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The Nonproliferation Emperor Has No Clothes

R. Scott Kemp

The Gas Centrifuge, Supply-Side Controls, and the Future of Nuclear Proliferation

What policies have most constrained the proliferation of nuclear weapons over the last sixty years? Will they continue to do so in the future?

Scholars have long acknowledged that states may forgo nuclear weapons if their security concerns, domestic politics, and social norms do not favor acquisition.¹ These political and cultural factors may be the primary determinants of proliferation, but they are not easily modulated by public policy. As such, policymakers have more often focused on impeding the path to nuclear weapons acquisition by controlling technology. This “supply-side” approach keeps with a long tradition. As far back as 1944, senior political officials in the United States and the United Kingdom believed that, although the bomb itself was not particularly difficult to fabricate, the effort needed to replicate the Manhattan Project’s enormous fissile material production facilities would provide an almost automatic barrier to the proliferation of nuclear weapons.² More recently, scholars have represented proliferation rings, illicit trade, and nuclear smuggling as being critical vectors that enable proliferation among the technically weak.³ A.Q. Khan has become a pop icon for contemporary prolif-

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1. On states’ motivations for not developing nuclear weapons, see Etel Solingen, “The Political Economy of Nuclear Restraint,” *International Security*, Vol. 19, No. 2 (Fall 1994), pp. 126–169; Scott D. Sagan, “Why Do States Build Nuclear Weapons? Three Models in Search of a Bomb,” *International Security*, Vol. 21, No. 3 (Winter 1996/97), pp. 54–86; George H. Quester, *The Politics of Nuclear Proliferation* (Baltimore, Md.: Johns Hopkins University Press, 1973); and Jacques E.C. Hymans, *The Psychology of Nuclear Proliferation: Identity, Emotions, and Foreign Policy* (Cambridge: Cambridge University Press, 2006).

2. Michael D. Gordin, *Red Cloud at Dawn: Truman, Stalin, and the End of the Atomic Monopoly* (New York: Farrar, Straus and Giroux, 2009), pp. 69–71, 219; and Alex Wellerstein, “Knowledge and the Bomb: Nuclear Secrecy in the United States, 1939–2008,” Ph.D. dissertation, Harvard University, 2010, p. 173.

3. Alexander H. Montgomery, “Ring in Proliferation: How to Dismantle an Atomic Bomb Network,” *International Security*, Vol. 30, No. 2 (Fall 2005), pp. 153–187; Douglas Frantz and Catherine Collins, *The Nuclear Jihadist: The True Story of the Man Who Sold the World’s Most Dangerous Secrets . . . And How We Could Have Stopped Him* (New York: Twelve, 2007); David Albright, *Peddling Peril:*

eration, and is widely blamed for the existence of Pakistan's, Iran's, Libya's, and North Korea's gas centrifuge programs. Technology now dominates how policymakers think about proliferation, and many share the view that, "with the exception of a few advanced industrialized countries, a state's ability to build nuclear weapons generally hinges on its ability to find an international supplier."⁴

In this article, I argue that this view is misguided. Alongside a few highly visible programs that relied on technology transfers, the historical record contains many more lesser-known examples of states developing nuclear weapon capabilities without foreign assistance. These cases establish a baseline by which the value and necessity of technology transfers can be judged. A review of just one weapon-enabling technology, the gas centrifuge, found fourteen states that were successful using only a minimum of technical and human resources—resources that I argue are within the reach of many or most of today's developing countries. That this is possible should not be surprising: the technologies needed to make nuclear weapons have remained static, whereas the indigenous capabilities of states have steadily grown over the last half-century. What was once exotic is now pedestrian, and nuclear weapons are no exception.

This article begins by describing the origins of supply-side controls. It then examines how the gas centrifuge emerged as the first technology to undermine seriously these controls. Evidence is provided in forms ranging from secret government studies to histories of real-world proliferation. The proliferation potential of centrifuges is then examined, looking first at the potential for centrifuges to be used clandestinely. This is followed by an examination of independent centrifuge programs, which taken together describe a modest technical challenge for building centrifuges from scratch. Counterevidence is then reviewed in detail, and the efficacy and necessity of foreign assistance is critically assessed.

This work concludes that the indigenous and clandestine production of nuclear weapons is within reach of many, if not most, of today's developing countries—at least as far as technological inputs, access to technical information, and industrial requirements are concerned. This assessment leads back to the opening question: What is apt to constrain proliferation in the future? This

How the Secret Nuclear Trade Arms America's Enemies (New York: Free Press, 2010); Catherine Collins and Douglas Frantz, *Fallout: The True Story of the CIA's Secret War on Nuclear Trafficking* (New York: Free Press, 2011); William Langewiesche, *The Atomic Bazaar: The Rise of the Nuclear Poor* (New York: Farrar, Straus and Giroux, 2007); and Matthew Kroenig, *Exporting the Bomb: Technology Transfer and the Spread of Nuclear Weapons* (Ithaca, N.Y.: Cornell University Press, 2010).

4. Kroenig, *Exporting the Bomb*, p. 178.

research suggests that the answer is not technology or industrial limitations, not export controls or information secrecy, and probably not intelligence coupled with counterproliferation action: none of these would have been able to counter the numerous clandestine-capable, indigenous nuclear weapon capabilities described herein. Organizational capability remains a constraint, and policymakers could, in principle, work to reduce the ability of governments to organize labor and domestic resources; but such actions are generally inimical to international peace and stability writ large. If there are no other supply-side constraints, the situation described here leaves policymakers having to look beyond supply-side controls, toward the cultural, normative, and political organization of the world, in search of ways to reduce the demand for nuclear weapons—an approach that has been largely neglected over the last sixty years. This is a difficult and politically expensive proposition, but it may be the only approach able to endure technological change.

Birth and Death of Supply Side Constraints

When reports of the first Soviet nuclear weapon test arrived at the White House, President Harry Truman and members of his cabinet were so doubtful of Soviet capabilities that they rejected the reports on the grounds that a Soviet weapon was impossible. One official later reported that he believed the radioisotope fallout that revealed the Soviet test was actually produced by a nuclear-reactor accident, a more likely Soviet achievement.⁵ U.S. intelligence analysts were similarly shocked in 1964 when they discovered that China had tested a nuclear weapon made from enriched uranium. The uranium path was understood to be more difficult than that of plutonium, and the production of either was thought to be well beyond China's capabilities. In its report following China's first test, the Central Intelligence Agency (CIA) confessed that China had "a much more ambitious advanced-weapons program than we had earlier thought possible."⁶

Despite these and other sobering experiences, technology is still seen as an important barrier to proliferation. For decades, the CIA based its proliferation assessments not on motivations, but on forecasts of how long it would take a

5. Gordin, *Red Cloud at Dawn*, pp. 69–71, 219; and Wellerstein, "Knowledge and the Bomb," p. 173.

6. Central Intelligence Agency, "Communist China's Advanced Weapons Program," Special National Intelligence Estimate 13-2-63, July 24, 1964, U.S. Department of State Archive, <http://2001-2009.state.gov/r/pa/ho/frus/kennedyjfviii/33843.htm>; and Central Intelligence Agency, "Communist China's Advanced Weapons Program," National Intelligence Estimate 12-2-65, January 27, 1965, U.S. Intelligence and China: Collection, Analysis, and Covert Action, CI01656, Digital National Security Archive, nsarchive.chadwyck.com.

country to develop the technical infrastructure needed to make a bomb.⁷ U.S. and international policies put heavy emphasis on developing export controls and technology safeguards. Despite some efforts in the 1960s to reduce the demand for nuclear weapons with the Multilateral Force, the North Atlantic Treaty Organization security coalition, and the Treaty on the Nonproliferation of Nuclear Weapons, nearly every nonproliferation institution before and since has focused on technology.⁸

If nuclear weapons are inherently difficult to produce, then why have technology constraints sometimes failed to prevent proliferation? The usual answer is to blame foreign assistance. The Soviets had spies in the Manhattan Project. China received uranium-enrichment technology from the Soviet Union. Canada built the reactor that produced the plutonium for India's first weapons.⁹ Pakistan's centrifuge program was purchased piecemeal from European suppliers. Brazil tried with technology bought from Germany.¹⁰ Iraq and Israel imported reactors from France. Iran and North Korea imported centrifuges from Pakistan, and so the history goes.¹¹ A significant literature is devoted to explicating the migration of capabilities from the most technically

7. Peter R. Lavoy, "Predicting Nuclear Proliferation: A Declassified Documentary Record," *Strategic Insights*, Vol. 3, No. 1 (January 2004); and William Burr, "National Security Archive Electronic Briefing Book No. 155: National Intelligence Estimates of the Nuclear Proliferation Problem: The First Ten Years, 1957–1967," June 1, 2005, Washington, D.C.: National Security Archive, <http://www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB155/index.htm>.

8. These include the Zangger Committee, formed to define the technologies that would require international supervision in the form of safeguards; the Nuclear Suppliers Group, an organization with forty-eight member states that governs transfers of sensitive nuclear technologies; UN Resolution 1540, a legally binding resolution that mandates the creation of export-control regimes in UN member states; the Proliferation Security Initiative, a group of states that have voluntarily agreed to cooperate with efforts to interdict in-progress transfers of sensitive technology; and new proposals such as fuel banks, multilateral fuel-cycle regimes, and cradle-to-grave nuclear energy frameworks, all of which are designed to eliminate the legitimate basis for acquiring sensitive nuclear technologies. Even the Nonproliferation Treaty (NPT), through its mandate for safeguards, seeks to limit the capability of states by regulating the use of declared technology. Furthermore, modern counterproliferation has focused on bombing nuclear facilities (Iraq and Syria) and sabotaging equipment and systems (Iran), a policy that makes the most sense when the supply of targeted technologies is scarce and the capacity to rebuild is beyond the means of the targeted states. One exception to this trend has been the creation of nuclear weapon-free zones, mainly at the initiative of nonweapon states. For a history of counterproliferation thought in the United States, see Joseph F. Pilat and Walter L. Kirchner, "The Technological Promise of Counterproliferation," *Washington Quarterly*, Vol. 18, No. 1 (Winter 1995), pp. 153–166.

9. George Perkovich, *India's Nuclear Bomb: The Impact on Global Proliferation* (Berkeley: University of California Press, 1999).

10. Michael Barletta, "The Military Nuclear Program in Brazil" (Palo Alto, Calif.: Center for International Security and Arms Control, Stanford University, August 1997), <http://iis-db.stanford.edu/pubs/10340/barletta.pdf>.

11. Joseph Cirincione, Jon B. Wolfsthal, and Miriam Rajkumar, *Deadly Arsenals: Nuclear, Biological, and Chemical Threats* (Washington, D.C.: Carnegie Endowment for International Peace, 2005); and Frank Barnaby, *How Nuclear Weapons Spread: Nuclear-Weapon Proliferation in the 1990s* (New York: Routledge, 1993).

advanced nations to some of the most technically indigent.¹² Scholars tend to agree that these transfers are of two major types: civil cooperation that enables later proliferation and cases of intentional proliferation assistance.¹³ While the technology-transfer model is rooted in historical evidence, all that has been established in the literature is that technology transfers took place. At times those transfers have been helpful, but it is often presumed that transfers were important, if not essential, to the acquisition of nuclear weapons, yet scant evidence is provided.

With time, the necessity of technology transfer must be questioned simply because information and technology that were once esoteric gradually become mainstream. In parallel, the utility of transfers for proliferation is apt to decline as motivations shift from the strategic (e.g., Soviet proliferation to China, or Pakistani proliferation to North Korea) to the pecuniary (e.g., commercial transfers or black markets). The latter motivation has tended to produce problematic outcomes for aspiring proliferators. Consider, for example, Brazil's purchase of jet-nozzle enrichment technology from Germany. Brazil squandered perhaps as much as \$100 million and half a decade before realizing that the nozzle was a dud.¹⁴ In some more recent instances, such as Iraq's nuclear weapon program, financially motivated transfers were helpful but arguably not necessary. For others, including some of the most oft-cited cases such as Pakistan, Iran, and even Libya, I find evidence to suggest that transfers set back these programs relative to what they might have accomplished acting alone.

The most difficult technological step in building nuclear weapons is the production of highly enriched uranium (HEU) or plutonium. If HEU can be obtained, then there are essentially no additional technologies needed to make a bomb. Unlike plutonium, HEU can be used in both implosion- and gun-type nuclear weapons. The latter type is a simple design that is extremely robust to manufacturing defects and needs no exotic parts, triggers, fuses, or materi-

12. Belief in the centrality of foreign assistance is also evident in U.S. government documents. For example, National Intelligence Estimate NIE-4-66 predicted that Pakistan, Egypt, and South Africa were likely nuclear weapon aspirants, but would all require "substantial outside help." Central Intelligence Agency, "The Likelihood of Further Nuclear Proliferation," National Intelligence Estimate 4-66, January 20, 1966, National Security Archive, <http://www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB155/prolif-12.pdf>.

13. For civil cooperation, see Harold A. Feiveson, "Latent Proliferation: The International Security Implications of Civilian Nuclear Power," Ph.D. dissertation, Princeton University, 1972; Barnaby, *How Nuclear Weapons Spread*; and Matthew Fuhrmann, "Spreading Temptation: Proliferation and Peaceful Nuclear Cooperation Agreements," *International Security*, Vol. 34, No. 1 (Summer 2009), pp. 7-41.

14. Barletta, "The Military Nuclear Program in Brazil," pp. 4-5, 12-14; and David J. Myers, "Brazil: Reluctant Pursuit of the Nuclear Option," *Orbis*, Vol. 27, No. 4 (Winter 1984), p. 886.

als. Such a weapon can be easily and quickly made, and confidently fielded without testing. Gun-type bombs can even be made small enough to fit onto missiles.¹⁵ Therefore, to demonstrate the effective absence of supply-side constraints, it would be sufficient to show that there exists a way to make HEU that is accessible to most states, that is well known, and that states could be confident of executing with a high chance of success. Several such paths now exist, most using the gas centrifuge as the principal technology.¹⁶

Centrifuges as a Proliferation Technology

Many states already regard the centrifuge as a good proliferation pathway. Since 1975, seven of eight nuclear weapon aspirants have pursued centrifuges.¹⁷ Four—Pakistan, Iraq, Libya, and Iran—made centrifuges a central focus of their programs. Furthermore, three of these states began exploring centrifuges prior to the receipt of any foreign assistance; hence the choice of centrifuges was not predicated on the promise of outside help. A fifth state, North Korea, recently replaced its long-standing plutonium capability with a centrifuge capability. A sixth, South Africa, also tried to upgrade from its original vortex technology to centrifuges, but regime change intervened. Only one state, Syria, made better progress with plutonium. Nonetheless, Syria was interested in centrifuge technology, but it never went forward for reasons that are still unknown.¹⁸ Centrifuges are even more popular as a latent nuclear

15. Although the first gun-type weapon (Little Boy) was heavy and bulky, this reflected a conservative design rather than necessity. Starting in 1952, the United States deployed more than 1,200 W33 gun-type warheads, each of which had a maximum yield of 40 kilotons, an exterior diameter of eight inches, and weighed about the same as the advanced W80 thermonuclear warhead (~114 kilograms). Such a weapon could be placed on a missile without difficulty. See Thomas B. Cochran et al., *Nuclear Weapons Databook: U.S. Nuclear Forces and Capabilities*, Vol. 1 (Cambridge, Mass.: Ballinger, 1984), p. 38.

16. A.S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation* (Milton Park, Abingdon, U.K.: Taylor and Francis, 1983); Houston G. Wood, Alexander Glaser, and R. Scott Kemp, "The Gas Centrifuge and Nuclear-Weapon Proliferation," *Physics Today*, Vol. 61, No. 9 (September 2008), pp. 40–45; Alexander Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation," *Science & Global Security*, Vol. 16, Nos. 1–2 (2008), pp. 1–25; R. Scott Kemp, "Gas Centrifuge Theory and Development: A Review of U.S. Programs," *Science & Global Security*, Vol. 17, No. 1 (2009), pp. 2–20; and R. Scott Kemp, "The End of Manhattan: How the Gas Centrifuge Changed the Quest for Nuclear Weapons," *Technology and Culture*, Vol. 53, No. 2 (April 2012), pp. 272–305.

17. The eight aspirants are Iran, Iraq, Libya, North Korea, Pakistan, South Africa, Syria, and Taiwan; only Taiwan has not pursued centrifuges. Argentina and Brazil are assumed to have pursued latent nuclear weapon capabilities but not to have decided to build a bomb, therefore they are not counted. If following the alternative interpretation in which Argentina and Brazil are categorized as having weapon programs, the reader should add one centrifuge case (Brazil) and one noncentrifuge case (Argentina) to the count.

18. In interviews, anonymous International Atomic Energy Agency (IAEA) officials reported that Syria had communicated multiple times with the A.Q. Khan network on the matter. See also

weapon capability. In total, at least twenty countries have developed or acquired centrifuges: Australia, Brazil, China, France, Germany, India, Iran, Iraq, Israel, Italy, Japan, Libya, the Netherlands, North Korea, Pakistan, South Africa, the Soviet Union/Russia, Sweden, the United Kingdom, and the United States.¹⁹

Despite the widespread pursuit of centrifuges, many scholars regard the centrifuge as “one of the most complicated technical challenges in the world.”²⁰ Panels as august as the National Academy of Sciences have written—albeit without performing a technical study—that “all enrichment techniques [including centrifuges] demand sophisticated technology in large and expensive facilities.”²¹ Matthew Fuhrmann and Gordon Corera independently have described centrifuge technology as “sophisticated.”²² In 2004, Jonathan Pollack and Mitchell Reiss went so far as to predict that centrifuge technology was probably beyond the capability of South Korea.²³ None of these scholars evaluated the technical requirements of the centrifuge; rather, their statements reflect a received wisdom pervasive in the nonproliferation community.

Technical experts have rarely been as confident that the indigenous development of centrifuges would be as insurmountably difficult. In the early 1960s—about one year after a prototype gas centrifuge of the modern variety was built and tested in the United States—the chairman of the U.K. Atomic Energy Authority (U.K. AEA), Lord Plowden, warned his counterpart, U.S. Atomic Energy Commission (AEC) Chairman John McCone, that the centrifuge might lead to the widespread acquisition of nuclear weapons.²⁴

Douglas Frantz, “Nuclear Ring May Have Aided Syria,” *Los Angeles Times*, June 25, 2004. Syria’s plutonium program is documented in IAEA, *Implementation of the NPT Safeguards Agreement in the Syrian Arab Republic*, GOV/2011/30 (Vienna: IAEA, May 24, 2011).

19. In addition to these verified programs, there is evidence of centrifuge-related research in Algeria (2007), Canada (1962), Denmark (1962), Mexico (1978, 1983–89, 1994), Poland (1957, 1976), South Korea (2004), and Taiwan (2004). This evidence is insufficient to prove that any of these states pursued development programs, but it does establish that interest in the centrifuge is potentially vast.

20. Collins and Frantz, *Fallout*, p. 8.

21. National Academy of Sciences, Committee on International Security and Arms Control, *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options* (Washington, D.C.: National Academies Press, 1995), p. 31.

22. Fuhrmann, “Spreading Temptation,” p. 22; and Gordon Corera, *Shopping for Bombs: Nuclear Proliferation, Global Insecurity, and the Rise and Fall of the A.Q. Khan Network* (New York: Oxford University Press, 2006), p. 58.

23. Kurt M. Campbell, Robert J. Einhorn, and Mitchell B. Reiss, *The Nuclear Tipping Point: Why States Reconsider Their Nuclear Choices* (Washington, D.C.: Brookings Institution Press, 2004), pp. 260, 339.

24. A.R. Luedecke, “Memorandum to John McCone et al. with Subject: Classification of Information Concerning the Gas Centrifuge Program,” October 21, 1960, p. 3, Records of Atomic Energy Commission Chairman McCone, National Archives, Washington, D.C.; and Glenn Theodore

Plowden's warning was effective. In March 1960, centrifuges were at the front of McCone's mind, and he discussed his concerns with President Dwight Eisenhower during the negotiations of the Partial Test Ban Treaty.²⁵ In April 1960, a fifty-four-page study of the centrifuge problem was prepared jointly by the AEC directors of classification, international affairs, and research.²⁶ It cited, inter alia, a study that the AEC commissioned from the General Electric Company—the firm that had built gas centrifuges for the Manhattan Project—which concluded that a plant capable of producing twenty nuclear weapons per year could be built using simple centrifuges for \$17 million in two to three years, and that this capability was already available to twenty or thirty countries.²⁷ Another study undertaken in 1960 by Union Carbide, the firm then operating the gaseous diffusion plant at Oak Ridge, concluded that even the technically indigent nations of Egypt and Cuba could build a centrifuge plant in about eight years.²⁸ The authors of the AEC report concluded, "The centrifuge, as compared with the reactor route, studied by the Hanford Operations Office, would be the easier to pursue."²⁹

By the fall of 1960, concern about centrifuges had spread beyond the executive branch of the United States to select individuals in Congress. At the third 1960 presidential debate, Senator John F. Kennedy famously said, "There are indications, because of new inventions, that ten, fifteen, or twenty nations will have a nuclear capacity—including Red China—by the end of the presidential office in 1964."³⁰ The only relevant invention at that time was the modern gas centrifuge, a prototype of which had been demonstrated earlier that year at the

Seaborg and Benjamin S. Loeb, *Stemming the Tide: Arms Control in the Johnson Years* (Lexington, Mass.: Lexington Books, 1987), p. 161. That the warning came initially from Plowden was reported in an interview with Myron Kratzer, May 5, 2011. According to the former director of the U.K. centrifuge program, the classified minutes of the U.K. Atomic Energy Authority and the Atomic Energy Executive minutes of 1959 and 1960 contain repeated references to the proliferation potential of the centrifuge. See N.L. Franklin, "Looking Back to 1959," *Nuclear Engineer*, Vol. 26, No. 1 (February 1985), p. 8.

25. U.S. Department of State, "Geneva Nuclear Test Negotiations," memorandum of conversation, Camp David, Maryland, March 29, 1960, p. 3, Dwight D. Eisenhower Library, Abilene, Kansas.

26. U.S. Atomic Energy Commission, "Gas Centrifuge Method of Isotope Separation: Report to the General Manager by the Directors of Classification, International Affairs, and Research," April 1960, record group 326, box 1427, folder 3, U.S. Department of Energy Archives, <https://www.documentcloud.org/documents/399995-doc-6-aec-april-1960-report.html>.

27. *Ibid.*, pp. 20, 40, 46.

28. S.A. Levin, D.E. Hatch, and Ed von Halle, "Production of Enriched Uranium for Nuclear Weapons by Nations X, Y, and Z by Means of the Gas Centrifuge Process" (Oak Ridge, Tenn.: Union Carbide Nuclear Company, February 26, 1960), p. 5, <https://www.documentcloud.org/documents/399993-doc-4-union-carbide-report-1960.html>.

29. U.S. Atomic Energy Commission, "Gas Centrifuge Method of Isotope Separation," p. 3.

30. John F. Kennedy, third 1960 presidential debate, interview by the Commission on Presidential Debates, transcript, October 13, 1960, <http://www.debates.org/index.php?page=october-13-1960-debate-transcript>.

University of Virginia. At the close of 1960, AEC Chairman McCone penned a cautionary note to the public that read, "Do not minimize the potential importance of this process. 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."³¹

Although these assessments were well informed by a prototype program and industrial firms experienced with similar centrifuge engineering, there had yet to be a real test that simulated the conditions of a neophyte proliferator. Both the United States and the United Kingdom decided to commission just such a test in separate *de novo* development programs, both of which are described later in this article. The concluding reports, now partly declassified, confirmed what the earlier General Electric, Hanford, and Union Carbide studies had predicted: that even in the 1960s it was feasible for countries with no prior experience, "that possess relatively little technical skills and which have relatively little industrial activity," to produce enriched uranium for nuclear weapons by means of a small centrifuge plant.³²

Technical capability does not by itself establish proliferation potential. If there is a high chance that a proliferator might be caught in the act of proliferation and subjected to international censure, then the state could be deterred from trying. International Atomic Energy Agency (IAEA) safeguards are designed to do just this. Indeed, historically most nuclear weapon programs were detected before the actual achievement of a weapon.³³ Most gas centrifuge programs, however, were not. Some technologies, such as the gas centrifuge, require only a modest industrial footprint and are capable of producing fissile materials for weapons without generating signatures that might reveal the existence of a program. Such programs have escaped detection by human, signals, and technical intelligence for decades at a time.

A final consideration is the organizational capabilities of states. Although centrifuges may be within the reach of small states, the ability of governments to organize a weapons program has been surprisingly limited. Such organizational constraints may be the only supply-side limitation still operational. Sur-

31. John McCone, "Appendix 20," in *Major Activities in the Atomic Energy Programs, January–December 1960* (Washington, D.C.: U.S. Department of Energy, 1961), p. 500.

32. U.S. Atomic Energy Commission Oak Ridge Operations Office et al., *Second Gas Centrifuge Appraisal Report*, Vol. 2: *Nth Power Evaluation*, No. ORO-652-2, 1966, p. 6. The authors of a subsequent U.S. government assessment of all proliferation pathways regarded the centrifuge as such an unusually worrisome technology that they reserved the discussion of centrifuges for a dedicated and presumably still-classified companion volume. The report is cited in "Nuclear Materials and Technology as They Affect Proliferation Potential," undated (declassified 6-11-1992), p. 8, national security file, committee file, box 4, Lyndon Baines Johnson Library and Museum, Austin, Texas.

33. Committee on International Security and Arms Control, *Monitoring Nuclear Weapons and Nuclear-Explosive Material* (Washington, D.C.: National Academies Press, 2005), p. 9.

prisingly, however, I find that foreign assistance and technology transfers have not been useful in overcoming these limitations. History shows multiple ways in which foreign assistance has been counterproductive: the supplied technology has been poor; the information provided has been incomplete; and programs have been directed toward unnecessary complications that strain the indigenous resources of the state. In general, financially motivated foreign agents have private objectives that differ from the proliferator's strategic objectives and, historically, this has tended to exacerbate organizational limitations. Additionally, foreign assistance has increased significantly the probability that a weapons program will be detected by an intelligence service and, as a consequence, subjected to sanctions, sabotage, or other counterproliferation action. While the utility of foreign assistance has been mixed, there is almost no evidence to indicate that foreign assistance with centrifuges has been critical.

PROLIFERATION DYNAMICS

The centrifuge raised alarm in the early 1960s, not because it could make fissile material for nuclear weapons—many other technologies including commonplace nuclear reactors could do that—but because centrifuges could do it on a small scale, and with almost no chance of detection.³⁴ That meant a state could rely on the clandestine nature of the plant to protect it from international censure rather than try to force its way past safeguards. This enabled a new sort of proliferation where states unable or unwilling to pursue billion-dollar, industrial-scale nuclear facilities could have access to the bomb, too.

A secret program is always at risk of detection, but the historical record suggests the risk might be low. To begin with, centrifuge facilities are nearly impossible to detect by technical means (e.g., measurement and geospatial intelligence) because they do not produce signatures that would reveal their existence at significant distances. A clandestine plant can be housed in a building with no identifying features that would easily escape detection by visual satellite imaging.³⁵ The plant's energy consumption would be low and, unlike

34. That this was specifically the concern is evident in McCone, "Appendix 20"; and Luedecke, "Memorandum to John McCone et al."

35. The most distinctive feature of centrifuge plants is their power lines, but a small plant does not need an unusual level of service. A 5,000 SWU/year plant populated with 1 SWU/year machines might draw approximately 100 kilowatts of electrical power if the machines were as energy inefficient as the primitive prototype built at the University of Virginia in 1960, and if 100 percent were added as an overhead factor (modern Urenco centrifuges with overhead would use about one-third this amount of energy). A typical power substation provides on the order of 10 megavolt-amps, 100 times the power required for the inefficient centrifuge plant. Large diesel- or natural-gas-fueled industrial standby generators can be rated as high as 100,000–200,000 kWe, a thousand times the required power level. Thus, power lines need not be distinct, and are not even necessary. See Gernot Zippe, "The Development of Short Bowl Ultracentrifuges," No. ORO-315

a nuclear reactor or gaseous diffusion plant, could not be identified with thermal-infrared imaging.³⁶ Centrifuge plants process uranium in the form of uranium hexafluoride, a gaseous compound. The gas is maintained at pressures below atmospheric, so any leaks in the plumbing tend to allow air into the system, rather than uranium to leak out. As a consequence, the total uranium released to the environment is typically small to the point of being undetectable.³⁷ A fourth kind of signature, the free-space electromagnetic emanations (radio signals) radiating from centrifuge motors, almost entirely cancel each other out because centrifuges utilize three-phase power, and what remains is so weak that it is physically impossible to detect at meaningful distances.³⁸ A fifth signature would be fluctuations induced on power lines from electronic circuits. These are significant, but can be easily filtered out using industry standard practices or simply avoided by using a diesel- or natural-gas fueled generator to power the plant.³⁹

Human and signals intelligence depend on the operational and programmatic security of a covert program. Large programs, those dependent on foreign entities, and those that depend on specialized tools, materials, or equipment, are especially vulnerable to monitoring. Centrifuge programs are remarkably small in comparison to other proliferation routes, and the prospects for detection are correspondingly smaller. Advanced centrifuges require specialized tools and materials, and procurements of these specialized inputs have led to detections. Simple but adequate centrifuges can be built without

(Charlottesville: University of Virginia Division of Engineering Physics, Research Laboratories for the Engineering Sciences, July 1960); and Urenco, "Enrichment Brochure," ver. 4 (Bells Hill, U.K.: Urenco, March 22, 2005).

36. A 5,000-machine plant could easily fit into a building 75 meters per side, resulting in an energy density of about 56,000 BTU/square foot/year, on par with a typical warehouse or storage facility and about half the average use for a retail outlet or one-fourth the power density used by a food-processing facility or a single-story hospital.

37. The most significant chemical effluent is the process gas, uranium hexafluoride. Measurements from existing centrifuge plants and uranium hexafluoride production facilities suggest the releases are far too small to be detectable at significant distances. The installation of high efficiency particulate air filters could further reduce these releases by three to five orders of magnitude. See R. Scott Kemp, "Source Terms for Routine UF₆ Emissions," *Science & Global Security*, Vol. 18, No. 2 (June 2010), pp. 119–125; and R. Scott Kemp, "Initial Analysis of the Detectability of UO₂F₂ Aerosols Produced by UF₆ Released from Uranium Conversion Plants," *Science & Global Security*, Vol. 16, No. 3 (December 2008), pp. 115–125.

38. Babur Habib, "Estimate of the Electromagnetic Radiation Emitted from a Small Centrifuge Plant," *Science & Global Security*, Vol. 15, No. 1 (2007), pp. 31–47. Note that Habib has neglected the fact that most centrifuge motors run on three-phase power, causing the signal to be even harder to detect than he estimates. On the fundamental limits of detector sensitivity, see Igor M. Savukov et al., "Tunable Atomic Magnetometer for Detection of Radio-Frequency Magnetic Fields," *Physical Review Letters*, Vol. 95, No. 6 (August 2005).

39. On filtering, see Dennis A. Jarc and Robert G. Schieman, "Powerline Considerations for Variable Frequency Drives," in *Conference Record IEEE-IAS-1985 Annual Meeting* (Toronto: Institute of Electrical and Electronics Engineers, Industry Applications Society, 1985), pp. 55–60.

these, however, using only resources completely within the domestic control of most countries.

The historical record helps illustrate the extent to which centrifuge programs have avoided detection in the past. The most dramatic case of nondetection is that of the Soviet Union—a country under the most intense Western scrutiny that resources would allow. The Soviet Union began operating its first large-scale centrifuge plant in 1957 and expanded by adding plants every few years thereafter.⁴⁰ The United States had known since at least January 1955 that the Soviet Union had been developing experimental centrifuges, but the intelligence community saw no evidence that the technology had been developed past the laboratory stage.⁴¹ Many years later, satellite reconnaissance showed that older gaseous diffusion plants were being shut down and disassembled, but the intelligence community still lacked credible evidence that the Soviets were replacing these with centrifuge plants. As such, the United States and the United Kingdom both assessed that the Soviet Union was reducing its enrichment enterprise.⁴² By 1970, some analysts felt that the Soviets must have deployed centrifuges, despite the absence of evidence—but these individuals were in the minority, and official assessments remained unchanged.⁴³ After the collapse of the Soviet Union in 1991, Russia disclosed to the United States that it had centrifuge plants, which had been operating undetected for thirty-four years, and which constituted at that time the largest centrifuge program in the world by almost a factor of ten.⁴⁴ Failure to assess correctly the existence of

40. V.V. Shidlovsky and G.S. Soloviov, "History and Status of Industrial Isotope Separation in Russian Federation" in Valentin D. Borisevich, ed., *Proceedings of the Seventh Workshop on Separation Phenomena in Liquids and Gases* (Moscow: Instituto de Estudos Avançado, 2000).

41. Central Intelligence Agency, "Atomic Energy Research Work at Institute C Headed by Manfred von Ardenne," information report, October 11, 1955, CIA-RDP80-00810A006600620008-6, Freedom of Information Act Electronic Reading Room, Central Intelligence Agency, <http://www.foia.cia.gov/>; Central Intelligence Agency, "Isotope Separation at the Hertz Institute," information report, February 5, 1955, CIA-RDP80-00810A004900090003-9, Freedom of Information Act Electronic Reading Room, Central Intelligence Agency, <http://www.foia.cia.gov/>; Central Intelligence Agency, "Development of Ultracentrifuges for Separation of Uranium Isotopes in the Soviet Union," information report EG-1795 (Scientific and Technical Information Branch September 18, 1957); and Central Intelligence Agency, "The Problem of Uranium Isotope Separation by Means of Ultracentrifuge in the USSR," information report EG-1802 (Scientific and Technical Information Branch, October 8, 1957).

42. The satellite evidence of gaseous diffusion shutdowns was described to the author independently by two anonymous sources: a retired U.S. official involved in the interpretation of imagery at the U.S. Department of Energy, and a retired consultant involved in the interpretation of imagery for the British government.

43. Central Intelligence Agency, "A Modest Suggestion for a Review of the Bidding," *Studies in Intelligence* [internal journal of the Central Intelligence Agency], Vol. 14, No. 2 (Fall 1970), pp. 128–132.

44. The public revelation made the news. See Mark Hibbs, "MAPI Official Says All Four Soviet SWU Plants Are in Russian Republic," *Nuclear Fuel*, Vol. 16, No. 23 (November 11, 1991), p. 4. The Russian capacity was about 20,000,000 kg-SWU/year, compared to about 2,500,000 kg-SWU/year

the Soviet centrifuge program led to errors in U.S. estimates for the amount of highly enriched uranium produced by the Soviet Union, and accordingly the number of possible warheads.⁴⁵

China is a similar case. In 1964, the United States was surprised when it learned from atmospheric sampling that China made its first nuclear weapon using highly enriched uranium. The following National Intelligence Estimate of China's program, endorsed by the entire the U.S. intelligence community, stated, "The gas centrifuge process has never been developed beyond the experimental stage in the Free World. There is no persuasive evidence that the Soviets have produced gas centrifuges in significant numbers and none that they have given any to the Chinese. We do not believe the Chinese have attained the manufacturing capability and technology required for domestic production of the necessary large numbers of suitable centrifuges."⁴⁶

The statement was clearly in error about the Soviet program, but it also underestimated the Chinese capability. The intelligence community had correctly assessed that China's uranium had been partly enriched at a gaseous diffusion plant in Lanchou, and also assessed that "the Lanchou facility was not responsible for producing the U-235 in CHIC-1 by the gaseous diffusion process alone but that another process was also involved."⁴⁷ The intelligence community, lacking information about the unidentified second process, assumed that it was probably electromagnetic isotope separation—mirroring what the United States had done during the Manhattan Project. The Chinese nuclear establishment, however, has since revealed that, at the time of the 1964 test, China was well on its way to a second- or third-generation centrifuge. An experimental centrifuge program had been established at China's Tsinghua University in 1958, and the first successful separation of isotopes by centrifuge achieved in 1961, three years prior to China's first nuclear test. Work on a second-generation machine started in 1962, two years prior to the test.⁴⁸ According to

for the next largest entity, the trilateral Urenco consortium. See Oleg Bukharin, "Russia's Gaseous Centrifuge Technology and Uranium Enrichment Complex" (Princeton, N.J.: Princeton University Program on Science and Global Security, January 2004); Pavel Podvig, ed., *Russian Strategic Nuclear Forces* (Cambridge Mass.: MIT Press, 2004), pp. 100–101; and R.B. Kehoe, *The Enriching Troika: A History of Urenco to the Year 2000* (Marlow, Buckinghamshire, U.K.: Urenco, 2002), p. 173.

45. Mark Hibbs and M. Knapik, "Technical Assumptions Led U.S. DOE to Underestimate Soviet HEU Output," *Nuclear Fuel*, Vol. 18, No. 22 (October 25, 1993), p. 2. According to one source, the transition from gaseous diffusion to gas centrifuge reduced energy consumption by a factor of 8.2 and increased overall output by a factor of 2.4. See Podvig, *Russian Strategic Nuclear Forces*, p. 603, n. 119.

46. Central Intelligence Agency, "Communist China's Advanced Weapons Program," January 27, 1965, pp. 20–21, https://www.fas.org/irp/cia/product/frus_30_077.htm.

47. *Ibid.*, p. 6.

48. Work was also performed at the former Shanghai Light-Bulb Factory, among other places. Remarks on the program from collected memoirs suggest the first centrifuge might have been a

an Australian news source, China had “perfected” the centrifuge at some point in the mid-1960s, and by April 1967 was preparing to replace parts of its gaseous diffusion plant with centrifuges.⁴⁹ In 1970, a second human source revealed to the CIA that he knew that the Soviet Union had transferred centrifuge “know-how” to the Chinese back in 1957 and, further, that the Soviet Union was confident that China had produced weapon-quantities of HEU through the centrifuge process alone.⁵⁰ The intelligence world is full of rumors, though, and without more reliable evidence, the CIA concluded, “Analysis of all available data has produced no evidence of a centrifuge plant [in China] because there are no specific identifying characteristics of a centrifuge plant.”⁵¹

The Soviet and Chinese programs existed in tightly controlled societies with few foreign connections or strong security cultures, and in an era before modern signals intelligence. The paucity of reliable signals might be expected. Future proliferation is apt to have a different character, perhaps more similar to the programs of Pakistan, South Africa, Libya, Iraq, and Iran. Five of these six programs were detected before they reached maturity, and on the surface lend support to the view that improved human access, and modern signals intelligence, can do much to uncover a clandestine program. A detailed review of these programs argues against this, however. It seems the A.Q. Khan proliferation network played a unique role in revealing these programs. Programs that did not depend on Khan (e.g., Iraq) were not detected.⁵²

Khan’s role in revealing clandestine programs is first demonstrated with his own centrifuge effort in Pakistan. Although other centrifuge options were available, Khan decided to pursue a centrifuge design that required advanced materials and manufacturing capabilities that were not readily available inside Pakistan in 1975. According to an investigation by the Dutch government, it was this decision that led to Pakistan’s program being detected. The first indication came in August 1975, when Pakistan approached a Dutch firm for information pertaining to power supplies for centrifuge motors.⁵³ A second

Beams-type design, and the second a subcritical design. See *Collected Commemorative Essays for the 50th Anniversary of the Isotope Separation Group at Tsinghua University, 1958–2008*, English trans. (Beijing: Tsinghua University Department of Engineering Physics, 2008). Dates also cited in *Science and Technology: China. Selections from “China Today: Nuclear Industry,”* trans. Joint Publications Research Service, JPRS-CST-88-02 (Washington, D.C.: Joint Publications Research Service, 1988), p. 51, <http://www.fissilematerials.org/library/jprs88.pdf>.

49. “Nuclear Plant in China,” *Anglican*, April 27, 1967. See also Central Intelligence Agency document ID: CIA-RDP69B00369R0002000100048-1.

50. Central Intelligence Agency, “Nuclear Energy,” *Weekly Surveyor*, January 12, 1970, Weapons of Mass Destruction, WM00139, Digital National Security Archive, nsarchive.chadwyck.com.

51. *Ibid.*

52. *Report of the Commission on the Intelligence Capabilities of the United States Regarding Weapons of Mass Destruction* (Washington, D.C.: U.S. Government Printing Office, 2005), p. 7.

53. *Dutch Government Report of the Interministerial Working Party Responsible for Investigating the*

suggestion came when Pakistan attempted to purchase aluminum tubes from a second Dutch firm.⁵⁴ Because of the dual-use nature of these items, however, the evidence was too ambiguous to conclude that Pakistan was interested in centrifuges.⁵⁵ It was not until September 1975, when Pakistan placed an order with a French firm named Metalimphy, for a product not listed in its catalog, and which had been custom designed for the European Urenco centrifuge program, that a conclusive link emerged between Pakistan's procurement activities and its centrifuge ambitions.⁵⁶

After the detection of Pakistan's program, the intelligence community began to watch Pakistan's procurement network.⁵⁷ When Khan and his associates later transferred centrifuge technology to Iran, Libya, South Africa, and North Korea, some of these activities were observed.⁵⁸ Court documents and an IAEA source, for example, report that one of Khan's suppliers, Gotthard Lerch, was independently attempting to sell centrifuge technology to South Africa. Surveillance of Lerch tipped off U.S. intelligence about South Africa's centrifuge pursuits, which led to an early termination of its program.⁵⁹ Similarly, initial suspicions about North Korea's possible centrifuge program were based on its interactions with A.Q. Khan, although North Korea later flatly admitted that it had centrifuge ambitions.⁶⁰ Thus, had these countries not relied on Khan, their programs might not have been detected in the way that they were.

The 2005 report of the Commission on the Intelligence Capabilities of the United States Regarding Weapons of Mass Destruction reviewed these early successes in the context of the Libyan case, and concluded that a "disproportionately large volume" of U.S. intelligence was related to procurement activities, whereas little to no information had been obtained about internal activities.⁶¹ It also noted that the Libyan centrifuge program was detected

"Khan Affair Report," October 1979, as reproduced in Krishna Sreedhar, *Pakistan's Bomb: A Documentary Study* (New Delhi: ABC, 1986); and Frantz and Collins, *The Nuclear Jihadist*, p. 42.

54. *Ibid.*, p. 41.

55. *Ibid.*, p. 42.

56. *Ibid.*, p. 44. See also Rehman, *Long Road to Chagai*, p. 89.

57. Collins and Frantz, *Fallout*, pp. 68, 190, 256; David Armstrong and Joseph John Trento, *America and the Islamic Bomb: The Deadly Compromise* (Hanover, N.H.: Steerforth, 2007), p. 54; and James C. Olson, *Stuart Symington: A Life* (Columbia: University of Missouri Press, 2003), p. 426.

58. *Report of the Commission on the Intelligence Capabilities of the United States Regarding Weapons of Mass Destruction*, p. 261. Both Iran's and Libya's programs appear to have been detected at some point after the initial transfers, however.

59. High Court of South Africa, Transvaal Provincial Division, Summary of Substantial Facts, pp. 26–27; and author interview with Trevor Edwards, March 9, 2008.

60. Stephen Fidler and Edward Luce, "U.S. Fears North Korea Could Gain Nuclear Capability through Pakistan," *Financial Times*, June 1, 2001; "Father of Pakistan's Nuclear Bomb Removed," Deutsche Presse-Agentur, January 31, 2004; and John Lancaster, "Pakistanis Say Nuclear Scientists Aided Iran," *Washington Post*, January 24, 2004.

61. Lacking insight into Libya's internal activities, the intelligence community routinely and erroneously equated Libya's procurement with Libya having acquired a nuclear capability. It later be-

around the year 2000, sixteen years after Libya started receiving centrifuge assistance from the Khan network in 1984. Under normal circumstances, this would not have constituted timely detection except that, in Libya's case, the program was so disorganized that it still had not made significant progress.⁶² Similarly, North Korea's first interactions with the Khan network appear to date to around 1986.⁶³ Over the decades, a few dozen of North Korea's procurements were observed in a scattershot fashion.⁶⁴ Lacking a coherent picture, the intelligence community wrongly assessed that North Korea had an interest in centrifuges, maybe a development program, but not a capability.⁶⁵ It was a surprise when North Korea revealed in 2010 that it had a full-scale, modern centrifuge plant in Yongbyon.

In sum, the historical record suggests that the probability of detecting a centrifuge program can be significant when states rely on watched foreign sources of specialized technology or well-known proliferators. The chances of detection will be lower, but perhaps adequate, if states depend on unwatched foreign providers, or mask their procurements with front companies, as North Korea did. Advances in signals intelligence might improve upon past performance. Despite all this, the use of foreign technology and materials is probably not necessary for a centrifuge program, and if states turn inward, the chances of detection might be significantly reduced. This may be why the 2005 intelligence commission concluded, "It is apparent to us that the [Intelligence] Community is not well-postured to replicate such success."⁶⁶

For states that built a centrifuge capability indigenously, the probability of timely detection has been approximately zero. In no case, including the most

came clear that Libya had made almost no internal progress. See *Report of the Commission on the Intelligence Capabilities of the United States Regarding Weapons of Mass Destruction*, p. 261.

62. IAEA, *Implementation of the NPT Safeguards Agreement of the Socialist People's Libyan Arab Jamahiriya*, GOV/2008/39 (Vienna: IAEA, September 12, 2008), para. 26. Another foreign agent, Emil Stache, was working to give Libya a centrifuge capability prior to 1984, and like the Germans helping Iraq, was not detected. The U.S. government's late detection is also corroborated in the account of an unnamed U.S. government official who claimed to have suspected a Libyan centrifuge program in early 2001. See David Rhode and Amy Waldman, "Musharraf Admits Early Doubts on Scientist; Pakistan Leader Says U.S. Delayed Sharing Evidence," *Chicago Tribune*, February 10, 2004.

63. Adrian Levy and Catherine Scott-Clark, *Deception: Pakistan, the United States, and the Secret Trade in Nuclear Weapons* (New York: Walker, 2007), p. 220; and Olli Heinonen, "The North Korean Nuclear Program," 38 *North*, April 26, 2012, 38north.org.

64. David Albright and Paul Brannan, *Taking Stock: North Korea's Uranium Enrichment Program* (Washington, D.C.: Institute for Science and International Security, October 8, 2010).

65. Dennis C. Blair, *Annual Threat Assessment of the Intelligence Community for the Senate Select Committee on Intelligence*, February 12, 2009, p. 24, <http://www.intelligence.senate.gov/090212/blair.pdf>.

66. *Report of the Commission on the Intelligence Capabilities of the United States Regarding Weapons of Mass Destruction*, p. 253.

contemporary instance of North Korea's full-scale centrifuge plant, has intelligence uncovered an indigenous program.⁶⁷ This is not surprising given the lack of technical indicators that can reliably find a clandestine plant, or even confirm the nature of a suspect one.⁶⁸ This problem is exacerbated by the fact that a small centrifuge program lends itself to organizational isolation. The prospect for recruiting defectors is diminished compared to larger, more traditional nuclear programs, which require a cadre of easily identified engineers with nuclear-specific expertise.

Finally, it is worth noting that, if a covert centrifuge program is detected, a state can argue that the program is intended for peaceful purposes, shifting its proliferation strategy from a clandestine route to a more overt strategy. Iran has done this with some success, and although suspicions will be high, sympathy, plausible deniability, and a desire of nonnuclear weapon states to keep their own nuclear weapon options open may help abate international pressure to terminate the centrifuge program absent conclusive evidence of weapon intent. Unlike dedicated plutonium-production programs, the ambiguity of dual-use centrifuges helps states to secure a weapon option even under international scrutiny.

The Development of Centrifuge Technology by Independent Programs

The history of centrifuge development is significant: at least twenty countries have developed or obtained a centrifuge capability. Five depended critically on illicit foreign assistance.⁶⁹ Two more are too poorly documented to tell.⁷⁰ The remaining thirteen, which brought their programs to a successful conclusion without depending on the black market, form a basis for assessing what states can do on their own.⁷¹

Most of the indigenous programs on record were started in the 1960s and early 1970s—prior to the mainstream availability of computer-aided design, globalized industrial manufacturing, or rapid prototyping technologies. This was also a time when the centrifuge was still largely a mystery and centri-

67. The discovery of the Fordow enrichment plant in Iran is qualitatively different than that of the Yongbyon plant in North Korea. At the time of the Fordow revelation, Iran's centrifuge program and infrastructure had been recognized for many years, visited by international inspectors, and systematically penetrated by foreign intelligence services.

68. On the generalities of finding undeclared activities, see Member State Support Programmes to the IAEA, *IAEA Use of Wide Area Environmental Sampling in the Detection of Undeclared Nuclear Activities*, STR-321 (Vienna: IAEA, August 27, 1999).

69. Pakistan, Libya, North Korea, Iraq, and Iran.

70. India and South Africa.

71. Australia, Brazil, China, France, Germany, Israel, Italy Japan, the Netherlands, the Soviet Union, the United Kingdom, and the United States.

fuge-specific technical information was scarce and hard to come by. Today, by comparison, there are hundreds of articles on centrifuge theory and design, including several review articles able to direct engineers to the relevant sub-literatures.⁷²

The programs described below, with the possible exception of Brazil, could be characterized as small, exploratory efforts with limited resources. All were started out of curiosity and a sense that the technology could be important—perhaps equally important for energy as for national security—but the technology was not needed for any immediate purpose. All the programs pursued “subcritical centrifuges,” an especially simple design developed a decade earlier in the Soviet Union, and from which all modern centrifuges are now derived. In some sense, these resource-poor programs, based on antiquated 1950s’ Soviet technology and built with 1960s’ machine tools, might be analogous to future proliferation programs in the developing world. Despite the simplicity, the average development time, measured over programs with known dates, was only twenty-four months (with a standard deviation of eleven months).⁷³

To get a sense of the character of these programs, the level of resources utilized, the trials experienced, and the achievements made, I review the four most indigenous programs in detail here. The program time lines for the other ten are summarized in figure 1.

UNITED STATES

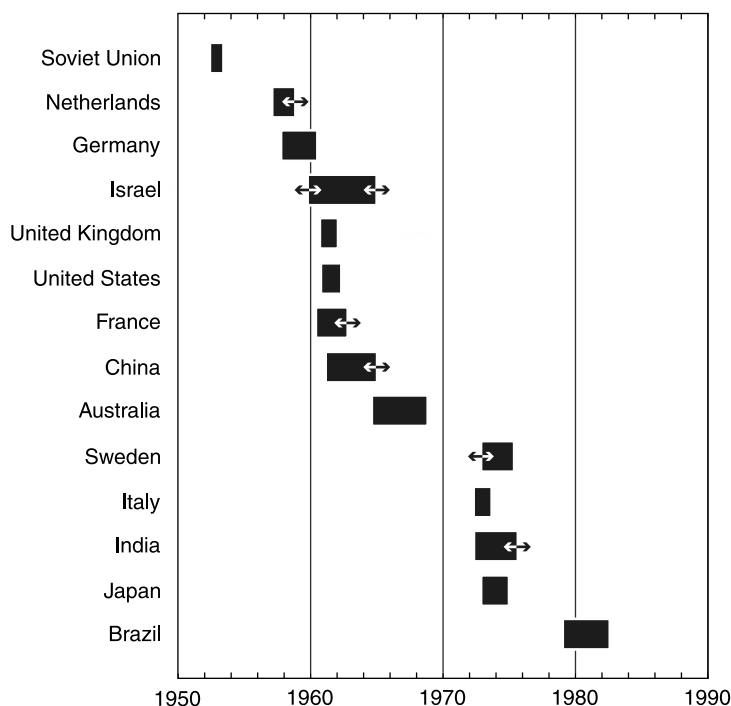
It seems counterintuitive to begin with the United States, one of the most highly industrialized nations in the world, but this subcritical centrifuge program bears no hallmarks of that advantage. At the time, the United States had no commercial interest in centrifuges but was concerned with their proliferation potential. In November 1960, the AEC organized a program to simulate development in a less-advanced country as part of an “Nth country” experiment.⁷⁴

72. A 1970 bibliography contained 306 entries. See G.E. Lowe, “Bibliography on Isotope Separation by the Gas Centrifuge, Part 1: Books, Reports, Journal Articles, and Conference Papers” (Capenhurst, U.K.: Capenhurst Works Library, British Nuclear Fuels Limited, April 1970). By the early 1980s, about fifty centrifuge papers were being added per year. See G.E. Lowe, D.F. McLeod, and P. Roberts, “Gas Centrifuge Bibliography: 1983–1986” (Capenhurst, U.K.: Capenhurst Works Library, British Nuclear Fuels Limited, March 1987). Key articles mapping out the literature include Stanley Whitley, “Review of the Gas Centrifuge until 1962,” *Reviews of Modern Physics*, Vol. 56, No. 1 (January 1984), pp. 41–97; and J. Billet Soubbaramayer, “Centrifugation,” in Stelio Villani, ed., *Uranium Enrichment* (Berlin: Springer-Verlag, 1979), pp. 183–244.

73. Development time is measured from program inception to the point when mass production of proliferation-capable centrifuges can begin. A proliferation-capable centrifuge is defined here as a centrifuge having an output of at least 0.5 kg-SWU per year and an expected operational lifetime of at least two years. Every program exceeded this performance by a large margin.

74. The summary findings were reported in U.S. Atomic Energy Commission Oak Ridge Opera-

Figure 1. Time Lines for the Indigenous Development of First-Generation Centrifuges



NOTE: Arrows indicate that date is uncertain by more than six months.

Three years prior the start of the experiment, the AEC had commissioned Gernot Zippe, an Austrian-born West German national who had helped invent the subcritical centrifuge in the Soviet Union, to write several technical reports about the machine.⁷⁵ Zippe's reports were unclassified and made available to the public through the Department of Commerce's Office of Technical Services (the predecessor to the U.S. National Technical Information Service). These reports formed the basis for the Nth country experiment. They were also the only public domain documents of significance during the 1960s and

tions Office et al., *Second Gas Centrifuge Appraisal Report*. A detailed chronology of this program can be found in Kemp, "The End of Manhattan."

75. Gernot Zippe, Jesse W. Beams, and A. Robert Kuhlthau, "The Development of Short Bowl Ultracentrifuges," No. ORO-202 (Charlottesville: University of Virginia Ordnance Research Laboratory, December 1, 1958); Gernot Zippe, "The Development of Short Bowl Ultracentrifuges," No. ORO-210 (Charlottesville: University of Virginia Ordnance Research Laboratory, July 1, 1959); Gernot Zippe, "The Development of Short Bowl Ultracentrifuges," No. ORO-216 (Charlottesville: University of Virginia Division of Engineering Physics, Research Laboratories for the Engineering Sciences, November 6, 1959); and Zippe, "The Development of Short Bowl Ultracentrifuges," No. ORO-315.

1970s, and were likely the driving force behind the centrifuge programs of nine other nations that began programs during the same period, all of which were successful.

None of the individuals involved with the U.S. program had interacted with Zippe before or during the development phase, nor did the engineers have any prior experience with centrifuges or similar high-speed rotating machinery.⁷⁶ This isolation and inexperience suggests that there was little to no transfer of tacit knowledge. Four of the eventual fifteen engineers and technicians had prior experience with gaseous diffusion, which, though not germane to the design of centrifuges, would have improved access to, and handling of, uranium. This sort of experience, however, is most relevant to the production and operating phases for a centrifuge plant; very little relates to centrifuge engineering, and that which does is today widely available in the public domain because of the requirements of the commercial nuclear industry.

In 1960, the engineers did not have access to computer-controlled machines or computer-aided design tools. The early U.S. centrifuges were machined by hand and required no more tooling than what might be available today in a high-school machine shop.⁷⁷ Problems were diagnosed by trial and error and by the repeated manufacture of slightly varied prototypes—an effort that today can be greatly reduced by modeling using commercially available software packages. Despite the trial-and-error approach, progress was rapid. The program began with only four engineers. Within five months, these four individuals accomplished all the design and testing needed to build the first prototype.⁷⁸ During months six through nine, the program was expanded from four

76. A. Robert Kuhlthau, "Notes by A.R. Kuhlthau from Discussion with Zippe," 1957, papers of Ralph A. Lowry, Oak Ridge National Laboratory, Oak Ridge, Tennessee; author interview with A. Robert Kuhlthau, November 27, 2007; Ralph A. Lowry, "Laboratory Notebook 7, Begun January 8, 1958," single notational entry, March 25, 1960, papers of Ralph A. Lowry; and S.W. Palmer, "Notes on the Roles of Early Members of the UCCND Gas Centrifuge Development Group," July 30, 1986, papers of Ralph A. Lowry.

77. This characterizes the tooling available to Gernot Zippe at the University of Virginia. See Zippe, "The Development of Short Bowl Ultracentrifuges," No. ORO-315. That this was indeed sufficient can be shown by various calculations. For example, the maximum permissible eccentricity for subcritical aluminum rotors operating at 400 meters per second can be achieved on a standard engine lathe.

78. Specifically, they developed test stands for the mechanical operation of the rotor, bearings, drive, and molecular pumps; learned how to make precise measurements of enrichment using a mass spectrometer; performed extensive studies on materials and their compatibility with uranium hexafluoride; tested an array of bearing, damper, and end-cap combinations; performed 300 separation experiments testing twelve scoop designs and baffle systems; determined centrifuge optimization parameters for each design experimentally; and drew up plans for a thirty-five machine cascade and a second-generation centrifuge. See Ernest C. Evans and Edwin F. Babelay, "Gas Centrifuge Development, Progress Report, November 1, 1960 through April 30, 1961," K-1481 (redacted), June 1, 1961, papers of Ralph A. Lowry; and Union Carbide Nuclear Company, "Gas Centrifuge Development of Process Development, Quarterly Report for Third Fiscal Quarter, Jan 1, 1961–March 31, 1961," K-1502 (redacted), July 24, 1961, papers of Ralph A. Lowry.

to fifteen. Most of these were relatively inexperienced technicians with only undergraduate degrees. The program was split into two teams: some worked on building a more advanced centrifuge, while the others began producing copies of the original design in order to experiment with cascades.⁷⁹

In the tenth month, the program had its first and only major stumble. Some of the early centrifuges began vibrating, which caused them to self-destruct. The group had no computers capable of analyzing the cause of the vibrations; they even lacked a correct mathematical theory of vibration.⁸⁰ A methodical study had to be carried out, and the vibration problem was soon rectified. By the end of month fifteen, the group was able to reliably build smooth-running centrifuges and operate them in a cascade that performed at 80 percent of the maximum possible efficiency—adequate for proliferation purposes.⁸¹

UNITED KINGDOM

The British centrifuge program paralleled the U.S. program, and was almost identical in size and duration. It began one month prior to the U.S. program and was also based on Zippe's technical reports.⁸² The group also grew to fifteen persons: ten worked on mechanics and gas dynamics at Capenhurst; two at Harwell worked on theory; and three at Culcheth did experiments on metallurgy and novel materials.⁸³

In June 1961, the British group ran into the vibration problem just as the United States later did, but the problem was apparently solved by the end of 1961 when the program was transferred from the research division to the production division of the U.K. AEA.⁸⁴ The British program diverges from the

79. Union Carbide Nuclear Company, "Gas Centrifuge Development of Process Development, Quarterly Report for First Fiscal Quarter, July 1, 1961–September 30, 1961," K-1504 (redacted), January 30, 1962, papers of Ralph A. Lowry.

80. Dean A. Waters, "A Vibration Study of Subcritical Gas Centrifuges, K-1485," October 3, 1961, papers of Ralph A. Lowry. The correct theory of vibration had already been published in R.E.D. Bishop, "The Vibration of Rotating Shafts," *Journal of Mechanical Engineering Science*, Vol. 1, No. 1 (June 1959), pp. 50–65. Apparently, researchers participating in the project did not find it, a search problem today much eased by computers.

81. Union Carbide Nuclear Company, "Gas Centrifuge Development of Process Development, Quarterly Report for Second Fiscal Quarter, October 1, 1961–December 31, 1961," K-1505 (redacted), April 27, 1962, papers of Ralph A. Lowry. For this estimate, the perfectly efficient cascade is a nonmixing cascade.

82. Stanley Whitley, "The Uranium Ultracentrifuge," *Physics in Technology*, Vol. 10 (1979), pp. 26–33; and "Report on Meetings with U.K.A.E.A. in England—December 12–14, 1960," KB-852 (redacted), February 20, 1961, papers of Ralph A. Lowry.

83. J.A. Friedericy, "Meeting with UKAEA Representatives at the University of Virginia, Charlottesville, Virginia, July 19 to 21, 1961," 1961, papers of Ralph A. Lowry; and Stanley Whitley, "Progress Report on British Centrifuge Project," P.G. Memorandum No. 799(CA), Sub Reference CEPC/P. 14 March 1962, papers of Ralph A. Lowry.

84. U.S. Atomic Energy Agency Technical Exchange Branch to Division of International Affairs, "Proposed Visit by U.K. Representatives for Discussions on Centrifuge Development," No. TEB-91, July 7, 1961, papers of Ralph A. Lowry; and Whitley, *Progress Report on British Centrifuge Project*.

track of the U.S. program in that—unlike the United States, which had made a large postwar investment in gaseous diffusion plants and had no motivation to replace them—the British wartime diffusion plant was failing and needed replacing. The British centrifuge team thus moved quickly toward a production machine in hopes of outcompeting the diffusion group.⁸⁵ They focused on building machines that had reasonably good performance and that would last ten to twenty years, long enough to pay off the capital investment. They succeeded in building a prototype that exceeded the requirements of a proliferation-scale program within fifteen months—the same time period as the U.S. program.

The British program also provides a view of what simple mass production might look like. Because of the need to demonstrate a working plant at an early date, the British program bootstrapped the mass production of centrifuges by hiring unskilled laborers to make and assemble centrifuge parts in a production line. According to interviews with one British engineer who worked on the United Kingdom's first pilot cascade, approximately 2,000 machines were assembled in about one year.⁸⁶

AUSTRALIA

Australia's centrifuge program started in 1965. The first machine built was a subcritical centrifuge, just like the ones built in the Soviet Union, the United Kingdom, and the United States.⁸⁷ None of the engineers involved had any prior experience with isotope separation, and no research on centrifuges had been done at Australian universities or other national institutions. The program was remarkably small: a team initially numbering three, and never exceeding six persons, began with nothing but a library of publicly available documents. Despite the program's tiny size and modest resources, Australia was operating a small cascade of proliferation-capable centrifuges in less than six years.⁸⁸ This is the slowest program of independent development on record.

BRAZIL

Brazil's centrifuge program was ambiguously designed to enrich uranium for weapons as well as commercial nuclear power. The program was organized by

85. Kehoe, *The Enriching Troika*, p. 56; Franklin, "Looking Back to 1959"; and Hermon M. Parker to R.C. Armstrong, Assistant Manager of Operations, U.S. Atomic Energy Commission, August 12, 1963, papers of Ralph A. Lowry.

86. Author interview with Edwards.

87. Author interview with Clarence Hardy, July 19, 2007. It is not known if the team tried other (e.g., Beams-type) designs first.

88. Keith F. Alder, *Australia's Uranium Opportunities* (Sydney: Pauline M. Alder, 1996); and author interview with Hardy.

the navy and began in earnest in early 1979. Individuals involved with the program estimate that it had reached ten to twenty persons by 1980.⁸⁹ After that, the program grew rapidly, reaching perhaps as many as fifty individuals by the time it had successfully enriched “macroscopic” amounts of uranium around the spring of 1982.⁹⁰ This makes Brazil’s program one of the largest on record, but it was also organized as a major military undertaking and took many wrong turns along the way. Brazil’s first centrifuge rotors were made from carbon steel, a material that corrodes when exposed to uranium hexafluoride. A second model was based on stainless steel, which, though non-corroding, introduces extra complications relative to aluminum because of its heavy weight and low strength-to-weight ratio. Such a centrifuge could not be practically used even for a crude program. Brazil then moved to maraging steel, a highly specialized steel capable of good performance, but one that is also complicated to use because of its metallurgy and heavy weight. Brazil did not at the time produce this special steel indigenously, so it had to develop a domestic production capability first.⁹¹ These dead-ends and delays could have been avoided if Brazil had had access to any of the several books and articles that discuss the suitability of materials, and which are now available in the public domain. Nonetheless, Brazil was successful in overcoming these hurdles in about three years.

Similar such programs were replicated in the Netherlands, Germany, Israel, France, China, Sweden, Italy, India and Japan. The programmatic time lines of these programs are shown in figure 1.⁹²

Every centrifuge program described above was engaged in the design of subcritical centrifuges—sometimes called short-bowl, Zippe-type, or Soviet-type centrifuges. The rotating part of subcritical centrifuge is typically no more than about a half-meter tall. This stands in contrast to “supercritical” centrifuges seen in commercial enrichment facilities, which are typically several meters tall.⁹³ The labels “subcritical” and “supercritical” refer to the absence or

89. Orpet Peixoto, who was personally involved in the program, estimated fifteen to twenty individuals. José Goldemberg estimated ten. Author interview with Peixoto, September 13, 2011; and author email interview with José Goldemberg, August 2, 2009.

90. Author interview with Peixoto.

91. Ibid. According to Peixoto, Brazil’s steel producers resisted because there was no commercial market for the steel. Based on the date when the first prototypes were built with imported steel (1982), and when the first cascades were built with domestic steel (1985), the creation of a domestic maraging steel capability took less than four years.

92. All data based on open source information. The time to develop a proliferation-capable design is shown in black. Arrows on a timeline boundary indicate a date may be off by more than six months.

93. Subcritical centrifuges will typically provide between 0.5 and 1 kg-SWU per centrifuge per year. For context, about 5,000 kg-SWU are needed to make a first-generation implosion-type nuclear weapon. For a technical discussion of the differences between subcritical and supercritical centrifuges, see Whitley, “Review of the Gas Centrifuge until 1962.”

presence of certain vibrational resonances that render the engineering of the centrifuges substantially more difficult; subcritical centrifuges avoid these by virtue of being short, and are thus easier to build. Centrifuges of this design were first perfected in the Soviet Union in 1954 and deployed on an industrial scale starting in 1957.⁹⁴ Ever since, they have been almost universally pursued as the first centrifuge by research programs. Subcritical machines tend not to garner much attention in the West because the economics of commercial enrichment have pushed Western firms to use higher-performance supercritical machines, although subcritical machines are still used in Russia where labor costs remain low. Subcritical centrifuges are nonetheless perfectly adequate for proliferation purposes, and the Soviet Union deployed them exclusively for fifty-three years in its weapons program.⁹⁵ In 1991, subcritical centrifuges made up about 90 percent of the world's centrifuge-enrichment capacity, and as of 2010, subcritical centrifuges still accounted for about 40 percent of the world's total (centrifuge and noncentrifuge) enrichment capacity.⁹⁶ It is important to note that the well-known P-1 and P-2 centrifuges marketed by the A.Q. Khan network were early supercritical centrifuges and thus substantially more difficult to build.

The independent centrifuge programs from the 1960s were based on technologies that a developing country might easily muster today. Even the human resources needed to design the centrifuge—four or so competent mechanical engineers, and six to ten technicians—seem within the reach of most nation-states, no matter how poorly developed or educated the country might be. This does not imply that every state can then build a centrifuge plant. A government's organizational and managerial capabilities are a third critical ingredient, and perhaps the most difficult for developing countries to muster.⁹⁷ Finally, the task of gathering a large numbers of reliable technicians for mass-producing centrifuges and subsequently operating the centrifuge plant is a task for which there is unfortunately a paucity of data from which to draw meaningful conclusions. There are some vignettes of what might be possible, however. The United Kingdom briefly mass-produced centrifuges using com-

94. Kemp, "The End of Manhattan."

95. G. Soloviev, "Iz Pokolenija v Pokolenie," *Nuclear.ru*, March 31, 2008, <http://www.nuclear.ru/rus/interviews/2109348/>; and World Nuclear Association, "Russia's Nuclear Fuel Cycle," July 2011, <http://world-nuclear.org/info/Country-Profiles/Countries-O-S/Russia--Nuclear-Fuel-Cycle/>.

96. World Nuclear Association, "Uranium Enrichment," May 2011, <http://world-nuclear.org/info/inf28.html>.

97. Aaron Karp reached a similar conclusion with respect to ballistic missile development. See Karp, "Ballistic Missiles in the Third World," *International Security*, Vol. 9, No. 3 (Winter 1984), pp. 166–195.

pletely unskilled labor and hand-operated machine tools. India and Pakistan organized programs and operated plants in the 1970s using only domestic engineers. In contrast, however, the lesser organized and generally less educated Libya did not succeed in organizing a successful effort. Nevertheless, the technology and core engineering requirements do not appear to be serious limitations.

Centrifuge Technology on the Black Market

Pakistan, Iran, Libya, South Africa, North Korea, and Iraq all went to the black market to buy stolen centrifuge technology from private individuals in secret deals. Much of the academic literature implicitly assumes that these countries were forced down this path because they lacked a viable indigenous option. This presumption would seem to be validated by three facts: (1) these states did, indeed, choose black market assistance over indigenous development; (2) these states were less developed and technologically weak compared to mainstream nuclear powers, and (3) despite the help received, many of these countries experienced long time lines, suggesting they struggled even after receiving help.

Concerning fact (1), a careful reading of history shows that states went to the black market because the offer of assistance was too alluring to pass up, not because they were forced to. In fact, of the six states that received foreign assistance, five had indigenous programs or indigenous ambitions—and to the extent that information is known about those programs, they made technology choices that were broadly consistent with the indigenous programs outlined above. Program managers availed themselves of foreign assistance for a mixture of reasons. In all cases, however, offers of assistance were received during formative stages, before any indigenous effort could prove its potential.

Concerning fact (2), that black-market customers have tended to be states with weaker-than-average technological infrastructure does not mean that these states were unable to muster enough fifty-year-old technology and general engineering expertise to build centrifuges on their own. In fact, the states that went to the black market pursued more difficult supercritical centrifuges and faced far more significant technological hurdles than they would have experienced had they stayed with a subcritical design.

Concerning fact (3), the long program time lines do not necessarily imply technological ineptitude: effects specific to the more difficult supercritical centrifuges pursued because of black-market assistance, limits on organizational capability, and supply-chain problems associated with black-market providers better explain the long program time lines. Black-market programs were also

detected, probably because of their dependence on foreign suppliers, and then subjected to counterproliferation action that caused significant delay.

Not all instances of foreign assistance have been counterproductive. Some states (e.g., Iraq) received well-directed assistance, whereas others (e.g., South Africa) received limited amounts of high-quality information that proved useful later. Most black-market programs, however, have depended on the extended A.Q. Khan network, from which assistance tended to be problematic. This section looks at these programs and their pathologies in detail.

PAKISTAN

Prime Minister Zulfika Ali Bhutto authorized Pakistan's centrifuge program in February 1975.⁹⁸ Sultan Bashir Mahmood, a nuclear engineer who had participated in a study group on uranium enrichment in 1967, was appointed to head the effort. In a recent interview, Mahmood reports that he had been given a copy of the Zippe report at the inception of the program and set out to build a replica of the simple centrifuge—the same centrifuge built by the United States, the United Kingdom, Australia, and others. He claims that a prototype was finished (but not necessarily tested or proven), and improvements to the design under way, when A.Q. Khan—then living in the Netherlands—began to furnish stolen information about a Dutch centrifuge called “CNOR.”⁹⁹ Mahmood and his chief scientist, Ghulam Dastagir Alam, began to incorporate CNOR design elements into their prototype—but what Mahmood, Alam, and apparently A.Q. Khan did not realize was that they were poisoning their program: the CNOR design was highly flawed.

The CNOR was an early attempt by Dutch designers to improve on the basic subcritical centrifuge. They sought to quadruple the performance of their subcritical centrifuge by increasing the length of the centrifuge and rendering it supercritical. Doing so, however, severely complicated the manufacture and operation of the centrifuge. For example, the new CNOR required difficult-to-manufacture bellows to join rotor segments together. The bellows were made from maraging steel, a material that is hard to come by and hard to work, and it corrodes when exposed to uranium hexafluoride unless specially treated. The extra weight forced a design change in the lower bearing, from a simple snip of wire to an engineered support using lubricated ball bearing.¹⁰⁰ Most significantly, unlike the subcritical centrifuge, the supercritical CNOR was sus-

98. Shahid-Ur Rehman, *Long Road to Chagai* (Islamabad: self-published, 1999), p. 50.

99. Sultan Bashir Mahmood, interview by Mansoor Ahmad, August 2009; and author interview with Mansoor Ahmad, September 17, 2009. CNOR stands for cultivated nuclear orbital rotor.

100. This requirement can be seen by applying the Archard wear law to the piano-wire bearings used in Zippe's incarnation of the subcritical centrifuge. The piano-wire wear rate is given in Zippe, “The Development of Short Bowl Ultracentrifuges,” No. ORO-315; and J.F. Archard and W.

ceptible to flexural resonances: vibrational modes that can cause the centrifuge to explode during start-up and shutdown.¹⁰¹ To guard against these vibrations, the manufacturing tolerances had to be tightened. No longer would a “high-school machine shop” suffice as it had for subcritical centrifuges—CNOR required high-precision lathes and specialized balancing equipment not generally used in everyday machining. The Dutch overcame many of these hurdles, but despite their best efforts they eventually abandoned the design in April 1973, leaving still imperfect drawings in the archives.¹⁰² It was these unfinished drawings that A.Q. Khan stole for Pakistan, and later sold to Iran and others.

Pakistan’s engineers did not have, at this early stage, sufficient expertise to understand CNOR, the machine tools needed to manufacture it, or knowledge of how to fix the problems that the Dutch engineers had left unsolved. Eager to improve their humble prototype, they began blindly incorporating some of CNOR’s design concepts—but, reportedly, Khan was not even providing enough information to replicate the CNOR properly. According to independent reports by both Mahmood and Alam, the initial information Khan sent by diplomatic pouch consisted of only handmade sketches that lacked detail and accuracy, causing delays and problems.¹⁰³

A.Q. Khan returned to Pakistan in December 1975, carrying with him a substantial number of proper CNOR drawings (although still not a complete set). He floated on the periphery of the Pakistani centrifuge program until the spring, when, perhaps seeing that his importance was beginning to wane, he started to criticize the foundering program. In April 1976, he organized a coup to take control of the program, and by July he was in charge.¹⁰⁴ According to Alam, the program had five technical staff members at the time (not counting Khan or the ousted Mahmood); Khan himself had not yet seen a centrifuge operate, and had no insights to offer about how to make one work.¹⁰⁵ Khan’s approach was not to understand how to build centrifuges, but to replicate CNOR by using his contacts in Europe to supply missing design information, equipment, tools, and the prefabricated components that Pakistan could not easily

Hirst, “Wear of Materials under Unlubricated Conditions,” *Proceedings of the Royal Society*, A236 (1956), p. 937. Pakistan’s experience with this is reflected in I. Qamar et al., “Design of Spiral Grooves on a Spherical Bearing,” *Mechanism and Machine Theory*, Vol. 29, No. 6 (August 1994), pp. 847–853.

101. M.Z. Khan et al., “Some Practical Aspects of Balancing an Ultra-Centrifuge Rotor,” *Journal of Nuclear Science and Technology*, Vol. 24, No. 11 (November 1987), pp. 951–959.

102. Kehoe, *The Enriching Troika*, p. 56.

103. Author interview with Mahmood; “Interview of Dr. Ghulam Dastagir Alam, Ex-Chief Scientific Officer KRL,” *Lashkar*, June 12, 1998; and “Exclusive Interview of Sultan Bashiruddin Mahmood,” WAQT News TV, Islamabad July 23, 2009.

104. Rehman, *Long Road to Chagai*, pp. 54, 59.

105. Author interview with Ghulam Dastagir Alam.

make. In a sense he proposed to buy, not build, a centrifuge for Pakistan. To his superiors, the approach might have seemed a sound way to reduce the risk of failure, but it turned out to be highly vulnerable to foreign interference. In December 1978, for example, Pakistan's third shipment of power inverters from England was frozen after somebody tipped off a British member of Parliament. According to Chief Scientist Alam, this happened because Khan attempted to cheat one of his suppliers, Gotthard Lerch, out of a commission.¹⁰⁶ In turn, the British government sent a *démarche* to like-minded nations asking them to block shipments of centrifuge-related technology to Pakistan.¹⁰⁷ Soon the denials were extended even to uncontrolled items, as long as the purchaser could be plausibly linked to the centrifuge program. In a personal letter dated July 25, 1979, Khan complained of these interventions: "The Britishers are stalling it more than before. They are even stopping nails and screws. And since we have said Good Bye to the French Ambassador, he is also mad and has stopped our material."¹⁰⁸ We are making the inverters ourselves and hoping that by the end of the year, if God willing, we will make them."¹⁰⁹

This history suggests that Pakistan was on course to build an indigenous, subcritical centrifuge, just as other indigenous programs had, until A.Q. Khan diverted the program to the pursuit of the CNOR supercritical centrifuge. Design flaws, incomplete information, and tacit-knowledge challenges specific to CNOR, as well as counterproliferation efforts aimed at interrupting Pakistan's supply of foreign technology, worked to delay Pakistan's program. Remarkably, Pakistan overcame all of these hurdles; hurdles that were far more demanding than those experienced by programs building subcritical designs.

In the end, Pakistan produced a slightly shorter but still supercritical version of CNOR, which it rebranded the "P-1" around 1981 or 1982.¹¹⁰ The machine took roughly six years to complete, in contrast to the average two years for indigenous, subcritical-centrifuge programs. Much of that delay can be attrib-

106. Ibid.; author interview with Olli Heinonen, deputy director-general for safeguards (ret.), IAEA, October 9, 2011.

107. U.S. Department of State, "UK Approach to Supplier Governments on Pakistan," telegram: STATE 278247 to Embassy Bonn et al., November 1, 1978.

108. This refers to an attack by plain-clothed security personnel on France's ambassador, Pol le Gourrierec, and his first secretary, Jean Forlot, when the two were spying on the Kahuta facility on June 26, 1979. See U.S. Diplomatic Cables from the Islamabad embassy, December 20, 1978, and June 29, 1979, as reproduced in Ali Abid, *The Secret Documents Recovered from the US Embassy, Tehran* (Karachi, Pakistan: Fore-Runners, 1986).

109. Abdul Qadeer Khan to Abdul Aziz Khan, July 25, 1979, as reproduced in Sreedhar, *Pakistan's Bomb*, p. 53.

110. David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium, 1996* (Stockholm: Stockholm International Peace Research Institute, 1997), pp. 274–275.

uted to Pakistan's dependence on foreign suppliers, including the delays imposed by counterproliferation action that would have presumably been avoided or postponed if Pakistan had held to the indigenous path begun under Mahmood. For all its efforts, Pakistan stopped producing the P-1 at some point before 1985.¹¹¹ The P-1s failed at high rates and performed poorly, not surprising given that many of the fundamental problems of its CNOR lineage remained. In the words of one informed U.S. government official, the "junk pile was sizeable."¹¹² Instead of sending the disused machines to the scrap heap, however, Khan found a new use for them: he sold them to unwitting nations such as Libya and Iran.

IRAN

According to Iran's declarations to the IAEA, the decision to launch a centrifuge program was taken in 1985. Iran later received centrifuge drawings from A.Q. Khan's associates around 1987.¹¹³ One of the early heads of Iran's program, Masud Naraghi, relates in an interview that Iran had initiated a research program well before any offer of foreign assistance. He reports that the Atomic Energy Organization of Iran had planned to build a centrifuge indigenously, and had hired an Iranian-American consultant, but the consultant quit after approximately six months because he was unable to locate any centrifuge-related papers in Iran's meager libraries. Iran lacked access to basic scientific journals at that time, in part because of sanctions imposed by the West.¹¹⁴

Naraghi became the first regular staff member of the Atomic Energy Organization to head the centrifuge program. He says he was appointed before Iran's interaction with the A.Q. Khan network and was simultaneously heading a number of other projects. The centrifuge project was not a priority for him. He believes, based on his interactions with Khan's associates during this time, that the network was connected at a high level to Iran's state-operated technical establishments and had become aware of Iran's interest in uranium enrichment. In early 1987, a handwritten offer was presented to Naraghi's manager, Reza

111. The phaseout of P-1s can be dated between 1983 and 1985. See Nadeem Malik, "Interview with Dr. Abdul Qadeer Khan," *Islamabad Tonight*, Aaj News Television, August 31, 2009, <http://www.fas.org/nuke/guide/pakistan/aqkhan-083109.pdf>; Mark Hibbs, "Khan Network Sought CNOR Bearings Long after KRL Gave Up Centrifuge," *Nuclear Fuel*, Vol. 30, No. 20 (September 26, 2005), p. 5; and Mark Hibbs, "Pakistan Says Access Denied to Khan to Avert Threat to Government," *Nuclear Fuel*, Vol. 31, No. 26 (December 16, 2006), p. 3.

112. Quoted in Albright, Berkhout, and Walker, *Plutonium and Highly Enriched Uranium*, 1996, p. 275.

113. IAEA, *Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, GOV/2003/63, August 26, 2003, para. 30. Although the offer was undated, the IAEA was able to confirm that 1987 was the likely date of the offer by its contents and the letterhead on which the offer was written.

114. Author telephone interview with Masud Naraghi, November 17, 2011.

Amrollahi, who proposed a decision to buy. This course of action was endorsed by Iran's prime minister, and probably also by the supreme leader.¹¹⁵ Amrollahi did not, however, choose to buy everything that was offered, which included parts sufficient to assemble 2,000 centrifuges and essentially all the auxiliary equipment needed to run a centrifuge plant—some of which were likely scrap parts from Pakistan's centrifuge program. Instead, he chose to buy only the engineering drawings and sample components, with the intention of making the centrifuges indigenously—an action that speaks to his confidence in Iran's domestic capabilities.

The drawings Iran received were for the P-1 that Pakistan had abandoned at least three years earlier. At minimum, Pakistan was selling Iran a centrifuge that it regarded as inferior and outmoded; at worst, Khan was intentionally cheating Iran. In a possible confirmation of the latter, Naraghi reports that when the drawings were delivered, he found them woefully inadequate: "Drawings we received were very incomplete. For something like this one should get a complete assembly drawing, with parts numbered, and then drawings for each part separately. There was an assembly drawing with parts numbered, but not complete drawings of parts, which were more than one hundred. Instead, there were multiple drawings of the same part, and these appeared to be rejected drawings, perhaps collected from a wastebasket. No tolerances. In addition we were supposed to receive one sample of all the parts separately, a complete [set of] parts for one P1. And we never received even half of those promised parts during the time I was with the project."¹¹⁶

A month after Pakistan's president granted A.Q. Khan clemency, Khan wrote a still-unpublished statement to Simon Henderson of the London *Times*. The letter is of dubious veracity in that it appears Khan is attempting to clear his name, but at least one part is consistent with Naraghi's claim: "Under pressure, Gen. Imtiaz asked Dr. Hashmi (I was out of station) to give some centrifuge parts and drawings etc. to the Iranians. He (Hashmi) asked him to wait until my return. When I got back, Gen. Imtiaz advised me to get components of two old (P-1) discarded machines and pack them into boxes together with 2 sets of drawings prepared by the late Mr. Khokhar. These drawings on their own were not sufficiently detailed to enable mastery of this difficult tech-

115. IAEA, *Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions 1737 (2006) and 1747 (2007) in the Islamic Republic of Iran*, GOV/2007/58, November 15, 2007, para. 10; and author interview with Masud Naraghi, October 18, 2011.

116. Email interview with Masud Naraghi, September 11, 2010. Heinonen reports that, based on unspecified interviews with Naraghi's successor, Hormuz Azodi, he believes Iran received complete drawings at the outset.

nology. . . . Furthermore, the components were old, mostly rejected due to being out-of-tolerances.”¹¹⁷

Both supplier and buyer agree that the drawings and parts transferred were inadequate for the task of replicating the P-1 centrifuge. According to both Naraghi and Iran’s communications with the IAEA, Iran worked independently for six years without any additional outside assistance.¹¹⁸ A small team of three researchers at the Atomic Energy Organization of Iran attempted to replicate the P-1 centrifuge using what Khan had provided but were unsuccessful. Naraghi says his team was unable to assemble even a single working centrifuge, and that he had lost all motivation to work on the project because of the hopeless situation. Demoralized, Naraghi left the program in 1989 and, at least initially, it appeared that A.Q. Khan’s claim was correct—the information provided was insufficient for Iran to re-create the P-1. Even if it had been sufficient, fundamental problems inherent in the supercritical P-1 design remained unseen.

Amrollahi continued to insist his investment in P-1 technology be made to work, and when Naraghi left, Hormuz Azodi replaced him and the program continued. Azodi worked fruitlessly on the P-1 for several more years, complaining to the Khan network that he needed further information—and soon luck befell the Iranians. The Khan network had separately agreed to sell Libya a complete set of components for a proliferation-scale centrifuge plant in a deal struck in 1989. In 1991, Libya refused to pay for those components, citing an inability to access funds as a consequence of sanctions resulting from its having bombed Pan Am flight 103.¹¹⁹ Khan’s subcontractors were reportedly furious that they had not been paid, forcing Khan to look for alternative buyers.¹²⁰ At least one offer went to Iraq, which declined to buy. Eventually the

117. Abdul Qadeer Khan to Pakistan Inter-Services Intelligence, “Statement by Dr A Q Khan March 2004,” March 2004, p. 3, <http://www.foxnews.com/world/2011/09/15/aq-khans-thirteen-page-confession/>; and R. Jeffrey Smith and Joby Warrick, “Pakistani Scientist Khan Describes Iranian Efforts to Buy Nuclear Bombs,” *Washington Post*, March 14, 2010.

118. Iran’s claim is not inconsistent with Iran’s subsequent activities and is consistent with separate testimony from Bukhary Seyed Abu Tahir, a Sri Lankan businessman based in Dubai who arranged for transfer of centrifuges to Iran. See IAEA, *Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, GOV/2005/87, November 18, 2005, para. 11; and Royal Malaysia Police Office, “Press Release by Inspector General of the Police in Relation to Investigation of the Alleged Production of Components for Libya’s Uranium Enrichment Programme” (Kuala Lumpur: Royal Malaysian Post Office, February 20, 2004). Naraghi notes, however, that at the end of his tenure he helped prepare a list of questions for going back to the network.

119. IAEA, *Implementation of the NPT Safeguards Agreement of the Socialist People’s Libyan Arab Jamahiriya*, GOV/2008/39, para. 27. The connection to Pan Am 103 is not documented in the above-cited IAEA report, but multiple IAEA sources confirm that this was Libya’s official explanation.

120. Author interview with Heinonen; and International Atomic Energy Agency, *Implementation of*

network reconnected with Iran and, in 1993, the two parties reached an agreement that rescued Iran's program from stagnation. Iran would buy what Libya could not, including difficult-to-make parts for 500 P-1 centrifuges. The network sweetened the deal by providing, among other things, a more complete set of drawings for the P-1 and P-2 centrifuges. Deliveries of parts were slow to arrive. They came in two shipments, one in March 1994 and the second in July 1996, adding two more years to Iran's already protracted time line. Then one type of component, the bellows, proved to be of poor quality (being discarded parts from Pakistan's scrapheap). Iran had to wait for a replacement delivery, which did not arrive until 1997.¹²¹ Eventually, after thirteen additional meetings with the Khan network, theoretical studies done with the help of Iran's universities, and further modifications to the design, Iran was finally able to master a modified version of the P-1 centrifuge by the end of the 1990s.¹²² In total, Iran's interactions with foreign suppliers, from the six years of futile work to the constant waiting, add up to approximately a full decade of imposed delay.

U.S. intelligence detected Iran's program at some point prior to 1991.¹²³ It seems plausible that the United States and its partners worked to interdict or sabotage shipments of centrifuge-related materials going into Iran's program starting at this time, just as they had done with Pakistan's program, thereby inducing further setbacks in Iran's time line.¹²⁴ Despite all of these hurdles, Iran's engineers were able to master the supercritical CNOR/P-1 design. It seems likely, however, that had Iran avoided foreign assistance, it could have mastered a simple subcritical centrifuge far more quickly, and without foreign interference. For all its efforts, Iran did not end up in a better position: Iran's version of the P-1, which it calls the IR-1, performs at about 0.6–1.1 kg-SWU per year when used in cascades—the same level of performance as the first-generation subcritical centrifuges built in the late 1950s and early 1960s by independent programs.¹²⁵

the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions 1737 (2006) and 1747 (2007) in the Islamic Republic of Iran, GOV/2007/58, para. 16.

121. IAEA, *Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, GOV/2004/83, November 15, 2004, para. 34.

122. *Ibid.*; and IAEA, *Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, GOV/2003/63, para. 27.

123. Jim Mann, "Iran's Nuclear Plans Worry U.S. Officials," *Los Angeles Times*, January 27, 1991.

124. For example, in 1992 Germany blacklisted Iran, preventing it from openly buying technology there. Albright, *Peddling Peril*, p. 94.

125. For example, the first West German centrifuge, completed in 1960, had an estimated performance of 0.6–0.8 kg-SWU per year; the first U.S. version completed in 1962 performed at 0.5 kg-SWU per year; the second Soviet version, deployed in approximately 1962 and also a subcritical centrifuge, had the same performance as the IR-1: 0.6–1.1 kg-SWU per year. See Zippe, "The Development of Short Bowl Ultracentrifuges," No. ORO-315, p. 87; Kemp, "Gas Centrifuge Theory

LIBYA

According to Libyan authorities, Libya tried twice to acquire centrifuge technology from foreign agents. The first case involved recruiting a German consultant, Emil Stache, in the early 1980s.¹²⁶ Stache was a metallurgist who had worked on centrifuge bearings at Dornier, a German aerospace firm under contract to the German-Urenco centrifuge program. At Dornier, Stache worked with Gotthard Lerch, who became a key figure in the A.Q. Khan network and a supplier to Pakistan. Stache and Lerch conspired to swindle the Libyan government by offering it a centrifuge program. According to IAEA investigators, Stache was not a centrifuge designer and had little relevant knowledge. Stache and Lerch's initial offer to Libya (circa 1982) was to develop "an original design" for Libya. Initial work was to be done in Germany. Although details of Stache's activities have never been publicly released, it appears that nothing of significance came of the project. Libya's actions during this time indicate that it was not receiving much in the way of competent advice. For example, Libya purchased Japanese-made equipment for chemically converting uranium, but the wrong kind for a centrifuge program.¹²⁷ The Libyan government terminated relations with Stache around 1992.

Libya's second attempt at buying a centrifuge program overlapped with its first. In January 1984, the Khan network offered to sell Libya a centrifuge program, which Libya initially rejected.¹²⁸ In the fall of 1989, Libya reconnected with Khan and agreed to purchase a package of centrifuge drawings and components, which its engineers—or perhaps Stache—would assemble. When Khan's associates were ready to make the delivery, Libya refused to pay for the entire order, buying only blueprints related to the CNOR/P-1 design.¹²⁹ According to senior IAEA officials, this disagreement resulted in the sale of the balance of the goods to Iran, which ultimately rescued the Iranian program. Libya and Stache made little progress with the P-1 drawings. In 1995, after Stache had been let go, Libya returned twice more to the Khan network,

and Development"; and Albright, Berkhout, and Walker, *Plutonium and Highly Enriched Uranium*, 1996, p. 103.

126. IAEA, *Implementation of the NPT Safeguards Agreement of the Socialist People's Libyan Arab Jamahiriya*, GOV/2004/12 (IAEA, February 20, 2004), para. 21.

127. IAEA, *Implementation of the NPT Safeguards Agreement of the Socialist People's Libyan Arab Jamahiriya*, GOV/2008/39, para. 24. Two independent confidential sources confirmed the name of the German consultant.

128. *Ibid.*, para. 26. Libya claims that it did not have the technical or industrial capability to build the centrifuge program that A.Q. Khan was offering. It is doubtful whether Libya really believed this, given that it also hired Stache to build an indigenous program at approximately this time. Furthermore, it is doubtful whether Libya could discern the complications of the CNOR-derived centrifuges; the German consultant might have understood these, but if so it does not explain why Libya later decided to pursue the CNOR while the consultant was still employed.

129. *Ibid.*, para. 27.

the first time ordering fully assembled centrifuges, and later a full-scale centrifuge plant.¹³⁰

Libya's program suffered from several problems. First, it remains unclear whether the country ever had the organizational capacity to build an indigenous program of any kind, or even to operate the turnkey plant that it eventually ordered from the Khan network. Testifying to its disorganization, a set of specialized machine tools bought for the indigenous fabrication of centrifuges sat in crates for years and were never unpacked.¹³¹ The uranium conversion facility bought from Japan remained crated for two years, then was partially assembled, then was moved to another site, but was never completed or operated.¹³² In addition, Libya suffered from internal security problems (or paranoia) that impeded progress. On several occasions, Libyan authorities ordered that centrifuge-related equipment be relocated to new sites.¹³³ The outcomes of Libya's interactions with the black market were mixed at best. Stache duped Libya for a decade. Later, the Khan network stepped up to save Libya's centrifuge program, but it was the Khan network that also led to the early termination of the program. Libya's dealings with the network were detected by U.S. intelligence around the year 2000, after Libya had placed the order for a full-scale centrifuge plant. Components being made abroad were monitored, sabotaged, and eventually seized by the United States in October 2003.¹³⁴ Under intense diplomatic pressure from the British and U.S. governments, and with essentially no viable prospect of completing its program, Libya surrendered its nuclear pursuits in December 2003. Although it cannot be said that Libya had the potential to make centrifuges on its own, it is equally evident that the black market did not serve Libya well.

CONCLUSIONS ON THE ROLE OF FOREIGN ASSISTANCE

Not every case of foreign assistance has been counterproductive. The United States, Germany, and the Netherlands all received valuable assistance from Gernot Zippe.¹³⁵ South Africa and Iraq also received high-quality information from Germans. North Korea initially received limited information about P-1s

130. IAEA, *Implementation of the NPT Safeguards Agreement of the Socialist People's Libyan Arab Jamahiriya*, GOV/2004/12, para. 22.

131. *Ibid.*, para. 26.

132. *Ibid.*, para. 17.

133. *Ibid.*, para. 17, 23.

134. *Ibid.*, para. 26; and Collins and Frantz, *Fallout*, on sabotage: pp. 48–58, 112–117, 137–141, 161, 178, 197, 249; on seizure: pp. 72–75, 76–92, 131, 237.

135. Rudolf Scheffel provided Germany with general guidance on machine concepts, and Zippe performed the same service for the United States and the Netherlands. This guidance is now publicly available to any country through Zippe's published reports. See Zippe, "The Development of Short Bowl Ultracentrifuges," No. ORO-315. See also Kemp, "The End of Manhattan."

from Pakistan, but later obtained significant assistance based on the more reliable P-2 centrifuge after establishing strong military relations. In sum, foreign assistance is unreliable, sometimes productive, and sometimes extremely problematic—but rarely necessary.

If subcritical centrifuges are easy to build and adequate for proliferation, why did proliferators not simply pursue small, subcritical centrifuges instead of risking dependence on foreign entities? In the broadest possible sense, most states did take that approach: thirteen of twenty centrifuge programs were fully indigenous, and many of those programs were started with proliferation or latent-proliferation intent. Furthermore, of the seven that received some foreign assistance, at least three (Pakistan, Iran, and Iraq) had indigenous programs first, making sixteen of twenty that pursued indigenous programs at the outset of their efforts. Too little is known about the early histories of North Korea's, India's, and South Africa's centrifuge programs to make a judgment. Only one program, Libya's, can be said with certainty to have been fully dependent on foreign assistance from the outset. This suggests that states are not shy about pursuing indigenous programs, and absent an offer of foreign assistance, most states would likely continue down that reliable path. The non-proliferation community should not believe that the absence of a black market will significantly restrain proliferation.

Finally, there remains the question of why states pursuing indigenous programs switched to foreign assistance. With only three cases, and without detailed knowledge of the decisionmaking in those states, there is too little data to draw reliable conclusions, but there is enough information to speculate. In Pakistan's case, it appears that the leadership either doubted national abilities or was greedy and wanted to move quickly to a European centrifuge design. In Iraq's case, the program was urgent, as Iraq was immersed in conflict and wanted a nuclear deterrent. According to the program's technical director, the political overseer of the program, Hussein Kamel Hassan al-Majid, was threatening to take the lives of the engineers if they did not make more rapid progress.¹³⁶ Engineers responded to this pressure by soliciting foreign assistance. Finally, in Iran's case there was a personal relationship between A.Q. Khan-network salesman Gotthard Lerch and head of the Atomic Energy Organization of Iran, Reza Amrollahi. This, perhaps coupled with a sense of self-doubt arising from the earlier, abortive attempt with the Iranian-American consultant, seems to have motivated the decision to buy the P-1 design. In all cases, there appears to have been an element of self-doubt combined with ex-

136. Mahdi Obeidi and Kurt Pitzer, *The Bomb in My Garden: The Secret of Saddam's Nuclear Mastermind* (Hoboken, N.J.: Wiley, 2004), p. 66.

tenuating circumstances such as sanctions, imminent conflict, or nepotism that interfered with better decisionmaking.

Bringing all strands of evidence together, I conclude that technology has rarely been the limiting factor for the acquisition of centrifuges. Several highly visible programs made it appear as though centrifuges were a difficult challenge, but these problems actually reflect challenges uniquely associated with the flawed CNOR/P-1/IR-1 design, not a general challenge of centrifuges. In nearly all cases, organizational capacity or managerial competence has been the true limiting factor.

If this assessment is correct, then policymakers should question the ultimate utility of technology controls. The historical record indicates that these controls have been valuable in detecting programs that were critically reliant on export-controlled technologies (e.g., Pakistan), but consistent with the 2005 intelligence commission's conclusions, these instances were anomalies linked to A.Q. Khan and are not likely to be repeated. Export controls have also slowed programs, sometimes meaningfully (e.g., Iran and Libya), but this was only possible because the CNOR (and the derivative P-1 and IR-1 centrifuges) required exotic tools, materials, and expertise not domestically available. The larger history of centrifuge proliferation stands in stark contrast. States built centrifuges that did not rely on controlled technologies,¹³⁷ and were organized in ways that seem able to escape detection and intervention.

Conclusion

From the earliest days of the nuclear age, before Hiroshima, even before Trinity, views on how to prevent the proliferation of nuclear weapons were divided over the role of technology. Nuclear weapon advocates, such as Winston Churchill and Leslie Groves, believed that other leaders would also see nuclear weapons as essential, and therefore could not be persuaded to forgo these advantages by normative arguments. It was therefore compulsory for the U.S.-U.K. alliance to maintain control over the scientific information, industrial tools, and uranium deposits needed to make the bomb. By 1945, the obsession with technology had become so great that Groves instituted secrecy rules preventing even the United Kingdom, the progenitor of the Manhattan

137. The only materials needed for a Soviet-style centrifuge that appear on U.S. export-control lists today are rotors. These are, however, currently controlled only when formed into cylindrical shapes. Even if this material were controlled in every form and shape, the infeasibility of enforcing such controls becomes evident when one considers that there are more than 2,400 aluminum smelters in the world, with at least one in nearly every country. Very few routinely make the grade of aluminum needed, but nearly all could if necessary. See Rudolf P. Pawlek and Light Metal Age, "Secondary Aluminum Smelters of the World," *Secondary Aluminum Smelters of the World*, December 31, 2010, <http://www.lightmetallage.com/producers.php>.

Project, from accessing U.S. nuclear information.¹³⁸ Groves also sought to secure exclusive rights to all the uranium deposits known in the Western world.¹³⁹ In keeping with this approach, the U.S. Congress passed the MacMahon Act in 1946, strictly limiting nuclear cooperation with foreign countries, including the closest of allies. Although President Truman and members of his cabinet were more skeptical of the secrecy effort, they eventually put their faith in a similar technology-based logic: for them, the Manhattan Project was the greatest industrial project in human history, and given that the United States was now the world's most capable industrial power and had gathered many of the finest minds from Europe, they felt it was, in Truman's words, "doubtful if such another combination could be got together in the world."¹⁴⁰

At the same time, a group of concerned Manhattan Project scientists, each with a deep understanding of international competence in scientific research, came to the opposite conclusion. Individuals such as Niels Bohr, Robert Oppenheimer, Glenn Seaborg, and Leo Szilard acknowledged that technology posed a temporary hurdle, but argued that there was no enduring security in its control. Any advantage, according to their experience, would be ephemeral. They wrote, "Even if we can retain our leadership in basic knowledge of nuclear physics for a certain time by maintaining the secrecy of all results achieved on this and associated Projects, it would be foolish to hope that this can protect us for more than a few years." Enduring protection, they concluded, "can only come from the political organization of the world."¹⁴¹

In a sense, both views were correct. In the 1940s and early 1950s, the industrial requirements of producing fissile materials were still far beyond the reach of most states. For this reason—and because the American political elite found it easier to put its faith in technological hurdles than to sort out the political difficulties of nuclear abolition—the supply-side approach prevailed.¹⁴² Even

138. Wellerstein, "Knowledge and the Bomb."

139. Lawrence S. Wittner, *One World or None: A History of the World Nuclear Disarmament Movement through 1953*, Vol. 1: *The Struggle against the Bomb* (Redwood City, Calif.: Stanford University Press, 1993), p. 25.

140. Harry S. Truman, "Statement by the President Announcing the Use of the A-Bomb at Hiroshima. August 6, 1945," in *Public Papers of the Presidents of the United States: Harry S. Truman: Containing the Public Messages, Speeches, and Statements of the President, April 12, 1945 to January 20, 1953* (Washington, D.C.: U.S. Government Printing Office, 1961), p. 197. Similar thinking led to the creation of Coordinating Committee for Multilateral Export Controls (CoCom) regulations. See Yoko Yasuhara, "The Myth of Free Trade: The Origins of COCOM, 1945–1950," *Japanese Journal of American Studies*, Vol. 4 (1991), pp. 127–148.

141. James Franck et al., *Report of the Committee on Political and Social Problems* (Chicago: Manhattan Project Metallurgical Laboratory, University of Chicago, June 1945), pp. 4, 2.

142. UN General Assembly, 1st sess., "Resolution 1 [Establishment of a Commission to Deal with the Problems Raised by the Discovery of Atomic Energy]," January 24, 1946, A/RES/1/1. Unanimously adopted.

if the United States could not maintain its nuclear monopoly, it would at least have a head start in the arms race.

In 1946, few if any could have imagined the dramatic effects technological change would bring. At the time, the prevailing image of uranium enrichment was the gaseous-diffusion plant built at Oak Ridge: a facility of such enormous scale that it employed at its wartime peak some 12,000 people, enclosed forty-four acres under a single roof, and by 1945 consumed nearly three times the electricity of the heavily industrialized city of Detroit.¹⁴³ By the 1960s, the enrichment challenge had changed completely. Using centrifuges, a handful of engineers and a few dozen technicians could build a plant capable of enriching uranium for one bomb per year. It would fit in a high-school cafeteria, and could be powered by a single diesel generator. In 2014, such a centrifuge plant might be had for as little as \$20 million.¹⁴⁴

The history of centrifuge proliferation bears out the warning of the Manhattan Project scientists. Technological developments and industrial evolution have moved the proliferation-potential frontier to the point where nearly any country can independently build an enrichment program and thereby produce highly enriched uranium. The required information has long been in the public domain: many of the indigenous programs cited in this article were started in the mid-1960s when the only available information was the U.S.-published Zippe reports. Since then, hundreds of additional technical publications have appeared, which can be easily found using digital catalogs available via the internet. The 1950s' era tools and equipment needed to build centrifuges are also modest, if not rudimentary, by modern standards. Few to none of the components or materials are esoteric enough to be effectively controlled, and a first-generation subcritical centrifuge does not require any currently controlled items. Organizational capacity is perhaps the only meaningful supply-side barrier to the fabrication of simple centrifuges; yet history suggests that all but the weakest states (e.g., Libya) have been able to organize themselves well enough to get the job done.

Building a bomb requires more than enriching uranium, but the additional steps, which include the mining of uranium, the production of uranium hexafluoride, the post-enrichment conversion of the uranium hexafluoride to uranium metal, and finally the fabrication of bomb components, are simple in

143. U.S. Atomic Energy Commission, *AEC Handbook on Oak Ridge* (Oak Ridge, Tenn.: Oak Ridge Operations Office, 1955).

144. In 1960, Germany offered its subcritical centrifuges for sale at a cost of \$235 per machine, about \$1,850 in 2014 dollars. These machines performed as well as the IR-1 centrifuges operating in Iran in 2014. Assuming the price reflected the actual cost of production, the centrifuges needed to produce about one nuclear weapon per year could be built for roughly \$10 million in 2014 dollars. A plant could be created for that sum plus overhead. See Zippe, "The Development of Short Bowl Ultracentrifuges," No. ORO-315, p. 87.

comparison to building subcritical centrifuges. These steps also require organizational capacity and specialized knowledge, but here too the knowledge needed is neither secret nor obscure, and these steps require little in the way of specialized materials or equipment. A state's ability to carry out these additional steps is also, therefore, largely independent of technology controls.¹⁴⁵

This is not to say that technology controls are completely without merit. Such controls may make the task of building and operating centrifuges more arduous by forcing states to build more of the required technology indigenously and to spend more time troubleshooting the challenges that will inevitably arise. Supply-side controls may also limit the ability of states to build high-performance centrifuges, which would increase the overall effort required to build a centrifuge plant of any given size, and would also limit the ability of states to make credible claims that their primitive centrifuges are part of a peaceful, commercial program should their efforts be detected. Finally, supply-side controls will continue to provide barriers to noncentrifuge modes of nuclear proliferation. Such controls should not be eliminated, but it must be recognized that these institutions are increasingly outmoded. They cannot restrict the indigenous centrifuge route described herein, and will not, therefore, eliminate a state's fundamental ability to build nuclear weapons. Nonproliferation governments should, therefore, reconsider how they apportion their efforts between supply-side and demand-side approaches.

Finally, it should be understood that this article has not described a novel proliferation strategy. The problem of centrifuge proliferation is already widespread and well established. Over the past thirty-five years, seven of eight states seeking nuclear weapons have pursued centrifuges; most made centrifuges the primary focus of their programs; and every indigenous program started with basic, subcritical centrifuges such as those described here. Even states that ultimately pursued black-market assistance started with indigenous programs. There is no evidence to suggest that states doubted their domestic capabilities enough to be deterred from pursuing centrifuges altogether, or that they failed to choose the right kind of centrifuge when they did. It seems the optimal path is already the path most states selected, and all else equal, future states will probably continue this trend. There is nothing novel about the centrifuge problem; it is only that the policy community puts its focus elsewhere.

A possible explanation for why the policy community failed to address this

145. This is especially true for gun-type devices; see note 15. This is also true for the delivery of a device. Although missile and aircraft delivery systems pose a greater technical challenge, as of 2014 the U.S. Department of Homeland Security has not identified a way to detect highly enriched uranium weapons smuggled in commercial shipping containers.

problem when it first emerged can be found in the archives of the U.S. Atomic Energy Commission. As demonstrated earlier, the U.S. government knew about the problem since 1959, warned the public in 1960, and pursued confirmatory studies between 1960 and 1966. Despite the outcome of these studies, the government did not waver in its predilection for technology controls. A careful reading of AEC Chairman McCone's papers suggests that the AEC acted to bury these findings, both within the executive branch and beyond, by publicly obfuscating the extent of the problem and withholding information from the U.S. Congress, while privately it worried increasingly about centrifuges and attempted to make information pertaining to them more and more secret. Fifty years and at least fifteen indigenous centrifuge programs later, however, it is evident that secrecy and denial is not a lasting solution.¹⁴⁶

It is only by chance of history that the centrifuge has become the premier example of a largely uncontrollable proliferation technology. It is not likely to be the last. Laser enrichment, and perhaps other still-undiscovered or unperfected technologies, may pose similar challenges for the technology-control regime. None of the foregoing suggests, however, that there will be a sudden outbreak of proliferation. To the contrary, this article describes a situation that has prevailed for decades without rampant proliferation. Apparently, states seeking a nuclear weapon capability do not necessarily seek to build nuclear weapons. The lack of proliferation in these cases cannot be attributed to technological barriers—motivations must have been key. While the specific causes of proliferation abstinence lie beyond the scope of this article, the subject clearly merits deeper analysis by both policymakers and academics, as such factors are probably the most viable basis for the future of the nonproliferation regime.

146. On obfuscation, see, in the context of previous citations, U.S. Atomic Energy Commission and Clinton P. Anderson, chairman of the Joint Committee on Atomic Energy, January 13, 1961, RG 326/Entry 14B/Box 35, National Archives, College Park, Md.