respectively), all based on P1-type centrifuges (see figure 1b). Two different strategies can be pursued for breakout: simple batch recycling, in which product material is fed back into the original cascades, and cascade interconnection, which involves reconfiguration of the cascades. In each scenario, the material to be used for breakout may be either natural uranium (0.72% ^{235}U) or a stock of low-enriched uranium (3.5% ^{235}U). The objective is the production of weapons-grade highly enriched uranium (90% ^{235}U or more).[6]



Breakout using natural uranium feed is less credible because most of the required separative work goes into enriching the uranium to LEU levels—an activity that could plausibly be carried out under safeguards prior to breakout. However, if it were done using the full 36-cascade plant, about 40 kg of HEU could be produced in one year by batch recycling; the process is much more efficient if about 12 of the 36 cascades, or about 2000 P1 centrifuges, are reconfigured as dedicated LEU-to-HEU cascades. More than 90 kg/yr of HEU can be obtained that way, but the reconfiguration requires replacement of the complex cascade pipework, which could add several weeks or months up front.

Breakout becomes more credible when preenriched feedstock is available. Then the 12-cascade plant can produce 90 kg of HEU per year, and the 36-cascade plant can yield three times that amount. One concern is that the cascades designed for LEU-to-HEU production may be located at an undeclared site, which would avoid the need to reconfigure the safeguarded centrifuge plant. The covert plant could be contained in a building as small as 500 m^2 and would be impossible to detect using satellite imagery alone. With a second covert plant, LEU from the declared facility, still in the form of uranium hexafluoride, could be transferred to the undeclared site, and HEU production could commence without further delay. There is still a risk of detection if the diverted LEU is subject to safeguards. However, existing safeguards might be unable to detect the production of excess LEU via certain covert arrangements, and that excess could serve as an unsafeguarded source of LEU for an undeclared facility.

flows are needed both in and around the plant. New technologies, such as RF identification tags, can automate and facilitate the tracking of UF_6 containers. Online monitors can report throughput and enrichment levels in real time. It is important that any new measures be put in place quickly because several large-scale facilities are under construction or planned for Iran, Brazil, France, Russia, and the US; it will be far more difficult to retrofit those plants later, given the delicate nature of centrifuges and their propensity for failure during spin-up and spin-down. Those facilities are likely to set a de facto standard for new plants in other countries, so there is now a unique opportunity to define a new baseline for best practices and safeguards by design.

Safeguards will not, however, be a complete solution. Breakout is still possible with a plant of sufficient size, and covert plants are possible, especially when combined with covert UF_6 production. Owing to the lack of good technical solutions, the centrifuge challenge might be better addressed in the political domain, with arrangements to limit the number of states owning centrifuges or to raise the barriers to using them for weapons purposes.

One proposal now receiving increasing support is the criteria-based approach, which aims to set minimally politicized criteria for the acquisition of a national enrichment capability. Proposed criteria have included the acceptance of certain voluntary safeguard measures, a minimum infrastructure requirement to justify domestic enrichment, and a requirement that the installation of the centrifuge plant not be regionally destabilizing. There may yet be hope for the international fuel-supply assurances discussed earlier, including multinational ownership of facilities, but that depends on whether nations can develop a fair fuel-supply framework that is robust enough to persuade existing nuclear states to give up their right to operate national enrichment plants.

Barring solutions, the problem is likely to grow, especially if there is an expansion in the total number of countries using nuclear energy, which might—or might not—happen in the coming decades. And even if proposed technological and institutional fixes are put in place, they cannot entirely solve the problem; incentives to acquire centrifuge enrichment as a nuclear weapons hedge will remain. Solutions to those problems must involve a country's national security—not just its energy security.

References

1. S. Villani, ed., *Uranium Enrichment*, Springer, New York (1979).
2. R. S. Kemp, *Sci. Global Sec.* (in press).
3. International Atomic Energy Agency Director General, *Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, GOV/2004/83, IAEA Board of Governors, Vienna, Austria (15 November 2004).
4. K. Cohen, *The Theory of Isotope Separation as Applied to the Large-Scale Production of U^{235}*, McGraw-Hill, New York (1951).
5. H. G. Wood, J. B. Morton, *J. Fluid Mech.* **101**, 1 (1980).
6. A. Glaser, *Sci. Global Sec.* (in press).

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