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The Implications of Additive Manufacturing and Nuclear Weapons Proliferation

January 2016

NC Lindsey

U.S. DEPARTMENT OF
ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Summary

The growth of additive manufacturing as a disruptive technology poses nuclear proliferation concerns worthy of serious consideration. Additive manufacturing began in the early 1980s with technological advances in polymer manipulation, computer capabilities, and computer-aided design (CAD) modeling. It was originally limited to rapid prototyping; however, it eventually developed into a complete means of production that has slowly penetrated the consumer market. Today, additive manufacturing machines can produce complex and unique items in a vast array of materials including plastics, metals, and ceramics. These capabilities have democratized the manufacturing industry, allowing almost anyone to produce items as simple as cup holders or as complex as jet fuel nozzles. Additive manufacturing, or three-dimensional (3D) printing as it is commonly called, relies on CAD files created or shared by individuals with additive manufacturing machines to produce a 3D object from a digital model. This sharing of files means that a 3D object can be scanned or rendered as a CAD model in one country, and then downloaded and printed in another country, allowing items to be shared globally without physically crossing borders. The sharing of CAD files online has been a challenging task for the export controls regime to manage over the years, and additive manufacturing could make these transfers more common. In this sense, additive manufacturing is a disruptive technology not only within the manufacturing industry but also within the nuclear nonproliferation world. This paper provides an overview of additive manufacturing concerns of proliferation.

Acknowledgments

The work described in this document was funded by the U.S. Department of Energy during the author's internship at the Pacific Northwest National Laboratory (PNNL). This document is solely the author's creation and does not reflect the views of PNNL or the U.S. Department of Energy. Finally, the author would like to thank everyone at PNNL who provided guidance on both the technical and policy aspects of this document. In particular, he would like to thank Christine Noonan for her assistance with everything from his research at PNNL to finding his way around Richland.

Acronyms and Abbreviations

3D	Three-dimensional
ABS	Acrylonitrile butadiene styrene
CAD	Computer-aided design
CNC	Computer numerically controlled
EBAM	Electron Beam Additive Manufacturing
EU	European Union
GAO	Government Accountability Office
IAEA	International Atomic Energy Agency
INFCIRC	Information Circular
NSG	Nuclear Suppliers Group
NNUMAN	New Nuclear Manufacturing
PNNL	Pacific Northwest National Laboratory
SLS	Selective laser sintering
STA	Stereolithographic apparatus
STL	Stereolithography

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1.0 Introduction

Every so often, innovation produces something that could potentially restructure preexisting markets or industries. These innovations are called disruptive innovations, and they can sometimes go so far as to alter society as a whole. Additive manufacturing has grown over the past few years to exemplify disruptive technology because it stands to completely reshape the manufacturing world from the ground up. As three-dimensional (3D) printers become more affordable and increasingly capable, the exclusivity of complex manufacturing will be expanded from industrial factories to home offices. While this is indeed a major disruption, the implications of this change are considerably further reaching. Sometimes referred to as the "third industrial revolution," additive manufacturing is poised to disrupt more than just the manufacturing world.

Similar to many manufacturing methods, additive manufacturing uses a computer-aided design, or CAD, downloaded from a computer to produce a 3D object. This means a design can be uploaded in one country, and then downloaded and printed in another. There is much to praise about this aspect of the democratization of manufacturing, from its expediency to its ingenuity; however, this unregulated and unmonitored transferring of goods poses some potentially serious problems for the export control regime. The prospect of digitizing goods will upset the norms of international trade, allowing items to be shared globally without the use of conventional shipping and transportation, and the types of goods that can be produced and the kinds of materials that can be used in additive manufacturing are growing steadily. Any individual with the right software, a capable printer, and access to the internet can produce a myriad of items from coat hangers to assault rifle receivers, and anyone with experience in CAD can create and upload those designs for anyone to print. The export control regime and participatory states have focused their efforts primarily on the movement of physical goods. In the realm of nuclear nonproliferation, these goods are generally classified as either dual-use or trigger list items. Dual-use items within the Nuclear Suppliers Group (NSG) guidelines are nuclear related items found in the commercial sector and used for peaceful purposes but could also be used by a military. The Wassenaar Arrangement has a Dual-Use and Technologies list; the Missile Technology Control Regime has its own version regarding missile technology; and the Australia Group has a similar Control List that focuses on the export controls of military and non-military chemical and biological materials. These lists can include materials, hardware, or even computer programs. For the purpose of this paper, the term "dual list" refers to nuclear technologies specified by NSG. Trigger list items are items that by their very presence require the implementation of nuclear safeguards. These items include nuclear reactors, the components of nuclear reactors, coolant pumps, gas centrifuge components, chemical storage containers, and almost everything else that can directly contribute to the production of nuclear energy (IAEA 2013a). The nuclear export control regime works with nation states to limit the unauthorized transfer of both dual-use and trigger list items to combat nuclear proliferation; however, additive manufacturing may begin to make that exceedingly difficult.

The transferring of CAD files online has been a difficult problem for the export control regime over the years and as additive manufacturing increases in popularity, this problem could potentially become worse.This paper examines the current state of additive manufacturing, providing a survey of the capabilities, materials, costs, benefits, limitations, and international use of the technology. It then outlines the export control regime and the NSG guidelines. Finally, this paper addresses the proliferation potential of additive manufacturing, taking into account the future applications of 3D printing and unconventional uses of the manufacturing process.

2.0 Export Controls and Additive Manufacturing

2.1 A Brief History of Additive Manufacturing

Additive manufacturing is a relatively young method of material fabrication that was born out of developments on several disparate technological fronts. In the late 1970s and early 1980s, the capabilities of computers and CAD reached a level of sophistication that allowed designers to create complex digital models. At the same time in Japan, developments in liquid photopolymers and lasers were making strides in prototype creation (Wohlers 2014b). These technological advances, as well advances in computer numerically controlled (CNC) machining, stereolithography, and powder sintering systems, made the development of additive manufacturing possible (Gibson et al. 2015).

In 1984, Charles Hull invented stereolithography and is widely credited as one of the founders of additive manufacturing. In 1992, Hull's company 3D Systems produced the first stereolithographic apparatus (SLA), which used a laser to solidify liquid photopolymer into 3D objects. That same year, DTM developed the first selective laser sintering (SLS) machine, which was similar in many ways to SLA but used a fine powder instead of a liquid (Wohlers 2014b). Both SLA and SLS designs continue to be used in additive manufacturing today. However, it is important to note that throughout the early years of additive manufacturing, this process was primarily used for rapid prototyping. The objects produced by these early pioneers could be made quickly at low cost but were not intended to be final products themselves. They were fragile and crude but provided manufacturers with a physical model of a design that could be examined and tested before committing to the high development costs of traditionally manufactured products.

Towards the end of the 1990s, 3D printers became increasingly available commercially at steadily decreasing prices, but they were still largely out of the hands of consumers. During this time, printers capable of manufacturing metal products also came on the market, significantly increasing the utility of additive manufacturing (Wohlers 2014b). In 2006, Objet, an Israeli company, produced the first printer capable of using multiple materials in the manufacturing process, and two years later, RepRap, an open source project, produced the first 3D printer capable of replicating the majority of its own components. In 2009, companies began selling do-it-yourself kits for individuals to build and then use their own 3D printers (Wohlers 2014b) and adaptive manufacturing broke into the consumer market. Today, 3D printers are available at a wide range of prices from less than $1,000 to over $1 million. These printers are capable of printing objects in metals, polymers, ceramics, waxes, sands, composites, and even organic materials. Unlike the original items built by additive manufacturing, the current capabilities of 3D printers allow items to function as final products. For this reason, "rapid prototyping" is no longer the preferred nomenclature. Instead, "3D printing" is the most commonly used term to describe the additive manufacturing process in both its commercial and personal applications.

2.2 The Current State of Additive Manufacturing

Since its creation in the 1980s, additive manufacturing has spread from the commercial world to consumer markets and has grown from limited prototyping applications to complete production capabilities. This is evidenced by the increased use of 3D printers, their prevalence in the media, their falling costs, and their evolving roles in both institutionalized and democratized manufacturing. It is an industry that is growing at a very healthy rate. In 2013, the additive manufacturing and 3D printing industry was valued at roughly $3.07 billion, but it is estimated to reach almost $13 billion by 2018 and $21 billion by 2020 (Wohlers 2014a). Currently, most of this money is still coming from the commercial sector as the more capable printers remain prohibitively expensive for the average consumer. Entry-level printers capable of sintering steel into 3D objects tend to cost at least $100,000, with higher-end units reaching $1 million. 3D Systems, the company co-founded by Charles Hull, offers 3D printers capable of using titanium for almost any price point within that range. Commercial polymer 3D printers tend to be slightly more affordable, occasionally dipping into the sub-$100,000 range. Businesses currently using traditional CNC machines would not find these prices prohibitively high, and significantly cheaper 3D printers are now being made for the average consumer in the sub-$5,000 range. MakerBot, one of the more popular consumer brands, offers their fifth-generation Polyactide (PLA) filament printer for $2,700. Dremel offers a similar printer for just under $1,000. The limitations of these printers compared to the commercial variety include smaller build sizes and inferior precision; however, they effectively bring the consumer into the manufacturing realm. Cost is becoming less of a concern for both commercial entrepreneurs and consumers who want to become involved in additive manufacturing.

Many industries have already begun to embrace additive manufacturing. Two of the most notable are the automotive industry and the aeronautical industry. The automotive industry uses additive manufacturing extensively for rapid prototyping; however, many small parts, including dashboards, exterior trim, pumps, valves, and vents, are now 3D-printed for final assembly in vehicles (Giffi et al. 2014). A benefit to additive manufacturing is that it can often build objects in one piece, unlike traditional manufacturing that requires the same object to be built in multiple pieces. In the aeronautical industry, General Electric, the world's largest producer of jet engines, has turned to 3D printing to produce 85,000 fuel nozzles for its new aircraft. A traditionally manufactured fuel nozzle has twenty pieces, whereas the 3D-printed design is one single piece and is arguably stronger and lighter (Catts 2013). This demonstrates not only the potential design capabilities but also the potential material capabilities of additive manufacturing, however in some cases traditional manufacturing is still considered superior.

A variety of materials are currently available as feedstock for additive manufacturing machines. Polymers are certainly a staple material of additive manufacturing, available in a variety of options such as acrylics, rubber, acrylonitrile butadiene styrene (ABS), and silicon; however, many other materials are used in additive manufacturing. Metals including aluminum, bronze, cobalt, copper, iron, nickel, steel, and titanium can be used by capable printers. Even gold and silver can be used, which has created a new industry of 3D printed jewelry. Gypsum and zirconia are among the few ceramics available, and wax and sands are also on the growing list of materials that can be used in additive manufacturing. Some innovative materials are also being used, such as carbomorph, which is a conductive thermoplastic composite capable of incorporating electronic sensors to respond to external stimuli (Leigh et al. 2012). These complex products can be manufactured in a single process entirely within a 3D printer. A number of additive manufacturing methods are available (see Table 2.1), each capable of handling specific materials or tasks, meaning a 3D printer suited for polymer filament cannot also be stocked with steel powder for sintering. As advanced as some of these printers may be, innovation in additive manufacturing is not limited to laboratories. Many individuals are using inexpensive polymer 3D printers to produce precision metal parts through investment casting. A mold is created by encasing a 3D printed polymer object in plaster and heating it until the polymer melts, leaving a cavity that is then filled with molten metal. This process is sometimes called "lost-wax casting" and is a very old technique that has been adapted for state-of-the-art applications. This method allows individuals to manufacture precise and unique metal parts at a very low cost.

Table 2.1. Additive Manufacturing Methods (Cotteleer et al. 2013)

Technology	Type	Materials	Pros/Cons
Stereolithography	Vat polymerization	Liquid photopolymer, composites	High complexity of design / Post-processing required
Fused Deposition Modeling	Material extrusion	Thermoplastics	Strong and complex designs / Slow build times
Electron Beam Melting	Powder bed fusion	Titanium powder	Fast build time with low waste / High-maintenance machines.
Selective Laser Sintering	Powder bed fusion	Polymer, metal, glass, ceramics, composites	Fast built time / Poor finish quality
Selective Heat Sintering	Powder bed fusion	Thermoplastic powder	Inexpensive, fast, complex designs / New method
Direct Metal Laser Sintering	Powder bed fusion	Steel, cobalt, nickel	Complex designs, unique materials / Limited to small objects
Laminated Object Manufacturing	Sheet lamination	Paper, polymer, metal, ceramics, composites	Inexpensive / Inaccurate
Laser Metal Deposition	Directed energy deposition	Metal	Can use multiple materials simultaneously, produces large objects / Expensive

This democratization of manufacturing is one of the most touted benefits of additive technology; however, there are many other advantages that are worth noting. 3D printing is often compared to CNC machining because at face value the two manufacturing processes are indeed similar. They both involve CAD models and contained processing machines, and there is overlap in the types of products made. In reality, CNC machining is actually quite different from additive manufacturing. CNC machining is a *subtractive* manufacturing process in which excess material is removed from a solid block of source material to reveal the final product. The additive nature of 3D printing presents several inherent advantages over this process. Building something through additive rather than subtractive means will produce much less waste, or perhaps no waste at all; this is called “waste stream elimination.” Additive manufacturing can also produce objects of far more complex designs at significantly lower costs than other manufacturing methods. In fact, the cost incentive to use 3D printing rises as the complexity of the design increases because other manufacturing methods tend to become drastically more expensive and involved when designs become more complex (Gibson et al. 2015). This is not the case with additive manufacturing. The accuracy of additive manufacturing is dependent on the material and printing device used, although sophisticated 3D printers can generally yield resolutions of less than one hundred microns (Gibson et al. 2015). Speed is another consideration. For low-volume production of goods, 3D printing dramatically expedites the manufacturing process because the design and production can all be done onsite without extensive assembly lines or supply chains. However, the actual additive process—meaning the physical layering of materials—is not exceptionally fast. Thus, large production operations will be slow compared to traditional manufacturing methods such as injection molding and casting. For this reason, as well as the somewhat limited selection of usable materials, additive manufacturing has failed to prove itself as a viable means of mass production. This is not to suggest that additive manufacturing has been widely rejected. On the contrary, additive manufacturing has been adopted in varying degrees all over the globe.

The largest consumer of additive manufacturing machines is the United States, which is responsible for 38.3% of all additive manufacturing installations from 1988 through 2011. Japan accounted for 10.2%, Germany for 9.3%, China for 8.6%, and the United Kingdom accounted for 4.4% of all additive manufacturing installations during this time (Ford 2014). Additive manufacturing is most popular in North America, Western Europe, and East Asia. Most of the world’s additive manufacturing technology originates in these three areas and Israel. Objet, one of the more prominent and innovative companies in additive manufacturing, was founded in Israel and continues to produce additive manufacturing technology, including printers, as a subsidiary of Stratasys. The Middle East, South America, Central Asia, and Africa remain relatively uninvolved in additive manufacturing, although this is likely to change as international sales of 3D printers are expected to increase significantly over the coming years. In 2015, the expected worldwide total shipments of 3D printers is estimated to reach 244,533 units. It is predicted that in 2016 that number will double, reaching 496,475, and by 2019, international 3D printer shipments are expected to reach approximately 5.6 million (Woods and Meulen 2015).

Additive manufacturing is not a fledgling enterprise; however, it has yet to replace any of the major manufacturing methods in large-scale production. The state in which additive manufacturing presently exists is not expected to last long. The current data and trends suggest additive manufacturing will continue to rise in popularity and begin replacing traditional manufacturing in many applications. Innovation within the field will push the boundaries further and new uses and applications will be found. In his 2013 State of the Union address, President Barack Obama proclaimed that 3D printing, “has the potential to revolutionize the way we make almost everything” (Obama 2013). Obama’s use of the word *revolutionize* is appropriate because this emerging disruptive technology is expected to transform the status quo by altering how goods are designed, manufactured, and shared.

2.3 Export Controls

Monitoring and controlling nuclear technology is an arduous task for a number of reasons. The nuclear nonproliferation regime has to contend with the dilemma of deterring the spread of nuclear weapons and nuclear weapons technology while simultaneously encouraging the use of nuclear technology for peaceful energy purposes. Peaceful applications of nuclear energy are used by many countries; however, there have been instances when nations with peaceful nuclear infrastructures have been suspected of diverting their nuclear resources to weapons development. The concern over further and future diversion has led to the development of export control guidelines as a nonproliferation measure. Export controls are put into place to monitor the movement of a variety of potentially dangerous technologies and materials across borders. This paper looks specifically at the export controls for the movement of nuclear goods. The intention of the export control regime is to ensure that states with peaceful nuclear programs can continue to develop those programs safely through international assistance and trade, while maintaining a watchful eye for signs of abuses, mistakes, theft, or creation of technology or materials that could lead to the production of nuclear weapons. Nations in compliance with the NSG, the Wassenaar Agreement, the Missile Technology Control Regime, and the Australia Group engage in export controls by focusing on two primary sources of diversion: dual-use items and trigger list items. Dual-use items within the NSG guidelines are technologies or materials that have legitimate peaceful purposes within the civilian nuclear energy sector but could be co-opted by militaries for use in nuclear weapons programs. Trigger list items are similar except their presence within a country will initiate International Atomic Energy Agency (IAEA) safeguards. This list includes items ranging from gas centrifuge components to complete uranium enrichment facilities. The export control regime provides guidelines for states to monitor the shipping and transportation of these items to ensure their use remains peaceful and their locations known.

2.3.1 Dual-Use Items

In the context of nuclear nonproliferation, dual-use items are nuclear technologies or materials that are used to produce nuclear energy for peaceful purposes but could also be used to produce nuclear weapons. The NSG's list of dual use items consists of six categories:

1. Industrial equipment
2. Materials
3. Uranium isotope separation equipment and components
4. Heavy water production plant related equipment
5. Test and measurement equipment for the development of nuclear explosive devices
6. Components for nuclear explosive devices (IAEA 2013b)

None of the items listed are trigger list items, meaning, for example, none of the gas centrifuge components listed as dual use items necessitate IAEA safeguards implementation. Each category provides extensive lists of items considered dual use within that field which require special considerations on behalf of both the exporter and importer states. One item of particular interest on this list is a rather generically defined category for software, which qualifies if it is used in conjunction with any nuclear equipment. Participatory nations attempt to track and record these items to ensure their use is not contributing to nuclear weapons development; however, the trading of these items is difficult to monitor and requires significant cooperation and input from state governments.

2.3.2 Trigger List Items

The presence of any item on the trigger list will "trigger" nuclear safeguards into effect. This allows the IAEA to verify its application with greater scrutiny, including onsite inspections, environmental sampling, and investigations into both declared and undeclared facilities. Items on the trigger list include the major components of the following:

- Nuclear reactors
- Nuclear fuel reprocessing plants

- Nuclear fabrication plants
- Uranium isotope separation plants and centrifuges
- Deuterium and heavy water production plants
- Uranium and plutonium conversion plants (IAEA 2013a)

Monitoring the transportation of these items is of paramount importance to the export control regime, as the trading and manufacturing of trigger list items can lead to clandestine nuclear weapons programs. While many of these are technically dual use items, a significant number of them are excluded from the dual use list because dual use items are not monitored as stringently as trigger list items; labeling items on the trigger list as "dual use" could potentially lead to them being exported under the comparatively lax dual-use regulations. Trigger list items are critical components of nuclear weapons programs and are regarded as high-priority concerns. Illicit proliferation networks face the difficulty of moving nuclear technology or materials across borders or shipping them through ports. To maintain this deterrent, the export control regime monitors trigger list items with dedicated acuity.

2.4 The Implications of Additive Manufacturing and Export Controls

Most current discussions about additive manufacturing and security focus on small arms proliferation. This topic was one of the earliest and most realistic "what-if" security concerns of the general public. In 2012, shortly after 3D printing began infiltrating the consumer market, a twenty-four-year-old law student in Texas founded Defense. This company used crowdfunding to design and develop a usable 3D-printed gun made out of ABS plastic. Shortly after the completed CAD files were published on the internet, the U.S. Department of State ordered the company to remove them while it reviewed the legality of the situation (Bryans 2015). After temporarily complying, Defense Distributed took advantage of the legal ambiguity surrounding additive manufacturing and resumed its efforts to design and distribute open source 3D-printable guns. The difficulty the company faced was designing a functional gun made out of plastic. After extensive research and development, Defense Distributed increased the lifetime of its plastic 3D printed AR-15 receiver from six rounds to six hundred rounds (Bryans 2015). Defense Distributed presents a weapons proliferation concern; however, there is no sign the company is doing any covert proliferation. The designs and capabilities have all been presented publicly, which is how the State Department was able to respond within days of the design's release. What if it had been done in secret? What if the CAD files had been created and then distributed on the deep web or through encrypted channels? The entire purpose of Defense Distributed's design was to allow anyone to produce an unregistered weapon; therefore, the required materials and printing devices were affordable and relatively easy to obtain, and little to no manufacturing expertise was required. This type of activity is the nuclear proliferation concern of additive manufacturing. The increasing capabilities of additive manufacturing to produce nuclear-related hardware, the waste stream elimination aspects of additive manufacturing, and the ability to transfer items virtually with CAD files rather than physically exporting goods across borders all present problems for the export control regime.

While some of these problems are not yet possible, the current capabilities of additive manufacturing warrant some degree of concern. The limitations faced by Defense Distributed were primarily caused by the company's philosophy: to design a weapon from substandard materials. Firearms are typically made from metal because plastics are not strong enough to withstand the explosive force of gunpowder. With the current variety of materials available to additive manufacturers, Defense Distributed's self-imposed material restrictions does not mean that fully functioning 3D-printed firearms are not possible. Individuals willing to spend some extra money have produced reliable metal firearms through additive manufacturing.

New Nuclear Manufacturing (NNUMAN) is a program in the United Kingdom researching innovative manufacturing methods for the nuclear industry. An article about NNUMAN stated that it is looking into weld-based additive manufacturing to produce nuclear components such as reactor vessel nozzles and valve bodies (Nuclear AMRC 2012). Weld-based additive manufacturing is more officially referred to as also called "Electron Beam Additive Manufacturing" (EBAM) and uses an additive method similar to that of plastic filament 3D printers to produce large and complex metal products. EBAM machines are significantly larger than typical additive manufacturing machines, are on the high end of the price range, are intricate, and require expertise to operate—all factors that would prevent the average consumer or sub-state actor from using them to produce the same goods envisioned by NNUMAN. Not all nuclear components require such sophisticated machinery, however, and the export control regime is fully aware of this. Centrifuges require extremely precise manufacturing and calibration to work properly, particularly the rotating mechanisms. These components are difficult to fabricate, even with adequate resources; however, not all of the components are as demanding. In INFCIRC/254, which outlines the trigger list items, the IAEA mentions that there are centrifuge components that "do not rotate and which although they are especially designed are not difficult to fabricate nor are they fabricated out of unique materials" (IAEA 2013a). The nuclear manufacturing industry recognizes the potential of additive manufacturing to produce high-precision, complex machinery needed for the production of nuclear energy, while the export control regime recognizes the potential for less sophisticated mechanisms to be produced through less sophisticated means. The construction of centrifuges is still exclusive to well-resourced and highly funded organizations, but the lower costs of additive manufacturing is as tempting to NNUMAN as it is to any other commercial actor. If the capability and cost trends of additive manufacturing continue undisrupted, the goods produced by the nuclear manufacturing industry will become increasingly available to individuals or actors with fewer resources and less funding. After all, the democratization of manufacturing is one of the many proclaimed benefits of this disruptive technology.

Another recognized benefit of additive manufacturing is decreased waste production. When compared to traditional manufacturing techniques, additive manufacturing receives praise for its reduction or elimination of material waste (Lucibella 2015). Although this waste stream elimination is financially beneficial to businesses, it is detrimental to nonproliferation safeguards and the export control regime (EPA 2006) because waste is evidence of possible proliferation and an indication of the activities performed at certain sites (Lucibella 2015). Without the presence of waste, nuclear watchdog organizations have fewer options for safeguards verification and proliferators may therefore be less deterred by the threat of inspections because the evidence is easier to conceal

Perhaps the most daunting implication of additive manufacturing and nuclear proliferation is the increased need for export controls in cyberspace. For the most part, additive manufacturing relies on file sharing on the internet rather than on shipping physical goods in crates. This is not a new problem for the export control regime, but additive manufacturing does exacerbate the situation. The transfer of files created by the nuclear manufacturing industry is theoretically possible, meaning designs for nuclear technology can be shared digitally then built physically without alerting the export control regime. In this capacity, additive manufacturing machines could serve as nodes in illicit proliferation networks. Bruce Goodwin, who is associate director for national security policy and research at Lawrence Livermore National Laboratory, was able to download a CAD file for a nuclear reactor component from the internet and print it in stainless steel. The original part consists of 168 separate welds and takes a long time to manufacture, while the 3D printed version was far simpler in design and took only four hours to build (Lucibella 2015). While this part may certainly appear capable, it is important to acknowledge that the material properties of additively manufactured parts are not yet fully accounted for so the question still remains of whether or not this part is truly functional. If these items were being shipped through traditional means and properly documented, the export control regime would be able to track them more easily and figure out their intended purposes. INFCIRC/254, in reference to the easy-to-fabricate centrifuge components, continues to say that a centrifuge facility, "requires a large number of these components, so that quantities can provide an important indication of end use." (IAEA 2013a) If a facility downloads or creates the necessary CAD files, it could theoretically amass a sizeable inventory of these components without any external indications. This scenario does more than simply introduce a potential avenue of covert proliferation, it undermines the value of international sanctions as a response or deterrent. Additive manufacturing could be another way to circumvent trade restrictions imposed on countries guilty of nuclear proliferation. These are the problems presented by the sharing of CAD files in cyberspace that may need to be addressed by the export control regime to prevent nuclear proliferation through additive manufacturing.

Several questions remain regarding export control and additive manufacturing. Will additive manufacturing become a dual-use technology? If so, which aspects? The software could potentially fall under the NSG guidelines as they are currently written, but what about the hardware? Would only the high-end sophisticated machines be considered dual use? When considering these questions, it is important to remember that much of the additive manufacturing technology is not new. Sharing CAD files has been taking place for decades, and while additive manufacturing allows for new and innovative designs, the traditional designs for nuclear components have existed for seventy years—and their blueprints have been shared in the past despite export controls. One could argue that the manufacturing knowledge needed to build a nuclear weapon is less necessary with additive manufacturing. Additive manufacturing can be a fairly automated process: an individual downloads someone else's CAD file, sends it to a printer, and waits for the final product to be built. Formal training in manufacturing techniques or CAD programs is not required. This argument may be realistic when it comes to individuals acquiring firearms through additive manufacturing, but nuclear proliferation is more complex. An individual who is capable of assembling a nuclear weapon, yet unable or unwilling to learn AutoCAD, is unlikely to exist. Finally, additive manufacturing machines require feedstock to produce anything, meaning that the need to mine, process, and enrich uranium still persists. It is not as simple as downloading Fat Man and hitting Print and it likely will not be for quite some time.

2.5 The Future of Additive Manufacturing

Additive manufacturing is still very much a nascent manufacturing medium. Based on its current trajectory, the technology is expected to continue to advance in capability; the consumer costs will continue to drop as that market continues to grow; more industries will begin to engage in additive manufacturing; and it will continue to prove itself a disruptive technology on many fronts. The majority of additive manufacturing technology mentioned in this paper is still evolving. EBAM machines, for example, are a rarity, and the tentative inclusion of that technology into the nuclear manufacturing industry has less to do with uninformed nuclear engineers and more to do with the immaturity of that method of additive manufacturing. In some cases, the consumers are ready and willing, but additive manufacturing has yet to prove itself as a viable alternative to current methods. In other cases, additive manufacturing is regarded with caution as a disruptive technology. Current market demands and research conducted at laboratories and universities are the driving forces behind much of the innovation taking place within additive manufacturing.

A number of concepts are being experimented with now, such as the use of a conductive composite material called carbomorph in 3D printers to build customizable electronics. Other new concepts include the printing of complete complex electronics and products printed with battery materials integrated into the design (Wohlers 2012). While the design frontier has been advanced significantly by additive manufacturing, material limitations still exist, not only in variety but also in quality. Additive methods such as fused deposition modeling, which rightly claims many of the novel benefits of 3D printing, lacks in material strength. Innovators are currently researching methods for using carbon fiber as a feedstock for 3D printers to improve strength without tarnishing 3D printing's weight-saving reputation (Eitel

2013). Another development on the horizon is 4D programmable matter, which essentially is a 3D printed product that is capable of restructuring its shape, appearance, or function after construction. A theoretical example of this would be 3D-printed high-heeled shoes that could "morph" into regular flat-soled shoes when the wearer goes from a formal wedding ceremony to a casual reception. Similar to the origins of additive manufacturing, 4D programmable matter has been made possible by developments on several different technological fronts, including 3D printing, miniaturized robotics, and smart materials (Campbell et al. 2014). 4D programmable matter exists today; however, it has yet to develop to the point of delivering practical real-world applications. Most 4D programmable matter exists within university laboratories and requires submersion in water to stimulate the programed behavior. For this technology to develop further, it must overcome a number of challenges including limitations of CAD software to accommodate programmable matter, high costs of production, the unorthodox assembly requirements, the standardization of this technology across the field, and of course the security implications of this disruptive technology (Campbell et al. 2014). These problems are still being dealt with by additive manufacturing as a whole, but in the coming years, they are expected to be overcome and these bold and innovative ideas will continue to develop.

Advances like this are expected to continue at a fast pace, encouraging an increasing number of industries to use additive manufacturing for their various needs. The health sector is beginning to use additive manufacturing to build orthopedic parts for end-use in patients because the design customization is desirable and the ability to build with titanium is ideal. Drones, another disruptive technology, are also potential candidates for additive manufacturing. The U.S. Air Force is considering this method to build its next generation of drones because it improves logistics and allows for superior designs that are more affordable and require fewer parts (Eitel 2013). It would also allow for replacement parts to be built in the field, increasing military survivability and resourcefulness. The military applications for 3D printing are expected to expand on this potential by providing soldiers with a means to manufacture equipment on the battlefield—saving both time and lives. The U.S. Army recently used additive manufacturing to rapidly prototype a new aircrew mask (see Figure 2.1), reportedly saving thousands of dollars in the design process by abandoning traditional manufacturing methods (Merritt 2015). This is an early example of what is expected to become a large-scale adoption of additive manufacturing by the U.S. Department of Defense; in fact, the Government Accountability Office has instructed the Pentagon to begin tracking its implementation of 3D printing. As of now, the Department of Defense does not collect this information, so this initiative will reduce the likelihood of research and development redundancy within the military.

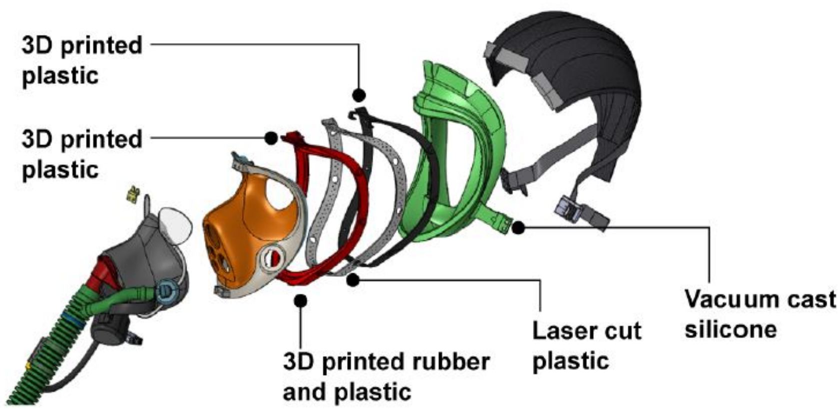

Figure 2.1. Aircrew Mask Prototype. Source: GAO (Merritt 2015).

The automotive and aerospace industries, both early adopters of additive manufacturing, have made claims of what they want to do with the technology; however, the commercial sector is not the only space in which additive manufacturing is expected to thrive. Consumers are enjoying the increasingly low entry costs into the manufacturing domain as desktop 3D printers offer individuals the chance to create and innovate on their own. Additive manufacturing machines are expected to become commonplace in households in the coming years as the costs and benefits begin to match any home appliance.

With the predicted proliferation of 3D printers comes the concern from both national security analysts and intellectual property rights advocates of how to control and monitor what the public is manufacturing. The music industry has been grappling with this problem ever since record albums went digital. Will 3D printing enforcement implement or expand on these protection mechanisms? It is certainly possible; however, 3D printing's catalytic effect on human innovation has inspired researchers to propose an intriguing solution. Objects built through additive manufacturing can be infused with unique formations of microbubbles or "random voids" that encode information into the object. These hollow structures can be incorporated into the additive process by first opening a crater in the layers and then using a step-over technique in which each layer overhangs the preceding layer until the hollow space is completely enclosed. A scanner operating in the Terahertz region can penetrate the 3D-printed object to locate these hollow spaces and map the unique pattern. This information can then be decoded to reveal data pertaining to the object's origins. Microsoft has called these identifiers "InfraStructs" (see Figure 2.2), and they work similar to radiofrequency identification tags found in security badges, meaning they can be harmlessly scanned to relay specific information (Willis and Wilson 2013). Should this technology be developed further, it could be adopted by the export control regime and used to monitor 3D-printed goods entering or leaving countries. However, the development of InfraStructs does not address the proliferation concern presented by the digital sharing of CAD files.

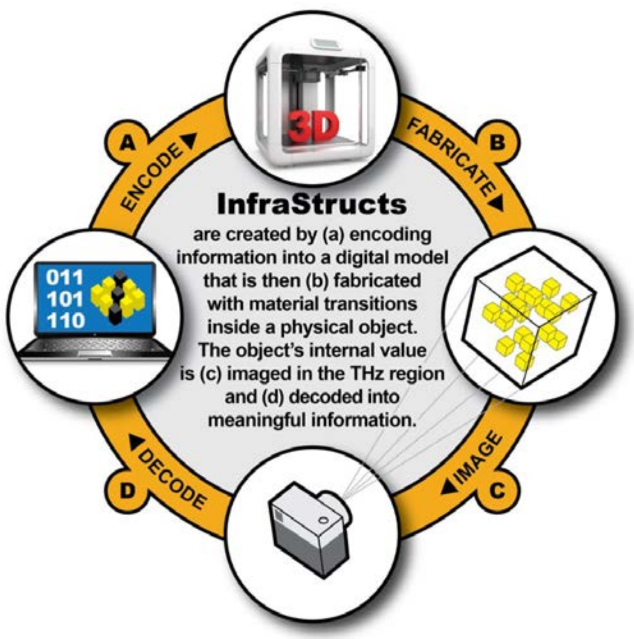

Figure 2.2. The InfraStructs Process (adapted from Willis and Wilson 2013)

3.0 Conclusion

Additive manufacturing has come a long way over the last three decades. Initially a means of convenient prototyping, it is now being used to democratize the manufacturing process. This means more than simply changing how things are built. It has the potential to change how things are shared, designed, valued, acquired, and used. Theoretically, additive manufacturing could completely restructure global commerce and make the current standards of business obsolete. This is why additive manufacturing is described as a disruptive technology. Additive manufacturing opens the doors to the manufacturing world to almost anyone who has access to the internet and owns any of the increasingly accessible 3D printers. Some of the most capable 3D printers, which today are in fact quite capable in terms of viability and practicality for select applications, are within reach of small businesses and risk-taking entrepreneurs. For the average consumer, 3D printers are available in the size and at the price point of a decent espresso machine, and enough CAD files are available online for people to build any number of small items without any knowledge or background in digital modeling. Additive manufacturing is seen as cost-effective, expedient, and innovative, and these traits are relevant to almost every application across the spectrum of the rapidly growing manufacturing realm. The material and design specifications of additive manufacturing allow for the production of simple coffee cups to advanced aerospace technology. For the coffee enthusiast, the cost of a cup is as low as the cost of the polymer filament used to build it. For the aerospace engineer, additive manufactured parts are cheaper to build because the production process is reduced and streamlined. For both of these individuals, additive manufacturing offers faster turnaround rates on production. Previously, models were built and molds were made, and then these molds were used to cast the final product, which then required post-processing or further assembly before finally being ready for use. This process would often involve offsite operations, possibly overseas, which would cost money and could take weeks or months to complete. Today, CAD models are created and the item is manufactured within hours with minimal post-processing or assembly required. Another advantage of additive manufacturing is that it allows items with complex functions to be built with fewer parts, which is attractive to the aerospace engineer because components can be built to stronger and lighter specifications.

For both the coffee enthusiast and aerospace engineer, additive manufacturing works because it offers fewer compromises in the manufacturing process. However, a number of the benefits of additive manufacturing are detrimental to the export control regime. The manufacturing power that additive technology surrenders to the general public has the potential to overburden the export controls currently in place. The nuclear technology applications of additive manufacturing have already been acknowledged by the nuclear manufacturing industry, suggesting that 3D printers could play an active role in illicit proliferation networks. The existence of dual-use and trigger list items as digital models will continue to force the export control regime to monitor the online distribution of CAD files, which is no simple task. Should proliferators, whether they be state, military, or subnational in origin, decide to adopt additive manufacturing for illicit purposes, it could prove difficult for the export control regime to carry out its mission.

4.0 References

Bryans, D. 2015. "Unlocked and Loaded: Government Censorship of 3d-Printed Firearms and a Proposal for More Reasonable Regulation of 3d Printed Goods," Indiana Law Journal, 90(901):901-934.
Campbell, TA, S Tibbets, and B Garrett. 2014. The Next Wave: 4d Printing - Programming the Material World, Atlantic Council.

Catts, T. 2013. "Ge Turns to 3D Printers for Plane Parts," *Bloomberg Business*. Accessed November 11, 2015 at
http://www.bloomberg.com/bw/articles/2013-11-27/general-electric-turns-to-3d-printers-for-plane-parts

Cotteleer, M, J Holdowsky, and M Mahto. 2013. The *3D Opportunity Primer: The Basics of Additive Manufacturing*, Deloitte University Press, Westlake, Texas.

Eitel, E. 2013. "The Future of Additive Manufacturing," Machine Design, 85(3):52-56.
http://search.proquest.com/docview/1427257851?accountid=28112

EPA. 2006. *The Lean and Environmental Toolkit: Identify and Eliminate Waste, Reduce Business Costs and Risk, Improve Environmental Results*, U.S. Environmental Protection Agency, Washington, DC.

Ford, SLN. 2014. "Additive Manufacturing Technology: Potential Implications for U.S. Manufacturing Competitiveness," *Journal of International Commerce and Economics*:1-35.

Gibson, I, D Rosen, and B Stucker. 2015. *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*. 2 ed., Springer, New York.

Giffi, CA, B Gangula, and P Illinda. 2014. *3D Opportunity in the Automotive Industry: Additive Manufacturing Hits the Road*, Deloitte University Press, Westlake, Texas.

IAEA. 2013a. "Communications Received from Certain Member States Regarding Guidelines for the Export of Nuclear Material, Equipment or Technology," Information Circular, Infcirc/254/Rev.9/Part 1, 2013. International Atomic Energy Agency.

IAEA. 2013b. "Communications Received from Certain Member States Regarding Guidelines for the Export of Nuclear Material, Equipment or Technology," Information Circular, Infcirc/254/Rev.9/Part 2, 2013. International Atomic Energy Agency.

Leigh, SJ, RJ Bradley, CP Purssell, DR Billson, and DA Hutchins. 2012. "A Simple, Low-Cost Conductive Composite Material for 3d Printing of Electronic Sensors," *PLoS ONE*. DOI: 10.1371. Accessed November 11, 2015 at
http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0049365

Lucibella, M. 2015. "Manufacturing Revolution May Mean Trouble for National Security," *APS News*. American Physical Society Accessed October 9, 2015, 2015 at
http://www.aps.org/publications/apsnews/201504/revolution.cfm

Merritt, ZD. 2015. *Defense Additive Manufacturing: DoD Needs to Systematically Track Department-Wide 3D Printing Efforts*, United States Government Accountability Office G.A. Office.

Nuclear AMRC. "Introducing Nnuman: The Next Generation of Nuclear Manufacturing." 2012. Nuclear AMRC, Sheffield, UK.

Obama, B. 2013. “Remarks by the President in the State of the Union Address.” The White House, Washington, D.C.

Willis, KDD and AD Wilson. 2013. “Infrastructs: Fabricating Information inside Physical Objects for Imaging in the Terahertz Region,” *ACM Transactions on Graphics*, 32(4). doi:10.1145/2461912.2461936.

Wohlers Associates. 2014a. “3D Printing and Additive Manufacturing Industry Expected to Quadruple in Size in Four Years,” Press Release, August 19, 2014. Accessed October 2, 2015, 2015 at http://www.wohlersassociates.com/press65.html

Wohlers, T. 2014b. “History of Additive Manufacturing,” Wohlers Associates, Inc.

Wohlers, T. 2012. “Additive Manufacturing Advances,” Manufacturing Engineering, 148(4):55-56,58,60-63. http://search.proquest.com/docview/1010038311?accountid=28112

Woods, V and RVD Meulen. 2015. “Gartner Says Worldwide Shipments of 3d Printers to Reach More Than 490,000 in 2016,” Gartner. Accessed October 1, 2015, 2015 at http://www.gartner.com/newsroom/id/3139118

5.0 Additional Bibliography

Anthony, I, C Ahlstrom, and V Fedchenko. 2007. *Reforming Nuclear Export Controls: The Future of the Nuclear Suppliers Group*, SIPRI Oxford University Press, Oxford, England.

Bird, J. 2012. “Exploring the 3d Printing Opportunity,” *Financial Times*.

Dobson, M. 2015. “From Wassenaar to Mars: Open Source Hardware, U.S. Export Controls, and Avoiding Missteps in the Maker Movement,” Kelley Drye (kelleydrye.com). Accessed November 11, 2015 at http://www.kelleydrye.com/publications/articles/1927/_res/id=Files/index=0/wassenaar_whitepaper_v3.pdf

The Economist. 2012. “A Third Industrial Revolution.” April 21, 2012. *The Economist*:1-14. The Economist Newspaper Limited.

Fergusson, IF and PK Kerr. 2014. “The U.S. Export Control System and the President's Reform Initiative,” Congressional Research Service C.R. Service.

Gao, W, Y Zhang, D Ramanujan, K Ramani, Y Chen, CB Williams, CCL Wang, YC Shin, S Zhang, and PD Zavattieri. 2015. “The Status, Challenges, and Future of Additive Manufacturing in Engineering,” *Computer-Aided Design*, 69:65-89. doi:http://dx.doi.org/10.1016/j.cad.2015.04.001. Accessed November 11, 2015 at http://www.sciencedirect.com/science/article/pii/S0010448515000469

Jarboe, KP. 2014. “Additive Manufacturing as a Disruptive Technology,” Working Paper, National Research Council/National Academies, 1-5 pp. Athena Alliance.

Mcnulty, CM, N Arnas, and TA Campbell. 2012. *Toward the Printed World: Additive Manufacturing and Implications for National Security*, National Defense University, Washington, D.C.

Mourdoukoutas, P. 2015. “How 3D Printing Changes the Economics of Outsourcing and Globalization,” Forbes.
http://www.forbes.com/sites/panosmourdoukoutas/2015/07/18/how-3d-printing-changes-the-economics-of-outsourcing-and-globalization/

Munoz, C, C Kim, and L Armstrong. 2013. *Layer-by-Layer: Opportunities in 3d Printing - Technology Trends, Growth Drivers, and the Emergence of Innovative Applications in 3d Printing*, MaRS Market Insights M.D. District.
http://www.marsdd.com/wp-content/uploads/2014/04/MAR-CLT6965_3D-Printing_White_paper.pdf

Sciaky Inc. 2015. “Make Metal Parts Faster and Cheaper Than Ever with Electron Beam Additive Manufacturing (EBAM) Systems or Services.” Accessed on 10/12/2015, 2015 at http://www.sciaky.com/additive-manufacturing/electron-beam-additive-manufacturing-technology

Ship, SS, N Gupta, B Lal, JA Scott, CL Weber, MS Finnin, M Blake, S Newsome, and S Thomas. 2012. *Emerging Global Trends in Advanced Manufacturing*, Institute for Defense Analysis, Alexandria, Virginia.

Stecker, S, KW Lachenberg, H Wang, and RC Salo. 2006. *Advanced Electron Beam Free Form Fabrication Methods and Technology*, Sciaky Incorporated, Chicago, Illinois.

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