The last decade has seen many new ideas for strengthening the nonproliferation regime. In 2004, the UN Security Council passed resolution 1540 mandating that all UN member states adopt systems of export control to restrict transfers of sensitive technologies used in the production of WMD. That same year, President George W. Bush proposed to restrict the rights of states to build enrichment and reprocessing plants. In 2005, the head of the IAEA, Mohamed ElBaradei, suggested that a multinational fuel-cycle be established to limit national capabilities. Since then many other concepts, from fuel banks to cradle-to-grave nuclear-power leasing, have been proposed as ways to deter the proliferation of national fuel-cycle capabilities. While these proposals are cast as general enhancements to the nonproliferation regime, they all share a common motivation: each was a response to a growing sense that something has to be done about the proliferation of the gas centrifuge.

The centrifuge appears to have become one of the most coveted pieces of nuclear technology. Every aspiring nuclear-weapon state since 1975 has invested significant resources in the pursuit of the gas centrifuge. Pakistan’s first nuclear bomb was built using centrifuges. In the late 1980s, Iraq had a clandestine nuclear-weapons program of which centrifuges was the most promising...
component. Subsequently, Libya, Iran, South Africa, Syria, and North Korea all attempted to buy centrifuges on the black market. Libya and Syria’s programs were successfully interrupted, South Africa shut its program to avoid embarrassment, but Iran and North Korea succeeded in building full-scale centrifuge capabilities.

If centrifuges have become the proliferation technology of choice, it is not without cause. They are small, highly flexible, easy to hide, and are much less resource intensive than alternative options. They can produce highly enriched uranium, which is easier to handle and use in nuclear weapons than plutonium. Moreover, centrifuge programs can be deployed for ostensibly peaceful purposes and then rapidly used to make fissile-material for weapons without significant modification or delay. Policymakers have responded with stronger technology controls and new institutional arrangements aimed at limiting the justification for peaceful centrifuge plants while simultaneously restraining the ability of states to build clandestine plants. Underlying these proposals, however, is an unspoken assumption that centrifuge technology can be controlled. The approach keeps with a long tradition of focusing on the supply side of the supply-demand equation.

The newest threat to the supply-side regime comes from black-market transfers, from Germany to Iraq and South Africa, from Holland to Pakistan, and from Pakistan to Libya, Iran, Syria, and North

Korea. By shutting down these networks, and by establishing appropriate guidelines for licit transfers, many hope the centrifuge problem can be largely solved. This approach does not, however, account for the technical reality that the centrifuge is a 50-year old device based on straightforward principles of mechanical engineering. Basic centrifuges require no exotic tools or materials to make. If indigenously produced, they will not be effectively restrained by export controls. Furthermore, the effort needed to make basic centrifuges appears to be modest: prototype centrifuges have been built by small groups of ten to twenty engineers in one to two years, and such machines have been subsequently deployed on large scales to make nuclear weapons (particularly in the Soviet Union). Of the twenty countries that have successfully acquired centrifuges, seventeen started with small, simple machines of the kind not effectively controlled by export restrictions. Fourteen of them succeeded in developing these centrifuges without foreign assistance to a level suitable for making weapons. Pakistan, Libya, South Africa, and Iran all had indigenous programs prior to receiving black-market assistance, and that assistance diverted these programs towards more complex designs that also relied more heavily on export-controlled items. An analysis of across all twenty programs suggests that simple centrifuges are probably within the technical capability of nearly any country, including many or most developing countries; only motivation and organizational capacity appears able to restrain the proliferation of basic centrifuges. Supply-side controls are not able to address this state of affairs, suggesting the nonproliferation system badly needs rethinking.


This report begins with a brief history of the effort to control the spread of fuel-cycle technologies. It explains how the centrifuge emerged from an array of other technologies as the most pernicious and most difficult to control. It then gives the history of centrifuge proliferation, first by black-market transfers, followed by indigenous development with a focus on important questions like the role of secrecy, tacit knowledge, and the human and industrial resources required for success.

Having established the limits of technology control, other technical characteristics of the centrifuge are discussed, drawing limits on safeguards and counterproliferation options. This is followed by a discussion of new proposals, presented in broad terms, along with a critical discussion of their ability to address the centrifuge problem. While this report does not outline a specific solution, it suggests that a focusing on the demand for nuclear weapons, rather than on the capabilities needed to produce them, might yield more success.

The Emergence of Supply-Side Controls

Plutonium, not uranium, was the material of choice during the first half of the nuclear age. It powers nearly all the nuclear weapons of the first four nuclear-weapon states. In time, however, some countries found it faster or less visible to enrich uranium and its popularity as a bomb fuel has been growing ever since. China (1960), South Africa (1977), and Pakistan (1979) all used highly enriched uranium (HEU) for their first nuclear weapons and three of the five most recent efforts to acquire nuclear weapons—those of Iraq, Libya, and Iran—had centrifuge-based HEU production as a central focus of the program. North Korea, the most recent nuclear-weapon state, started with a
plutonium capability but has since replaced it with a centrifuge capability. Of this group, only Syria has focused exclusively on plutonium. Of this group, only Syria has focused exclusively on plutonium. Of this group, only Syria has focused exclusively on plutonium. Of this group, only Syria has focused exclusively on plutonium. Of this group, only Syria has focused exclusively on plutonium.

The increasing popularity of uranium enrichment as a route to the bomb is due in part to an easing of the technical hurdles involved in its production. In the 1950s, uranium enrichment entailed the construction of large, energy- and resource-intensive plants. A basic nuclear reactor was comparatively simple, and although easily detectable because of its production of large quantities of heat, could be justified as peaceful research program. Large research reactors could even be bought from advanced nuclear countries, while enrichment plants had yet to be commercialized.

To counter the growing threat of plutonium, nonproliferation advocates focused on several policies. The light-water reactor was promoted over other more weapon-friendly designs. This reactor is refueled every one to two years. More frequent refueling to produce the weapon-grade plutonium preferred by weapon designers would raise suspicions. Light water reactors also require enriched uranium to operate, which during the 1950s and 60s could only be practically purchased from major weapon states like the United States or the Soviet Union. This gave nuclear-weapon states the ability to shut down a non-weapon-state’s nuclear program in the event that program began to pursue nuclear weapons. Finally, the spent-fuel reprocessing facilities required to extract plutonium from reactor fuel (needed regardless of reactor type) were delegitimized as a part of the civilian nuclear fuel cycle by making clear that they were nonessential aspects of the fuel cycle and

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that their use to separate and recycle plutonium was uneconomic. The United States took the lead in this effort by abandoning its own reprocessing efforts in 1970.\textsuperscript{8}

But while the plutonium route was getting more difficult, the uranium route was becoming easier. In the early 1960s a new enrichment technology—the gas centrifuge—became available.\textsuperscript{9} By 1970 it had become the most economically viable method for enriching uranium and it remains so today.\textsuperscript{10} Whereas the preceding enrichment technology, called \textit{gaseous diffusion}, had required massive plants and was successfully developed only by nations with large nuclear programs; centrifuge cascades were small and modular and therefore potentially within the reach of many more nations. States that had bought light-water reactors, and had thus become dependent on the United States or Soviet Union for the supply of nuclear fuel, could now free themselves from this dependency by building enrichment plants of their own. In 1973, the dangers of this dependency were dramatized when the United States, fearing that the demand for enrichment services would outgrow its capacity to supply, briefly closed its order books, catapulting much of Europe into a mindset of self-sufficiency.

By the early 1960s, U.S. officials in the United States recognized that gas centrifuges would pose a special-kind of proliferation problem. Their potential modularity and affordability had already been


\textsuperscript{9} The technology was deployed on a large scale in the Soviet Union in 1957, was not perfected in the West until 1960. Information sufficient to start a well-directed centrifuge plant was published in: G. Zippe, \textit{The Development of Short Bowl Ultracentrifuges} (Division of Engineering Physics, Research Laboratories for the Engineering Sciences, University of Virginia, November 6, 1959).

\textsuperscript{10} The history of the effort to commercialize the centrifuge is given in: R. B. Kehoe, \textit{Urenco. The Enriching Troika. A History of Urenco to the Year 2000} (Urenco Limited, Marlow, U.K., 2002).
recognized by several non-weapon states and research programs began to emerge. U.S. officials soon realized that the same centrifuges that would produce civilian power-reactor fuel could also produce HEU for nuclear weapons with little or no modification. Further still, the low energy use of gas centrifuge plants would make them difficult to detect. A proliferation-scale gas-centrifuge program could be hidden in a warehouse or office building. In 1960, John McCone, Chairman of the U.S. Atomic Energy Commission warned of the problem the centrifuge had created:

[D]o not minimize the potential importance of this process... If successfully developed, a production plant using the gas centrifuge method could be simply housed. Its power requirements would be relatively small, and there would be no effects of the operation which would easily disclose the plant. Although the gas centrifuge does not pose an immediate prospect for the production of weapons material, there is no doubt in my mind it will introduce an additional complicating factor in the problems of nuclear arms among nations and our quest for controlled disarmament.

The United States acted immediately to classify centrifuge-design information worldwide. Delegations were sent to every research program in the West, all of which complied. Unfortunately, this effort came too late. The United States itself had already published most of the basic information required in a series of technical reports, now widely distributed around the world. Within a decade nine countries had successful gas-centrifuge programs. Today, at least

11 This was not immediately evident given the difficulties experienced by the Manhattan Project of enriching uranium to high levels with gaseous diffusion. A research program in the United States showed it to be trivial circa 1963; see: Union Carbide Nuclear Company, *A Proposal for the Development of the Gas Centrifuge Process of Isotope Separation* (Oak Ridge, Tennessee: Union Carbide Nuclear Company, July 11, 1960).

twenty countries have successfully developed or acquired gas centrifuges: Australia, Brazil, China, France, Germany, India, Iran, Iraq, Israel, Italy, Japan, Libya, the Netherlands, North Korea, Pakistan, South Africa, the Soviet Union, Sweden, the United Kingdom and the United States.

The inability to detect covert centrifuge plants has not changed, but the ease with which they could be built has. By the end of the 1990s, further technical publications and advances in computing and manufacturing had come together to create a situation in which nearly any country could build a proliferation-scale centrifuge program, including developing countries. The inability to detect covert centrifuge plants has not changed, but the ease with which they could be built has. By the end of the 1990s, further technical publications and advances in computing and manufacturing had come together to create a situation in which nearly any country could build a proliferation-scale centrifuge program, including developing countries. Furthermore, Pakistan, Iraq, and Iran’s centrifuge-based nuclear-weapons programs have each expanded awareness of the technology and underlined its proliferation advantages. Today, the centrifuge may be regarded as the proliferation technology of choice.

The Development and Spread of Centrifuge Technology

The nonproliferation community has always responded to new threats by attempting to build intuitions designed to help prevent the most recent kind of proliferation. Most of the proposals now under consideration are responses to Iran, Libya, and Iraq. However, with over twenty cases of centrifuge-development programs worldwide, there is the potential for a more substantial analysis. From this larger dataset, we can determine the technological and human resources

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required to build a proliferation-scale centrifuge program, and understand better whether
technology controls are still meaningful barriers to the acquisition of HEU.

The question of technology barriers is important because preventing the acquisition of uranium
enrichment and reprocessing technology has and continues to be a major focus of the
nonproliferation regime. The Nuclear Suppliers Group and other coordinated export-control
regimes, domestic export controls, UN Security Council Resolution 1540, and more recently the
Proliferation Security Initiative. All of these are tools for restricting transfers of technology from
advanced states to potential proliferators. When considering the larger history of centrifuge
proliferation, the limits of technology-based controls, become evident.

BLACK-MARKET NETWORKS AND STATE-TO-STATE TRANSFERS

The spread of gas centrifuges is widely, but perhaps incorrectly, understood to be primarily the
work of illicit black-market networks, notably that of A.Q. Khan. Khan was a Pakistani metallurgist
who, in 1975 while working for a centrifuge contractor in the Netherlands, stole design and
supplier information to help Pakistan build a centrifuge capability for its nuclear-weapons program.
Khan later retransferred the technology from Pakistan to Libya, Iran, North Korea and probably
Syria and China (then already in possession of centrifuges). Pakistan’s program and some of its illicit
retransfers were aided by a number of Canadian, Dutch, Swiss, British and especially German
engineers, and some of the German engineers appear to have independently assisted centrifuge
programs in Iraq, India, South Africa, and Brazil.

While black-market transfers are not unimportant, their importance is often exaggerated. China,
Pakistan, India, Iran, South Africa, and Brazil all had centrifuge programs prior to the receipt of
foreign assistance. These programs were either already successful, or would almost certainly have been successful if left to their own autonomous development.\textsuperscript{14}

In Pakistan’s case, it seems probable that A.Q. Khan-provided drawings actually retarded the national centrifuge program. According to histories of the program and statements from the former head of the program as well as the program’s chief scientist, the information initially supplied by A.Q. Khan was incomplete, lacked key information about the difficulty of making advanced machines, and pushed the program in the direction of a highly problematic design. In the cases of Iran, Libya, and Iraq, all had an interest in centrifuges prior to their interactions with the black market, but the receipt of black-market assistance may have meaningfully increased their levels of technical sophistication, funding, and confidence. At least in Iran’s case, however, it seems likely that the national effort could have progressed to a proliferation-scale capability faster without A.Q. Khan’s assistance, which was again incomplete, unreliable, and directed toward the development of a problematic design.

Of all black-market collaborations, only South Africa and Iraq appear to have received foreign assistance of sufficient quality and timeliness that it advanced the date at which a meaningful centrifuge capability could have been produced. In both cases, the assistance came from highly experienced German engineers, not A.Q. Khan.\textsuperscript{15} South Africa’s program was probably not motivated primarily by an immediate desire for nuclear weapons. It was nonetheless kept secret

\textsuperscript{14} South Africa claims to have had an early centrifuge program, but no information has been published in the public domain to back this claim. However, South Africa did have a successful uranium-enrichment program based on a different technology, called the vortex or ‘stationary-wall centrifuge’ process. This process was used to make South Africa’s HEU-based nuclear weapons.

\textsuperscript{15} These German engineers were at times also associated with Khan, but they also operated separately from Khan providing better assistance.
and terminated shortly after its connections with the black market were revealed during an investigation. Iraq’s program was for weapons, but was cut short by the 1991 Gulf War. Libya’s program was never successful, either prior to or after A.Q. Khan’s assistance, but as Libya showed no indications that it could have succeeded on its own, A.Q. Khan’s assistance, however poor, was probably necessary.

Despite the limited effect of the black market on centrifuge proliferation thus far, the potential for high-impact technology transfer remains. The South African and Iraqi cases demonstrate that technically competent foreign consultants can accelerate a program. The transfer of turnkey facilities is also a concern. North Korea has been known to provide comprehensive assistance for missile programs and is believed to have provided a complete nuclear reactor to Syria; the same could easily be done for a centrifuge plant. Among all states currently possessing centrifuge technology, Iran and North Korea are the most probable suppliers of centrifuge technology given their status as nonproliferation pariahs and their relative freedom from international political constraints.\(^{16}\)

The problem of state-to-state and black-market transfers thus remains.

A LARGER HISTORY OF INDEPENDENT DEVELOPMENT

The alternative to buying or bartering for centrifuge technology is to develop it indigenously. In fact, most countries have developed centrifuges in this way. Almost all of these indigenous programs preceded A.Q. Khan and are informative as to the challenge involved in building a proliferation-scale centrifuge capability from scratch.

The basic Soviet centrifuge, from which all modern designs are derived, was perfected in 1953. Austrian and German scientists captured by the Soviet Army during World War II were used as a source of skilled labor. Starting with an unsuccessful American design, these scientists, working with Soviet scientists, were able to evolve a very successful machine. When the POWs were repatriated to Germany in the mid 1950s, they carried in their heads the basic principles of the successful design. U.S. intelligence obtained this information through interviews, and the United States later commissioned one of the POW scientists—Gernot Zippe—to come to the United States and replicate the Soviet machine.¹⁷

Until this point the basics of modern gas-centrifuge design were not public knowledge. However, between 1958 and 1960, reports written by Zippe in fulfillment of his contract with the U.S. Atomic Energy Commission were publicly released by the U.S. Government.¹⁸ While the U.S. Atomic Energy Commission considered its own centrifuge research secret at the time, doubts as to the potential of the Soviet design and the inconvenience of classifying reports written by a foreign national were sufficient for the AEC to ignore its own classification guidelines.

¹⁷ TC QQ [Citation forthcoming]
¹⁸ G. Zippe, J. W. Beams, and A. R. Kuhlthau, *The Development of Short Bowl Ultracentrifuges*, Progress Report (Ordnance Research Laboratory, University of Virginia, December 1, 1958); G. Zippe, *The Development of Short Bowl Ultracentrifuges*, Progress Report (Ordnance Research Laboratory, University of Virginia, July 1, 1959); G. Zippe, *The Development of Short Bowl Ultracentrifuges* (Division of Engineering Physics, Research Laboratories for the Engineering Sciences, University of Virginia, November 6, 1959); G. Zippe, *The Development of Short Bowl Ultracentrifuges* (Division of Engineering Physics, Research Laboratories for the Engineering Sciences, University of Virginia, July 1960). On the spread of the report, see R. Scott Kemp, “Nonproliferation Strategy in the Centrifuge Age” (PhD, Princeton University, 2010).
Zippe’s reports appear to have fueled an expansion in the number of centrifuge programs around the world during the 1960s and 70s. The United States did what it could to classify all further centrifuge research at home and abroad, but new programs nonetheless emerged in Israel (circa 1960), France (1960), China (1961), Australia (1965), Sweden (1971), Italy (1972), India (1972), Japan (1973), and Brazil (1979). Many if not most of these programs were motivated by the understanding that centrifuges would give their countries a latent nuclear-weapon capability and almost all of them developed the centrifuge indigenously using the reports released by the U.S. Government as the basis for their research. Along with this accidental proliferation, the United States also deliberately transferred the technology to the British government in 1960, and informally assisted the Israeli effort by allowing Israeli students to study centrifuge physics with U.S. centrifuge experts during the 1970s and 80s.

Detailed program histories are available for a number of independent programs. They reveal that the effort needed to build a basic, Soviet-style machine is considerably smaller than the effort needed to build the more difficult designs that were provided by A.Q. Khan and other black-market suppliers.

The engineers in the early U.S. and British centrifuge programs, for example, had very little relevant prior knowledge of centrifuges and, unlike the scientists involved in the Manhattan Project, had only modest training. Both programs started in 1960, and had access only to basic metalworking equipment similar to that found today in a high-school machine shop and their engineering staffs never exceeded 15 persons. Despite the modest resources, these programs were able to perfect a centrifuge suitable for mass production in little over a year (15 months). The Australian program started in 1965 is another example. Notable because it is the slowest program of independent development, it took almost six years to go from nothing to a working cascade of small
centrifuges enriching uranium to low levels. However, the program was also very small: it started with three and at no point grew any larger than six persons.

The record of centrifuge development for twenty historical cases is summarized in the timelines shown in Figure 1. The average time to develop a basic centrifuge ready for mass production of all historical programs with known dates is $25 \pm 11$ months (about 1–3 years). Note that these programs mainly occurred in the 1960s and 70s. A present-day program could also benefit from more modern machine tools, vastly more open-source publications about centrifuge design, desktop computers to aid in design and diagnostics, and the internet to ease in the sourcing of technical information.

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Figure 1: Time required to develop a centrifuge capability suitable for weapons production by programs operating free of foreign assistance.
The mass production of centrifuges, and operation of a centrifuge plant, is a larger but easier effort than the R&D phase. About 5000 Soviet-type machines are needed to produce 25 kg of weapon-grade HEU (enriched to greater than 90%) per year—the approximate quantity needed for a first-generation implosion-type weapon, or one-half the amount required for a gun-type weapon. A program of this scale would be consistent with many historical weapon programs.\(^{19}\) For a basic Soviet-type centrifuge, mass production does not require specialized tooling or skilled labor. The British program, for example, built its first pilot plant by hiring unskilled labor (“milkmen”) to make centrifuge parts on an assembly line. If such an assembly line were able to produce 20 centrifuges per day, this would be sufficient to produce the 5000 centrifuges needed for a proliferation-sized plant in one year. The effort might require 15–30 workers. Thus, the core staff sizes required for a basic centrifuge program are sufficiently small. A small cadre of half-a-dozen suitably trained engineers, and a slightly larger force of unskilled but trainable laborers can probably be gotten together in nearly any country. Building a centrifuge program may still be outside the capability of loosely organized terrorist groups, but the task is within the capability of a small engineering firm with a few dozen people.

The potential of technology controls to prevent the emergence of indigenous centrifuge programs is limited. Export controls can be applied to a small subset of highly specialized materials and tools.

\(^{19}\) Many countries start with programs of this scale: It is estimated that Pakistan started with a capability of one bomb every two years around 1983. North Korea, during its plutonium program, maintained a capability of less than one weapon per year. Iraq’s nuclear weapons program, though interrupted by war, had plans to build about one bomb every 2.5 years. South Africa’s nuclear weapons program produced at a rate below one bomb every two years.
The simple Soviet-style centrifuge, however, needs very few of these. A high-strength metal is needed, but these are widely used and only controlled when in pre-formed into centrifuge-rotor shapes. Basic billets are not controlled, and most countries could also develop the ability to produce these materials domestically. Variable-frequency drives designed for high-speed centrifuges are also controlled, but alternatives exist. The British program, for example, used hi-fi stereo amplifiers to drive its first centrifuges. Beyond these two items, basic Soviet machines require not other export-controlled items.

**Further Complications in the Control of Indigenous Centrifuge-based Proliferation**

**URANIUM VERSUS PLUTONIUM**

For a nuclear weapon of a given design, a highly enriched uranium (HEU) version will always be larger and heavier than a plutonium version because its critical mass is about three times larger. This is why advanced nuclear weapon states favor plutonium devices. However, as China and Pakistan’s arsenal—both initially based on HEU—suggest that HEU weapons can be militarily relevant.

One advantage of HEU for weapon makers is that it can be used to make relatively simple “gun-type” devices. In a gun-type device, one subcritical piece of HEU is fired down a tube (a gun barrel) towards another. When they join, they make a supercritical mass and explode (see Figure 2). The Little Boy weapon detonated over Hiroshima was a gun-type device. Gun-type weapons are simple devices and have been built and stockpiled by the United States and South Africa without nuclear explosive testing. The U.S. Department of Energy has warned that it even may be possible for
intruders in an HEU storage facility to improvised nuclear explosive device in so short a time that they would be finished before security guards could intervene, most probably in a gun-type arrangement.

Gun-type devices need not be as massive as the Little Boy device used over Hiroshima. In 1952, the United States began building the W33 HEU gun-type weapon. It was designed to be fired by an artillery piece, was 8-inches in diameter, and produced a nuclear yield of 40 kilotons, three times that of the Hiroshima bomb. The W33 weighed about the same as the W80 and is small and light enough to fit on a missile.

**DIFFICULT TO DETECT, DIFFICULT TO COUNTER**

Counter-proliferation strategies—including but not limited to diplomacy, interdiction, sabotage, military destruction of facilities, and regime change—all require that a program be detected first. If
a state can successfully keep its nuclear-weapon program secret, it has great flexibility in how and when it decides to produce nuclear weapons.

Historically, most nuclear-weapon programs have been detected at early stages; but most centrifuge programs have not. For example, Iraq’s nuclear-weapon ambitions were suspected from the early 1980s because of its visible pursuit of various fuel-cycle technologies, but its centrifuge program was missed and not discovered until after the 1991 invasion when it was inadvertently mentioned by an Iraqi engineer during a routine IAEA/UNSCOM inspection.

The Soviet Union opened its first large gas-centrifuge-based uranium enrichment plant in 1957. Although the Soviet nuclear-weapon program was the target of an intense intelligence effort, the United States routinely missed its massive centrifuge plants. They were only learned of when Russia declared them to the United States in 1991, some 34 years later.

Similarly, China’s centrifuge program started in 1961. A U.S. national intelligence estimate released after China’s first nuclear test in 1964 states with conviction that China did not have centrifuge technology, but internal histories from China’s program indicate that they were already working on second-generation centrifuges. It seems plausible that China might even have used centrifuges (for the final stages of enrichment) to make the highly enriched uranium used in its first nuclear bombs. It appears that China’s centrifuge program was not detected by the United States for almost two decades.

The record of detection is somewhat better for states that went to the black market. Based on newspaper reports, Iran’s program had to have been detected before January 1991, within six years of the program’s inception, and may have been detected much earlier. According to data published in the 2005 report of *The Commission on the Intelligence Capabilities of the United States Regarding*
Weapons of Mass Destruction, however, Libya’s program went undetected for approximately 16 years. The report also notes that a "disproportionately large volume" of U.S. intelligence related to Libya's procurement activities (i.e., its dealings with the A.Q. Khan network) and that little or no information was known about Libya’s internal activities. It appears that A.Q. Khan not only slowed programs by providing incomplete assistance and problematic designs, he also caused his customers’ programs to be discovered because he was himself being watched. Similarly, IAEA officials have said it was the German centrifuge engineer Gotthard Lerch, a member of the Khan network, who led investigators to South Africa’s secret centrifuge program.

Independent centrifuge programs would not have connections to known proliferators. The detection of these programs, therefore, would require either technical signatures that indicate the presence of a centrifuge plant or penetration of the country’s political or technical leadership.

As to technical signatures, centrifuge plants are very easy to hide. Nuclear reactors have visual and thermal signatures that can usually be seen using satellite reconnaissance, and they emit radioactive and chemical tracers that can be detected in the environment. Centrifuge plants have no such signatures, nor do they produce significant electromagnetic emanations that might reveal their existence as significant distances. At present, there is no known way of reliably detecting a covert centrifuge programs by technical means. This helps explain why Russia and China’s programs went undetected for so long.

The ability to penetrate leadership targets is also in question. The U.S. intelligence community failed to detect Iraq and Libya’s centrifuge programs at early stages, despite the overt nuclear-weapon ambitions of these countries. Likewise, North Korea’s sale of a nuclear reactor to Syria
seems not to have been detected until late stages of development. These cases suggest that penetrating the inner workings of suspect proliferators is not always easily done, even for obvious targets.

PAST EFFORTS TO REVERSE PROGRAMS

Should good fortune lead to detection, it still does not ensure the program will be abandoned. The early detection of Pakistan and Iran’s program was used to stifle procurement efforts and delay the program, but delay it did not produce a reversal. Regime change was the causal factor in the termination of Argentina, Brazil, and Iraq’s nuclear-weapon programs (and internally generated in the cases of Argentina and Brazil). Egypt’s program was similarly abandoned after the nation’s priorities changed following the Six Day War with Israel. Iran’s nuclear-weapon-design program—not its centrifuge program—may have also been abandoned because of an exogenous change in its security situation. According to the U.S. intelligence community, the Iranian nuclear-weapon program was likely halted in 2003 immediately following the fall of the Iran’s principal adversary, Iraq’s Saddam Hussein.

Military attacks on nascent nuclear-weapon programs have had mixed success. Thus far, Israel appears to have ended Syria’s nuclear program when it bombed the Al-Kibar reactor. Syria’s reactor was detected because of its black-market connections, and Syria lacked an indigenous capability to rebuild. Israel tried to do the same with Iraq’s Osirak reactor in 1981, but in that case

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the bombing probably strengthened Iraq’s nuclear ambitions and drove the program to indigenous
development. That development proceeded relatively undetected until 1991 when it was
interrupted by war. One might conclude that military intervention can work in a case such as Syria
where the state is heavily reliant on a foreign supplier and not apt to re-establish the relationship a
second time, but a more indigenous capability is apt to be harder to eliminate unless the military
attack also kills most of the engineers who retain the knowledge required to rebuild. This may
explain why there have been several assignation attempts against key scientists in the Iranian
centrifuge program.

Diplomatic engagement is yet another way to counter a revealed nuclear-weapons program. This
has been most successful in cases where significant political pressure could be brought to bear, such
as in the nuclear-weapon programs of Taiwan and South Korea (neither of which were based on
centrifuges). However, pressure approaches appear mainly to have worked for states that are
dependent for their security on a strong nonproliferation advocate. Pressure has not been
successful, for example, in the cases of Pakistan and Iran.

Complicating diplomatic efforts is the fact that centrifuges are a legitimate part of a peaceful
nuclear-fuel cycle, so a state can declare its capability as entirely peaceful and stare down criticisms.
In principle, an incentives-based approach might work where pressure has not, but the incentives
would need to outweigh the perceived benefit of having a nuclear weapon or nuclear-weapons
option. In Libya’s case, it was sufficient to provide major sanctions relief and minor cooperation in
peaceful nuclear activities, such as nuclear medicine. In 1994 North Korea suspended its
plutonium-based program in exchange for massive foreign aid and negative security assurances. In
other cases, the abandonment of a program might require more than bilateral offers, possibly
requiring that influential states act to reshape the security environment of the potential proliferator
to eliminate the initial motive for the nuclear-weapons program. Such steps can be exceptionally difficult when the proliferator is seen as a violator of international agreements and thus not worthy of security assurances.

Reconsidering Nonproliferation Options

Centrifuges, because of their technical qualities—including the ease with which they can be made, the difficulty of detection and the inability to distinguish between weapon-oriented and peaceful-oriented facilities—challenge existing nonproliferation institutions like never before. It could be said to increase the chance that nuclear weapons will proliferate to more countries. A modification of approach is therefore necessary if the nonproliferation regime is to keep pace with technological change.

TECHNOLOGY-FOCUSED CONTROLS

Most nonproliferation institutions created since the signing of the NPT were designed to address state-to-state technology transfers, like those that backed the nuclear-weapon programs of China, India, Brazil, and Iraq. The newest institutions, such as U.N. Resolution 1540, the Proliferation Security Initiative, and various national export and financial regimes, have responded to black-market technology transfer like that which backed the centrifuge programs of Pakistan, Iraq, Libya, and

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21 According to Myron Kratzer (then Science and Technology counselor and subsequently (in 1975) Senior Deputy Assistant Secretary for Nuclear Energy at the U.S. Department of State), Brazil’s program was the major impetus behind the Nuclear Suppliers Group. The Indian nuclear test of 1974 served mainly to finalize an already active discussion. Author Interview with Myron Kratzer, April 19, 2011.
North Korea, and Iran. Neither set of institutions attempts to address the problem of indigenous technology development.

There has been no lack of interest in indigenous technology development: Pakistan, Iraq, Iran, Libya, and South Africa all started indigenous centrifuge programs before receiving outside assistance. It was only because outside assistance was later obtained that these programs shifted their mode of operation to one of dependency. As nonproliferation champions work to eliminate black market agents, future proliferators might be more likely to stay the course with indigenous programs, and in doing so, maintain or possibly even increase their probability of proliferation success.

Unfortunately, general export controls are unable to restrict access to the basic technologies needed for a Soviet-type centrifuge, the type of centrifuge that has formed the basis of nearly every indigenous centrifuge program in history. A second category, called “catch all” controls, extends export restrictions to any general-use item if the state is suspected of having a WMD-related program. Catch-all controls can restrict the technologies needed for indigenous centrifuge programs, but they will only be implemented if the program has been detected in advance, but indigenous centrifuge programs have showed a remarkable ability to stay secret. Catch-all controls also require that most states agree that the proliferator has non-peaceful intent, otherwise the proliferators access to international markets will not be effectively blocked. This is complicated by

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22Catch-all controls, while useful in principle, are highly imperfect. They are more easily bypassed through the creation of front companies intended to deceive exporters of the true end use. The detection of front companies is an intelligence function and is highly imperfect. Compliance is also problematic because manufactures of normally uncontrolled items may not be aware that they needed an export license for particular buyers. Furthermore, not all states implement catch-all controls.
the fact that centrifuges intended for weapon purposes, even if detected, are functionally
indistinguishable from those that have legitimate peaceful uses.

A novel strategy might be to redirect proliferation programs along slow and problematic
paths. One could imagine creating fake black-market purveyors of centrifuge technology to lure
emerging indigenous programs into a path of dependency—rather like A.Q. Khan appears to have
done. Unfortunately, one could not be sure that this approach would not result in an overall
reduction in the proliferation rate. The historical record suggests that black-market assistance,
however misdirected, has also given states a false sense of confidence and may have ultimately
increased funding and the determination to succeed. A well-intended effort by Germany’s foreign
intelligence agency, the BND, to create a black market for stolen fissile material to capture thieves
appears to have backfired by encouraging theft, causing an overall increase in total crimes. In a
similar manner, one could imagine that false offers of centrifuge technology might either prompt
proliferation, or empower internal advocates beyond what would naturally occur.

Another strategy is to directly influence the technology of the indigenous program through
sabotage. The difference between luring, above, and sabotage is that sabotage is specifically targeted
at known programs. Sabotage thus requires the saboteur know about the program first, which is a
problematic perquisite given the poor track record of detecting indigenous centrifuge programs.

Still, in certain cases sabotage could be very effective in slowing a program. Slowing provides
greater opportunity for exogenous factors to intervene and reverse or stabilize the program at a
point short of a complete nuclear weapon. However, if sabotage is detected or suspected, it may
also work against diplomatic efforts to reverse the program through trust building.
TECHNOLOGY REGIMES: REDUCING THE MOTIVATION TO BUILD

CENTRIFUGE PLANTS

This situation described above suggests that policymakers might more productively focus their attention on the underlying motivations for building a centrifuge capability. One way to do that is to establish a technology regime that governs the normative use of sensitive technologies like the centrifuge.

The primary motivation for building centrifuges apart from weapons is nuclear power. A concern arises because nuclear power is frequently used as a cover story when a state may really be seeking a weapon or weapon option. States with nuclear power are justified in building a national centrifuge plant for the purposes of energy security, provided their reactors use enriched uranium as fuel. Proposals have been made to suppress this justification by establishing regimes that re-define the accepted use of dangerous technologies like centrifuges. The most dramatic include international agreements to establish enrichment-free zones or switching to reactor designs that do not require enriched uranium. Some intermediate ideas include regulating enrichment through flag-rights on raw uranium (a bilateral agreement that if you buy uranium you promise not to enrich it in a domestic facility) or reverse-flag rights (if you buy a reactor, you promise not to put domestically enriched uranium in it without prior consent). Softer proposals include fuel-supply guarantees ensuring that all states would had unfettered access to the existing nuclear-fuel market coupled with either a normative or legal obligation not to build new national facilities, as well as proposals that would require any new centrifuge plant to be built on a multilateral basis.

In general terms, technology regimes are similar to the economic and normative regimes that helped to limit the spread of plutonium reprocessing plants in the 1970s and 80s. The benefit of an
enrichment-focused regime will be of a different character than the regimes surrounding reprocessing technology. In the reprocessing case, a state’s willingness to forgo a reprocessing plant could prevent it from suddenly using that plant to establish a large-scale weapons program. However, it never prevented the quick-and-dirty separation of reactor-grade plutonium at a makeshift facility. That said, the quick-and-dirty approach was rendered somewhat unattractive and potentially difficult because of the challenges involved in handling spent reactor-fuel and the potentially suboptimal qualities of reactor-grade plutonium for first-generation weapon designs. Together, this collection of challenges created a moderate barrier to using plutonium in the nuclear-power fuel cycle for rapid nuclear proliferation.

MULTINATIONAL ENRICHMENT PLANTS

The rapid repurposing of a centrifuge plant from peaceful to weapon purposes is feasible if there is a plant located on one’s own territory. One proposal to raise the political cost of such a breakout is to require that any such plant be under the auspices of a multinational consortium. Multinational ownership does not eliminate a country’s ability to overtly pursue centrifuge technology, but it requires that other states be mutually invested in the plant’s operation. It may still be technically possible for the government of the host country to take over the centrifuge plant and produce weapon-quantities of HEU within several days. The political costs of taking over a multinational plant are likely to be higher than simply violating safeguards and using a national plant, but whether the additional costs be significant compared to the political costs of leaving or violating the NPT and nonproliferation norms is debatable.

Even if the extra costs were not significant, it could be argued that a multinational arrangement would help prevent proliferation by facilitating a military attack, or some equivalent forced
shutdown, of the plant being used for non-peaceful purposes. Other ‘owners’ from the multinational consortium would presumably have standing to ask for, or to execute, an attack against the plant once it had been taken over. Unfortunately, a multinational employee base would also provide a hostage opportunity that could be used to deter an attack on the facility, or defeat any autodestruct system.

It remains to be determined whether a multinational arrangement can provide substantial safeguard against breakout compared to a national facility. The arrangement might even exacerbate proliferation if it facilitated overt centrifuge R&D that could be used to build a parallel centrifuge program in secret, or if the mantle of a multinational consortia allowed a state to buy high-performance centrifuges from commercial vendors, thereby enhancing the breakout capability beyond what would have been available in a go-it-alone approach.

**FUEL-BANKS, GUARANTEES, AND LIFETIME SUPPLY CONTRACTS**

Other types of technology regimes seek to ban the construction of enrichment facilities altogether, or ban them default except when meeting specific nonproliferation criteria. Such ‘bans’ will tend to be a more significant barrier to proliferation because states would not, in general, have access to a rapid breakout capability.

One such proposal is to implement a legal or normative ban incentivized by a fuel bank or other kind of fuel-supply guarantee such as reactor-lifetime fuel-supply contracts. The difficulty with these proposals is in their appeal. It is not clear that there exists a state that would value a contrived

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23 Such a right could be further codified in the original terms of cooperation. However, legal barriers have not deterred some states, notably Israel, from attacking facilities that belonged wholly to Iraq and Syria. Still, other states may feel more apprehension about military attacks.
fuel-security mechanism enough to trade the option of building a national plant for the benefit of that mechanism. So far, no state has expressed an interest in trading fuel-assurances for freedom of action, most being satisfied that the marketplace will provide. Those states that are probably not comfortable for fear of political manipulation of the markets are probably no more assured by an international fuel-supply assurance mechanism, which even in the best of worlds is likely to be subject to some political manipulation. The number of probable proliferators that such an arrangement would successfully capture may prove to be vanishingly small.

**CABALS, FLAG RIGHTS, AND AGREEMENTS OF COOPERATION**

In the 1970s the construction of numerous spent-fuel reprocessing plants was successfully stayed, yet no state expressed an interest in giving up its right to reprocessing technology. Still, mildly coercive bilateral agreements backed by economics and norms were effective in preventing the proliferation of reprocessing plants. Because the United States abandoned its own reprocessing plants, it had moral standing to request that other states refrain from using U.S.-provided technology or materials in any activity connected to reprocessing (executed through flag rights).

A similar approach for enrichment would be possible. It would be less principled, since leading nuclear powers like the United States do not plan to abandon enrichment any time soon, and most of the nuclear power reactors being sold rely on enrichment in one way or another. It would also lack the economic incentives present in the reprocessing case. Still, suppliers of uranium or of nuclear reactors could ask recipients to foreswear enrichment, or at least seek prior approval before

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24 One the opinions of states see the proceedings of the International Fuel Cycle Evaluation (INFCE), 19–21 October 1977, Washington DC, as published by the International Atomic Energy Agency.
building an enrichment facility. If nuclear suppliers colluded to withhold technology from states not willing to make this commitment, this would create a new kind of strong incentive to abstain from building an indigenous centrifuge program—at least for countries whose primary interest is cost-effective nuclear power and not nuclear weapons.

Such an arrangement has already been codified in the agreement for cooperation between the United States the United Arab Emirates. It might be possible to globalize this approach. There is a collective-action problem in building the supplier cabal, however. There is strong incentive for a supplier government to be a regime holdout, and thereby avail its domestic nuclear industry to a broader market. However, these problems are not insurmountable and have been overcome in the past, for example, in the creation of the Nuclear Suppliers Group. While the current U.S. approach has been to implement this approach through its bilateral agreements for cooperation, it might be worth continuing on more multilateral and principled grounds. Such an approach should have better international support, and should more effectively connect the technology regime to existing nonproliferation regimes like the Non-Proliferation Treaty (NPT). One such approach has been outlined in the INFCA proposal and it, or a similar arrangement, may be worth pursuing.\textsuperscript{25}

PROBLEMS WITH TECHNOLOGY REGIMES

A number of factors work against technology regimes, whether they be multinational arrangements, bans backed by fuel-supply assurances, or regimes enforced by a supplier cabal.

With centrifuges, their potential for clandestine development means a greater potential for cheating

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than there had been with no-reprocessing regimes of the past. These regimes may also have greater
negative implications for the NPT than the no-reprocessing regime because they more directly
affect states’ abilities to build totally self-sufficient nuclear power programs. Furthermore, the
economics of nuclear power are such that a state could easily reject the regime on energy-security
grounds alone.

In the reprocessing case, the diversion of plutonium-bearing reactor fuel to a clandestine
reprocessing plant could be readily detected by safeguards, and nuclear reactors were themselves
highly visible. As such, there was never much potential for a covert plutonium program. This made
a ban on reprocessing fairly effective. By contrast, the historical record suggests that indigenous
centrifuge programs can be kept secret for years, even decades at a time. Secrecy has even been
effective in countries like Iraq and Libya that were known to have nuclear-weapon ambitions and
presumably under intense scrutiny. This would suggest that efficacy of a technology regime for
enrichment will be limited, because states will always have the covert option. That said, the
technology regime helps increase the cost of being caught violating the regime.

Whether the risk associated with a covert program—computed as the probability of detection
multiplied by the extra political costs that would result of being exposed—can be made high
enough to deter such a program depends entirely on the proliferator’s particular objectives and the
international political context of the day. That said, the more international and principled the
technology regime can be made, the more a violation of the technology regime would be seen as
blatant attempt to pursue nuclear weapons. However, if the state intends to pursue nuclear
weapons anyway, and to violate the NPT anyway, then it might be argued that the technology
regime hasn’t added much in the way of political cost.
It is also important to note that, whatever virtues of a technology regime, the arguments for flagrantly rejecting the regime from the outset are strong. The predominant fuel-cycle uses light-water reactors, which require enriched uranium to operate. Thus, uranium-enrichment technology might be regarded as an essential component of a self-sufficient program. The NPT guarantees that all states shall have access to the technologies needed to enjoy the benefits of nuclear power in Article IV, and whether enrichment is one of them is open to debate. An attempt to infringe on this right might undercut the NPT in the eyes of states that's already feel slighted by its inequities. The problem of economics is similar. A domestic enrichment program is rarely cost effective when compared to the alternative of purchasing enrichment services from established suppliers.

However, a state with nuclear power would incur far greater costs if they suddenly lost access to enrichment services, and domestic enrichment is cheap insurance relative to the cost of an idle nuclear-power plant.\(^\text{26}\) No international guarantee that enrichment services will always be available can be made totally free from political manipulation. Those states whose relations are most strained, and thus most likely to be interested in centrifuges for weapon purposes, are also those

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\(^{26}\) Even if not competitive with the international market, centrifuges would still be a reasonable insurance against a possible fuel-supply cutoff. To demonstrate this, consider that estimates for the real levelized cost of nuclear power per kilowatt-hour can range from $0.09 in optimistic, forward-looking case studies to values in excess of $0.20/kWh (2008 dollars) for first-of-a-kind construction in regulation-heavy regions. Assume, for the sake of calculation, a median value of $0.15/kWh. Nearly all of that cost comes from the capital charge and staffing costs; less than $0.01 is the cost of fuel. At 85% capacity factor, the plant operates for about 7,500 hours/year. Thus, the real levelized cost for a non-operating full-size (1GWe/yr) plant is about $1.1 billion/year, approximately the cost of a modern centrifuge plant able to support approximately 30 GWe of nuclear power annually. For a primer on the economics of nuclear power, including estimates of the real levelized cost; see: Massachusetts Institute of Technology, *The Future of Nuclear Power*, July 2003. The estimated cost of a modern enrichment plant is based on the projected cost of the Urenco/LES plant in Eunice, New Mexico; see: Michael Knapik, “LES hopes for fresh start in New Mexico,” *Nuclear Fuel*, September 1, 2003.
states that are most likely to be the victims of political manipulation and thus most justified in building national centrifuge plants of their own. States can always appeal to the argument that their energy security is at stake, regardless of the prevailing regime. This will be the case for as long as nuclear reactors require enriched uranium to run.

**REDUCING THE MOTIVATION TO BUILD NUCLEAR WEAPONS**

Technology controls and technology regimes are both imperfect. Controls have the potential to delay programs if the program has been detected, but prevention of indigenous centrifuge programs by technology control appears next to impossible. Delay by itself has not demonstrated that it can reliably reverse programs, and detection is statistically unlikely. Regime might be developed that have the potential to deter states from building overt centrifuge programs to acquire a nuclear-weapon capability, but they are unlikely to deter a covert centrifuge program, especially if intended for the immediate production of nuclear weapons. Those regimes are also not economically credible. It may be that the only approaches that comprehensively address the problems created by the centrifuge are those that directly influence a state’s perceived need for nuclear weapons in the first place.

Classically, states tend to pursue nuclear weapons because they feel a security threat justifies the need, because nuclear weapons are seen as a symbol of great-power status, or as tools of coercion. Nonproliferation in the centrifuge age may require that nonproliferation advocates better prepare themselves to address these motivations face on. More attention may need to be given to the

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27 Another common explanation is that nuclear weapons can be used to satisfy domestic constituencies, but presumably, for constituencies are large and well supported, they want nuclear weapons for one of the listed reasons.
security situation of states that feel their existence is threatened by more powerful states and which thus seek nuclear weapons as a kind of existential guarantee. Nuclear-armed states that are not at peace with their neighbors (e.g., Israel) may need to reconsider the value of their own nuclear armaments if they prefer to maintain a conventional rather than nuclear standoff. Established nuclear powers may need to accelerate progress towards the reduction, and ultimately the complete elimination, of their arsenals if they are to devalue weapons a symbol of great-power status. And finally, champions of the nonproliferation regime may need to be prepared to offer security guarantees of various sorts when a potential proliferator emerges on the international stage. All these require major changes in the way states conduct their foreign policy. They are unlikely to happen easily, but they are increasingly important in an age when nearly any state can make a proliferation-scale centrifuge program covertly using only indigenous resources.