CHAPTER 8

CENTRIFUGES: A NEW ERA FOR NUCLEAR PROLIFERATION

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The last decade has seen many new ideas for strengthening the nonproliferation regime. In 2004, the United Nations (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 weapons of mass destruction (WMD). That same year, U.S. President George W. Bush proposed to restrict the rights of states to build enrichment and reprocessing plants.[1] In 2005, the head of the International Atomic Energy Agency (IAEA), Mohamed ElBaradei, suggested that a multinational fuel cycle be established to limit national capabilities.[2] 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 are all motivated by instances of centrifuge proliferation.

The uranium-enriching gas centrifuge has become one of the most coveted pieces of nuclear technology. Every aspiring nuclear-weapons state since 1975 has considered the centrifuge for its weapons program. Pakistan's first nuclear bomb was built using centrifuges, and Brazil, Iraq, Libya, Iran, South Africa, Syria, and North Korea all sought centrifuge technology for military purposes.

If centrifuges have become the proliferation technology of choice, it is not without cause. They are small, highly flexible, easy to hide, and much less resource-intensive than alternative options.[3] They 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 to recent cases of centrifuge proliferation by advocating for stronger export controls that would make it harder for states to build centrifuges. In parallel, policymakers have also considered new institutional arrangements that would make it more difficult for states to claim that their acquisition of centrifuge technology had a peaceful basis. These policies keep with a long tradition of focusing on the supply of nuclear technology rather than the demand for nuclear weapons. The newest threat to the supply-side regime has come from black-market transfers: from Germany to Iraq and South Africa; from the Netherlands to Pakistan; and from Pakistan to Libya, Iran, Syria, and North Korea.[4] By shutting down these networks and by establishing appropriate guidelines for licit transfers, many hope the centrifuge problem can be largely solved.[5] Underlying these proposals, however, is an unspoken assumption that centrifuge technology can be controlled. The proposals do not acknowledge that the centrifuge is a 50-year-old device based on straightforward principles of mechanical engineering, that essentially all of the required design information needed is in the public domain, or that basic centrifuges require no exotic tools or materials to make. If centrifuges can be indigenously produced, they cannot be effectively restrained by technology controls.

The effort needed to make basic centrifuges is, by today's standards, quite modest: Prototype centrifuges have been built by small groups of 10 to 20 engineers in 1 to 2 years, and such machines have been subsequently deployed on large scales to make nuclear weapons (particularly in the Soviet Union). Of the 20 countries that have successfully acquired centrifuges, 17 started with small, simple machines of the kind not effectively controlled by export restrictions. Fourteen of them succeeded without foreign assistance in developing these centrifuges to a level suitable for making weapons. An analysis across all 20 programs suggests that simple centrifuges are probably within the technical capability of nearly any country, including many or most developing countries.[6] Supply-side controls would not address this state of affairs; only motivations and the organizational capacity of states would restrain centrifuge proliferation. If this is indeed the case, then the nonproliferation system needs rethinking.

This chapter begins with a brief history of the effort to control the spread of fuel-cycle technologies. It explains how the centrifuge emerged from the field 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. The discussion of the potential for states to acquire centrifuges is followed by a discussion of how difficult it would be to prevent centrifuges from being used for weapons purposes. The centrifuge has certain technical characteristics that make both safeguards and counterproliferation difficult or impossible. The chapter concludes with a critical review of several recent proposals for coping with proliferation. While this report does not outline a specific solution, it suggests that none of the supply-side options appear to offer any hope of success. As such, a focus on the demand for nuclear weapons, rather than on the capabilities, is perhaps the only way to mitigate centrifuge proliferation in today's technologically advanced world.

THE EMERGENCE OF SUPPLY-SIDE CONTROLS

Plutonium, not uranium, was the material of choice during the first half of the nuclear age. Plutonium powers nearly all the nuclear weapons of the first four nuclear-weapons states. In time, however, some countries found it convenient 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-weapons state, started with a plutonium capability but has since replaced it with a centrifuge capability.[7] Of this group, only Syria has focused more on plutonium, its centrifuge program having been interrupted at an early stage.[8]

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 it would be difficult to hide because reactors produce large quantities of heat, it could be easily justified as part of a 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 began to minimize its role in the nuclear fuel cycle. Research reactors that produced weapons-grade plutonium as a byproduct of operation were replaced by models that used low-enriched fuel and only produced plutonium very slowly. For electricity production, the light-water power reactor was promoted over other more weapon-friendly designs. For power production, the light-water reactor needs to be refueled only every 1 to 2 years. More frequent refueling is needed to produce the kind of weapons-grade plutonium preferred by weapons designers, and such refueling would easily raise suspicions. Finally, the spent-fuel reprocessing facilities required to extract plutonium from reactor fuel (needed regardless of reactor type) were delegitimized by emphasizing that they were neither economic nor technically essential elements of the civilian nuclear fuel cycle. The United States took the lead in establishing this norm by abandoning its own reprocessing efforts in the 1970s.[9]

But while the plutonium route was getting more difficult, the uranium route was becoming easier. One of the unintended consequences of anti-plutonium policies was that reactors that were poor at producing plutonium also require enriched uranium to operate. During the 1950s and 1960s, this material could only be practically purchased from major weapons states like the United States or the Soviet Union. This gave nuclear-weapons states the ability to regulate to some extent the nuclear activities of nonweapons states. In the early-1960s, all this began to change. A new enrichment technology—the gas centrifuge—was invented. Unlike its predecessor, the centrifuge was a small-scale, affordable technology that was potentially within the reach of a great number of states.[10] By 1970, the centrifuge had become the most economically viable method for enriching uranium, and it remains so today.[11] Whereas the preceding enrichment technology, called gaseous diffusion, had required massive amounts of infrastructure and was therefore successfully developed only by nations with large nuclear programs, centrifuge plants could be built on smaller scales out of simple modules that were individually cheap to build and inexpensive to operate. Countries that depend on the United States or the Soviet Union for the supply of nuclear fuel began to look toward the centrifuge as a way to free those countries from dependency. The Netherlands, Germany, Israel, the United Kingdom, France, China, Australia, Sweden, Italy, India, and Japan all started centrifuge programs for the nominal purpose of self-sufficiency. In 1973, the perils of dependency were dramatized when the United States, fearing that the demand for enriched uranium would outstrip its capacity to supply, briefly closed its order books, reinforcing the perceived importance of self-sufficiency.

Officials in the United Kingdom (UK) and United States immediately recognized that gas centrifuges could be used to make weapons.[12] Further still, they understood that the small footprint and low electricity requirements of a gas-centrifuge plant would make weapons production by means of the centrifuge difficult or impossible to detect. In 1960, Chairman of the U.S. Atomic Energy Commission (AEC) John McCone warned of this problem:

> [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.[13]

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 had already published most of the basic information required to build a centrifuge in a series of technical reports, now widely distributed around the world. Within a decade, nine countries had successful gas-centrifuge programs, despite the U.S. Government's classification efforts.[14]

With time, centrifuges have become easier and easier to build. By the end of the 1990s, additional technical publications and advances in computing and manufacturing had come together to create a situation in which nearly any country—including developing nations—could access the technology and information needed to build a proliferation-scale centrifuge program (whether they could organize themselves well enough was a different matter).[15] Compounding this problem, Pakistan, Iraq, and Iran all built centrifuge programs for nuclear weapons, raising global awareness of the technology and demonstrating its proliferation advantages. Today, many regard the centrifuge as the proliferation technology of choice.[16]

THE DEVELOPMENT AND SPREAD OF CENTRIFUGE TECHNOLOGY

Traditionally, the nonproliferation community looks towards the most recent cases of proliferation for guidance on how to improve the nonproliferation regime. The approach has the advantage of being empirical, but selecting the dependent variable can lead to misinterpretations of causality. It is better to look at a broader history of centrifuge development and the spread of centrifuge technology to understand the true nature of centrifuge proliferation. With over 20 historical cases, there is a considerable basis for drawing new conclusions about the nature of the proliferation problem.

Black Market Networks and State-To-State Transfers.

The spread of the gas centrifuge is widely, but incorrectly, understood to be primarily the work of black market networks. Most famous is A. Q. Khan, a Pakistani metallurgist who worked for a Dutch centrifuge contractor. In 1975, he stole design and supplier information to help Pakistan build a centrifuge capability for its nuclear weapons program. Khan later sold this stolen technology to Libya, Iran, North Korea, and possibly China (then already in possession of basic centrifuges, but interested in learning as much as it could). He offered it to several others, including Iraq and Syria. Pakistan's program and many of its subsequent retransfers were aided by a number of Canadian, Dutch, Swiss, British, and especially German engineers, and some of the German engineers appear to have assisted independently centrifuge programs in Iraq, South Africa, and Brazil.

While black market transfers are not unimportant in the history of centrifuge proliferation, 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.[17]

In some cases, assistance may even have been counterproductive. Consider Pakistan, for example. The drawings A. Q. Khan provided were for an advanced and difficult-to-make centrifuge. The machine was immensely complex relative to most entry-level designs, and this diversion probably slowed his country's nuclear progress relative to what could have been accomplished had Pakistan simply worked on its own. According to histories of the program and statements from its former head, as well as the program's chief scientist, the information initially supplied by A. Q. Khan was not even complete: It lacked key manufacturing specifications that would have hinted at the difficulty of making the advanced machine, and it forced the program to make a number of compromises that ultimately eliminated the performance advantages the advanced machine supposedly offered. The result was a machine that performed less well than the machines usually developed by programs of independent development. Iran, Libya, and Iraq also had centrifuge programs prior to their interaction with the black market. The receipt of black market assistance may have improved the level of funding and support from political leadership, but the technical information they received was frequently problematic. Those who turned to A. Q. Khan for assistance also received incomplete, unreliable assistance and were directed to develop the same highly problematic design with which Pakistan started. Only South Africa and Iraq appear to have received foreign assistance that was technically sound and of sufficient timeliness that it advanced the date at which a meaningful centrifuge capability could have been produced. In both of these cases, assistance came from highly experienced German engineers, not A. Q. Khan.[18]

Despite the limited benefit the black market has had for centrifuge proliferation, the potential for high-impact technology transfers remain. The South African and Iraqi cases demonstrate that technically competent foreign consultants can accelerate a program—especially if it consists of hands-on engineering guidance and well-annotated design documents. Another appropriate concern is the transfer of a complete, turnkey centrifuge plant purchased outright from a foreign nation. North Korea has been known to provide this kind of comprehensive assistance for missile programs and is believed to have provided a complete nuclear reactor to Syria on such a basis. The same could easily be done with a centrifuge plant. Among all states currently possessing centrifuge technology, Iran and North Korea are the most probable suppliers of the technology, given their status as nonproliferation pariahs and their relative freedom from international political constraints.[19] The problem of state-to-state and black market transfers thus remains, but it is not the only path of concern.

A Larger History of Independent Development.

The alternative to buying or bartering for centrifuge technology is to develop it indigenously. In fact, most countries with centrifuges acquired them in this way. By studying these programs, we can learn about the resources required to build a proliferation-scale centrifuge capability from scratch and the potential for other states to do the same in the future.

The history of independent development goes back to the late-1950s. 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 German prisoners of war (POWs), in collaboration with Soviet scientists, were able to evolve a very successful machine. When the POWs were repatriated in 1956, they carried in their heads the basic principles of the successful design. In 1957, this information spread to three new countries. U.S. intelligence obtained Soviet design information through interviews with one of the POWs; West Germany hired two of the POWs to build centrifuges; and Dutch centrifuge designers met one of the POW engineers at a conference and learned of the basic design concepts in a long discussion. In 1958, the United States commissioned one of the POWs—Gernot Zippe—to come to the United States and replicate the Soviet machine.[20]

Until this point, the basics of modern gas-centrifuge design were not public knowledge. The knowledge was spreading slowly in the expert community, but there was no physical documentation of how the

Soviet centrifuge worked. Then between 1958 and 1960, the reports written by Zippe in fulfillment of his contract with the AEC were released to the public by the U.S. Government.[21] While the AEC 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.

The publication of Zippe's reports appears to have fueled a rapid expansion in the number of centrifuge programs around the world. 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). Although nominally for peaceful purposes, many, if not most, of these programs were motivated by the understanding that centrifuges would give their countries a latent nuclear-weapons capability; and almost all of them developed the centrifuge 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 1980s.

Detailed histories are available for a number of independent programs. They reveal that the effort needed to build the basic, Soviet-style centrifuge is considerably smaller than the effort needed to build the more difficult designs that were provided by A. Q. Khan. The engineers in the early U.S. and British centrifuge programs, for example, had essentially no prior knowledge relevant to centrifuges and, unlike the scientists involved in the Manhattan Project, had only modest educations. Both programs started in 1960 and had access only to basic metalworking equipment, similar to what might be found today in a college machine shop. The technical staff never numbered more than 15 persons. Despite modest resources and the small effort, these programs were able to perfect a centrifuge design suitable for mass production in a little over a year (about 15 months). The Australian program is another interesting case. Notable because it is the slowest program of independent development on record, it took Australia almost 6 years to go from nothing to a working cascade of proliferation-relevant centrifuges. However, the program was also the smallest: It started with three and at no point exceeded six persons.

The record of centrifuge development for 20 historical cases is summarized in Figure 8-1. The average time taken to develop a basic centrifuge so it is ready for mass production across all historical programs with known dates is 25±11 months (about 1 to 3 years, in round terms). Note that these initiatives were mainly from the 1960s and 1970s. A present-day program could also benefit from more modern machine tools, vastly more numerous open-source publications about centrifuge design, desktop computers to aid in design and diagnostics, and the Internet to ease the sourcing of technical information.

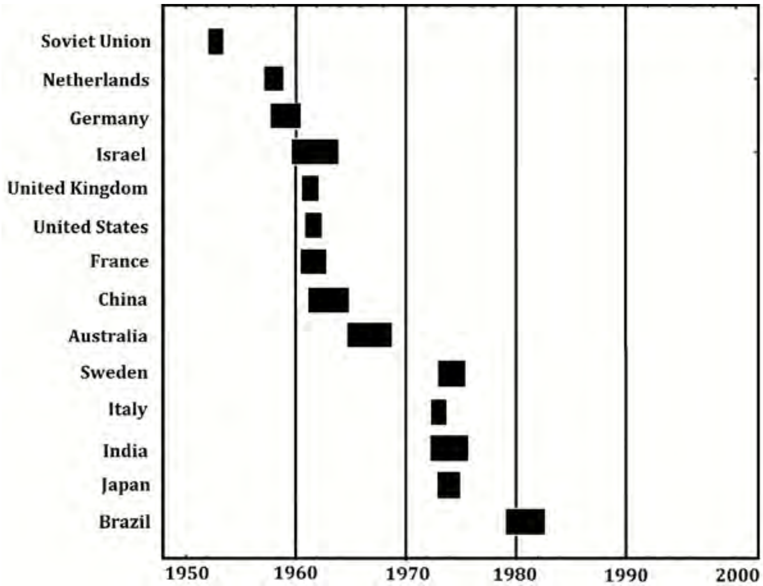

Figure 8-1. Time Required to Develop a Centrifuge Capability Suitable for Weapons Production by Programs Operating Free of Foreign Assistance.

The mass production of centrifuges, along with the operation of a centrifuge plant, is a larger but technically easier effort than the research and development (R&D) phase. About 5,000 Soviet-type centrifuges are needed to produce 25 kilograms (kg) of weapons-grade (enriched to greater than 90 percent) uranium per year, the approximate quantity needed for a first generation implosion-type weapon, or one-half the amount required for a primitive gun-type weapon. A program of this scale would be consistent with many historical weapons programs.[22] Mass production of the basic Soviet-type centrifuge 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 5,000 needed for a proliferation-sized plant in 1 year. The effort might require 15 to 30 workers. Thus, the core staff sizes required for a basic centrifuge program are small. A small cadre of half-a-dozen suitably trained engineers and a slightly larger force of unskilled but trainable laborers can probably be organized 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 cost of a program would also be modest. The first German version of the Soviet-type centrifuge was built by a firm named DEGUSSA in 1959 and had about the same performance as Iran's IR-1 centrifuge (possibly slightly better).[23] This centrifuge was offered for sale for a small-batch cost of U.S.$235 per centrifuge, about U.S.$1,800 per centrifuge in 2012 currency. Assuming the DEGUSSA price reflected the actual cost of production, the centrifuge portion of the plant might be built for less than U.S.$10 million in 2012 currency. The majority of the final costs of the plant might actually be associated with noncentrifuge costs, such as building costs, piping, and control systems.

Not only are centrifuges economical and relatively straightforward to make, but the potential of export and other technology controls to stop indigenous centrifuge programs is very limited. Under normal circumstances, export controls can only be applied to a small subset of highly specialized materials and tools. The simple Soviet-style centrifuge needs few, if any, of these. The most controlled items are the materials for rotor tubes and the variable-frequency drives used to run the centrifuges. Centrifuge rotors need high strength, lightweight materials. They are export controlled when pre-formed into centrifuge rotor shapes. Unformed material, however, is not controlled, and most countries could acquire the simple tools needed to produce centrifuge rotors from the raw inputs. Even if the raw materials were themselves controlled, most states could probably produce a suitable material 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. The basic Soviet machines require no other export-controlled tools or materials.

Counterproliferation.

If it is not possible to prevent the acquisition of centrifuge technology with export controls, might it be possible to reverse proliferation programs using counterproliferation strategies such as diplomacy, interdiction, sabotage, military destruction of facilities, or regime change? The critical prerequisite for all of these strategies is that the proliferation program becomes known to the international community well before the successful acquisition of a weapon. Historically, most nuclear weapons programs have been detected at early stages, but most centrifuge programs have not. For example, Iraq's nuclear weapons ambitions were suspected from the early-1980s because of its visible pursuit of various fuel cycle technologies, but its centrifuge program was missed. The international community did not learn about it until after the 1991 invasion, when Iraq disclosed its existence during an IAEA inspection.

The Soviet Union opened its first gas-centrifuge plant in 1957 and proceeded to build additional plants in the following years as it slowly replaced much of its older diffusion capability with centrifuges. Although the Soviet nuclear weapons program was the target of an intense intelligence effort, the United States routinely assessed that the Soviets did not have centrifuges. The Soviet capability was only learned of after the collapse of the Soviet Union, when Russia told the United States about the existence of these plants, some 34 years after the first large-scale plant opened.

China's centrifuge program started in 1961, 3 years prior to China's first nuclear weapons test. A U.S. national intelligence estimate released after China's 1964 test states with conviction that China did not have centrifuge technology, but internal histories from China's program indicate that the Chinese were working on second-generation centrifuges at the time. In the 1970s, U.S. intelligence received a human source tip-off that China had made weapons-grade uranium with centrifuges, but as the intelligence community had no way to validate this tip, it continued to assess that there was no credible evidence of a centrifuge plant in China.[24] Knowledge of China's centrifuge remained ambiguous for almost 2 decades.

The record of detection is somewhat better for states that were connected to the black market. Newspaper reports indicate that Iran's program must have been detected before January 1991, within 6 years of the program's inception, and may have been detected 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 was related to Libya's procurement activities—in other words, 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 down programs by providing incomplete assistance and problematic designs, but he also caused his customers' programs to be discovered because he was being watched. Similarly, IAEA officials have said it was German centrifuge engineer Gotthard Lerch, a member of the Khan network, who led investigators to South Africa's secret centrifuge program.

Independent centrifuge programs rarely 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. Regarding 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 at significant distances. This may help explain why Russia and China's programs went undetected for so long.

The value of human and signals intelligence is also in question when it comes to finding centrifuge plants. The U.S. intelligence community failed to detect Iraq's and Libya's centrifuge programs in early stages, despite the overt nuclear-weapons ambitions of these countries. North Korea was long suspected of having a centrifuge program because of visits by North Koreans to Pakistan and North Korea's purchase of several centrifuge-related materials, but it was not possible to confirm that this constituted anything more than curiosity. The existence of centrifuge research could not be validated. Even though North Korea has revealed that it does, indeed, have a centrifuge program, there are strong reasons to suspect that other facilities exist, but their locations are still unknown. These cases suggest that penetrating the inner workings of suspected proliferators is not always easily achieved, even with obvious targets. This in turn implies that the opportunities for trying counterproliferation mainly depend on states having connections to known proliferators, and that even when a state is a known proliferator, there may be sufficient ambiguity for it to be difficult to formulate a coherent counterproliferation strategy.

*The Counterproliferation Track Record***.**

Should good fortune lead to detection, it still does not ensure that counterproliferation will work. The early detection of Pakistan's and Iran's program was used to stifle procurement efforts and delay the program, but it did not produce a reversal. Military attacks on nascent nuclear weapons programs have had mixed success. Thus far, Israel appears to have ended Syria's nuclear program when it bombed the Al-Kibar reactor in 2007. This reactor was detected because of its black market connections to North Korea, and the program remained dead after the attack because Syria lacked an indigenous capability to rebuild. Israel tried to do the same with Iraq's Osirak reactor in 1981, but in that case, the bombing appears to have strengthened Iraq's nuclear ambitions and drove the country to pursue the indigenous development of centrifuges, which were not detected. 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 comfortable with re-establishing the relationship, but a more fully 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 build a weapons 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 weapons programs of Taiwan and South Korea. However, pressure approaches appear mainly to have worked for states that depend on a strong nonproliferation advocate for their security. Pressure has not been successful, for example, in the cases of Pakistan and Iran.

Centrifuges complicate diplomatic efforts because the technology is a legitimate part of the peaceful nuclear-fuel cycle. This allows a proliferator to declare its capability as entirely peaceful and stare down criticisms, and so slow the rate at which the international community can apply political pressure to reverse the program. In principle, an incentives-based approach might work where negative 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, minor cooperation in peaceful nuclear activities, and general rapprochement. In 1994, North Korea responded positively to incentives of massive foreign aid and negative security assurances, although the motivations behind North Korea's program were not fundamentally addressed, and the weapons program later re-emerged. The abandonment of a program might require more than simple bilateral incentives. Influential states may need to reshape the security environment of the proliferator to eliminate a security threat that is the essential motivation behind the nuclear weapons program. Such steps can be exceptionally difficult when the proliferator is seen as a violator of international agreements and norms, 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 detecting them, and the lack of visible distinction between weapon oriented and peaceful facilities—are a challenge the like of which existing nonproliferation institutions have never known. A modification of the current approach, which relies heavily on technology controls and detection, is obviously necessary if the nonproliferation regime is to keep up with the changes brought about by the centrifuge.

Technology Controls.

Most nonproliferation institutions created since the signing of the Nuclear Nonproliferation Treaty (NPT) were designed to address state-to-state technology transfers, like those that backed the nuclear weapons programs of China, India, Brazil,[25] and Iraq. The newest of these institutions, such as UN Resolution 1540, the Proliferation Security Initiative, and various national export and financial regimes, respond specifically to black market technology transfers like those that backed the centrifuge programs of Pakistan, Iraq, Libya, North Korea, and Iran. Neither set of institutions attempts to address the problem of indigenous technology development.

However, history shows that 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, which resulted in opportunities for detection and counterproliferation. 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, keep their programs secret and increase their probability of proliferation success.

Unfortunately, export controls are unable to restrict access to the basic technologies needed for a Soviet-type centrifuge, the type that has formed the basis of nearly every indigenous centrifuge program in history. A more expansive set of export controls, called "catch-all" controls, prohibit the sale of any general-use item if there is a reason to believe it might assist a WMD program. Catch-all controls can restrict the technologies needed for simple Soviet-type centrifuge programs, but they will only be implemented if the program has been detected in advance, and history shows that indigenous centrifuge programs have a remarkable ability to stay secret for decades.[26] Catch-all controls also require that most states agree that the proliferator is seeking weapons because, without consensus on this point, the proliferator's access to international markets will not be effectively blocked. Building this consensus is difficult because centrifuge plants built for peaceful purposes have an inherent weapon-making capability.

Enrichment Regimes: Reducing the Motivations to Build Centrifuge Plants for Peaceful Purposes.

The situation previously described suggests that policymakers might more productively focus their attention on the underlying motivations for building a centrifuge capability. One possible motivation, apart from weapons, is the desire to use centrifuges to make fuel for a civilian power reactor. This entirely peaceful application is not itself problematic, but these peaceful plants give their possessors a weapons making capability that might be used later. More significantly, countries can build centrifuge plants claiming peaceful intent but actually harbor ulterior motivations to acquire a weapons or a weapon-making capability. This has led to a growing interest in restricting the legitimate use of centrifuges—although it is not yet clear whether this is a useful way to restrict proliferation, given the potential for small-scale indigenous production of centrifuges. Nevertheless, policymakers are now considering technology regimes that would establish legal or normative limits on the use of centrifuges for peaceful purposes.

In principle, 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; CANDU-type reactors do not require enriched fuel). Proposals have been made to suppress this justification by banning national plants and by creating alternative ways of guaranteeing the supply of reactor fuel. The most dramatic include international agreements to establish enrichment-free zones, such as the now-defunct agreement between North and South Korea. A widely used tactic is to implement so-called "flag rights" on raw uranium. Flag rights constitute a bilateral agreement between the buyer and seller of raw uranium. The buyer promises not to enrich it in a domestic facility without the prior approval of the seller. One can also imagine reverse-flag rights in which the buyer of a reactor promises not to put domestically enriched uranium fuel into it without prior consent. Softer proposals allow national enrichment but seek to render it less attractive for those with proliferation intent. These proposals include multilateral enrichment and fuel-supply guarantees, both of which would help ensure that all states have unfettered access to enrichment services, making it more difficult to justify the creation of a national enrichment plant.

In general, all of these enrichment regimes are conceptually similar to the normative regime that helped limit the spread of plutonium reprocessing plants in the 1970s and 1980s. However, these regimes are more formal and also may be more difficult to enforce. When a state chose not to build a reprocessing plant, it lost its ability to establish a large-scale weapons program easily, but it still retained an ability to build a quick-and-dirty reprocessing setup in the event of a crisis. Restrictions on enrichment would be more complete. Without a plant, there is no quick-and-dirty enrichment-based path to the bomb. At the same time, forgoing enrichment has greater consequences for civil nuclear power. Reprocessing of spent fuel essentially made no sense from an economic perspective and thus had arguably little to no role in a civil nuclear power program, whereas national enrichment clearly does. Thus, a ban on enrichment, while more complete in its ability to block some proliferation routes, may be more difficult to justify and sustain. Given both the more severe effect on proliferation potential and the consequences for national energy security, nations may be less willing to sign up to such a regime in the first place.

*Multinational Enrichment Plants***.**

One of the most widely supported enrichment regimes is to require that all new (and possibly existing) enrichment plants be operated as part of a multinational consortium. Multinational ownership does not eliminate a country's ability to pursue centrifuge technology overtly, but it requires that other states be mutually invested in the plant's operation and, in principle, may reinforce the barriers to using it for weapons. It may still be technically possible for the government on whose territory the plant is built to take unilateral control of the facility and produce weapon quantities of HEU in just a few days. In this sense, the host state retains a quick-and-dirty option, and this may satisfy many states that see no immediate need for a weapon but nonetheless want a weapons capability as insurance. 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 are significant compared to the political costs of leaving or violating the NPT in the first place is debatable. If they are not, the multilateral arrangement has not increased the political barriers to proliferation.

Even if the barriers were not significantly enhanced, it could still be argued that a multinational arrangement would facilitate counterproliferation by legitimizing a military strike against the plant, or some equivalent forced shutdown, if it were being used to make weapons without international approval. Co-investors from the multinational consortium presumably would have standing to ask for, or to execute, an attack against the plant once it had been taken over.[27] 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.

Uncertainty about the ability of multinationals to increase the barriers to proliferation deserves to be taken seriously, because a multinational requirement might have unintended consequences that exacerbate the proliferation problem. For example, the legitimization of multinational plants might facilitate acquisition of a capability, or worse, overt centrifuge research that could be used to build a parallel centrifuge program in secret. The mantle of a multinational consortium might also help a state buy high-performance centrifuges from a commercial vendor, thereby enhancing its breakout capability beyond what would have been available in a go-it-alone approach. In other words, the world might wind up with more threshold states rather than fewer.

Fuel Banks, Guarantees, and Lifetime Supply Contracts.

Other types of technology regimes seek to deter the construction of enrichment facilities altogether or ban them by default except when meeting specific criteria. These include fuel banks and other guarantees of supply. These regimes will tend to be a more significant barrier to proliferation because states participating in them would not, in general, have a recognized reason to build centrifuge plants. On the other hand, the potential for these regimes to capture proliferation aspirants is in question.

One such proposal is to implement a legal or normative ban on national enrichment, balancing the loss of freedom with an improved assurance of supply backed by a fuel bank or other kind guarantee. The difficulty with these proposals is in their appeal. It is not clear if a state exists that would value a contrived fuel-security mechanism enough to trade the option of building a national plant for the benefit of that mechanism. The reason is that the marketplace traditionally has provided all the assurance that the state needs by default, and the additional benefit of the mechanism is seen to be marginal at best. States for which the market might not provide significant assurance because they are ultimately subject to some political manipulation probably are no more assured by an international fuel-supply assurance mechanism, which is also likely to be subject to political manipulation, perhaps even more so than the market. As such, the number of proliferation aspirants that the arrangement would capture successfully might prove to be vanishingly small.

*Cabals, Flag Rights, and Agreements of Cooperation***.**

The no-reprocessing regime of the 1970s successfully stayed the completion of several reprocessing plants, yet the regime was completely voluntary. Participating states were explicit that they were not willing to give up their right to reprocess spent fuel.[28] In the enrichment case, states may be less likely to buy into the normative regime because the lack of economic incentives and the centrality of enrichment for fuel-supply security are too important to forgo on a voluntary basis. A more coercive approach might be needed to formalize the regime. Flag rights, in which suppliers of uranium or nuclear reactors ask recipients to forswear enrichment, are at the leading edge of the coercive approach. A stronger sort of coercion could be had if nuclear suppliers colluded to withhold all nuclear fuel and civil technology from states that are not otherwise willing to give up their unconstrained right to enrich. There is a collective-action problem in building this kind of supplier cabal, as there is a strong incentive for a supplier government to be the last holdout in the creation of the regime, and thereby benefit its domestic nuclear industry by providing access to a broader market. However, these problems are not insurmountable and have been overcome in the past, such as in the creation of the Nuclear Suppliers Group. One such approach has been outlined in the International Nuclear Fuel Cycle Association proposal and it, or a similar arrangement, may be worth pursuing.[29]

*Problems with Technology Regimes***.**

All technology-control regimes aimed at stopping the spread of legitimate enrichment plants prevent states from building totally self-sufficient nuclear power programs, with the result that a state legitimately could reject the regime on the basis of economics and energy-security grounds alone.[30] If a large number of states do this up front, the regime has little chance of success. The coercive regimes resolve this problem by creating a difficult choice for client states, but the inequity in these regimes may begin to erode support for the broader NPT regime, which is already plagued by problems of inequity.

Even if a regime could be implemented, it is necessary to ask to what extent banning legitimate enrichment activities helps to prevent nuclear proliferation. In the reprocessing case, the normative ban prevented large-scale nuclear programs, but states retained an unattractive quick-and-dirty option. Use of that option still required the diversion of plutonium-bearing reactor fuel to a makeshift or clandestine reprocessing plant. The diversion of fuel would almost certainly be detected by safeguards, so any breakout attempt would come with the large political cost of violating the NPT regime. Thus, proliferation via the plutonium route was attractive only in an emergency situation, and even then only feasible on a small scale. By contrast, the historical record suggests that indigenous centrifuge programs can be built and 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-weapons ambitions and presumably were under intense scrutiny. The technology regime would compound the political costs associated with detection, but the probability of detection is low. One must ask if the extra political risk of getting caught violating the technology regime—computed as the probability of detection multiplied by the political cost—is substantial relative to the existing political cost of overtly violating the NPT with a national facility. If the extra risk is small relative to an NPT violation, then the technology-control regime has not added much. Furthermore, this gain then needs to be weighed against the potential negative consequences of legitimizing proliferation of fuel-cycle facilities or exacerbating the already contentious inequity in the NPT regime. It is obviously impossible to quantify these effects and make an actual computation of the relative costs and benefits, but this article has argued that detection rates are probably small and that support for a technology-control regime will be tepid given the legitimate purpose of centrifuges. Both of these arguments lead to the conclusion that the benefit of attempting to control states' legitimate access to centrifuge technology is probably small, and may even be negative.

REDUCING THE MOTIVATION TO BUILD NUCLEAR WEAPONS

Instead of focusing on export controls that limit access to technology, which this article has argued are inoperative in the case of indigenous centrifuge development, or the motivations behind building legitimate facilities, which appear to be of uncertain value, it may be better to direct nonproliferation efforts to reducing the motivation for nuclear weapons.

Classically, it is argued that states tend to pursue nuclear weapons because they feel a security threat justifies the need or because nuclear weapons are seen as a symbol of great-power status or as tools of coercion.[31] 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 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 deny weapons the symbol of great-power status. 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.

ENDNOTES - CHAPTER 8

1. George W. Bush, "President Announces New Measures to Counter the Threat of WMD," Speech at National Defense University, Washington, DC, February 14, 2004, available from *www.fas.org/irp/news/2004/02/wh021104.html*.

2. Mohamed ElBaradei, "Nobel Lecture," Lecture at the Nobel Peace Prize Ceremony, Oslo, Norway, December 10, 2005.

3. Houston G. Wood, Alexander Glaser, and R. Scott Kemp, "The Gas Centrifuge and Nuclear-Weapon Proliferation," *Physics Today*, Vol. 61, No. 9, September 2008.

4. Chaim Braun and Christopher F. Chyba, "Proliferation Rings: New Challenges to the Nuclear Nonproliferation Regime," *International Security,* Vol. 29, No. 2, October 2004, pp. 5–49.

5. For example: Alexander Montgomery, "Ringing in Proliferation: How to Dismantle an Atomic Bomb Network," *International Security*, Vol. 30, No. 2, 2005, pp. 153-187; David Albright, *Peddling Peril: How the Secret Nuclear Trade Arms America's Enemies*, 1st Ed. New York: Free Press, 2010, Chap. 12.

6. R. Scott Kemp, "Nonproliferation Strategy in the Centrifuge Age," Ph.D. Dissertation, Princeton University, Princeton, NJ, 2010.

7. Siegfried S. Hecker, "What I Found in Yongbyon and Why It Matters," *APS News*, March 2011.

8. *Implementation of the NPT Safeguards Agreement in the Syrian Arab Republic*, GOV/2011/30, Vienna, Austria: International Atomic Energy Agency (IAEA), May 24, 2011.

9. Frank von Hippel, *Managing Spent Fuel in the United States: The Illogic of Reprocessing*, Research Report No. 3, International Panel on Fissile Materials, January 2007.

10. The technology, 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 Gernot Zippe, *The Development of Short Bowl Ultracentrifuges*, Progress Report No. ORO-216, Charlottesville, VA: Division of Engineering Physics, Research Laboratories for the Engineering Sciences, University of Virginia, November 6, 1959.

11. For the history of the effort to commercialize the centrifuge, see R. B. Kehoe, *The Enriching Troika: A History of Urenco to the Year 2000,* Marlow, UK: Urenco Limited, 2002.

12. This was not immediately evident, given the difficulties experienced by the Manhattan Project of enriching uranium to high levels with gaseous diffusion. A U.S. research program showed it to be trivial circa 1963; see Union Carbide Nuclear Company *Proposal for the Development of the Gas Centrifuge Process of Isotope Separation*. KA-621, Papers of Ralph A. Lowry, Oak Ridge National Laboratory, Oak Ridge, TN: Union Carbide Nuclear Company, July 11, 1960.

13. U.S. Atomic Energy Commission, *Major Activities in the Atomic Energy Programs, January–December 1960* Washington DC: U.S. Government Printing Office, 1961, Appendix 20, p. 500.

14. 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 (UK), and the United States.

15. For the most part, this change was due to general progress in mechanical and aerospace engineering. Of the documents originating from centrifuge programs, perhaps the most important were Zippe, *The Development of Short Bowl Ultracentrifuges,* final report No. ORO-315, Charlottesville, VA: Research Laboratories for the Engineering Sciences, University of Virginia, July 1960; S. Whitley, "The Uranium Ultracentrifuge," *Physics in Technology*, Vol. 10, No. 1. January 1979. pp. 26–33; S. Whitley, "Review of the Gas Centrifuge Until 1962," *Reviews of Modern Physics,* Vol. 56, No. 1, January 1984, pp. 41–97; H. G. Wood and J. B. Morton, "Onsager's Pancake Approximation for the Fluid Dynamics of a Gas Centrifuge," *Journal of Fluid Mechanics*, Vol. 101, 1980 pp. 1–31; F. Doneddu, P. Roblin, and H. G. Wood, "Optimization Studies for Gas Centrifuges," *Separation Science and Technology*, Vol. 35, No. 8, 2000, pp. 1207–1221.

16. Kurt M. Campbell, Robert J. Einhorn, and Mitchell B. Reiss, *The Nuclear Tipping Point: Why States Reconsider Their Nuclear Choices,.* Washington, DC: Brookings Institution Press, 2004, p. 339.

17. 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.

18. These German engineers were at times also associated with Khan, but they also operated separately from Khan, providing better assistance. Libya is an outlier here. Its program was never successful, either prior to or after A. Q. Khan's assistance, largely because the country could not organize a stable development program.

19. Sheena Chestnut, "Illicit Activity and Proliferation: North Korean Smuggling Networks," *International Security*, Vol. 32, No. 1, July 2007, pp. 80–111.

20. Gernot Zippe, "Unclassified Spots on History of Modern Gascentrifuges," *Workshop on Gases in Strong Rotation*, 1983.

21. Gernot Zippe, Jesse W. Beams, and A. Robert Kuhlthau, *The Development of Short Bowl Ultracentrifuges*, Progress Report No. ORO-210, Charlottesville, VA: Ordnance Research Laboratory, University of Virginia, December 1, 1958; Gernot Zippe, *The Development of Short Bowl Ultracentrifuges*, Progress Report No. ORO-202, Charlottesville, VA: Ordnance Research Laboratory, University of Virginia, July 1, 1959; Zippe, *The Development of Short Bowl Ultracentrifuges*, Progress Report No. ORO-216; Zippe, *The Development of Short Bowl Ultracentrifuges*, Progress Report No. ORO-315. On the spread of the report, see Kemp, "Nonproliferation Strategy in the Centrifuge Age."

22. Many countries start with programs of this scale: It is estimated that Pakistan started with a capability of one bomb every 2 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 and 1/2 years. South Africa's nuclear weapons program produced at a rate less than one bomb every 2 years.

23. The IR-1 was supposed to operate at about 2.5 kg-Separative Work Unit (SWU)/year, but in reality, it operates at only 0.6-1.0 kg-SWU/year. The DEGUSSA machine was claimed to have had a performance of about 1.02 kg-SWU/year. There was an error in the calculation of this figure. The actual performance was probably closer to 0.9 kg-SWU/year. See Zippe, *The Development of Short Bowl Ultracentrifuges*, p. 87.

24. U.S. Central Intelligence Agency, "Nuclear Energy," *Weekly Surveyor*, January 12, 1970.

25. According to Myron Kratzer (then Science and Technology counselor and in 1975, as 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. See Myron Kratzer, interview with the author, April 19, 2011.

26. Catch-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 also 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.

27. 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 than these may feel more apprehension about military attacks.

28. On the opinions of states, see the proceedings of the International Fuel Cycle Evaluation (INFCE), October 19–21, 1977, Washington DC, as published by the IAEA. (I assume by proceedings, he means part or all of the 8 volumes plus 1 summary volume published by the IAEA in 1980, which covered all 134 INFCE working group sessions from 1977-79 and the final plenary conference held in Vienna, Austria, in February 1980.)

29. See Christopher E. Paine and Thomas B. Cochran, "Nuclear Islands: International Leasing of Nuclear Fuel Cycle Sites to Provide Enduring Assurance of Peaceful Uses," *The Nonproliferation Review,* Vol. 17, No. 3, July 2010.

30. Even if a national centrifuge program were not competitive with the international market, a small centrifuge program might still be reasonable and economic insurance against a possible fuel-supply cutoff. To demonstrate this, consider that estimates for the real levelized cost of nuclear power per kilowatt-hour (kWh) 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 percent capacity factor, the plant operates for about 7,500 hours/year. Thus, the real levelized cost for a nonoperating full-size 1 gigawatt/year (GWe/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, NM; see Michael Knapik, "LES Hopes for Fresh Start in New Mexico," *Nuclear Fuel*, September 1, 2003.

31. Another common explanation is that nuclear weapons can be used to satisfy domestic constituencies, but presumably, constituencies that are large and well supported want nuclear weapons for one of the listed reasons.