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Evaluating WMD Proliferation Risks at the Nexus of 3D Printing and Do-It-Yourself (DIY) Communities

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EXECUTIVE SUMMARY

This report summarizes the analysis and findings of our research project entitled "Evaluating WMD Proliferation Risks at the Nexus of 3D Printing and Do-It-Yourself (DIY) Communities."

Conducted by a team with the Middlebury Institute of International Studies at Monterey's (MIIS) James Martin Center for Nonproliferation Studies (CNS), our project builds upon emerging literature in the weapons of mass destruction (WMD) nonproliferation field highlighting additive manufacturing (AM)—which includes 3D printing—as a potential proliferation risk.[1] Specifically, our project analyzes a set of export-controlled items to understand the degree to which 3D printing might be used to produce—and thus represent a new pathway for proliferators to acquire—dual-use goods useful for the development of WMDs. Additionally, in the context of the widespread, global distribution of AM technology, the study considers the degree to which communities using and promoting 3D printing may impact the risk of WMD proliferation.

This executive summary describes briefly our study's methodology, the structure of this report, and most importantly, key findings and recommendations.

OUR STUDY: METHODOLOGY AND OUTPUTS

Our study examines the WMD proliferation risk of AM using three levels of analysis:

» the "item"-level by analyzing a set of export-controlled dual-use items and the degree to which 3D printing offers a new path to their production. Items include vacuum pumps; missile components such as heat shields and rocket-propulsion systems; and unmanned aerial vehicles (UAVs);

» the "legal user"-level by analyzing civilian/commercial user communities of 3D printing, including industrial promotion efforts at the nation-state level, 3D printing service providers, and Do-It-Yourself (DIY) communities of 3D printing enthusiasts; and,

» the "illicit user"-level by analyzing potential interest in 3D printing from state-level WMD programs (as exemplified by North Korea) and non-state actor terrorist organizations (as exemplified by the Islamic State/IS).

Examining AM across these three levels—encompassing the technology and its users—yields a more comprehensive picture of the proliferation risk. Driving the data collection and analysis, the project team prepared working papers linked to each of these levels of analysis. The papers covered vacuum pumps, missile components, UAVs (drones), nation-state level industrial policies that

1 See Matthew Kroenig and Tristan Volpe, "3D Printing the Bomb? The Nuclear Nonproliferation Challenge," *The Washington Quarterly*, Vol. 38, No. 3, Fall 2015, pp. 7-19; Grant Christopher, "3D Printing: A Challenge to Nuclear Export Controls," *Strategic Trade Review*, Vol. 1, No. 1, Autumn 2015, pp. 18-25.

concern 3D printing, DIY communities and 3D printing, profiles of Makerspaces[2], 3D printing services, North Korea and 3D printing, and potential interest by terrorist organizations in 3D printing with a focus on the IS.

Outputs for this project include the following:

Main Report (this section): a summary of the findings of our working papers, organized according to the three levels of analysis. Additionally, subsections correspond to specific working papers that guided our overall study. The full set of working papers can be found in the Appendix to this report as described below;

"Risk Matrix" (included as a distinct section in the Main Report): a tabular summary of WMD proliferation risks associated with 3D printing, organized by the export-controlled items surveyed and includes relevant DIY-community activity/interest in using 3D printing to produce the items; and,

Appendix (separate section in this document that supplements the Main Report): the full set of complete working papers that guided our overall study. Details of our research and sources consulted are included in this document.

KEY FINDINGS

Organized according to the three levels of analysis described above, our findings are summarized below, followed by our recommendations for policy and further research.

ITEM-LEVEL FINDINGS

- » For the set of export-controlled items surveyed, and within the parameters of our investigation, we found no evidence of 3D printing being used to support WMD development actively, although we cannot rule out the possibility.
    - » The items surveyed included vacuum pumps, missile components (specifically heat shields and propulsion systems for rockets), and UAVs as defined by specific technical parameters on relevant nonproliferation export-control lists, e.g. Nuclear Suppliers Group (NSG) Guidelines Part 1 and/or Part 2 or the Missile Technology Control Regime (MTCR) Annex.

2 The Maker Movement is realized through hundreds of physical spaces where individuals can be trained and experiment with machinery that can "make" objects that they themselves invent. These spaces generally allow access to 3D printers, laser cutters, microcontrollers, CNS machines and other machines for fabrication and creation (see M. Krebs, *Manufacturing Expertise for the People: The Open-Source Hardware Movement in Japan*, EPIC 2014, p. 28035. 2014.). These spaces are often referred to synonymously as "Hackerspaces", "Makerspaces,", "Techshops" and "Fablabs", but in fact there are subtle differences between all of these. This report focuses primarily on Makerspaces, which are places utilized "to democratize the act of making something from scratch as well as you can (whatever it may be)." (Quote is from G. Cavalanti, "Is it a Hackerspace, Makerspace, TechShop, or Fablab?" *Make Magazine*, May 22, 2013.)

- In theory, 3D printing can be used to make any of the items surveyed; however, among the items surveyed, the only publicly reported examples of 3D printing as the primary manufacturing method involve specific makes of UAVs.

- Due to the emergence of multiple print-head systems, the size of 3D printers is no longer a fundamental constraint on what can be printed.

- The primary barriers to use of 3D printers are non-technical in nature. The principal constraint is not what can or cannot be 3D printed, but instead whether a) it is economical to print; b) required materials can be obtained; and c) electronic design files (Computer Aided Design/CAD or Stereolithography/STL files) used with 3D printers are available.

  - In our discussions with private sector-based practitioners familiar with 3D printing in industrial settings, the electronic design files emerged as the key dimension of 3D printing that should require robust controls on access, distribution, and trade/export.

- DIY communities display visible interest and activity regarding vacuum pumps and UAVs, especially, as well as the sharing of CAD and STL files. It is less apparent for heat shields and rocket-propulsion systems, although well-resourced civilian/commercial operations such as NASA and SpaceX are active in these areas and both are experimenting with 3D printing components of spacecraft (notably engine components).

- Among the items surveyed, UAVs pose the greatest proliferation risk, due to extensive use of AM (including 3D printing services) in production of certain drone types, and strong interest and experimental activity within DIY communities.

LEGAL-USER-LEVEL FINDINGS

- Nation-states, 3D printing services, Makerspaces, and DIY communities are working constantly to increase the capabilities, lower the costs, and expand the number of entities with access to 3D printing technology.

- 3D printing is viewed almost entirely in terms of the potential economic and human welfare gains the technology offers rather than the potential security risks posed by its dissemination.

- Across the spectrum of legal users (nation-states exploring 3D printing from an industrial growth perspective, 3D printing services, Makerspaces, and DIY communities), there appears to be very little concern regarding the proliferation threat from 3D printing.

  - Beyond US government agencies focused on nonproliferation, the only notable exception is a subset of US-based 3D printing services that serve large US corporations primarily and that offer solutions in compliance with export control regulatory requirements.

ILLICIT USER-LEVEL FINDINGS

- This study has found no evidence suggesting active pursuit or deployment of AM technology with a WMD proliferation aim in either case study (North Korea and IS) surveyed at this level.
- Although North Korea's foray into AM has been limited to small-scale demonstration of the technology for ostensibly civilian applications, state-supported institutions there claim to have produced at least two 3D printers, one of which is suspiciously akin to the MakerBot-branded 3D printer. This claim suggests North Korea's intention is not merely to explore the use of 3D printing, but also to explore the production of AM equipment itself.
- In the context of scaling 3D printers, any North Korean success in customizing 3D printers with advanced industrial applications could benefit its WMD programs directly by reducing development/production time and engineering resources needed.
- While this study was not able to confirm evidence of the IS's interest in AM's potential for WMD development, the widespread geographic distribution of AM technology and DIY-oriented Makerspaces has made the technology accessible by users in countries where the IS has been particularly active: Pakistan, Afghanistan, Egypt, Morocco, and Turkey.
- Accordingly, if the IS leadership were to make the decision to vigorously explore AM as a potential pathway to WMD, the technology would be readily accessible, with little need to import from producer countries.

Additional findings are summarized in the Item-Level, Legal-User Level and Illicit-User Level sections of the Main Report, as well as in the corresponding working papers (see Appendix).

RECOMMENDATIONS

Based on the findings of our study, the project team has identified a set of Recommendations for policy communities and further research. These are summarized below, with some additional thoughts on next steps covered in this report's "Conclusion" section.

- Given the diminishing technical barriers to 3D printing of the dual-use export-controlled items we surveyed, the following policy-related measures should be considered:
  - Augmentation of export controls and user-awareness strategies relevant to materials used in 3D printing.
  - Augmentation of export controls and user-awareness strategies relevant to design files such as CAD or STL files (and the platforms used to share them) that are used with 3D printing.

- Additionally, further research on the specific cost-driven barriers to 3D printing is recommended, as these are emerging as more salient than technical barriers (which have been reduced considerably).
- Any comprehensive nonproliferation strategy for 3D printing needs to consider the availability and use of professional 3D printing services.
- For awareness-building among industry and DIY communities, we recommend two first entry-points for new outreach efforts:
  - 3D printing services already familiar with export-control compliance
  - DIY communities and Makerspaces already explicitly prohibiting/restricting weapons-related development among their participants/users
- In the context of North Korea's apparent interest in 3D printers, further research is recommended on the production of 3D printers from the standpoint of both export controls and broader nonproliferation strategies.

ITEM-LEVEL ANALYSIS OF ADDITIVE MANUFACTURING

US nonproliferation policy has relied principally on the notion that the proliferation of nuclear weapons can be controlled by limiting access to nuclear or missile technology through export controls on items of concern and preventing access to nuclear materials. According to this approach, the sophistication of the technology limits its direct proliferation. The key to preventing proliferation is therefore to "restrict access rather than reduce demand."[3]

Export controls for nuclear technology have been based on the Zangger Committee's Trigger List for the past several decades. It is now necessary to consider whether items in the NSG Guidelines Parts 1 and 2 (which together encompass the Zangger Committee's Trigger List plus a broader list of dual-use items) might become more accessible due to the advent of 3D printing and the democratization of other technology and knowledge in the DIY community.[4] In response to this concern, this section seeks to assess a set of export-controlled sensitive technologies that WMD proliferators may be able acquire by exploiting these new manufacturing capabilities and pathways.

3 R. Scott Kemp, "The Nonproliferation Emperor Has No Clothes: The Gas Centrifuge, Supply-Side Controls, and the Future of Nuclear Proliferation, "*International Security,* Vol. 38, No. 4 (Spring 2014), pp. 39–78.

4 The NSG Guidelines Parts 1 and 2 are the NSG's export control lists. The NSG Guidelines Part 1 is based on the Zangger Committee's Trigger List—items specially designed for nuclear applications—whereas the NSG Guidelines Part 2 controls items that are truly dual-use (e.g. their application may benefit a nuclear program greatly, but the items may have other commercial or civilian applications that are non-nuclear).

In this section, we focus on a particularly concerning set of items: vacuum pumps, which could be used for uranium enrichment or other purposes; missile components, such as heat shields and rocket-propulsion components; and UAVs. See Table 1 for a list of export-control codes and references in the NSG and MTCR.

Table 1:

ITEM	NSG/MTCR CODE[5]	US CODE / ECCN
Roots Pump	NSG 3.A.8	10 CFR 110.8(b)[6] / 2B231
Rotary Vane Pump	NSG 3.A.8	10 CFR 110.8(b) / 2B231
Oil Diffusion Pump	NSG 3.A.8	10 CFR 110.8(b) / 2B231
Turbomolecular	NSG 3.A.8	10 CFR 110.8(b) / 2B231
Copper Heat Shield	MTCR 2.A.1.b	USML Category IV(h) and Category XV(e)[7]
RCC	MTCR 2.A.1.b	USML Category IV(h) and Category XV(e)[8]
AVCOAT	MTCR 2.A.1.b	USML Category IV(h) and Category XV(e)
Rocket Propulsion System	MTCR 2.A.1.c	USML Category IV(d)
UAVs	MTCR 1.A.2, 19.A.2, and 19.A.3	USML Category VIII(a)

Note that this is a subset only, and we will focus on other technologies of concern, such as lasers for laser enrichment, in a future study. Also, much of our analysis focuses on the potential for 3D

5 Nearly all of the items listed may include specific makes with technical characteristics that fall just below the threshold of the technical parameters requiring inclusion in the major nonproliferation regime export control lists (the NSG Guidelines Part 2 and the MTCR Annex); however the major regimes and their member states (as well as non-members who nonetheless adhere to the regime guidelines) have adopted "catch-all" rules in which an item with technical characteristics not sufficient for inclusion on the relevant control list is still subject to export controls (and licensing requirements) if a particular export transaction is intended for a WMD proliferation-related end-use or end-user.

6 Ultimate listing depends heavily on end-use. Various varieties of vacuum pumps are controlled on the Commerce Control List (ECCN 2B231 and 2B233). However, this section is concerned with vacuum pumps being used to enrich uranium. As such, any vacuum pump that is intended to be used in uranium enrichment is controlled by the Nuclear Regulatory Commission (NRC) in the US as part of its obligations under the NSG. Accordingly, the NRC-administered Part 110 code referenced in this table may be the most applicable listing (in a US regulatory context). The EU controls these items as well on the EU list of dual-use items under 0B002.f

7 USML = US Munitions List; placement depends on the size of the payload and the end-use.

8 This listing depends significantly on the item's end-use. This table assumes the end-use is a heat shield.

printing to support applications relevant for WMD proliferation; we have thus far not found any evidence that 3D printing is definitively in use to develop or aid in the production or delivery of WMD.

We evaluated each item of concern according to a set of criteria:

» The item's relevance to WMD-proliferation concerns (e.g. why is it export-controlled?);

» Current manufacturing methods and steps involved to produce the item;

» The degree to which 3D printing is used in the production of the item; and

» The potential for DIY communities, specifically, to use 3D printing to produce the item.

We conducted this assessment through data-mining of the following: a) literature hypothesizing which items could be 3D printed or discussing which are being 3D printed already; and b) the online discussion boards of relevant DIY communities. We have reached out also to industry and technical experts familiar with these items to gain a better understanding of the possibility of 3D printing the items.

BRIEF OBSERVATIONS FROM THE STUDY

Our analysis revealed that all the items or parts of the items can be 3D printed. We then chose to focus on the barriers to 3D printing, and found that there is no algorithm that quantifies the complexity of parts to be printed. It can, however, be estimated by the factors that 3D printing service companies use to determine the costs of producing items. This can be summarized according to three principal factors: the 3D print time, the cost of labor, and the cost of raw materials and consumables. These translate into quantitative price factors as shown in Table 2.[9]

9 Adapted from: http://www.3ders.org/articles/20160721-how-do-suppliers-calculate-pricing-for-3d-prints.html

Table 2: Factors that affect the cost of the item to be 3D printed. The factors collectively contribute to the "3D printability" of the object.

Cost Driver	Common Price Factors
3D print time	» Part bounding box volume (how much of the printer does the part use?) » Height of part (how many layers will be needed?)
Labor	» Setup fee (how much time is needed to set up the print?) » Finishing fee (how much time is needed to do post-print surface finishing?)
Raw materials	» Part volume (how much material goes into the part?) » Support volume (how much material goes into the supports?)

Based on the price factors in Table 2, we can gain a qualitative understanding of why certain items might be more difficult to print. Our hypothesis is that if the price factor is high enough, it will not be in the interest of adversaries to use 3D printing. In these cases, the conventional (but illegal) ways of attaining the technology will be a more suitable approach.

Our study found also that size is no longer a significant barrier because multiple printer-head systems are now available, and are expected to become more mainstream in the future. When multiple heads can print simultaneously, horizontal extent is not a limitation.

Therefore, our study concludes that the only true barriers to operationalizing 3D printing for the manufacture of illicit items involve obtaining the 3D printers themselves, the materials used in 3D printing, and the sensitive CAD and STL files required for the printer's software to produce the desired design. There are currently several websites and online platforms dedicated to sharing CAD/STL files, including files required for pumps, missile parts, and DIY drone components. 3D printing files that describe these items in detail eliminate the need for specialized knowledge or expertise in item production. Controlling these files and related software will therefore be key in preventing the proliferation of dangerous technologies. Future studies will need to focus on barriers to obtaining 3D printers, necessary materials, and CAD/STL files.

In the rest of the section we investigate each of the three item groups according to the criteria discussed. The groups include 1) vacuum pumps 2) heat shields and rocket-propulsion systems and 3) UAVs. Each of these subsections is guided by a working paper found in this report's appendix. Detailed analysis and citations are included in the working papers; the subsections presented here capture the highlights only.

VACUUM PUMPS

This section describes the key findings of a working paper (see appendix) that examines the 3D printability of vacuum pumps that are useful for the production of enriched uranium and for other applications relevant to nuclear proliferation. Vacuum pumps are included in the NSG's export-control lists (NSG Guidelines Part 1 if specifically designed for enrichment of uranium; NSG Guidelines Part 2 category 3.A.8 if usable for both nuclear and non-nuclear applications). As summarized below, the working paper identifies specific pump types amenable to 3D printing and of interest to DIY communities:

» The purpose of all vacuum pumps is simply to "withdraw gas" (or evacuate gas) from a specific volume so that the pressure in that volume decreases; the gas withdrawn is then released at the exit of the pump. Ultimately, this implies that the extracted gas is compressed and released at a higher pressure at the outlet of the pump.

» For gas centrifuge enrichment plants, vacuum pumps help maintain uranium hexafluoride (UF_6)—the compound that is enriched for nuclear purposes—in gaseous form at room temperature throughout the enrichment process.

» Vacuum pumps are used also in mobile gas-sampling stations to measure the isotopic quality of the gas throughout the enrichment process and to conduct helium leak checking to ensure the quality of the vacuum in the process lines.

» Positive displacement pumps (roots, rotary vane, and screw pumps) have blades on rotors that form cavities, trap gas, compress it as the rotor turns by decreasing the volume of the cavity, and finally release it through the outlet. The pump types vary in the impeller shape and technique for compressing the gas. While they do not create a vacuum strong enough to satisfy all requirements of NSG Guidelines Part 2 category 3.A.8, they are essential "backing pumps" for those that do satisfy the requirements, and one cannot function without the other.

» Oil diffusion pumps are inexpensive and useful for creating high vacuums in the uranium-enrichment process. Turbomolecular pumps have complicated rotors and are not used often in uranium enrichment because they are more expensive and have a lower yield in comparison to the cheaper oil-diffusion pumps.

» The rotor of a pump is usually the most complicated pump part to 3D print, and the turbomolecular pump has the most complex rotor of all the pumps we have mentioned. As a proof of concept, we hypothesize that if turbomolecular pump rotors can be 3D printed, then all other pump rotors must also be 3D printable. We find that the rotors of turbomolecular pumps are very similar to jet turbines, which have been 3D printed successfully. Therefore, we conclude that all the pump-type rotors can be 3D printed successfully.

» In DIY communities with CAD and STL designs available on websites such as GrabCAD.com, there is interest in roots, rotary vane and oil diffusion pumps.

» DIY communities are interested in oil diffusion pumps because they have no moving parts and are relatively simple. However, they require UF_6-compatible oils such as the PFPE (perfluoropolyether)-based oil called Fomblin oil. PFPE is not easy to obtain and should be strengthened as a barrier.

» There are active efforts to devise multiple print-head devices so that the lateral extent (width of the device) would not be a limitation, and large objects could be manufactured by building up the part layer by layer. In the future, size will not be a significant limitation in 3D printing.

MISSILE COMPONENTS

This section describes the key findings of a working paper that considers the potential for existing (or plausible near-future) 3D printing technology to manufacture items controlled under the MTCR. The working paper (see appendix) examines specifically the items controlled under 2.A.1 subparagraphs a, b, and c of the MTCR.

Those subparagraphs control for individual rocket stages, re-entry vehicles (and their subsystems such as heat shields, heat sinks, and associated electronic equipment), and rocket-propulsion subsystems (solid and liquid propellant rocket motors/engines).

Of these, the analysis focuses on re-entry vehicles and rocket-propulsion subsystems, and concludes that 3D printing will significantly increase the ease with which these MTCR-controlled items can be produced. However, production of these items will still require significant technical expertise. At the moment, most of the technical capability for producing 3D printed parts is limited to advanced research labs and advanced aerospace corporations.

The analysis reaches additional conclusions about heat shields and rocket-propulsion systems:

» The ablative heat shields used today are not well suited to 3D printing. Better suited are advanced ceramic heat shields and advanced titanium honeycombed heatshields. 3D printed ceramics capable of withstanding high temperatures have already been developed, and better ones are being pursued. Titanium can be 3D printed with existing technology.

» Propulsion systems stand the most to gain from 3D printing. Current engine parts are very expensive. Rocket engines that employ 3D printed parts already exist, and the development of more advanced engines is underway.

In addition, the analysis finds that DIY communities have minimal interest in ablative heat shields. This is most likely because in amateur rocketry, the rockets do not travel to high altitudes and even if they do, the re-entry qualifications are not significant. However, companies such as SpaceX, Sierra Nevada Corporation, and Boeing use state-of-the-art heat shields. DIY communities also have little interest in the type of rocket-propulsion systems controlled under the MTCR, most likely because engineering and scaling is challenging, independent of 3D printing. NASA—a well-resourced state-level civilian program—and SpaceX are experimenting with 3D printing rocket-propulsion components and subsystems.

UAVS (DRONES)

This section describes the key findings of a working paper (see appendix) that examines the 3D printability of UAVs, with attention to the types of UAVs under export controls outlined in MTCR Categories 1.A.2, 19.A.2, and 19.A.3, and with regard to the threat these UAVs pose as potential delivery vehicles for WMD. The paper's analysis illustrates that, because of the convergence of 3D printing capabilities, their distribution among service providers, and the DIY community's keen interest in drones, the risk of UAVs being acquired and/or diverted to WMD applications is increasing dramatically. Key findings from the paper are summarized below:

» Manufacturers are recognizing the advantages of 3D printing, resulting in the production of advanced, high-speed, and even jet-powered 3D printed UAVs.

» The DIY manufacturing communities that are focused on UAVs have taken full advantage of 3D printing already. They regularly share techniques, designs, and even CAD files for printable drone components across numerous open-source online forums.

» Terrorist groups (such as the IS) are using drones for reconnaissance or as a possible delivery system for explosive materials. We are not aware of any drone used for the delivery of WMD.

» The company Stratsys Ltd has already produced a UAV with 80 percent 3D-printed parts that weighs only 15 kilograms and can move at speeds exceeding 150 miles per hour.

» The US military has invested in the 3D printing of drones. The Navy assembles drones in a matter of hours on ships, and the Army experiments with drones for pre-emptive threat detection and surveillance, even deploying drones from jets travelling close to the speed of sound.

» DIY communities are very much interested in the development of drones with platforms, such as GrabCAD and Thiniverse, and share CAD files for anyone to download and convert to the STL files required for 3D printing.

» DIY communities can increase payload weight in two ways: (1) Multiple rotors can be placed on an existing frame; this requires knowledge of building drones. (2) Multiple commercial, off-the-shelf UAVs can be connected to transport higher weight payloads; this could be a threat in the future. One scientist working on the project stated that "simple off-the-shelf components lifting a 20 kg payload with precision control is very possible and straightforward (the math/implementation is easy given hobby-grade resources)."

» The DIY community's interest in drones focuses mainly on the development of small quadcopters for hobbyist or civilian purposes; the well-known website DIYdrones.com prohibits discussions of UAVs for military, weaponry, or illegal uses. However, we have found at least one discussion on DIYdrones.com that discusses drones of any payload as well as the feasibility of testing in areas outside the United States where laws are "more lenient." We wonder how well these sites are monitored and whether alternative websites exist that permit the discussion of nefarious purposes for amateur drones.

» At least one civilian has constructed a drone armed with a paintball gun, and has demonstrated its use for targeting individuals on the ground. Their purpose was to raise awareness that this technology has the potential to be used for nefarious purposes. We are unclear whether any components were 3D printed, but we highlight it here to illustrate the possible threat of drones produced by DIY communities.

LEGAL USERS-LEVEL ANALYSIS OF ADDITIVE MANUFACTURING

For this section, "legal users" is defined as entities seeking to utilize 3D printing for a primary purpose other than the circumvention of US trade controls. Though these entities may in fact use the technology to manufacture dual-use items capable of employment in a WMD program, or may develop 3D printers with the potential to do just that, they intend to utilize 3D printing primarily to make items with a legitimate, commercial end-use. Legal end-users make up the overwhelming majority of 3D printing end-users. Legal end-users are also the primary drivers behind the spread and advancement in 3D-printing capabilities. It is necessary to examine these entities to fully understand the proliferation challenges associated with 3D printing.

This examination was conducted by classifying the end-users by their size and scope. The resulting levels are the nation-state, 3D printing services, Makerspaces, and finally DIY communities or individuals. This section analyzes these levels individually.

The analysis guiding this section examines the motivation for each entity to exploit the benefits of 3D-printing technology and the method by which each entity assesses and addresses various proliferation risks (if they are addressed at all). First, 3D printing is examined at the broadest level (the nation-state) through a survey of states that have developed national strategies to exploit 3D printing. Second, 3D printing at the level of industry/private-sector level is examined. These services emerge frequently and allow individuals or companies access to state-of-the-art 3D-printing technology. Since many individuals and organizations cannot afford to purchase the printers themselves, these services fill that gap. Third, private organizations commonly referred to as Makerspaces promote and teach 3D printing techniques to individuals, and are examined through case studies. Fourth, the analysis considers the individuals and DIY communities that use 3D printing, as well as the items they are interested in printing.

Overall, our analysis yields the following key observations and takeaways:

» At each user level, there is little concern among the users regarding the proliferation threat from 3D printing. The only exception is a subset of US-based 3D-printing services whose primary customers are large US corporations that may expect support in meeting export compliance-related requirements.

- 3D printing is viewed almost entirely in terms of the potential gains, rather than the potential risks, offered by the technology.
- Entities and end-users at every level are working constantly to expand capabilities, lower costs, and expand the number of entities with access to 3D printing technology. This is done both independently and in coordination with other groups within their level.

Similar to the Item-Level analysis section, this section is based on working papers examining the legal users of 3D printing, which can be found in this report's appendix.

NATION-STATE RESPONSES

The AM industry has developed rapidly, with an average growth of 27.3 percent over the last twenty-six years, leading to increased national-level interest in the AM field.[10] Several countries have published AM strategies to better inform their future actions, and have funded allocations to develop the industry and maintain (or gain) a presence in the AM field.

Manufacturing accounts for approximately 16 percent, or more than $12.8 trillion, of the global economy. AM has captured the attention of governments and academia because if AM were to capture even a portion of this manufacturing total, it would create huge profits for those involved.[11] Beyond personal 3D printers, AM can be used on the commercial scale to revolutionize current manufacturing methods.

The importance of manufacturing in general and the potential of 3D printing specifically is compelling countries to develop their own strategies for developing and using 3D printing within their domestic manufacturing industries. The working paper (see appendix) guiding this analysis surveyed the 3D-printing strategies of Finland, the United Kingdom, South Africa, and Japan to illuminate how mature economies are looking to exploit the benefits of 3D printing, and to see the extent to which proliferation concerns are considered in the development of these strategies.

Each of these countries has their own strategy for developing and exploiting 3D printing. However, they are characterized by several common considerations:

- The usability of AM technology for manufacturing;

10 South Africa. Department of Science and Technology. A South African Additive Manufacturing Strategy. By Deon De Beer, et.al. Johannesburg, 2016. iv.
11 Ibid., 6.

- » Possible changes in industry and society caused by new technologies in an era when manufacturing processes continue to be digitalized;
- » Potential strategies for enhancing enterprises' earning capabilities and global competitiveness by taking advantage of such changes for business innovation; and
- » Necessary policies the country should adopt to take advantage of these changes.

The final common characteristic was the overall absence of measures to address the proliferation challenges associated with 3D printing.

Of the countries surveyed, Japan had the most comprehensive and ambitious 3D printing development plans and was alone in mentioning any sort of security concerns regarding 3D-printing technology. However, when discussed in Japan, 3D printing appears to be seen as too new of a development to pose a real proliferation risk.

3D PRINTING SERVICES

Although the overall cost of 3D printers has decreased, more advanced 3D printers are too expensive for most ordinary individuals or even small businesses. To fill this gap, several online services offer access to cutting edge 3D printers capable of printing with a number of materials. These services profit from providing 3D-printing capabilities to entities that ordinarily would not be able to access the technology.

The working paper (see appendix) considers the proliferation risks associated with this arena of 3D printing. It examines the websites of ten services and compares their costs, materials offered, and the level of export-control guidance (if any) offered to users.

The paper identifies several trends:

- » Online printing services can be classified into two categories—hobbyists and industry—based on the target customer base.
- » Sites that target hobbyists have no information within their terms of service or elsewhere on their website regarding export controls, though some do explicitly prohibit their services from being used to manufacture weapons.
- » Almost all industry-oriented services mention US export controls in their terms of service or elsewhere on their website.
- » Almost all industry-oriented services offer some sort of ITAR/EAR-based compliance system (ITAR = International Traffic in Arms Regulations; EAR = Export Administration Regulations), which vary between the 3D printing services, but have two universal characteristics:

» Only US personnel are permitted to interact with data specified as being export-controlled.

» The data is stored on encrypted servers located exclusively within the United States and will not be transmitted outside of the United States.

In addition, there is a strong correlation between the price of the service and the level of guidance offered to users on export controls. This correlation extends to the internal compliance systems within these 3D-printing services as well. In other words, the services which provide the most export-control guidance and information are also the most expensive and possess the greatest 3D-printing capabilities.

MAKERSPACES

The working paper (see appendix) guiding this section examines Makerspaces, which are locations that contain manufacturing equipment and are shared by user groups. There is considerable overlap among these groups and DIY manufacturing communities (discussed in the next section).

The paper examines three popular Makerspaces as case studies: TechShop, Fab Lab, and Staten Island Makerspace. The case studies reveal the ease with which an individual may acquire membership to these communal workspaces and gain access to advanced fabrication technologies including Computer Numerical Control (CNC) milling machines, 3D printers, and laser cutters. In general, membership to these groups requires a monthly fee and the completion of basic safety training courses for equipment use. Even non-members may access these spaces if they are willing to pay higher fees.

An initial investigation suggests these companies incorporate little to no guidance on export controls into member training. Even if members must agree to certain terms and conditions, these are made available just prior to purchase of membership, and focus exclusively on safety, liability, and in some cases intellectual property. It is unclear whether export controls are indirectly referenced or included alongside the discussion of applicable federal and state laws.

Fab Lab presents the most comprehensive set of terms and conditions, covering issues of state law violation; illegal downloading and reproduction, distribution, or file displaying; and violation of laws through the creation of a false identity. This may be due partially to the extensive nature of the Fab Foundation, which offers direct guidance on establishing Fab Labs around the world.[12] At TechShop, individuals must agree to "policies and procedures" to purchase membership, but these policies are not clearly available online. Finally, while Staten Island Makerspace defines its terms and conditions, prospective members apply to the company that owns the web platform used by Staten Island

12 Note: The terms and conditions for Fab Lab discussed in this work are designed for Fab Lab San Diego specifically. It seems likely, however, that each Fab Lab tailors its own Terms & Conditions to its respective location. For example, Fab Lab London has a different set of Terms & Conditions which are not nearly as extensive (available at http://www.fablablondon.org/terms/).

Makerspace rather than to the Makerspace itself. It should be noted that this investigation only simulated the purchase of a membership online, and it is therefore possible that at any of these spaces, prospective members are required to sign additional documents at the first visit.

Overall, membership prerequisites—and, therefore, access to these advanced fabrication technologies—center around payment and equipment safety training courses rather than guidance on legal issues or anything related to export control. These organizations focus primarily on promoting social responsibility and making specialized equipment available to the community for the purposes of advancing education and creativity. If an institution is interested in qualifying as a Fab Lab, for instance, the Fab Foundation requires that the institution uphold values including the promotion of the local community, collaboration, education, and entrepreneurship.

This value set suggests that those taking advantage of the spaces are not nefarious actors, but rather members of the local community seeking to advance education and innovation. However, some spaces such as Fab Lab place a heavy emphasis on sharing (especially via digital means) projects and inventions designed in the Makerspace. This sharing philosophy extends even across national borders (see below). In this context, Makerspaces may need to be engaged on issues of nonproliferation and related export controls in order to raise awareness among their participants.

DIY ("DO-IT-YOURSELF") COMMUNITIES

The working paper (see appendix) guiding this section examines DIY ("do-it-yourself") communities—enthusiasts for manufacturing technologies applied at the individual level, whether for entrepreneurial or hobby purposes. DIY communities are embracing 3D printing, and this analysis explores these particular users of the technology and considers the potential for advanced dual-use items to be produced by such enthusiastic groups.

Advancements in manufacturing technologies and trends toward digitization of the manufacturing process are rapidly increasing the capacity of small businesses and members of DIY communities to engage in small-scale production of customized items. Large-scale manufacturing processes tend to be inaccessible to anyone outside of the production lines of major companies. However, the so-called "democratization" of fabrication technologies, including 3D printing, is making it possible for the individual to produce a variety of items in small workshops and even at home. These goods may include anything from household items and jewelry to drones and firearms.

In the last decade, the convergence of newly accessible, small-scale fabrication technologies with enthusiastic DIY communities has given rise to the rapidly advancing "Maker Movement." Encompassing a variety of individuals—with specialties and interests ranging from art to engineering to hobbyist drone production—the Maker Movement is founded upon the belief that with the right technologies, "regular people will be able to create their own goods without having to rely on the industrial model of supply and demand."[13]

With an overarching commitment to collaboration and an aim to advance values such as learning, sharing, innovation, and transparency, the Maker Movement has leveraged small-scale manufacturing technologies to produce a variety of products across a range of sectors, launching what some refer to as the "Third Industrial Revolution." A series of Makerspaces have emerged around the United States to provide widespread public access to new fabrication tools including 3D printers; a series of Maker Faires showcases the new technologies and goods. Well-established as hotbeds for innovation, Makerspaces and Maker Faires have caught the interest of major companies and even parts of the US government.

Of all the key technologies that enabled the Maker Movement and DIY activities, 3D printing emerged as one of the "most high-profile 'maker' tools" and a catalyst for interest in Makerspaces as well.[14] Maker Movement enthusiasts are taking advantage of the multitude of new companies that sell small, affordable 3D printers, and are increasingly utilizing 3D printing to pursue entrepreneurial efforts through the small-scale production of customized goods. Individuals starting out at the DIY-level have leveraged 3D-printing technology to establish successful and sometimes large companies in a variety of fields including civilian drone production.

3D printing has extended the means to produce innovative goods to those operating outside of major industries. As a result, the growing accessibility of these small-scale fabrication technologies makes it increasingly easy for non-traditional actors to produce dual-use technologies and weapons previously limited to the defense sector. As demonstrated in this work, these technologies have a real and problematic capacity to undercut existing legal regulations and export controls on dual-use goods. Moving forward, the defense and export control sectors will likely need to engage DIY and Maker enthusiasts to curb DIY production of dangerous weapons and raise awareness about relevant rules and regulations on dual-use goods.

Evidence suggests that many of the groups and companies emerging from DIY communities do not want their fabrication technologies to fall into the hands of nefarious actors. To conduct successful engagement, these efforts should be grounded in a consideration for and respect of the philosophies and aims underlying the rapidly growing Maker Movement. By understanding how these aims shape the Movement's use of new manufacturing technologies and related entrepreneurial pursuits, we can leverage the Maker Movement for its innovative potential while also limiting the production of dangerous weapons and dual-use components.

13 Dan Gettinger et al., "The Drone Primer: A Compendium of the Key Issues," *Center for the Study of the Drone,* 2014, p. 21. Available at: http://dronecenter.bard.edu/files/2013/08/2014_Drone_Primer_Spreads.pdf
14 Sam Gustin, "How the 'Maker' Movement Plans to Transform the US Economy," *Time,* October 1, 2012. Available at: http://business.time.com/2012/10/01/how-the-maker-movement-plans-to-transform-the-u-s-economy/

ILLICIT USERS-LEVEL ANALYSIS OF ADDITIVE MANUFACTURING

This section covers the third angle of this project's overall analysis by examining potential illicit users of AM, namely WMD proliferators and terrorist organizations, that may have an interest in unconventional weapons. As with the prior sections, working papers have guided our data collection and analysis, and the subsections herein describe their key findings.

Two working papers consider the respective potentials for a well-resourced nation-state (North Korea) and a well-resourced terrorist organization (Islamic State a.k.a. "IS") to utilize AM as a means of acquiring/advancing WMD capabilities. Common to both North Korea and IS, our initial investigation of publicly available data reveals no evidence of an active pursuit of AM technology with a proliferation-relevant aim. However, we have identified two key developments—one specific to North Korea and one specific to IS—that raise concerns about the potential for both entities to incorporate AM into proliferation-relevant efforts:

» North Korea: Although North Korea's foray into AM has been limited to small-scale demonstrations of the technology for ostensibly civilian applications, the DPRK claims to have produced at least two 3D printers, one suspiciously akin to the MakerBot-branded 3D printer. This claim suggests North Korea's intention is not merely to explore the use of 3D printing but also to explore the production of AM equipment itself. In the context of scaling 3D printers, any North Korean success in customizing 3D printers with advanced industrial applications could directly benefit its WMD programs by reducing the development/production time and the engineering resources needed. North Korea appears to have pursued this strategy successfully with traditional CNC machine tools, importing them initially and then acquiring the technology needed to make the machines.

» IS: While this study was not able to confirm evidence of the IS's interest in AM with regard to WMD development, the widespread geographic distribution of AM technology and DIY-oriented Makerspaces has made the technology accessible to users in countries where the IS has been particularly active: Pakistan, Afghanistan, Egypt, Morocco, and Turkey. Accordingly, if the IS leadership were to make the decision to vigorously explore AM as a potential pathway to WMD, the technology would be readily accessible, with little need to import from producer countries. Although Pakistan has introduced some trade controls specific to AM, the export-control systems of these five countries are still developing with limited implementation. This suggests that the IS could distribute AM equipment or dual-use items to affiliates throughout the Middle East and North Africa region (and potentially beyond) by exploiting weaknesses in these systems.

NORTH KOREA

This section is guided by a working paper (see appendix) evaluating North Korea's current interest in 3D printing and the potential for the wider, proliferation-relevant adoption of the technology in the country's industrial and manufacturing sectors. The paper's key findings are described below.

AM appears to be in its infancy in North Korea. It has begun to attract the interest of researchers and has been featured in the official media, but it has yet to attract the public spotlight of attention from top leaders. 3D printers do not seem to have appeared in a heavy-industrial setting so far. Whether AM will progress beyond the current exploratory phase remains to be seen, but wider adoption would be consistent with North Korea's ambition to achieve the "cutting edge" of technology.

There have been few sightings of 3D printers in North Korea. A video shot in May 2016 at the 19th International Trade Fair in Pyongyang captured an exhibit, by the Pyongyang University of Mechanical Engineering, that displayed a photograph of a 3D printer the students had allegedly invented. An attentive blogger pointed out that it looked very much like a MakerBot Replicator—a 3D printer available at Amazon.com, among other places.[15] A North Korean media report dated February 2016 had described this 3D printer as a strictly indigenous development, a claim the North Korean media often makes about technology.[16]

A different 3D printer appeared in the North Korean media at the Dental Hospital of the Ministry of Public Health in August 2016. This appearance involved a more insistent portrayal of the technology as indigenous. The report quoted a doctor who discussed its usefulness for making customized facial prostheses and dental implants. Photographs showed the printer with its logo in prominent Korean lettering, as well as patent documentation.[17]

Whether or not either 3D printer was produced locally, the North Korean media's insistence on the point suggests the DPRK has an interest in building and customizing AM equipment. When considered in the context of North Korean successes in the realm of CNC machines and other industrial production systems, the potential for the DPRK to pursue a similar path with 3D printing should not be underestimated. As underscored by our findings in this report's item-level analysis, the cost of printing may be the major barrier at the moment, but this may soon be reduced by the ubiquity of 3D printing and its users.

15 Clare Scott, "North Korean Trade Show Advertises 3D Printer… That Looks a Lot Like a MakerBot," 3DPrint.com, 3 June 2016, https://3dprint.com/137135/north-korea-3d-printer/.

16 *Rodong Sinmun* (Pyongyang), 1 February 2016.

17 Korean Central Television, 8 August 2016.

TERRORIST ORGANIZATIONS (ISLAMIC STATE)

In considering WMD proliferators' potential interest in AM, our study has also produced a working paper—included in this report's appendix—that examines the possibility that terrorist groups aspiring to acquire WMD will misuse AM. The paper first revisits a fundamental question that, since 9/11, has guided analysis of terrorist organizations with the potential to acquire WMD. Specifically, the paper's analysis uses two primary strategies to pinpoint potential terrorist groups that are interested in WMD acquisition:

» examining broad categories of groups with different ideological orientations, goals, *modus operandi*, and level of required capabilities; and

» investigating the motivation(s) of the potential groups in order to understand their weapon choice(s) and the possible acquisition path(s) indicated by these choices.

The paper's findings suggest that there may be only a few relevant non-state actors, and only one terrorist group that is serious about WMD acquisition: Islamic State, which has at this time actually acquired and used chemical weapons. Moreover, the nature, shape, and magnitude of the IS's motivations and general capabilities indicate that it is following a multitrack proliferation path. If the group were to choose to access AM technology and study its potential, it would facilitate the pursuit of WMD by mitigating the technical barriers.

At the same time, though, the study found no clear evidence of IS incorporating AM into its weapon-acquisition path or connecting it with pursuit of WMD capabilities.

That said, the geographic spread of AM technology and its wider accessibly suggests that, were the IS to make a determined effort to explore the potential of AM, the necessary resources are within its reach. Notably, this study found evidence of Makerspaces operating in countries where the IS has a) either direct presence or affiliates, and b) followers that can facilitate the IS in misusing the technology for its WMD-acquisition purposes. These countries include Pakistan, Afghanistan, Egypt, Morocco, and Turkey.

The working paper examined the use of AM in Pakistan in more depth, highlighting that the country's one prominent Makerspace is based at a university—noteworthy because academic institutions have been arenas for extremist recruitment in Pakistan. This is not to say that the Makerspace is being exploited today for illicit purposes. Much like the Makerspaces surveyed in our study's other working papers, it focuses on the benefits of AM and encourages students to explore them.

Notably, the data collection driving the paper's Pakistan case study confirmed that the Pakistani government has introduced regulatory restrictions on the import of 3D printers. Security concerns appear to be driving this regulation, raising questions as to whether terrorist organizations in Pakistan have explored AM technology. Whether the import control is or can be adequately enforced is another matter; the countries noted above receive development assistance from the United States and/or European Union to improve their strategic trade control systems, but gaps in these systems (and especially their implementation) still persist.[18] Accordingly, it is pertinent to consider the potential that the IS or similarly resourced organizations could use these countries as hubs to acquire AM technology or distribute dual-use products of AM.

RISK MATRIX

This section is a supplement to our study's overall analysis, and it describes our exploration of how proliferation risks associated with 3D printing might be captured in a quantitative, tabular format. Our goal was to develop an experimental "Risk Matrix" consisting of two tables and a corresponding bar graph that, considered together, describe a) the degree to which 3D printing lowers barriers to production of export-controlled dual-use items; and b) the effect of DIY communities on the potential for 3D printing to be used for production of export-controlled dual-use items. This "Risk Matrix" summarizes the three item groups at the center of this study—vacuum pumps, missile-related components represented by heat shields and rocket propulsion, and UAVs—and the DIY community's interest in manufacturing these items and/or their components. Additionally, the contributors to this study hope to apply and refine this developing Risk Matrix to the analysis of additional items in the future, potentially leading to a standardized analytical framework that can guide continued study of AM-associated proliferation risks as the adoption of 3D printing spreads globally to a variety of users.

THE DEGREE TO WHICH 3D PRINTING LOWER BARRIERS TO PRODUCTION OF EXPORT-CONTROLLED DUAL-USE ITEMS

Understanding how 3D printing can decrease barriers to the production of items of concern is key to our overall study and builds upon the item-level and legal-user analyses presented earlier in this report. This requires understanding the difficulty of producing each item without using AM, which is influenced by (1) the number of steps involved, (2) the difficulty of obtaining the materials or components out of which the item is produced, and (3) the advanced skills and knowledge required to produce the item. To assess how AM makes it easier to produce sensitive items, we developed a graphical "Risk Matrix" to estimate both the barriers to producing items according to each of the above criteria and the degree to which AM lowers these barriers. This discussion describes the graphics that, collectively, comprise the "Risk Matrix" featured in this section.

We first scored each criterion for every item on a 3-point Likert scale according to the degree to which that criterion contributes to a technical barrier for producing each item without AM. A low barrier for production has a quantitative value of 1, a medium barrier a value of 2, and high barrier

18 "Strategic trade control" is a term often used synonymously with export control, but encompasses a wider scope of controls over the movement of goods and technologies across borders. The term can include import, export, transit, transshipment, and brokering controls.

a value of 3. For example, all of the vacuum pumps (excluding the turbomolecular pump) are not expected to be challenging to produce, since many instructions are available in the literature. However, turbomolecular pumps are more complex, and therefore have a higher manufacturing barrier than do the other pump types. Furthermore, the type of AVCOAT heat shield used in the Apollo missions and RCC (reinforced carbon-carbon) heat shields (see appendix for details) have many production steps and are complex materials to produce, so their scores are higher than that for vacuum pumps. Table 3 lists the determined score for the items and materials.

Estimating the score for each characteristic allows us to evaluate the relative heights of the various barriers to production. We do this by simply summing the score for each item: a roots pump (not difficult to manufacture) has a score of 5, whereas the AVCOAT heat shield has a score of 11. It is important to emphasize that the score estimates are based on our research described in the working papers in the appendix. This risk matrix is heavily dependent upon publicly available information, but many of the manufacturing details are proprietary, classified, or both. As such, several of the entries are the results of estimates informed by the best information available at the present time. This assessment should not be viewed as an industry consensus. However, these estimates allow us to get a sense for how AM actually lowers the barrier and hence increases the proliferation risk at the item-level.

We accomplish this by estimating the fraction, F_{3D}, of the most challenging item components that can be produced through 3D printing. For example, it is reasonable to assume that 95 percent of UAVs can be 3D printed. Not all criteria that contributed to the barrier are influenced by the use of 3D printing, since the same complications may be relevant whether an item is produced with or without 3D printing. Obtaining the material, components, and knowledge about the structure of the item would be required regardless of whether AM is used. However, the number of steps involved and skills necessary may be influenced by AM because many parts may be consolidated into one complex part—a well-known and significant advantage of 3D printing. We take this into account in an estimate of the degree to which the barrier is lowered if 3D printing is utilized.

Table 3: Manufacturing barriers for items of concern with and without AM. The value without including AM (column titled "Fraction of Components 3D Printed) corresponds to the sum of the scores (a score of 1 is the lowest barrier and 3 is the highest) for the five criteria (columns titled "Criteria Not Affected by 3D Printing" and "Criteria Affected by 3D Printing"). The final column is the fraction of components (F3D) that can be 3D printed, providing an estimate of how the barrier would be decreased through AM.

	COMPONENTS	CRITERIA NOT AFFECTED BY 3D PRINTING			CRITERIA AFFECTED BY 3D PRINTING		HEIGHT OF BARRIER WITHOUT 3D PRINTING	FRACTION (F_{3D}) OF COMPONENTS 3D PRINTED (1=ALL)
		Difficulty in obtaining key materials	Difficulty in obtaining key components	Necessity of advanced knowledge	Number of Steps	Necessity of advanced Skills		
Vacuum Pumps	Roots Pump	1	1	1	1	1	5	0.8
	Rotary Vane	1	1	1	1	1	5	0.8
	Scroll	1	1	1	1	1	5	0.8
	Screw	1	1	1	2	1	6	0.8
	Oil Diffusion	1	1	1	1	1	5	0.9
	Turbomolecular	1	2	3	2	1	9	0.9
Heat Shields	RCC	2	0	3	3	3	11	0.2
	AVCOAT	2	0	3	3	3	11	0.2
	Titanium	2	0	1	1	1	5	0.9
	UHTC	2	0	3	2	3	10	0.9
Missile Components	Turbopump	2	2	3	3	3	13	0.8
UAV	UAVs	1	1	1	1	1	5	0.95

We first calculate the height of the barrier without 3D printing: the sum of the scores of the various criteria (B – see header of column titled "Height of Barrier without 3D Printing"). Next, we estimate the fraction of item components that can be 3D printed (F_{3D}), and we multiply this by the sum of the score corresponding to the criteria that are simplified because of 3D printing. For most items, this includes the number of steps involved in item manufacturing and the skills necessary to produce the 3D printed item, and we represent this sum for each item as S3D (see header of column titled "Criteria Affected by 3D Printing"). For example, the vacuum-pump rotors may have been fabricated in multiple steps due to their complexity, so the additional scaling factor S3D accounts for this improvement. However, for some items such as the composite heat-shield materials, the number of steps remains the same, so 3D printing does not necessarily simplify the process beyond the fraction of the material that is 3D printed. The height of the barrier including 3D printing is B-(F_{3D})(S_{3D}): the original height B decremented by the product of the fraction of the item simplified through 3D printing and the score of the criteria affected. In principle, the fraction F_{3D} should be scaled by another factor describing the difficulty in 3D printing the item (see Section: Item-Level Analysis of Additive Manufacturing) based on the cost of 3D printing, but for the remainder of this analysis we assume this factor to be the same (value of 1) for all items. Figure 1 illustrates this result on a bar chart where the height of the bars represents the height of the barrier before and after 3D printing is included.

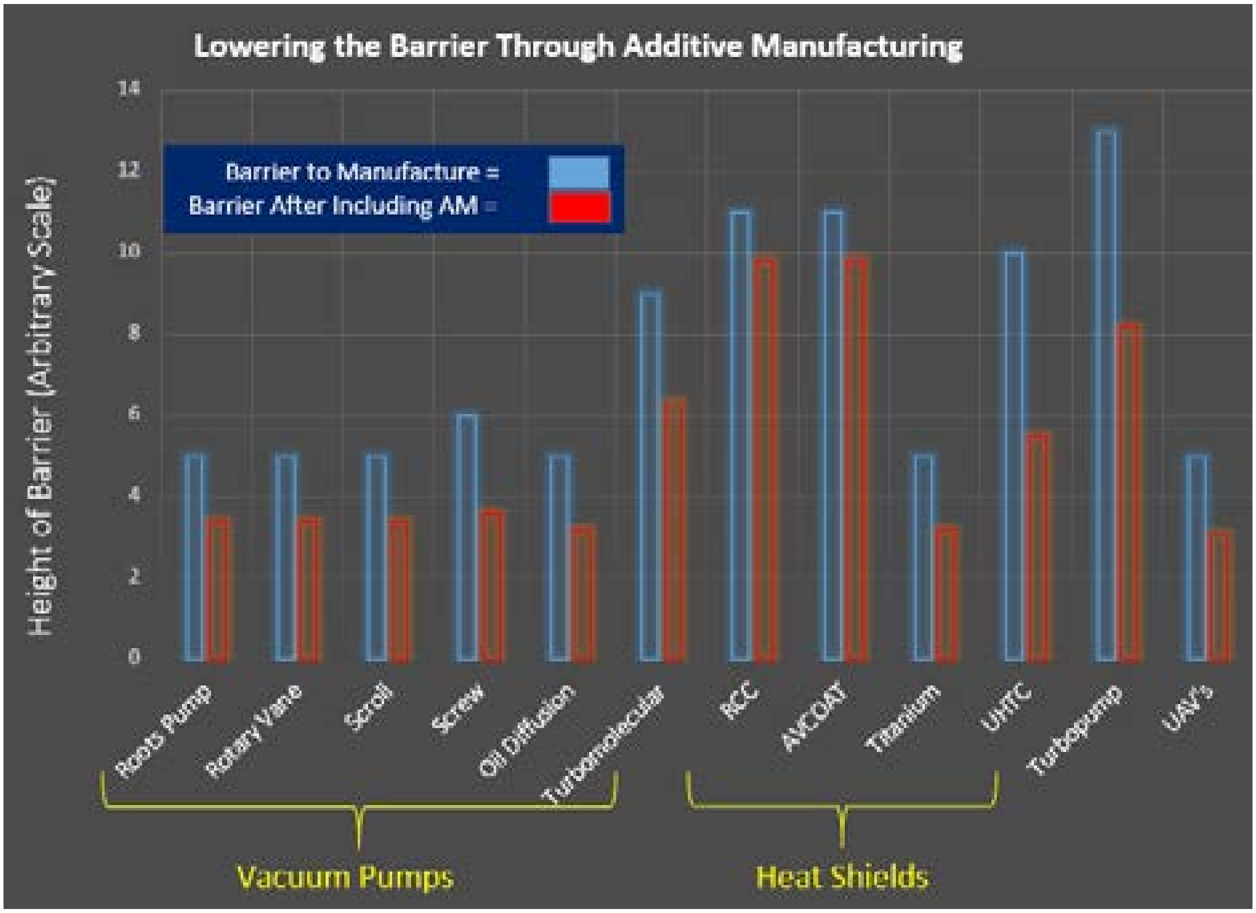

Figure 1: How AM can lower the barrier to producing items of concern. For example, the barrier for vacuum pumps (with the exception of turbomolecular pumps) is decreased since a large fraction of components such as rotors can be 3D printed. We calculate the height of the barrier when 3D printing is included as $B-(F_{3D})(S_{3D})$ where B is the height of the barrier without including 3D printing, F_{3D} is the fraction of the item that can be 3D printed, and S3D is the score of the criteria that are affected by 3D printing.

Details of these "Height of Barrier" calculations for each item surveyed are presented in the item-related sections of the appendix.

THE EFFECT OF DIY COMMUNITIES ON THE POTENTIAL FOR 3D PRINTING TO BE USED FOR PRODUCTION OF EXPORT-CONTROLLED DUAL-USE ITEMS

Our study examines the potential of export-controlled (or similar) items to be produced by DIY communities in order to gauge how significantly the wider availability of 3D printers and other advanced technologies will increase the knowledge, components, and availability of sensitive items. If knowledge and capability proliferates, we assume that the barriers discussed above will decrease further. It is not possible currently to estimate the quantitative effect of DIY communities on lowering the production barrier. However, we can get a sense of the interest in the technology and then compare this to the degree that 3D printing and other technologies could potentially produce the item. This represents our approximation of the risk DIY communities pose for the proliferation of the technology.

We found from the present analysis that, while 3D printing could have an impact on producing these items, the DIY community is not explicitly considering manufacturing all items. We have analyzed this by data-mining online discussion boards, websites serving the DIY community, and publications covering 3D printing and additive/subtractive manufacturing. We used a 3-point Likert scale (Low, Medium, High) to evaluate the importance of the DIY community and the increase in democratization of technology for lowering the barrier for access to the items of concern. See Table 4 below (also a "Risk Matrix") for an assessment of the degree to which DIY communities could potentially lower the barrier to the proliferation of the items of concern.

Table 4: Items assessed according to the level of interest, current production status, and status of production information, as disseminated by the DIY communities. Note that "sub-threshold" items include those with technical characteristics just below the technical parameters that would result in the item's inclusion on one of the major nonproliferation export control lists. The last two columns describe why there may be an interest, and the degree to which 3D printing could potentially produce the items.

Item of Concern	Level of interest in components and "sub-threshold" items (Low, Medium, High)	Currently producing item or "sub-threshold" item	Releasing relevant knowledge for manufacture (Yes = knowledge freely disseminated or files shared)	Why there is interest in "sub-threshold" relevant items	Advantage of 3D printing
Roots Pump	High Interest	Yes Producing	Yes	Automotive	High
Rotary Vane	Medium Interest	Yes Producing	Yes	Automotive	High
Scroll	Low Interest	Not Producing	None	Low interest	High
Screw	Low Interest	Not Producing	None	Low interest	High
Oil Diffusion	High Interest	Test Production	Yes	High vacuum application (DIY fusion research)	High
Turbomolecular	Medium Interest	Test Production	None	Low interest	High
RCC	Low Interest	Not Producing	None	Low interest	Medium
AVCOAT	Low Interest	Not Producing	None	Low interest	Medium
Titanium	High Interest	Yes Producing	Yes	Automotive	High
Turbopump	Medium Interest	Test Production	Yes	Rocketry	High
UAVs	High Interest	Yes Producing	Yes	Many applications	High

We found that most items have low interest (column 1), but we need to leverage this with the fact that the advantage of 3D printing might be high (column 6). This difference expresses the potential for 3D printing or other sophisticated technologies to affect proliferation of these items because the interest of DIY communities are fluid. If interest changes because novel dual-use applications are sought, then 3D printing and other advanced manufacturing techniques may be poised to expedite the proliferation of the items through dissemination of knowledge, files, or techniques. Notably, as Table

4 illustrates, there is a high risk that DIY communities will lower the barrier to production of UAVs—some of which are export-controlled for reasons related to WMD proliferation.

CONCLUSION

The key findings of our study and the project team's corresponding recommendations are all presented and described in this report's Executive Summary. In the interest of efficiency, they will not be duplicated here, and the contributors will use this concluding section to highlight next steps in their research instead.

Most significantly, the project team is conducting a similar study—but covering a completely distinct set of items—under a grant award from the Project for Advanced Systems and Concepts for Countering Proliferation (PASCC). The item-level methodology applied to this study will be utilized in the PASCC study as well, increasing its potential robustness and usefulness as a means for examining the complex intersection of 3D printing and proliferation risk. Indeed, perhaps the central takeaway from this study (in addition to the key findings) is that the project team found the 3-level analysis to be an effective methodology for yielding findings that reflect both the technologies involved in AM and their users.

Additionally, the project team anticipates a new study on 3D printing design files and the measures taken by companies and other institutions to control file distribution and limit the risk of diversion. Even if the primary motive is to protect intellectual property rather than to comply with nonproliferation export controls, the current best practices in controlling the transfer of intangible technology such as CAD and STL files deserve closer attention. Over the course of this project, some industry practitioners and policy experts, consulted by our team for professional opinions, voiced skepticism about whether 3D printing represented a new threat requiring augmented controls. Driving these opinions is the reality that advanced industry 3D-printing systems typically require some training, and assembling components produced by 3D printers into finished systems may not be possible without tacit knowledge. However, the same practitioners and experts would also qualify their remarks by noting that, with access to the right equipment and, especially, the right design file, a proliferator would be able to produce export-controlled items with minimal know-how about traditional manufacturing. For this reason, strategies on effective control of 3D printing design files in the context of cloud computing and other file-sharing vehicles warrant closer study. The project team anticipates starting this effort in 2018 to identify best practices for a variety of settings, ultimately yielding the right balance between facilitating the genuine benefits of 3D printing while reducing the WMD proliferation risk associated with this increasingly ubiquitous technology.

APPENDIX

This Appendix is a collection of the working papers developed by contributors to the project titled "WMD Proliferation Risks at the Nexus of 3D Printing and Do-It-Yourself (DIY) Communities." The papers informed the findings and recommendations of this project's Main Report.

It is important to note that these are working papers. The contributors may opt to develop them further, but they are presented here to share the research, data collection, and analysis that guided this project.

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A NOTE REGARDING "ITEM-LEVEL" WORKING PAPERS: ESTIMATING THE DEGREE TO WHICH ADDITIVE MANUFACTURING DECREASES THE BARRIER TO MANUFACTURING ITEMS

This Appendix begins with three working papers that each feature "item-level" analysis of the proliferation risks associated with the expansion of Additive Manufacturing (AM), inclusive of 3D printing. Each of the three "item-level" working papers discusses a grouping of export-controlled items: vacuum pumps, missile components as represented by heat shields and rocket propulsion systems, and unmanned aerial vehicles (UAVs).

The goal of each of these three "item-level" working papers is to evaluate the degree to which AM can aid in the production of various sensitive items used to produce either nuclear weapons, missile components, or drones. For each of the items and materials, we describe the significance of the item, current known methods of manufacture, and materials used, the difficulty of which constitutes a barrier to manufacturing the item. To gauge interest in the item, we give known cases where manufacturing the item has been attempted by industry and the "Do It Yourself" (DIY) community, and give examples where 3D printing was used. We then estimate how the manufacturing barrier decreases when 3D printing is used for every item. We evaluate how various criteria contribute to the barrier by scoring each criteria on a 3-point Likert scale (with a value of 1 as the lowest production barrier and 3 as the highest). The sum of these scores constitute the total score and the height of the barrier without utilizing 3D printing. The height of the barrier including 3D printing was calculated by decrementing the product of the fraction of components that can be 3D printed by the sum of the scores of those criteria that are affected by 3D printing from the height of the barrier when 3D printing is not included. The difference between the height of the barrier with and without 3D printing is a measure of the impact 3D printing may have on item production. We conclude each section by summarizing the results of the above calculations in the form of a table. The tables at the end of the "item-level" working papers inform the experimental "Risk Matrix" presented in Main Report.

VACUUM PUMPS

(Contributor: Dr. Ferenc Dalnoki-Veress)

This section describes the 3D printability of vacuum pumps that could be used to produce enriched uranium or could have other applications for developing nuclear weapons. We make the following observations in the working document provided in the Appendix:

» The purpose of all vacuum pumps is simply to "withdraw [or evacuate] gas" from a specific volume so that the pressure in that volume decreases. The withdrawn gas is then released at the exit of the pump. Ultimately this implies that the extracted gas is compressed and released at a higher pressure at the outlet of the pump.

- For gas centrifuge enrichment plants, the purpose of vacuum pumps is to maintain uranium hexafluoride (UF_6), the chemical form of the uranium compound to be enriched, in gaseous form at room temperature throughout the enrichment process.

- In addition, vacuum pumps in enrichment plants are used as mobile gas sampling stations. Vacuum pumps are components of instruments that measure the isotopic quality of the gas at various points throughout the enrichment process and can also check for helium leaks, ensuring the quality of the vacuums in the process lines.

- Positive displacement pumps (Roots, Rotary Vane, and Screw Pumps) use blades on rotors to form cavities, trap gas, compress it as the rotor turns by decreasing the volume of the cavity, and finally release it through the outlet. The pump types vary in the impeller shape and technique for compressing the gas. While they do not reach a vacuum level sufficient to satisfy all requirements of "3.A.8" of National Suppliers Group (NSG) Guidelines Part 2, they are essential "backing pumps" for other more powerful pumps that do satisfy the requirements; one can't function without the other.

- Oil Diffusion pumps are used in uranium enrichment to reach high vacuums and are inexpensive. Turbomolecular pumps have complicated rotors and are not often used in uranium enrichment since they are more expensive and do not have the same throughput as Oil Diffusion pumps.

- The rotor of a pump is usually the most complicated pump part to 3D print. The Turbomolecular pump has the most complex rotor of all the pumps we have mentioned. As a proof of concept, we hypothesize that if rotors of a Turbomolecular pump can be 3D printed, then all rotors for other pumps must also be 3D printable. We find that the rotors of Turbomolecular pumps are very similar to jet turbines, which have been 3D printed successfully. Therefore, we conclude that all of the pump type rotors can be 3D printed successfully.

- There is interest in Roots, Rotary Vane and Oil Diffusion pumps in the DIY communities, and Computer Aided Design (CAD) and Stereolithography (STL) designs are available on websites such as GrabCAD.com.

- Oil Diffusion pumps are relatively simple since they have no moving parts, and the DIY community has shown interest in these pumps. However, they require UF6 compatible oils such as the Perfluoropolyether (PFPE) based oil called Fomblin Oil, which is not easy to obtain and is a barrier.

- There are active efforts to devise multiple printing head devices so that the horizontal extent would no longer be a limitation and large objects could be manufactured by building up the part layer-by-layer. In the future, size will not be a significant limitation in 3D printing.

We summarize how 3D printing affects manufacture by lowering the barriers to producing the items in the table below.

Table 1: Manufacturing barriers for various vacuum pumps with and without AM. The value without including AM (column 7) corresponds to the sum of the scores (a score of 1 is the lowest barrier and 3 is the highest) for the five criteria (columns 2-6). The 8th column is the fraction of components (F3D) that can be 3D printed, and the final column is an estimate of how the barrier would be decreased through AM: the product of the fraction of 3D printed components and the sum of the scores of criteria that are affected by 3D printing is subtracted from the height of the barrier without 3D printing.

COMPONENTS	CRITERIA NOT AFFECTED BY 3D PRINTING			CRITERIA AFFECTED BY 3D PRINTING		HEIGHT OF BARRIER WITHOUT 3D PRINTING	FRACTION (F3D) COMPONENTS 3D PRINTED (1=ALL)	HEIGHT OF BARRIER INCLUDING 3D PRINTING ADVANTAGE
	Difficulty in obtaining key materials	Difficulty in obtaining key components	Necessity of advanced knowledge	Number of Steps	Necessity of advanced Skills			
Roots	1	1	1	1	1	4	0.8	2.4
Rotary Vane	1	1	1	1	1	4	0.8	2.4
Scroll	1	1	1	1	1	4	0.8	2.4
Screw	1	1	1	2	1	5	0.8	2.6
Oil Diffusion	1	1	1	1	1	4	0.9	2.2
Turbomolecular	1	2	3	2	1	9	0.9	6.3

THE ITEM'S RELEVANCE TO WMD PROLIFERATION CONCERNS (I.E., WHY IS IT EXPORT-CONTROLLED?)

The NSG Guidelines Part 2 classification "3.A.8" concern vacuum pumps used for Electromagnetic Isotopic Separation (EMIS) and arose because of the discovery that Iraq had made progress in nuclear weapon development and had enrichment technology. Vacuum pumps in general are critical for many applications that concern WMD, but the "3.A.8" classification is restricted to pumps with specific technical characteristics.

Pumps that require a license of export according to "3.A.8" must have an input throat size greater than 38 centimeters (cm), equivalent to15 inches (in), a pumping speed greater than 15 cubic meters per second ($m^{3/s),}$ and the capacity to produce an ultimate vacuum better than 13.3 millipascal (equivalent to 0.1 millitorr [mTorr] or 0.13 microbar [µBar]). The diffusion pump has large throughputs that meet these specifications.

Vacuum pumps are also covered by NSG Guidelines Part 1 classification "5.4.3," which focuses on pumps with a suction capacity of 5 m3 per minute (m3/min) or more, or that are designed specifically for dealing with the highly corrosive environment of the gas UF_6—the molecular form of uranium used in various uranium enrichment techniques (gas centrifuge, gas diffusion, aerodynamic, laser enrichment, etc.). All other vacuum pumps that are not covered by the above classifications but are useful for uranium enrichment would likely be covered by "Catch-all" provisions in the export control codes.

The purpose of all vacuum pumps is simply to "withdraw" (or evacuate) gas from a specific volume so that the pressure in that volume decreases as the withdrawn gas is released at the exit of the pump. Ultimately this implies that the extracted gas is compressed and released at a higher pressure at the outlet of the pump.

For gas centrifuge enrichment plants, the purpose of vacuum pumps is to maintain UF_6, the chemical form of the uranium compound to be enriched, in gaseous form at room temperature throughout the enrichment process. This is necessary because normally, at room temperature and ordinary atmospheric pressure, the material is a solid and cannot be used in a gas centrifuge.

Vacuum pumps facilitate the enrichment process by being a component of mobile gas sampling stations, as well. Vacuum pumps measure the isotopic quality of the gas at various points throughout the enrichment process and check for helium leaks to ensure the quality of the vacuum in the process lines.

Vacuum pumps have been items of interest for illicit WMD-related procurement networks in the past.[1] Prior to the institution of the Joint Comprehensive Plan of Action between the P5+1 and Iran, the Iranian regime worked actively to acquire vacuum pumps and related equipment (valves, controllers, custom cables for specific pumps, etc.).

For example, the Glendale, California-based company X-Vac purchased and exported vacuum pumps and related accessories to Iran by sending them first to the United Arab Emirates, and then forwarding them to Iran. The individuals involved in the scheme deliberately "re-labeled and undervalued the contents of the shipments in order to mask the true contents and to avoid interception by U.S. officials."

An Oil Diffusion pump was among the items shipped to Iran despite the fact that it did not meet the pumping speed qualification of "3.A.8," though it did meet all the other specifications. Connecting two of these pumps together in parallel would be sufficient to meet all characteristics and serve as a critical component for gaseous diffusion.

Other types of pumps, such as Roots, Rotary Vane, Screw, and Turbomolecular pumps [2] do not strictly meet all the characteristics of "3.A.8" or "5.4.3," but are captured under "catch all" provisions to deny shipment of these sensitive items. Despite this, evidence indicates through X-Vac, Iran was able to acquire most of these items. [3]

PUMP TYPES RELEVANT TO URANIUM ENRICHMENT

The pumps above can be divided into three classes, and this analysis will discuss two of them. The first class is positive displacement pumps, including Roots, Rotary Vane, and Screw pumps and their variants. These vacuum pumps have blades on rotors that form cavities, trap gas, decrease the volume of the cavity to compress the gas, and finally release it through the outlet.

The pumps differ in the shapes of the rotors that form cavities to compress the gas. For example, Roots pumps use two impellers that rotate in a very tight tolerance housing where one turns clockwise and the other counter-clockwise. This traps a volume that decreases as the impellers rotate and releases gas through the outlet.

1 See document 1 on http://www.plainsite.org/dockets/i0lsklje/california-central-district-court/usa-v-avanessian-et-al/

2 Note that Turbomolecular pumps are also known as "turbo pumps," but we purposely use the complete word in this text to distinguish this technology from other proliferation-sensitive turbo pumps used in missile technology—the subject of another section.

3 Court records indicate that Rotary Vane, Oil Diffusion, and Screw pumps have been exported. There is evidence that Turbomolecular pumps, too, may have been exported: a very specific accessory (a 3 m connection cable) was exported that can be used only between a Turbomolecular pump and a Turbotronik NT20 controller.

Rotary Vane pumps, Screw pumps, and Scroll pumps all have impellers that rotate inside a stationary housing to define a volume of gas that decreases as the rotor turns and the gas exits from the pump. See the figure below for an illustration of some of these rotors.

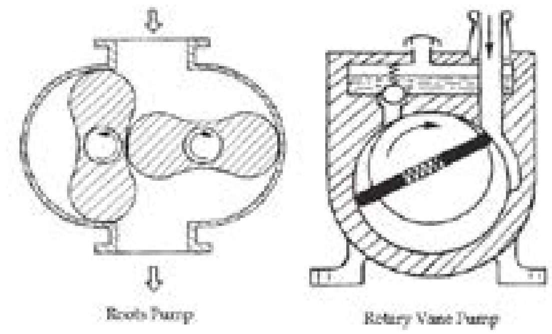

Figure 1: The operation of the Roots and Rotary Vane pumps.[4]

The second class of pumps is kinetic pumps. These propel gas molecules at high speeds by using either liquid as a carrier (Oil Diffusion pumps) or angled blades in discs to "kick" gas molecules toward the outlet (Turbomolecular pumps).

Turbomolecular pumps use complicated rotors with eight to twenty stages of rotor discs along the axis towards the outlet (similar in shape to a turbine used in jet engines). The critical components of a Turbomolecular pump are the rotor, the motor (which rotates at very high speeds), and the bearing (which allows the rotor to pump in a friction-free environment).

In contrast, an Oil Diffusion pump has no rotating components but instead sprays oil vapor downward through a series of conical shapes known as the "jet assembly," where it transfers momentum to the gas molecules to propel them toward the outlet (see figure below). In this case, the critical component of the pumps are the independent parts required for the jet assembly and the pump housing, which is cooled on the outside with the continuous flow of cold water through coils.

4 Used with permission. Adapted from J. Moore, Building Scientific Apparatus, Cambridge University Press, 2009.

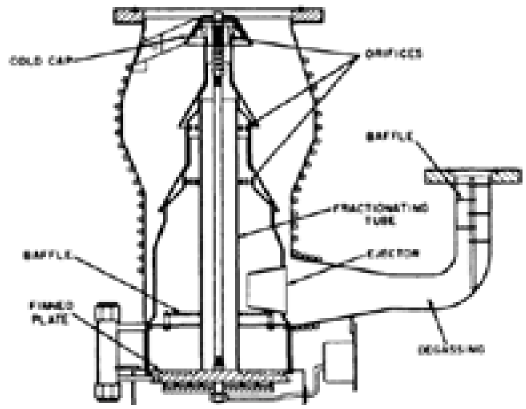

Figure 2: The Oil Diffusion pump. The jet assembly is the central component that contains the orifices.[5]

The process of evacuating a volume starts at atmospheric (or ambient) pressure, and then proceeds to higher vacuums after the pump is turned on. However, one pump type (that includes the Oil Diffusion pump) cannot achieve high vacuum from starting with the atmospheric pressure. These high vacuum pumps require a certain pressure before the pump can be turned on and also require a certain level of vacuum at the outlet. Even if a single pump could be used throughout the full pressure range, it would ultimately be uneconomical.

These pumps must therefore be connected to a series of multiple pumps, known as forepumps or backing pumps. Oil Diffusion pumps and Turbomolecular pumps require mechanical pumps such as Roots pumps as backing pumps to function effectively and can't function without being connected to a suitable backing pump.[6] Roots pumps themselves may also require a Rotary Vane pump as a backing pump to vent the gas into the atmosphere. If an Oil Diffusion pump is exported to an enrichment plant, it is highly likely that a backing pump will also be purchased perhaps from the same vendor with appropriate specifications.

5 Used with permission. Adapted from J. Moore, Building Scientific Apparatus, Cambridge University Press, 2009.
6 Lindberg, Vacuum Pumps, Rochester Institute of Technology, 2012. https://people.rit.edu/vwlsps/LabTech/Pumps.pdf

CURRENT MANUFACTURING METHODS AND STEPS INVOLVED IN PRODUCING THE ITEM

Rotors for positive displacement pumps and components of the jet assembly of interlocking individual cones can be made by standard subtractive manufacture. Oil Diffusion pumps in particular also have a "cold cap assembly": a small, conical shape connected to the cold water supply of the housing to prevent oil vapor from backstreaming into the inlet. This is a simple shape that can be produced through conventional manufacture.[7]

However, manufacturing rotors for Turbomolecular pumps is more complex. Rotors can be made by "individually machined disks that are heat-shrunk to the rotor shaft, by machining complete groups of disks from a single block of material or by manufacturing the rotors using spark erosion."[8] Spark erosion, also known as Electrical Discharge Machining, uses high voltage discharges from materials through a dielectric to remove material, and is used to manufacture materials like tungsten that are difficult to machine.

When the rotors are made from individually machined disks, the shape can be made optically opaque (i.e., without a line of sight through it), which increases the compression ratio (i.e., ratio of the outlet to inlet pressure) and decreases the pumping speed, essentially decreasing the conductance. Other methods can maximize pumping speed while decreasing the compression ratio.

A Turbomolecular pump is made of multiple stages, with rotor or stator disks, and the gas throughput is constant in each stage. The gas throughput is the product of the pumping speed and the pressure (a measure of the concentration/quantity of gas). Because the pressure will decrease through according to each stage's compression ratio, the pumping speed must adjust to keep the throughput constant. For this reason, the blade configurations change for different stages. Since it is not economical in traditional manufacturing to construct individual stages with slightly different specifications, groups of stages with the same specifications are produced as a compromise.

7 http://www.pchemlabs.com/product.asp?pid=6992

8 Hoffman, Dorothy, Bawa Singh, and John H. Thomas III. *Handbook of vacuum science and technology*. Academic Press, 1997, pg 191.

THE DEGREE TO WHICH 3D PRINTING IS USED IN ITEM PRODUCTION

In the case of high vacuum systems, it very advantageous to use the finest metal finishes to eliminate contaminants from the "peaks" and "valleys" and resist corrosion. Printed stainless steel parts tend to have a "matte" finish (> 100 average roughness per micro-inch) and need to be significantly polished to be appropriate for high vacuum applications.[9]

For example, recent studies have shown that the pump-down time for volumes containing an array of finishes matters only at high vacuums (<10-3 μBar, equivalent to 0.75 μTorr)). This is far beyond the quality of vacuum needed for enrichment applications. Thus, except for Turbomolecular pumps, it may not be necessary for ultra-high vacuum applications to polish the surface beyond removal of obvious surface features that may affect sealing. Surfaces can always be cleaned, treated, and baked out to preserve corrosion resistance even if the surface is not very fine.

3D PRINTABILITY OF PUMP ROTORS: COMPANIES

Rotors and stators are the most complicated item to 3D print because of their size and the fact that many shapes vary layer-by-layer, complicating the design and post-processing. Components such as controllers, motors, and heaters are all essential for pump functioning, but are related to the electronics operating the pump and are not practical to 3D print in their entirety. Therefore, the rest of this section will focus specifically on rotors and stators that normally would be produced through conventional manufacturing.

Specifically, this analysis will focus on the rotors of Turbomolecular pumps as proof of concept of the "3D printability" of complicated form factor rotors, since Turbomolecular pumps are the most complex. The assumption is that if these can be 3D printed, then so can all rotors that are similar in dimension and simpler in shape. Turbomolecular rotors are similar in design to the axial turbines used in aeronautics, which have more complexly shaped blades with tapered ends and have already been 3D printed.

Companies such as General Electric (GE), Siemens, Turbocam, Rapid Prototyping services, and others have used 3D printing to produce metal blades and other such materials for turbines. For example, GE engineers created a jet engine that was built using the AM Method Direct Metal Laser Melting. When tested, the engine achieved 33,000 rotations per minute.[10]

Siemens, a large industrial group that produces gas turbines, is using SLM Solutions machines to cut the cost and time to replace blades on broken turbines. Not only does 3D printing streamline production, it also allows Siemens to specialize in constructing items in-house at a low volume, providing bargaining leverage when it comes to outsourcing part production. However, the company

9 Personal communications with Derek Ferramosca from 3d printing company Xometry.com.
10 GEreports. "The 3D Printed Jet Engine." YouTube. May 07, 2015. https://www.youtube.com/watch?v=W6A4-AKICQU.

does admit the process has its flaws: some pieces need further finishing once printed to make them less prone to corrosion.[11]

THE POTENTIAL FOR 3D PRINTING TO BE USED IN PRODUCTION IN THE DIY COMMUNITY

3D PRINTABILITY OF PUMP ROTORS: INDIVIDUALS

AM of turbines is not the domain of companies alone. An individual who goes by the username Harcoreta designed a working scale model of the Boeing 787 Jet Engine, which includes sixty blades. It also has a reverse thruster with enough power to stop the remote controlled plane the maker designed it to work with.[12]

DIY INTEREST IN HIGH VACUUM PUMPS

The DIY community has interest in building vacuum pumps. However, that interest does not always include 3D printing specifically. For example, a Google Group Forum posted in June/July 2016 about exploring the potential for creating a DIY high vacuum, defined as 0.75 mTorr–0.37 µTorr. However, there has not been much activity with the group since early July 2016, with relatively few posts and a concluding suggestion of purchasing a turbopump controller.[13]

There is interest in creating a 3D printable vacuum pump that is accessible to the "every-day" person. One individual tests the possibility of 3D printing the pump and posts their progress on the hackaday.com site. This individual's goal is to create a vacuum pump that is capable of pulling a vacuum of 1 µTorr, based on the design of the "bladeless turbine" invented in 1909 by Nikola Tesla. This person has been unable to complete the pump at the time of writing and it is possible the project has since been suspended.[14]

DIY INTEREST IN ROOTS PUMPS

As mentioned before, Roots pumps can aid the process of uranium enrichment by backing Oil Diffusion pumps. They also attract a great deal of interest from the DIY community because they are simple and have many applications. Their uses are not limited to simply producing a vacuum at the inlet; the outlet can be used to blow gas, which can be used in a range of applications even while

11 "Heavy Metal." *The Economist*. May 03, 2014. http://www.economist.com/news/business/21601528-three-dimensional-printing-may-help-entrench-worlds-engineering-giants-heavy-metal.

12 Millsaps, Bridget. "Designer 3D Prints Working Scale Model of Boeing 787 Jet Engine at Desktop, Includes 60 Blades." 3DPrintcom. September 01, 2015. https://3dprint.com/93014/3d-print-boeing-engine/.

13 "Google Groups." Google Groups. June 2016. https://groups.google.com/forum/#!topic/diybio/CDIE0M9UGhs.

14 Reilly, Keegan. "Project Details." Details • Everyman's Turbomolecular Pump • Hackaday.io. October 23, 2015. https://hackaday.io/post/26986.

maintaining the basic pump design. For example, some versions of Roots pumps are superchargers in hot rod cars. The pumps increase the amount of oxygen in the combustion chamber of the cars.

AM print files (STL files) are readily available for a small Roots pump which is used to deliver air through a tube to a 3D printer nozzle. Users claim that the Roots blower delivers 15l/min to a nozzle through 1 m of 8 mm bore silicone tubing. See the figure below for an illustration of the finished object.

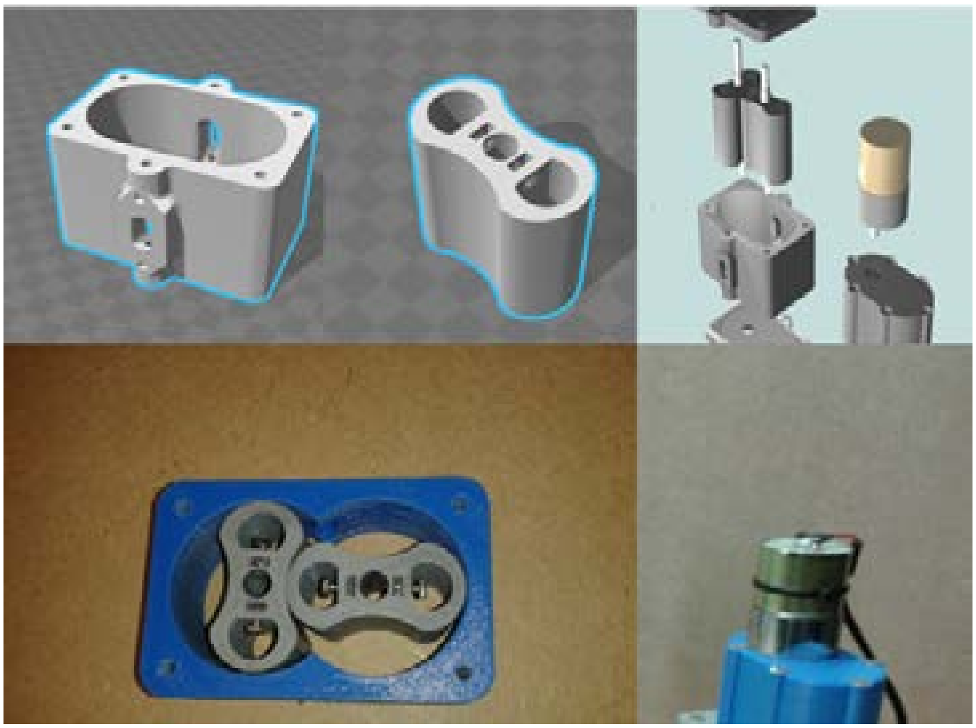

Figure 3: 3D printed model of Roots pump.[15]

It is natural to produce these parts by 3D printing layer-by-layer, so that the thickness of the items and height of the part increase. Note that for the rotor, the item increases in thickness but does not change much in shape as the height increases, with the exception of holes for bolts that could be produced after 3D printing the main item. In contrast, the rotor of the Turbomolecular pump changes shape with each additional layer.

In other words, the 3D printer for the rotor of the Roots pump can repeat a similar pattern layer-after-layer. While this item was printed in plastic and would not produce an adequate vacuum

15 By user "leadinglightsh". December 9, 2014. https://www.thingiverse.com/thing:585301

because of outgassing of the plastic, the design could very well be printed with stainless steel and dimensions scaled up for enrichment applications. The barrier to producing such an object would be the large build volume of the 3D printer (see Conclusions).

DIY INTEREST IN ROTARY VANE PUMPS

Rotary vane pumps can be used as backing pumps for Roots pumps as well as for other applications. On the website GrabCAD.com, a portal that distributes CAD files freely for anyone to download, user Umit posted the detailed CAD files for a Sliding Vane (multiple vane) Rotary Vane pump (see figure below for an illustration). These files consist of the housing, the impeller blades, and the rotor. None of these items are complicated to print and have essentially the same shape layer-by-layer. CAD files are not the same as STL files, but there are tools available to convert directly from one file type to the other.

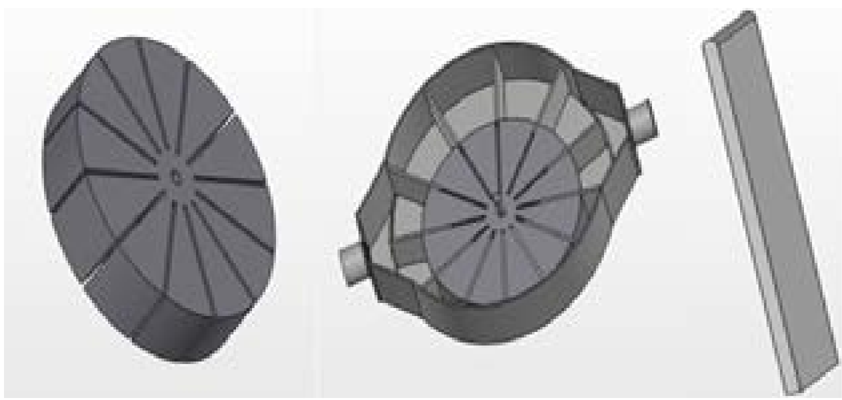

Figure 4: CAD model of Rotary Vane pump, freely available online.[16]

DIY INTEREST IN OIL DIFFUSION PUMPS

In addition to the rotors and other components of the backing pumps mentioned above, the jet assembly of a high vacuum Oil Diffusion pump can be 3D printed. These are composed of interlocking cones in conventional manufacture, but may be 3D printed in one piece. In addition to the jet assembly, the cold cap assembly prevents backstreaming of gas and oil vapor into the inlet of the pump.

Due to the simplicity of these pumps, their design is no secret and can be found in many laboratories around the world. The barrier preventing individuals from using these pumps for uranium enrichment is access to UF_6 compatible oils, such as the PFPE based oil called Fomblin Oil (made by Dow

16 Credit GrabCAD user "Umit-9" https://grabcad.com/library/rotary-vane-pump

Corning) or Krytox Oil (made by Du Pont). Silicon oils can be used for these pumps but are not compatible with UF_6.

Because this is a simple way to produce pumps for a high vacuum, there is considerable interest production. It has not been possible to identify individuals that are using 3D printing to produce these items, but a user named Random Canadian on the website instructables.com describes a detailed method for constructing an Oil Diffusion pump from items that are easy to find. While the item produced is extremely crude, the individual claims to have reached a vacuum of 22 mTorr, at least two orders of magnitude higher than what is required for uranium enrichment. They also used a commercially available Silicon based oil such as "3-in-one silicon lubricant" (manufactured by WD-40 Company). See the figure below for the pump assembled by the individual.

Figure 5: Simple Oil Diffusion pump constructed by Random Canadian on the instructables.com website.[17]

DIY INTEREST IN TURBOMOLECULAR PUMPS

Turbomolecular pumps are useful for high vacuums and for minimizing risk of oil contamination. There is some interest in the DIY community, but there is more interest in Oil Diffusion pumps because they are simpler. However, at least one online forum that focuses on amateur fusion technology has produced electronics controllers for Turbomolecular pumps while purchasing the actual Turbomolecular pump second hand.[18] The advantage of 3D printing has not really been seriously considered for the manufacture of Turbomolecular pumps.

17 Photo by Random_Canadian, 2012. http://www.instructables.com/id/Diffusion-Vacuum-Pump/
18 See: http://www.fusor.net/board/viewtopic.php?f=10&t=4036 and the video: https://www.youtube.com/watch?v=dRKgAIp7uXU

CONCLUSIONS

It is clear the DIY community has interest in printing/constructing high vacuum pumps such as Roots and Rotary Vane pumps. These items have many dual-use applications especially when operated as a "blower" instead of evacuator for large volumes. However, it is surprising that 3D printing has not been used explicitly for printing Oil Diffusion pump components, given the simple geometry of the objects that would be relatively straightforward to 3D print.

Essentially, all rotors of vacuum pumps can be 3D printed. This analysis has identified factors that 3D printing service companies use to evaluate the cost of a 3D printed item, which we use as a measure of the "3D printability" of an item. Beyond the size and material of the object, there are few other technical limitations in 3D printing objects, so the "3D printability" is a semi-qualitative measure of the cost of the item.[19] If the cost of an item is too high, there would be insufficient interest to 3D print the item even if the item could be 3D printed.

Based on this, we ranked the 3D printability of the vacuum pumps relevant for uranium enrichment in the following qualitative order, from most 3D printable to the least: Roots pump, Rotary Vane, Sliding (multiple blade) Rotary Vane Pump, Scroll Pump, Oil Diffusion Pump, Screw Pump, Turbomolecular pump. If the 3D print files of the parts were provided and metal printers and materials were available, the parts could be 3D printed by any individual.

The limitations, from the point of view of proliferation of the technology, are the STL printer files, the material, and access to metal 3D printers. Size is a significant limitation, but there are active efforts to devise multiple printing head devices in which the horizontal extent is not a limitation and large size objects can be manufactured by building up the part layer-by-layer. [20]

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19 Personal communication with Prof. Riccardo Cassati from Mech. Eng. Polytechnico Milano
20 Personal communication with Prof. Riccardo Cassati from Mech. Eng. Polytechnico Milano

3D PRINTING MISSILE COMPONENTS

(Contributor: Shea Cotton)

This report will examine the plausibility and potential of existing (or plausible near-future) 3D printing technology to manufacture items controlled under the Missile Technology Control Regime (MTCR). More specifically, this report will examine items controlled under 2.A.1 subparagraphs a, b, and c.

Those subparagraphs control individual rocket stages, re-entry vehicles (and their subsystems such as heat shields, heat sinks, and associated electronic equipment), and rocket propulsion subsystems (solid and liquid propellant rocket motors/engines).

This report examines this issue by answering the following four questions:

» What is the item's relevance to WMD concerns (i.e., why is the item controlled)?

» What are the current techniques for manufacturing the items?

» To what extent is 3D printing currently used in the manufacturing process?

» What is the potential for 3D printing to be incorporated into the production of these items?

This analysis will focus on re-entry vehicles and rocket propulsion subsystems and will answer each of the four questions as they are applicable. As this analysis will show, 3D printing will significantly increase the ease with which these MTCR controlled items can be produced; however, production of these items still requires significant technical expertise.

Succinctly, this report draws the following conclusions for each question and subsection:

» Current ablative heat shields (the heat shields used today) are not well suited to 3D printing. More advanced ceramic heat shields and advanced titanium honeycombed heatshields are much better suited to 3D printing. 3D printed ceramics capable of withstanding high temperatures have already been developed, and better ones are being pursued. Titanium can be 3D printed with existing technology.

» Propulsion systems stand the most to gain from 3D printing. Current engine parts are very expensive. Rockets engines exist that employ 3D printed parts already exist, and development of more advanced engines is underway.

At the moment, most of the technical capability for producing 3D printed parts is limited to advanced research labs and advanced aerospace corporations.

We summarize how 3D printing affects manufacture by lowering the barrier to producing the item in the Table below.

Table 2: Manufacturing barrier for various missile components with and without using AM. The value without including AM (column 7) corresponds to the sum of the scores (a score of 1 is the lowest barrier and 3 is the highest) for the five criteria (columns 2-6). The 8th column is the fraction of components (F_{3D}) that can be 3D printed, and the final column is an estimate of how the barrier would be decreased through AM: the product of the fraction of 3D printed components and the sum of the scores of criteria that are affected by 3D printing is subtracted from the height of the barrier without 3D printing. Note that the value of 0 is given for the difficulty in obtaining key components because this is relevant for components such as electronics or motors only, not for materials.

COMPONENTS	CRITERIA NOT AFFECTED BY 3D PRINTING			CRITERIA AFFECTED BY 3D PRINTING		HEIGHT OF BARRIER WITHOUT 3D PRINTING	FRACTION (F3D) COMPONENTS 3D PRINTED (1=ALL)	HEIGHT OF BARRIER INCLUDING 3D PRINTING ADVANTAGE
	Difficulty in obtaining key materials	Difficulty in obtaining key components	Necessity of advanced knowledge	Number of Steps	Necessity of advanced Skills			
RCC	2	0	3	3	3	11	0.2	9.8
AVCOAT	2	0	3	3	3	11	0.2	9.8
Titanium	2	0	1	1	1	5	0.9	3.2
UHTC	2	0	3	2	3	10	0.9	5.5
Turbopump	2	2	3	3	3	13	0.8	8.2

RE-ENTRY VEHICLES

WMD RELEVANCE

The WMD relevance of re-entry vehicles is clear: Re-entry vehicles are essential for delivering a payload intact to a target. Surviving atmospheric re-entry is difficult and requires significant technical expertise. As such, that expertise is tightly controlled.

EXISTING MANUFACTURING TECHNIQUES

Generally, a re-entry vehicle consists of a few key parts. This analysis will focus on one in particular: the thermal protection system, or heat shield. The heat shield requires the most technical expertise. Ideally, a heat shield would be extremely light (to cut down on weight) and would protect the re-entry vehicle from the heat and pressures associated with re-entry. It is tricky to manufacture a material that meets both of these requirements.

In the broadest sense, there are two main types of heat shields used in re-entry vehicles: ablative heat shields and thermal soak heat shields. Ablative heat shields were used on the Mercury, Gemini, and Apollo spacecraft. Ablative heat shields are designed to slowly burn and chip away during re-entry. When the material chips away with heat—a process called ablation—it effectively removes some of the heat and thus allows the vehicle to survive re-entry.

Thermal soak heat shields function differently and are less common. In contrast to ablative heat shields, which remove heat by gradually burning away, thermal soak heat shields absorb the heat and keep it away from sensitive objects in the reentry vehicle. This type of heat shield is probably most well-known from its use on the Space Shuttle. The shuttle used two different types of tiles in its thermal protection system. The materials used in thermal soak shields are extremely poor conductors of heat (i.e., it is very difficult to heat them up), they could "literally be held in the hand and be heated with a blow torch". [21] The shuttle used tiles composed almost entirely of silica glass (about 99.9 percent) with an extremely low density. In fact, by volume, the tiles themselves are about 90 percent air.[22] This also means they are extremely delicate.

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21 Griffin, Michael D. Space vehicle design. AIAA, 2004.

22 Ryan Oakes, "Space Shuttle Ceramic Tiles". University of Washington. Accessed at http://depts.washington.edu/matseed/mse_resources/Webpage/Space%20Shuttle%20Tiles/Space%20Shuttle%20Tiles.htm on December 13, 2016

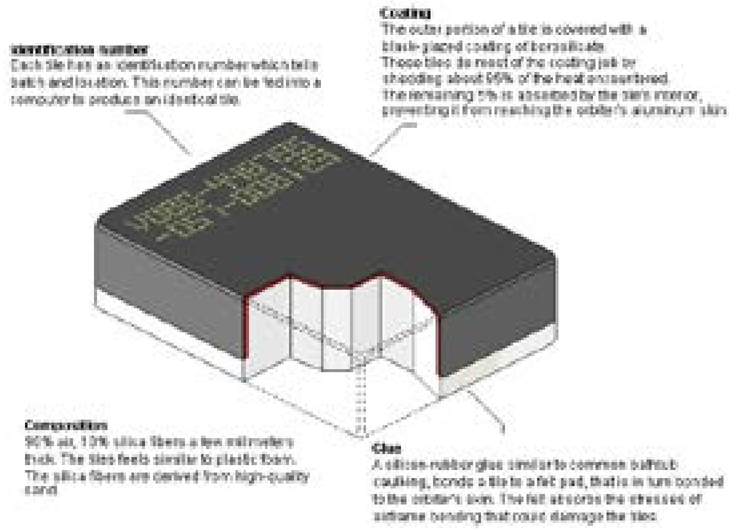

Figure 6: Space shuttle tile.[23]

Though they could survive the heat and pressure of re-entry, the silica glass tiles themselves could not survive in-flight rain.

The second type of tiles, used on the nose cone and leading edges of the wings, were made from reinforced carbon-carbon (RCC). The material is extremely light, with a low density, but is very bad at withstanding impacts.[24] RCC was first developed for use in ballistic missiles but has since been adapted for other purposes, such as the brakes on Formula One racing cars. This material will be discussed in greater detail in subsequent sections. Thermal soak materials can also be re-used, hence why they were employed on the Space Shuttle.

Since the retirement of the Shuttle in 2011, no other known space craft employs thermal soak heat shields. Because of the extremely delicate nature of the silica glass tiles, this analysis finds it doubtful they would be of much value in heat shields for re-entry vehicles. They are extremely delicate, require regular replacement, and are very time consuming to install.[25] Because of this, and because of the extremely limited use of silica glass tiles for heat shields, this analysis will narrow its focus to two types of heat shields: ablative heat shields and RCC thermal soak heat shields.

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23 Photo credit: Ulfbastel, July 2007. Wikipedia creative commons. https://en.wikipedia.org/wiki/File:Space_Shuttle_(HRSI_tile).png

24 The Space Shuttle Columbia was destroyed during re-entry because a piece of foam broke off and struck the wing edge during launch.

25 Richard S. Lewis *The voyages of Columbia: the first true spaceship*. Columbia University Press. 1984

ABLATIVE HEAT SHIELDS

There are several types of ablative heat shields that differ in composition. The compounds used in a heat shield can vary significantly depending on the intended use and the pressures that the final device is expected to be subjected to. Many of these materials and the manufacturing processes are highly classified. The main sources of information come from what has been publicly released about National Aeronautics and Space Administration (NASA) spacecraft. It is quite possible heat shields used on re-entry vehicles for US missiles are made from different materials.

The first material this paper will examine is called AVCOAT or Avcoat. It was used as the heat shield for the Apollo missions and will be used for the coming Orion missions. It was employed on a spacecraft that needed to be able to withstand re-entry at speeds of 11 kilometers per second (km/s). These speeds are on the higher end of what any ballistic missile re-entry vehicle would have to withstand. Avcoat is made from "silica fibers with an epoxy-novalac resin filled in a fiberglass-phenolic honeycomb."[26] The process for making this is complicated. In fact, NASA stopped using Avcoat for several decades when they started using the Space Shuttle. As such, NASA forgot how to make the product and had to spend about $25 million over five years figuring out how to make it again.[27] The picture below provides a general overview of the multi-step process to produce it.

Figure 7: Avcoat manufacturing process.[28]

As the figure above depicts, constructing a heat shield is a complex process and the exact manufacturing process is a closely guarded secret.

26 Kylie Clem, Ashley Edwards, Grey Hautaluoma. "NASA Selects Material for Orion Spacecraft Heat Shield" April 7, 2009. Accessed at http://www.nasa.gov/home/hqnews/2009/apr/HQ_09-080_Orion_Heat_Shield.html on August 12, 2016.

27 Sylvia M. Johnson. "Thermal Protection Materials: Development, Characterization, and Evaluation." September 2012. Accessed at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120016878.pdf on August 12, 2016.

28 Photo credit: NASA. September 2012. Wikipedia Commons https://commons.wikimedia.org/wiki/File:Avcoat_manufactoring_statges.jpg

Ablative heat shields are composed of multiple compounds such as the AVCOAT material, and it is not expected that AVCOAT in particular can be 3D printed. However, AVCOAT is added to a skeleton structure (titanium honeycomb) that may be 3D printed, thereby simplifying the manufacturing process. Titanium honeycomb itself can also be used as a heat shield and is manufactured by companies such as Benecor. This structure sandwiches a honeycomb made from titanium between two other titanium sheets. It is already possible to manufacture such a structure with existing 3D printing technology.

We have no evidence that AM is currently implemented, or that there is interest in the DIY community to manufacture, AVCOAT or the underlying titanium honeycomb structure.

REINFORCED CARBON-CARBON

RCC is another heat shield system used in the Space Shuttle program. It is advantageous because the material re-radiates the heat it absorbs, making it an excellent protective material in the leading edges of spacecraft. RCC consists of a Carbon-Carbon composite with a silicon carbide coating and a tetraethylorthosilicate coating to reduce oxidation. Carbon-Carbon is a carbon fiber inside a carbon matrix, and the composite material shares the properties of both the matrix and the fiber as well as the methods of processing. This allows unique combinations of materials for specific purposes. Carbon-Carbon becomes "stronger and stiffer at elevated temperatures" but unfortunately oxidizes in air at 500 degrees Celsius.[29]

Manufacturing RCC is expensive.[30] The specific process varies depending on the final use and desired properties; as such, exact manufacturing techniques may differ from the following description. First, layers of carbon filament cloth are laid in what will be the product's final shape. This is then coated in an organic (carbon) binder such as plastic or pitch. Depending on the desired final properties, coke, pitch, or some other fine carbon aggregate can be added to the mixture. Next, the materials are heated up to allow pyrolysis[31] to transform the binder into pure carbon. This process causes small voids to form in the material. After a certain amount of time passes, the voids are filled gradually by forcing a carbon-forming gas such as acetylene through the material at high temperature, causing the carbon to form large, graphite crystals. This usually takes several days or even weeks, and usually requires advanced machinery capable of keeping the material at the required temperature and pressures for this extended period of time. This machinery and the technical expertise required to operate it account for the high cost of the material.

Given the complexity in manufacturing the material, it is not possible to 3D print completed RCC. The process for creating it involves an intense heat treatment that alters the material at the molecular level. It is unclear if RCC will ever be fully 3D printable. However, it is quite possible to use 3D

29 http://infohouse.p2ric.org/ref/32/31676.pdf
30 The nose cone and wing edges on the Space Shuttle cost an estimated $100,000 per square foot. Though much of this high cost was due to initial research and the unique geometry of the Shuttle, it is still an extremely high price.
31 Pyrolysis is the process something is heated, in the absence of oxygen, to a temperature that would cause combustion under ordinary circumstances. The process turns organic material into relatively pure carbon.

printing during the first stage of manufacturing RCC (creating the shape of the item), and AM could be extremely useful for this step. The intense heat treatment, however, is essential in the production process. There is no evidence to suggest that any organizations are attempting to do this.

ULTRA-HIGH TEMPERATURE CERAMICS (UHTC)

However, there is enormous potential to use 3D printing to produce other heat resistant ceramics with properties that may be similar to RCC. Recently, a lab called HRL Laboratories in Malibu, California managed to produce a variety of ceramics and a 3D printer for the ceramic.[32] The ceramic still must undergo an intense heat treatment, but it can be done with a furnace that is simple in comparison to the incredibly advanced and expensive furnaces required for RCC. The lab itself receives funding from Boeing and the Defense Advanced Research Project Agency (DARPA). They hope the lab will produce ceramic that can be used on a future hypeSrsonic jet.[33] Such a material would be useful in a heat shield for a hypersonic missile as well. The method they use is patented but is described in a detailed article in Science Magazine. We summarize the score for the potential to manufacture UHTC in the Table below.

Figure 8: 3D printed ceramic being blowtorched.[34]

CORPORATE AND DIY INTEREST

In our review, we found that DIY interest in ablative heat shields is not high. In amateur rocketry, the rockets do not travel to very high altitudes and even if they do, the re-entry qualifications are not very significant. Companies such as SpaceX, Sierra Nevada Corporation, and Boeing are, however,

32 Mary-Ann Russan. "3D printing breakthrough: Heat-resistant ceramics for use in hypersonic jets now possible". *International Business Times*. January 4, 2016. Accessed at http://www.ibtimes.co.uk/3d-printing-heat-resistant-ceramics-building-hypersonic-jets-spaceships-now-possible-1535919 on August 16, 2016.
33 Mike Orcutt. "Heat-Resistant Ceramic Parts Are Now 3-D Printable." *MIT Technology Review*. December 31, 2015. Accessed at https://www.technologyreview.com/s/545086/heat-resistant-ceramic-parts-are-now-3-d-printable/ on August 16, 2016.
34 Photo Credit: HRL Laboratories. Used with permission. 2016.

using state-of-the-art heat shields.[35] For example, SpaceX has hired a former NASA employee who designed the PICA (Phenolic Impregnated Carbon Ablator) for use in the Dragon spacecraft.[36] Similarly, Sierra Nevada corporation has designed the Dreamcatcher spacecraft, which is similar to the Space Shuttle and uses Alumina Enhanced Thermal Barrier tiles (a high-temperature tile incorporating alumina fibers)[37] and other composites. Also, Boeing is considering using AVCOAT or PICA for their CST-100 spacecraft.[38]

ROCKET PROPULSION SYSTEMS

WMD RELEVANCE

Rockets are the choice WMD delivery system for many states. They are sought for their ability to deliver their payload almost anywhere in the world within a short period of time and with relative precision. Perhaps the most essential part of a rocket is an efficient propulsion system, which can significantly boost a rocket's range.

EXISTING MANUFACTURING TECHNIQUES

Under existing manufacturing techniques, parts often take months to make and are incredibly complex. They are often made from expensive and exotic alloys capable of withstanding extreme heat and stress. The durability required from the material makes it extremely difficult and expensive to manufacture. AM could make it much easier to produce parts consistently, in different locations, and by different teams.

3D PRINTING AND MANUFACTURING

As with many previous items in this analysis, there is limited information concerning exact manufacturing techniques. Much of the available information comes from NASA, which has been testing 3D printing capabilities extensively for rocket engine manufacturing and has made notable progress. Space X currently uses a 3D printed main oxidizer valve in the Merlin engines it uses to launch payloads into orbit.[39] The United Launch Alliance, a joint-venture between Boeing and Lockheed Martin, is experimenting with 3D printed engine parts. They aim to produce an engine composed of about 150 3D printed parts by 2019.[40]

35 https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140002341.pdf

36 http://spacenews.com/spacexs-high-velocity-decision-making-left-searing-impression-on-nasa-heat-shield-guy/

37 https://www.nap.edu/read/5115/chapter/6#50

38 https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140002341.pdf

39 Space X. "SpaceX Launches 3D Printed Part to Space, Creates Printed Engine Chamber." SpaceX.com. July 31, 2014. Accessed at http://www.spacex.com/news/2014/07/31/spacex-launches-3d-printed-part-space-creates-printed-engine-chamber-crewed on August 18, 2016.

40 Jeff Stone. "Vulcan Rocket: 3D Printing Launch Plan Includes More Than 100 Components." *International Business Times*. April 21, 2015. Accessed at http://www.ibtimes.com/vulcan-rocket-3d-printing-launch-plan-includes-more-100-components-1890292 on August 18, 2016.

3D PRINTING POTENTIAL

Rocket propulsion systems have the most potential in 3D printing and have the most active research. No 3D printed spacecraft has flown in space at the time of writing, but many have been proposed. Perhaps the most ambitious design involves deploying 3D printing satellites into orbit, which would then assemble entire spacecraft in orbit.[41] Such a manufacturing method could reduce costs sharply. Such a system would likely have to involve 3D printers capable of printing not only simple engine parts, but also rocket stages and rocket propellants.

NASA has been working to build an entire 3D printable rocket engine and has made considerable progress to date. In December 2015, NASA reached a major milestone when they produced an engine test[42] that used 3D printed parts for 75 percent of its components,[43] including the turbopump (one of the most complex parts of the engine) and the injector. They produced the injector with 200 parts fewer than is used conventionally.[44]

Figure 9: Test of 3D Printed Engine[45]

41 Sammy Medina. "Future Spacecraft Will Be 3-D Printed In Space, By Robots". Fast CoDesign. September 24, 2013. Accessed at http://www.fastcodesign.com/3016893/future-spacecraft-will-be-3-d-printedin-space-by-robots on August 18, 2016.
42 NASA's budget for 2016 was $18.4 billion. By US standards that is a fairly limited budget.
43 Tracy McMahan. "Piece by Piece: NASA Team Moves Closer to Building a 3-D Printed Rocket Engine." NASA. December 17, 2015. Accessed at http://www.nasa.gov/centers/marshall/news/news/releases/2015/piece-by-piece-nasa-team-moves-closer-to-building-a-3-d-printed-rocket-engine.html on August 15, 2016.
44 Tracy McMahan. "Piece by Piece: NASA Team Moves Closer to Building a 3-D Printed Rocket Engine." NASA. December 17, 2015. Accessed at http://www.nasa.gov/centers/marshall/news/news/releases/2015/piece-by-piece-nasa-team-moves-closer-to-building-a-3-d-printed-rocket-engine.html on August 15, 2016.
45 Photo credit: NASA. Public domain. 2016.

DRONES AND DRONE COMPONENTS

(Contributor: Ruby Russell)

This section describes the 3D printability of Unmanned Aerial Systems (UAS) and the potential threat that these devices pose despite the fact that, to our knowledge, UAS have not been used for delivery of WMD. Based on our research, we make the following observations:

» Recognized advantages of 3D printing have already resulted in the production of advanced, high-speed, and even jet powered 3D printed UAS.

» The DIY drone community has already taken full advantage of 3D printing, regularly sharing techniques, designs, and even CAD files for printable drone components across numerous open sources online forums.

» Terrorist groups (such as the Islamic State, or IS) are already using drones as a possible delivery system for explosive materials or for reconnaissance. We are not aware of any use for delivery of WMD at this time.

» The company Stratsys Ltd has already produced a UAS with 80 percent 3D printed parts that weighs only 15 kilogram (kg) and can move at speeds exceeding 150 miles per hour (mph).

» The US military has invested in 3D printing of drones. The Navy can assemble drones in a matter of hours on ships. The army is experimenting with drones for preemptive threat detection and surveillance, even deploying drones from jets travelling close to the speed of sound.

» The DIY community is very interested in developing drones and uses platforms such as GrabCAD and Thiniverse to share CAD files for anyone to download. The CAD files can be converted to STL files for 3D printing.

» The DIY community can increase payload weight in two ways: (1) Multiple rotors can be placed on an existing frame; this requires knowledge of building drones. (2) Multiple commercial, off-the-shelf UAS can be connected to transport heavier payloads, and could be a threat in the future. One involved scientist stated in an email that "simple off-the-shelf components lifting a 20 kg payload with precision control is very possible and straightforward (the math/implementation is easy given hobby-grade resources)."

» The majority of the DIY community develops small quadcopters for hobbyist or civilian purposes, and the well-known website DIY Drones prohibits discussions of military, weaponized, or illegal uses of UAVs. However, we have found at least one discussion on DIY Drones that discusses testing drones of any payload outside the US where laws are "more lenient." We wonder how well these sites are monitored and whether there are alternative websites to DIY Drones that are dedicated to discussing nefarious purposes for drones.

» At least one civilian has constructed a drone armed with a paint ball gun, and has demonstrated its use for targeting individuals on the ground. Their purpose was to bring attention to the potential for this technology to be used for nefarious purposes. We are not clear whether any components were 3D printed, but we highlight it here as a possible threat of DIY drones.

We summarize how 3D printing affects manufacture by lowering the barrier to producing the item in the Table, below.

Table 3: Manufacturing barrier for UAV with and without using AM. The value without including AM (column 7) corresponds to the sum of the scores (a score of 1 is the lowest barrier and 3 is the highest) for the five criteria (columns 2-6). The 8th column is the fraction of components (F_{3D}) that can be 3D printed, and the final column is an estimate of how the barrier would be decreased through AM: the product of the fraction of 3D printed components and the sum of the scores of criteria that are affected by 3D printing is subtracted from the height of the barrier without 3D printing.

COMPONENTS	CRITERIA NOT AFFECTED BY 3D PRINTING			CRITERIA AFFECTED BY 3D PRINTING		HEIGHT OF BARRIER WITHOUT 3D PRINTING	FRACTION (F3D) COMPONENTS 3D PRINTED (1=ALL)	HEIGHT OF BARRIER INCLUDING 3D PRINTING ADVANTAGE
	Difficulty in obtaining key materials	Difficulty in obtaining key components	Necessity of advanced knowledge	Number of Steps	Necessity of advanced Skills			
UAV	1	1	1	1	1	5	0.95	3.1

EXECUTIVE SUMMARY

Given its cost-effective value and ability to reduce cycle time while allowing for a rapid iterative design process, multiple well-resourced defense and aeronautics companies are turning to 3D printing. This growing interest has resulted in experimentation and production of advanced, high-speed, and even jet powered 3D printed UAS.[46] Manufactures repeatedly point to the low-cost, efficient, and flexible benefits of 3D production, underscoring its potential to become the primary means of producing military UAS in the future.

In the last decade, military and civilian reliance on drones (UAV or UAS) has become increasingly widespread. The spectrum of technologies and capabilities with which UAS may be equipped is incredibly broad. Applications range from assessing crop water levels through field mapping to carrying out military intelligence, surveillance, reconnaissance (ISR), and strike missions. For this reason, there is a huge potential for dual-use in the UAS sector.

Because UAS are capable of delivering a variety of payloads—potentially including WMD—the international community used the MTCR to control UAS with specific capabilities. These controls include UAS capable of delivering a 500 kg payload over a range of 300 km or more. Notably, however, the MTCR does not control model aircraft designed specifically for recreational or competition purposes. As experts point out, it is problematic that "current commercial off-the-shelf technology enables hobbyist drones to perform aerial surveillance or deliver payloads—including explosives or chemical or biological agents—of a few kilograms at ranges up to a few kilometers."[47] There is an increasingly real potential for non-traditional actors to repurpose these smaller, readily accessible UAV systems to carry out deadly missions.

Importantly, 3D printing technologies are increasingly available on the open market, granting access to individuals and non-state actors who would not otherwise have access to traditionally restricted technologies. As experimentation, innovation, and growth in the 3D printing drone industry continues to accelerate, so too will non-traditional actors' access to advanced UAS components. Nowhere is this more evident than in the DIY drone community, which has taken full advantage of 3D printing. These communities regularly share techniques, designs, and even CAD files for printable drone components across numerous open sources online forums.

Discussions within these online DIY forums range from debates over the best 3D printers and filament materials to designs for a variety of unmanned quadcopter models. While the majority of the DIY community is working on small, seemingly harmless quadcopters, some clearly seek to go beyond the hobby domain. For example, some of the open source 3D print designs include replacement and upgraded parts for commercially available drones, including the Phantom by Dà-Jiāng

46 Business Wire, "Aurora Flight Sciences and Stratasys Deliver World's First Jet-Powered, 3D Printed UAV in Record Time," November 9, 2015. Available at: http://www.businesswire.com/news/home/20151109005240/en/

47 Kelley Sayler, "A World of Proliferated Drones: A Technology Primer," *Center for New American Security,* June 2015, p. 5. Available at: http://www.cnas.org/sites/default/files/publications-pdf/CNAS World of Drones_052115.pdf

Innovations (DJI), which reportedly has been modified by actors including Ukrainian forces and IS for surveillance purposes in conflict zones.[48] There is also evidence that the DIY drone community has interest in using 3D printing to produce UAS with features forbidden under US law. [49]

The advantages of 3D printing, as well as the already widespread use of this advanced fabrication technology in UAS production, indicates that reliance on AM in this sector will only continue to grow. In addition to offering a rapid, cost-effective design and production process, emerging technologies such as 3D printing are making advanced military technologies increasingly accessible to our adversaries. The US therefore has additional incentives to revise traditional processes for UAS acquisitions and incorporate more efficient fabrication technologies. Such changes may ultimately facilitate a "new paradigm" in UAS acquisition.[50]

Finally, as 3D printing technologies become more accessible and trends in DIY and crowdsourcing continue to advance, the gap between manufacturer and user will begin to shrink. Such innovation has the potential to improve efficiency and even save lives in many cases, but increasingly advanced capabilities make it more likely that non-traditional actors will soon have access to or even the ability to produce UAS systems controlled under current MTCR guidelines.

THE ITEM'S RELEVANCE TO WMD PROLIFERATION CONCERNS

UAS may be equipped with a broad spectrum of technologies and capabilities. UAS applications include assessing crop water levels through field mapping,[51] conducting aerial photography for real estate,[52] and carrying out military ISR and strike missions. For this reason, there is a huge potential for dual-use in the UAS sector.

In the military field specifically, UAS "have become emblematic of twenty-first century military technologies," with at least thirty countries maintaining or developing armed drone programs as of 2014. [53] UAS are not WMD in and of themselves, but they are capable of delivering a variety of payloads

48 Thingiverse.com, "DJI Phantom 3," Last updated August 19, 2016. Available at: http://www.thingiverse.com/Tsch-ich/collections/dji-phantom-3/page:1; Oriana Pawlyk, "U.S. organization sends drones to Ukrainian military," *Aiforce-times,* February 19, 2015. Available at: http://flightlines.airforcetimes.com/2015/02/19/u-s-organization-sends-drones-to-ukrainian-military/; Defense One, "In Ukraine, Tomorrow's Drone War is Alive Today," March 9, 2015. Available http://www.defenseone.com/technology/2015/03/ukraine-tomorrows-drone-war-alive-today/107085/.

49 DIYdrones.com, "Strategic Supply Drones." Available at: http://diydrones.com/group/strategic-supply-drones

50 Aaron Martin and Ben FitzGerald 2013, p.12.; Dazhong Wua et al., "Cloud-based design and manufacturing: A new paradigm in digital manufacturing and design innovation," *Computer-Aided Design*, 59 2015, pp 1-14

51 CALSO, "Drones & Good: To save Water." Available at: http://www.drones4good.co/

52 AUVSI, "Commercial UAS Exemptions: By the Numbers." Available at: http://www.auvsi.org/advocacy/exemptions70

53 Michael C. Horowitz and Matthew Fuhrmann, "Droning on: Explaining the Proliferation of Unmanned Aerial Vehicles," October 24, 2014. Available at: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2514339

including WMD. Some of the US military's largest drones, such as the General Atomics's MQ-9 Reaper, have surveillance-strike capabilities and can carry payloads greater than 1,000 kg over 1,150 miles.[54] Other, smaller military drones may also be capable of delivering "dangerous payloads, including explosives or chemical or biological weapons."[55]

In an effort to curb the proliferation of UAS capable of carrying WMD payloads, Multilateral Export Control Regimes (MECRs)—which includes the MTCR and Wassenaar Arrangement (WA)—control specific types of UAS/UAVs and components. Under Article 1.A.2., the MTCR Category 1 Annex controls complete UAV systems (including cruise missiles, target drones, and reconnaissance drones) capable of delivering a 500 kg payload over a 300 km range or more.[56] Articles 19.A.2 and 19.A.3 under the Category II Annex control complete UAV systems with a range of 300 km or more, as well as those incorporating (or capable of incorporating) inter alia, an aerosol dispensing system with a capacity greater than 20 liters.[57]

Notably, MTCR article 19.A.3. does not control model aircraft designed for recreational or competition purposes specially. However, according to one study by the Center for New American Security (CNAS), "Current commercial off-the-shelf technology enables hobbyist drones to perform aerial surveillance or deliver payloads—including explosives or chemical or biological agents—of a few kilograms at ranges up to a few kilometers."[58] Studies estimate the value of the emerging global commercial drone market to reach $127 billion by 2020, so the variety of commercially accessible technologies and the capabilities with which they may be equipped is only expected to grow.[59]

Already, there is deep concern that commercial drones are being repurposed for violent or terrorist-related activities.[60] According to US authorities, "Germany, Spain and Egypt have foiled at least six potential terrorist attacks with drones" since 2011.[61] Terrorist groups including the IS increasingly turn to commercially available drones such as the popular DJI Phantom to conduct surveillance missions and even carry explosive payloads.[62] Such incidents have driven speculation over potential

54 US Air Force, "MQ-9 Reaper," September 23, 2015. Available at: http://www.af.mil/AboutUs/FactSheets/Display/tabid/224/Article/104470/mq-9-reaper.aspx

55 Kelley Sayler, "A World of Proliferated Drones: A Technology Primer," *Center for New American Security*, June 2015, p. 15. Available at: http://www.cnas.org/sites/default/files/publications-pdf/CNAS World of Drones_052115.pdf

56 MTCR/TEM/2016/Annex. Available at: http://mtcr.info/wordpress/wp-content/uploads/2016/07/MTCR-TEM-Technical_Annex-2016-03-17-Current_Version.pdf

57 Ibid.

58 Kelley Sayler, p.5.

59 PricewaterhouseCoopers, "Global Market for Commercial Applications of Drone Technology Valued at over $127 bn," May 9, 2016. Available at: http://press.pwc.com/News-releases/global-market-for-commercial-applications-of-drone-technology-valued-at-over--127-bn/s/ac04349e-c40d-4767-9f92-a4d219860cd2

60 Yasmin Tadjdeh, "Islamic State Militants in Syria Now Have Drone Capabilities," *National Defense Magazine,* August 28, 2014. Available at: http://www.nationaldefensemagazine.org/blog/Lists/Posts/Post.aspx?ID=1586

61 Jack Nicas, "Criminals, Terrorists Find Uses for Drones, Raising Concerns," *The Wall Street Journal*, January 28, 2015. Available: http://www.wsj.com/articles/criminals-terrorists-find-uses-for-drones-raisingconcerns-1422494268

62 Michael S. Schmidt and Eric Schmitt, "Pentagon Confronts a New Threat From ISIS: Exploding Drones," *New York Times*, October 11, 2016. Available: http://www.nytimes.com/2016/10/12/world/middleeast/iraq-drones-isis.html

disastrous scenarios facilitated by off-the-shelf drone technologies. In 2013, for example, a protestor at a rally in Germany flew a small, commercially available Parrot AR quadcopter near German Chancellor Angela Merkel. Experts commented, "even a small explosive charge or grenade aboard a similar drone would have been catastrophic."[63]

Viewing such threats as a reality, security forces including the New York Police Department are developing strategies to counter weaponized drones, especially in light of their potential to deliver a small WMD payload.[64] In addition to the threat posed to human targets, US government officials are increasingly concerned about the "imminent threat" that small commercial UAS pose to sensitive nuclear facilities. Secretary of Defense Ashe Carter recently acknowledging the issue as "a concern."[65]

As the commercial and hobbyist UAS industries grow, individuals and non-state actors will inevitably have greater access to drones with increasingly advanced capabilities. Because drones and drone technologies have potential for dual-use, advancements could play a significant role in lowering the threshold for WMD delivery.

CURRENT MANUFACTURING METHODS TO PRODUCE DRONES

Traditional UAS manufacturing processes tend to rely on composite construction, including the assembly of a variety of molded components, some of which may be produced via injection molding.[66] At its most basic level, UAV composite construction involves assembling two outer surfaces or "skins" and a lightweight core.[67] A wide variety of materials may be used for the skin, including composite laminates like fiberglass, Kevlar, and graphite fibers.[68] The main body of the aircraft, known as the fuselage, may be constructed by layering a core material such as polystyrene, polyurethane, or aluminum honeycomb with the exterior skin.[69] Resins are used to "bond the outer skin to the core materials."[70]

63 Sean Gallagher, "German chancellor's drone 'attack' shows the threat of weaponized UAVs," *ArsTechnica.com*, September18, 2013. Available at: http://arstechnica.com/information-technology/2013/09/german-chancellors-drone-attack-shows-the-threat-of-weaponized-uavs/.

64 CBS News, "NYPD scanning the sky for new terrorism threat," October 29, 2014. Available at: http://www.cbsnews.com/news/drone-terrorism-threat-is-serious-concern-for-nypd/

65 Leigh Giangreco, "Drone defense for nuclear sites awaits government approval," *Flight Global*, September 20, 2016. Available at: https://www.flightglobal.com/news/articles/drone-defense-for-nuclear-sites-awaits-government-ap-429541/; Aaron Mehta, "US Government Tied in Legal Knot Over Drone Countermeasures at Nuclear Sites," Defense News, September 27, 2016. Available at: http://www.defensenews.com/articles/us-gov-tied-in-legal-knot-over-drone-countermeasures-at-nuclear-sites

66 Paul Fahlstrom and Thomas Gleason, *Introduction to UAV Systems*, West Sussex, United Kingdom: John Wiley & Sons, 2012, p 96; Bill Canis, "Unmanned Aircraft Systems (UAS): Commercial Outlook for a New Industry," Congressional Research Service, September 9, 2015, p.3. Available at: https://www.fas.org/sgp/crs/misc/R44192.pdf

67 Paul Fahlstrom and Thomas Gleason, 2012, p 96.

68 Ibid, p. 97.

69 Bill Canis, , 2015, p.3.

70 Ibid, p.3.

This process may also be achieved via injection molding, in which thermoplastics or other materials are melted and injected into a mold, where they cools and harden into the shape of the mold's cavity.[71] The cooled part is then ejected from the mold. The molds themselves must be manufactured, and are often machined from steel or aluminum.[72] In the context of UAV construction, the skin and resin are "[draped] . . . inside the mold so as to form hollow structures. Molded panels and substructures can be bonded to make a completed structure."[73]

One study noted that because UAS are composed of relatively few components, these unmanned systems are "fairly simple to build" even by traditional manufacturing standards.[74] However, as new technologies emerge, traditional defense manufacturing processes including those for UAS are increasingly viewed as "outdated, expensive, inflexible and slow."[75] Experts argue that the current process at the Department of Defense (DOD) for developing and acquiring weapons systems is hampered by long development cycles that are often compounded by schedule delays and rising costs.[76] In order to manage investment returns on these lengthy, expensive acquisition processes, the DOD may operate military aircraft twenty to fifty years after reaching initial operating capability, leaving little flexibility for integration of technological advancements.[77]

To overcome the obstacles associated with traditional manufacturing techniques, defense and aeronautics companies rely increasingly on 3D printing in UAS production. According to experts, 3D printing is integrating into defense manufacturing because it establishes an acquisition process in which "development cycles are short, production schedules are accelerated and both overall and unit costs are reduced to create an environment in which forces can surge rapidly to meet operational needs."[78]

THE DEGREE TO WHICH 3D PRINTING IS USED IN ITEM PRODUCTION

The use of 3D printing in drone manufacturing is increasing rapidly within both defense and DIY sectors. Multiple well-resourced defense and aeronautics companies are turning to 3D printing because it is cost-effective and reduces cycle time while facilitating a rapid iterative design process.[79] At the same time, the DIY drone community has taken full advantage of 3D printing,

71 Rutland Plastics Limited, "What is the Injection Moulding Process?" Available at: http://www.rutlandplastics.co.uk/advice/moulding_process.html

72 Leslie Langnau "3D printing versus injection molding," *MakePartsFast*, March 14, 2016. Available at: http://www.makepartsfast.com/3d-printing-versus-injection-molding/

73 Paul Fahlstrom and Thomas Gleason, 2012, p 98.

74 Ibid, p.2.

75 Aaron Martin and Ben FitzGerald, "Process Over Platforms A Paradigm Shift in Acquisition Through Advanced Manufacturing," *Center for New American Security*, December 2013, p.3. Available at: http://www.cnas.org/sites/default/files/publications-pdf/CNAS_ProcessOverPlatforms_FitzGerald.pdf

76 Ibid, p.12.

77 Ibid, p. 12.

78 Ibid, p.3.

79 Raytheon, "Additive Manufacturing at Raytheon." Available at: http://www.raytheon.com/news/technology_today/2015_i1/additive.html

sharing techniques, designs, and even CAD files for printable drone components across numerous open source online forums.

DEFENSE INDUSTRY AND THE MILITARY

Multiple well-known defense manufacturers and aeronautics companies—including Raytheon, Lockheed Martin, and Northrop Grumman—as well as branches of the US Military are exploring or employing 3D printing in drone production.[80] In addition to minimizing time and cost of production, 3D printing allows for the creation of customized parts and complex geometries that are not afforded by conventional manufacturing. This process reduces weight and fuel costs while allowing for a larger payload.[81] Importantly, 3D printing expedites innovation in the prototype and testing stages by enabling rapid design iteration and permitting late, on-site design changes without hampering production time and or increasing costs.[82]

The last five years in particular have witnessed widespread reporting on the use of 3D printing within defense industries. In some cases, manufacturers are beginning to experiment with only a limited number of 3D printed parts. In 2013, for example, Northrop Grumman announced it had incorporated a 3D printed metal part into its X-47B Unmanned Combat Aircraft System.[83] To overcome traditional manufacturing's time and budget constraints, including injection molding, defense manufacturers are turning to AM to produce numerous drone components.

In some cases, manufacturers are using AM for the majority of the design. In November 2015, Stratasys Ltd, one of the leading companies in 3D printing and AM, collaborated with aeronautics company Aurora Flight Sciences to develop "what is believed to be, the largest, fastest, and most complex 3D printed UAV ever produced."[84] With 80 percent of the design composed of 3D printed parts, this jet-powered UAS weighs only 15 kg and can reach speeds greater than 150 mph. According to one Aurora research engineer, "a primary goal for us was to show the aerospace industry just how quickly you can go from designing to building to flying a 3D printed jet-powered aircraft."[85] Engineers say 3D printing halved the design and build time.

80 Ibid; Lockheed Martin, "3D Printing Advanced Manufacturing." Available at: https://www.youtube.com/watch?v=qLJ8iUZCx0o; Tom Vice, "Tom Vice Discusses Unmanned Systems at the National Press Club," *Northrop Grumman*, August 20, 2013. Available at: http://www.northropgrumman.com/MediaResources/Presentations/2013/Pages/082013TomViceAtNationalPressClub.aspx; Martyn Williams, "The U.S. Navy Is 3D-Printing Custom Drones On Its Ships," *The Naval Postgraduate School*, August 2, 2015. Available at: http://my.nps.edu/web/cruser/blog/-/blogs/the-u-s-navy-is-3d-printing-custom-drones-on-its-ships; David McNally, "Army selects 3-D printed unmanned aircraft systems concept for future experiment," *ARL*, February 15, 2016. Available at: http://www.arl.army.mil/www/default.cfm?article=2671.

81 Stratasys, "Aerospace & Defense 3D printing means innovating fast and flying with confidence," 2016. Available at: http://www.stratasys.com/industries/aerospace-defense

82 Ibid; Raytheon.

83 Tom Vice, 2013.

84 Business Wire, "Aurora Flight Sciences and Stratasys Deliver World's First Jet-Powered, 3D Printed UAV in Record Time," November 9, 2015. Available at: http://www.businesswire.com/news/home/20151109005240/en/

85 Ibid

In another case, Honeywell Aerospace and AAI Textron Systems sought out 3D printer manufacturer 3DSystems to produce DARPA's T-Hawk unmanned micro air vehicle in 2014. Through 3D printing, producers consolidated "the fabrication complexity and cost of multiple components into a single-built part—a 1 piece unitized assembly."[86] The 3D printing process allowed the production team "to achieve precise and repeatable accuracy for multiple production years—manufacturing in excess of 600 systems for our warfighters."[87] Each completed T-Hawk system ultimately included up to seventy-six 3D printed parts.

The US Military itself is experimenting with UAS 3D printing, with the aim of rapidly producing customized drones "outfitted for specialized missions."[88] In the summer of 2015, the Navy used a 3D printer installed aboard the USS Essex to produce parts for drone assembly.[89] According to one source, "data files and models of the drones can be sent via satellite from land to the USS Essex, and eventually other ships within the Navy fleet, and then these files can be 3D printed in a matter of hours."[90] Once assembled with electronic components pre-stocked on the ship, sailors can produce "virtually any type of drone that may be required."[91] The Essex drone in particular was designed to support anti-piracy and anti-drug smuggling missions by surveying ships at sea.

The Navy is not alone in its exploration of 3D printing. The Army Research Laboratory (ARL) announced in February that it would be taking its 3D printed drone system, known as "On-Demand Small Unmanned Aircraft Systems," to the 2017 Army Expeditionary Warrior Experiments (AEWE).[92] The on-demand system was chosen for AEWE because ARL "saw the trajectories of two beneficial technology areas converging in the future"—namely, 3D printing and small unmanned aircraft systems.[93] Finally, recently released footage shows the Pentagon leveraging this emerging nexus as well, deploying 3D printed micro drones from an F-16 at 430 mph.[94] Secretary of Defense Ash Carter himself highlighted the use of 3D printing in this regard, stating in February 2016 that micro drones "use a lot of commercial components and are actually 3-D printed."[95]

86 3DSystems, "Customer Success Story - Quickparts The Lighter, Better UAV," 2014. Available at: http://www.3dsystems.com/files/cs-t-hawk-0214-usen-2pg.pdf

87 Ibid.

88 Martyn Williams, 2015.

89 Ibid; Eddie Krassenstein, US Navy is 3D Printing Custom Drones Onboard the USS Essex," *3Dprint.com*, July 30, 2015. Available at: https://3dprint.com/85654/us-navy-3d-printed-drones/

90 Eddie Krassenstein, 2015.

91 Ibid.

92 David McNally, 2016; Alec, "US Army's 2017 Expeditionary Warrior Experiments to include customizable 3D printed drones," *3ders.org*, February 17, 2016. Available at: http://www.3ders.org/articles/20160217-us-armys-2017-expeditionary-warrior-experiments-to-include-customizable-3d-printed-drones.html

93 Ibid.

94 Alec, "Pentagon releases secret footage of 3D printed drone swarm launched from fighter jets," March 11, 2016. Available at: http://www.3ders.org/articles/20160311-pentagon-releases-footage-of-3d-printed-drone-swarm-launched-from-fighter-jets.html

95 Ash Carter, "Remarks by Secretary Carter on the Budget at the Economic Club of Washington, D.C.," *Press Operations US Department of Defense*, February 2, 2016. Available at: http://www.defense.gov/News/Transcripts/Transcript-View/Article/648901/remarks-by-secretary-carter-on-the-budget-at-the-economic-club-of-washington-dc

3D printed UAS are not all necessarily capable of being equipped with WMD, nor are they controlled under the MTCR guidelines, but the above examples demonstrate the increasingly widespread use of 3D printing to manufacture drones within the defense and aeronautics sectors. Manufacturers repeatedly point to the low-cost, efficient, and flexible benefits of 3D production, underscoring its potential to become the primary means to produce UAS in the future. Importantly, 3D printing technologies are increasingly accessible not only by states, but by non-state actors and individuals as well. As experimentation, innovation, and growth in the 3D printing drone industry continue to accelerate, so too will the availability of advanced UAS components to non-traditional actors.

DIY COMMUNITIES

According to a study Conducted by Bard College's Center for the Study of the Drone, DIY drone hobbyists constitute "much of the technological bedrock for a burgeoning market of start-up drone manufacturers."[96] In fact, DIY communities serve as a major driver in the drone technology industry, including in 3D printing. Given the recent relaxation in Federal Aviation Administration (FAA) regulations on commercial drone use, production and sales of commercial drones are expected to grow rapidly in the coming years, including in the hobbyist sector.[97]

The online DIY community for drone 3D printing is well established and expanding. There are a plethora of websites—including DIYdrones.com, Thingiverse.com, Instrutables.com, 3Dprinting.com, and GrabCAD.com—that make it easy to access forums with detailed instructions on 3D printable drones, free downloadable CAD files for specific drone parts, and instructions on where to find non-printable parts. Within the DIY process it is generally possible to print the frame, supporting, and housing structures of a drone, including motor holders, landing gear, and propellers, while it is not possible to print electrical components such as Global Positioning System (GPS), electronic sensors, or Wi-Fi receivers. Notably, however, these non-3D printable parts can be purchased online easily.[98]

Discussions within these online DIY forums range from debates over the best 3D printers and filament materials to designs for a variety of quadcopter models. In one group on DIYdrones.com titled "3D Printing Drone Parts,"[99] discussion forums include "Getting an affordable 3D Printer;"[100] "Best

96 Dan Gettinger et al., "The Drone Primer: A Compendium of the Key Issues," *Center for the Study of the Drone*, 2014, p. 20.
97 Alyssa Newcomb, "Drones for Businesses Can Take Off Under New FAA Regulations," *NBC News,* August 29, 2016. Available at: http://www.nbcnews.com/tech/tech-news/drones-businesses-can-take-under-new-faa-regulations-n639451; Federal Aviation Administration, "FAA Releases 2016 to 2036 Aerospace Forecast," March 24, 2016. Available at: https://www.faa.gov/news/updates/?newsId=85227.
98 For an example of the availability of non-3D printable parts visit: Instructables.com, "3D Printed Quadcopter with Arduino." Available at: http://www.instructables.com/id/3D-Printed-Quadcopter-with-Arduino/
99 DIYdrones.com, Groups: 3D Printing Drone Parts. Available at: Federal Aviation Administration, "FAA Releases 2016 to 2036 Aerospace Forecast," March 24, 2016. Available at: https://www.faa.gov/news/updates/?newsId=85227
100 Ibid, "Getting an affordable 3D Printer." Available at: http://diydrones.com/group/3d-printing-drone-parts/forum/topics/getting-an-affordable-3d-printer

Material for 3D Printing of Drone Parts/Plane Parts;"[101] and "Component Parts for 3D Printed Drones."[102] In the "best materials" forum, the discussion covers the pros and cons of various filament materials including PLA (PolyLactic Acid) and ABS (Acrylonitrile-Butadiene Styrene) for printing drone parts. Companies too may use such forums to advertise new products in 3D printing. This includes materials for replacing components that would normally not be 3D printed, such as wires and soldered connections, with fully 3D printed circuits and power traces.[103]

Beyond discussion forums, other websites including GrabCAD and Thingiverse provide platforms for sharing 3D print designs via downloadable CAD files, as well as detailed instructions on building specific models. GrabCAD advertises itself as home of 3,250,000 engineers with over 1,430,000 free CAD files, encompassing aerospace, architecture, and agriculture. A quick search for "drones" or "UAVs" reveals many downloadable CAD files for related components and even military models.[104]

Some of these 3D printable designs include replacement and upgraded parts for commercially available drones including the DJI Phantom—a quadcopter that is popular for its easy-to-fly quality and ability to capture excellent aerial footage.[105] Notably, the Phantom has reportedly been modified for surveillance purposes in conflict zones. The groups responsible include Ukrainian forces[106] and the IS,[107] which is beginning to take modifications a step further, attaching "small explosive devices to [commercially available drones like the Phantom], essentially making them remotely piloted bombs."[108] Available CAD files for Phantom 3D printable replacement parts include lens hoods, anti-drop pins/clips, gimbal parts including stabilizers, and motor caps.[109]

Commercial manufacturers recognize online forums as valuable spaces for the exchange of ideas on 3D printing and drone production. They are turning to DIY communities and hobbyists with access

101 Ibid, "Best Material for 3D Printing of Drone Parts/Plane Parts." Available at: http://diydrones.com/group/3d-printing-drone-parts/forum/topics/best-material-for-3d-printing-of-drone-plane-parts
102 Ibid, "Component parts for 3D Printed Drones" Available at: http://diydrones.com/group/3d-printing-drone-parts/forum/topics/component-parts-for-3d-printed-drones
103 Ibid, "3D printed drones without wires/solder!" Available at: http://diydrones.com/group/3d-printing-drone-parts/forum/topics/3d-printed-drones-without-wires-solder
104 GrabCAD, "RQ-11 Raven Military Drone," Available at: https://grabcad.com/library/rq-11-raven-military-drone-1/details?folder_id=1664993.
105 Thingiverse.com, "DJI Phantom 3," Last updated August 19, 2016. Available at: http://www.thingiverse.com/Tschich/collections/dji-phantom-3/page:1
106 Oriana Pawlyk, "U.S. organization sends drones to Ukrainian military," *Aiforcetimes*, February 19, 2015. Available at: http://flightlines.airforcetimes.com/2015/02/19/u-s-organization-sends-drones-to-ukrainian-military/; Defense One, "In Ukraine, Tomorrow's Drone War is Alive Today," March 9, 2015. Available http://www.defenseone.com/technology/2015/03/ukraine-tomorrows-drone-war-alive-today/107085/.
107 Yasmin Tadjdeh, 2014; Uğur Ergan, "Three Turkish soldiers wounded in ISIL drone attack in Syria," *Hurriyet Daily News*, September 28, 2016. Available at: http://www.hurriyetdailynews.com/three-turkish-soldiers-wounded-in-isil-drone-attack-in-syria.aspx?utm_source=facebook.com&utm_medium=post&utm_campaign=three-turkish-soldiers-wounded-in-isil-drone-attack-in-syria.aspx&utm_term=post&pageID=238&nID=104339&NewsCatID=352
108 Michael S. Schmidt and Eric Schmitt, 2016.
109 Thingiverse.com, "DJI Phantom 3," Last updated August 19, 2016. Available at: http://www.thingiverse.com/Tschich/collections/dji-phantom-3/page:1

to 3D printing technologies to drive product innovation. For example, in an effort to create a new life-saving tool for lifeguards and rescue teams, Chinese commercial drone-producer DJI recently collaborated with 3D printing company Shapeways to sponsor a contest to modify DJI's Phantom into a rescue drone.[110] The companies sought new 3D printable parts "that [could] improve the drone's visibility, carry payloads . . . land on water" and "[maneuver] in a tricky flight situation, despite the presence of some wind or rain."[111] Such initiatives demonstrate the potential to shrink the gap between producer and consumer in drone manufacturing.

The DJI competition indicates that drone producers are always looking for means to improve the payload capacity of quadcopters and micro aerial vehicles (MAVs). For example, current research by the University of Pennsylvania's General Robotics, Automation, Sensing and Perception (GRASP) laboratory is exploring multiple quadcopters cooperatively grasping and transporting payloads, which could overcome weight bearing limitations.[112] Researchers are developing "gripping mechanisms" to enable teams of quadcopters to "cooperatively [grasp], [stabilize], and [transport] payloads of different configurations to desired positions and along three-dimensional trajectories."[113] The grasping mechanism increases the capacity for MAVs to carry heavier payloads through combined strength. The MAVs's total weight capacity is calculated by summing the capability of all the MAVs and dividing by 2. In other words, 4 MAVs that can each carry 5 kg could carry a payload of 10 kg collectively. Thus far, the GRASP lab has focused on combinations of 4 MAVs. However, the number of MAVs could be increased (perhaps to 16 MAVs carrying one item) to increase the payload capability. In the words of one researcher, "simple off-the-shelf components lifting a 20 kg payload with precision control is very possible and straightforward (the math/implementation is easy given hobby-grade resources)".[114] In the future, these mechanisms could greatly enhance the ability of individuals or nefarious actors to repurpose simple, 3D printable quadcopters to deliver dangerous payloads, especially if the mechanisms themselves are 3D printable. Online forums may present excellent venues for discussing such additions.

It is important to remember that the majority of the DIY community is working on small, seemingly harmless quadcopters for hobbyist or civilian purposes. Like the broader DIY movement, the DIY drones community emphasizes the power of the individual to design and produce custom, well-priced goods. Collaboration, sharing, and public access are also critical facets of the DIY drone community. For example, the well-known website DIYdrones emphasizes that it was "explicitly built as a social network, which means that the community is as important as the content."[115] The site's policies emphasize civility, sharing, and informative discussion, while prohibiting discussion of

110 Kelly McSweeney, "How drones could save you from drowning," *ZDNet*, October 2, 2016. Available at: http://www.zdnet.com/article/how-drones-could-save-you-from-drowning/

111 Ibid

112 Daniel Mellinger, Michael Shomin, Nathan Michael, Vijay Kumar, "Cooperative Grasping and Transport using Multiple Quadrotors," GRASP Laboratory, University of Pennsylvania,2010, p. 1. Available at: http://faculty.engineering.asu.edu/acs/wp-content/uploads/2016/11/Cooperative-Grasping-and-Transport-using-Multiple-Quadrotors-2010.pdf

113 Ibid.

114 Private communication, Prof. Nathan Michael, Robotics Institute, Carnegie Mellon University

115 DIYdrones.com, "The DIY Drones Mission (aka The Five Rules)" Available at: http://diydrones.com/profiles/blog/show?id=705844:BlogPost:17789

politics and religion, which could be divisive.[116] Notably, the site explicitly prohibits discussion of military, weaponized, illegal, or harmful applications of UAVs.[117].

Despite these policies, however, some clearly seek to go beyond the hobby domain. One forum on DIYdrones disregards the site's policies and discusses "design, 3D printing, [and] geodesic airframe structures…for any payload over long distances," noting that though "US laws forbid our design to fly it its airspace, other nations are more lenient."[118] As noted above, it is possible to repurpose commercial drones for non-civilian purposes, a goal which could potentially be augmented with 3D printing. A user known as Milo Danger constructed a six-rotor drone with a camera and a paint ball gun—of similar weight to a real gun—and demonstrated their use for targeting individuals on the ground. The purpose of the demonstration was to bring attention to this technology's potential for nefarious purposes. The user stated that "if this is what a novice with a small budget can accomplish, then clearly this technology has a lot of potential. Considering the growing popularity of these DIY devices, it seems inevitable that they are going to be used in ways that the inventors and manufacturers could have never imagined."[119] Similarly, a user named FPS Russia appears to have demonstrated the predictably destructive effects of a machine gun mounted on a quadcopter.[120] We are unsure whether any components were 3D printed, but we highlight it here as a possible threat of DIY drones. As DIY drone production becomes more advanced, it seems possible that fully 3D printed designs could be modified or even produced specifically for nefarious purposes.

THE POTENTIAL FOR 3D PRINTING TO BE USED IN FUTURE PRODUCTION OF THE ITEM

The above examples make it clear that well-resourced defense and aeronautics companies, as well as DIY communities, are either exploring or already employing 3D printing in the production of drones and drone parts. 3D printing is advantageous in UAS production because it produces cost-effective parts while reducing cycle time and facilitating a rapid iterative design process. Reliance on AM in this sector will only continue to grow.

As discussed in the second section of this report, the DOD's traditional manufacturing processes, including those for UAS, are viewed as largely outdated and inefficient. According to experts, the "current paradigm is clearly unsustainable across all operational domains and critically so, given the strategic and economic trends facing the US."[121] Such considerations are compounded by the fact that emerging technologies such as 3D printing have created an international situation in which "the barriers to entry are being lowered for access to advanced military capability and

116 Ibid
117 Ibid
118 DIYdrones.com, "Strategic Supply Drones." Available at: http://diydrones.com/group/strategic-supply-drones
119 See video from 2:20 sec – 5:50 sec: https://www.youtube.com/watch?v=5BiagDsddkM (the original video has been removed).
120 https://www.youtube.com/watch?v=SNPJMk2fgJU
121 Aaron Martin and Ben FitzGerald 2013, p.15.

technology that has military utility."[122] The knowledge that new manufacturing processes make advanced military technologies increasingly available to our adversaries may be driving the US to revise its own acquisitions process.

According to studies, we are approaching a "new paradigm" in UAS production through a combination of 3D printing and emerging technologies such automated robotics and cloud-based design manufacturing (CBDM).[123] CBDM facilitates 3D printing by operating on a cloud-based platform that enables a more dynamic manufacturing sequence. Consumers, engineers, and designers have greater access to one another and can therefore "collaborate and share 3D geometric data instantly."[124] In terms of manufacturing, the cloud-based approach offers flexible scaling that allows development teams to "rapidly scale up and down manufacturing capacity."[125] Such advantages have the potential to facilitate the DOD's ability to produce a variety of specialized, on-demand UAS in the field.

Advancements in 3D printing technology itself will only increase the potential for its widespread use in drone production. Research teams at the Massachusetts Institute of Technology (MIT), for example, are experimenting with new 3D printing techniques that enable users "to program parts made of soft materials, including plastic and rubber, for an exact degree of stiffness and elasticity, giving it a specific quality of bounce and energy transfer depending on the needs of the final product."[126] In the context of drone production, researchers believe these new techniques will allow producers to make systems that are "more resilient in case of contact with their surroundings."[127]

Innovation in 3D printing has already sparked the emergence of offshoots that are potentially more advanced in drone production. A primary example is the project by British-based defense and aeronautics company BAE Systems to grow drones chemically. This process relies on a device called a "Chemputer" to grow small-scale aircraft by "speeding up evolutionary processes and chemical reactions," with the goal of establishing the capability to rapidly design and manufacture aircraft tailored to meet specific emerging threats.[128] This would allow military forces to produce aircraft systems on site within a few weeks rather than years.[129]

Finally, as 3D printing technologies become more accessible and trends in DIY and crowdsourcing advance, the gap between manufacturer and user will shrink. In many cases, such innovation has the potential to save lives, but increasingly advanced capabilities—such as the ability to carry heavier

122 Ibid, p.3.
123 Aaron Martin and Ben FitzGerald 2013, p.12.; Dazhong Wua et al., "Cloud-based design and manufacturing: A new paradigm in digital manufacturing and design innovation," *Computer-Aided Design*, 59 2015, pp 1-14.
124 Ibid, p. 5.
125 Ibid, p. 12.
126 Darrell Etherington, "MIT's new 3D-printed, shock-absorbent materials make for resilient drones," *techcrunc*h, October 3, 2016. Available at: https://techcrunch.com/2016/10/03/mits-new-3d-printed-shock-absorbent-materials-make-for-resilient-drones/
127 Ibid
128 BAE Systems, "Lifting the lid on future military aircraft technologies." July 3, 2016. Available at: https://techcrunch.com/2016/10/03/mits-new-3d-printed-shock-absorbent-materials-make-for-resilient-drones/
129 Ibid.

payloads and maneuver under high stress conditions—make it more likely that in the near future, non-traditional actors will have access to or even the ability to produce UAS systems controlled under current MTCR guidelines.

NOTES AND ADDITIONAL THOUGHTS

CONTROLLING THE FILAMENTS AND RESINS

The materials with which 3D printed objects are constructed are key to AM, and vary according to the type of 3D printing process employed. Perhaps the most basic 3D printing method is Fused Deposition Modeling (FDM), in which heated thermoplastic filament is "deposited layer by layer in the print area to build the workpiece."[130] FDM is used widely in the DIY community, with online discussion forums featuring debates over which filaments are best for producing drone components.[131] Common FDM filaments include PLA and ABS, and are widely available for online purchase at a low cost.[132]

More advanced manufacturers employ higher-grade filaments in FDM-based drone production. For example, in the case of the 80 percent 3D printed Aurora UAV (discussed above), manufacturers relied on Stratasys's high-performance thermoplastic material ULTEM™ 9085, a top choice material within the aerospace industry. ULTEM's "lightweight mechanical properties provide ideal conditions for aerospace operations," offering "the greatest durability and highest heat and chemical resistance of any FDM thermoplastic."[133] While not nearly as cheap as PLA or ABS, ULTEM 9085 is available for purchase online as well.[134]

FDM is only one of many 3D printing methods. Alternative methods include Stereolithography (SLA or SL), which employs a liquid resin rather than plastic filament to print an object. Given the variety of materials available for 3D printing and their accessibility to individual and large-scale drone manufacturers, it is questionable whether such materials are or should be controlled by MECRs. Theoretically, it is possible that such materials already fall under the WA dual-use list, potentially under 9.B.10 on "Equipment specially designed for the production of items specified by 9A.12.," which refers to specific UAV systems. It is unclear, however, whether this would cover materials or the

130 Fran Grieser, "3D Printer Buyers Guide," *All3DP*, October 18, 2015. Available at: https://all3dp.com/fdm-vs-sla/
131 DIYdrones.com, "Best Material for 3D Printing of Drone Parts/Plane Parts." Available at: http://diydrones.com/group/3d-printing-drone-parts/forum/topics/best-material-for-3d-printing-of-drone-plane-parts
132 3DUniverse, "3D Universe PLA Filament 2.85mm (3.0mm) - 1 kg," Site Accessed September 29, 2016. Available at http://shop3duniverse.com/collections/3d-printer-filament/products/3d-universe-pla-filament-2-85-mm?variant=1313320040&gclid=CjwKEAjw97K_BRCwmNTK26iM-hMSJABrkNtbLdTSbDAF9QjNyfXc9vC8q0E3ZRBsn-MFRKIsloB_xmBoCpYXw_wcB; Amazon.com, "Octave Black ABS Filament for 3D Printers - 1.75mm 1kg Spool," Site Accessed September 19, 2016. Available at: https://www.amazon.com/Octave-Black-ABS-Filament-Printers/dp/B0083HSPH2
133 Stratasys, "World's First Jet-Powered, 3D Printed UAV Tops 150 MPH with Lightweight Stratasys Materials" Stratasys Blog, November 9, 2015. Available at: http://blog.stratasys.com/2015/11/09/aurora-uav-3d-printing/
134 Proto3000, "ULTEM," Site Accessed September 29,2016. Available at: http://store.proto3000.com/products/ultem

printers only. Similar questions involve 1.E.1. of the MTCR annex. Both the WA and MTCR have "materials" sections (9.C. and 1.C., respectively), but both sections list only the word "None."

CONTROLLING 3D PRINTING SOFTWARE OR CAD FILES

Much like the materials required to physically build 3D printed objects, CAD files are key to the AM process. They are generated via 3D modeling software or 3D scanners and contain the virtual 3D model design for the printed object. The file is transmitted to a 3D printer, which physically produces the CAD.

Currently, as noted above, there are a number of websites and online platforms dedicated to the sharing of CAD files, including many for DIY drone components. While the majority of these files are unlikely to encompass those components found in controlled UAV systems, it is clear that the potential and willpower to share such files exists already. Importantly, when paired with 3D printers, CAD files contain advanced models that eliminate the need for specialized knowledge or expertise in weapons production, including in drone production. Controlling these files and related software will therefore be key in preventing the proliferation of dangerous drone technology.

Under current regulations, such software may potentially be controlled under sections 9.D. and 9.E. of the WA's dual-use list, which cover software and technology, respectively, that is used in the development of UAV systems specified under 9.A.12. Similarly, related software may be controlled under sections 1.D.1, 1.E.1, and 2.D of the MTCR Annex.

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NATIONAL-LEVEL INTEREST IN AM AND STRATEGIC PLANNING

(Contributor: Olivia Vassalotti)

INTRODUCTION

In recent years, the AM industry's rapid growth—an average growth of 27.3 percent over the last twenty-six years—has led to increased national-level interest in the AM field.[135] Several countries have published AM strategies to better inform their future actions and funding allocations in order to develop the industry further and to maintain or gain a presence in the AM field.

AM is most heavily utilized in the automotive and aerospace industries, which have the potential to utilize printed parts in the final product, and in the medical industry, with the potential to create highly personalized medical products.[136] AM is being investigated as an advantageous method of manufacturing because it allows for more design freedom, creates less waste, has the ability to create structures that were previously impossible, and lowers costs.[137]

Manufacturing accounts for approximately 16 percent—more than $12.8 trillion—of the global economy. If AM were to capture even a portion of this total, it would create huge profits for those involved. This has sparked increasing government and academic interest in the implications of AM.[138] Beyond the use of personal 3D printers, AM can be used on the commercial scale to revolutionize current manufacturing methods.

FINLAND

Tekes, the Finnish Funding Agency for Innovation, assessed Finland's current AM industry to be too small and underdeveloped to compete on a global scale. The industry lacks technological advancement as well as awareness and understanding of AM's benefits. Tekes notes that though the infrastructure and mechanisms are in place, they have yet to be fully utilized and there is significant room for improvement.[139]

135 South Africa. Department of Science and Technology. A South African Additive Manufacturing Strategy. By Deon De Beer, et.al. Johannesburg, 2016. iv.
136 Ford, Sharon L.N. "Additive Manufacturing Technology: Potential Implications ..." September 2014. Accessed November 16, 2016. https://www.usitc.gov/journals/Vol_VI_Article4_Additive_Manufacturing_Technology.pdf.
137 Finland. Tekes. *Policy Brief: 3D Printing for Industrial Innovation*. Helsinki, 2016. 3.
138 Ibid., 6.
139 Ibid., 1.

Finland's three most active industries in AM are medical and dental, consumer products and electronics, and industrial and business machines. These industries comprise 80 percent of AM use.[140] However, AM is generally used for rapid prototyping in these industries, especially in consumer products, electronics, and industrial and business machines, so beyond medical uses, materials made with AM are rarely used in the finished product.[141]

If AM were more heavily utilized and the technology were to continue improving in efficiency, Tekes predicts a 60 percent decrease in the production costs for consumer goods. This improvement would lead to even further development of the AM field.[142]

Though Finland initially had great impact on the AM industry, innovation has stalled. There are two companies in Finland that were particularly impactful: Electro Optical Systems (EOS) Finland and DeskArtes. EOS Finland revolutionized the Direct Metal Laser Sintering process, and DeskArtes was among the leaders in developing AM software.[143]

Based on the aforementioned findings, Tekes has established a list of policy challenges that need to be addressed by the Finnish government to allow Finland to become a trendsetter in the AM field. Tekes has flagged the following issues within the Finnish AM sector: insufficient awareness, lack of cooperation and knowledge sharing, the general youth of the AM industry in Finland, and "weak internal 'cluster' structures."[144]

Tekes has proposed several courses of action for the Finnish government to bolster interest in and the success of the AM industry. The first involves "increasing input for innovation," research, and development. Essentially, the government must pay attention to making Finland a trendsetter in the AM field and needs to provide funding to allow for these innovations.[145] Furthermore, research is warranted to determine the implications of AM development.

Second, the Finnish government should acknowledge the current lack of an experienced and skilled AM workforce by "improving and increasing the supply of skill."[146] This proposal encourages schools and universities to continue with preexisting initiatives that integrate AM education in order to create an informed and skilled workforce for the industry.

Finally, the government should capitalize on AM's potential for growth within rapid manufacturing by "generating and exploiting connections and complementarities."[147] This would be particularly important for increasing the competitiveness of SMEs.

140 Ibid., 3.
141 Ibid.
142 Ibid.
143 Ibid., 4.
144 Ibid., 5.
145 Ibid., 6.
146 Ibid.
147 Ibid.

Tekes notes that Finnish investment in AM is far below that of other countries such as the US, Japan, the UK, China, or even smaller countries such as Belgium that have dedicated money to AM development.[148] Currently, Finland designates approximately €2 million to AM, but the proposed Tekes initiatives would require an increase to €20 million over the next five years.[149]

UK

The UK has demonstrated remarkable growth in their AM industry in the last four years. Innovate UK, the UK's version of the Finnish Tekes, implements the government's interest in AM. After a 2012 Innovate UK report raised concerns about gaps in the AM industry, funds and research projects dedicated to AM skyrocketed. In 2012, £15 million were committed to AM, increasing to £30 million in 2014.[150] Furthermore, there has been an 80 percent increase in research projects associated with AM coupled with a 200 percent increase in the number of organizations involved in AM projects.[151]

AM research in the UK covers a variety of applications, the largest of which is labeled "Enabling Technologies" and has received nearly £47 million in funding.[152] This category funds research specifically about further uses for AM across the manufacturing industry, as well as projects where the final purpose of the research has yet to be determined. Furthermore, the UK has dedicated more than £10 million to support PhDs with applications or focuses relating to AM.[153] Academic/industrial collaboration projects receive the most funding, followed by research centers, PhD programs, academic research, industrial research, and career funding. Among academic institutions, the University of Nottingham and the University of Sheffield receive the most funding for AM research.

Having established itself as a leader in the AM field, the UK aspires to hold 8 percent of the global AM market (an estimated £5 billion) by 2025.[154] In 2014, a steering group was established from a conglomerate of independent individuals in relevant manufacturing and research fields. In September 2016, the group published goals for the UK's AM industry to reach by 2025. The goals promote the UK's development as the leading country for AM, with printed parts becoming commonplace across different sectors.[155] The goals also describe the role AM should play in the Fourth Industrial Revolution, and predict that most large companies will have adopted AM in their production processes by 2025.[156]

148 Ibid.
149 Ibid., 7.
150 United Kingdom. Innovate UK. Mapping UK Research and Innovation in Additive Manufacturing. By Richard Hague, Phil Reeves, and Sophie Jones. London, 2016. 2.
151 Ibid., 2.
152 Ibid., 14.
153 Ibid., 15.
154 United Kingdom. Innovate UK. Additive Manufacturing UK. London, 2016. 8.
155 Ibid., 9.
156 Ibid.,9.

The steering group has identified five programs to ensure that the UK will achieve the goals and maximize its AM network: coordination and communication, strengthening the industry sectors, developing knowledge and skills, investing in UK capacity, and measuring progress.[157] The steering group's report details ten recommendations that are necessary for the implementation of the five programs. In general, the ten recommendations encourage further utilization of AM across different sectors, policies and programs that cater to the AM industry, development of a knowledgeable and experienced workforce, and an overall increase in the demand for AM goods both domestically and abroad.[158]

The steering group recommendations are not an official UK AM strategy, but the steering group will publish the official strategy under the auspices of Innovate UK in April 2017. This is expected to embody many of the programs and recommendations that appear in the September 2016 steering group report.[159]

SOUTH AFRICA

The Rapid Product Development Association of South Africa (RAPDASA), established in 2000, has been a critical driver of AM development within South Africa.[160] The number of AM machines in South Africa grew 85 percent in 2013, and government research funding in AM platforms/machines has exceeded R380 (South African Rand).[161] The most notable of these platforms is Aeroswift, touted as a high-speed metal printer with a build volume of 2 m x 0.6 m x 0.6 m.[162] According to the RAPDASA website, this South African developed system is the "largest and fastest metal powder bed system in the world."[163] The system was developed as a project funded by the Department of Science and Technology and managed by the Titanium Centre of Competence at the Council for Scientific and Industrial Research Materials Sciences and Manufacturing.[164]

In South Africa, as in the global AM landscape, the aerospace industry is one of the most important industries utilizing AM. Several prominent companies in South Africa, including Aerosud, Adept Airmotive, Denel Aviation, Denel Dynamics, and Airbus DS Optronics, have used AM to produce final parts for aircraft.[165]

157 Ibid., 9.
158 Ibid., 48.
159 Ibid., 49.
160 South Africa. Department of Science and Technology. A South African Additive Manufacturing Strategy. By Deon De Beer, et.al. Johannesburg, 2016. 26.
161 Ibid., 26.
162 "Aeroswift." Accessed November 16, 2016. http://www.rapdasa.org/sitevisit.aspx.
163 Ibid.
164 South Africa. Department of Science and Technology. A South African Additive Manufacturing Strategy. By Deon De Beer, et.al. Johannesburg, 2016. 27.
165 Ibid., 34.

Also mirroring the global landscape, AM is important for the South Africa medical and dental industries because AM expedites molding to create personalized parts. South Africa has been a leader in the development of injection molding, as well as sand casting and investment casting.[166]

AM is similarly relevant to the footwear industry, which has an estimated value over R5 billion and expects to surpass 100 percent growth in the next five years.[167] AM would benefit the footwear industry by allowing producers to rapidly produce molds for different components of shoes, including soles, or create prototypes for new-concept products.[168]

South Africa has the potential to surpass many nations, including those in the EU, in the development of powders for AM. Presently, South Africa produces 30 percent of the minerals necessary for titanium alloys.[169] Furthermore, South Africa is the second largest producer of ilmenite and rutile, which produce Titanium pigment, and the second largest producer of Vanadium, a critical component for titanium alloys.[170] There are companies within South Africa with the ability to produce powders and filaments for use in AM. If they were to capitalize on this ability, it would constitute a significant step in the development of a South African AM infrastructure, giving South Africa an important advantage.[171]

RAPDASA published an AM strategy in April 2016, commissioned by the Department of Science and Technology, to guide further development of the field through 2023. This strategy is focused "on the development of niche areas to take advantage of high-priority opportunities" to implement the nine-point plan introduced by President Zuma in February 2015.[172] The strategy is designed to utilize existing research, development, innovation capabilities, South African natural resources, and existing demand in local markets.[173]

The strategy identifies seven high-priority opportunities that the AM field should actively strive to take advantage of: "production of medical devices and implants; production of parts for the aerospace industry; refurbishment of parts and tools…; impact on the local footwear industry…; raw material development for AM processes; development of high-end AM systems; and development of low-cost 3-D printers."[174]

166 Ibid., 35.
167 Ibid., 36.
168 Ibid.
169 Ibid., 39.
170 Ibid., v.
171 Ibid., 39.
172 Ibid., iii & 46.
173 Ibid., 46.
174 Ibid., 47.

The South African economy has been growing at an increasingly slow rate, with an underemployment rate of 24.9 percent.[175] New manufacturing frontiers are crucial to creating new jobs. However, there are very few educational programs that focus on AM in South African schools or higher educational institutions—similar to the shortage found in both Finland and the UK. The RAPDASA strategy outlines several initiatives to expose young students to AM, establish an AM curriculum, and provide more widespread, consistent access to AM technologies.[176] Topics of interest include engineering, design, medicine, materials science, and reverse engineering.[177] This is intended to create a more knowledgeable and skilled workforce.

Lastly, the South African strategy addresses the many myths surrounding AM and the initial disappointment with AM exploration in the 1990s. Despite increased news coverage in South Africa, AM's finer details are still subject to many misconceptions, so according to the strategy, there should be increased promotion of the benefits associated with AM. The initiative includes the creation of a strong brand-name for the "South African AM Initiative."[178] The promotional campaign uses social media, workshops, and websites to raise awareness and promote further interest in AM.[179]

In order to implement the strategy, RAPDASA proposes the creation of a steering committee, similar to the steering group in the UK, that would be comprised of representatives from various industries crucial to AM as well as entities conducting AM research.[180] This steering group would be responsible for reviewing and revising the strategy, finding funding for programs, encouraging further innovation in both AM and initiatives for promotion, and advising on the implementation of the strategy.[181]

175 Ibid., 56.
176 Ibid., 63.
177 Ibid., 64.
178 Ibid., 65.
179 Ibid.
180 Ibid., 67 – 68.
181 Ibid., 68.

CONCLUSION

Though AM has been around for several decades, national-level interest in AM appears to be a relatively new phenomenon; the majority of reports on national AM capacity appeared in the last five years, and AM strategies appeared within the last eighteen months. Some countries have publicized the existence of an AM strategy, but some of these strategies are so recent that they have yet to be published online for public viewing.

National-level interest in AM appears to focus on building the national infrastructure for such an industry. States focus primarily on increasing funding for research and innovation in the field as well as creating of a highly skilled and knowledgeable workforce, which does not exist currently.

It also appears that new national goals involve both building the capacity for AM goods to be final products and developing national capabilities across all stages of the AM process, including powder production and treatment of printed goods. Companies and countries with advanced AM capabilities have existed since the 1980s but are still in the minority, so it appears that the majority of countries have significant room for improvement and technological advancement in their industries.

It is highly likely that in the near future, more countries will analyze their AM capabilities and formulate strategies for future action. Given the projected increases in AM market value, countries will begin to plan how to maximize their share of the profits by analyzing gaps in their industries and funding further research and innovation. Government funding for the AM field has increased by an unprecedented amount in the last four to five years, and this number will only increase as the industry becomes more profitable.

JAPAN'S METAL 3D PRINTERS

(Contributor: Masako Toki)

BRIEF HISTORY

Japan has made considerable strides in metal 3D printing technology. For example, as early as 2003, Matsuura Machinery Corporation collaborated with Matsushita Electric Works (now Panasonic Corporation) to develop a hybrid metal AM system that combined laser sintering and milling functions. Nevertheless, there has been concern among Japanese officials and industries that Japan lags behind Europe and the US with regards to addressing and incorporating this new technology into a wider range of market needs. Against this backdrop, the Japanese Ministry of Economy, Trade and Industry (METI) established a study group on New Manufacturing in October 2013. It held four meetings to study the added value of 3D printers and future manufacturing trends. The group compiled a final report in February 2014.[182]

Throughout their meetings, the study group discussed the following primary issues:

- Usability of AM technology for manufacturing;
- Possible changes in industry and society caused by new technologies in an era when manufacturing processes continue to be digitalized;
- Potential strategies for enhancing Japanese enterprises's earning capabilities and global competitiveness by taking advantage of such changes for business innovation; and
- Necessary policies for Japan to take advantage of these changes.

The study group concluded that Japan should focus on the following four elements to overcome current challenges in this field:

- Developing technology that integrates devices, materials, and software;
- Developing environments to expedite New Manufacturing on open networks;
- Fostering human resources with knowledge and skills in processing 3D data; and
- Seeking optimum approaches to creating relevant enterprises.[183]

182 http://www.meti.go.jp/english/press/2014/0221_02.html
183 http://www.meti.go.jp/english/press/2014/0221_02.html

The Japanese government predicted the economic ripple effect derived from AM technology would be about 21.8 trillion yen (approximately $200 billion US Dollars, or USD) by 2020. They foresee two main benefits for Japanese manufacturing. First, it will enhance capacity to manufacture precision devices such as vehicles, aircraft, and medical equipment. This will require close collaboration between designers and manufacturers. Second, it will expand the universe of manufacturing firms to include small independent manufacturers and new entities that do not have large scale investment or facilities.[184]

ESTABLISHMENT OF TRAFAM

Following the report, METI invested about $36.5 million in April 2014 to establish a new research association entitled the Technology Research Association for Future Additive Manufacturing (TRAFAM).[185] The association established two major milestones: first, to develop the next generation of 3D printing technology for the industrial level; second, to develop binder jetting equipment for the rapid production of sand molds. Other goals include developing innovative metal AM systems that will meet the world's highest standards, and developing manufacturing technologies for high value-added products of any complicated shape for aerospace, medical, and transportation industries. The government aims to realize these goals through the "all Japan" cooperative structure for technology development that focuses on machine, materials, and software.

TRAFAM is an evolving organization. As of December 2016, it had brought together thirty-two entities including two universities, two semi-governmental entities (the National Institute of Advanced Industrial Science and Technology and the Japan Aerospace Exploration Agency), and twenty-eight corporations.[186] The President of TRAFAM is Atsushi Maekawa, also Vice president of Mitsubishi Heavy Industries. Professor Hideki Kyogoku of Kinki University leads the metal AM systems project, while the Binder Jetting of sand molds project is led by Dr. Toshimitsu Okane of the Japan Association of International Security and Trade (JAIST).

TRAFAM now aims to produce the next generation of metal 3D printers by September 2017. Three companies in TRAFAM are planning to develop these new generation 3D printers and expect the cost per machine to be approximately 100 million yen ($1 million USD).[187]

184 http://www.meti.go.jp/committee/kenkyukai/seisan/new_mono/pdf/report01_02.pdf (for the entire report of the Study group. In Japanese)

185 https://trafam.or.jp/top/ https://www.semiconportal.com/en/archive/news/news-by-sin/1400801-sin-3d-printer-market.html http://www.worldpm2016.com/post-event/presentations/sis-presentations/sis-presentations-am/46-the-current-status-and-outlook-of-metal-additive-manufacturing-in-japan/file

186 https://trafam.or.jp/top/about/member/ see membership here.

187 https://www.nikkan.co.jp/articles/view/00388656

Apart from TRAFAM, the New Energy and Industrial Technology Development Organization (NEDO) launched the Innovative Design and Production Technology Project under the Cross Ministerial Strategic Innovation Promotion program in October 2014. NEDO is pursuing the establishment of a new manufacturing style by developing innovative technologies in twenty-four areas related to design, production, and manufacturing technologies. AM technology is part of this initiative as well.[188]

NONPROLIFERATION OR EXPORT CONTROL CHALLENGES

Although the Japanese government has increased its efforts to enhance collaboration between AM technologies, industries, and academia through the establishment of TRAFAM, policy discussions on nonproliferation and/or export control challenges related to 3D printing are still scarce. The nonproliferation challenges associated with the AM technology have not been widely discussed among the officials in the Ministry of Foreign Affairs who are in charge of nonproliferation issues.

However, nonproliferation and export control communities have discussed this issue since 2014. The Center for Information on Security Trade Controls ran a brief article about regulating metal 3D printers in its 2014 and 2015 Journal. In its March 2015 annual symposium, the JAIST dedicated one session to 3D printers from perspectives of technology development and export control.

There has also been some development in Japan's export control legal framework in response to the recent technological development in this field. In response to the Wassenaar Arrangement's amendment to add "AM equipment" to its control list in December 2014, Japan made an appropriate amendment to its export controls. However, dual-use metal 3D printers are not included in the list of controlled items.

From the perspectives of nonproliferation and export control, it is desirable to investigate the possibility of controlling such equipment. METI's 2017 priority policies include enhancing export control of sensitive technology and items.[189] It is possible this will finally produce the controls for—or at a minimum, the conversation about controlling—AM in Japan.

188 http://www.nedo.go.jp/content/100575974.pdf
189 http://www.meti.go.jp/main/yosangaisan/fy2017/pdf/01_3.pdf

ONLINE 3D PRINTING SERVICES

(Contributor: Shea Cotton)

EXECUTIVE SUMMARY

There has been a recent surge of interest in 3D printing. With this surge, a number of new online services developed to offer access to cutting edge 3D printers capable of printing with a number of materials. These services aim to provide access to expensive and state-of-the-art 3D printers that would otherwise be out of the financial reach of ordinary users.

This paper examines ten of those sites and compares their costs, the materials they offer to users, and the level of export control guidance (if any) they offer to users.

This paper has identified several trends:

- Online printing services can be classified into two categories based their target customer base: hobbyists or industry.
- Sites that target hobbyists have no information about export controls within their terms of service or elsewhere on their websites, though some explicitly prohibit their service from being used to manufacture weapons.
- Industry oriented services almost all mention US export controls somewhere in their terms of service or elsewhere on their websites.
- Industry oriented services almost all offer some sort of compliance system that allows users to comply with regulations laid out in the International Traffic in Arms Regulations (ITAR) and the Export Administration Regulations (EAR).
- The aforementioned compliance systems vary between the 3D printing services; however, they have two universal characteristics:
    - Only US personnel are permitted to interact with data specified as being export controlled.
    - The data is stored on encrypted servers located exclusively within the US and will not be transmitted outside of the US.

This paper will begin with the services that target hobbyists and proceed to the more expensive services that target industry. The level of export control guidance becomes more and more robust with each service this paper describes.

This increase in export control guidance also correlates directly with an increase in expense and the number of printing materials available to users. In other words, the services that provide the most export control guidance and information are also the most expensive and possess the greatest capabilities in terms of 3D printing.

HOBBYISTS

YOU3DIT

This service is the 3D printing equivalent of the ride sharing service Uber. In other words, this service does not appear to own any 3D printers themselves, but instead connects people without 3D printers to others with 3D printers who are looking to make money. The service works simply: users without printers post the item they're looking to print, and users with printers capable of printing the item bid for the job. Because of the diffused nature of the printers, it was not possible to determine what materials were available to print items.

In terms of export control guidance, there is no reference to the ITAR or EAR anywhere on the You3DIt website, nor was there any mention of exporting in general. The website's terms of service states clearly that the site does not permit users to produce weapons or weapon components using their service. However, the site lacked any sort of clear enforcement mechanism to ensure this.

MAKEXYZ

Similar to You3DIt, this service connects those without 3D printers to those with them. Like You3DIt, MakeXYZ prohibits weapons manufacturing but makes no mention of export controls. However, MakeXYZ does have a much clearer, and incredibly cheap, pricing system—it provides the cheapest quote out of all the services covered in this outline.

PONOKO

Unlike You3DIt, the New Zealand company Ponoko appears to own 3D printers. This makes it considerably less diffused than You3DIt and offers Ponoko greater control over what the site is used for. This site encourages users to design jewelry and toys and then sell them on Ponoko. When someone purchases another user's design, Ponoko will print out the design, ship it to the purchaser, and pay the designer a share of the payment.

Users can choose to print in gold plate, stainless steel, and two types of plastic. Designs are meant to be sold to others on the site, not purchased by the uploader, though it is possible to order a printed version of your own designs. This differentiates Ponoko from most of the other printing services later in this paper. It also makes it difficult to determine the cost of printing an item through Ponoko.

Ponoko offers no guidance on export control compliance. There is no mention of the ITAR or EAR anywhere on their site. Furthermore, unlike other printing services, Ponoko's terms of service do not explicitly prohibit the manufacture of weapons or weapon components.

SHAPEWAYS

This service is similar to Ponoko, though they make it much easier for users to upload and order prints of their designs. Much like Ponoko, ShapeWays is aimed at amateur jewelry makers. The cost to print items varies depending on the material customers request, but it generally appears moderately priced. Like others in this section, ShapeWays makes no mention of export controls, the ITAR, or the EAR. In fact, ShapeWays makes no mention of exporting at all. However, ShapeWays does maintain a strict ban on using their service to manufacture weapons or weapon components.

I.MATERIALISE

This service seems to be aimed at the more serious hobbyists that border on small companies. i.materialise offers a wide range of printing materials to customers. The full list is available on its website.[190]

i.materialise provides no information on the ITAR/EAR, nor does it mention anything about export controls or exporting in general. The farthest they go is forbidding their service from being used to manufacture weapons or weapon components.

INDUSTRY

SCULPTEO

Sculpteo is an interesting service because it seems to target both hobbyists and small businesses, straddling the categories used by this paper. They are based out of France and offer services in both Europe and the US. They offer many printing materials, and their services are cheap relative to some of the other printing services examined in this section. Much like the other printing services in the hobbyist section, they make no reference to export controls of any sort, though they prohibit weapons production like other hobbyist services do. Sculpteo is most interesting because it markets services toward aerospace and satellite companies. This firmly enters into export control territory, making the lack of information on the ITAR or EAR all the more surprising.

190 I.Materialize, "3D Printing Materials". 2016. Accessed at https://i.materialise.com/3d-printing-materials on December 1, 2016.

PROTOLABS

This service resembles other services in this subsection in terms of cost and the materials customers can print. Protolabs's website did not provide much information about export controls; however, they do state clearly that they are registered with the Directorate of Defense Trade Controls (DDTC) as a manufacturer of defense articles. Because of this, they likely offer some sort of service specifically for prospective customers interested in manufacturing such items. It is likely that such a system is available only upon request. Protolabs's Terms of Service states clearly that both parties are to follow US export control regulations.

Export Compliance. Buyer and Seller will comply with all applicable export restrictions and regulations of any U.S. agency or authority including but not limited to the Export Administration Regulations ("EAR") administered by the U.S. Department of Commerce, International Traffic in Arms Regulations ("ITAR") under the U.S. Department of State, and embargo controls administered by the U.S. Department of the Treasury's Office of Foreign Asset Controls ("OFAC") with respect to the goods or services that are subject to this Agreement. In order for Seller to conduct appropriate export control checks, the Buyer agrees to identify any export controlled (e.g., ITAR) goods in writing to Seller by the time Buyer accepts a quotation and to provide all pertinent information pertaining to the particular end Buyer, destination and intended use of goods. Seller reserves the right to stop shipping or providing goods if Seller has reason to believe that any shipment or sale of goods may violate any export control law.

Figure 10: Protolabs Export Compliance Statement[191]

More information was not available on exactly what services Protolabs offers customers to ensure compliance with export controls.

3D SYSTEMS

3D Systems owns a number of advanced 3D printers and offers many materials to customers. 3D Systems targets businesses almost exclusively. This is reflected in the cost of printing, which is considerably more expensive than the previous services we examined.

Likely because of their target market, 3D Systems has a special system for carrying out printing jobs for defense articles. However, there is little information about this system on their website; they instead provide a phone number for prospective users who wish to print defense articles or whose items fall under regulations in the ITAR or EAR. Their terms and conditions provided similarly minimal information other than requiring users to comply with existing US export control regulations.

191 Citation: Protolabs. "Legal: Terms and Conditions of Sale," June 2017. Accessed at https://www.protolabs.com/legal-notices/ on October 3, 2017.

11. **EXPORT COMPLIANCE** – Customer shall not export, re-export, or otherwise transmit, directly or indirectly, any Equipment or Software except in full compliance with all U.S. export control laws and regulations. These obligations shall survive the termination of the Agreement.

Figure 11: 3D Systems' Export Compliance Statement[192]

XOMETRY

Among the services examined in this paper, Xometry is one of the best in terms of the range of materials and relatively affordable prices.

When it comes to export controls, Xometry offers an explicit ordering and manufacturing option for items that fall under the ITAR or EAR. This costs customers an extra $20, but it guarantees that the uploaded data will stay in encrypted servers located in the US and will be handled by US citizens only.

On its website, Xometry clearly notes that it is "ITAR Registered," and provides a link to their letter of registration with the DDTC.[193]

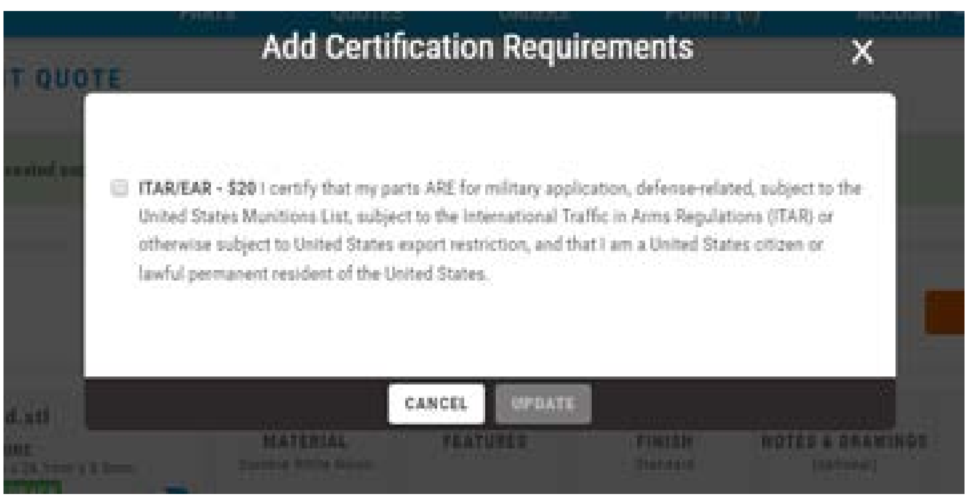


Figure 12: Xometry's ITAR/EAR Product Ordering Option[194]

192 3D systems "Sales Terms And Conditions," August 3, 2009. Accessed at https://www.3dsystems.com/sites/default/files/downloads/Terms-And-Conditions-For-Equipment-Materials-And-Software.pdf on October 3, 2017.

193 https://www.xometry.com/wp-content/uploads/Xometry_ITAR.pdf

194 Xometry. "Add Certification Requirement," April 2017. Accessed at Xometry.com on October 3, 2017

There is only one sentence in the final section of Xometry's terms of service regarding export controls.

21. Miscellaneous

Our failure to exercise or enforce any right or provision of the Terms of Use shall not constitute a waiver of such right or provision. If any provision of these Terms of Use shall be unlawful, void, or for any reason unenforceable, that provision shall be deemed severable from these Terms of Use and shall not affect the validity and enforceability of any remaining provisions. By offering this Site, the Services, and any information, products or other content through the Site and/or Services, Xometry does not purport to distribute to or solicit you or any person to use the Site, Services or such information, products or other content in jurisdictions where providing such is prohibited by law. You agree to comply with all local rules regarding online conduct and acceptable materials. Specifically, you agree to comply with all applicable laws regarding the transmission of technical or other data exported from the United States or the country in which you reside. You also agree that, regardless of any statute or law to the contrary, any claim or cause of action arising out of or related to the use of the Site or Service or the Terms of Use must be filed within one (1) year after such claim or cause of action arose or be forever barred. These Terms of Use, and any web pages or other documents incorporated by reference, set forth the entire understanding and agreement between us with respect to the subject matter hereof. If you have any problems, questions, suggestions or complaints about these Terms of Use or the Site, please contact us at info@Xometry.com.

Figure 13: Xometry's Export Compliance Statement[195]

Given the ease with which they allow customers to add special ITAR compliance requirements to their product, it is surprising that they do not provide a more detailed export control requirement within their terms of service.

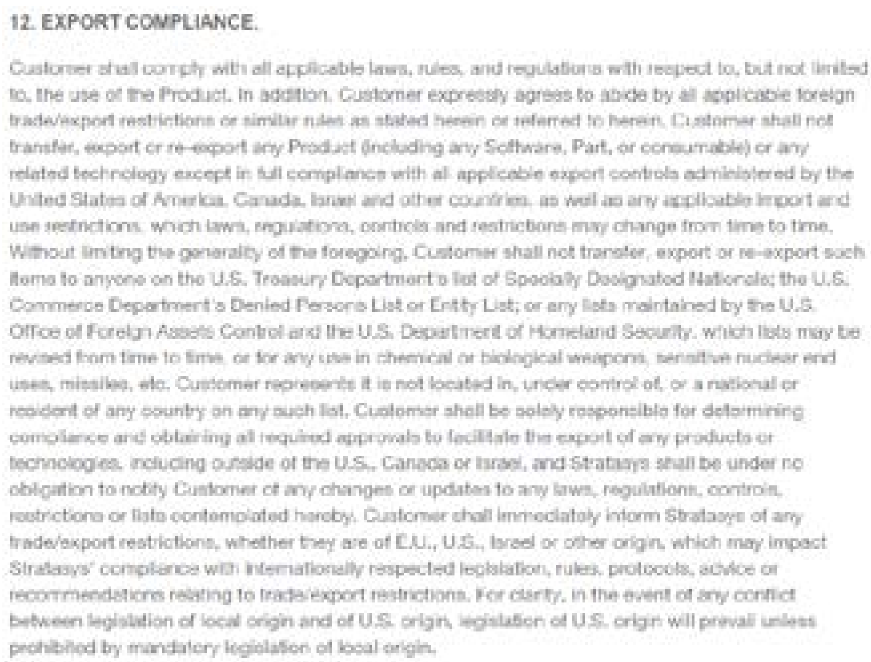
STRATASYS DIRECT MANUFACTURING

This service is the gold standard of online 3D printing services. Stratasys offers the widest range of materials of any service examined within this document and does so at a relatively affordable cost. While their main target market is industry, their service is readily accessible for hobbyists as well.

They are also quite aware of export control requirements. Like Xometry, Stratasys offers customers a compliant system for dealing in items regulated by the ITAR/EAR. When users check a box on the site, the data is saved in an encrypted set of US-based servers. The associated order is then handled by US personnel exclusively. Unlike Xometry, Stratasys offers this at no additional charge to users.

195 Xometry. "General Terms and Conditions," April 4, 2017. Accessed at www.Xometry.com/terms on October 3, 2017.

Figure 14: Stratasys' ITAR Compliance Option[196]



12. EXPORT COMPLIANCE.

Customer shall comply with all applicable laws, rules, and regulations with respect to, but not limited to, the use of the Product. In addition, Customer expressly agrees to abide by all applicable foreign trade/export restrictions or similar rules as stated herein or referred to herein. Customer shall not transfer, export or re-export any Product (including any Software, Part, or consumable) or any related technology except in full compliance with all applicable export controls administered by the United States of America, Canada, Israel and other countries, as well as any applicable import and use restrictions, which laws, regulations, controls and restrictions may change from time to time. Without limiting the generality of the foregoing, Customer shall not transfer, export or re-export such items to anyone on the U.S. Treasury Department's list of Specially Designated Nationals; the U.S. Commerce Department's Denied Persons List or Entity List; or any lists maintained by the U.S. Office of Foreign Assets Control and the U.S. Department of Homeland Security, which lists may be revised from time to time, or for any use in chemical or biological weapons, sensitive nuclear end uses, missiles, etc. Customer represents it is not located in, under control of, or a national or resident of any country on any such list. Customer shall be solely responsible for determining compliance and obtaining all required approvals to facilitate the export of any products or technologies, including outside of the U.S., Canada or Israel, and Stratasys shall be under no obligation to notify Customer of any changes or updates to any laws, regulations, controls, restrictions or lists contemplated hereby. Customer shall immediately inform Stratasys of any trade/export restrictions, whether they are of E.U., U.S., Israel or other origin, which may impact Stratasys' compliance with internationally respected legislation, rules, protocols, advice or recommendations relating to trade/export restrictions. For clarity, in the event of any conflict between legislation of local origin and of U.S. origin, legislation of U.S. origin will prevail unless prohibited by mandatory legislation of local origin.

Figure 15: Stratasys's Export Compliance Terms of Service[197]

196 Stratasys. "ITAR Option", April 2017. Accessed at Stratasys.com on October 3, 2017.
197 Stratasys. "Legal: Terms and Conditions of Sale," 2017. Accessed at www.stratasys.com/legal/terms-and-conditions-of-sale on October 3, 2017.

Stratasys also has a lengthy and detailed export compliance section it its terms of use. Of the sites surveyed, this terms of service agreement contains the most detail on export control requirements and the user's compliance duties. Furthermore, Stratasys provides the easiest (and free) method for a potential customer to ensure that they stay in compliance with US export control regulations when using Stratasys's service.

MAKERSPACES: ENTRY AND ACCESS

(Contributor: Ruby Russell)

EXECUTIVE SUMMARY

Examination of three popular Makerspaces—including TechShop, Fab Lab, and Staten Island Makerspace—reveals the ease with which any individual may acquire membership to these communal workspaces and gain access to advanced fabrication technologies including Computer Numerical Control (CNC) milling machines, 3D printers, and laser cutters. In general, membership to these groups requires a monthly fee and the completion of basic safety training courses for equipment use. Even non-members may access these spaces if they are willing to pay higher fees.

An initial investigation suggests these companies incorporate little to no guidance on export controls into training for their members. Although some companies require new members to agree to Terms and Conditions, these are made available just prior to purchase of membership and focus narrowly on safety, liability, and intellectual property in some cases. It is unclear whether export controls are indirectly referenced/included through mention of the applicability of federal and state laws.

Fab Lab presents the most comprehensive set of Terms and Conditions, covering issues related to violation of state law; downloading and illegally reproducing, distributing, or displaying files; and violation of laws through creation of a false identity. This may be due partially to the extensive nature of the Fab Foundation, and the direct guidance it offers on establishing Fab Labs around the world.[198] Although TechShop requires members to sign "Policies & Procedures" to purchase membership, these policies are not readily available online. Finally, while Staten Island Makerspace uses a Terms and Conditions, prospective members apply to the company owning the Makerspace's web platform rather than to the Makerspace itself. It should be noted that this investigation only simulated the purchase of a membership online, and it is therefore possible that any of these spaces require signatures on additional documents during the prospective member's first visit.

Overall, membership prerequisites and subsequent access to advanced fabrication technologies center around payment and equipment safety training courses rather than legal issues or anything related to export control. These organizations focus primarily on promoting social responsibility and making specialized equipment available to the community for the purposes of advancing education and creativity. For example, the Fab Foundation requires that qualifying "Fab Labs" uphold specific values, including the promotion of the local community, collaboration, education, and entrepreneurship.

198 The terms and conditions for Fab Lab discussed in this work are designed specifically for Fab Lab San Diego. It seems likely, however, that each Fab Lab tailors its own Terms & Conditions to its respective location. For example, Fab Lab London has a different set of Terms & Conditions which are not nearly as extensive (available at http://www.fablablondon.org/terms/).

The values upon which these institutions are founded ostensibly suggest that the users taking advantage of the spaces are not nefarious actors, but rather members of the local community seeking to advance education and innovation. However, some spaces, such as Fab Lab, place a heavy emphasis on sharing (especially via digital means) projects and inventions designed in the Makerspace. This sharing philosophy extends even across national borders (see below). In this context, it is very important to raise awareness and offer guidance on relevant export controls.

TECHSHOP PROFILE

ABOUT

Website Description: "A playground for creativity, TechShop is an open-access, DIY workshop and fabrication studio. We are a community-based space where entrepreneurs, artists, makers, teachers and students come together to learn and work together."[199]

AVAILABLE EQUIPMENT[200]

- Prototyping tools
    - 3D FDM printer, ABS
    - Laser cutter, 60 Watt
    - 3D Scanner
- Machining tools
    - Lathe
    - Large Milling Machine,
    - Four-axis CNC Milling machine
- Electronics Equipment (Oscilloscope, frequency counter, variable transformer…)
- Full list: http://www.techshop.ws/tools_and_equipment.html

199 TechShop, "Welcome." Available at: http://www.techshop.ws/index.html; Full list available here: http://www.techshop.ws/tools_and_equipment.html
200 TechShop, "Core Tools & Equipment." Available at: http://www.techshop.ws/tools_and_equipment.html

CLASSES (SAN JOSE LOCATION)[201] [202]

- CNC (Concepts of CNC, CAD to CAM software, etc)
- Rapid Retyping (3D printing, 3D Scanning and Editing)
- Electronics
- Computers (CNC related classes)
- Fabrication (Injection molding, Vacuum Forming, etc)
- Laser Cutting
- Machining (Milling Machine, Metal Lathe, Tramming and Precision on a Mill)
- Full list here
- **Note**: Membership is not required to take classes, but there are discounted prices for members. (See here for the full list of class prices.)

MEMBERSHIP OPTIONS/COSTS[203]

Offering a variety of payment plans and enrollment options, TechShop provides members with access to "over $1 million worth of advanced machines and tools, sophisticated 2D and 3D design software, and other professional equipment."[204] Members may sign up for individual monthly payment plans, student and active duty military plans, and corporate memberships. TechShop offers non-members the opportunity to take classes for a higher price.

- Individual Membership: Monthly Recurring
  - Access to all TechShop facilities nationwide and all membership perks (includes access to all machines following the completion of Safety and Basic Use classes; many machines do not require these classes)
  - Monthly autopay: credit card information must remain on file for renewal charges (applicable to all)
  - Price: $150.00 per month
- Individual Membership: 1 Year

201 Full list available here: http://www.techshop.ws/take_classes.html?storeId=5
202 TechShop, "Take Classes: TechShop San Jose Class Listings" Available at: http://www.techshop.ws/take_classes.html?storeId=5
203 TechShop, "TechShop Memberships - Select a TechShop Location" Available at: https://secure.techshop.ws/memberships.cfm?step=select_location#notes
204 TechShop Homepage. Available at: http://www.techshop.ws/

- » Access to all TechShop facilities nationwide and membership perks for 12 months
- » Price: $1,650 (Savings from month-by-month: $450)

» Family Add-On Membership: Monthly Recurring / 1 Year

- » Add spouse/Child to current individual membership
  - » To Monthly: $50.00 per month
  - » To Yearly Membership: $500.00
- » Student and Active Duty Military Membership: Monthly Recurring / 1 year
  - » Current School ID or active military ID confirmation required
    - » Monthly: $95.00
    - » One Year: $995.00
- » Corporate Membership
  - » Group Membership, Price not listed

» Non-member Class Price: usually $99.00 per class

HOW TO JOIN

Prospective members follow a simple step-by-step process accessible through the TechShop website. After choosing a membership type (see above), the prospective member must accept the "Recurring Monthly Membership Notice" (automatic monthly renewal), enter their basic information (name, address, phone, email, date of birth), and billing information. This page provides a link to the TechShop Privacy Policy, which covers TechShop's use and protection of its member information. Finally, the prospective member must agree to the TechShop "Purchase Agreement Terms," including compliance with all TechShop Policies and Procedures before using any TechShop equipment[205] as well as other policies related to payment, credit cards, automatic renewals, and cancellations.

NON-MEMBER CLASS SIGN-UPS

To sign up for classes as a non-member, the interested party must select the class type (e.g., Rapid prototyping) under the "Classes" section at the preferred TechShop location. The party must then click the "non-member sign up" option. The registration "Notes and Disclaimers" states that "Individuals who register for a class as a member will be asked to present a valid member ID before entering the class. Any non-member taking the class who paid the member price, will be required to pay the difference at the front desk before the class begins." This notice seems aimed less at ensuring

205 No information available other than "Class Policies and Procedures," listed below.

security and more at validating that the party paying the member price is, in fact, a member. It would appear non-members are required only to pay the more expensive price, not to present ID.

LOCATIONS[206]

- Arizona (TechShop Chandler)
- California (TechShop Mid-Peninsula, San Francisco, San Jose, Los Angeles)
- Michigan (TechShop Detroit)
- Missouri (TechShop St. Louis)
- Pennsylvania (TechShop Pittsburgh)
- Texas (TechShop Austin-Round Rock)
- Virginia/DC (TechShop DC-Arlington)

FUNDING

In addition to charging somewhat substantive membership fees, TechShop maintains a website dedicated to investor recruitment.[207] Promoting investments as an opportunity to support learning, creativity, collaboration, local entrepreneurs, and small businesses by providing resources to local communities, the website provides guidance on how to support the cause. Investors may either purchase TechShop, Inc. Series B preferred stock ($2.286/share) or make a loan either directly to TechShop Inc. or to an individual TechShop location.[208] TechShop specifies a minimum investment of $25,000 and requires lenders to be accredited by the US Securities and Exchange Commission. Investors receive a free VIP TechShop Lifetime Membership that extends to the investor's spouse and children.

To facilitate investments, TechShop has also taken advantage of the Jumpstart Our Business Startups (JOBS) Act, "which lifts the ban on general solicitation and advertising for certain offerings."[209] When the act went into effect in September 2013, for example, it enabled TechShop to launch a campaign that raised $60 million to build new facilities in the US.

206 TechShop, "TechShop Locations" Available at: http://www.techshop.ws/locations.html
207 TechShop, "Invest in TechShop." Available at: http://www.techshop.ws/invest.html
208 Ibid.
209 TechShop, "TechShop Leads Charge to Leverage JOBS Act with $60 Million Investment Offering." Available at: http://www.techshop.ws/press_releases.html?&action=detail&press_release_id=49

According to their website, TechShop partners with companies that promote the democratization of technology. Notably, according to reports, TechShop has also received grants from DARPA, which awarded TechShop $3.5 million in 2014 to establish new Makerspaces.[210]

TERMS AND CONDITIONS/SECURITY BARRIERS/EXPORT CONTROL GUIDANCE

As noted above, prospective members who purchase online memberships must agree to the TechShop "Purchase Agreement Terms" prior to securing membership. These terms center on the "Class Policies and Procedures," which cover issues including prompt arrival, carrying a TechShop ID at all times, appropriate dress, and participation expectations. The terms cover refunds and cancellation policies as well. While the photo ID does present one security measure, the Procedures make no mention of issues related to export control or rules about sharing or providing designs/projects fabricated in the Shop to outside parties. [211]

FAB LAB/FAB FOUNDATION PROFILE

ABOUT

The Fab Foundation is a non-profit that was established by MIT's Center for Bits & Atoms (CBA) in 2009. Its stated mission is to "provide access to the tools, the knowledge and the financial means to educate, innovate and invent using technology and digital fabrication to allow anyone to make (almost) anything… thereby creating opportunities to improve lives and livelihoods around the world."[212] The Fab Foundation provides access by encouraging and providing guidance on the establishment of "Fab Labs," defined as "technical prototyping platform[s] for innovation and invention, providing stimulus for local entrepreneurship . . . place[s] to play, to create, to learn, to mentor, to invent." Today, Fab Labs comprises "global network of local labs, enabling invention by providing access to tools for digital fabrication."[213] According to the Fab Foundation Website, launching a Fab Lab "requires assembling enough of the hardware and software inventory to be able to share people and projects with other Fab Labs, posting the Fab Charter to provide context for doing that, and contacting fab-info@cba.mit.edu to be added to the fab lab network."[214]

210 Evgeny Morozov, "MAKING IT: Pick up a spot welder and join the revolution," The New Yorker, January 13, 2014. Available at http://www.newyorker.com/magazine/2014/01/13/making-it-2/

211 TechShop, "Class Policies & Procedures." Available at: http://www.techshop.ws/TechShop_Class_Policies_and_Procedures.html

212 Fab Foundation, "About: Fab Foundation Mission." Available at: http://www.fabfoundation.org/index.php/about-fab-foundation/index.html

213 Fab Foundation, "What is a Fab Lab?" Available at: http://www.fabfoundation.org/index.php/what-is-a-fab-lab/index.html

214 Fab Foundation, "Fab FAQ." Available at: http://www.fabfoundation.org/index.php/faq/index.html

AVAILABLE EQUIPMENT

- Recommended Fab Lab equipment:[215]
    - Laser cutters for 2D/3D design and fabrication
    - High precision milling machine
    - Vinyl cutter
    - Sophisticated electronics workbench for prototyping circuits and programming microcontrollers
    - Large wood routing machine
    - 3D printers (generally inexpensive, robust, fair resolution)

- Available at Existing Fab Lab: San Diego[216]
    - 3D printers
        - 19 FDM (Plastic) 3D printers
            - (2) Robo3D R1
            - (1) Ultimaker 2
            - (1) XYZ DaVinci AIO
            - (15) XYZ DaVinci 1.0
        - (1) Full color Powder 3D printer
        - (1) STL 3D printer
    - CNC Tools
        - (1) Taig four-axis CNC metal mini-mill
        - (1) Epilog 40W Laser cutter

215 Because the Fab Foundation does not establish Fab Labs uniformly, but rather provides guidance and resources to enable any given community to establish a Fab Lab, no two Fab Labs will necessarily house the same equipment. Adherence to the Fab Charter (see below), rather than an exact set of equipment, qualifies a space for the "Fab Lab" name. For a full inventory breakdown of recommended equipment, see Fab Foundation, "Fab Lab Inventor." Available at https://docs.google.com/spreadsheets/d/1U-jcBWOJEjBT5A0N84IUubtcHKMEMtndQPLCkZCkVsU/pub?single=true&gid=0&output=html

216 Fab Lab San Diego, "Tools and Equipment." Available at: http://www.fablabsd.org/tools/

- (1) Roland Modela MDX-20 3 axis mill
- (1) 2×3 foot (ft) Blackfoot wood CNC router
- (2) 24 in Roland GX-24 CAMM-1 Servo vinyl cutter

NOTE: Fab Lab team members are always present to assist with tools and lab oversight

CLASSES

The "Fab Academy" provides a list of classes recommended for Fab Labs, which includes a breakdown of the necessary equipment, materials, components, and assignments to conduct classes.[217] Recommended class topics include CAD, computer-controlled cutting, computer-controlled machining, 3D printing and scanning, mechanical design, and machine design. It is also possible to access free tutorials on topics ranging from CAD to Computer Controlled Cutting to 3D printing and scanning through Fab Academy Website.[218]

- Available at existing Fab Lab: San Diego[219]
  - Intro to 3D modeling
  - Intro to robotics
  - Intro to electronics
  - Intro to Programming with Arduino
  - The Wet Lab ("The San Diego Wet Lab project is a local instance of the global DIY Bio Hacker phenomenon. The skills and tools for modifying plant and animal genes is becoming cheaper, faster, and more widely available, allowing 'citizen scientists' unparalleled new opportunities.")[220]

MEMBERSHIP OPTIONS

Membership varies from location to location; the options below are for Fab Lab San Diego,[221] which offers a wide range of membership options. The most basic option, the "Maker Membership," provides members access to the Fab Lab Makerspace and Tools with a 15 percent discount on classes for a monthly fee of $75.00. Other options include Family Memberships, Group Memberships, and

217 Fab Academy, "Classes." Available at: http://academy.cba.mit.edu/classes/index.html
218 Fab Academy, "Fab Academy 2016 Tutorials." Available at: http://archive.fabacademy.org/archives/2016/doc/index.html
219 Fab Lab San Diego, "Upcoming Classes. Available at: http://www.fablabsd.org/upcoming-classes/
220 Meetup: Fab Lab San Diego, "[Meetup] The Wet Lab - Weekly Lab Meetup @ La Jolla Library." Available at: https://www.meetup.com/FAB-LAB-San-Diego/events/235168926/
221 Fab Lab San Diego, "Memberships." Available at: https://fablabsd.org/members/memberships/

options for "Supporting Members." All memberships appear to grant the same amount of lab access, differing only on price and group numbers. The "Supporting Members" option provides access to special Fab Lab events.

- Maker Membership
  - Access to Fab Lab Makerspace and Tools
  - $75.00 monthly
  - 15 percent discount on classes
- Maker Membership Family
  - Same access, good for the primary member, a second adult in same household, and up to 2 children (under 18)
  - $150.00 monthly
- Maker Membership Group of 3 (discount)
  - Not stated, but presumably the same access as a basic Maker Membership
  - $200.00 monthly
- Group of 4
  - $250.00 monthly
- Group of 5
  - $300.00 monthly
- Supporting Member: $15.00/$25.00/$50.00/$75.00 monthly
  - Seems to apply to those "supporting the fab lab mission," most likely major investors or donors
  - Depending on their monthly payment amount, Supporting Members may be invited to free programs and community gatherings ($15), entered into raffles for free tickets to partner events/parties/conferences ($25), invited to monthly member socials ($50), and contributing to low-income student scholarships, among other perks.
- Classes range from about $30 to thousands of dollars[222]

222 Eventbrite, "Intro to Electronics." Available at: https://www.eventbrite.com/e/intro-to-electronics-nov-12-tickets-29060385395

HOW TO JOIN

In order to join the Fab Lab San Diego, prospective members must choose a membership option (see above) and create a user account (username, email, etc.). Prospective members must then agree to the "Terms of Service" (see below) and provide credit card information. The new member must complete the "Lab Safety Orientation" and the "Basic Operations and Safety Classes" before using specific equipment (e.g., laser cutters, CNC mills, and 3D printers).

LOCATIONS[223]

As of December 1, 2016, there were 1006 Fab Labs located around the world, of which 141 Fab Labs were registered in the US.

FUNDING

The Fab Foundation receives support, sponsorship, and partnership from a number of major companies including Dassault Systems SolidWorks Corporation, 3D PrintLife, Autodesk, Chevron, and Cisco.[224] In 2014, for example, Chevron provided Fab Foundation with a $10,000,000 grant to establish ten new Fab Labs across the US.[225] For details on financial reporting, the Fab Foundation posts tax returns, balance sheets, and annual reports on its website.[226]

Given that the Fab Foundation aims to enable local communities to establish Fab Labs rather than to establish Labs entirely on its own, it appears that the establishing individual or group is responsible for their own acquisition of funds in many cases, though the Foundation provides guidance on how to acquire resources. As part of this guidance, for example, the Fab Foundation provides a detailed sample budget that includes pricing on various fabrication technologies.[227] Through its Fab Connect website, the Fab Foundation also provides options and guidance on acquiring grants.[228] Finally, the Fab Foundation maintains a Fab Fund "to provide global access to capital and markets for businesses incubated in Fab Labs."[229]

223 Fab Labs, "Labs: All Countries." Available at: https://www.fablabs.io/labs

224 Fab Foundation, "Fab Lab Resources." Available at: http://www.fabfoundation.org/index.php/fab-lab-resources/index.html; Fab Foundation, "Homepage." Available at: http://www.fabfoundation.org/

225 Fab Lab Connect, "Chevron announces generous $10,000,000 grant to Fab Foundation," June 18, 2014. Available at: http://www.fablabconnect.com/chevron-announces-generous-10000000-grant-to-fab-foundation/

226 Fab Foundation, "About." Available at: http://www.fabfoundation.org/index.php/about-fab-foundation/index.html

227 Fab Foundation, "How to start a Fab Lab: The Funds." Available at: http://www.fabfoundation.org/index.php/the-funds/index.html

228 Fab Lab Connect, "services." Available at: http://www.fablabconnect.com/solutions/

229 Fab Foundation, "FAQ." Availabe at: http://www.fabfoundation.org/index.php/faq/index.html

TERMS AND CONDITIONS (ACCESSIBLE AFTER CREATING AN ACCOUNT)

The full terms and conditions are long and detailed. This analysis will highlight several sections and subsections that are the most relevant for export controls. Fab Lab, like many of the other services discussed, does not reference export controls explicitly within its Terms and Conditions. As such, the items listed below encompass the Terms and Conditions that come the closest to prohibiting Fab Lab's services from being used to circumvent or violate US export controls.

The Terms and Conditions include the following items:

» Fab Lab Values (Community, collaborative education, entrepreneurship…)

» "All users must first meet with the Fab Lab, Inc. Lab Manager and/or Safety Instructor and complete an orientation in workshop and facility safety procedures."

» The Lab Rules and conduct

» "When using electronic, computing, or network devices ("Services") owned by Fab Lab, Inc., or connected to its network," you will not

  » Use the Services for any contests, pyramid schemes, chain letters, junk email, spamming, or any duplicative or unsolicited messages (commercial or otherwise);

  » Defame, abuse, harass, stalk, threaten, or otherwise violate the legal rights (such as rights of privacy and publicity) of others;

  » Publish, post, upload, distribute, or disseminate any inappropriate, profane, defamatory, obscene, indecent, or unlawful topic, name, material, or information on or through Fab Lab, Inc. Services;

  » Upload or otherwise make available files that contain images, photographs, software, or other material protected by intellectual property laws;

  » Upload files that contain viruses, Trojan Horses, worms, time bombs, cancelbots, corrupted files, or any other similar software or programs that may damage the operation of another's computer or property;

  » Download any file(s) that you know, or reasonably should know, cannot be legally reproduced, displayed, performed, and/or distributed in such manner;

  » Violate any code of conduct or other guidelines that may be applicable for any particular Service; or

  » Violate any applicable laws or regulations by creating a false identity for the purpose of misleading others.

» Compliance with the Law: Member agrees to comply with all relevant laws and regulations in its use of the Fab Lab, Inc. facilities.

- Governing Law; Venue: "This Agreement shall be construed in accordance with, and governed by, the laws of the State of California as applied to contracts that are executed and performed entirely in California…"
- Signatory agrees "TO INDEMNIFY AND HOLD HARMLESS the RELEASEES from any loss, liability, damage or costs, including court costs and attorney fees that they may incur due to my participation in said activity, WHETHER CAUSED BY NEGLIGENCE OF RELEASEES OR OTHERWISE."
- Confidentiality agreement
- For Ownership
  - According to the Fab Charter: "Designs and processes developed in Fab Labs can be protected and sold however an inventor chooses, but should remain available for individuals to use and learn from."[230]

OTHER/SOCIAL RESPONSIBILITY

The Fab Foundation repeatedly emphasizes the importance of adhering to the Fab Charter for an institution to qualify as a Fab Lab. The Charter covers topics including the definition of a Fab Lab and what it should contain, who can use a Fab Lab, and who owns Fab Lab inventions.[231]

The Fab Foundation also maintains a section on its website describing "What Qualifies as a Fab Lab,"[232] which includes the provision of public access (considered "essential"), a subscription to the Fab Charter, and the facilitation of sharing, designing and collaborating across international borders. The emphasis on sharing across international borders is particularly interesting from an export control perspective.

According to Fab Lab, "The idea is that all the labs can share knowledge, designs, and collaborate across international borders. If I make something here in Boston and send you the files and documentation, you should be able to reproduce it there, fairly painlessly. *If I walk into a Fab Lab in Russia, I should be able to do the same things that I can do in Nairobi, Cape Town, Delhi, Amsterdam or Boston Fab Labs* [emphasis added]."[233]

230 Fab Foundation, "Fab Charter." Available at: http://www.fabfoundation.org/index.php/the-fab-charter/index.html
231 Ibid
232 Fab Foundation, "Who/What qualifies as a Fab Lab." Available at: http://www.fabfoundation.org/index.php/what-qualifies-as-a-fab-lab/index.html
233 Ibid.

STATEN ISLAND MAKERSPACE

ABOUT

Founded in 2013 by two sculptors, Staten Island Makerspace is a "non-profit, STEAM education and community innovation center offering low-cost access to individuals and groups to the tools, equipment, and resources in our 6000 ft2 facility."[234]

AVAILABLE EQUIPMENT[235]

- Metal Shop
    - Two Mig Welders, three Tig welders
    - Plasma cutter
    - Horizontal and vertical band saws
    - Drill press
    - Causing lathe
    - Bridgeport milling machine
    - Finger brake
    - 4 ft slip roller
    - 275 pounds anvil
    - Note on Access: "Use of the metalshop is exclusive to Pro members who have taken and passed a metal tool safety test. Basic and Co-Working members who have purchased a daily or weekly pass and have passed the metal tool safety test may also have temporary use of the metal shop**.** *Non-members are also eligible to take classes in the metalshop* [emphasis added]."
- Computer Lab
    - Computer work stations
    - Large format printer
    - 3D printer
    - Access: Pro members eligible to use, Basic member may purchase daily or weekly pass. Non-members can take classes in the computer lab.

234 Staten Island MakerSpace, "Home." Available at: http://www.makerspace.nyc/home
235 Staten Island MakerSpace, "the space." Available at: http://www.makerspace.nyc/the-space

- Digital Fabrication
  - CNC router: 4 ft x 8 ft bed that cuts materials including plastics, wood, sheet goods, and soft metals
  - Laser cutter: 100w Boss Laser with a 16 in x 30 in bed that cuts wood, leather, acrylics, and fabrics
  - Both available for rent
    - Design time: $25.00 per hour
    - Cut time cost varies for different members
- Additional Spaces
  - Wood Shop
  - Sewing Studio
  - Shared workspace
  - Project space
  - Private studies

CLASSES[236] (RELEVANT CLASSES)

- Plasma Cutting
  - $60 members
  - $75 non-members
  - $10 materials fee
- Steel Mig welding
  - $190 members
  - $230 non-members
  - $20 materials fee
- Intel Edison 101: Arduino to Beyond
  - $55
- Intro to Coding: Python
  - $150
- There are likely more classes, but the website lists classes on a monthly basis.

236 Staten Island MakerSpace, "Workshops." Available at: http://www.makerspace.nyc/workshops-c1otf

MEMBERSHIP OPTIONS[237]

General Overview: Staten Island Makerspace offers a variety of membership options. The most basic option is the Basic Individual Membership, which includes a 25 percent discount on classes and discounted rates on project spaces, but no automatic access to shared workspaces or shops, for a rate as low as $72 per month. The Individual Co-Working Membership provides access to everything in the Space aside from metal and wood workshops, as well as a 25 percent discount on classes and discounts on project spaces for monthly rate of $120–$135. The Individual Pro Membership includes everything for a monthly rate of $200–$225. There are additional options for organizational memberships as well as for the purchase of daily or weekly passes. According to the website, "Memberships are available to anyone who purchases a membership and agrees to the rules of the communal working space."

- » Individual Co-Working Membership
  - » Provides access to everything aside from metal and wood workshops (**NOTE**: members purchase daily/weekly pro passes to use metal and wood workshops, and must pass Equipment use Clearance)
  - » 25 percent discount on most classes and discount rates on project spaces
  - » 12 Month Membership: $120 per month
  - » 6 Month Membership: $135 per month
- » Individual Pro Membership
  - » Provides access to everything, including metal and wood workshops
  - » 25 percent discount on classes
  - » Discounted rates on project space
  - » 12 Month Membership: $200 per month
  - » 6 Month Membership: $225 per month
- » Organizational Co-working Membership/Pro Membership
  - » Five member groups have co-working/pro membership benefits
  - » Receive three passes that are transferrable between the five members
  - » 12 Month Organizational Co-working Membership: $250 per month
  - » 6 Month Organizational Co-working Membership: $300 per month

237 Staten Island MakerSpace, "Join the SI Maker community." Available at: http://www.makerspace.nyc/membership-plans

    - 12 Month Organizational Pro Membership: $350 per month
    - 6 Month Organizational Pro Membership: $375 per month
- Basic Individual Membership
    - 25 percent discount on all classes and events
    - Discounted member rate on the project space and conference room rentals
    - No access to shared workspaces and shops, but can purchase daily and weekly co-working / pro passes
    - 12 Month Individual Basic Membership: $120
    - 6 Month Individual Basic Membership: $72
    - 12 Month Group Basic Membership: $480
    - 6 Month Group Basic Membership: $260
- Daily/Weekly Passes
    - Co-Working Day Pass
        - Basic Members: $20 per day/$80 weekly (6 days)
        - Non-Members: $50 per day/$150 weekly (6 days)
        - Access to open workspace, hand tools, worktables, sewing room, computer lab, and the shared conference room
    - Pro Day Pass
        - Basic and Co-Working Members: $40 per day/$150 weekly (6 days)
        - Non-Members: $75 per day/$220 weekly (6 days)
        - Access to open workspace, hand tools, worktables, sewing room, computer lab, the shared conference room, and metal and wood shops. Use of the metal and wood shops requires passing the Tool Safety Test prior to purchase of the day or weekly pass.

HOW TO JOIN

To join Staten Island Makerspace online, the prospective member must select a membership option (see above) and create a user account (email address, username, etc.). The interested party must then enter their address and accept the "Terms and Conditions" (see below). Finally, the prospective member must enter their billing information.

LOCATIONS (STATEN ISLAND)

Staten Island Makerspace is located in Staten Island, New York. There are no other current locations.

FUNDING/SUPPORT

State Island Makerspace has received support from multiple organizations, including Staten Island Arts, the College of Staten Island's Small Business Development Center, **New York City (NYC) Business Solutions**, and the **Staten Island Chamber of Commerce.**[238] It has also been designated as an official NYC Small Business Incubator and is sponsored by the NYC Economic Development Corporation.[239]

Other listed community partners include Digital NYC, NYC Public Library, razorfish, The Lois and Richard Nicotra Foundation, Joan Mitchell Foundation, intel, Freshkills Park, Lulzbot, Made in NYC, MRO Supply, Boss Laer, **NYC Small Business Development Center**, Inventables, **NYC Business Solutions**, Honor wines, Original Founder.NYC, Stapleton, **Microsoft**, Staten Island Arts, NYC Department of Youth & Community Development, Flagship, and Make.[240]

Like other TechShop and Fab Labs, Staten Island Makerspace receives funding through its membership fees as well. Its website includes a donation option, which notes that such donations are tax deductible.

TERMS AND CONDITIONS[241]

Prospective members must agree to Terms and Conditions that are stipulated by Cobot, the web platform used by Staten Island Makerspace. It is unclear whether these terms apply to use of the website and online payment mechanisms only, or whether the platform is used for other purposes within the Makerspace. The Terms include language on "Proper Use" of the web service as well as restrictions on "third party" use of the service. For example, the member shall not "(i) use the Service to upload, transmit or otherwise distribute any content that is unlawful, defamatory, harassing, abusive, fraudulent, obscene, contains viruses, or is otherwise objectionable as reasonably determined by upstream; (ii) upload, transmit or otherwise distribute content that infringes upon another party's intellectual property rights or other proprietary, contractual or fiduciary rights or obligations; (iii) prevent others from using the Service; or (iv) use the Service for any fraudulent or inappropriate purpose." Notably, there appears to be nothing directly related to export controls.

238 Staten Island MakerSpace, "our story." Available at: http://www.makerspace.nyc/si-makerspace-story
239 Staten Island MakerSpace, "Home." Available at: http://www.makerspace.nyc/home
240 Ibid.
241 Staten Island MakerSpace, "Individual Co-Working 12 Month Terms and Conditions." Available here:"https://simakerspace.cobot.me/plans/db25782d7dfc13711d401b50c5200745/terms"

OTHER

According to the Staten Island Makerspace website, "Memberships are available to anyone who purchases a membership and agrees to the rules of the communal working space."[242] This reflects the open and inclusive nature that defines most Makerspaces. To ensure safety in the Space, the Staten Island Makerspace requires the completion of the Tool Safety Test before members use the wood and metal shops. Notably, non-members also can participate in workshops but do not receive a discount. Non-members can participate in certain free events, rent the Project Room, and rent the Conference Room at an hourly, daily, or weekly non-member rate.[243]

ADDITIONAL THOUGHTS

While not covered in this set of profiles, one notable aspect of our research included the emergence of public libraries as venues for Makerspaces across the US According to the director of the Center for the Future of Libraries at the American Library association, "Makerspaces are part of libraries's expanded mission to be places where people can not only consume knowledge, but create new knowledge."[244]

One of the first "modern library Makerspaces" popped up around 2011 at the Fayetteville Free Library in upstate New York, and many others have emerged under the Fab Lab network.[245] At the time of writing, this space has evolved into a 2,500 ft Fab Lab, with at least nine 3D printers, a laser cutter, and a CNC mill.[246] At the Martin Luther King Jr. Memorial Library in Washington D.C., another Makerspace houses eight 3D printers, a laser scanner, and a laser cutter.[247]

Much like other Makerspaces, the D.C. library Fab Lab requires users to sign a release form and complete orientation classes.[248] The form covers the risks associated with equipment use, liability release, covenant not to sue, and third party indemnification.[249] Notably, this release form is only one page long and is not the same as the "Terms and Conditions" for the San Diego Fab Lab, described above.

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242 Staten Island MakerSpace, "Join the SI Maker community," Available at: http://www.makerspace.nyc/membership-plans

243 Staten Island MakerSpace, "Join the SI Maker community." Available at: http://www.makerspace.nyc/membership-plans

244 Deborah Fallows, "How Libraries Are Becoming Modern Makerspaces," *The Atlantic*, March 11, 2016. Available at: http://www.theatlantic.com/technology/archive/2016/03/everyone-is-a-maker/473286/

245 Ibid.

246 Faytteville Free Library, "FFL Fab Lab." Available at: http://www.fflib.org/make/fab-lab

247 Deborah Fallows, "How Libraries Are Becoming Modern Makerspaces," *The Atlantic*, March 11, 2016. Available at: http://www.theatlantic.com/technology/archive/2016/03/everyone-is-a-maker/473286/; DC Public Library, "The Fabrication Lab at DC Public Library." Available at: http://www.dclibrary.org/labs/fablab#orientation

248 DC Public Library, "The Fabrication Lab at DC Public Library." Available at: http://www.dclibrary.org/labs/fablab#orientation

249 DC Public Library, "The The Labs DC Public Library Participant Release Form." Available at: http://www.dclibrary.org/sites/default/files/ReleaseForm_0.pdf

In general, the major difference between the library Makerspaces and those covered above is the absence of membership fees—instead, eligibility is contingent upon holding a public library card. According to the D.C. public library website, "Anyone who resides, works, pays property taxes or attends school in the District of Columbia can get a card."[250] To acquire a card, the applicant must present two forms of ID, including one to prove place of residency (e.g., driver's license, rent receipt, utility bill, bank book, apartment lease, or letter on letterhead from a shelter).[251] In fact, the requirements for obtaining a library card may be more strict than buying a membership at TechShop San Diego Fab Lab, or Staten Island Makerspace, both of which appear to require only a functioning credit card to obtain membership.

250 D.C. Public Library, "Get a Library Card." Available at: http://www.dclibrary.org/getacard

251 Ibid.

DIY COMMUNITIES, MANUFACTURING, AND 3D PRINTING

(Contributor: Ruby Russell)

EXECUTIVE SUMMARY

Advancements in manufacturing technologies and digitization of the manufacturing process are rapidly increasing the capacity of small businesses and members of the DIY community to engage in small-scale production of customized items. While large-scale manufacturing processes tend to be inaccessible to individuals operating outside of the housing production lines of major companies, the so-called "democratization" of fabrication technologies, including 3D printing, is making it possible for the individual to produce a variety of items in small workshops and even at home. These goods span a range of sectors and may include anything from household items and jewelry to drones and firearms.

In the last decade, newly accessible, small-scale fabrication technologies have converged with enthusiastic DIY communities, giving rise to the rapidly advancing Maker Movement. Encompassing a variety of individuals with specialties and interests including art, engineering, and hobbyist drone production, the Maker Movement is founded upon the belief that with the right technologies, "regular people will be able to create their own goods without having to rely on the industrial model of supply and demand."[252]

The Maker Movement has an overarching commitment to collaboration and the advancement of values including learning, sharing, innovation, and transparency. It has leveraged small-scale manufacturing technologies to produce a variety products across many sectors, launching what some refer to as the "Third Industrial Revolution" (TIR). Makerspaces around the US provide widespread public access to new fabrication tools including 3D printers, and Maker Faires showcase new technologies and goods. Well-established as hotbeds for innovation, Makerspaces and Maker Faires captured the interest of major companies and even parts of the US Government.

Several technologies have been key to enabling the Maker Movement and DIY activities, but 3D printing has emerged as one of the "most high-profile 'maker' tools."[253] The Maker Movement takes advantage of the multitude of emerging companies that sell small, affordable 3D printers, which enthusiasts utilize to pursue entrepreneurial efforts through the small-scale production of customized goods. Individuals that started out at the DIY level have leveraged 3D printing technology to establish successful and sometimes large companies in a variety of fields, including civilian drone production.

252 Dan Gettinger et al., "The Drone Primer: A Compendium of the Key Issues," *Center for the Study of the Drone,* 2014, p. 21. Available at: http://dronecenter.bard.edu/files/2013/08/2014_Drone_Primer_Spreads.pdf
253 Sam Gustin, "How the 'Maker' Movement Plans to Transform the U.S. Economy," *Time*, October 1, 2012. Available at: http://business.time.com/2012/10/01/how-the-maker-movement-plans-to-transform-the-u-s-economy/

3D printing has extended the means to produce innovative goods to those operating outside of major industry, and the growing accessibility of these small-scale fabrication technologies makes it easier for non-traditional actors to produce dual-use technologies and weapons that were previously limited to the defense sector. This work demonstrates that the capacity for these technologies to undercut existing legal regulations and export controls on dual-use goods is real and problematic. Moving forward, it will be critical for the defense and export control sectors to engage DIY and Maker enthusiasts to curb DIY production of dangerous weapons and raise awareness about the relevant rules and regulations on dual-use goods.

Evidence suggests that many of the groups and companies emerging from DIY communities do not want their fabrication technologies to fall into the hands of nefarious actors. To conduct successful engagement, however, these efforts should be grounded in consideration of and respect for the Maker Movement's philosophies and aims, which shape the Movement's use of new manufacturing technologies and related entrepreneurial pursuits. This understanding is essential to leverage the Maker Movement for its innovative potential while limiting the production of dangerous weapons and dual-use components.

INTRODUCTION

Advancements in manufacturing technologies and trends toward digitization of the manufacturing process are rapidly increasing the capacity of small businesses and members of the DIY community to engage in small-scale production of customized items. While large-scale manufacturing processes tend to be inaccessible to those operating outside of major companies housing production lines, the so-called "democratization" of fabrication technologies including 3D printing is making it possible for the individual to produce a variety of items in small workshops and even at home. Spanning a range of sectors, these goods may include anything from household items and jewelry to drones and firearms.

The so-called "democratization" of new manufacturing technologies has intersected with, and further fueled, the rapidly advancing Maker Movement. Based upon principles of sharing, collaboration, and innovation, the Maker Movement is driven by the belief that with the right technologies, "regular people will be able to create their own goods without having to rely on the industrial model of supply and demand."[254] This movement is driving entrepreneurship and small-scale business innovation across a variety of sectors, in some cases receiving support from US Government agencies. At the same time, however, the growing accessibility of 3D printers and other technologies makes it easier for non-traditional actors to produce dual-use technologies and weapons that were previously limited to the defense and military sector. The US government and its export control community should enact regulations in the context of the Maker Movement's philosophy and aims, to preserve the Movement's innovative potential while reducing its risk of co-option for nefarious purposes.

254 Dan Gettinger et al., "The Drone Primer: A Compendium of the Key Issues," *Center for the Study of the Drone*, 2014, p. 21. Available at: http://dronecenter.bard.edu/files/2013/08/2014_Drone_Primer_Spreads.pdf

Moving forward, it will be important for the export control community and broader US Government to understand the philosophies and aims underlying the rapidly growing Maker Movement, and how these aims shape its use of new manufacturing technologies and related entrepreneurial pursuits. Such understanding will prove key in efforts to properly leverage the Maker Movement for its innovative potential while also limiting the production of dangerous weapons and dual-use components.

UNDERLYING PHILOSOPHIES OF MAKERS AND THE DIY COMMUNITY

To better understand the forces driving the DIY community and Maker Movement to use new manufacturing technologies, it is important to consider the underlying philosophies and ethos of these groups.

The Maker Movement itself is a well-established phenomenon encompassing a variety of people with specialties and interests including art, engineering, and hobbyist drone production. This large and diffuse community is bound by a set of loosely defined common principles with an overarching commitment to collaboration. According to Mark Hatch, CEO of TechShop, these core values include making, sharing, giving, learning, participating, supporting, and a willingness to embrace change.[255] These principles guide and shape DIY communities, where innovation is enhanced by flexibility and an openness to the input and support of others.

Beyond committing to collaboration, the DIY community and Maker Movement recognize the individual's capacity for creativity and their ability to make and produce items independently from the "industrial model of supply and demand."[256] This motivation reflects not only an inherent human desire to exercise creativity, but also a rejection of the standard means of production. It may be a byproduct of American punk counter-culture, "which rejected consumerism and corporatism and embraced manual labor and skilled crafts as a means of anti-capitalist activism."[257]

The "Maker's Bill of Rights" and other guidelines further reflect and reinforce the Movement's underlying beliefs. Issued by Make magazine in 2005, the Maker's Bill of Rights outlines "17 commandments that manufacturers should follow to make their products repairable and hackable," and includes the idea that "profiting by selling expensive special tools is wrong and not making special tools available is even worse."[258] *Make* focuses on Makers and the DIY community, and is published by Maker Media, a "global platform for connecting Makers together" and founder of the Maker Faire.[259]

DIY and Maker values demonstrate the importance of collaboration, creativity, sharing, and transparency in the production of new and innovative goods. The growing accessibility of new manufacturing

255 Mark Hatch, *The Maker Movement Manifesto: Rules for Innovation in the New World of Crafters, Hacks and Tinkerers*, New York: McGraw Hill, 2014, pp. 1-2. Available at: http://www.techshop.ws/images/0071821139 Maker Movement Manifesto Sample Chapter.pdf

256 Dan Gettinger et al., 2014, p. 21.

257 Ibid, p. 21; Mark Hatch, 2014, p. 12.

258 "The Maker's Bill of Rights," *Make (magazine)*. Available: http://makezine.com/2014/08/14/lifes-lessons-from-the-makers-bill-of-rights/

259 Maker Media "About Us." Available at: https://makermedia.com/

technologies and methods, including 3D printing, is crucial for enabling this ethos. The intersection of the DIY and Maker mantra with new, increasingly low-cost fabrication technologies has facilitated the recent rapid advancement of these communities, allowing them to pursue largely successful entrepreneurial manufacturing initiatives.

THE MAKER AND NEW MANUFACTURING TECHNOLOGIES

According to Chris Anderson, founder of the popular DIY drones website and CEO of 3D Robotics (3DR), a "Maker" refers to "a new category of builders who are using open-source methods and the latest technology to bring manufacturing out of its traditional factory context, and into the realm of the personal desktop computer." These methods rely upon increasingly accessible "small scale fabrication technologies" such as 3D printers, laser cutters, and garage-scale CNC mills.[260]

Critically, this democratization of small-scale manufacturing technology has provided DIY communities, Makers, hackers and hobbyists with "modes of production previously only available to large organizations."[261] According to experts, this "democratized technological practice . . . unifies playfulness, utility, and expressiveness, relying on some industrial infrastructures while creating demand for new types of tools and literacies."[262] The availability of new, small-scale manufacturing technologies has expanded the potential for DIY and further fueled the Maker mantra, culminating in what many have branded the "Third Industrial Revolution."[263]

According to one report by the Atlantic Council, the TIR "is changing the way things are made, [changing] where and when they are produced . . . and altering the relationship of people to production."[264] Notably, it is "moving the world from mass production of standardized items to bespoke products to meet the requirements of individual needs."[265] Key to shaping this revolution is the Maker and DIY ethos, which reinforces the potential for the individual to produce and disseminate new, customized items and solutions on a small-scale.

Makerspaces anchoring the nexus between new manufacturing technologies and DIY communities. They are designed to be incubators for collaboration, providing public access to a variety of new fabrication tools and a host of instructive courses on how to operate them. These spaces are notable for

260 Joshua G. Tanenbaum et. al., "Democratizing Technology: Pleasure, Utility and Expressiveness in DIY and Maker Practice," *CHI 2013: Changing Perspectives*, Pairs: April 27–May 2, 2013, p. 2605. Available at: https://pdfs.semanticscholar.org/1553/79ab94e87ee9cf7648eb53dfc8749887eee7.pdf

261 Ibid, p. 2605.

262 Ibid, p. 2603.

263 Paul Markillie, "A Third Industrial Revolution," *The Economist,* April 21, 2012. Available at: http://www.economist.com/node/21552901.; Atlantic Council, "Envisioning 2030: US Strategy for the Coming Technology Revolution." *Strategic Foresight Initiative, Atlantic Council*, December 2013.

264 Atlantic Council, December 2013, p. 15.

265 Ibid, p. 5.

"radically democratizing access to the tools of innovation" and carving out local environments that enable DIY experimentation and innovation.[266]

The popular "TechShop," for example, describes itself as "an open-access, DIY workshop and fabrication studio . . . a community-based space where entrepreneurs, artists, makers, teachers and students come together to learn and work together."[267] TechShop provides nationwide access "to over $1 million worth of advanced machines and tools," including design software and 3D printers.[268] Techshop offers classes in Computer Numerical Design (including instruction in CAD software), as well as classes in rapid prototyping that cover 3D printing and 3D scanning.[269]

A similar initiative includes MIT's Fab Lab, originally launched by the MIT CBA to establish a "technical prototyping platform for innovation and invention, providing stimulus for local entrepreneurship . . . a place to play, to create, to learn, to mentor, to invent."[270] Fab Labs now exist in at least thirty countries and establish a global "knowledge sharing network" that provides access to digital fabrication technologies to facilitate individual entrepreneurship.[271] Notably, the Fab Foundation offers guidance, including about the layout, hardware, software, and funding, for anyone interested in establishing a Fab Lab.[272]

The Maker Faire offers another popular forum for the intersection of DIY communities and new manufacturing technologies. Launched in the Bay Area in 2006 by Maker Media (the same organization that published *Make*), Maker Faire brings together "tech enthusiasts, crafters, educators, tinkerers, hobbyists, engineers, science clubs, authors, artists, students, and commercial exhibitors . . . to show what they have made and to share what they have learned."[273] Maker Faires have since spread around the world, offering venues for makers to showcase "new forms and new technologies."[274]

Well-established as hotbeds for innovation, Makerspaces and Maker Faires have caught the interest of major companies and even parts of the US Government. For example, Maker Faires have received sponsorship from large companies including Microsoft, GE, Google, and Intel.[275] The DOD's DARPA has begun to invest in the Maker Movement as well, providing $3.5 million to TechShop to

266 Mark Hatch, 2014.
267 TechShop, "Welcome." Available at: http://www.techshop.ws/index.html
268 TechShop, "Core Tools & Equipment." Available at: http://www.techshop.ws/tools_and_equipment.html
269 TechShop, "Take Classes." Available at: http://www.techshop.ws/take_classes.html?storeId=5
270 Fab Foundation, "What is a Fab Lab?" Available at: http://fabfoundation.org/index.php/what-is-a-fab-lab/index.html
271 Ibid.
272 Fab Foundation, "Setting up a Fab Lab." Available at: http://fabfoundation.org/index.php/setting-up-a-fab-lab/index.html
273 Maker Faire "A Bit of History." Available at: http://makerfaire.com/makerfairehistory/
274 Ibid.
275 Joshua G. Tanenbaum et. al., April 27–May 2, 2013, p. 2606.

establish new Makerspaces, and awarding $10 million in grants to "promote the maker movement among high school students.[276]

Taken together, DIY philosophies and new small scale fabrication technologies are driving a movement that has not only "[created] a new breed of artisans and inventors," but is also fueling production of cutting edge, innovate goods and enabling entrepreneurship at unprecedented levels. [277]

THE ROLE OF 3D PRINTING

Several technologies have been key to enabling the Maker Movement and DIY activities, and 3D printing has emerged as one of the "most high-profile 'maker' tools."[278] In its most basic form, the 3D printing process involves the transmission of digitally generated designs (known as CAD) to a 3D printer, which then deposits layer upon layer of varying types of filament to produce the design physically.[279]

In addition to minimizing time and cost of production, this single-tool manufacturing process allows for the creation of customized parts and complex geometries not afforded by conventional manufacturing. Furthermore, and perhaps most importantly for DIY, 3D printing enables the "design and efficient manufacture of personalized products," representing a shift from "mass production to mass customization."[280]

Recognizing the utility and easy-to-use nature of this advanced fabrication technology, many companies have emerged in recent years to sell small, affordable 3D printers. Companies including Makerbot sell 3D printers for a few thousand dollars, while other printers are available for only a few hundred dollars.[281] Notably, 3D printers have surged in popularity because of "the DIY movement, with tens of thousands of early adopters buying personal 3D printers for experimentation or starting their own mini-manufacturing enterprises."[282]

The Maker Movement and DIY enthusiasts utilize 3D printing increasingly for entrepreneurial efforts. For example, AirDroid's Pocket Drone is a "miniature drone made with 3-D printed parts and open-source software."[283] This project emerged from collaboration among members of the Drone User Group Network, a global network of civilian drone users and organizations seeking to elevate

276 Evgeny Morozov, "MAKING IT: Pick up a spot welder and join the revolution," The New Yorker, January 13, 2014. Available at: http://www.newyorker.com/magazine/2014/01/13/making-it-2/
277 Dan Gettinger et al., 2014, p. 21.
278 Sam Gustin, "How the 'Maker' Movement Plans to Transform the U.S. Economy," *Time*, October 1, 2012. Available at: http://business.time.com/2012/10/01/how-the-maker-movement-plans-to-transform-the-u-s-economy/
279 Fran Grieser, "3D Printer Buyers Guide," All3DP, October 18, 2015. Available at: https://all3dp.com/fdm-vs-sla/
280 Atlantic Council, December 2013, p. 16-22.
281 3ders.org, "Price Compare-3D printers." Available at: http://www.3ders.org/pricecompare/3dprinters/
282 Atlantic Council, December 2013, p. 16.
283 Dan Gettinger et al., 2014, p. 21.

the benefits of drones.[284] With funding from Kickstarter, AirDroid produced miniature drones for sale at less than $500.[285] Though the group has ceased operations due to financial issues, experts point to the Pocket Drone as "a poster child for the DIY drone business community, demonstrating the commercial power of DIY" and 3D printing.[286]

3DR is another example of a successful company born out of a DIY community and heavily dependent on 3D printing. Founded by former editor and chief of *Wired* magazine Chris Anderson, 3DR is a widely popular commercial drone producer. Its roots, however, can be traced to DIYdrones.com: an online communal platform, also founded by Mr. Anderson, that is dedicated to sharing knowledge—mostly involving 3D printing—that is essential for DIY drone production.[287] Through his own website, Chris Anderson met his future 3DR partner and co-founder.[288]

Today, this largely successful company continues to push out new products, including the world's first smart drone and an open aerial analytics platform.[289] Furthermore, in a nod to its DIY foundations, 3DR recently teamed up with Myminifactory, a "social platform for 3D printable objects," to release a free 3D printable version of its popular IRIS+ drone. In addition to releasing these designs, 3DR has encouraged the DIY drone community to "add to and embellish components of the IRIS+ in order to modify and customize the drone to suit their individual needs."[290] The 3DR example demonstrates how companies with roots in the DIY sector continually tap into and leverage the creative potential of the very community from which they emerged. This iterative process not only perpetuates the DIY ethos, but also drives business innovation and entrepreneurship by revealing new ways to "modify or in some cases completely alter and improve 3D designs."[291]

Finally, Shapeways, a major online platform for sharing, buying, and designing 3D printable prototypes and projects, also was founded in DIY. Originally launched in 2007 by members of the start-up community, this "3D printing marketplace" enables the Maker Movement and DIY efforts by designing and producing of a variety of 3D printable items, from jewelry to drones.[292] Through the Shapeways marketplace, users can acquire designs for 3D printable drone parts, customize and purchase 3D printed drone parts, and, for a fee, upload original designs for printing.[293] Shapeways provides yet another example of a company with roots in the DIY sector that enables and leverages its community to further creativity and entrepreneurship.

284 Drone User Network Group. Available at: https://dugn.org/

285 Dan Gettinger et al., 2014, p. 21.

286 Ibid, p. 21; Chris Anderson, "AirDroids (PocketCopter) ceasing operaions," *DIYDrones.com,* May 21, 2015. Available at: http://diydrones.com/profiles/blogs/airdroids-pocketcopter-ceasing-operations

287 DIYdrones.com, Groups: 3D Printing Drone Parts. Available at: http://diydrones.com/group/3d-printing-drone-parts

288 3DR.com "Overview." Available at: https://3dr.com/about/

289 Ibid.

290 3Dprint.com, "3DRobotics Releases 3D Printable IRIS+ Drone Free on MyMiniFactory." Available at: https://3dprint.com/124508/3drobotics-iris-drone-mmf/

291 Ibid

292 Shapeways, "Tech: Drone Parts." Available at: http://www.shapeways.com/marketplace/tech/drone-parts/; Pete, "Shapeways raises $5M and opens HQ in New York." *The Shapeways Blog*, September 23, 2010. Available at: http://www.shapeways.com/blog/archives/595-Shapeways-raises-5M-and-opens-HQ-in-New-York.html

293 Shapeways, "How Shapeways works. Available at: http://www.shapeways.com/how-shapeways-works/

There are numerous examples of entrepreneurs using 3D printing technologies to produce valuable innovative goods, and these new small-scale fabrication technologies present problematic opportunities for individuals to produce weapons and dual-use items. One prime example is rifle production, for which 3D printing offers "a potentially easy way around restrictions and registrations."[294] One individual who 3D prints gun parts points out that "there's really no one controlling what you do in your own home."[295] These concerns are not limited to rifle production, and expose the potential for 3D printing to undermine strategic trade controls that apply to a host of military and dual-use items.

In some cases, individuals use 3D printing to demonstrate purposefully that the technology has the capacity to undercut existing legal regulations and restrictions. In the rifle sector, Defense Distributed is a "post-political" project designed to "create a political and legal vehicle for demonstrating and promoting the subversive potential of publicly-available 3D Printing technologies."[296] Defense Distributed has produced and shared 3D print designs for AR-15 stripped lower receivers, as well as for the 3D printable handgun known as the "liberator pistol."[297] In May 2013, only days after Defense Distributed posted 3D print designs for the liberator pistol online, the US Department of State demanded the files be taken down and launched an investigation into whether the files violated ITAR requirements.[298]

These examples of 3D printing in the rifle sector illustrate the broader potential for small-scale fabrication technologies to undermine established rules and regulations that restrict the production and transfer of dangerous weapons and dual-use materials. The public and government is focused primarily on 3D printed rifles for now, but files for the production of other questionable items, including drone components, exist online already. One forum on DIY drones, for example, discusses "design, 3D printing, geodesic airframe structures…for any payload over long distances," noting that although "US laws forbid our design to fly it its airspace, other nations are more lenient."[299]

To prevent subversions of existing strategic trade controls, it is essential to curb DIY production of controlled goods. Given the increasingly widespread use of small-scale fabrication technologies like 3D printing in the civilian sector, it will be key to engage and raise nonproliferation awareness within the DIY and Maker communities.

294 Michael S. Rosenwald, "Weapons made with 3-D printers could test gun-control efforts" *Washington Post*, February 18, 2013. Available at: https://www.washingtonpost.com/local/weapons-made-with-3-d-printers-could-test-gun-control-efforts/2013/02/18/9ad8b45e-779b-11e2-95e4-6148e45d7adb_story.html

295 Ibid.

296 Ibid; Defense Distributed, "History. Available at: https://defdist.org/dd-history/

297 Defense Distributed, "History."

298 Ian Steadman, "US government seizes 3D-printed gun files, but still shared elsewhere," *Wired*, May 10, 2013. Available at: http://www.wired.co.uk/article/defcad-gun-design-taken-down

299 DIYdrones.com, "Strategic Supply Drones." Available at: http://diydrones.com/group/strategic-supply-drones

ENGAGING DIY AND MAKER COMMUNITIES

The intersection of the DIY and Maker mantra with increasingly low-cost fabrication technologies has enabled individuals to produce and customize goods on a small scale, thereby fueling innovation and generating opportunities for entrepreneurship that were stifled previously by limited access to large-scale production technologies. At the same time, however, the growing accessibility of technologies including 3D printers makes it increasingly easy for non-traditional actors to produce dual-use goods and weapons that have been restricted traditionally to major defense companies.

Moving forward, it will be critical that the defense and export control sectors engage DIY and Maker enthusiasts to curb DIY production of dangerous weapons and raise awareness about relevant rules and regulations on dual-use goods. Importantly, engagement must be conducted in a way that does not alienate this burgeoning group, but rather embraces the Maker Movement for its innovative potential.

Members and promoters of the DIY and Maker community already are working to prevent the use of small-scale fabrication technologies to produce controlled or restricted products. For example, following the Sandy Hook shootings in December 2012, 3D printer producer Makerbot removed gun designs posted on its popular 3D printing website "Thingiverse."[300] Similarly, 3D manufacturing company Stratasys rescinded its 3D printer lease to Defense Distributed, citing concerns that the 3D print designs for the liberator pistol were illegal under the Undetectable Firearms Act of 1988.[301]

Even still, these new companies face a moral dilemma regarding restrictions on the very technologies they view as critical to driving their movement and enabling creativity, learning, and innovation. The Maker's Bill of Rights states that there is nothing worse than "not making special tools available." Abe N. Reichental, CEO of 3DSystems, illustrates these challenges: "We don't want to prevent printing anything that is legal and proper. But we want to be responsible. We want to do good. We want to be a force that helps shape the goodness of this technology and its use."[302] Recognizing these good intentions—which tend to reflect the broader sentiment of DIY and Maker communities—will be essential to engaging these groups.

As discussed in the first section of this report, Makers operate according to a set of core principles that includes a commitment to collaboration and transparency as well as recognition and promotion of the individual's capacity for creativity. Importantly, these principles, along with the rise of Maker culture, "[are] creating new values around technological practices," which hinge upon an "emphasis on education and empowerment through DIY."[303] Given this developing reality, the US Government must strike a balance between uplifting these new values and curbing the unregulated production of dual-use goods.

300 Michael S. Rosenwald, February 18, 2013.
301 Ibid.
302 Ibid.
303 Joshua G. Tanenbaum et. al., April 27–May 2, 2013, p. 2605.

US Government agencies including DARPA have already recognized the Maker Movement for its innovative potential, awarding grants and funds to various incubators including TechShop.[304] As experts point out, however, defense agencies should be aware of the challenges associated with "channeling . . . defense spending into a movement whose parties often challenge military and industrial structures."[305] In this regard, it will be important for the government to avoid the appearance of "coopting" the DIY and Maker Movement for military purposes. Engagement and funding must center upon respect and commitment to the Maker values of creativity, collaboration, and, transparency.

Makerbot and Stratasys, among other companies, have taken steps to prevent the production of illegal goods, illustrating an existing will within the DIY industry to ensure fabrication technologies are not used for nefarious purposes. Problematically, however, the community lacks widespread knowledge about controls for dual-use goods, especially those related to the nuclear and broader defense sectors. In this regard, it is paramount that the government actively engages and educates the DIY community on export controls, taking advantage of the Maker's commitment to learning.

By working within venues, such as Makerspaces and Maker Faires, that are already committed to advancing DIY education, government officials could raise awareness about threats and the importance of export controls associated with dual-use technologies. If the government were to provide examples of nefarious uses, for example to produce components for centrifuges or lethal weapons, it might generate a sense of responsibility within these communities. Rather than impose regulations upon DIY efforts directly, the government should make DIY community members feel empowered to regulate themselves and ensure that key Maker tools are not employed in the pursuit of activities contrary to their own movement.

Finally, as illustrated by Abe N. Reichental's remarks, DIY and Maker enthusiasts are committed to leveraging small-scale fabrication technologies to do good. Engagement should therefore center on the presumption (within reason) that DIY and Maker communities are not pursuing nefarious causes, but rather advancing innovation. Such an approach demonstrates respect for these communities as valuable and critical actors in establishing a more secure and peaceful world.

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304 Evgeny Morozov, January 13, 2014.
305 Ibid.

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SCIENCE, ADVANCED INDUSTRIAL TECHNOLOGY, AND STRATEGIC WEAPONS PROGRAMS IN NORTH KOREA

(Contributor: Joshua H. Pollack)

INTRODUCTION

The Democratic People's Republic of Korea (DPRK), or North Korea, is technologically advanced to an extent that is rarely appreciated. This point may elude many observers because of the unusually lopsided nature of the country's investments and achievements. Three generations of leaders have subordinated the needs of the North Korean public to the needs of the military and the comforts of the "royal court," (i.e., the ruling Kim family and its close associates).[306] Most North Koreans are impoverished, some are underfed, and most reside in cities that are supplied with electricity irregularly. But the country's scientific and industrial establishments are not so deprived of resources that they cannot play their intended roles—especially those that support defense requirements.

The country's industrialization began under Japanese rule prior to the Second World War. In its continued pursuit of post-independence heavy industry, the new Communist regime followed the models offered by Stalin and Mao. American air power had wreaked massive destruction during the Korean War, but the Soviet Union and its allies generously rebuilt North Korea's steel plants and other infrastructure after the armistice took hold.[307]

Despite the support of China and the Union of Soviet Socialist Republics (USSR) during the war, and the signing of defense pacts with both countries after the war, a series of developments convinced North Korean leaders that they were fundamentally on their own in the world and could not depend on others to guarantee that their interests were met. These developments included Khrushchev's denunciation of Stalin's personality cult; a joint Soviet-Chinese intervention in North Korean politics in the late 1950s; the USSR's withdrawal from Cuba in 1962; China's shift toward radical policies and aggression toward its neighbors in the late 1960s; China's turn to "reform and opening" of the economy after the death of Mao; Soviet and Chinese courtship of an increasingly wealthy and attractive South Korea in the late 1980s; and finally, the collapse of the Warsaw Pact and then the USSR itself.

North Korea's leaders responded to their growing sense of isolation through an evolving series of ideological positions, all designed to underscore that North Korea will set its own course. These ideas are evident not only as slogans but also in the decision to acquire strategic technologies, including nuclear and space/missile capabilities, that provide the country with independent national defense and the means to achieve long-deferred prosperity. Investments in science and technology

306 Kim Kwang Jin, "The Defector's Tale: Inside North Korea's Secret Economy," *World Affairs Journal*, September/October 2011, http://www.worldaffairsjournal.org/article/defector%E2%80%99s-tale-inside-north-korea%E2%80%99s-secret-economy.

307 Charles K. Armstrong, *Tyranny of the Weak: North Korea and the World*, 1950-1992 (Ithaca and London: Cornell University Press, 2013), pp. 52-79.

(S&T)—education and training, basic research, applied research, and the modernization of industry—have taken precedence over society's most basic needs, such as food and medicine.

Most prominently, North Korea in has introduced CNC machine tools in recent decades. Different types of precision, programmable lathes, grinders, and other tools are both imported and manufactured inside North Korea; domestic varieties are showcased frequently in the media's photographs and videos of leadership tours of industrial facilities, including underground factories that appear to be military in nature. These tools are offered for export as well.

Imported industrial robots and automated warehouse technology has supplemented CNC machines in the last few years. Together, these technologies have enabled the automation of production facilities, the reduction of demand for skilled machinists—evidently a bottleneck for North Korean industry—and the consistent precision manufacturing of metal components. They should enable North Korea's defense industries to improve the quality and quantity of production.

AM appears to be in its infancy in North Korea. It has begun to attract the interest of researchers and has been featured in the official media. But it has yet to attract the public spotlight of top leadership attention, and 3D printers do not seem to have appeared in a heavy-industrial setting, so far. It remains to be seen whether AM will progress beyond the exploratory, but wider adoption would be consistent with the North Korean ambition of achieving the "cutting edge" of technology.

"IDEOLOGY, THE GUN BARREL, AND SCIENCE AND TECHNOLOGY"

The impulses that have propelled North Korea's leaders to adopt and promote advanced industrial technologies have been described in prominent and authoritative policy declarations over several decades.

In December 1962, close on the heels of the Cuban Missile Crisis, Kim Il Sung, the founder and Supreme Leader of the DPRK, promulgated the "Four-Point Military Guidelines": arming the entire population, making the entire country an "impregnable fortress," creating a properly indoctrinated "cadre-based military," and modernizing the entire military. These "guidelines" reflected a newfound conviction that North Korea could not rely on the Soviet Union if confronted by the US. Kim Il Sung also began systematically promulgating "*Juche sasang*," or "the *Juche* idea," often translated as "self-reliance" but better understood as "self-determination." Articulated as early as the mid-1960s, *Juche* involves three major principles: *Jaju*, or political independence; *Jarip*, or economic self-reliance; and Jawi, or self-reliance in national defense.[308] During this period, North Korea began seeking active assistance from other Communist states to acquire nuclear and missile technology. This strategy began to bear fruit in the 1980s, when North Korea completed its first indigenously designed and manufactured nuclear reactor—a small, gas-cooled, graphite-moderated model that appears still to be the source of most, if not all, North Korean plutonium—and began the serial production and export of theater ballistic missiles.

308 Dae-Sook Suh, *Kim Il Sung: The North Korean Leader* (New York: Columbia University Press, 1988), pp. 301-313.

Kim Jong Il, the son and successor of Kim Il Sung, assumed power in 1994 after a long and gradual transition. His ascendancy followed the loss of Soviet aid, the collapse of the USSR, and his father's death. Famine was taking hold inside North Korea, but Kim Jong Il's public writings from this period focused instead on the threat of political subversion from outside and from within. He observed repeatedly that "renegades from socialism" had introduced capitalist ideas in their own countries—an allusion to the Gorbachev-era "reform" and "openness" initiatives, which echoed Deng Xiaoping's more successful policies in China—leading to the collapse of the Communist bloc. He warned against similar "renegades" at home.[309]

Seemingly informed by the Chinese Communist Party's reliance on army units and subsequent near-death experience in June 1989, Kim Jong Il developed a new master concept for national policy that was nested within the *Juche* idea and called "*Songun chongchi*," or "military-first politics." The military enjoyed a disproportionate share of national resources already; in practice, the new "politics" meant elevating the National Defense Commission (NDC), headed by Kim Jong Il and consisting of senior military officers, over all affairs of state at the expense of the Cabinet. It also meant prioritizing national defense, especially through the development of new strategic weapons and the devotion of greater attention to S&T. Kim Jong Il discarded any pretense of seeking near-term economic recovery during the so-called "Arduous March," preaching "belt-tightening" to the starving public. The government stopped producing traditional long-term plans for economic development even as it instituted long-term plans for S&T development.

The formal inauguration of "military-first" politics took place near the end of the famine years with a highly publicized technological achievement. In late August 1998, North Korea used a three-stage rocket booster to attempt its first space-launch attempt. The launch failed in the eyes of the world, but succeeded as far as the DPRK was concerned: the stage-separation mechanisms had worked as designed. A few days later, the Supreme People's Assembly (SPA) amended the constitution to make the NDC, headed by Kim Jong Il, the state's ruling body. The media organs of the Korean Workers' Party (KWP) promoted the "military-first" concept and promised the coming of a "strong and prosperous state." On New Year's Day 1999, the joint editorial of three official Party newspapers—Kim Jong Il's preferred method of delivering his annual policy statement, akin to a State of the Union Address—proclaimed the adoption of military-first politics:

> Our socialist powerful state is an invincible country where the *Juche*-oriented military-first politics are brilliantly realized. On the revolutionary gun barrel are the fatherland's strength and reconstruction, and socialist victory. The People's Army is the first pillar of the socialist and military powerful state….[310]

The 1999 editorial granted a new and elevated status for S&T, calling it "the powerful driving force for the construction of a powerful state" and citing the success of the August 1998 space launch.[311]

309 The writings of Kim Jong Il can be found in English translation at http://www.korea-dpr.com/e_library.html.
310 *Rodong Sinmun* (Pyongyang), 1 January 1999.
311 Ibid.

The next year's joint editorial went further still, proclaiming that "[i]deology, the gun barrel, and science and technology are the three pillars in the construction of a powerful state."[312] It added:

> We should adhere to the idea of placing importance on science. Our party maintains a firm position to build socialism with the help of science. Socialism will succeed when our highly revolutionary character is backed by science and technology. We should thoroughly establish the ethos of placing importance on science in the entire society. Everyone should have deep interest in the development of science and technology, and should praise scientists and technicians in society.
>
> All the scientists and technicians should possess a far-reaching ambition, the spirit of earnest quest, and clean conscience to actively contribute to our fatherland's development of science and technology. We should develop the *Juche*-based science and technology to the world level in the shortest period, and solve the problems of science and technology, which is imperative to building a powerful state.
>
> We should develop forces of science and technology with prospects. We should adopt new achievements of science research and technological innovations to production in a timely manner and improve the administration of science and technology.[313]

Subsequent joint editorials continued to extol the importance of advancing science and updating industrial plants with the latest production technology. Nor was this simply rhetoric: Kim Jong Il toured industrial establishments frequently, praising those with modernized equipment and giving orders for further investments. Some of the outcomes were visible to the entire world. In 2006, North Korea tested its first nuclear device and began a campaign of space launches using a three-stage booster with a four-engine cluster for its first stage. In April 2009, the clustered stage worked on the second try; in December 2012, the entire booster worked successfully on the fourth try. In November 2010, North Korea exhibited a complete gas-centrifuge enrichment facility—which it described as wholly indigenous—as well as the construction site for the country's first domestically produced light-water reactor. These developments all were founded upon decades of S&T investments.

Kim Jong Il died in December 2011 and was replaced by his third son, Kim Jong Un, who continued to order space launches and nuclear tests, and accelerated missile testing. In December 2015, a month before North Korea conducted what it described as its first H-bomb test, Kim Jong Un visited the Pyongchon Revolutionary Site, a museum on the site of North Korea's first arms factory, allegedly selected by Kim Il Sung in 1945. Kim Jong Un proclaimed that the sound of a submachine gun once personally test-fired by Kim Il Sung at Pyongchon "turned the DPRK into a powerful nuclear weapons state ready to detonate self-reliant [emphasis added] A-bomb and H-bomb to reliably defend its sovereignty and the dignity of the nation."[314] He continued:

312 *Rodong Sinmun* (Pyongyang), 1 January 2000.

313 Ibid.

314 *Rodong Sinmun* (Pyongyang), 10 December 2015.

> If we struggle in the same spirit with which the workers produced submachine guns by their own efforts just after the liberation of the country when everything was in need, we can further build up our country into a powerful one no enemy dares provoke, he said, stressing the need to steadily put big efforts on the development of the country's munitions industry associated with devoted efforts of Kim Il Sung and Kim Jong Il.[315]

In May 2016, North Korea held the Seventh Congress of the KWP, the first meeting since 1980. Kim Jong Un's speech praised the labors of the "national defense science sector" and enshrined a new ideological "principle of giving priority to self-development," based on S&T:

> Our heroic working class of Kim Il Sung and Kim Jong Il, scientists and technicians waged an unyielding struggle on the principle of giving priority to self-development to develop and manufacture new machines and equipment based on local efforts and technology, thereby presenting them as gifts to the Congress of the motherly Party.[316]

The Party Congress also sharply curtailed the standing of military men in the senior party ranks. The next month, the SPA amended the DPRK constitution, abolishing the NDC and replacing it with a mostly civilian State Affairs Commission responsible for both civil and military affairs, headed by Kim Jong Un. The era of "military-first politics" came to a close, and the stature of the scientific establishment rose higher than ever.

THE DEVELOPMENT OF NORTH KOREA'S S&T SYSTEM

North Korea's military-technological successes did not come quickly or independently. In the 1980s, North Korea fell behind South Korea economically and technologically, so North Korea's leaders initiated reform to address their frustration with the pace of their country's progress. In August 1985, Kim Jong Il spoke frankly to senior members of the Party Central Committee, admitting the country's shortcomings even at the level of industrial training:

> We fail to register all the success we could in socialist economic construction because science and technology are developing slowly. Scientific and technological levels in this country are so low that the modern plant we have imported from other countries is not being operated at full capacity. However modern the equipment the people have is, they cannot use it effectively if their technical levels are low.[317]

Kim Jong Il saw shortcomings in "raw materials, fuel, and energy" as the greatest weaknesses of the national economy; modernization was needed to overcome them. He advocated updated approaches to coal mining and the construction of new hydroelectric, thermal (coal-fired), and nuclear power

315 Ibid.

316 Kim Jong Un's Speeches at the 7th Workers' Party Congress, 6-9 May 2016, as reproduced by the National Committee on North Korea, http://www.ncnk.org/resources/news-items/kim-jong-uns-speeches-and-public-statements-1/KJU_Speeches_7th_Congress.pdf.

317 Kim Jong Il, "On the Further Development of Science and Technology," 3 August 1985.

plants. New, automated machinery would be needed, as would substitute or synthetic materials to replace expensive imported resources.[318]

Kim Jong Il envisioned a system in which one machine tool would make another, electronics and robots would be produced domestically, and research in the natural sciences would advance rapidly. Specifically, he exempted scientists and technicians from forced manual labor with the rest of the urban population, provided them with adequate facilities and resources, and directed young people into the natural sciences. He also berated officials for not taking sufficient advantage of foreign technology, alluding indirectly to South Korea's successful absorbtion of foreign-origin S&T. Part of the problem, he asserted, was a rigid interpretation of the *Juche* idea. "The introduction of advanced science and technology from abroad," he asserted, "does not go against the requirement of developing the country's science and technology in a *Juche*-orientated manner."[319]

Kim Jong Il wished to import new production technology, invite foreign experts to provide lectures and training, and build a domestic scientific information network. He wished to develop annual and long-term S&T plans on the basis of assessments that evaluated the promise of emerging technologies to meet near-term North Korean needs. He outlined the need for new scientific laws and regulations, language training for scientists, rapid and broad dissemination of information, opportunities for scientists to study abroad, and exposure of scientists to major North Korean "factories and enterprises" to familiarize them with "the actual situation" in the country. He required the overhaul of systems for re-training scientists, awarding patents, and granting degrees and recognition to high achievers.[320]

Much of Kim Jong Il's vision was codified in law in 1988. The new DPRK Law on Science and Technology established S&T as a national priority and created formal S&T development plans, supported by a system of administrative guidance. Scientific administrators were to review foreign S&T developments methodically, identify the most promising from North Korea's perspective, and oversee their introduction into the country. Individual scientists were to benefit from the protections of the national patent system and retain a share of "profits" from both patents and new technologies in production settings. Scientists were to mobilize to production facilities in "shock brigades" to solve problems and focus their research on meeting "work needs." Publications, presentations, lectures, and public exhibitions were all to be promoted to diffuse knowledge of scientific developments broadly throughout the country.[321]

Since the early 1960s, the Central Scientific and Technological Information Agency (CSTIA), originally part of the DPRK Academy of Sciences, has been responsible for acquiring foreign technical information and disseminating it within North Korea.[322] CSTIA itself publishes most of North Korea's scientific journals, some of which are dedicated to monitoring foreign developments, and others to publishing works by North Korean researchers. The latter set of journals has a pronounced

318 Ibid.
319 Ibid.
320 Ibid.
321 As reproduced in *Tongil News* (Seoul), 5 April 2004.
322 Now called the State Academy of Sciences. CSTIA was not listed in a seemingly exhaustive brochure from 2011 describing its structure. "State Academy of Sciences, DPR Korea: Branch Academies and Affiliated Institutions," 2011, http://usdprkscience.org/wp-content/uploads/2013/04/Branch-academies-and-affiliated-institutions.pdf.

tendency to cite Japanese, Chinese, and Russian sources in particular.[323] This has given researchers broader access to scientific information through the Internet, foreign commercial scientific databases, and North Korea's growing body of scientific literature worthy of citation.

The North Korean media and patent award announcements often testified to the realization of Kim Jong Il's vision for S&T. Kim Jong Il visibly directed resources toward this agenda in his later years, ordering the construction of new housing complexes and other amenities for scientists and their families in and around Pyongyang. He also ordered the creation of elaborate new "E-Libraries" at the country's most prominent universities, Kim Il Sung University and Kim Chaek University of Technology, both in central Pyongyang. For almost two decades, the Three Revolutions Museum in Pyongyang has hosted spring and fall trade fairs, which showcase both foreign and domestic manufactures. The official media routinely announces upcoming lectures by scientists at the Great People's Study House, the ornate national library of the DPRK, which looms over Pyongyang's symbolic heart, Kim Il Sung Square.

Kim Jong Il's 2008 stroke accelerated plans for succession. In 2009. North Korea cited its technological successes, attempted a space launch, and tested a nuclear device to secure the regime's legitimacy. Three developments received special prominence in slogans and commemorative stamps: CNC machine tools, space technology, and the production of "*Juche* steel." The latter is described as a high-quality steel made with locally mined anthracite coal, and may be a code name for maraging steel, a specialized alloy employed in North Korea's current generation of gas centrifuges.

The promotion of science has accelerated under Kim Jong Un. When there is a successful space launch, nuclear test, or test of a submarine-launched ballistic missile, the scientists and technicians deemed responsible have been feted in the capital for days. A new national library and exhibition hall opened to commemorate science specifically. Shaped like an atom, the S&T Complex stands on Ssuk Island in the Taedong River in Pyongyang, its central atrium dominated by a full-scale reproduction of the three-stage space launcher employed successfully in December 2012.

In November 2013, Kim Jong Un addressed a "national meeting of scientists and technicians," apparently the first of its kind. Judging by the formal group photographs published in the official media, roughly 4,800 people were in attendance. His remarks portrayed the indigenization of foreign-origin S&T as the key to overcoming sanctions:

> Suppressing and keeping other countries under their control with science and technology is the modern imperialists' arrogant viewpoint of thinking and of dominationist strategy.… The imperialists are strengthening political pressure, military threat and blackmail, and a psychological smear campaign while enforcing a scientific and technological blockade and sanction policy at the same time in a bid to isolate, suffocate, and crush our Republic.

323 Stephen C. Mercado, "Hermit Surfers of P'yongyang: North Korea and the Internet," *Studies in Intelligence* (2004) vol. 48, no. 1, https://www.cia.gov/library/center-for-the-study-of-intelligence/csi-publications/csi-studies/studies/vol48no1/article04.html.

> …The way to shatter the imperialists' monopoly and blockade of science and technology and to accomplish the independent development of the country and the nation lies in putting great strength into developing our own science and technology[324]

It can be difficult to assess the precise extent to which North Korea has actually succeeded in indigenizing domestic production of particular items, although careful study of the patent literature, scientific publications, and media photographs can be quite revealing.[325] In one striking instance, however, the overwhelmingly domestic nature of manufacturing can be seen clearly. After the South Korean Navy recovered most of the first stage airframe, including the engines, of the space launcher used in December 2012, experts identified all of the foreign-made components and their origins. Mostly, these were unremarkable, commercial, off-the-shelf electronics. Only a single imported item—Soviet-made radial ball bearings from the clustered engine's turbopumps—met any of the criteria for international export-control lists.[326] It was largely on the strength of indigenous S&T that North Korea reached low-earth orbit.

THE INTRODUCTION OF ADVANCED INDUSTRIAL TECHNOLOGIES

In the background of dramatic achievements in the space, missile, and nuclear fields, there are more prosaic forms of "high-tech" in the form of advanced industrial technologies. These production technologies came from a variety of imported and indigenous origins. Indigenous systems often involve imported electronic components, since the North Korean electronics industry appears to have progressed very slowly so far.

North Korea's heavy industry has been a staple of its propaganda at least since the late 1950s "Chollima movement," named in honor of the Chollima Iron and Steel Complex in Kangson. In the 1980s, the DPRK media often boasted of the mammoth 10,000-ton press at the Ryongsong Machine Complex in the industrial town of Hamhung. New achievements in metallurgy are heralded regularly in the press. But in recent years, the introduction of precision manufacturing equipment has claimed a prominent place in North Korean news and propaganda, and garnered attention from DPRK leadership.

324 *Rodong Sinmun* (Pyongyang), 26 November 2013.

325 Choe Sang-hun, "North Korea Learning to Make Crucial Nuclear Parts, Study Finds," *New York Times*, 23 September 2013.

326 United Nations Security Council, "Report of the Panel of Experts established pursuant to resolution 1874 (2009)," S/2014/1467, 6 March 2014, pp. 22-23.

CNC MACHINE TOOLS

Since the 1990s, CNC machine tools have been by far the most important and heavily publicized industrial technology in North Korea. North Korea has two major domestic producers, Kusong and the more prominent Ryonha, whose products are often seen on factory floors around the country. A 2012 interview with the president of Unsan, a subsidiary responsible for exporting Ryonha's products, described the firm as follows:

> The president claimed annual exports of 30,000,000 euros to Europe, South America and South East Asia. He didn't have exact details on profits, but mentioned that Unsan imported 10,000,000 euro[s] worth of parts, mostly from Europe, such as control units and electronic relays [from] Siemens and Arno. Their main CNC factory is 40,000 sq. meters and the "biggest in the world" according to the manager. They have two facilities, one in Pyongyang and one in Jagang with 12,000 employees in total. They want to open a factory in Rason, ideally without investors. Prices were said to be: 150,000 EUR for a European made CNC machine but only 52,000 EUR for an equivalent machine made in the DPRK, with the "same quality."[327]

Ryonha is under international sanctions, but it has come to light that front companies in China and Russia are marketing Ryonha's products.[328] At home, North Koreans celebrate Ryonha's sprawling factory in Huichon, Jagang Province, which received numerous well-documented visits from Kim Jong Il, especially in his last few years.[329] In 2011, the official newspaper of the North Korean cabinet credited Ryonha with North Korea's long history of successes in space:

> Many truly miraculous achievements have been attained in this land since our-style CNC machines were born.
>
> Among them was such a huge event as the successful launch [in August 1998] of artificial earth satellite "Kwangmyongsong-1." The parts used in the multi-stage carrier rocket all had to be processed with CNC machines. Furthermore, they could be processed only by high-performance class multi-axis CNC machines, not ordinary standard-type CNC machines.
>
> Our CNC machines developed by Ryonha machine developers successfully processed all the parts necessary to manufacture the multi-stage carrier rocket and artificial earth satellite, and the might of *Juche* Korea was demonstrated once again before the world.

327 "Why is the DPRK in love with CNC?," Choson Exchange, 7 February 2012, http://www.chosonexchange.org/our-blog/1388.
328 Jeffrey Lewis and Catherine Dill, "Smoke and Mirrors: DPRK Front Companies in China and Russia," 38North.org, 18 November 2014, http://38north.org/2014/11/jlewis111814/.
329 Jeffrey Lewis and Amber Lee, "Happiness is a Warm CNC Machine Tool," 38North.org, 4 September 2013, http://38north.org/2013/09/jlewis090413/.

> Today, up-to-date CNC machines are covering many factories and enterprises and stoking up the flames of modernization across the whole country.[330]

In October 2011, according to multiple North Korean media reports, Kim Jong Il approved functionaries at the Ryonha plant in Huichon to commence the manufacturing of a so-called "mother machine:" a nine-axis CNC machine tool meant for the construction of the bodies of other CNC machines. By implication, these bodies must have been either imported or manufactured in a more laborious manner in the past. The mother machine was reportedly completed in March 2012.

FLOW-FORMING MACHINES

The alleged completion of a "mother machine" at Ryonha's Huichon plant may explain the subsequent appearance of the flow-forming machine, a special type of CNC machine tool, in North Korean factories. These specialized, visually distinctive lathes compress, harden, lengthen, and reshape a variety of metal tubes, disks, and cylinders, typically made of high-performance aluminum or steel alloys. Flow-forming machines produce maraging-steel centrifuge rotors and potentially solid-rocket motor cases, among other things.

Eight or nine different models of flow-forming machines have appeared in interior photographs of North Korean factories since 2001.[331] Except for one rudimentary-looking machine without CNC controls shown to Kim Jong Il at the Kusong factory in 2006, none looked like a distinctly North Korean-made machine, and a few resembled German-made machines. Patent literature searches reveal components of flow-forming machines, perhaps representing either progress toward indigenous production or the selective refitting or upgrading of imported machines. In April 2016, Kim Jong Un visited the Tonghungsan Machine Plant, an underground facility located underneath the Ryongsong Machine Complex in Hamhung. Media photographs showed a row of at least half a dozen identical flow-forming machines, each with the visual signatures—body shape and paint scheme—of a Ryonha machine.[332]

INDUSTRIAL ROBOTICS

The North Korean media portray the adoption of CNC machine tools as only the first step toward full automation of industry. In the same April 2016 news report that documented Kim Jong Un's visit to the Tonghungsan underground plant, the leader described it as a model facility and outlined the plan of action for industrial modernization across the country:

330 *Minju Joson* (Pyongyang) 8 December 2011.
331 Possibly the first two such machines noticed by outside observers may be seen here: R. Scott Kemp, "Is This Where North Korea Makes Its Centrifuges?" ArmsControlWonk.com, 24 June 2013, http://www.armscontrolwonk.com/archive/206637/is-this-where-north-korea-makes-its-centrifuges/.
332 *Rodong Sinmun* (Pyongyang) 2 April 2016.

> Stressing that it is important to struggle by properly setting stage-by-stage goals to be attained in the modernization drive, [Kim Jong Un] said that the plant should update its old facilities and achieve their CNC-ification and partial robotization of the production processes as the first-stage goal, and place all production processes on a fully automated and streamlined basis as the second-stage goal.[333]

"Partial robotization" had already been seen at other facilities, notably the newly expanded and renovated 18 January General Machinery Factory in Kaechon, which Kim Jong Un visited in December 2015 and again in August 2016. Of particular interest on both occasions was a partially robotized line that made crankshafts for what appeared to be V-12 engines—large and powerful diesel engines usually associated with locomotives or tanks. The line featured a row of machine tools, some with a Ryonha "look," between which were brightly painted industrial robots bearing the initials of a major foreign manufacturer—ABB of Switzerland—and a track motion platform resembling those on the ABB website.[334] The facility also included an automated warehouse system that stores and retrieves products from massive vertical racks.

In the report on the December 2015 visit, Kim Jong Un is quoted lauding the facility's increased production and improved quality with less manpower:

> The plant has been turned in keeping with the trend of the development of industry in the 21st century as it possessed enough modern equipment and established a flexible manufacturing system, made up of [C]NC machine tools, robots, unmanned material carrier, automatic storehouse, etc., with domestic design, technology and efforts, he noted, saying: The plant has been put on a scientific, IT, automated and unmanned basis at a high level, making it possible to remarkably raise the production with less manpower and further improve the quality of products.[335]

Robotics is a prominent area in North Korean patent announcements as well. But judging by the relatively simple robots exhibited at the S&T Center in November 2016, the domestic robot industry is still in its infancy.[336]

ADDITIVE MANUFACTURING

AM seems to be even less developed in North Korea than robotics. A video shot in May 2016 at the nineteenth International Spring Trade Fair in Pyongyang captured an exhibit that displayed a photograph of a 3D printer allegedly invented by the Pyongyang University of Mechanical Engineering. An attentive blogger pointed out that it looked very much like a MakerBot Replicator—a 3D printer available at Amazon.com, among other places.[337] This observation may have touched a sensitive

333 *Rodong Sinmun* (Pyongyang), 2 April 2016.
334 See http://new.abb.com/products/robotics.
335 *Rodong Sinmun* (Pyongyang), 20 December 2015. See also *Rodong Sinmun* (Pyongyang), 10 August 2016.
336 Korean Central Television, 9 November 2016.
337 Clare Scott, "North Korean Trade Show Advertises 3D Printer… That Looks a Lot Like a MakerBot," 3DPrint.com, 3 June 2016, https://3dprint.com/137135/north-korea-3d-printer/.

point; a February 2016 North Korean media report had described the same 3D printer as a strictly indigenous development.[338]

When a 3D printer next appeared in the North Korean media in August 2016, it involved a more insistent portrayal of the technology at the Dental Hospital of the Ministry of Public Health as indigenous. The report quoted a doctor who discussed its use for making customized facial prostheses and tooth implants. Photographs prominently showed a printer—distinct from the one seen earlier—with a logo in Korean lettering, as well as patent documentation.[339]

IMPLICATIONS

North Korea is often seen as dependent on imports of foreign technology, making it vulnerable to export controls and sanctions. However, North Korea is better understood as a purposeful assimilator and adapter of foreign-origin S&T. Its scientific and industrial establishments are substantial and enjoy disproportionate resources and leadership attention. Kim Jong Un is openly seeking to reduce his country's dependence on foreign supplies and make the most of domestic resources and talents, even as he remains committed to the absorption of foreign knowledge. CNC technology, followed by industrial robotics, has led the way in the modernization of defense production; AM may join these other technologies if it fulfills a suitable role in due course. Regardless of North Korea's specific choices of industrial technology, it has a sufficiently strong resource endowment, S&T system, and commitment of its leaders not to be swayed decisively by new or strengthened sanctions. We should expect North Korea's strategic weapons development to continue.

338 *Rodong Sinmun* (Pyongyang), 1 February 2016.
339 Korean Central Television, 8 August 2016.

POTENTIAL WMD[340] TERRORISTS AND ACCESS TO AM: ASSESSING THE MICROPROLIFERATION[341] THREAT

(Contributor: Gohar Altaf)

ABSTRACT

AM's easy accessibility has led some to worry about its utilization for the proliferation of WMD. In this context, this study investigated the possibility that AM may be misused by potential terrorist WMD aspirant groups. This assessment first tried to pinpoint potential terrorist groups that are interested in acquiring WMD. We analyzed broad categories of groups with different ideological orientations, goals, modus operandi, and levels of capabilities required to construct WMD; by understanding the motivations of the potential groups, we may predict their weapon choices and possible acquisition paths for such choices. The study found only a few serious WMD aspirant terrorist groups, with the extremely serious Islamic State (IS) in the foreground. The nature, shape, and magnitude of the IS's motivations and general capabilities suggest that it is following a multi-track proliferation path and can access AM easily, potentially facilitating its WMD pursuit by mitigating technical barriers. The investigation has found evidence that the IS can access Makerspaces easily in countries that have both accessible technologies and the presence of either the IS or affiliates/followers that can facilitate its misuse of technology to acquire WMD. Moreover, the group can purchase the technology through these countries or elsewhere because trade of this technology is controlled minimally. Therefore, this study reveals that organizations need to control access to AM because it is susceptible to misuse by non-state terrorist groups that are seeking WMD acquisition desperately.

340 Although WMD traditionally encompass chemical, biological, radiological, and nuclear weapons, for the sake of the scope of this paper, the term will focus on nuclear weapons and their delivery means, particularly nuclear-capable missiles.
341 Microproliferation implies the proliferation activities of sub-state actors including, though not limited to, terrorist groups. However, the scope of this research is limited to terrorist groups only. The term has been used previously in this sense by Gavin Cameron, "Multi-Track Microproliferation: Lessons from Aum Shinrikyo and Al Qaida," *Studies in Conflict and Terrorism* 22 (1999).

Some terrorist groups have shown serious interest in acquiring WMD, and the ongoing revolution in increasingly accessible technology raises serious questions about the possibility of terrorist groups misusing such technology. Past cases of WMD pursuit by subnational groups[342] indicate clearly that it was technological barriers, not lack of intent, that hampered their acquisition programs.[343] Despite the emergence of unscrupulous and strategically driven suppliers like the Abdul Qadeer (AQ) Khan Network,[344] global nonproliferation regimes have hampered the ability of terrorist groups to access the necessary technology, equipment, know-how, and materials considerably.[345]

However, technological advancement and innovation has decreased technical constraints considerably, thereby increasing terrorist capabilities. There has been an upward trend in terrorist use of innovative operational tactics and modern technology in their modus operandi, demonstrating the threat that modern technology may be misused for purposes of WMD acquisition.[346]

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342 For the scope of this study,"subnational group" implies terrorist groups only, and excludes other categories of groups like criminal groups/networks, though they have been considered from the angle of their possible collaboration with, sympathy for, support of, and assistance to the potential terrorist proliferators.

343 It is pertinent to clarify here that this is the primary factor, but not the sole barrier. Nevertheless, al-Qaeda's and Aum Shinrikyo's active WMD pursuit clearly demonstrate that technological sophistication, among other factors, plays the primary role and hampered these groups's WMD pursuits and motivations to pursue such weapons. For detailed analysis on al-Qaeda and Aum Shinrikyo microproliferation, see (for example) Morten Bremer Maerli, "Relearning the ABCs: Terrorists and Weapons of Mass Destruction," *Nonproliferation Review 7* (Summer 2000); David Albright, "Al-Qaeda's Nuclear Program: Through the Window of Seized Documents," Nautilus Institute Policy Forum Online, 6 November 2002; Gavin Cameron, "Multi-Track Microproliferation: Lessons from Aum Shinrikyo and Al Qaida," *Studies in Conflict and Terrorism* 22 (1999); Richard Danzing et al., "Aum Shinrikyo: Insights in to How Terrorists Develop Biological and Chemical Weapons," *Center for New American Security* (December 2012).

344 Mathew Kroenig argued that nuclear technology and equipment has been transferred by states—though these transfers were state-to-state or by non-state actors, like clandestine suppliers such as AQ Khan—because of certain well-calculated strategic logic. It is pertinent to mention that Kroenig rightly argued that even the AQ Khan Network was not working on its own, but was the expression of a well-calculated strategic move by the state of Pakistan. See Matthew Kroenig, *Exporting the Bomb: Technology Transfer and the Spread of Nuclear Weapons* (Ithaca: Cornell University Press, 2010): pp. 134-151.

345 Jean Paul Zanders, "Assessing the Risks of Chemical and Biological Weapons Proliferation to Terrorists," *Nonproliferation Review* 6 (Fall 1999): 17-34. However, to be vigilant about all possible routes and scenarios apart from the strategically driven trade control violations, it is advisable to consider the non-state actor's involvement on the basis of other parochial interests like inter alia and economic benefits. For various benefits that may drive or stop a non-state actor from enabling and facilitating the proliferators, see Ian J. Stewart and Daniel Salisbury, "Non-State Actors as Proliferators: Preventing their Involvement," *Strategic Trade Review*, Vol. 2, No. 3 (Autumn 2016): pp. 5-26.

346 In October 2016, the Taliban used a drone to film a suicide attack launched on a police base in the Helmand province of Afghanistan. Although the drone is not military-grade, it indicates a clear change in that group's modus operandi, which previously showed conservatism in terms of tactics and weapons. See "Taliban Release Drone Footage of Suicide Attack," *Reuters*, October 22, 2016, http://www.reuters.com/article/us-afghanistan-taliban-idUSKCN12M0LD?il=0, accessed on 5 15 November 2016. In 2012, the FBI arrested an Islamist jihadi who was plotting to use model airplanes loaded with explosives to attack the Pentagon and US Capitol, see "Man Accused of Pentagon Bomb Plot Accepts Plea Deal," *CNN*, July 11, 2012, http://www.cnn.com/2012/07/10/justice/massachusetts-pentagon-plot/index.html, accessed on November 14, 2016.

In this regard, of particular interest is the advent of AM and its uncontrolled availability.[347] Virtually any object of any shape can be constructed with digital build files that contain instructions for printers to lay down layers of material additively.

The advent of AM undoubtedly has the potential to initiate a second industrial revolution,[348] but it carries serious risk of misuse by potential terrorists to achieve their WMD ambitions.[349] Current assessments of this possibility indicate serious concerns[350] because experts have shown that the technology can potentially enhance capabilities that are required for acquiring WMD.[351]

Although we lack evidence about whether AM has hitherto been used by any non-state actor (or even by a state) in WMD production, the aerospace industry is using the technology to produce precision components of high significance and utility. This underlines a genuine concern that the technology can be used for construction of components related to critical weapons or even a nuclear device.[352]

Unfortunately, since AM requires only the blueprint and 3D printer, it reduces the technical threshold required for manufacturing the necessary material and even constructing the weapons.[353] It subsequently affects strategic trade because it reduces the dependence on conventional illicit trade networks

347 AM, commonly known as 3D printing, is a manufacturing technique in which an object is produced by adding ultrathin layers of material one by one, see Martin LaMonica, "Additive Manufacturing: GE, the World's Largest Manufacturer, is on the verge of Using 3-D Printing to Make Jet Parts," *MIT Technology Review*, https://www.technologyreview.com/s/513716/additive-manufacturing/, accessed on November 15, 2016.

348 Interestingly, although it still requires much more development and acceptability, it is being adopted by some rather advanced industrial manufacturing sectors, including aerospace and defense sectors, in the manufacturing of critical "precision" components including those of jet engines, see "Entering the Jet Age," *The Economist*, March 7th, 2015, http://www.economist.com/news/science-and-technology/21645712-aircraft-engines-may-soon-be-built-one-layer-time-entering-jet-age, accessed on November 17, 2016; Martin LaMonica, *Additive Manufacturing*, Op. Cit.

349 *The Economist*, March 7th, 2015, http://www.economist.com/news/science-and-technology/21645712-aircraft-engines-may-soon-be-built-one-layer-time-entering-jet-age, accessed on November 17, 2016; Martin LaMonica, *Additive Manufacturing, Op. Cit.*

350 Matthew Kroenig and Tristan Volpe, "3-D Printing the Bomb: The Nuclear Nonproliferation Challenge?", *The Washington Quarterly*, 38:3 (Fall 2015): p. 10.

351 "As Do-It-Yourself Manufacturign Emerges, Experts Consider Security Risks," AAAS, 16 May 2014, https://www.aaas.org/news/do-it-yourself-manufacturing-emerges-experts-consider-security-risks, accessed on November 16, 2016.

352 For the construction of a critical part of its Trent xwb-97 jet engine, Rolls Royce reportedly plans to use the AM, see "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-onelayer-time-entering-jet-age, accessed on November 4, 2016; General Electrics produced critical components of the Leap jet engine, see 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, accessed on November 5, 2016; Chinese People's Liberation Army has already been using the AM for the production of sophisticated metal parts fighter aircraft, see Kroenig and Volpe, *3-D Printing the Bomb, op. cit.*; Brooke Kaelin, "World's Largest 3-D PrintedTitanium Aircraft Part on Display in China," 3-D Printer World, August 19, 2013, http://www.3dprinterworld.com/article/worlds-largest-3d-printed-titanium-aircraftpartdisplay-china.

353 Maria Martens, "Chemical, Biological, Radiological and Nuclear Terrorism: The Rise of Daesh and Future Challenges," *Report: NATO Parliamentary Assembly: Science and Technology Committee* (20 November 2016): p. 16;

substantially.[354] In addition, 3D printing requires only a small space instead of a big manufacturing facility. The dual-use nature of 3D printing exempts it from many export control limitations and makes the technology easily accessible to anyone, including terrorist groups. This problem is compounded by the fact that the technology is already present in Makerspaces that are within the operational spheres of potential WMD terrorists,[355] creating easy access and potential for misuse.[356]

Against this background, the fact that some terrorist groups have shown serious intent to acquire WMD intensifies concerns about the potential misuse of AM for WMD proliferation. As discussed briefly above, some terrorist groups have pursued WMD. It is even more concerning that there are now additional, more dangerous terrorist groups interested in acquiring WMD, particularly nuclear weapons, for various reasons.

This paper acknowledges this serious issue and investigates the possibility that terrorist groups will misuse AM to acquire WMD. We focus on three primary tasks:

» Identifying the potential terrorist groups;

» Assessing the nature and underlying motivations of potential WMD sub-state terrorists (groups/organizations/networks); and

» Assessing their access to and potential of misuse of AM for WMD proliferation purposes.

The paper is divided into two main sections. The first endeavors to pinpoint the potential WMD terrorists that seem interested in both acquiring and utilizing WMD and qualified to meet the primary capability criteria. It then assesses the nature, shape, and magnitude of each potential group's WMD acquisition motivations. Although the capabilities of potential terrorist groups have been examined previously, it was from the standpoint of their potential to be considered serious non-state proliferators, rather than their potential to use AM to mitigate their constraints.

We conclude that the IS is the most potent microproliferation threat, and the second section investigates the ideological foundations, goals, and relation of the modus operandi to the IS's weapon choice. It analyzes potential methods to access AM and addresses the important question of whether the IS or any other terrorist group/organization has hitherto produced weapons with AM technology and technique. Finally, we present our conclusions and findings drawn from the overall investigation in the last section.

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354 Experts maintain that even Maraging Steel and 7075 aluminum, the controlled metals currently used in a centrifuge for enrichment, can be 3D printed easily if the necessary metal powders are available. However, these powders are not controlled by any export control regimes. For detailed analysis, see Grant Christopher, "3D Printing: A Challenge to Nuclear Export Controls," *Strategic Trade Review*, Vol. 1, No. 1 (September 1, 2015), http://local.droit.ulg.ac.be/jcms/service/49/pdf/str01/2_3D_Printing_A_Challenge_to_Nuclear_Export_Controls.pdf, accessed on October 12, 2016; and Kroenig and Volpe, *3-D Printing the bomb*, Op. Cit.

355 MakerSpaces, sometimes referred to as hackerspaces, hackspaces, and Fab Labs, are creative DIY spaces where people gather to create, invent, and learn. These spaces often have 3D printers, software, electronics, craft and hardware supplies, tools, and more. See "A Librarian's Guide to Maker Spaces," March 12, 20013, http://oedb.org/ilibrarian/a-librarians-guide-to-makerspaces/, accessed on October 9, 2016.

356 This particular issue is discussed in detail along with empirical evidence in the second part of the paper.

POTENTIAL WMD TERRORISTS: ARE THERE ANY?

Before identifying the potential terrorist groups, it is logical to note at the outset that the scope and purpose of this investigation is limited to those groups that can benefit from AM in some way for their WMD acquisition purposes. Moreover, the investigation focuses primarily on nuclear weapons and missiles because AM has the highest utility for mitigating the difficulties involved in the production of critical components of these weapons programs. However, the analysis incorporates other weapons that fall within the WMD weaponry class as well, while identifying, categorizing, and evaluating each group's choice of weapons from within the WMD class.

In 1975, Brian M. Jenkins of RAND Corporation raised the question, "will terrorists go nuclear?" He answered, "terrorists want a lot of people watching and listening, not a lot of people dead."[357] This implies that the terrorists are not motivated to use nuclear weapons because they want to exploit the fear they create through attacks to achieve their political objectives.

The argument is convincing within the context of the time, when terrorists were constrained by purely "political" goals, moral and strategic constraints regarding mass-casualty attacks, and other capability-related barriers. Also, most of those terrorists operated on the principle of "minimum force necessary," implying that the use or threat of force was tempered with cost-benefit considerations.[358]

This approach is obsolete in today's "new age of terrorism," featuring the emergence of transnational and religiously motivated groups. Interestingly, Jenkins himself revised his conception by adapting to the new age of terrorism: "Many of today's terrorists want a lot of people watching and a lot of people dead."[359] Before identifying the potential WMD subnational aspirants, it is important from a conceptual as well as analytical standpoint to understand why contemporary terrorists should be considered the more potent WMD threat.

WHY ARE THE NEWER TERRORISTS MORE DANGEROUS THAN THE OLDER TERRORISTS?

The nature, character, and form of terrorism has undergone a process of evolution of ideology, goals, tactics, operations, modus operandi, and capabilities. Understanding this evolution is indispensable from both an analytical and policy standpoint.

This evolution is most obviously manifested in the fact that terrorism has become bloodier. Today's terrorists such as al-Qaeda, the IS, and other Islamist transnational terrorists, in contrast to the terrorists that operated in the 1960s, 1970s and 1980s, are fuelled predominantly by extremist religious ideologies that are based on irrational theological underpinnings. Modern groups utilize these

357 See, Brian Michael Jenkins, "International Terrorism: A New Mode of Conflict", in David Carlton and Carlo Schaerf, eds., *International Terrorism and World Security* (London: Croom Helm, 1975), p. 15.
358 Ibid., p. 6.
359 See, Brian Michael Jenkins, *Will Terrorists Go Nuclear* (New York: Prometheus Books, 2008).

ideologies to rationalize vengeance, punishment, and destruction as both the means and the end to their preconceived ideal world.[360]

An offshoot of this characteristic of contemporary terrorists is the increasing lethality and frequency of terrorist attacks during the last three decades.[361] Beginning with the 1988 terrorist attack on Pan AM 103, which killed 270 people, there has been a burgeoning trend in mass-casualty incidents that culminated in the September 11, 2011 attacks.[362] Objectives affect strategy, and the shift from political to apocalyptic and religious objectives has arguably caused the aforementioned rise in mass-casualty terror attacks.

Apart from that, technical know-how and physical technology is more accessible today than it was even a decade ago and may be another factor underlying increasing terrorist motivations. The trend in technology has boosted confidence in a way that if a terrorist group goes down a more violent path, they can acquire the necessary weapons. The advent of 3D printing has the potential not only to increase the terrorists' capabilities, but also to decrease constraints on capability and therefore increase motivation.

However significant the aforementioned developments may be in the evolution of terrorism, a genuine question arises at this point: are all terrorist groups whose modus operandi and operational tactics have surged in brutality, lethality, and access to knowledge/technology actually interested in acquiring these weapons? The proceeding analysis addresses this fundamentally important question, evaluating the extent, to a low level of certainty, to which the wheat can be separated from the chaff. We identify the threat, clarify its nature, and suggest effective policy responses.

SEPARATING WHEAT FROM CHAFF: POTENTIAL ASPIRANTS

Although most terrorist groups will not go down the path to WMD acquisition, some might find it an attractive option. It is reasonable to argue and demonstrate that a combination of factors—including the group's ideology, goals, modus operandi, capabilities, and opportunities—may explain and predict a group's interest in this choice and utility of weapons.

It is not only analytically erroneous, but also methodologically dangerous, to lump together all terrorists into one category of "insane fanatics" who are always ready to resort to indiscriminate mass

360 For the terrorists of 1960s, 1970 and 1980s see, Bruce Hoffman, *Inside Terrorism* (New York: Columbia University Press, 1998), pp. 87-88.

361 Global Terrorism Database, *University of Maryland*, https://www.start.umd.edu/gtd/search/Results.aspx?start_yearonly=1970&end_yearonly=2015&start_year=&start_month=&start_day=&end_year=&end_month=&end_day=&asmSelect0=&asmSelect1=&dtp2=all&success=yes&casualties_type=b&casualties_max=, accessed on November 24, 2016; and Nadine Gurr and Benjamin Cole, *The New Faces of Terrorism: Threats from Weapons of Mass Destruction* (New York: I.B. Tauris, 2000), pp. 22-23; Gavin Cameron, *Nuclear Terrorism: A Threat Assessment for the 21st Century* (New York: Palgrave Macmillam, 1999), p. 138.

362 See, Bruce Hoffman, "Terrorism Trends and Prospects," in Ian Lesser, ed., *Countering the New Terrorism*, Rand Corporation document MR-989-AF, 1999, pp. 10-27.

murder. Such an approach not only blurs the inherent differences between terrorist groups, but also leads to flawed threat assessments upon which life-and-death questions of any polity are based.

For this very reason, it is necessary from both an analytical and a political standpoint that we clarify the differences between distinct groups with distinct worldviews, operational and strategic objectives, and modus operandi. To better understand the potential groups, their weapons choice, and policy, it is beneficial to first categorize the relevant groups broadly in terms of ideological makeup, goals and modus operandi.[363] Note that the assessment of motivations has been done on the basis of the same factors mentioned above (i.e., ideological orientation, operational as well as long-term strategic goals, past cases, and modus operandi), though such groups may fall under different categories when considered in terms of other factors.

First, however, it is indispensable to distinguish terrorists based on secular vs divine ideological standpoints. Table 4 illustrates the categories, weapon choices, and projected level/seriousness of the threat from each category. Each of the following categories is discussed in its own section, below:

- Single-Issue Terrorist groups[364]
- Nationalist/Separatist groups[365]
- Apocalyptic groups[366]
- Politico-Religious groups[367]

SINGLE-ISSUE TERRORIST GROUPS

Arguably, not all terrorists should be considered serious aspirants of WMD, particularly nuclear weapons. The single-issue terrorist groups such as anti-nuclear and/or pro-environmental groups might find it unnecessary, beyond their capabilities, and even counterproductive to pursue a weapons program.

Since the primary goal of these groups is to undermine the public's confidence in nuclear energy and/or influence nuclear energy policy, they can do so easily through nuclear hoax techniques, as they

363 These categories are ordered, from the top down, by (a) lesser motivated groups; (b) ideologically lesser radical groups; (c) groups that might choose lesser destructive types of WMD; and (d) groups interested in wreaking lesser destruction and human-casualties. This can also be thought of as a ranking of motivations, extremism and radicalism, choice of most destructive weapon, inclinations towards mass-casualty terrorism, and possibly strategic utility of weapons. It is particularly relevant in the case of politico-religious-cum-apocalyptic groups like the IS.
364 Terrorist groups/individuals who commit themselves to catalysing a change in policies or behaviours of the respective government, pertaining to some clearly defined political or social issue, fall under the broad category of single-issue terrorist groups.
365 Terrorist organizations that focus on achieving political objectives for a certain tribal or ethnic group fall under the category of nationalist/separatist groups.
366 This category includes those who a hold firm belief that the end of the current world order is in the offing, and that they have a special role to bring that about.
367 These groups are predominantly religious in outlook, yet political in objectives.

have done previously, or at the most, occupying a nuclear facility.[368] These groups do not seem to possess the intent to acquire weapons, and even if they did, they might not have the required capabilities to produce such weapons.

Based on past behavior and current motivations/capabilities, it is therefore highly likely that the weapon of choice for these groups would be nuclear hoax. There has been no precedent that any of such groups has ever endeavored to acquire nuclear weapons capabilities, which seem to be incompatible with their very ideology and overall goals. The weapons choice of single-issue terrorists is affected primarily by their goals and objectives, which flow from their beliefs about the issue in question, and secondarily by their possession or lack of required precursor capabilities. It is not just matter of will, but also reality. Single-issue groups tend to be secular ideologically, and thus less likely to choose high-end, mass-casualty tactics and/or strategies.

NATIONALIST/SEPARATIST TERRORIST GROUPS

The separatist/nationalist terrorist groups similarly lack both the will and the basic capabilities required for weapons acquisition. There are several convincing reasons why separatist/nationalist groups seem to have minimal intent to produce an intact nuclear weapon or even an Improvised Nuclear Device (IND).

First, these groups have a fixed territorial base. The vulnerability of their own community/society can be the target of retaliatory attacks, and this deters such groups from using WMD.[369] Second, most of the nationalist/separatist terrorist groups have limited financial resources. These groups lack the resources, or at least the willpower to spend all of their limited resources, on such a vulnerable, highly technical, and risky project. It is instructive to mention here that despite their territorial connection and links to the Chechen criminal networks, the Chechen terrorists have not been able to acquire a nuclear weapon, nor even enough weapon-grade material.[370]

However, there could be some motivation to acquire such a weapon as a deterrent, a tool for strategic coercion, or a legitimizer. Against the backdrop of possible Israeli nuclear weapons, the Palestinian Liberation Organization has asserted that if Israel acquires nuclear weapons, Palestine will follow suit,

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368 For detailed analysis and their past activities involving hoaxes and other modes, see Brent L. Smith, *Terrorism in America: Pipe Bombs and Pipe Dreams* (New York: State University of New York Press, 1994), pp. 35-40; Bruce Hoffman, *Inside Terrorism* (New York: Columbia University Press, 1998), pp. 157-161.

369 There has been disagreement on the effectiveness of measuring deterrence based on threat to societal targets, but the November 1995 incident at Ismailovsky Park, Moscow—where Chechen terrorists under the command of Shamil Besayev planted a Radiological Dispersal Device (RDD)—calls these doubts into question. Chechen terrorists never stated clearly why they did not detonate the RDD despite planting it successfully. One possible reason could be fear of Russian retribution. The Chechen terrorists had, in their historical memories, the 1944 Russian response to reports of Chechen collaboration with German military units that were trying to occupy the Northern Caucasus. For a detailed account, see Brian Michael Jenkins, *Will Terrorists Go Nuclear* (New York: Prometheus Books, 2008): pp. 79-82; for deterrence through the threat of targeting the society of terrorists in retaliation, and deterring WMD terrorism in general as well, see, Jeffrey W. Knopf, "Terrorism and the Fourth Wave in Deterrence Research," in Andreas Wenger and Alex Wilner, eds., *Deterring Terrorism: Theory and Practice* (Stanford: Stanford University Press, 2012): pp. 31-32.

370 See, Jenkins, *Will Terrorists Go Nuclear, Op. Cit*. (2008): pp. 77-84.

perhaps to equalize and legitimize their standing. Nevertheless, there has been no evidence that they have ever exerted any effort in this regard.[371]

APOCALYPTIC GROUPS

In this broad category, terrorist groups firmly believe that the apocalypse is in the offing, and their role is to catalyse it. The Japanese cult Aum Shinrikyo, influenced by the Shoko Ashara creed,[372] is the best example. The ideology and goals of the IS clearly indicate that it falls in both the apocalyptic and politico-religious categories of terrorist groups, as will be explained in the next section.[373]

The goals and objectives of these terrorist groups are subordinate to their ideology, which is often based in religion. They consider the Apocalypse necessary to purify the world. These terrorist groups do not consider this world the final destination, but rather a temporal journey that needs to be finished as soon as possible to reach the final destination. Therefore, any terrorist group with such outlook and goals should be considered serious WMD aspirants.

In current times, the groups that are both apocalyptic and politico-religious pose the highest risk from the standpoint of WMD microproliferation. Although al-Qaeda, which falls under the fourth category, poses a WMD proliferation risk, it is the IS that should be considered the highest WMD microproliferation risk, given its ultra-extreme ideological orientation, apocalyptic as well as political goals, brutal modus operandi, and the possession of the primary required capabilities.

POLITICO-RELIGIOUS TERRORIST GROUPS

These groups are predominantly religious in outlook, yet political in objectives.[374] Further, however political their objectives might look, in reality these are embedded in religious validation and commandments. As mentioned above, the IS falls under this category, but has apocalyptic elements as well in its ideology and goals calculus.[375]

There are two sub-camps within this broad category, divided on the basis of the dominant aspect of their ideology and goals. In the first camp, nationalist movements are waged in the name of religion. Post-9/11 terrorism is overwhelmingly dominated by terrorist groups with both political and religious motivations. In the first camp, the political (not religious) aspect of their motivation

371 William Quandt, Fuad Jabber, and Ann Lesch, *The Politics of Palestinian Nationalism* (Berkeley: University of California Press, 1973).

372 See, Jenkins, *Will Terrorists Go Nuclear*? 2008, *Op. Cit.*, pp. 71-77; Cameron, *Multitrack Microproliferation, Op. Cit.*; Danzinf et. al, *Op. Cit*.

373 See for this, Graeme Wood, "What ISIS Really Wants," *The Atlantic* (March 2015 Issue), http://www.theatlantic.com/magazine/archive/2015/03/what-isis-really-wants/384980/, accessed on October 13, 2016.

374 For a detailed explication of the connection between the political and religious, see Majid Khudduri, *War and Peace in the Law of Islam* (Washington DC: The John Hopkins Press, 1955): pp. 3-19.

375 See, Jay Sekulow et. al., *Rise of ISIS: Threat We Can't Ignore* (New York: Howard Books, 2014): 15-27; Yonah Alexander and Dean Alexander, *The Islamic State: Combating the Caliphate Without Borders* (London: Lexington Books, 2015): 33-78; Fawaz A. Gerges, *ISIS: A History* (Princeton: Princeton University Press, 2016): 23-49

seems dominant, as is illustrated by their ethno-nationalist and/or irredentist aims and objectives.[376] On the other hand, in the second camp, the religious aspect dominates and shapes the very conception and definition of "political." This religious tinge leads groups to seek radical political changes through violence to perpetuate religious goals. According to the second camp, political is to serve the religious; the former is subordinate to the latter.[377]

While analyzing the ideological underpinnings, goals, operational considerations, and weapons choices of terrorist groups under these four categories, this investigation has inferred several important findings regarding the danger of potential WMD terrorist groups.

First, it has been established clearly that the level of motivation and weapons choice of any terrorist group is determined by the underlying ideological orientation coupled with the goals and operational modus operandi, apart from capabilities and opportunities. Second, it is not only desirable, but also necessary from the analytical and political standpoints to admit (as the case of Chechen terrorists suggests) that a correlation exists between overall motivation level and required capabilities, which together determine the terrorist group's perception of weapon utility.

The logical implication is that technical and technological barriers not only mitigate the microproliferation drive, but also negatively affect the motivations and acquisition behavior of the aspirant groups, some of which might not advance from square one after discovering the technical and technological barriers involved in the process of acquisition.

Nonetheless, it varies from case to case, and depends directly on each group's overall shape and nature of the interactive relationship between ideology, goals, operational modus operandi, leadership, and psychology and financial resources, apart from other relevant dynamics. In this regard, the apocalyptic and politico-religious groups—particularly Islamist transnational groups like al-Qaeda or the IS—are the top concern from a WMD proliferation angle. Documented acquisition efforts of al-Qaeda and the ongoing willingness and efforts of the IS demonstrate clearly that such groups should be considered the prime WMD microproliferation concern, because of both their extremity of intent and capacity to launch serious efforts for the realization of their WMD ambitions.

The primary factors driving this conclusion are present in the cases of both al-Qaeda and the IS. First, both tried to rationalize their intent by employing religious (albeit distinct) doctrinal explanations.[378] Second, both possess financial capacity with which they can exploit vulnerabilities in the existing nonproliferation and nuclear security structures at the national and international levels. However, the financial ability of al-Qaeda has decreased a great deal due to the setbacks in the Global

376 Bruce Hoffman, *Inside Terrorism: Revised and Expanded Edition* (New York: Columbia University Press, 2006), p.82.
377 Ibid; for the roots of this theological explanation for subordination of the political to the religious, see Khudduri, *War and Peace, Op. Cit*.
378 Osama called acquisition of nuclear weapons a "religious duty." For Osama bin Laden's explicit statements in which he tried to rationalize nuclear weapons acquisition, see Peter Bergen, *The Osama bin Laden I Know: An Oral History of Al-Qaeda's Leader* (New York: Simon and Schuster): p. 339; and "Exclusive Interview: Conversation with Terror," Osama bin Laden interview with Rahimullah Yusufzai, *Time*, January 11, 1999, http://content.time.com/time/magazine/article/0,9171,174550,00.html, accessed on October 13, 2016.

War on Terror (GWOT). From the financial angle, therefore, the IS stands out as the most capable Islamist terrorist organization.[379]

Third, both have shown clear interest in acquiring nuclear weapons. Although al-Qaeda has pursued a nuclear weapons acquisition program, its ability to further such a program has been thwarted substantially because of the GWOT. Fourth, both are transnational organizations, and thereby enjoy the ability to exploit opportunities around the globe, particularly in Muslim-dominated countries including Pakistan—a country with an increasing level of terrorism, insurgency, corruption, and above all, a nuclear weapons program with relatively inadequate security. This adds fuel to the fire: these countries are high risk zones for WMD microproliferation because they contain available Makerspaces; increasing networks and influence of terrorism;[380] increasing radicalization of engineers, students with S&T backgrounds,[381] and the population in general;[382] and further uncontrolled access to AM technology.

379 Al-Qaeda had huge economic resources. According to one source, in 1993 al-Qaeda had a budget of $1.5 million for acquiring uranium, see Kimberly McCloud and Matthew Osborne, "WMD Terrorism and Usama bin Laden," in *CNS reports* (Monterey, CA: James Martin Center for Nonproliferation Studies, 2001), including the full text of Jamal Ahmad al-Fadl, who revealed this figure to the US law enforcement authorities after getting apprehended for involvement in the bombings on the US embassies in East Africa in 1993, in the US District Court, Southern District of New York, *United States Vs. Usama bin Laden et al.*, February 6, 7 and 13, 2001. However, al-Qaeda's financial capability has been damaged greatly due to the GWOT. But the IS enjoys possession of huge financial resources based on indigenous economic structure, which requires a much different approach to combat financing of its terrorist activities and programs. For a detailed analysis of the IS's economic strength, capability and weaknesses, see Carla E. Humud, Robert Pirog, and Liana Rosen, "Islamic State Financing and U.S. Policy Approaches," *Congressional Research Service (CRS) Report* (April 10, 2015), https://fas.org/sgp/crs/terror/R43980.pdf, accessed on November 26, 2016.

380 For the growing influence and expanding network of the IS in Pakistan, see John Hall, "The Growing Influence of ISIS Now Reaches Pakistan As Taliban Leaders Pledge Allegiance to Brutal Jihadist Network," *Daily Mail*, October 15, 2014, http://www.dailymail.co.uk/news/article-2793622/the-growing-influence-isis-reaches-pakistan-taliban-leaders-pledge-allegiance-brutal-jihadist-group.html, accessed on November 12, 2016; another important account by a former Chief of Pakistan's *National Counter Terrorism Authority (NACTA),* Tariq Parvez, "The Islamic State in Pakistan," *The United States Institute of Peace*, Policy Brief 213 (September 2016), http://www.usip.org/publications/2016/09/21/the-islamic-state-in-pakistan, accessed on November 10, 2016; The current Intelligence Bureau (IB) Chief Aftab Sultan also warned that the threat of the Islamic State (IS) to pakistan is looming, see "IS Emerging as a Threat, Wars IB Chief," *Dawn*, February 11, 2016, http://www.dawn.com/news/1238771, accessed on October 18, 2016.

381 For a discussion about why people with backgrounds in hard sciences or engineering in the Islamic world become more susceptible to radicalization and recruitment to Islamist terrorist groups, see Elias Groll, "There is a Good Reason Why SoMany Terrorists are Engineers," *Foreign Policy* (July 11, 2013), http://foreignpolicy.com/2013/07/11/theres-a-good-reason-why-so-many-terrorists-are-engineers/, accessed on November 18, 2016.

382 For the increasing radicalization in Pakistani youth, see Moeed Yusuf, "Prospects of Youth Radicalization in Pakistan: Implications for U.S. Policy," *The Brookings Institution*, Analysis Paper Number 14 (October 2008), https://www.brookings.edu/wp-content/uploads/2016/06/10_pakistan_yusuf.pdf, accessed on November 12, 2016.

Table 4. Group Categories and Motivation Level along with Potential Weapons Types.

Group Categories	Motivation Level				Potential Weapons Choices	Rationale
	Extremely High	Fairly High	High	Low		
Single-Issue Groups					Nuclear/radiological hoaxes	-Single cause -Moderate goals -Limited resources
Nationalist/Separatist Groups					Nuclear weapon (for deterrent or coercion purposes)	-Ethno-national, ideology -Secular goals -Limited resources -Fixed territory; thus, vulnerable base
Apocalyptic Groups					-Chemical -Biological -Radiological -Nuclear	-Mass-casualty -Sparking Armageddon
Politico-Religious Groups					-Chemical -Biological -Radiological -Nuclear	-Mass casualty -Deterrent -Blackmail -Coercion

THE IS AND ACCESS TO AM: THE THREAT

As the preceding discussion establishes, the IS stands out from the list of contemporary terrorist groups as the biggest WMD aspirant and terrorism threat. It is the biggest threat because it not only possesses an extreme level of intent to acquire WMD, particularly nuclear weapons, but also stands a better chance of surpassing the technical barriers. However, the IS still lacks many of the required capabilities, and without bypassing them, the IS fortunately cannot acquire high-end weapons.[383]

With radical religious ideology, apocalyptic goals, huge financial resources, modus operandi that reflect an unprecedented level of brutality, and an expanding transnational network of followers, affiliate groups, supporters and sympathizers, the IS stands out as the biggest contemporary sub-state terrorist threat to international peace and security. Since the IS has explicitly shown serious interest in WMD, particularly nuclear weapons, it is critical to investigate whether the IS can acquire and subsequently use WMD. Also important to note is the fact that apart from Aum Shinrikyo, which used chemical weapons albeit ineffectively, the IS is the only terrorist group that has utilized chemical weapons in Syria and Iraq. Even more concerning than the history of chemical weapons use is the fact that the IS has been seeking WMD actively.[384] This concern has been echoed by many world leaders.[385]

There is little doubt that the IS desires to acquire and use biological weapons. In 2014, during the raid on the IS's stronghold in Idlib, moderate Syrian rebels found a laptop containing files instructing IS operatives on the preparation and use of biological weapons.[386] In its propaganda magazine, the IS clearly expressed its desire as well as route to acquiring nuclear weapons. It claimed in May 2015 that it would buy a nuclear weapon from Pakistan within the coming year.[387]

This claim has not hitherto materialized, though it should be considered neither absent nor static because the IS's network and foothold in Pakistan is increasing. Pakistan ostensibly has a low probability of selling a nuclear device to the IS because Pakistan considers the group a national security

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383 Harold Doornbos and Jenan Moosa, "Found: The Islamic State's Terror Laptop of Doom," *Foreign Policy,* August 28, 2014.

384 Stephen Hummel, "The Islamic State and the WMD: Assessing the Future Threat," *CTC Sentinel*, Vol. 9, No 1 (January 2016).

385 After the November 2015 IS attacks in Paris, French Prime Minister Manual Valls echoed this concern by highlighting the risk of a WMD weapons attack by the IS. In June 2015, Australian Foreign Minister Julie bishop had raised the same specter by underlining the IS's desire and increased technical expertise, alluding to a membership base that may overcome technical barriers for the production of WMD. During the 2016 Nuclear Security Summit, President Obama shared the same concern by terming the IS nuclear-radiological threat as real. For PM Valls's statement, see Adam Withnall, "Paris Attacks: ISIS Chemical Weapons Warning Issued by French PM Mnuel Valls," *Independent*, November 19, 2015; Speech by Australian Foreign Minister Julie Bishop to Australia Group Plenary, Perth, Australia, 19 June 2015; for President Obama's concern, see "Barack Obama at Nuclear Summit: 'Madmen' Threaten Global Security," *The Guardian*, April 1, 2016, https://www.theguardian.com/us-news/2016/apr/01/obama-nuclear-security-summit-stop-madmen-isis-terrorism.

386 Harold Doornbos and Jenan Moosa, "Found: The Islamic State's Terror Laptop of Doom," *Foreign Policy*, August 28, 2014.

387 See, *Dabiq*, Issue 9, p. 77, http://media.clarionproject.org/files/islamic-state/isis-isil-islamic-state-magazine-issue%2B9-they-plot-and-allah-plots-sex-slavery.pdf, accessed on October 18, 2016.

threat. Yet the claim does need to be taken seriously given Pakistan's past involvement in illicit nuclear trade and collaboration.

Moreover, within the context of Pakistan, the possibility of insider threat cannot be ruled out. In the past, there has been a reported meeting between two Pakistani nuclear scientists and Osama bin Laden, during which they discussed the possibility of constructing nuclear weapons. In addition, AQ Khan, the father of Pakistan's nuclear weapons program, was involved in illicit nuclear technology trade. The Khan network did not collaborate with any non-state actors, but it raises the possibility of insider collusion involving nuclear material, if not an intact weapon.

Another chilling conclusion that can be inferred from this claim is the possibility that IS has been pursuing a multi-track acquisition path. It is important to note that Mohammad Bakkali, one of the suspects linked to the November 3rd, 2015 Paris attacks, was carrying out surveillance by video-tapping a high-ranking Belgian nuclear official.[388] Some observers have declared it as attempted planning for radiological terrorism.

However, it is unclear whether the surveillance activity was motivated by a radiological terrorism/ acquisition plan or an attempt to acquire fissile material, which Belgium does possess in the form of a civilian Highly Enriched Uranium (HEU) stockpile.[389] The radiological terrorism argument is further undermined by reports that IS already possessed radioactive material at the time of surveillance.[390]

Investigations into this case could clarify the nature of the activities—and in turn the threat—related to the IS's pursuit of nuclear capability. There has been no further disclosure of details, despite the fact that eight people, including Bakkali, have been in detention. However, the available information is sufficient to conclude that there is a possibility that the IS has been pursuing a multi-track acquisition path.

It is clear that the IS has been actively seeking WMD in general and nuclear weapons in particular. Logically, the next questions are as follows: Why is the IS interested in WMD, and nuclear weapons specifically? Can AM accelerate the IS's nuclear weapons aspiration, and if so, how? How can the IS access, if it has not already, AM to realize its goals and objectives? The following analysis investigates these questions.

388 See, "Video Found in Belgium of Nuclear Official May Point to Bigger Plot," *New York Times*, February 18, 2016, http://www.nytimes.com/2016/02/19/world/europe/belgium-nuclear-official-video-paris-attacks.html?_r=0, accessed on October 2, 2016.
389 For Belgium's Civilian stockpiles of HEU, see "Civilian HEU: Who Has What?", NTI, November 2014, http://www.nti.org/media/pdfs/heu_who_has_what_2014_11.pdf?_=1416267490.
390 See, "Isis's dirty bomb: Jihadists have seized 'enough radioactive material to build their first WMD," *Independent*, June 9, 2015, http://www.independent.co.uk/news/world/middle-east/isiss-dirty-bomb-jihadists-have-seized-enough-radioactive-material-to-build-their-first-wmd-10309220.html, accessed on November 22, 2016.

WMD INTENT OF THE IS: WHAT AND WHY?

The preceding findings clearly demonstrate that the IS has been seeking capabilities for nuclear weapons and other advanced chemical and biological weapons. However, it is important to investigate its motivations and the magnitude of this intent to understand its weapon-choice calculus properly. The conclusions drawn from this investigation indicate that the group's ideology, goals, and modus operandi point to strategic and tactical reasons.

To understand those reasons and the magnitude of the IS's motivations, consider its broader ideology, goals, and modus operandi calculations. The IS, unlike other terrorist WMD aspirants, is unique in character, goals, and goal-oriented actions, all of which flow from its ideology.

IDEOLOGY, GOALS, MODUS OPERANDI AND UTILITY OF WMD

The ideology of the IS originates in the Salafi[391] interpretation of Islam. At the heart of its ideology is the idea of Caliphate. It is important to distinguish a Caliphate from the modern state, based on the Westphalian state system, to understand how the IS's ideology, goals, and most importantly, capabilities are useful in the realization of its nuclear weapons acquisition objective.[392]

The IS considers the Caliphate to be defined by the seventh century Islamic state model that was established by the Prophet Muhammad and his companions, Abubakar, Umar, Uthman and Ali, who later became Caliphs.[393] The IS believes that establishing the Caliphate in Iraq and Syria is the first, not the last, step to achieve its broader goal of a borderless universal state.[394]

For the IS, therefore, establishing a territorial state in Iraq and Syria is not the end in itself, but rather a means to an end, namely, establishing a global Islamic Caliphate. It views the world as a struggle between *Dar-ul-harb*—the house of war; areas with a non-Muslim majority and non-Muslim rule—and *Dar-ul-Islam*, the world of Islam. At the very heart of the ideology is the desire to expand *Dar-ul-Islam* until the whole of *Dar-ul-Harb* is converted. By establishing Waliyat (Arabic for "province," or Muslim areas run by affiliates of the IS in states including Egypt, Afghanistan, Pakistan,

391 For IS's version of Salafi interpretation, see Jacob Olidort, "What is Salafism: How a Nonpolitical Ideology Became a Political Force," *Foreign Affairs*, November 24, 2015, https://www.foreignaffairs.com/articles/syria/2015-11-24/what-salafism, accessed on October 10, 2016.

392 For the difference between Caliphate and modern Westphalian State, see Khudduri, *War and Peace in the Law of Islam, Op. Cit.*, pp. 3-19.

393 The very idea of Caliph in Islam manifests subservience of the political to the religious. According to Islamic law, the Caliph implies that human and all his activities are subject to God's (Allah's) mastery (the only Sovereign). According to the Quran, human is God's appointed Caliph (Vicegerent) on earth, and it is his duty to implement his (Allah's) will on earth in all spheres, including politics. According to this conception, the political is to serve the religious. And in the Salafi theory, it cannot be achieved without the establishment of global, borderless Islamic Caliphate. See, Verse 30, Chapter 2 of the Quran, https://quran.com/2/30, accessed on October 30, 2016;

394 Sekulow et. al., *Rise of ISIS: Threat We Can't Ignore, Op. cit.*, pp. 16-25.

Libya) and extending its tentacles throughout the Muslim world, the IS hopes to increase both its ability and its appeal to radicalized Muslims around the globe.[395]

Moreover, the IS has been utilizing unprecedented brutality in its terrorist tactics, cumulatively leading to the conceptualization of its modus operandi. Extreme brutality/savagery for IS is not the end in itself, but rather the means to end (i.e., creation of fear): the IS wields that fear to blackmail/coerce/deter the international community, surpassing other Islamist transnational groups like al-Qaeda and thereby attracting more recruits from the Muslim world.[396] Therefore, it is safe to infer that although the ideology and goals of the group are utopian, its modus operandi is based on pragmatic end-means calculations without any respect for morality and the law of war,[397] making the group more dangerous.[398]

Apart from ultimately establishing a global Caliphate, the IS also seeks to bring about the apocalypse. The IS believes that the time will come when the forces of Islam will fight the forces of "Rome" at Dabiq, Syria—incidentally, the name of its magazine. When Islam triumphs over the forces of evil, it will lead to the final day of the world, the apocalypse. Therefore, the IS considers itself the key agent in triggering the apocalypse.[399] Further, the IS seeks to change US foreign policy, particularly in the Middle East.[400]

Therefore, the ideology, goals, and even modus operandi of the IS should not be confused with those of al-Qaeda. The stated goals of al-Qaeda focus on changing US foreign policy by dint of using violence. It does not seek to establish an Islamic State on the lines that the IS wants to.[401] These fundamental differences between the IS and al-Qaeda are instructive for understanding the IS's WMD motivations and conception of their utility. Without properly understanding the foundational conceptions that lie at the heart of strategic thinking, we cannot understand the significance and utility of WMD to the IS.

Although there is no evidence as to what the IS wants nuclear weapons for, it can argued based on the preceding analysis that mass-casualty terrorism is not the best reason for IS WMD acquisition.

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395 For expanding affiliates and network of the IS, see Daniel Byman, "ISIS Goes Global: Fight the Islamic State by Targeting its Affiliates," *Foreign Affairs* (March/April 2016), https://www.foreignaffairs.com/articles/middle-east/isis-goes-global; Khudduri, *War and Peace in the Law of Islam*, Op. Cit., pp. 3-19;

396 For this see, Gerges, ISIS: *A History, Op. Cit.*, 39-41; Abu Bakr Naji, "The Management of Savagery: The Most Critical Phase through which Umma will Pass," *Treatise,* 23 May 2006, https://azelin.files.wordpress.com/2010/08/abu-bakr-naji-the-management-of-savagery-the-most-critical-stage-through-which-the-umma-will-pass.pdf, accessed on October 24, 2016;

397 Sekulow et. al., *Rise of ISIS: Threat We Can't Ignore, Op. cit.*, pp. 32-42.

398 See, for detailed account of the ideological underpinnings, goals modus operandi and correlation between the three, Yonah Alexander and Dean Alexander, *The Islamic State: Combating the Caliphate Without Borders* (London: Lexington Books, 2015).

399 See, Wood, *What ISIS Really Wants, Op. Cit*.

400 Ibid.

401 For the differences in goals and targets of IS and Al-Qaeda, see Daniel L. Byman, "Comparing Al-Qaeda and ISIS: Different Goals, Different Targets," *Prepared testimony before the Subcommittee on Counterterrorism and Intelligence of the House Committee on Homeland Security*, 29 April 2015, available at https://www.brookings.edu/testimonies/comparing-al-qaeda-and-isis-different-goals-different-targets/, accessed on October 16, 2016.

Most of the recent discourse on sub-state WMD acquisition has blurred the distinction between acquisition and use, assuming that any sub-state terrorist organization that acquires a WMD—particularly nuclear weapon—is going to use it. This approach is flawed and has significant implications for understanding threat and formulating policy.

Against the background of these prior findings, this study concludes that the IS selects certain WMD for strategic, rather than tactical, utility. First, it is important to note that the goal of establishing a state indicates that the IS might try to acquire nuclear weapons for deterrence. Second, its goal of changing US policy might also shape its nuclear policy, motivating acquisition for purposes of coercion/blackmail.

Thirdly, since the IS cherishes the goal of the apocalypse and its own crucial role in bringing that about, it can also utilize the weapons for wreaking mass casualties. However, while considering the overall outlook and modus operandi of the group, it is reasonable to believe that such utility will be considered the ultima ratio by the group.[402] Remember the clear evidence that the group possesses chemical weapons and radioactive material.[403]

Moreover, there are two potential sources of radiological material that are under the control of the IS: medical sources and research facilities at universities.[404] It seems implausible that the group does not know about such sources since it has made several attempts to acquire radioactive, including fissile, material. It used chemical weapons in Syria and Iraq, but never used radiological weapons, which raises serious question regarding the group's thinking and calculations about WMD utility. Therefore, it seems more likely that the group is not currently considering acquisition or use of radiological weapons for tactical purposes, though it could be a possibility in the future. The IS may be most likely to use radiological weapons in the case of exhaustion. It might utilize these weapons for

1. Domestic consumption;
2. Bolstering internal organizational morale and determination;
3. Saving face within the global Jihadi movement;
4. Project resilience of the group abroad in times of severe pressure; and/or
5. Pursue its goals and ends of its ideology when it has exhausted all other possibilities.

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402 Omar Al-Sheshani, the IS's Military commander for its forces in Syria, said "we will bring back the caliphate, and if God does not make it our fate to restore the caliphate, then we ask him to grant us martyrdom." This statement clearly shows the adjustment of goals; it places the establishment of Caliphate as the primary goal. The reference to martyrdom indicates a commitment to bringing the apocalypse by using violence even if it results in death, the *ultima ratio*. See Martin Chulov, "How an Arrest in Iraq Revealed ISIS's $2 billion jihadist Network," *Guardian*, June 15, 2014, https://www.theguardian.com/world/2014/jun/15/iraq-isis-arrest-jihadists-wealth-power, accessed on October 24, 2016.

403 See, "Isis's dirty bomb: Jihadists have seized 'enough radioactive material to build their first WMD," *Independent*, June 9, 2015, http://www.independent.co.uk/news/world/middle-east/isiss-dirty-bomb-jihadists-have-seized-enough-radioactive-material-to-build-their-first-wmd-10309220.html, accessed on November 22, 2016.

404 See, Hummel, "The Islamic State and the WMD: Assessing the Future Threat," *Op. Cit.*, p. 19.

This study finds that nuclear weapons stand at the top of the IS's weapons choice list, as established above. However, this finding is accompanied by a caveat: the barriers to nuclear weapons acquisition—even a IND requiring far lower level of technical expertise and resources—are rather hard to overcome for any sub-state terrorist group, including the IS. Nonetheless, as the following subsection demonstrates, uncontrolled access to changing technology may downgrade many technical barriers. AM has the cumulative potential to mitigate at least some hurdles related to device construction, technical expertise, and technological base. Therefore, access to AM in Makerspaces or otherwise—now easily accessed by the IS and other groups—facilitate the terrorists in many ways.

EXISTING CAPABILITIES AND ACCESS TO AM: THE ROUTES

Surpassing technological barriers to acquire nuclear weapons or the missile capability for delivering them is the hardest task even for state actors with huge resources, a technological base, infrastructure, expertise, and domestic legitimacy underpinning their activities. The top hurdle is acquisition of fissile material. Terrorists, on the other hand, face a far greater degree of difficulty in acquiring these weapons, as has been established in preceding analyses.

However, there is a major distinction between a terrorist organization's nuclear weapons capability and that of a state: even a crude nuclear device is sufficient for any terrorist group's purposes if it is for deterrence, coercion, blackmail, or even mass-casualty terrorism. Unlike states, terrorists do not require production capability. This has major implications for the capabilities required to build such weapon. It diminishes, though does not eliminate, the technical and technology-related hurdles in terrorists's acquisition path.

Unfortunately, the IS possesses some worrisome capabilities that, if combined with AM, can arguably help the IS overcome the barriers to building a workable nuclear weapon. First, the IS enjoys substantial financial capabilities. According to one source, it is the richest jihadist terrorist organization in the world, with a $2 billion financial base.[405] Second, it controls a large swath of land, providing it with the best ungoverned sanctuary for a clandestine nuclear weapons production facility with low risk of detection. Third, it has the potential to connect to the nuclear black market. A recent report revealed the presence of a nuclear black market in the former Soviet Union, involving an uncovered case in which a Moldovan criminal network member tried to convince an IS member—actually an undercover agent of the Federal Bureau of Investigation (FBI) on sting operation—to buy nuclear material.[406],[407]

Moreover, it is important to note that the group has some strong connections to Chechen terrorists, who can possibly help the IS acquire fissile material. Abu Omar al-Shishani, the IS's military commander in Syria, is an ethnic Chechen and maintains close relations with the Chechen terrorists, who

405 Chulov, "How an Arrest in Iraq Revealed ISIS's $2 billion jihadist Network," *Op. Cit.*

406 The material in this deal was Cesium-137, not fissile material. However, it does raise questions regarding possible collusion between the nuclear black market and the IS.

407 See, Kathy Gilsinan, "Why Moldova May be the Scariest Country on Earth: A New Report Details a Black Market in Nuclear Material," *The Atlantic*, October 8, 2015, http://www.theatlantic.com/international/archive/2015/10/moldova-nuclear-weapons-isis/409456/, accessed on November3, 2016.

are considered to have relations with some Russian nuclear scientists.[408] This substantially increases the ability of the IS to access the nuclear black market in Russia and the former Soviet Union, where many orphan sources, corruption, and the nexus between the criminal network and black market can help the IS acquire fissile material.

Some experts have raised logical questions about the possibility of collusion between North Korea and the IS.[409] With sanctions increasing the economic pressure on North Korea, there is a possibility that North Korea could sell its nuclear information, expertise, critical knowledge, or even weapon blueprint to the IS, especially given North Korea's past unscrupulous illicit nuclear trade with Pakistan. However, it seems likely that North Korea would not sell the whole nuclear device because of the threat of retaliation from the US that might follow a post-detonation/declaration attribution of the weapon to North Korea.[410]

Further, in the case of Pakistan, the possibility of insider collusion with the IS cannot be ruled out. The IS has an increasing presence in the country, Pakistan's populace is increasingly radicalized, and the county's bureaucracy is regarded as considerably corrupt. The past cases of the AQ Khan's illicit transfer of equipment and knowledge, and a meeting between Pakistani nuclear scientists and al-Qaeda leadership in Afghanistan a month before the 9/11 terrorist attacks, raise serious concerns about the susceptibility of Pakistani fissile material and knowledge security to insider collusion with the IS.[411]

As shown above, the IS stands a chance of gaining access to fissile material for its nuclear weapons. It is logical to wonder about the possibility that AM will be misused by the group to construct a workable device. It has been established above that the group already possesses some of the major capabilities required to surpass technical barriers.

The IS has been involved in the manufacturing of Improvised Explosive Devices (IEDs)—though based on subtractive manufacturing techniques and tools like lathes—as well as weaponized drones and other small arms manufacturing, indicating its ability to maneuver within the technical domain. Moreover, according to recently revealed documented evidence, under the command and supervision of its Committee for Military Development and Production, the IS has established a Research and Development component for manufacturing and innovating different arms. This

408 See, Yonah Alexander and Dean Alexander, *The Islamic State, Op. Cit.*, p. 116; Bassem Mroue, "Chechen in Syria a Rising Star in Extremist Group," *AP*, July 2, 2014, http://www.usnews.com/news/world/articles/2014/07/02/chechen-in-syria-a-rising-star-in-extremist-group, accessed on October 18, 2016.

409 Tom Batchelor, "Fears grow North Korea could SELL nuclear secrets to ISIS in terrifying coalition," *Express*, March 30, 2016, http://www.express.co.uk/news/world/656742/North-Korea-nuclear-threat-grows-amid-fears-Islamic-State-could-buy-atomic-secrets, accessed on November 3, 2016.

410 For detailed analysis and argument on why states won't dare give their nuclear weapons to terrorists, see Keir A. Lieber and Daryl G. Press, "Why States Won't Give Nuclear Weapons to Terrorists," *International Security*, Vol. 38., No. 1, (Summer 2013), pp. 80–104.

411 For AQ Khan network and its activities, see Gordon Corera, *Shopping for Bombs: Nuclear Proliferation, Global Security, and the Rise and Fall of the A. Q. Khan Network* (New York: Oxford University Press, 2006); and William Langewiesche, *The Atomic Bazaar: Dispached from the Underground World of Nuclear Trafficking* (New York, Farrar, Straus and Giroux, 2007); Kroenig, *Exporting the Bomb, Op. Cit.*, pp. 111-150.

indicates that the IS possesses the capacity for organizational learning and adaptation to different innovate manufacturing techniques.[412]

The following analysis investigates how the IS can potentially access AM and Makerspaces by utilizing its capabilities and exploiting loopholes in the global strategic control regimes. In this regard, the investigation has found that there are two possible, easy ways in which the IS can access AM, Makerspaces, and the necessary expertise to exploit the technology for its weapons purposes:

» Purchasing from the open market; and/or

» Accessing AM Makerspaces that exist already within the operational realm of the IS or its affiliates.

This investigation finds that the IS will require access to AM and Makerspaces through other countries because of two primary reasons: first, import of such technology to Syria or even Iraq is not possible; second, any such attempt would alert the security forces that are watching the region vigilantly, at least from the angle of trade controls. Nevertheless, there is a high plausibility that the IS can use some of its members/affiliates in advanced countries in Europe or elsewhere.[413] In this regard, it is worth noting the recent revelations regarding the procurement of components the IS uses in the manufacturing of its IEDs. First, it has been discovered that the IS has manufactured IEDs and related arms equipment, including weaponized drones, on a quasi-industrial scale and in a rather organized manufacturing network established within the IS's territory.[414] More surprising is the fact that it has cobbled together a supply-chain network involving some fifty companies spanning over twenty countries.[415] There is documented evidence that within this network, Turkey has been the chokepoint of this illicit procurement supply chain, which raises the possibility that the IS possesses the ability to illicitly procure AM technology and related material through Turkey.[416] More importantly, the IS can utilize its network to exploit the existing Makerspaces and AM in the countries where it enjoys operational presence and has affiliate groups.

This study finds that there exists no documented unclassified evidence indicating that the IS or any other terrorist group has used 3D printing in the construction of weapons—either conventional or unconventional. However, as mentioned above, the technology is available in Makerspaces within certain operational realm of the group and its affiliates. The present study has found clear evidence

412 See, "TRACING THE SUPPLY OF COMPONENTS USED IN ISLAMIC STATE IEDs: Evidence from a 20-month investigation in Iraq and Syria," *Conflict Armament Research*, Investigative Report, February 2016, http://www.conflictarm.com/wp-content/uploads/2016/02/Tracing_The_Supply_of_Components_Used_in_Islamic_State_IEDs.pdf, accessed on December 16, 2016.
413 For increasing numbers joining the IS from Europe, see Kukil Bora, "ISIS Recruiting Increasingly Young Europeans; About 4000 joined Islamic State in Syria: EU," *International Business Times*, June 18, 2015, http://www.ibtimes.com/isis-recruiting-increasingly-young-europeans-about-4000-joined-islamic-state-syria-eu-1972462, accessed on October 29, 2016; See, Byman, "ISIS Goes Global," *Op. Cit.*.
414 See, "TRACING THE SUPPLY OF COMPONENTS USED IN ISLAMIC STATE IEDs: Evidence from a 20-month investigation in Iraq and Syria," *Conflict Armament Research*, Investigative Report, February 2016, http://www.conflictarm.com/wp-content/uploads/2016/02/Tracing_The_Supply_of_Components_Used_in_Islamic_State_IEDs.pdf, accessed on December 16, 2016.
415 Ibid.
416 Ibid.

that the technology and easily accessible Makerspaces are present in the following countries, which have either existing IS strongholds or increasing IS influence:

» Afghanistan,

» Turkey,

» Pakistan,

» Egypt, and

» Morocco.

These countries will be analyzed separately within the framework of possible AM misuse by the IS.

It is surprising that despite an adverse security situation in the region, given the potential for misuse of 3D printers and AM even in conventional weapons manufacturing, there are readily available 3D printers and even Makerspaces.[417] As established above, it is not AM that is the threat, but rather AM's dual-use nature that is susceptible to terrorists as well as state actors from the proliferation perspective. The presence and uncontrolled access of such technology raises serious questions about the possibility of misuse. The IS established a Waliyat, named Khurasan, in the Afghanistan-Pakistan region in January 2015.[418] It has also compiled affiliations with other regional groups like the Tehrik-i-Taliban Pakistan (TTP), which is based in Pakistan but has a presence in Afghanistan as well.

As argued at the outset of this paper, there is a substantial possibility that these groups can help the IS access AM technology for weapons acquisition. Moreover, the absence of restrictions on the import of 3D printing technology in Afghanistan adds fuel to the fire. The IS can exploit this vulnerability by importing printers into Afghanistan and, if required, smuggling them from there.

As mentioned above, the IS seems to have established its network in Turkey.[419] There are not only 3D printing Makerspaces accessible to the public, but also 3D printer markets, from which the IS can ship printers to Syria as it procures the components of its IEDs.

The same problem is present in Pakistan. The country has been facing a new wave of terrorism accompanied by radicalization of the population, leading the IS to recruit Pakistanis increasingly.[420] According to authoritative top Pakistani security and intelligence officials, the IS has become a threat

417 See, "Printing Service Companies in Afghanistan," http://www.printingservices1.com/printing-companies/afghanistan.html, accessed on November 1, 2016.

418 See, Tariq Parvez, "The Islamic State in Pakistan," *The United States Institute of Peace*, Policy Brief 213 (September 2016), http://www.usip.org/publications/2016/09/21/the-islamic-state-in-pakistan, accessed on November 10, 2016

419 For this, see Aaron Stein, "Islamic State Networks in Turkey: Recruitment for the Caliphate," *Atlantic Council*, Issue Brief (October 2016), http://www.publications.atlanticcouncil.org/wp-content/uploads/2016/09/Islamic-State-Networks-in-Turkey-web-1003.pdf, accessed on December 12, 2016.

420 "IS Recruiter Arrested in Karachi," *Dawn*, January 2, 2016, http://www.dawn.com/news/1230186, accessed on November 14, 2016.

to the state of Pakistan, clearly implying that the IS has already established itself in the country.[421] Moreover, some top commanders that started in the TTP later pledged allegiance to IS.[422]

It is unfortunate that there are not only 3D printing services available in Pakistan, but a fully accessible Makerspace as well. Furthermore, this Makerspace is located in the city of Karachi, which has been a major target of terrorism, extremism, and jihadi activities for the past many years. This Makerspace is available in NED University of Engineering and Technology, which has unrestricted access to any hobbyist. More depressing is the fact that a former engineering student of the university, who later lectured at Shaheed Zulfiqar Ali Bhutto Institute Science and Technology, was arrested by counterterrorism authorities for his connection to the banned terrorist organization Hizbut Tahrir (HT). Although there is controversy regarding the nature of the relationship between HT and the IS, this example demonstrates the susceptibility of unregulated spaces that the IS can exploit easily.

It is important to note here that the government of Pakistan has enacted new restrictions on the import of 3D printers.[423] According to the new Strategic Trade Policy framework of 2015–2018, importation of 3D printers requires a No Objection Certificate (NOC) from the Pakistani Ministry of Interior.[424]However, this policy seems to have no major impact because such products can be imported to the country without NOC through corruption and bribery, even amongst customs officials directly checking the entrance of travelers at Pakistan's airports.[425]

Smuggling is another easy option for the IS, which already undertakes substantial smuggling activities between Pakistan and Afghanistan.[426] This route has easy access and requires no NOC. Therefore, the IS can easily exploit the Pakistani rules and regulations to realize its goals of either acquiring its own 3D printing resources or utilizing the existing Makerspace—open to everyone, including members of banned terrorist jihadi groups. This creates a worrisome situation that can be exploited easily by the IS and its affiliates.

421 See for the analysis of a former Chief of the national Counter Terrorism Authority of Pakistan Tariq Parvez, Parvez, "The Islamic State in Pakistan," *Op. Cit.*; for the current chief of the Intelligence Bureau (IB) Aftab Sultan's statement, see "IS Emerging as a Threat, Wars IB Chief," *Dawn*, February 11, 2016, http://www.dawn.com/news/1238771, accessed on October 18, 2016.

422 "EX-TTP Members Pledge Allegiance to ISIS," *Dawn*, January 11, 2015, http://www.dawn.com/news/1156376, accessed on November 20, 2016.

423 See, "Strategic Trade Policy Framework 2015-2018," *Governement of Pakistan*, http://www.commerce.gov.pk/wp-content/uploads/2016/03/STPF-2015-18-Document.pdf, accessed on October 28, 2016; Mubarak Zeb Khan, "Government to Allow Import of New Products," Dawn, December 06, 2015, http://www.dawn.com/news/1224443, accessed on October 28, 2016.

424 Ibid.

425 See, "Islamabad Custom Official Offers to not Check Luggage in Exchange of Money Drink," *Express Tribune*, March 9, 2015, http://tribune.com.pk/story/850342/islamabad-airport-custom-official-offers-to-not-check-luggage-in-exchange-of-money-drink/, accessed on November 8, 2016.

426 Amraiz khan, "Afghan Transit Trade Main Smuggling Funnel," *The Nation*, May 11, 2015, http://nation.com.pk/national/11-May-2015/afghan-transit-trade-main-smuggling-funnel, accessed on November 28, 2016.

In Morocco, French companies are bringing that 3D printing and metal 3D printing into the country, alongside industrial competence.[427] According to experts, the IS threat has been increasing in Morocco. In conjunction with increasing uncontrolled access to AM, related technology, and expertise, the increasing presence of the IS is worrisome from the standpoint of microproliferation.[428]

Lastly, AM Makerspaces exist in Egypt as well, and may be vulnerable to the IS's acquisition efforts especially as Egypt witnesses a rise in IS influence.[429] A new group Egypt, called "Misr" (Arabic word for Egypt), has claimed allegiance to the IS.[430] The affiliation of this group may help the IS take advantage of the openly accessible 3D printing Makerspace mentioned above for its acquisition purposes.

This investigation therefore suggests that if the IS were interested in utilizing AM, it will face no difficulty in accessing the technology and expertise, as long as the technology stays uncontrolled and unregulated. The IS can access the technology directly or through its affiliate groups in several vulnerable Islamic countries.

CONCLUSION

The study finds that there are some terrorist groups that might be interested in WMD microproliferation. However, there are just a few that possess the level of will and basic capabilities required to go down this path. Among those few, only one terrorist group has both expressed its high level of intent to acquire WMD and acquired the basic capabilities to pursue this ambitious and difficult task. The investigation has found that the IS stands a substantial chance of exploiting vulnerabilities in the system for its WMD acquisition programs.

It is observed that the IS also possesses the ability to access Makerspaces, either directly or through its expanding network of affiliates. Makerspaces exist in many countries—most notably Afghanistan, Turkey, Pakistan, Morocco, and Egypt—that are within the operational realm of the IS or its close affiliates. The most susceptible countries are also those with available and easily accessible technology. Moreover, the study discovered that in these countries, the IS has been expanding its influence and presence, which it can leverage to access and misuse AM to acquire WMD.

Finally, it is observed that the unregulated and uncontrolled access of 3D printing technology might easily end up in hands of terrorists, thereby becoming a major enabling factor in any future sub-state nuclear weapons program. Therefore, the study finds that access to 3D printing technology needs to be controlled through a revision of strategic trade control regimes before AM falls into the hands of terrorists and is misused in a WMD program.

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427 See, "Thales Brings Metal 3-D Printing to Morocco with New Industrial Competence Center," December 11, 2015, http://www.3ders.org/articles/20151211-thales-brings-metal-3d-printing-to-morocco-with-new-industrial-competence-center.html, accessed on November 27, 2016.

428 See, Sirwan Kajjo "Islamic State Threat Rising in Morocco, Analysts Say," *VoaNews*, March 9, 2016, http://www.voanews.com/a/islamic-state-threa-rising-morocco/3227858.html, accessed on December 1, 2016.

429 See, Fab Lab Egypt, http://fablabegypt.com, accessed on November 26, 2016.

430 See, Daniel Nisman and Michael Horowitz, "New Islamic State Franchise Threatens Egypt," *Reuters*, February 16, 2016.

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