Matthew Kroenig and Tristan Volpe

3-D Printing the Bomb? The Nuclear Nonproliferation Challenge

A revolution in manufacturing is underway that may enable the most sensitive pieces of a nuclear weapons program to be transferred and produced around the globe. In the Additive Manufacturing (AM) process, 3-D printing machines build objects of virtually any shape from digital build files—the essential data telling printers how to construct an object—by laying down successive layers of material.[1] Since objects are built from scratch, one can make products in shapes and to standards impossible under any other method, and the digital nature of this automated process takes most of the skill out of fabrication. AM allows the manufacture of better products, with less effort, and at a fraction of the cost of traditional methods. As a result, it is hardly surprising that General Electric, Aerojet Rocketdyne, and the Chinese People's Liberation Army are already using AM to print sophisticated metal parts for jet engines, rocket propulsion systems, and fighter aircraft, respectively.[2]

Like many disruptive technologies, however, AM has a dark side. The widespread adoption of AM will make it easier for countries to acquire nuclear weapons, and more difficult for the international community to detect and stop them. If building the bomb is like solving a giant jigsaw puzzle, one of the hardest parts is simply getting all the necessary pieces.[3] Attempts to buy or build

Matthew Kroenig is Associate Professor of Government and Foreign Service at Georgetown University, a Senior Fellow at the Brent Scowcroft Center on International Security at The Atlantic Council, and author of *Exporting the Bomb: Technology Transfer and the Spread of Nuclear Weapons* (Ithaca: Cornell University Press, 2010). Follow him on Twitter at @kroenig or email him at matthew.kroenig@georgetown.edu. Tristan Volpe is a Stanton Nuclear Security Fellow and an associate in the Nuclear Policy Program at the Carnegie Endowment for International Peace. Email him at tvolpe@ceip.org or follow him on Twitter at @teeandersvolpe.

The Washington Quarterly • 38:3 pp. 7–19
http://dx.doi.org/10.1080/0163660X.2015.1099022

these items—such as the components of a gas centrifuge—are fraught with obstacles and set off alarm bells to the existence of a covert weapons program. In contrast, with a 3-D printer and the right digital build files, a country can print many of the specialized components for a nuclear program quickly, with little technical skill, and at low cost. Moreover, hiding such a fabrication effort would be much easier than under traditional manufacturing methods, rendering obsolete many of the international community's tools for spotting illicit nuclear activity. In short, AM may provide a way for countries to print the pieces of the nuclear jigsaw indigenously before anyone notices.

3-D printing will render obsolete many of the tools for spotting illicit nuclear activity.

Fortunately, the proliferation potential of AM has not yet fully materialized, so the United States can still lead an international effort to prevent an AM-enabled cascade of nuclear weapons proliferation before it is too late. This multifaceted problem demands a strategy that combines the bottom-up efforts of expert working groups and top-down attention from the highest levels of national governments and international organizations. Together, they can work to create new multilateral frameworks, update existing control regimes, and develop technical fixes that will allow the world to reap the benefits of AM while mitigating its proliferation dangers.

The Allure of Printing Anything, Anywhere, Anytime

Additive Manufacturing (AM) harnesses major innovations in robotics, digital computing, and the flow of global information over the Internet to give its users the ability to "make (almost) anything, anywhere," to use the words of Neil Gershenfeld in a recent article.[4] Contemporary 3-D printers create solid items in almost any form by depositing layer upon layer of metal, ceramic, or plastic powders. Each strata of material is then welded or melted together using a laser or electronic beam. This new method of building components from the ground up stands in contrast to traditional "subtractive" manufacturing. Since the Stone Age, humans have crafted objects by removing material from a larger block. The ancient Egyptians developed the first machines to facilitate this process. The modern metalworking lathe, for example, still follows the same basic principle employed in antiquity: spin a piece of metal along its axis so the operator can cut material away from it in a precise and controlled fashion to create, for example, a symmetrical baseball bat. A 3-D printer, however, frees engineers from this ancient method, thereby giving them the ability to dream up novel designs and print unique shapes at standards previously thought to be impossible.

Another important characteristic of AM is that a digital build file provides the 3-D printer with all the information it needs to make a final component. The digital nature of 3-D printing takes much of the skill out of fabricating precise components. Once the build program is loaded, the printer operates autonomously on a continuous basis. Subtractive machine shops require a team of skilled technicians to operate multiple and highly specialized machines, even when automated processes such as computer numeric control are employed to assist the human operators. Furthermore, AM simplifies logistics trains because there is no need to ship and store parts and virtually no waste; the end user can just download the digital file and print the component whenever and wherever it is needed.

The digital nature of 3-D printing takes much of the skill out of fabricating precise components.

While AM, more commonly known as 3-D printing, has been in the spotlight for its ability to produce plastic toys, artificial limbs, and even biotechnology, less noticed in the public sphere is its potential in advanced industrial production, including for items with sensitive defense and national security applications.[5] In March, *The Economist* reported that Rolls Royce plans to use AM to construct a critical part of its Trent XWB-97 jet engine.[6] GE followed suit by producing components for its Leap jet engine, which received Federal Aviation Administration certification.[7] Engineers at Airbus leveraged AM to produce titanium structural brackets for its A350 XWB aircraft.[8] Government agencies are also getting into this game. NASA astronauts onboard the International Space Station used a zero-gravity 3-D printer to fabricate a wrench from a digital build file transmitted from the ground in December 2014. And on the military side, the U.S. Department of Defense highlighted the introduction of AM into the U.S. defense acquisitions and manufacturing process as one way to maintain U.S. strategic capabilities in a constrained fiscal environment by boutique printing the sort of special parts needed in weapons platforms, rather than purchasing them in large batches.[9]

The AM process is attractive to the aerospace and defense sectors because it facilitates the production of precision components on demand and around the world far more cheaply (and often of higher quality) than with subtractive machines. Indeed, given 3-D printing's unique ability to cut costs, simplify logistics, and spur innovation, it is hard to overstate its upside potential; AM could lead to significant reductions in the U.S. defense and nuclear weapons budget, to a revival of U.S. manufacturing, and even to a worldwide manufacturing revolution.[10]

While much of AM's impact will be positive, it also presents a vexing threat to international security. Machines that can print an infinite range of precise metallic components from digital files obtained over the Internet are quite appealing to a country or non-state actor that wants to produce small arms, major conventional weapons systems, or even nuclear weapons.

The Next Chapter in Nuclear Proliferation

To build nuclear weapons, a state must first produce the fissile material that fuels the nuclear explosion either by enriching uranium or reprocessing plutonium from spent reactor fuel and then assembling this nuclear material into a functioning nuclear device.[11] Enrichment and reprocessing are difficult technical feats, made more complicated by the need to manufacture thousands of metal component parts to extremely high standards and very close tolerances at each stage, such as structures to hold the core of a nuclear reactor or the specially-designed rotating components of a gas centrifuge.[12]

At present, nuclear suppliers are likely to deny requests for turnkey enrichment or reprocessing facilities, or their key component parts, due to the proliferation risks. Stringent international export controls regulate the transfer of related materials and technology. Transfers of maraging steel or multi-axis computer numerical controlled lathes, for example, trigger close scrutiny because they can be used to produce the components in a uranium enrichment centrifuge. Even if they could acquire samples or designs for component parts, less developed countries need a long period of time for trial and error to master indigenous production processes. Iran's nuclear program provides a case in point: the Iranians took advantage of lax export controls and illicit supply networks to procure model centrifuges and centrifuge designs in 1987, but it took another fifteen years before Tehran broke ground on its first enrichment facility.[13]

Beyond the inherent technical challenges, international monitoring and response create further obstacles. Export controls slow down proliferators by forcing them to comb illicit procurement markets in relative secrecy and at great risk of discovery by the international community. Attempts to buy controlled items set off alarm bells to the existence of a covert weapons program, thereby giving the international community time to respond.

Compare this to the realities made possible by AM. At present, an aspiring proliferator can purchase a state-of-the-art 3-D printer on the open market for about $1 million and the powders that form the raw material of the AM process for only thousands more. This presents a serious challenge for international technology controls, made worse by the fact that much of the information needed to print a component is contained in digital build files. Whereas traditional machining with lathes or grinders requires substantial skill and tacit knowledge to produce a finished piece, an unskilled technician can print perfect components once the materials and relevant design files are in hand.

Accessing the necessary files will not be as challenging as one might think. The United States and China are already using AM in their defense industries, and other countries will likely follow suit—meaning that sensitive build files already, or will soon, exist. While government and private contractor databases present tough targets for cyber theft, they are not impenetrable.[14] Beyond state-sponsored hacking, rogue "insiders" might be willing to release or sell critical files. At a minimum, nuclear suppliers might be more willing to export sensitive nuclear technology as a matter of policy because it would be much easier to hide their fingerprints.[15] Alternatively, aspiring proliferators could get their hands on a single model, or even high-quality photographs, of the necessary part and digitally scan it to reverse-engineer a build file.[16]

To make matters worse, it will be much more difficult for the international community to detect and respond to such a production program because a 3-D printer is the ultimate manifestation of dual-use technology. While the purchase of specialized lathes may trigger export controls, anyone can freely buy a cutting-edge 3-D metal printer and associated metal powders on the open market without raising alarm. AM provides a true general-purpose fabrication capability. The latest 3-D printers can make a wide range of components on a single machine, and even build multiple and completely different parts at the same time. Unlike the specialized lathes needed to make nuclear weapon components or low-noise submarine propellers, the purpose to which an AM machine will be put is unknowable.

A 3-D printer is the ultimate manifestation of dual-use technology.

The international community will also find it increasingly difficult to detect and respond to nuclear programs that utilize AM. Industrial 3-D printers are about the size of a commercial refrigerator, use little energy, and produce close to zero waste. Since the additive process eliminates the need for long production lines housed in large factories, a bevy of metal printers could be dispersed in various locations throughout a country. One could conceivably house a centrifuge-production program in garages, hiding signatures of suspect activity and rendering detection by international inspectors or national intelligence agencies much harder. Moreover, by simplifying the logistics train and relegating the transfer of technical designs to the digital realm, AM reduces the nodes that authorities monitor in order to regulate exports and interdict suspicious shipments around the globe. In short, 3-D printing may provide a way for countries to assemble all of the necessary components for a nuclear weapons production program while avoiding detection by the international community.

To be clear, there are limits to what an aspiring proliferator can accomplish with 3-D printing. AM does not yet offer the promise of printing the bomb from scratch. Even if a country already possessed significant quantities of highly-enriched uranium or plutonium, no country has, to our knowledge, demonstrated the ability to feed this fissile material into a 3-D printer to additively manufacture the core of a nuclear weapon. But we do not want to be caught by surprise down the road. Moreover, while the ability to print necessary parts in secret greatly enables a potential proliferator, it does not guarantee success. Would-be proliferators often run into other supply chain issues when they try to acquire restricted materials. Even with all the necessary materials and machines in place, proliferators may struggle to assemble all the pieces into a working fissile material production capability. The enrichment process in particular presents technical hurdles beyond production of the necessary parts, such as mastering the ability to produce UF6—or uranium hexafluoride, a key compound used in the uranium enrichment process to produce fuel for reactors and weapons—and then scaling up centrifuge cascades.[17] For example, Libya purchased complete P-1 centrifuges off the black market, but the program struggled to move beyond testing single machines.[18]

Moreover, AM may help a state to acquire the components needed for fissile material production in relative secrecy, but countries can still be unmasked as they move into the actual operation of facilities using these components. They can be caught, for instance, in the act of associated tasks of uranium mining, milling, purification, conversion, and enrichment. Similarly, the construction and operation of nuclear reactors rarely goes unnoticed. Even if a country prints everything needed for the front or back end of the nuclear fuel cycle, reactors or centrifuges will still give off tell-tale signatures, such as effluent waste, which make them prone to detection.[19]

In other words, 3-D printers will not make uranium conversion easier, plutonium less toxic to handle, or nuclear reactors any easier to hide. But this new manufacturing technology does promise to facilitate the procurement and production of necessary component parts that often took countries years to produce on their own or procure on the black and grey supply markets. AM thereby erodes an initial and important bulwark to the diffusion of sensitive nuclear fuel cycle technology.[20]

At present, the international community is concerned that Iran may use its known nuclear facilities to "break out" and build nuclear weapons. Ever since Saddam Hussein surprised the world by the extent of his secretive nuclear buildup in the 1990s, nonproliferation experts have also been concerned about a so-called "sneak out" scenario, in which a country secretly builds nuclear weapons using material from undeclared nuclear facilities.[21] In the future, the ability to use 3-D printing technology to surreptitiously manufacture components may create additional concerns. The ability to stockpile large quantities of centrifuge parts in secret without being detected might turbocharge a covert "surge out" towards the bomb. A hybrid approach is also possible, whereby a country uses its secret jump-start to then assemble all the parts in plain view and quickly present a fait accompli. Indeed, by reducing detection time and making it easier to fabricate sensitive items, production workshops equipped with AM technology threaten to enable unprecedented variants of the classic "sneak out" and "break out" proliferation scenarios.

What Can Be Done?

This is not the first time the international community has grappled with the spread of dual-use technology, but past efforts to control the bomb have largely been reactive. Improvements to the nonproliferation regime almost always spring up in response to major breakdowns or crises. Fortunately, it is possible to anticipate the proliferation potential of AM. The United States and its partners should get out in front of this problem by employing both top-down and bottom-up approaches.

> It is possible to anticipate the proliferation potential, not just respond to a crisis.

Top-Down: Improve Control Regimes

The United States and other countries have long attempted to control the spread of sensitive nuclear technology. In the early 1970s, worries that civilian nuclear programs might spawn weapons proliferation motivated representatives from nuclear supplier nations to meet in Vienna. Under the chairmanship of Claude Zangger, thus forming the Zangger Committee, these officials discussed how to better implement export controls mandated by Article III of the Nuclear Non-proliferation Treaty (NPT). Unfortunately, business interests and politics among the member states prevented consensus over strict regulations. On May 18th, 1974, India conducted a "peaceful" nuclear explosion, using plutonium from a Canadian-supplied heavy water power reactor. The next year, then-U.S. Secretary of State Henry Kissinger convened his counterparts in the other advanced nuclear countries for a series of meetings in London, which culminated in the establishment of the Nuclear Suppliers Group (NSG), a cartel of nuclear suppliers that enacted further restrictions on the availability of sensitive nuclear technologies.[22]

When Iraq circumvented these controls by purchasing unregulated items to build its own sensitive components, the suppliers closed this loophole in 1992

The 2016 Nuclear Security Summit presents an ideal opportunity to address this problem.

by subjecting dual-use technology to enhanced scrutiny. Over the last few decades, members of the NSG and the Zangger Committee expanded the list of items that "trigger" controls and conditional safeguards to keep pace with advances in nuclear technology, and established new guidelines to better deal with the rise of illicit nuclear trade networks. While imperfect, this system has proven effective in retarding the global spread of nuclear weapons, in part because the supplier regimes continue to evolve, adding new members and reacting to troubling developments by updating international regulations.[23]

Like the advent of nuclear technology over seventy years ago, AM represents a new dual-use technology that presents economic opportunity and security risk. The current leaders in AM production should take a page out of the nuclear supplier's playbook and work to set up a new system of multilateral controls and update existing regimes, most notably the NSG and Zangger Committee but also the Missile Technology Control Regime (MTCR) and Wassenaar Arrangement, which establishes export controls for conventional arms and other dual-use technologies. Such efforts would allow the world to harness the benefits of AM while mitigating its downside dangers.

To begin, Washington should immediately convene a high-level meeting with counterparts in the roughly ten other major AM-producing countries to put the issue on the international agenda. The upcoming 2016 Nuclear Security Summit, scheduled to be held in the United States, presents an ideal opportunity for such a gathering. Fortunately, with the exception of China, all of the companies that produce industrial-grade AM printers are U.S. allies in Europe and Japan. Emerging producers—South Korea, New Zealand, Singapore, and South Africa—must also be included. Some technical and policy experts within the U.S. (and presumably other) governments are already aware of this issue, but the potential magnitude of the problem demands that it be elevated to the highest government levels in order to set the stage for a coordinated whole-of-government and, eventually, international approach.[24]

This new group would work together to develop a set of common-sense standards for controlling the export of metal 3-D printers, sensitive build files, and specialized metal powders.

One obvious step would be to develop a multilateral system of end-user and end-use controls, so that the approval of an export license for AM capabilities depends on the nature of the intended recipient and the proposed activity. Building upon "catch-all" rules used by the multilateral control regimes, these provisions would prohibit the transfer of 3-D printers or build files to countries or non-state actors of ongoing proliferation concern, while ensuring the availability of the technology for industrial applications or even for some peaceful nuclear activities under appropriate safeguards.

Working within existing nuclear trade regimes would be a pragmatic next step to translate other conclusions from the AM suppliers conference into policy. The export control regimes already have a formal set of standards to coordinate actions among members, and AM-related materials and technology should be controlled much like other sensitive inputs and information. First, technical working groups should meet to build consensus on possible recommendations. Next, the United States and its partners could hold special plenary sessions devoted to updating respective guidelines so that exports of advanced AM printers, sensitive digital build files, and special metallic powders trigger the same robust scrutiny and requirements for end-user specification as subtractive manufacturing equipment. As a leading member of the NSG, Washington will have great sway in advancing this agenda from inside—and since the leading developers of AM are located in countries that participate in either the NSG or the Wassenaar Agreement, action within these institutions could have a significant impact.

Bottom-Up: Control New Technologies

Beyond updating the export control regimes, the AM suppliers should also develop an effective system for protecting sensitive build files. States clearly need to discover unauthorized intrusions into relevant databases much more quickly. The Obama White House has adopted a number of cybersecurity initiatives to safeguard information in the digital realm and develop standards with private stakeholders although recent setbacks, including the OPM data breach, demonstrate that much work remains to be done.[25]

Beyond updating export controls, suppliers should also protect sensitive build files.

Government and industry should explore methods for building safeguards directly into the build files to make them intrinsically secure. Single-use build files, programmed to corrupt themselves after completing a specified task, could ensure proper use by the intended recipient. Designers could disperse information for the most sensitive items across multiple files on segregated databases to prevent cyber thieves or insiders from gaining access in one fell swoop. Private industry may innovate and adopt creative safeguards to protect intellectual property and share best practices. In the end, devising a solution will ultimately require close collaboration between national authorities, the cyber community, and commercial developers of AM technology.

Finally, the international community needs new protocols and capabilities to monitor AM-facilitated fabrication. Governments could track purchases of 3-D printers able to produce components traditionally made by specialized cutting lathes and grinders. Collaborative research by government, industry, and university stakeholders into the art of the technically possible with nuclear-related AM would help ensure that those charged with monitoring and verification remain a step ahead of proliferators. Sales of special metallic, ceramic, and plastic powders used in the additive fabrication process must be reviewed and controlled for the same way that sales of billets of maraging steel or 7075 aluminum are today, as these materials can be used to produce centrifuge components. To facilitate these efforts, AM producers should consider placing a unique identifier on each and every metal 3-D printer produced, even causing the ID to be embedded in any component made on that machine. Countries could consider funding an international data fusion clearinghouse, perhaps located at the IAEA, to collect and store information on the transfer and operation of sensitive 3-D printers around the world.

To be sure, many of these efforts will not be easy. The NSG operates on political consensus and countries may be unwilling or unable to control AM technology. Some of these recommendations go beyond what is currently done with lathes and grinders, so an expansion of obligations for both governments and businesses could prove a tough sell. Further, and more fundamentally, some might object that attempting to limit the spread of a fast-moving major technology such as AM is a fool's errand, akin to the failed attempt to control high-performance computing (HPC) in the 1990s.[26] HPC technology moved far too quickly for governments to ever put in place effective export controls, and as a result the United States and China continue to race to bring online the most powerful supercomputers in the world.

Nevertheless, these are exactly the sorts of questions that expert working groups must consider and that must move to a higher government level in order to focus sustained attention on the issue. Vigorous discussion and debate will help separate the wheat from the chaff so that solutions with technical merit and political viability can be implemented *before* a crisis happens. At a deeper level, while the costs of overcoming these various obstacles to the development of a successful AM nonproliferation strategy are real, they pale in comparison to the risks of inaction. 3-D printing represents a major step forward in production technology, and the nuclear nonproliferation regime must adapt to meet this challenge.

No Time Like the Present

The emerging AM revolution will have profound implications for how technology is produced around the world. As a result, the United States should engage in a broad-based effort to anticipate these likely consequences and position itself to maximize its associated benefits and minimize risks. Among these efforts, Washington should develop a national strategy for becoming a global leader in AM fabrication and to incorporate AM into defense production to reduce defense spending and the national deficit. Most importantly, however, the United States must also consider the game changing effects of 3-D printing beyond its borders and work with the international community to prevent an AM-enabled cascade of nuclear weapons proliferation.

Some may argue that the measures we recommend are premature because states are not yet using AM to build nuclear components. But if we wait until the next proliferator uses AM workshops to surge out to a significant quantity of fissile material, the international community will once again have been too late. Others may argue that we are already behind the curve; multiple countries are producing 3-D printers and the machines are already in use in firms and research organizations around the world. While true, efforts at control, especially if implemented in a timely manner, can have a powerful and lasting effect. After all, strict international nuclear supply controls were not adopted until nearly 30 years after the first nuclear test. Fortunately, we have identified the emergent threat posed by AM much earlier. Now is the time to act.

Notes

1. "3D Printing Scales Up," *The Economist*, September 7, 2013, http://www.economist.com/news/technology-quarterly/21584447-digital-manufacturing-there-lot-hype-around-3d-printing-it-fast.
2. Andrew Zaleski, "GE's Bestselling Jet Engine Makes 3-D Printing a Core Component," *Fortune*, March 5, 2015, http://fortune.com/2015/03/05/ge-engine-3d-printing/; "Aerojet Rocketdyne Successfully Demonstrates 3D Printed Rocket Propulsion System for Satellites," Reuters, December 15, 2014, http://www.reuters.com/article/2014/12/15/idUSnGNX8FQrs1+1d8+GNW20141215; Brooke Kaelin, "World's Largest 3-D Printed Titanium Aircraft Part on Display in China," 3-D Printer World, August 19, 2013, http://www.3dprinterworld.com/article/worlds-largest-3d-printed-titanium-aircraft-part-display-china.
3. Matthew Kroenig, *Exporting the Bomb: Technology Transfer and the Spread of Nuclear Weapons* (Ithaca: Cornell University Press, 2010); David Albright, *Peddling Peril: How the Secret Nuclear Trade Arms America's Enemies* (New York: Free Press, 2010).
4. Neil Gershenfeld, "How to Make Almost Anything: The Digital Fabrication Revolution," *Foreign Affairs* 91, no. 6 (November/December 2012), pp. 43–57.
5. Jacqueline Mroz, "Hand of a Superhero: 3-D Printing Prosthetic Hands That Are Anything but Ordinary," *The New York Times*, February 16, 2015, http://www.nytimes.com/2015/02/17/science/hand-of-a-superhero.html?_r=0; Laurie Garrett, "Biology's Brave New World: The Promise and Perils of the Synbio Revolution," *Foreign Affairs* 92, no. 6 (November/December 2013), pp. 28–46. But for exceptions, see Connor M. McNulty,

Neyla Arnas, and Thomas A. Campbell, "Toward the Printed World: Additive Manufacturing and Implications for National Security," Institute for National Strategic Studies, National Defense University, September 2012, www.dtic.mil/dtic/tr/fulltext/u2/a577162.pdf; Matthew Hallex, "Digital Manufacturing and Missile Proliferation," *Public Interest Report* 66, no. 2 (Spring 2013).

6. "3D Printing: Entering the Jet Age," *The Economist*, March 7, 2015, http://www.economist.com/news/science-and-technology/21645712-aircraft-engines-may-soon-be-built-one-layer-time-entering-jet-age.
7. Zaleski, "GE's Bestselling Jet Engine."
8. Larry Dignan, "Airbus A350 XWB used more than 1,000 3D printed parts," ZDNet, May 6, 2015, http://www.zdnet.com/article/airbus-a350-xwb-used-more-than-1000-3d-printed-parts/.
9. Yasmin Tadjdeh, "Navy Beefs Up 3D Printing Efforts with New 'Print the Fleet' Program," *National Defense Magazine*, October 2014, http://www.nationaldefensemagazine.org/archive/2014/October/Pages/NavyBeefsUp3DPrintingEffortsWithNewPrinttheFleetProgram.aspx; Cheryl Pellerin, "Hagel Announces New Defense Innovation, Reform Efforts," Press Release, U.S. Department of Defense, November 15, 2014, http://www.defense.gov/news/newsarticle.aspx?id=123651; John Markoff, "Pentagon Shops in Silicon Valley for Game Changers," *The New York Times*, February 26, 2015, http://www.nytimes.com/2015/02/27/science/pentagon-looking-for-edge-in-the-future-checks-in-with-silicon-valley.html.
10. Thomas Campbell, Christopher Williams, Olga Ivanova, and Banning Garrett, "Could 3D Printing Change the World? Technologies, Potential, and Implications of Additive Manufacturing," Strategic Foresight Report, The Atlantic Council, October 2011, http://www.atlanticcouncil.org/publications/reports/could-3d-printing-change-the-world.
11. Robert Harney et al., "Anatomy of a Project to Produce a First Nuclear Weapon," *Science & Global Security* 14, no. 2–3 (December 2006): 163–82.
12. Michael D. Zentner et al, "Nuclear Proliferation Technology Trends Analysis," Pacific Northwest National Laboratory, September 2005, fissilematerials.org/library/zen05.pdf.
13. Matthew Kroenig, *A Time to Attack: The Looming Iranian Nuclear Threat* (New York: Palgrave Macmillan, 2014), pp. 15–18.
14. Ellen Nakashima, "Chinese Breach Data of 4 Million Federal Workers," *The Washington Post*, June 4, 2015, https://www.washingtonpost.com/world/national-security/chinese-hackers-breach-federal-governments-personnel-office/2015/06/04/889c0e52-0af7-11e5-95fd-d580f1c5d44e_story.html.
15. On why countries have exported sensitive material in the past, see Matthew Kroenig, "Exporting the Bomb: Why States Provide Sensitive Nuclear Assistance," *The American Political Science Review* 103, no. 1 (February 2009), pp. 113–133.
16. See, for example, Michael Moltich-Hou, "Afinia Unveils ES360 Tabletop 3D Scanner," 3-D Printing Industry, July 28, 2015, http://3dprintingindustry.com/2015/07/28/afinia-unveils-es360-tabletop-3d-scanner/.
17. On knowledge and experience barriers to the production of nuclear weapons, see Donald MacKenzie and Graham Spinardi, "Tacit Knowledge, Weapons Design, and the Uninvention of Nuclear Weapons," *The American Journal of Sociology* 101, no. 1 (July 1995), pp. 44–99; and Alexander H. Montgomery, "Stop Helping Me: When Nuclear Assistance Impedes Nuclear Programs," in Adam Stulberg and Matt Fuhrmann, eds., *The Nuclear Renaissance and International Security* (Stanford, C.A.: Stanford University Press, 2013), pp. 177–200.

18. Wyn Q. Bowen, *Libya and Nuclear Proliferation: Stepping Back from the Brink*, (London, U. K., Routledge for the IISS Adelphi Papers, 2006), pp. 25–46.
19. For a good overview of the challenges faced in the collection of information on nuclear programs, see Michael Crawford, "Exploring the Maze: Counter-proliferation Intelligence," *Survival* 53, no. 2, (2011), pp. 131–158.
20. In this sense, AM promises to significantly exacerbate the problem created by the spread of computer numeric controlled machines and other technical advances that "shortened timelines and allowed programmes to overcome or sidestep important hurdles." See Crawford, "Exploring the Maze," p. 148.
21. Robert Gates, Director of Central Intelligence, "Weapons Proliferation in the New World Order," Statement before the Senate Government Affairs Committee, 102nd Cong., 2nd sess., January 15, 1992.
22. J. Samuel Walker, "Nuclear Power and Nonproliferation: The Controversy over Nuclear Exports, 1974–1980," *Diplomatic History* 25, no. 2 (Spring 2001), pp. 215–249.
23. For an excellent overview of the past, current, and future challenges facing the NSG, see Mark Hibbs, *The Future of the Nuclear Suppliers Group* (Washington DC: The Carnegie Endowment for International Peace, 2011).
24. For example, the Comptroller General of the United States recently convened a forum to address the benefits and potential risks of AM technology with participants from government, business, and academia. For a summary, see "3D Printing: Opportunities, Challenges, and Policy Implications of Additive Manufacturing," United States Government Accountability Office, Report to the Chairman, Committee of Science, Space, and Technology, House of Representatives, GAO-15-505SP, June 2015.
25. Katie Zezima, "Obama Signs Executive Order on Sharing Cybersecurity Threat Information," *The Washington Post*, February 12, 2015, http://www.washingtonpost.com/news/post-politics/wp/2015/02/12/obama-to-sign-executive-order-on-cybersecurity-threats/.
26. See Glenn J. McLoughlin and Ian F. Fergusson, *High Performance Computers and Export Control Policy* (CRS Report No. RL31175) (Washington, DC: Congressional Resedarch Service, February 10, 2003).