Additive Manufacturing: Implications for the Interagency's Nuclear Counterproliferation Task

by John W. Andrews

The emerging technology of additive manufacturing (AM) is rapidly revolutionizing the world of industry. Additive manufacturing enables the layering of materials, using precise, computer-controlled machines, to quickly build objects with complex shapes at low cost. Indeed, AM promises to produce things that, only a few years ago, would have been utterly inconceivable to the traditional manufacturer. However, these same technologies include the potential for misuse in unthinkably, harmful ways, including the illicit production of nuclear weapon components. For over seven decades, the interagency has worked to create and maintain barriers that prevent the illicit development and transfer of nuclear weapon technology. However, these barriers were designed to counter traditional, "subtractive" forms of manufacturing; their efficacy does not readily transfer to newly emerging AM technologies. As AM matures, it certainly will become increasingly interesting to those seeking to produce nuclear weapons outside the established strictures of the international legal system. Additive manufacturing could be used to facilitate illicit nuclear weapon production by:

- Dramatically reducing both time and expense associated with nuclear weapon production.
- Dramatically increasing nuclear supply-chain efficiency.
- Providing more effective manufacturing options for aspiring proliferators, reducing the technical challenges associated with developing nuclear weapons.
- Reducing the footprint of illicit nuclear transactions.
- Exacerbating the problem of insider threats.
- Fundamentally altering the nuclear weapon acquisition pathway.

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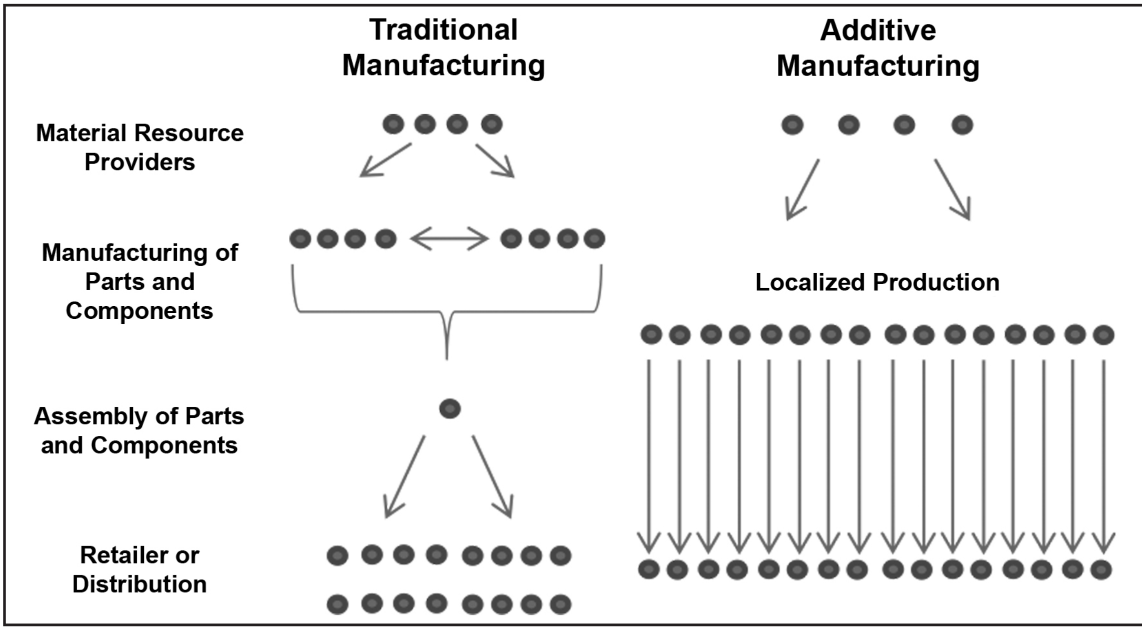

Figure 1. Supply chain comparison. [4]

Reducing Both Time and Expense of Nuclear Weapon Production

Although nuclear weapon development facilities are very large and include highly-sophisticated equipment, they generally do not require mass production techniques, and AM is particularly well-suited for sm all production runs. Indeed, Lawrence Livermore National Laboratory (LLNL) has embraced the use of AM systems to cut costs and increase the speed of operations for its nuclear stockpile lifetime-extension program.[1] The Department of Energy (DOE) National Nuclear Security Administration estimates that within five years AM systems will be capable of making 50 percent of its tools, which would cut tooling production costs by 75 percent, cut development time by 80 percent, and cut production time by 60 percent. These efficiencies would truly revolutionize DOE's nuclear stockpile lifetime-extension program. Nuclear proliferators may use AM systems to obtain similar efficiencies to streamline challenges associated with the illicit production of nuclear weapon technology.[2]

Increasing Nuclear Supply-Chain Efficiency

Material resource providers for traditional supply chains deliver to manufacturers of disparate parts and components. Those manufacturers might then ship their component parts to other manufacturers and then to an assembly plant. The assembly plant fabricates the final product and then delivers to a retailer or distributer. At any of the points or nodes in the supply chain, a disruption results in the delay of deliveries to the retailer or distributer. In contrast, the AM supply chain contains fewer nodes and, thus, less potential for disruption. Additive manufacturing may require no assembly of parts or components, with localized production occurring as additive systems utilize raw materials to fabricate the final product. However, these same efficiencies appeal to illicit networks because they are shorter and easier to compartmentalize, making them easier to conceal. Figure 1 illustrates the comparison between the supply chains of traditional manufacturing and AM.

Reducing the Technical Challenges Associated with Developing Nuclear Weapons

Additive manufacturing systems will provide more effective manufacturing options for aspiring proliferators, reducing the technical challenges associated with developing nuclear weapons. Nuclear weapon production facilities include lengthy, multi-step production processes. Each step requires specific expertise and careful planning and execution. Many steps in the process require parts with complex geometries made to very precise specifications that are difficult to fabricate with traditional methods. Very specific material designs and highly-precise process controls are required. The introduction of advanced AM systems with highly-precise control mechanisms and a vast array of material options could offer better alternatives to address some of these challenges.

Additive manufacturing systems can produce sophisticated parts with complex geometries and material properties that previously required several steps or were impossible to make with traditional subtractive manufacturing or forming methods. Traditional manufacturing techniques often require turning, milling, and grinding machines. These machines have multi-axis parts that must continually coordinate with each other to maintain a predetermined path. If state-of-the-art equipment is not available, significant work by hand is often required to re-position parts during machining or to produce component parts that are joined together later. The quality of the final product is heavily dependent on the skill of the machinist.[5] In the future, AM techniques will potentially meet or exceed the quality of some traditional techniques, while requiring far less machinist skill.

Additive manufacturing systems will provide ways to more efficiently design and fabricate nuclear weapon detonation mechanisms. A nuclear weapon of any kind requires sophisticated technical expertise to build, but the degree of precision required to construct a highly-efficient detonation depends on the amount, shape, and purity of the weapons-grade material (uranium-235 or plutonium-239), as well as the quality of the weapon design. Additive manufacturing techniques could improve the precision and accuracy with which nuclear devices are built, mitigating some of these design challenges. Additive manufacturing systems also offer potential to print exotic materials, such as high explosives with material properties that improve performance. High-explosive performance is heavily dependent on small imperfections or pores in the crystal structure of the material. Because some AM systems can manipulate material at the scale of the pores, which is about 1 to 100 micrometers, materials can potentially be created that yield more effective and predictable explosions, a critical factor in creating effective nuclear weapon detonation mechanisms.[6]

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Researchers at LLNL are not just using AM systems to save time and money, they are also using AM to create technically-superior parts. For example, LLNL is using AM systems to optimize the structure of metal components associated with the U.S. nuclear stockpile. Also, researchers are creating complex metal lattice structures with millions of millimeter-high struts that can conform to a curved surface, allowing LLNL to address some previously unresolved technical challenges. Additive manufacturing systems have also been used to create parts with unique material properties, like pads that are easily compressible at one end and stiff at the other, enabling more uniformed production for certain components.[7] The same spirit of resourcefulness and creativity exhibited by LLNL researchers to improve stockpile lifetime extension programs may be mirrored by aspiring nuclear proliferators whom seek to acquire nuclear weapons or transfer nuclear weapon technology.

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Reducing the Footprint of Illicit Nuclear Transactions

Additive manufacturing techniques will allow nuclear proliferators to reduce the signatures associated with their illicit transactions. Acquiring nuclear weapons is not a trivial task. Many steps are needed to generate or obtain the fissile nuclear material and the required equipment and expertise. Because most countries or groups seeking nuclear capabilities cannot build them on their own, they must rely on assistance from external entities, which creates a vast network of people and organizations that are involved with the various steps or acquisition pathways required to obtain nuclear weapons. At each step or node along the acquisition pathway, proliferation networks generate signatures. Over the past several decades, the interagency has created mechanisms to detect these signatures, effectively creating barriers to nuclear proliferation. Illicit networks adapt to interagency barriers over time, often exploiting advancements in technology. Additive manufacturing is not the first great technological advancement to be utilized by proliferation networks—the invention of the internet is another example. However, AM represents a serious concern due to the rapid nature of its growth, both in popularity and sophistication. As proliferators embrace AM, the signatures associated with the many transactions along the nuclear weapon acquisition pathway will be reduced.

Additive manufacturing technology will reduce the signatures associated with purchasing parts. No matter how effective illicit networks are at concealing their activities, they must expose themselves to some degree when they purchase equipment and parts. Detecting suspicious purchases is one of the most effective interagency tools for discovering an illicit network. If a group seeking nuclear weapons can fabricate a part using a 3D printer or similar device, it does not need to engage with a supplier. As additive technologies become more sophisticated and compatible with more materials, proliferators will be able to build more parts on their own. The potential decrease in purchasing transactions will have a corresponding decrease in the ability of the interagency to detect them.

The vulnerabilities associated with protecting 3D design information will be exasperated due to the emergence of AM technologies. Additive manufacturing systems will alleviate the need for proliferators to order certain pieces of equipment that can be fabricated by an AM system. If a nuclear-related part is capable of being printed by an AM device, but a proliferator does not know how to fabricate it, the proliferator could buy or steal the 3D design information. For example, suppose Country A needs a "dual-use item" tracked by the Nuclear Supplier's Group (NSG). Instead of trying to purchase that item from a supplier, Country A may be able to obtain the 3D design information and simply print the item with an AM system.

Additive manufacturing systems will increase the difficulty of detecting illicit networks because the number of people and activities associated with individual nuclear weapon acquisition pathways will decrease. Each person or activity associated with a nuclear black market offers an opportunity for the network to be discovered by authorities. If an illicit network can decrease the number of people and transactions associated with it, it can increase its chances of evading detection. Additive manufacturing will increase the pool of people capable of contributing to nuclear proliferation, but it will decrease the number of people involved with individual nuclear weapon acquisition pathways in many cases. For example, future AM advancements in selective laser sintering machines may allow groups to fabricate complex metals parts without the need for several other traditional manufacturing techniques requiring the use of multiple pieces of equipment and several different machinists. By substituting the selective laser sintering machine and its operator for several pieces of equipment and several people, the signature-creating activities associated with the previous method have been greatly reduced. This example covers just one node within the overall nuclear weapon acquisition pathway. Consider the AM supply chain cost and timeline efficiencies illustrated in Figure 1. Since AM supply chains contain fewer nodes than traditional manufacturing supply chains, they inherently create fewer exploitable signatures than traditional manufacturing supply chains. Not only do fewer nodes result in fewer interagency detection opportunities, they also result in fewer interdiction or sabotage opportunities.

Additive manufacturing systems decrease the ability of interagency mechanisms to interdict illegal shipments of equipment. Since proliferators will be able to fabricate more items using 3D design data, the number of items they will need to purchase for delivery will be decreased. Instead, they could simply purchase the 3D design data, which can be delivered via email. Interagency mechanisms to detect and interdict physical shipments of equipment, such as the Proliferation Security Initiative, will be less effective due to decreased nuclear-related trafficking of physical objects.

The emergence of AM will create the potential for aspiring proliferators to decrease their signature-producing activities. This will affect every facet of the complex patchwork of interagency safeguards designed to detect illicit activity. The effectiveness of these safeguards will be degraded across the entire spectrum unless they are modified to account for AM.

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Exacerbating the Problem of Insider Threats

The emergence of AM technologies may also increase the difficulty of detecting insider threats. Many people involved with peaceful nuclear energy installations have access to technology that would be of great value to a proliferator. A.Q. Khan, for example, gained access to nuclear technologies in the 1970s while working for an Urenco subcontractor in Amsterdam. Khan later exploited his access to create a black market that contributed to the nuclear weapon programs of Pakistan, Iran, North Korea, Libya, and possibly others. As AM becomes more sophisticated and the pool of people capable of contributing to nuclear proliferation increases, the black-market demand for 3D design information may also increase. Illicit networks, encouraged by the increased capabilities that AM techniques offer, may make more attempts to bribe or blackmail workers at legitimate nuclear facilities. Alternatively, a disgruntled worker may be more inclined to seek out a nuclear black market. Insider threats of this nature are very difficult to detect. Stealing a 3D design file from an organization can be done from behind a desk. The illegal spread of nuclear weapon and technology design information was an issue long before AM existed; however, the emergence of AM may increase the likelihood of it occurring.

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Fundamentally Altering the Nuclear Weapon Acquisition Pathway

Due to advances in AM, aspiring proliferators will have more options to pursue while simultaneously having more capability to conceal their activities. As AM devices become more sophisticated, this effect will become increasingly more exaggerated, which will exacerbate interagency detection and interdiction challenges.

Consider the idea of a nuclear weapon acquisition pathway. For a group to acquire a nuclear weapon, it must conduct a large number of activities. The number of activities between different proliferators will vary greatly depending on the ambition of the group, its resources, and many other factors. If a group is intending to develop its own fissile material and produce a nuclear weapon indigenously, it will face many more challenges and probably conduct many more activities than a group that is simply looking to buy or steal fissile material and fabricate a weapon using the acquired uranium or plutonium. Whichever way a group attempts to acquire a weapon, the path it goes down can be characterized as its nuclear weapon acquisition pathway. The pathway includes any entity or action associated with the acquisition network. This includes the facilities the group utilizes, the people associated with it, the supplier companies in its network, and any communications, financial transactions, or other activities it conducts. A nearly infinite number of possible pathways exist, and every country or group seeking nuclear weapons will have a unique pathway.

When an aspiring proliferator sets out to acquire nuclear weapons, every activity it conducts on its pathway creates a signature. These signatures can vary greatly and can include anything associated with a myriad of activities, including buying or building facilities, hiring people, purchasing equipment, mining materials, transporting items, and creating communication networks. The interagency relies on these signatures to detect illicit networks. The successful discovery and interdiction of an illicit network often can be attributed to a combination of detected signatures gathered over a long period, none of which would have independently provided sufficient evidence of illicit activity. Since almost all nuclear-related technology and equipment have other purposes in legitimate industries, proliferators have a myriad of options to consider when navigating its pathway. Weeding out the illicit activity from normal industrial activity can be very challenging for counterproliferation officials. Figures 2 and 3 represent two different notional nuclear weapon acquisition pathways: the traditional pathway and the pathway made possible by AM.[8]

The dots represent possible nodes, or steps, on the acquisition pathway, and the lines connecting the dots represent relationships between those nodes. For example, a centrifuge supplier company and the uranium enrichment facility of the aspiring proliferator would be two nodes that have a relationship or connection. The thicker lines connecting the stars represent the actual pathway the proliferator has chosen, and the stars represent signatures associated with the proliferator's actions that make it susceptible to detection by law enforcement. As shown in Figure 2, traditional manufacturing acquisition

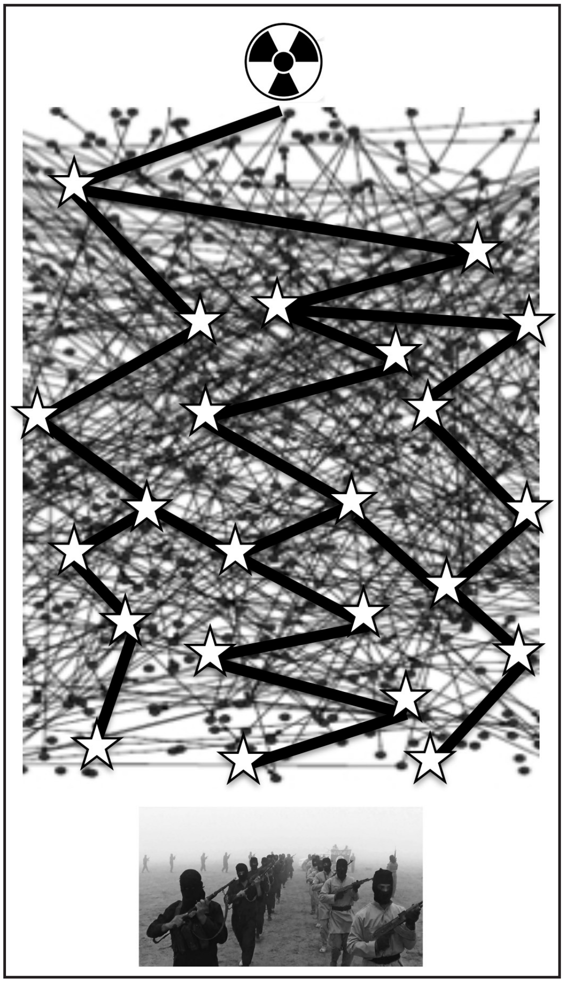

Figure 2. Pre-AM Nuclear Weapon Acquisition Pathway

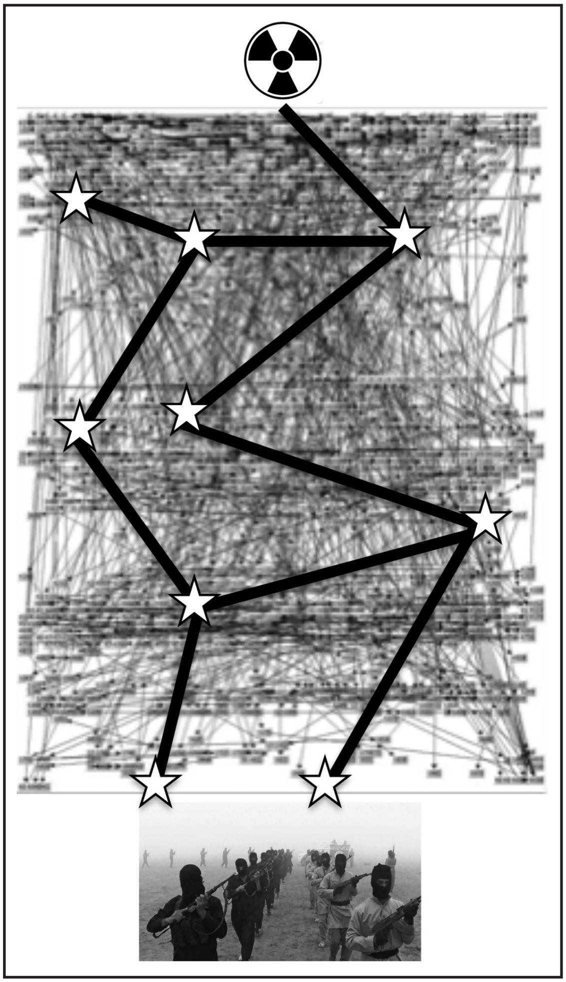

Figure 3. Future Nuclear Weapon Acquisition Pathway with AM

schemes provide interagency mechanisms with many opportunities to detect the signatures created by proliferation activities. In Figure 3, however, the number of potential illicit transactional pathways dramatically expands, while the transactional signatures—and the opportunity for interception—dramatically diminish. In short, law enforcement officials in the future will need to monitor a greater number of nodes in search of illicit activity, while the actual number of detectable illicit activities will decrease. If weeding out illicit proliferation transactions from legitimate industrial activities can be compared to searching for needles in a haystack, the introduction of AM effectively increases the size of the haystack while decreasing the number and size of the needles.

Looking Ahead

The AM industry is forecasted to grow exponentially in the coming years. While the forecasted growth is promising in many ways, it will increase the difficulty of detecting and tracking illicit nuclear technology procurement networks. All research suggests rapid growth of the AM industry. Some forecasts estimate a $20+ billion market by 2020.[9] This growth will create an entirely new segment of the world population with some level of engineering skill. Some members of this population will inevitably be motivated, persuaded, or coerced to become involved in nuclear proliferation. The sheer increase in potential bad actors caused by the explosive growth of the AM industry will stress the capacity of intelligence and security agencies to track proliferation networks.

As different industries utilize AM to improve business, nuclear proliferators will utilize it to develop and transfer nuclear technology.

The growth of the AM industry will also put stress on export control enforcement. One of the great vulnerabilities of proliferation networks is their need to purchase dual-use equipment. Creating schemes to detect illicit procurement attempts may seem straightforward in theory, but it is difficult in practice. Only a very small fraction of inquiries that a legitimate company receives originate from a nuclear proliferator. Persistent efforts on the part of the nonproliferation regime are required to keep companies focused on preventing the inappropriate transfer of dual-use technology. Many companies that emerge during the inevitable explosion of the AM industry in the coming years will be completely unfamiliar with the nonproliferation regime. Without special efforts to educate and inform AM companies of illicit proliferation, it is unreasonable to expect them to prevent it. Even with ideal export-control policies and new intelligence collection schemes, the sheer number of new companies may strain interagency safeguards. The Department of Commerce, tasked with administering and enforcing export controls, will face especially difficult challenges in handling the rapid influx of companies emerging during the AM industry boom. The Department of Commerce relies on many interagency partners to carry out its nonproliferation-related export control duties, including the Departments of State, Homeland Security, Treasury, Defense, and Energy.[10] These partners will also be challenged to update policies and procedures commensurate with the vulnerabilities created by the influx of AM-related companies.

As different industries utilize AM to improve business, nuclear proliferators will utilize it to develop and transfer nuclear technology. Countries like China, Russia, North Korea, and Pakistan may be able to more effectively modernize their capabilities, enabling vertical nuclear proliferation. Horizontal proliferation is perhaps a greater concern. Countries previously discouraged by the technical, financial, and legal barriers associated with developing nuclear weapons may reconsider their options. Perhaps most troubling, non-state actors may embrace AM systems as a way to create an improvised nuclear device. Since a single nuclear weapon in the hands of a terrorist organization would have devastating consequences, the new risks posed by advances in AM must not be taken lightly. As the emergence of AM decreases the barriers to nuclear proliferation, the interagency will be forced to address new challenges.

The keys to addressing the vulnerabilities created by AM systems are understanding AM technologies and how they might be leveraged to advance nuclear weapon development efforts. No single organization can obtain this level of understanding. Most leaders in the AM industry will not be aware of how their technologies might contribute to proliferation. Similarly, most interagency nonproliferation officials will not have a nuanced understanding of AM technologies. Even some engineers in the nuclear weapon stockpile complex familiar with traditional methods of fabricating nuclear weapons may not yet recognize the applicability of AM to nuclear weapon development. Organizations from all facets of the nonproliferation regime should team with the AM industry to enable a whole-of-government approach to mitigating the risks of AM without inhibiting the economic benefits of the AM industry.

Officials responsible for crafting export and trade control laws and regulations will face considerable challenges. The interagency should consider how the effectiveness of the NSG's "trigger" and "dual-use" lists will be degraded by AM systems. For example, will AM systems be capable of printing any of the items on the lists? If so, proliferators will be able to circumvent detection measures. Perhaps those AM systems capable of printing "dual-use" or "trigger" list items should be added to one of the NSG lists, along with the raw materials needed to do so. However, what if the growth in the AM industry reaches a level such that thousands of different types of AM systems and materials can contribute to nuclear proliferation? Would it be realistic to include these in the NSG lists and expect them to be regulated? What about the countries that embrace AM techniques that are not members of the NSG? How much easier will it be for illicit networks to leverage those countries' capabilities to develop or transfer nuclear technology?

The interagency should strengthen mechanisms to protect nuclear-related design information. Since AM systems will allow for easier and faster fabrication techniques, the motivation to buy or steal 3D design information may increase. This is particularly concerning due to the recent surge of cyber-attacks that will likely only increase in quantity and sophistication in the future.

Since the technical barriers to creating nuclear weapons will be reduced, the interagency may be forced to strengthen detection techniques that focus on individuals. Counter-bioterrorism techniques offer an appropriate template for addressing a serious threat with very low technical barriers to proliferation. Biological weapon production requires far less expertise, infrastructure, and money than nuclear weapon production, yet a devastating biological attack on the U.S. has never occurred.[11] The counter-nuclear proliferation community should seek lessons learned from the biological community to address the threat posed by AM industry growth.

The intelligence community should consider how to best strengthen detection schemes. For example, some intelligence collection frameworks could simply be expanded to include AM-related entities. Other frameworks may have to be created from scratch to address the growing threat. Perhaps a starting point is to identify existing academic and industry groups with possible ties to foreign military programs that are investing in AM technologies.

Creative technical solutions to mitigate proliferation risks should be solicited from the AM industry. The potential to create AM systems that create unique microscopic tags or identifiers on each piece of equipment that they fabricate has been discussed as a way to improve attribution capabilities. This and other similar proposals are intriguing, but they must be balanced with commercial motivations to remain competitive in the marketplace.

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Perhaps most importantly, the interagency should identify AM as a priority and take steps to set up lasting, whole-of-government approaches to address it. The interagency should institutionalize periodic reviews of the AM industry to discuss how it might contribute to nuclear proliferation, and then update policies and procedures to prevent problems before they occur. These reviews should include personnel from the intelligence community; the nuclear weapon science and technology community from the Departments of Energy and Defense; leaders from the commercial AM community; nonproliferation policymakers from the Departments of State, Commerce, Homeland Security, and Treasury; international partners; and possibly others. Only vigorous and iterative reviews, inclusive of all entities, can yield well-reasoned recommendations for implementation that both mitigate the threat and avoid over-regulation that stifles economic growth.

While the pool of possible contributors to nuclear proliferation is increasing, the methods of illicit networks that embrace AM capabilities are creating fewer detectable signatures. By circumventing interagency barriers like export control regulations, aspiring proliferators will be able to navigate the pathway to acquiring a nuclear weapon with greater ease. The path to acquiring nuclear weapons outside the international legal system remains a daunting task even with the help of AM, but the interagency must stay steps ahead of illicit networks by making this emerging threat a priority and implementing a process to address it. The explosive growth in AM technology will not wait for policymakers—it is naïve to think that adversaries have not already recognized the potential of AM. The time to address this problem is now. ***IAJ***

NOTES

1 “Next-Generation Manufacturing for the Stockpile,” January 2015, <https://str.llnl.gov/january-2015/marrgraff>, accessed on September 27, 2015.

2 Ibid.

3 D.S. Thomas, and S.W. Gilbert, “Costs and Cost Effectiveness of Additive Manufacturing a Literature Review and Discussion,” *NIST Special Publication 1176*, December 2014, <http://dx.doi.org/10.6028/NIST.SP.1176, accessed on October 3, 2015.

4 Ibid.

5 *Federation of American Scientists Special Weapons Primer*, October 1998, <http://fas.org/nuke /intro/nuke/produce.htm>, accessed on November 1, 2015.

6 “Next-Generation Manufacturing for the Stockpile.”

7 Ibid.

8 Figures 2 and 3 are purely notional. They were not derived from a specific threat and are for illustrative purposes only.

9 Louis Columbus, “2015 Roundup of 3D Printing Market Forecasts and Estimates,” March 31, 2015, <http://www.forbes.com/sites/louiscolumbus/2015/03/31/2015-roundup-of-3d-printing-market-forecasts-and-estimates/#2715e4857a0b79d5645b1dc6>, accessed on February 7, 2016.

10 “A Resource on Strategic Trade Management and Export Controls,” <http://www.state.gov /strategictrade/resources/c43182.htm>, accessed on February 8, 2016.

11 The “Amerithrax” attacks in October 2001 were certainly disruptive and tragic for the victims, but are not considered “major” in this case due to the relatively low number of casualties when compared to what could occur in the event of a nuclear attack or a more serious biological warfare attack.