H-Diplo|RJISSF Policy Forum on Nuclear Nonproliferation and Emerging Technologies

"Nonproliferation Implications of the Spread of Emerging Technologies"

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Introduction

The spread of emerging technologies—such as additive manufacturing (AM, aka 3-D printing), artificial intelligence (AI), and remote sensing (RS, including surveillance drones and imaging satellites)—could have significant implications for both the proliferation of nuclear weapons and nonproliferation efforts to stop them. These technologies could diffuse more easily due to their dual-use nature and digital formats. However, like previous advances, they do not independently help or hinder proliferation: countervailing efforts of states and regimes as well as properties of these technologies and their potential users tend to limit the likelihood and effects of diffusion. These factors mean that the net effect over time of introducing novel technologies on either proliferation or nonproliferation is likely to be small.

The failure of previous waves of technological spread to lead to runaway nuclear proliferation or disarmament should induce skepticism regarding the revolutionary potential of emerging technologies. As Jacques Hymans put it, given the constantly increasing gap between the number of nuclear-capable and nuclear-weapons states, "Why are there so few nuclear weapons states?"[2] Even Kenneth Waltz, proliferation's most ardent advocate, has pointed out that the spread of nuclear weapons has been "glacial."[3] On the other side, disarmament has also failed to catch on, with only one case of a state (South Africa) that truly possessed nuclear weapons. The nuclear proliferation–nonproliferation balance appears to exhibit what Robert Jervis termed "quasi-homeostasis," in which negative feedback "often reduces the amount of change

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[1] For their helpful feedback, I would like to thank the participants of Working Group 6 (Nuclear Disarmament and Non-Proliferation) at the first and second first annual conferences of the Alva Myrdal Centre for Nuclear Disarmament at Uppsala University in Uppsala, Sweden

[2] Jacques E. C. Hymans, *The Psychology of Nuclear Proliferation: Identity, Emotions, and Foreign Policy* (Cambridge University Press, 2006), 4–8.

[3] Scott Sagan, Kenneth Waltz, and Richard K. Betts, "A Nuclear Iran: Promoting Stability or Courting Disaster?" *Journal of International Affairs* 60, no. 2 (Spring/Summer 2007): 136, https://www.jstor.org/stable/24357975.

that occurs as actors respond to each other."[4] Interactions between regimes, proliferators, nonproliferators, and technologies are complex and so can produce outcomes that are not reducible to individual factors alone. Understanding the effects of technology spread requires examining countervailing forces at each stage of the process.

In this essay, I first examine the barriers to the successful spread of proliferation-relevant technologies across four stages: diffusion, adoption, integration, and stabilization. I next use a case study of the A.Q. Khan network to demonstrate how diffusion can actually slow proliferation due to feedback loops. I then turn to emerging technologies, analyzing how AM, AI, and RS may have little net effect on the proliferation–nonproliferation balance. I conclude with implications for scholarship and policy.

Barriers to the Spread of Technologies

Proliferation, spread, and diffusion are often used interchangeably and confusingly in the nuclear weapons literature. Since *proliferation* commonly refers to the acquisition of nuclear weapons by additional states, I use *spread* here as the more generic term for actors acquiring and employing technologies. In Figure 1, I divide spread into four stages: *diffusion* is where new users gain access to a technology, *adoption* refers to users putting that technology into production or widespread use, *integration* involves altering existing systems to incorporate the technology, and *stabilization* takes into account countervailing efforts by other agents to contain or roll back spread.

Each of these stages involves processes that present different challenges to effective spread; initial diffusion does not guarantee successful adoption or integration.[5] Technologies may also diffuse and be adopted or integrated for purposes other than proliferation or nonproliferation. Even if integration occurs, countervailing action may minimize or eliminate the effects. Consequently, looking at net rather than initial effects is required to assess the impact of technologies.

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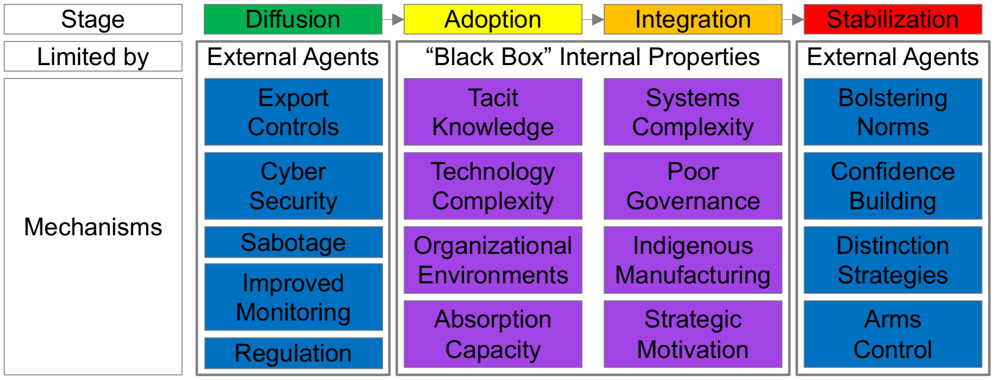
[4] Robert Jervis, *System Effects: Complexity in Political and Social Life* (Princeton, UNITED STATES: Princeton University Press, 1997).

[5] This discussion of invention, innovation, diffusion, adoption, and technologies is adapted from Alexander H. Montgomery, "Double or Nothing? The Effects of the Diffusion of Dual-Use Enabling Technologies on Strategic Stability," Center for International and Security Studies at Maryland, July 2020, https://cissm.umd.edu/research-impact/publications/double-or-nothing-effects-diffusion-dual-use-enabling-technologies.



Stage	Diffusion	Adoption	Integration	Stabilization
Limited by	External Agents	"Black Box" Internal Properties		External Agents
Mechanisms	Export Controls	Tacit Knowledge	Systems Complexity	Bolstering Norms
	Cyber Security	Technology Complexity	Poor Governance	Confidence Building
	Sabotage	Organizational Environments	Indigenous Manufacturing	Distinction Strategies
	Improved Monitoring	Absorption Capacity	Strategic Motivation	Arms Control
	Regulation			

Figure 1: Four stages of the spread of proliferation-relevant technologies along with mechanisms that limit effects.

Figure 1 shows the impediments to successful spread that occur at each stage. I focus first on the two middle stages, examining the internal dynamics of adoption and integration to open the "black box" of proliferation. Adoption can be limited by tacit knowledge requirements, the inherent complexity of a technology, and the user's existing organizational environments and absorption capacity. Technological inventions (novel ways about how to accomplish tasks) typically diffuse in the form of artifacts (devices) and/or explicit knowledge (e.g., blueprints or instructions), but do not typically include the *tacit knowledge* (i.e., things that we know but cannot express in explicit forms) required to comprehend or even operate the invention successfully.[6] High tacit knowledge requirements significantly limit the effectiveness of diffusion of any technology, including nuclear weapons.[7] Additionally, *technology complexity* increases the likelihood of error when adopting a technology since mistakes are easy to make and difficult to diagnose. Complexity is a feature of many proliferation-relevant technologies, including fissile materials production, nuclear weapons manufacturing, and warhead miniaturization. Diffused inventions from another actor, whether partial or complete, are difficult to adopt because they rely on conditions specific to the

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[6] As we are all too aware, many devices are at best partially useful without their instructions and often entirely useless without them. Tacit knowledge (such as knowing how to program a computer, ride a bicycle, or design nuclear weapons) cannot be explained but must be learned through practice. Michael Polanyi, *The Tacit Dimension* (Doubleday, 1966).

[7] Michael Aaron Dennis, "The Less Apparent Component—Tacit Knowledge as a Factor in the Proliferation of WMD: The Example of Nuclear Weapons," *Studies in Intelligence* 57, no. 3 (September 2013), https://www.cia.gov/library/center-for-the-study-of-intelligence/csi-publications/csi-studies/studies/vol-57-no-3/the-less-apparent-component2014tacit-knowledge-as-a-factor-in-the-proliferation-of-wmd-the-example-of-nuclear-weapons.html; Donald MacKenzie and Graham Spinardi, "Tacit Knowledge, Weapons Design, and the Uninvention of Nuclear Weapons," *American Journal of Sociology* 101, no. 1 (1995): 44–99, https://doi.org/10.1086/230699; Alexander H. Montgomery, "Ringing in Proliferation: How to Dismantle an Atomic Bomb Network," *International Security* 30, no. 2 (2005): 153–87, https://doi.org/10.1162/016228805775124543.

original actor's context that are often incompatible with the adopter's environment.[8] This creates a poor fit with existing *organizational environments* if they lack a sufficient educational, technological, and industrial base, including indigenous materials, supporting technologies, and domestic expertise. For example, proliferation-relevant technology that relies on embedded assumptions about easy access to aluminum manufacturing facilities, precision engineering, or engineers may thus fail to speed or even impede proliferation. Finally, diffusion may end up placing actors on suboptimal or even retrograde technological trajectories when they lack the general institutional factors that are needed to successfully adopt an invention (aka *absorption capacity*)[9], including financial ability, capital, an ability to focus and experiment, and organizational maturity.[10]

Even if a technology is adopted, it may not be successfully integrated due to systems complexity, poor governance, a lack of strategic motivation, or institutional resistance (such as from notoriously conservative military establishments). *Systems complexity* can be a barrier, since the more complex the system, the more difficult it is to reorganize it to incorporate new technologies. Nuclear weapons programs, by the nature of the tasks they need to complete, are organized as complex large technical systems—spatially extended and functionally integrated socio-technical networks.[11] A nuclear weapons program designed around one form of fissile materials production such as gaseous diffusion may find it difficult to pivot to a different option such as centrifuges, or even to switch to a different method of diffusion. Failure to integrate is also related to regime type—for example, neopatrimonial and personalistic regimes (except for military ones) seem to pursue nuclear weapons at a greater rate but succeed less often due to *poor*

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[8] Najmedin Meshkati, "Technology Transfer to Developing Countries: A Tripartite Micro- and Macroergonomic Analysis of Human-Organization-Technology Interfaces," *International Journal of Industrial Ergonomics* 4, no. 2 (September 1989): 101–15, https://doi.org/10.1016/0169-8141(89)90038-3.

[9] Alexander H. Montgomery and Tristan Volpe, "Hiding in Plain Sight? The Effect of Nuclear-Enabling Technologies on Strategic Surprise" (58th Annual Convention of the International Studies Association, Baltimore, MD, 2017). Also referred to as adoption capacity or enterprise capacity.

[10] Michael C. Horowitz, *The Diffusion of Military Power: Causes and Consequences for International Politics* (Princeton University Press, 2010), 30–39.

[11] Renate Mayntz and Thomas Parke Hughes, eds., *The Development of Large Technical Systems*, Publications of the Max-Planck-Institut Für Gesellschaftsforschung, Köln (Frankfurt am Main : Boulder, Colo: Campus Verlag ; Westview Press, 1988), 5. A lengthier definition is also given in the introduction: "…systems of machineries and freestanding structures performing, more or less reliably and predictably, complex standardized operations by virtue of being integrated with other social processes, governed and legitimated by formal, knowledge-intensive, impersonal rationalities." Bernward Joerges, "Large Technical Systems: Concepts and Issues," in *The Development of Large Technical Systems*, ed. Renate Mayntz and Thomas P. Hughes (Westview Press, 1988), 23–24.

governance.[12] Without the ability to implement *indigenous manufacturing*, actors are dependent on foreign suppliers, which can slow progress. Those who seek assistance are often those who are least well-placed to receive it, potentially resulting in little or no net change.[13] Finally, states may partially adopt a technology (or set of technologies) but due to lack of sufficient *strategic motivation* may put little effort into integrating them. Lack of motivation is inherently difficult to study, but appears to have been a significant influence in keeping a number of nuclear weapons programs at the "exploration" phase (Japan, Switzerland, Sweden, Australia, West Germany) or a limited "pursuit" phase (Brazil, Argentina) due to a lack of a clear motivation for continuing any further.[14]

These internal mechanisms that hinder adoption and integration are complemented by the external reactions that limit diffusion and act to stabilize the environment. Initial diffusion can be limited through export controls, cyber security, sabotage, improved monitoring, or better domestic or international regulation surrounding the use or diffusion of technologies. After diffusion, limiting the effects of spread can be achieved through bolstering norms, adopting confidence building measures, using distinction strategies, or implementing arms control. These external mechanisms can interact significantly with internal ones: e.g., sabotage and export controls can hinder integration of centrifuges if indigenous manufacturing proves difficult. Internal mechanisms often interact as well; for example, the organizational environment determines how much the complexity of a technology affects its integration into existing systems.

Diffusion of technologies, particularly dual-use ones, may (and often do) affect both the proliferation process *and* nonproliferation efforts by actors and institutions

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[12] Christopher Way and Jessica Weeks, "Making It Personal: Regime Type and Nuclear Proliferation," *American Journal of Political Science* 58, no. 3 (July 2014): 705–19, https://doi.org/10.1111/ajps.12080; Alexander H. Montgomery, "Stop Helping Me: When Nuclear Assistance Impedes Nuclear Programs," in *The Nuclear Renaissance and International Security*, ed. Adam N. Stulberg and Matthew Fuhrmann (Stanford University Press, 2013), 177–202; Lisa Langdon Koch, "Military Regimes and Resistance to Nuclear Weapons Development," *Security Studies* 32, no. 2 (May 10, 2023): 239–70, https://doi.org/10.1080/09636412.2023.2197621; Malfrid Braut-Hegghammer, *Unclear Physics: Why Iraq and Libya Failed to Build Nuclear Weapons*, 1st edition (Cornell University Press, 2016); Jacques E. C. Hymans, *Achieving Nuclear Ambitions: Scientists, Politicians and Proliferation* (Cambridge University Press, 2012).

[13] Montgomery, "Stop Helping Me."

[14] Philipp C. Bleek, "Why Do States Proliferate? Quantitative Analysis of the Exploration, Pursuit, and Acquisition of Nuclear Weapons," in *Forecasting Nuclear Proliferation in the 21st Century: Volume 1, the Role of Theory*, ed. William C Potter and Gaukhar Mukhatzhanova (Stanford University Press, 2010), 159–92. Note that these general codings conceal a great deal of variation, e.g., Sweden's program was much more advanced than Japan's initial research. Thomas Jonter, *The Key to Nuclear Restraint* (Palgrave Macmillan UK, 2016), https://doi.org/10.1057/978-1-137-58113-6.

simultaneously, further complicating the process of determining the net effects of diffusion. For example, artificial intelligence could assist with proliferation through rapid prototyping of centrifuge components but could also help nonproliferation via identification of likely centrifuge production sites.

Technology Diffusion and Nuclear Weapons Proliferation

Diffusion of "sensitive" technologies (including uranium enrichment, plutonium reprocessing, and weapons designs), should aid proliferation. These kinds of transfers occurred at least fourteen times between 1958 and 2002.[15] Yet the success of these transfers has been limited, with the causes for failure ranging from regime type and lack of oversight to normative influence.[16] In order to illustrate the mechanisms that limit the effectiveness of technology spread, I focus here on a most-likely case for diffusion success: the A.Q. Khan network. A typical account of the network argues that A.Q. Khan stole centrifuge plans from Urenco (a European nuclear fuel consortium), created a network that lowered the barriers to nuclear weapons programs by offering a "Nuclear Wal-Mart,"[17] assisted Iran, Libya, and North Korea, and ended up accelerating nuclear proliferation.[18] The details of the dynamics of the A.Q. Khan network, however, tell a different story.

Khan stole centrifuge plans for a design that was abandoned by Urenco even before he stole them.[19] The plans were incomplete and inaccurate,[20] and did not come with the *tacit knowledge* of the designers as to, for example, why they decided to use certain materials rather than others as well as why certain dimensions or tolerances were chosen. Trying to use this multi-rotor, supercritical centrifuge with connecting bellows increased *technology complexity*. Libya and Iran inherited these same difficulties. The *organizational environment* and low *absorption capacity* inhibited domestic production in Pakistan and required the formation of a vulnerable network, derailing plans for a

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[15] Matthew Kroenig, *Exporting the Bomb: Technology Transfer and the Spread of Nuclear Weapons* (Cornell University Press, 2010).

[16] Braut-Hegghammer, *Unclear Physics*; Hymans, *Achieving Nuclear Ambitions*; Montgomery, "Stop Helping Me"; Maria Rost Rublee, *Nonproliferation Norms: Why States Choose Nuclear Restraint* (University of Georgia Press, 2009).

[17] Christopher Clary, "Dr. Khan's Nuclear WalMart," *Disarmament Diplomacy* 76 (April 2004), http://www.acronym.org.uk/dd/dd76/76cc.htm.

[18] Kroenig, *Exporting the Bomb*.

[19] R. Scott Kemp, "The Nonproliferation Emperor Has No Clothes," *International Security* 38, no. 4 (Summer 2014): 65, https://doi.org/10.1162/ISEC_a_00159.

[20] Mansoor Ahmed, *Pakistan's Pathway to the Bomb: Ambitions, Politics, and Rivalries* (Georgetown University Press, 2022), 119, https://doi.org/10.2307/j.ctv27qzs9k.

simpler single-rotor subcritical centrifuge.[21] As far as the Iranians and Libyans were concerned on these measures, Khan himself said that they "didn't have the required infrastructure, the trained manpower or technical know-how."[22] When the subcritical centrifuge efforts were abandoned in favor of Khan's plans, all of the uranium enrichment plans had to be changed, causing delays. Scott Kemp estimates that the eventual Pakistani centrifuge design took six years to complete, versus the average of two years for indigenous, subcritical programs.[23] *Systems complexity* also worked against Iran, which recognized that the original centrifuge was a poor design, but was unable to test its first centrifuge based on a new design until 2009.[24] The Pakistani program suffered from *poor governance*, with deleterious competition between the plutonium and uranium enrichment programs as well as little to no oversight of A.Q. Khan; the Libyan and Iranian programs were hardly models of good governance, either.[25] Pakistan, Libya, and Iran were all slow to create *indigenous manufacturing*. Incomplete plans and used and broken parts for a weak centrifuge with no tacit knowledge or quality control meant that indigenization barriers were quite high. Libya also suffered from a lack of clear *strategic motivation*: the nuclear program may have been intended as a bargaining chip as much as anything else.[26]

Since the centrifuges all used the same parts, it created an external negative feedback loop via a new set of indicators and warnings that led to better *export controls*, *improved monitoring*, and new *regulations*. The US and UK intelligence agencies knew that Khan was shipping technology to Libya by 2000 and had so extensively infiltrated the network that the famous interception of the German-owned ship BBC China in 2003 was enabled by tracking the parts it carried all the way from the original factory. The network was only allowed to last until it seemed to be dangerous, at which point it was shut down.[27] When the supplier network was discovered, it exposed not just Pakistan's program but aspects of the recipient countries' plans as well. Knowledge of the systems aided the *sabotage* of Iran's uranium production, including the famous Stuxnet virus.

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[21] Ahmed, *Pakistan's Pathway to the Bomb*, 85.

[22] Joshua Pollack, "The Secret Treachery of A.Q. Khan," *Playboy*, February 2012, 12.

[23] Kemp, "The Nonproliferation Emperor Has No Clothes," 66.

[24] Frederik Voûte and Valerie Lincy, "Beyond the IR-1: Iran's Advanced Centrifuges and Their Lasting Implications" (Wisconsin Project on Nuclear Arms Control, November 2021), https://www.iranwatch.org/sites/default/files/beyond_the_ir-1_pdf_draft_3_1.pdf.

[25] Braut-Hegghammer, *Unclear Physics.*

[26] John Prados, "How Qaddafi Came Clean," *Bulletin of the Atomic Scientists* 61, no. 6 (December 2005): 30, https://doi.org/10.2968/061006011.

[27] Christopher O. Clary, "The A.Q. Khan Network: Causes and Implications: Thesis" (Monterey, CA, Naval Postgraduate School, 2005), 84, http://hdl.handle.net/10945/1833.

These indicators and warnings, in turn, made it possible to cut deals, since some of the nuclear programs were either small (Iran) or nonexistent (Libya).

The North Korean nuclear success would seem to be a different story, since they indigenized centrifuge designs, although not until after they ordered aluminum tubes with tell-tale dimensions,[28] a key piece of intelligence that, if handled better, could have constrained the program. They made better choices than the Iranians and Libyans, selecting the superior Pakistani P-2 design as the basis for their program and moving quickly to manufacture the parts for it domestically, probably by 2009.[29] While this no doubt has contributed to the size of North Korea's stockpile, the 2006 North Korean test used plutonium rather than highly enriched uranium for its core, and so Khan's network did not materially accelerate North Korea's initial weapons test.

Indeed, the net effect of the diffusion of centrifuges is a nonproliferation success: the dual effect of the adoption and integration problems and the creation of indicators and warnings slowed the programs. A sensitive technology that should have been unambiguously bad for nonproliferation turned out instead to aid the cause. This outcome is due to a complex set of interactions between the technology (complicated and demanding), the countries (which sought shortcuts due to a lack of confidence in their domestic production capabilities and the lure of get-nukes-quick), opposing countries (who used the indicators and warnings to undermine the effectiveness of, and eventually shut down, the procurement network), and international regimes more broadly (which promulgated export controls that made procurement difficult).

Emerging Technologies and Proliferation

If the diffusion of sensitive technologies such as centrifuges actually slowed proliferation, the case for dual-use emerging technologies accelerating it is significantly weakened. Emerging technologies are generally considered to be novel, fast-growing, and likely to have significant future (but uncertain) impacts.[30] The digitization of these technologies makes their diffusion much more difficult to control.[31] Nonetheless, they

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[28] Montgomery, "Ringing in Proliferation," 161.

[29] Stephan Haggard, "Kemp and Pollack on North Korean Enrichment," *North Korea: Witness to Transformation* (blog), October 2, 2013, https://www.piie.com/blogs/north-korea-witness-transformation/kemp-and-pollack-north-korean-enrichment.

[30] Daniele Rotolo, Diana Hicks, and Ben R. Martin, "What Is an Emerging Technology?," *Research Policy* 44, no. 10 (December 1, 2015): 1828, https://doi.org/10.1016/j.respol.2015.06.006.

[31] Amy J. Nelson, "Innovation Acceleration, Digitization, and the Arms Control Imperative," SSRN Scholarly Paper (Rochester, NY: Social Science Research Network, March 26, 2019), https://papers.ssrn.com/abstract=3382956.

face the same barriers to adoption and integration as well as some of the same countervailing forces as sensitive technologies.

Additive Manufacturing

Enthusiasts and doomsayers alike see AM as a technology that will quickly diffuse, revolutionizing the manufacturing of everything from conventional weapons to nuclear weapons, writing articles with titles such as "You Can Print Your own Guns at Home. Next it Will be Nuclear Weapons. Really."[32] However, as one assessment put it, "ideas regarding the performance, potential applications and impacts of AM technologies are manifold and often highly exaggerated." The adoption of AM presents difficulties due to problems with constructing larger components, low build-up rates, manual upstream and downstream production steps, and lack of knowledge of the properties of printed components compared to traditionally machined ones.[33]

AM may make it easier for facilities to be hidden (since eliminating waste streams removes a significant source of indicators and warnings) and for proliferators to circumvent sanctions.[34] Additionally, AM may lower the barriers to entry, or accelerate traditional development pathways.[35] However, the indicators and warnings problem due to the lack of waste streams mainly applies to actual pit production, which is not the most likely route to discovery of a clandestine program. A building full of AM centrifuges will give off as much heat as a building full of conventionally-manufactured ones, a signature that allowed for the probable discovery of North Korea's Kangson covert uranium enrichment site.[36] It may also provide for new indicators and warnings:

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[32] Daniel C. Tirone and James Gilley, "You Can Print Your own Guns at Home. Next it Will be Nuclear Weapons. Really.," *Washington Post: Monkey Cage* (blog), September 7, 2015, http://www.washingtonpost.com/blogs/monkey-cage/wp/2015/09/07/you-can-print-your-own-guns-at-home-next-it-will-be-nuclear-weapons-really/.

[33] Office of Technology Assessment at the German Bundestag, "Additive Manufacturing (3D Printing)," TAB Policy brief, September 18, 2017, 1, https://www.tab-beim-bundestag.de/en/news/20170918.html.

[34] Kelsey Atherton, "In the Future, Iran Could 3D-Print Its Way around Sanctions," *C4ISRNET* (blog), May 9, 2018, https://www.c4isrnet.com/it-networks/2018/05/09/in-the-future-iran-could-3d-print-its-way-around-sanctions/; Michael Lucibella, "Manufacturing Revolution May Mean Trouble for National Security," American Physical Society, April 2015, https://www.aps.org/publications/apsnews/201504/revolution.cfm.

[35] Tristan A. Volpe, "Dual-Use Distinguishability: How 3D-Printing Shapes the Security Dilemma for Nuclear Programs," *Journal of Strategic Studies* 42, no. 6 (September 19, 2019): 820, https://doi.org/10.1080/01402390.2019.1627210.

[36] Ankit Panda, "Exclusive: Revealing Kangson, North Korea's First Covert Uranium Enrichment Site," *The Diplomat* (blog), July 13, 2018, https://thediplomat.com/2018/07/exclusive-revealing-kangson-north-koreas-first-covert-uranium-enrichment-site/.

unless key materials can be indigenized, orders of certain powders such as maraging steel will provide warnings where orders of (some) aluminum tubes did in the past.[37]

While the printing of weapons-grade materials into a pit for a nuclear weapon is clearly out of reach for the present,[38] some of the components of systems that produce fissile materials could be made using AM. While the build files for these components are digital and consequently easier to spread and the machines are not (yet) export-controlled, the tacit knowledge and machinery requirements for AM are quite high,[39] and some of the powders required are already controlled.[40] Moreover, the ease of spreading digital files cuts both ways, since (if detected) it serves to augment existing indicators and warnings regarding the intentions of potential proliferators. While advanced nuclear weapons states such as the United States may benefit from AM,[41] the barriers to entry make it more likely that vertical rather than horizontal proliferation is the major risk posed by diffusion of AM. Currently, there is no evidence that AM has increased the risk of weapons of mass destruction (WMD) proliferation by state or non-state actors.[42]

AM could, in fact, help to contribute to nonproliferation—if states choose strategies to clearly signal that they are employing dual-use technologies for civilian purposes. Signaling could occur through accepting an intrusive monitoring regime, allowing dependence on foreign suppliers, or employing third parties to underwrite

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[37] The North Korean apparent order of aluminum tubes for their P-2-based centrifuges turned out to be a good indicator—samples they gave the U.S. government had highly enriched uranium on them: see Siegfried S. Hecker, "Denuclearizing North Korea," *Bulletin of the Atomic Scientists* 64, no. 2 (May 2008): 46–47, https://doi.org/10.1080/00963402.2008.11461145. The Iraqi order of aluminum tubes that were actually for rocket motors was, well, not: see David Albright, *Iraq's Aluminum Tubes: Separating Fact from Fiction*, 2003, http://www.isis-online.org/publications/iraq/IraqAluminumTubes12-5-03.pdf.

[38] Although the U.S. national labs have already indicated some success with reactive and radioactive powders, including a Uranium-Niobium alloy. See Melissa Marggraff, "Next-Generation Manufacturing for the Stockpile," *Science and Technology Review*, January 2015, 4–11, https://str.llnl.gov/january-2015/marrgraff.

[39] Grant Christopher, "3-D Printing: A Challenge to Nuclear Export Controls," *Strategic Trade Review* 1, no. 1 (2015): 21, https://strategictraderesearch.org/wp-content/uploads/2017/09/2_3D_Printing_A_Challenge_to_Nuclear_Export_Controls.pdf.

[40] Amy J. Nelson, "The Truth About 3-D Printing and Nuclear Proliferation," *War on the Rocks* (blog), December 14, 2015, https://warontherocks.com/2015/12/the-truth-about-3-d-printing-and-nuclear-proliferation/.

[41] Bruce T Goodwin, "Additive Manufacturing and Nuclear Security: Calibrating Rewards and Risks," (Center for Global Security Research, Lawrence Livermore National Laboratory, November 2019).

[42] Robert Shaw et al., eds., *Evaluating WMD Proliferation Risks at the Nexus of 3D Printing and Do-It-Yourself (DIY) Communities* (James Martin Center for Nonproliferation Studies (CNS), 2017), https://www.jstor.org/stable/resrep17539.

nonproliferation commitments.[43] Additionally, it may allow advanced states with strong enterprise capacity to follow policies of restraint: the deterrence value of demonstrating a strong AM capacity while remaining a non-nuclear weapons state may be greater than the value of break-out.[44]

Artificial Intelligence and Remote Sensing

Whereas AM initially appears to benefit proliferation, AI and RS at first glance show an initial tendency to benefit nonproliferation. Recent work on the intersection of AI and nonproliferation has shown a great deal of promise, although success rates in pilot studies have varied. For example, some attempts at using machine learning to identify proliferation-relevant activities from open source news articles resulted in a failure to spot known proliferation risks.[45] While optimism about the potential uses of AI is widespread, practical applications of AI to nonproliferation will require designing systems to meet the needs of the nonproliferation community rather than re-use of off-the-shelf systems for nonproliferation purposes.[46] Moreover, the fragility of AI and its lack of transparency may decrease confidence in AI-generated results.[47] AI can also be used by actors to create deepfakes and sow disinformation, creating potential cover for proliferants.

RS technologies appear to benefit nonproliferation as well. Even with the relative stealth of centrifuge programs,[48] facilities can be located through open-source methods due to advances in these technologies and the ability to crowdsource intelligence collection.[49] Open-source analysts have readily identified North Korean launch sites (as well as their

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[43] Volpe, "Dual-Use Distinguishability," 825.

[44] Montgomery and Volpe, "Hiding in Plain Sight? The Effect of Nuclear-Enabling Technologies on Strategic Surprise."

[45] Jeffrey A. Pike et al., "Machine Learning Using Open Data Sources for Detection of Nuclear Proliferation Activities (U)," (Savannah River Site (SRS), Aiken, SC (United States). Savannah River National Lab. (SRNL), January 3, 2021), https://doi.org/10.2172/1764825.

[46] Francis J. Alexander et al., "Workshop Report for Next-Gen AI for Proliferation Detection: Accelerating the Development and Use of Explainability Methods to Design AI Systems Suitable for Nonproliferation Mission Applications," (Brookhaven National Lab. (BNL), Upton, NY (United States); Idaho National Lab. (INL), Idaho Falls, ID (United States); National Nuclear Security Administration (NNSA), Washington, DC (United States), September 15, 2020), https://doi.org/10.2172/1768761.

[47] Jane Vaynman, "Better Monitoring and Better Spying: The Implications of Emerging Technology for Arms Control," *Texas National Security Review* 4, no. 4 (Fall 2021), https://doi.org/10.26153/TSW/17498.

[48] Kemp, "The Nonproliferation Emperor Has No Clothes."

[49] Melissa Hanham et al., "Geo4nonpro.Org: A Geospatial Crowd-Sourcing Platform for WMD Verification," CNS Occasional Paper 28 (Middlebury Institute of International Studies at Monterey, June 2017), https://www.jstor.org/stable/resrep19698.

failures and successes),[50] and found new Chinese ICBM fields in the Gobi desert.[51] Remote sensing can also be combined with AI to improve detection, since machine learning can identify potential anomalies in datasets that can be checked by humans. However, while RS may increase transparency, it can also inform clandestine proliferators what kinds of facilities are easily discovered, allowing them to adapt and improve their camouflaging strategies. Moreover, some kinds of RS (small satellites) are often more transparent than others (drones).[52] Adoption of RS technologies can also have significant unintended consequences: Although drone proliferation is already rampant,[53] the level of sophistication varies across countries, and the acquisition of advanced drone technologies may occur through unlikely channels—such as when they are shot down in an adversary's airspace.[54] Small satellite constellations can have their own perverse consequences, such as undermining the ability to detect potentially harmful meteors.[55]

Implications

The challenges to nonproliferation presented by emerging technologies must be considered in the context of previous challenges. The discovery of new proliferation pathways has frequently led to counter-reactions that strengthen the nonproliferation regime. For example, the nuclear export control regime has been bolstered multiple times after significant lapses, particularly after the discovery of Iraq's clandestine program after the Gulf War and the A.Q. Khan network.[56] We should expect similar reactions should any of these emerging technologies significantly lower the barriers to proliferation, continuing the general tendency of the struggle between proliferation and nonproliferation towards quasi-homeostasis. Technology does not inherently help or

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[50] Zach Dorfman, "True Detectives," May 2018, http://middleburymagazine.com/features/true-detectives/.

[51] "Open-Source Intelligence Challenges State Monopolies on Information," *The Economist*, August 2021, 12, https://www.economist.com/briefing/2021/08/07/open-source-intelligence-challenges-state-monopolies-on-information.

[52] Vaynman, "Better Monitoring and Better Spying."

[53] Michael Horowitz, Joshua A Schwartz, and Matthew Fuhrmann, "Who's Prone to Drone? A Global Time-Series Analysis of Armed Uninhabited Aerial Vehicle Proliferation," *Conflict Management and Peace Science* 39, no. 2 (March 1, 2022): 119–42, https://doi.org/10.1177/0738894220966572.

[54] H. I. Sutton, "Iran Rebuilds U.S. Navy Global Hawk UAV It Shot Down," Forbes, July 14, 2020, https://www.forbes.com/sites/hisutton/2020/07/14/shot-down-us-navy-global-hawk-reconstructed-by-iran/.

[55] Dvida, "Starlink Satellite Constellation – Possible Interference with Meteor Observations?," *Global Meteor Network* (blog), November 25, 2019, https://globalmeteornetwork.org/?p=570.

[56] Jacob Blackford, "Multilateral Nuclear Export Controls After the A.Q. Khan Network," (Institute for Science and International Security, August 2, 2005), http://www.isis-online.org/publications/expcontrol/multilateralexportcontrols.pdf.

hinder proliferation: properties of technologies, their users, and countervailing efforts need to be examined to gain insight into the effects of diffusion.

Simple measures can be taken to limit such effects even now, such as implementing export controls on specialized AM equipment that can be used to produce large, complex components.[57] As one publication put it, "An approach to prevent a possible proliferation of armament technologies by means of AM technologies could consist in making the export of at least particularly powerful systems and associated materials subject to authorisation."[58] Improved monitoring of end-use cases for legally exported emerging technologies would raise barriers to repurposing those technologies for proliferation purposes. The lowest-cost improvements in this area may lie in aiding countries that can or have adopted recent emerging technologies but do not yet have strong export controls. Decisions to restrict, however, must be made strategically, taking into consideration alternate paths to diffusion that might be used instead by proliferators. Will implementing export controls simply send signals that indicate that such equipment is strategically valuable and therefore desirable? Or do exports produce strategic leverage in other ways through inducing dependence on supplies; discouraging domestic invention, innovation, and production; enabling monitoring; or opening opportunities for sabotage?[59]

Digitized, dual-use emerging technologies, such as additive manufacturing, artificial intelligence, and remote sensing, are diffusing. Fortunately, the barriers to adoption are high, the benefits for nonproliferation may be significant, and the strategies for countering any benefits to proliferation are many. There are low-hanging policy options to address diffusion, including export controls, cyber security, sabotage, improved monitoring, and regulation as well as efforts to stabilize outcomes after diffusion through bolstering norms, confidence building, distinction strategies, and arms control.

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[57] Nelson, "The Truth About 3-D Printing and Nuclear Proliferation."

[58] Office of Technology Assessment at the German Bundestag, "Additive Manufacturing (3D Printing)," https://www.tab-beim-bundestag.de/en/news/20170918.html.

[59] I thank Richard Danzig for pointing out the need to consider the net effects of implementing such controls.

Biographical Sketch

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