THE GAS CENTRIFUGE AND THE NONPROLIFERATION OF NUCLEAR WEAPONS

R. Scott Kemp and Alexander Glaser
Program on Science and Global Security
Princeton University

Abstract

The gas centrifuge is a particularly challenging technology for the institutions of the existing nonproliferation regime. Centrifuge facilities can be reconfigured for the production of weapon-grade uranium in a comparatively short time-frame, while clandestine facilities are virtually impossible to detect with technical intelligence tools. A potential expansion in nuclear power and the natural maturing of states' technical abilities suggest a world where centrifuge proliferation could become an even more serious threat to global security. This overview reviews the proliferation-relevant technical characteristics of the gas centrifuge and examines how effective control strategies must differ from traditional approaches. A well-informed policymaking process is needed to address these issues. We outline current gaps in understanding that ought to be closed in order to formulate robust nonproliferation policies.

Keywords: Nonproliferation, Nuclear Power, Expansion, Safeguards, Detection

1. Introduction

Even though the decision to acquire nuclear weapons is mainly a political one, it can be influenced by many technical factors. The most simple of these is the availability of specific fuel-cycle technologies needed to produce weapon-usable fissile materials. A less obvious example is the technical constraints governing how long a covert program can be expected to remain undetected by the international community. The combination of such technical factors renders some nuclear technologies better suited for proliferation than others, and if these factors are considered in the decision of whether to pursue nuclear weapons, then they can increase the likelihood of nuclear proliferation. In other words, technologies better suited to proliferation are also more likely to be used for proliferation. Logically then, a decision to deploy proliferation-prone technologies on a global scale thus requires balancing both economic cost and proliferation risk (informed by technical analysis) against expected gains. Notably, this balance is central to the question of whether or not to expand global use of nuclear power in an effort to partly address the climate-change problem. This paper elucidates the proliferation-relevant technical aspects of one of the fuel-cycle technologies likely to play a major role in such an expansion: the gas centrifuge for uranium enrichment.

◆

It is generally understood that, in the whole process of building nuclear weapons, the step of acquiring significant amounts of weapon-usable fissile material is the most difficult one. For this reason, nonproliferation efforts have focused here as the point of control. The gas centrifuge provides a way of acquiring fissile material while reducing many of the existing implementation costs associated with other routes. Specifically:

- Because centrifuges have a small inventory hold-up and short equilibrium time, they offer a rapid breakout capability compared to other enrichment technologies. In other words, the state can easily convert its peaceful facility to weapon purposes, leaving little or no time for the international community to react.
- Clandestine centrifuge plants are difficult to detect. They do not produce significant signatures normally used to detect hidden nuclear facilities, and special signatures specific to centrifuges are probably too weak to be useful for detection at significant distances.

These are the main proliferation concerns, which are unique to centrifuge technology, and we will discuss them in some detail further below. Other relevant aspects are:

- Highly enriched uranium can be used in the most basic of nuclear weapon design. From a technical perspective, plutonium weapons are more challenging, requiring extensive development and usually also nuclear testing of the design.
- Centrifuges can be operated in hardened underground facilities rendering them almost invulnerable to preemptive strikes. This is more difficult for other enrichment processes and also for plutonium production reactors.
- Centrifuges offer plausible deniability. Because centrifuges are unquestionably part of a modern commercial fuel cycle, a state can credibly declare that it is pursuing centrifuges for strictly peaceful purposes. Once successfully acquired, a peaceful plant can be rapidly converted to production of weapon-grade material.

Despite these factors, centrifuges have historically been viewed as a lesser problem for nonproliferation because the technical barriers to their acquisition were unassailably high. However, as states develop their own industrial base and as manufacturing technologies become more capable, this may change. If these final barriers erode, then the international community will need to take a different approach to nonproliferation, i.e. one based on motivational rather than on implementation restraints. It is thus fitting that experts familiar with building centrifuges consider this question.

2. The Interaction between Technical Aspects of the Fuel Cycle and the Political Decision to Proliferate

The decision of whether to seek nuclear weapons is essentially a judgment weighing the perceived costs and benefits of possessing *and* acquiring nuclear weapons. For possession, the perceived benefits are usually security related, but may include other domestic factors, such as political necessity or national identity. The costs of possession are the risk of unauthorized use, unfavorable changes to political and strategic position on the world stage, and various penalties that might be imposed by external actors. States who evaluate the sum of these factors in favor of abstinence can be said to be held back on *motivational* grounds. Most states fall into this category, and they are not the main concern of proliferation today. It is still important to realize that things can change, so preserving the motivational impediments is paramount to the overall success of nonproliferation.

States that resolve the motivational factors in favor of acquisition are the primary concern of non-proliferation policy. In these cases, it is only the additional cost associated with acquiring nuclear weapons that serves to deter them. We can say these states are held back on *implementation* grounds. These implementation costs take the form of economic and social costs needed to overcome technical barriers in building weapons, as well as penalties imposed on states when their program is discovered by the international community. The goal for nonproliferation is to create implementation penalties that are severe enough, imposed early enough, and possibly capable of delaying a nuclear program further, so that the state subjected to penalties abandons its efforts before acquiring the bomb. For this reason, the technical difficulty, detectability, and the time between a program's detection and the actual acquisition of the weapon are the three factors governing the extent to which any particular route to building weapons is proliferation resistant. These three areas are thus the focus of the analysis below.

3. The Gas Centrifuge and Nuclear Proliferation

Safeguards on centrifuge facilities can be effective against some proliferation routes. They would likely detect excess production of low-enriched uranium as well as covert production of weapon-grade uranium at declared facilities. However, the unique and main proliferation concerns of centrifuge technology cannot be addressed by safeguards: these are the potential for rapid breakout and clandestine operation.

3.1 Rapid Breakout

The use of nuclear technologies under national control in a breakout-scenario can never be excluded once the decision has been taken to violate international treaties banning proliferation. The key factor here is the speed with which this can be done, in order to minimize penalties and negative repercussions. Some enrichment technologies are easier and/or faster than others. The breakout potential of centrifuges is a well-known characteristic of the technology and was, in fact, considered when the original safeguards concept for centrifuge facilities was developed in the early 1980s.[1]

To illustrate the relevance of the breakout scenario using centrifuges, we consider an ideal symmetric cascade based on an early-generation machine with a separative performance of 5 SWU per year — in the following, a "P-2 type" machine. Assuming a default feed-rate of 30 mg of uranium-hexafluoride per second, the target separative power is consistent with a separation factor of 1.28, i.e. to enrichment and depletion factors of about 1.13 if operated close to a cut of 0.5. The reference LEU-cascade illustrated in Figure 1 has 15 enriching and 6 stripping stages and yields a 4.4%-enriched product if the feed is natural uranium.

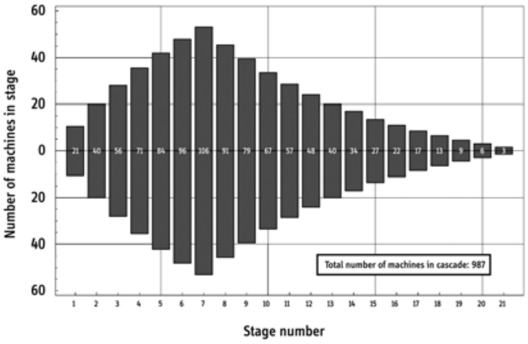

Figure 1: Ideal symmetric cascade designed for LEU-production using about 1,000 P-2-type machines. 21 stages (6 stripping, 15 enriching). The cascade produces 3.3 kg of UF_6 per day at an enrichment level of 4.4% if natural uranium is used as feed-material.

The feed into the cascade is 32.4 kg of UF_6 per day, 3.3 kg of which leaves the cascade as product. Assuming typical parameters for the machine,[2] the UF_6-inventory per centrifuge is about 2 grams.

The crudest breakout approach is to leave the cascade unmodified and batch-recycling the previously enriched product as new feed.[3] If we assume that the separative power of the centrifuge remains constant during this feed-concentration transient,[4] the equilibrium time is determined by the shape of the cascade and the total UF_6 holdup in the cascade, which amounts to about 2 kg in the present case.

Figure 2 shows the result of a simple calculation simulating the flow of UF_6 through the reference cascade. At the moment of breakout, 4.4%-pre-enriched material is fed into the cascade. In less than eight hours of operation, the new equilibrium is nearly reached. Instead of LEU, the cascade now produces 26.0%-enriched material at its default production rate of 3.3 kilograms per day.

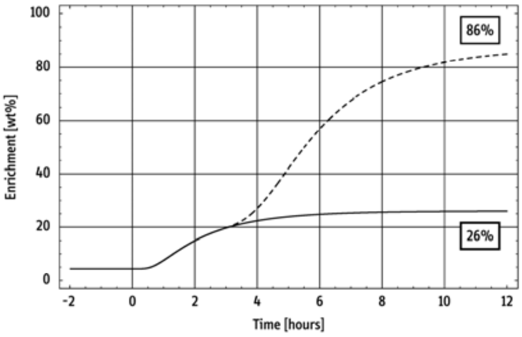

Figure 2: Enrichment of product during transient. At t = 0 hours, pre-enriched material is fed into the cascade (batch-recycle mode). Simulation based on holdup in the machines and the cascade only, no transient effects, δU = constant.

To produce weapon-grade uranium, the cascade would have to be operated for an extended period of time to produce the feed-stock for a second phase of the batch-recycling mode. Alternatively, if several reference cascades are available, these could be operated in parallel and series. Specifically, we consider the case where ten cascades work in parallel to feed an eleventh cascade. As illustrated in Figure 2, an enrichment level of almost 90% can be achieved with this two-stage batch-recycling strategy. Our simplified model predicts that equilibrium is reached within the first 24 hours. Using this configuration, one significant quantity (25 kg) of weapon-grade HEU can be produced in less than two weeks.[5] Clearly, this strategy (batch operation in series) is highly inefficient because large quantities of enriched UF_6 are discarded as tails in the second stage of the operation. Yet, this breakout scheme is simple and fast to implement and minimizes the risk of timely detection and thus international response.

3.2 Clandestine Option

The International Atomic Energy Agency (IAEA) can verify the non-diversion of material and proper operation of an enrichment facility during routine inspections. New verification technologies might improve the timeliness of detection, giving the international community at least some time to respond, perhaps triggering a plan designed to stop an in-progress operation, or contain a state already possessing significant quantities of HEU. The question arises, are there ways for the proliferator to circumvent detection altogether? The proliferator could do this if it were able to build and operate an entirely clandestine program.

Traditional safeguards were not designed for the detection of clandestine plants. They may be able to infer the existence of such plants by tracking material flows (namely UF_6) upstream of the facility, provided there is no covert production in parallel. However, the agency has no way of detecting the existence of a completely parallel, undeclared "fuel-cycle" dedicated to the production of nuclear weapons.

After Iraq was shown to have had an undeclared nuclear program in 1991, the IAEA made a series of identical bilateral agreements with states called the Additional Protocol. These agreements gave the agency additional inspection capabilities to search for undeclared facilities through ad-hoc inspections of nearly any facility. Moreover, with special approval from the Board of Governors, the agency may use wide-area environmental monitors to sniff-out covert operations. However, the inspection rights conferred by the Protocol cannot be used for *routine* verification. These additional rights are thus useful for investigative activities once the agency suspects undeclared activities and knows where to look, but they are not useful for uncovering such activities in the first place.

Wide-area environmental sampling does not provide a solution to the problem either. Because the Board of Governors must give its authorization, there are large (some say insurmountable) political barriers to wide-area monitoring. It is argued that only in the most unusual of circumstances, where there is already substantial evidence that a state is engaged in covert activity, would the board be willing to give its approval. Even if approved, the agency does not presently possess a technology that could detect covert facilities at significant distances.

The inability to detect covert operations is thus the primary limit to the power of safeguards. Because of this, safeguards do not protect against the replication of centrifuge technology from declared to undeclared facilities. As long as states can replicate their technology in this way, they are able to reduce or remove the political cost associated with early detection.

♦

Classically, there are a number of ways to detect clandestine nuclear activities: optical imaging (using satellites), thermal-infrared imaging, and effluent monitoring. For centrifuges, we can also consider electromagnetic emanations generated by the centrifuge electronics. All of these seek to detect centrifuges directly by their signatures. In addition to direct detection, we can consider indirect detection by looking for covert fuel-cycle facilities that infer the existence of a clandestine centrifuge program.

3.3 Direct detection

Direct-detection techniques are practical for other sensitive (i.e. fissile-material producing) fuel-cycle technologies. For example, a nuclear reactor (a plutonium producer) emits a large thermal signature. A gaseous diffusion plant can be found because of its large size and thermal signature. However, the small size and high-energy efficiency of centrifuges mean that neither optical nor thermal imaging can detect them.[6]

Effluent from gas centrifuges is also small. Little data is available on the routine emissions from gas centrifuge plants, but rough estimates suggest that the emissions would be too low to detect at *significant distances*, which we consider to be 100–200 km. Detection of airborne hydrofluoric acid (a product of UF_6 hydrolysis) may be useful for detecting centrifuges at closer distances on the order of kilometers. However, technologies that offer only kilometers detection range would not be practical for use in sensor nets designed to find clandestine plants over a significant area because the number of detectors required would be too large and the cost prohibitive.[7]

3.4 Indirect detection

Indirect detection of centrifuges by looking for supporting fuel-cycle facilities may be the most promising route. If the IAEA implemented safeguards to monitor all UF_6 stocks and was able to verify the amount of UF_6 produced at conversion facilities, then a clandestine enrichment plant could not be operated undetected unless there were also a covert conversion plant to supply it with uranium feedstock. Because conversion plants operate at much higher pressures than centrifuge plants, their leakage is typically greater, and thus their potential for detection also greater. Conversion plants produce unenriched uranium hexafluoride, so leaks cannot be isotopically distinguished from the uranium that is naturally present in air, and the total increase from routine leaks is not large enough to be detectable at significant distances in the presence of the uranium background. However, the uranium from conversion plants is bonded to fluorine, whereas natural sources are not. Thus, if it is possible to discern uranium chemically bonded to fluorine from other uranium in the atmosphere, it may be possible to detect the leaked uranium at a much greater distance.

We modeled the release of uranium-hexafluoride from a “reference facility” scaled to produce 12,500 kg of natural uranium contained in UF_6 per year, just enough to produce annually one significant quantity (25 kg of 90%-enriched uranium) when operated with a 0.525% U-235 tails assay. Based on data from Albright and Barbour, we estimate that conversion plants release about 0.24 grams of uranium for every kilogram of uranium in UF_6 produced. For our reference facility, this translates to an expected release of 10 grams per day.[8]

After taking into consideration aerosol effects and atmospheric chemistry, we modeled the transport of the remaining effluent using the NOAA's Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) transport code.[9] The results of our analysis, as shown in Figure 3, suggest that uranium aerosols could be used to detect clandestine conversion facilities at distances of 200–400 km (a significant distance), provided that a chemical assay method capable of detecting UO_2F_2 to 1 ppb in suspended solids was developed. This is within the typical range of sensitive assay techniques, but whether it could be done for this specific chemical remains unknown. A matrix of detectors designed to find 200–300 km plumes would consist of dozens of units for an average-size country, and hundreds of units for a small geographical region like Western Europe. It is unlikely that such a large system could be practically employed. When considering detection techniques, it is also necessary to consider countermeasures to those techniques. If a state can easily foil detection, then the associated costs are again avoided. For example, a proliferator could place its clandestine conversion facility next to a declared (and perhaps intentionally leaky) facility in order to mask the effluents from the smaller, covert plant. Simple measures like these undermine all the detection schemes we are aware of.

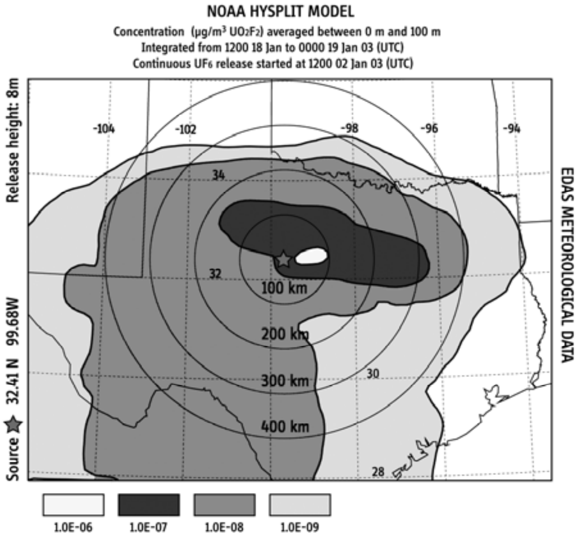

Figure 3: Airborne-concentration isopleths for the routine release of UF_6 from a covert conversion facility. Concentrations are in $\mu g(UO_2F_2)/m^3$. Based on the results obtained in these simulations, uranium aerosols could be used to detect clandestine conversion facilities at distances of 200–400 km.

In sum, the publicly available information suggests that there is no practical method of detecting clandestine facilities or their supporting fuel-cycle facilities. This makes centrifuges the only mainstream fuel-cycle technology capable of producing weapon-usable fissile material without a significant possibility (or risk) for detection. The clandestine option, and to a lesser extent the rapid-breakout option, are already concerns—but they would be even more so, were a rapid expansion in the use of nuclear energy to occur in the coming decades.

4. Potential Future for Centrifuge Technology

Nuclear energy is being considered today as an option for mitigating the problem of greenhouse-gas induced climate change. To significantly reduce greenhouse-gas emissions, however, nuclear power would have to expand several-fold. For illustrative purposes, let us assume that nuclear power grows to about 1,500 GWe, which corresponds to a four-fold expansion from today's level and, if achieved by 2050, would be equivalent to about 28% of the estimated global electricity supply, compared to about 15% today. In assessing the possible future expansion of nuclear energy, one of the most important questions for nonproliferation will be the geographical distribution of the reactors *and* the distribution of the fuel-cycle facilities supporting their operation.

The geographical distribution of nuclear capacity for the 1500-GWe scenario below is based on a 2003 MIT study, which took into account various country-specific factors such as current nuclear power deployment, urbanization, stage of economic development, and energy resource base. Based on these assumptions, the MIT study concluded that 56 countries would plausibly have commercial nuclear plants in a 1500-GWe scenario.[10] Here we are primarily interested in the enrichment services that would support these reactors. Our scenario below for enrichment demand distribution, illustrated in Figure 4, assumes a continued reliance on the traditional once-through fuel cycle, which is generally considered preferable for both cost and nonproliferation reasons.[11]

We assume, based on today's distribution of enrichment facilities, that only those countries with an installed capacity of at least 10 GWe would seek to establish a domestic enrichment industry, regardless of the opportunity for foreign assistance.[12] The SWU-capacity needed to support 10 GWe corresponds to a typically sized commercial centrifuge plant in operation today (about 1.5 million SWU/yr). In addition, there may be an incentive for the major suppliers of uranium ore, *viz.* Australia, Canada, and South Africa, to provide enrichment services. We further assume that the United States and Europe would continue to import up to 50% of the needed enrichment services, while Russia would continue to be a major exporter.

It is clear from this simple analysis that a large-scale nuclear expansion could require countries with no or negligible current commercial nuclear power programs, such as Iran, Pakistan, Mexico, or Indonesia, to deploy large uranium-enrichment facilities with capacities far exceeding one million SWU/yr. Yet even a small plant, like the one that Iran proposes to build at Natanz to fuel a single reactor (less than 150,000 SWU/yr) can produce enough highly enriched uranium for tens of nuclear weapons per year. In other words, the enrichment requirement to sustain even the smallest power program simultaneously offers a platform for a significant nuclear weapons program.

It could be that countries would seek a domestic enrichment capability only when it is economically justified, as we have conservatively assumed for the scenario depicted in Figure 1. However, it must be noted that fuel and enrichment costs are only a few percent of the cost of nuclear power, which is dominated by the costs of constructing, operating, and maintaining nuclear power plants. If a country had to pay *five* times the market-price for domestic enrichment services (i.e. $500 instead of $100 per SWU), the premium would only raise the overall cost of electricity by about 10%. In short, economics are not a significant basis for foregoing an indigenous enrichment capability when it simultaneously offers a measure of energy security. For this reason, it may be very hard to convince countries to abstain from developing their own enrichment capability.

◆

An expansion in the number of states possessing centrifuge plants has several ramifications. First, it directly increases the number of states with a breakout capability. Second, unrestricted spread of centrifuge technology — even if it is initially only to those states that can economically justify the need for domestic enrichment — further establishes the norm of right-to-ownership, which helps legitimize the centrifuge ambitions of other states.

If it is concluded that the dangers of deploying centrifuge technology around the globe are unacceptable, then there are at least three alternatives: first, choose not to pursue a large scale expansion of nuclear energy; second, develop a new global arrangement in which the states currently with enrichment capability would expand their capacity to supply the great expansion in nuclear power at home and in other countries. Leaders and the public in both sets of countries would have to accept this and the corresponding risk inherent to energy interdependence; or third, develop an international framework to avert the proliferation consequences through non-discriminatory, equitable, and multi-national provision of enrichment services that can simultaneously assure supply.

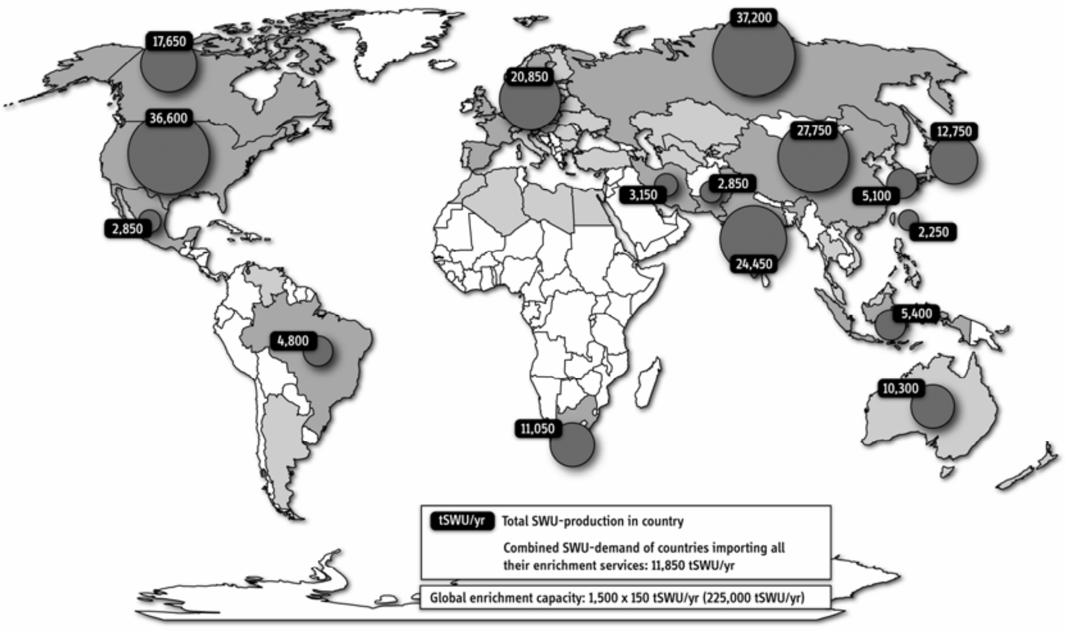

Figure 4: Hypothetical global distribution of enrichment capacities in a 1500 GWe scenario. In this scenario, 56 countries operate commercial nuclear power reactors and 16 countries operate large-scale uranium enrichment facilities.

5. Conclusion and Outlook

There have been proposals for important new features in the existing nonproliferation regime to address the challenges it is facing. These proposals range from incremental changes of the existing regime, e.g., more and better safeguards, to fundamental transformations of the international nuclear fuel cycle, which could require facilities to be placed under multinational control, or limits placed on their acquisition combined with assurances of fuel supply. These and yet more radical changes may be needed to fully cope with a potential expansion of nuclear power large enough to have a relevant impact on the climate-change problem.

All of the major proposals under discussion seek to restrict access to basic fuel-cycle technologies by formalizing a supplier-state/client-state arrangement. In our judgment, it is unlikely that a significant set of states would willingly join the client category.[13] We note that those states that are most likely to have security justifications for pursuing nuclear weapons are also those states most likely to be worried about being denied access to enrichment services by other states, and thus also the most hesitant to join such an arrangement in the first place. Remarkably, since U.S. President G.W. Bush first presented the idea of restricting enrichment and reprocessing to those states that “already possess full-scale functioning enrichment and reprocessing plants” in February 2004, several countries expressed a renewed interest in uranium enrichment: Argentina, Australia, Canada, Kazakhstan, South Africa and the Ukraine, in addition to Iran and Brazil's in-progress programs. Thus, in the short- and medium-term, attempts to implement more restrictive fuel-cycle policies may in fact spur national enrichment projects rather than prevent them.

A fundamental shortcoming of these approaches is that they do not effectively address the unique proliferation concerns of centrifuge technology discussed above. For example, multinational ownership does not alleviate the breakout problem. If states are allowed to choose their multinational partners themselves, it may even be counterproductive to nonproliferation efforts by pooling the efforts of like-minded proliferators. More important, none of the approaches can directly address the clandestine problem. Thus the only apparent remaining barrier is that centrifuge technology is still too complex for most states to develop with primarily indigenous efforts. If this technical barrier begins to lessen, however, the long-term effectiveness of export controls would be seriously challenged. And even if assurances-of-supply and similar arrangements were in place, the existence of clandestine programs could not be discarded with confidence. Thus, before devising more restrictive fuel cycle schemes, the question of the remaining “technological challenge” must be answered.

Figure 5 illustrates the time required to develop indigenously a centrifuge programs for select countries, beginning with the R&D phase through to the successful operation of a pilot-scale facility. At this stage, we assume that the technology has been mastered and, even though it may not yet be ready for large-scale commercial use, would be sufficient to support a small nuclear weapons program. The figure suggests that the time required to go through the phases of a centrifuge program has *not* significantly decreased in the last few decades: it has taken about 15–20 years to develop the technology in all cases. Even massive outside assistance, as in the case of Pakistan, can apparently reduce the R&D period by only a few years.[14] More important, though, is the recognition that countries may begin to pursue an enrichment program sooner or later, depending on when they feel sufficiently confident to be able to carry out such an R&D project, provided that they have previously concluded that a need for such a capability exists.

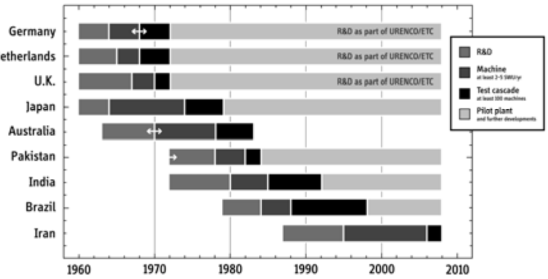

Figure 5: Timelines of centrifuge programs.

There are several reasons to conjecture that the technological challenge of developing centrifuge technology may be easing. Key technologies that were previously used specifically for centrifuge-component manufacturing are expanding into additional sectors of modern industry and/or require less experience or expertise to be operated.[15] As technology develops, and relatively advanced scientific and engineering skills and capabilities become embodied in machines and software, and these are in turn produced and traded in the global market, more countries are likely to move to a position where indigenous development of centrifuge technology becomes feasible in principle. Then, if the incentives to acquire national enrichment capabilities, for either peaceful *or* military purposes, continue to exist, we can indeed expect successful independent development and deployment of centrifuge technology in more states. As already pointed out, economic aspects are largely irrelevant in this context. Newcomers will not be able to compete with established enrichment providers on the international market, but for a small-sized domestic civilian or military program, obsolete P-1 or P-2 like technology, which would be reasonable first and second product of any new R&D project, may be entirely sufficient.

What is the marginal risk of expanding nuclear power given these characteristics of centrifuge technology and given the structure of today's or tomorrow's international nuclear fuel cycle? Important uncertainties about the effectiveness of traditional or potential new containment approaches remain, especially in view of the dynamics of technological development in all regions of the world. Despite current efforts to set-up a system of assurances of supply, incentives to acquire national enrichment capabilities remain high. The only effective approach to reduce the risk of proliferation from these plants is to focus on motivations by increasing countries' sense of security and decreasing their normative valuation of nuclear weapons. Progress in nuclear disarmament has been the central element of this agenda. To consider a global expansion of nuclear energy *before* one reestablishes confidence in the future of the nuclear nonproliferation and disarmament regime is an imprudent proposition. Therefore, those who envision an important role for nuclear power and the gas centrifuge in tomorrow's energy system should also be the strongest supporters of global nuclear disarmament.

6. Notes

[1] In order to address the specific safeguard challenges of centrifuge technology, the limited-frequency unannounced access (LFUA) concept was developed. See, for example, A. von Baeckmann, *Implementation of IAEA Safeguards in Centrifuge Enrichment Plants,* Proceedings of the Fourth International Conference on Facility Operations-Safeguards Interface, September 29–October 4, 1991, Albuquerque, New Mexico, pp. 185–190.

[2] To specify the inventory of the reference P-2-type machine, we assume a rotor length of 100 cm, a peripheral speed of 480 m/s, and a wall pressure of 100 torr.

[3] A more material-efficient approach would be to reconfigure the cascade, which avoids discarding enriched tails, but is likely to introduce time-delays that are difficult to estimate. Also, if more than one LEU-cascade is available, several cascades may be operated in the so-called parallel-overlap mode, in which the original cascades form separation units for stages of a larger super-cascade.

[4] This is a simplifying assumption because the separative performance of a centrifuge can be expected to degrade in a transient situation. Note also that separative power is a steady-state concept that is not well defined when sudden changes of the feed composition or rate occur.

[5] This 25 kg of HEU, which is contained in about 37 kg of UF_6, require 3,900 kg of UF_6 LEU feedstock. Note that up to 2500 kg of enriched UF_6 can be stored in one standard product cylinder (Type 30B). To prepare for this breakout scenario, LEU feedstock could be collected over a period of less than four months (110 days).

[6] A. Bernstein, "Monitoring Large Enrichment Plants Using Thermal Imagery from Commercial Satellites: A Case Study," *Science and Global Security,* Vol. 9, No. 2, 2001, pp. 143–163.

[7] The authors are unaware of other effluents from centrifuge plants that could be used for wide-

area monitoring. There is some work on detection of centrifuge plants by their electromagnetic emanations. Preliminary calculations suggest that emanations from motors and traveling through space would easily shielded and unlikely to offer detection at distances larger than about a kilometer. Induced emanations traveling through power lines may provide a way of detecting centrifuges within a region, but the extent to which this is practical remains unknown. For a general discussion of potential methods, see for instance, D. E. Sanger and W. J. Broad, *How to Listen for the Sound of Plutonium,* The New York Times, January 31, 2006.

[8] D. Albright and L. Barbour, *Source terms for uranium enrichment plants,* Institute for Science and International Security, compiled for the U.S. Support Program to the IAEA.

[9] R. R. Draxler and G. D. Hess, *Description of the HYPSPLIT_4 modeling system,* Air Resources Laboratory, NOAA, ERL ARL-224, 2004.

[10] *The Future of Nuclear Power: An Interdisciplinary MIT Study,* Massachusetts Institute of Technology, 2003. Original methodology and data for the global distribution of nuclear energy are from C. M. Jones, *Nonproliferation Issues in the Nuclear Energy Future,* Master's Thesis, MIT, June 2003.

[11] A once-through cycle could be based on today's light-water reactors or high-temperature reactors. The SWU-demand would be comparable for LWRs and HTRs. A typical 1,000 MW(e) LWR requires about 20 metric tons (MT) of fresh fuel per year if the average burnup is 50 megawatt-days (thermal) per kilogram of uranium in the fuel. For an initial enrichment level of 4.5%, a separative power of about 150,000 SWU/yr would required to enrich the fuel needed for the LWR, if the tails are stripped to a low value.

[12] Today, 31 countries operate nuclear reactors for power production with a total global generating capacity of 370 GWe. Only nine countries have 10 GWe or more installed and 12 countries have less than 2 GWe, often with minimal domestic nuclear infrastructure.

[13] Some analysts have expressed more optimism about the feasibility to reach such arrangements: “Instituting the supplier/user model is largely a matter, albeit not a simple one, of formalizing the current situation more permanently through new agreements that reinforce commercial realities.” From: *The Nuclear Option,* by J. M. Deutch and E. J. Moniz, *Scientific American,* September 2006.

[14] Note that Iran already represents an “anomaly” in this comparative chart, as it has taken longer than one would expect to build and operate the first machines and cascades. This suggests that the unreliable support and dependencies of proliferation networks might actually delay programs as compared to an entirely indigenous effort.

[15] A discussion of this aspect is beyond the scope of this paper, but an example is the production of the centrifuge rotor, whose successful (mass) production is considered one of the more challenging steps in a centrifuge program. Until the 1990s, the application of the so-called flowforming technique to fabricate rotors was limited to the aerospace and defense industries. Today, the technique is used more widely and includes, for example, applications for the automotive industry. Similarly, rotor balancing has become a less demanding process as balancing machines have evolved into a pushbutton technology: “With the aid of today's faster computers and high quality manufacturing techniques, rotor balancing is no longer the technical challenge it was in the 1980s.” From: Ronald F. Green (Senior Vice President of USEC and director of the centrifuge program, 2003–05), Back to the Future, *Nuclear Engineering International,* September 2003, pp. 36–39.