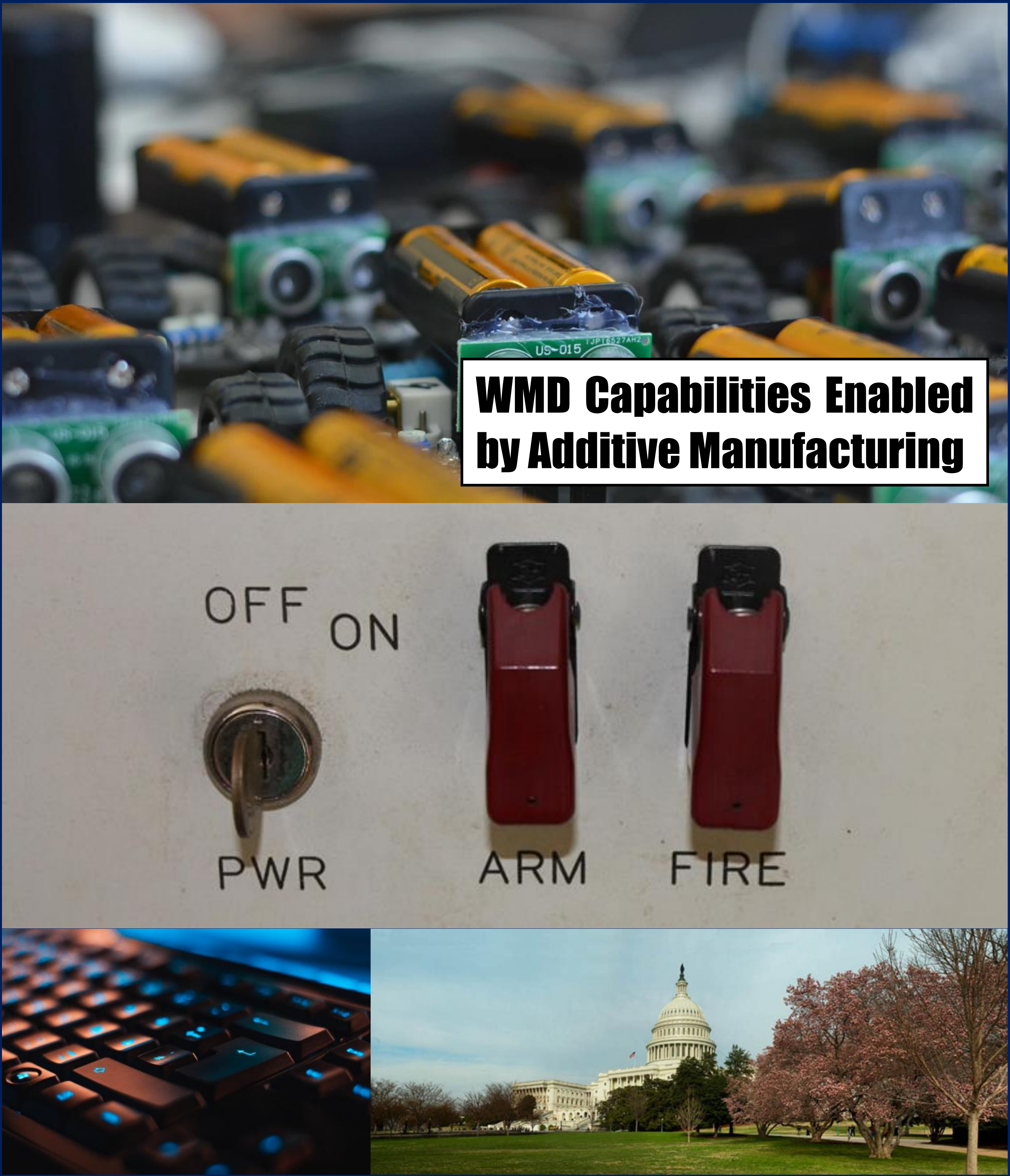
WMD Capabilities Enabled by Additive Manufacturing



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PROJECT ON WMD CAPABILITIES ENABLED BY ADDITIVE MANUFACTURING

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Abstract

WMD Capabilities Enabled by Additive Manufacturing

Additive Manufacturing (AM) is emerging at a rapid pace. The critical fields of metal, ceramics, and ultra-strong polymers have seen significant changes in the scope of AM applications over the past 18 months alone. The growing relevance of AM in the proliferation of Weapons of Mass Destruction (WMD) is of increasing concern for scholars and policymakers. Previous studies addressing the issue have largely concentrated on AM's potential impact on nuclear proliferation. What had remained underexplored was its growing impact on WMD delivery systems as well as on chemical and biological weapons programs.

This project highlights recent developments in AM relevant to nuclear proliferation and adds analyses of the impact of AM on delivery systems as well as chemical and biological weapons programs. Focusing on AM developments in both North America and Western Europe, this report maps latest AM developments, projects AM development out to 2030, and applies those findings to WMD proliferation pathways. Breaking new ground, project findings provide experts as well as government officials with a well-supported window into emerging risks and threats as a basis for strategic planning.

Project Team

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Professor Dr. Christopher Daase is one of Germany's most acclaimed international relations scholars. He is the Deputy Director of Peace Research Institute Frankfurt (PRIF), the head of PRIF's International Security Research Department, Professor for International Relations at Goethe University Frankfurt, and a subject matter expert with Negotiation Design & Strategy (NDS). Professor Daase coordinates PRIF's activities in the steering committee of the EU Non-Proliferation Consortium. He is a co-editor of Arms Control in the 21st Century: Between Coercion and Cooperation (Routledge, 2017) and has published over 50 monographs, edited volumes, and academic articles on security politics, international institutions, and international law.

Grant Christopher

Dr. Grant Christopher is a senior researcher at VERTIC, a London-based think tank focused on supporting the development, implementation and verification of international agreements. There he researches nuclear non-proliferation issues, including assessment of emerging technologies. Prior to joining VERTIC, Grant was a Research Fellow at King's College London and the spinout company Ridgeway Information, focused on non-proliferation. Before working on nuclear issues, Grant was a research scientist, and was a member of the collaboration that discovered the Higgs boson at CERN.

Ferenc Dalnoki-Veress

Dr. Ferenc Dalnoki-Veress is a physicist whose work at the Middlebury Institute of International Studies (MIIS) at Monterey's James Martin Center for Nonproliferation Studies (CNS) bridges science and policy. He uses physics to develop methods of detecting clandestine nuclear weapons activity and also works on proliferation of fissile materials, nuclear spent fuel issues, and verification of arms-control treaties. Ferenc was part of the team that was cited in the 2015 Nobel Prize for Physics and in the 2016 Breakthrough Prize in Physics.

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Miles Pomper is a Senior Fellow in the Washington DC office of the James Martin Center for Nonproliferation Studies (CNS). He is the author of numerous reports, book chapters, and articles on nuclear nonproliferation, nuclear energy, nuclear security, and nuclear arms control. He holds a master's degree in international affairs from Columbia University and a master's degree in journalism from Northwestern University.

Robert Shaw

Robert Shaw is the Director of the Export Control and Nonproliferation Program for the Middlebury Institute of International Studies (MIIS) at Monterey's James Martin Center for Nonproliferation Studies (CNS). His research interests include strategic trade controls and their relationship with emerging dual-use technologies such as additive manufacturing, industry-based due diligence strategies to counter illicit WMD-related trafficking and supply chain networks, and the growth of nonproliferation-attuned export and trade compliance professional communities. Prior to joining CNS in 2010, Mr. Shaw worked for over a decade in the private sector, specializing in export control compliance and international supply chain management.

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Contents

Foreword

WMD Capabilities Enabled by Additive Manufacturing

Additive Manufacturing (AM) is a rapidly emerging technology with growing relevance for the proliferation of Weapons of Mass Destruction (WMD) and their means of delivery. The rapid pace of AM development makes it increasingly difficult to keep track of AM's potential impact on proliferation pathways.

As an innovative pilot study, this report provides a comprehensive approach towards explaining latest AM developments and mitigating the risk of WMD proliferation. Effectively, this report is the first beyond-the-horizon assessment of the impact of AM developments not only on potential nuclear weapons programs, but also relevant to other WMD modalities and their delivery systems.

For this project, Negotiation Design & Strategy (NDS) assembled an expert team of well-known AM and nonproliferation specialists from Germany, the United States, and the United Kingdom, three countries at the forefront of AM development. The research team's contextual knowledge of AM facilities in Europe and the United States allowed for in-depth on the ground interviews with U.S. and European experts from the private sector, national laboratories, and research institutions. Interviews were augmented with an analytical deep dive into latest AM developments, based on open source technical literature, including academic papers and patents.

The final report allows us to better forecast technological developments and raises awareness for the critical role that AM plays in international security. This report also demonstrates the importance of emerging technologies in the nonproliferation field and underscores the need for further research of this kind. Studies such as this report are crucial to inform the broader examination of the relationship between technology and international security.

I would like to thank all "WMD Capabilities Enabled by Additive Manufacturing" project team members for their hard work and professionalism that made this report possible. My colleagues and I thank NDS for facilitating our research and overseeing this project to successful completion.

Professor Dr. Christopher Daase
Principal Investigator, Project on WMD Capabilities Enabled by Additive Manufacturing

September 3, 2019

Executive Summary

Our Study: Goal and Acknowledgements

This report summarizes the findings and analysis of our study titled "WMD Capabilities Enabled by Additive Manufacturing."

The goals of this study are to: a) examine current developments in Additive Manufacturing (AM); b) understand how the technology's anticipated trajectory across the next decade may impact pathways for Weapons of Mass Destruction (WMD) proliferation; and thereby; c) inform nonproliferation policymakers and practitioners in order to help them shape strategies to mitigate proliferation risks associated with expanded AM capabilities and use.

The contributors to this report would like to acknowledge research and analytical support provided by Cameron Henderson and Adin Insoft. The contributors would also like to acknowledge the support and inspiration provided by Ulrich Kühn and Marco Fey in the conceptualization of this study.

Additionally, the project team wishes to express our sincere thanks for the generous support provided by the Project on Advanced Systems and Concepts (PASCC). This support enabled this study to be realized and was essential to the publication of this report.

The Context: Current Policy Concerns

The purpose of this report is to raise the awareness of proliferation risks associated with additive manufacturing or AM. In the past, people were quick in identifying the technology's huge opportunities, but also the dangers for national and international security. The risk remains that malign state and non-state actors could acquire the technological means to independently produce complex components of weapons of mass destruction. But the question of 'how big is the risk and what can be done about it?' persists.

Given the great uncertainties associated with new technologies, our report sets out to shed some light on recent developments in the field of AM and related technologies, on US activities especially related to the aerospace sector, and on developments in Europe as they appeared in a recent tradeshow and conference in Germany, and on whether and how they open possible proliferation pathways.

Technological innovations can affect international security gravely as history can tell. The so-called new technologies, however, differ from earlier technological innovations in three important aspects. First, new technological innovation is no longer focused on hardware, but increasingly on software, i.e. knowledge, know-how and skills, which are much more difficult to control than hardware. Second, new technological innovation no longer follows the linear process of basic research, applied research, development and production, but discontinuously so that advances in basic research can have instant effects on production and distribution. Third, new technological innovation is no longer driven by the military but by the civilian sector, making control much more difficult than in the past. It remains true, however, if technological innovation favors the defensive, states and societies are likely to feel secure and stable. If technological innovation favors the offensive, possible attackers have an advantage and instability results.

To assess the impact of technological innovations on international security, it is important to differentiate between "sustaining innovation" and "disruptive innovation" leading to military revolutions or as we say game-changing developments. While AM is in many ways still a sustaining innovation insofar as it makes existing production quicker, cheaper and easier, it could have disruptive effects in four different ways:

1. Western armed forces could lose their technological edge because adversaries could use AM to copy or develop advanced weapon systems.
2. Malign state and non-state actors could use AM to accelerate their biological, chemical and even nuclear programs and conceal such efforts for a long time.
3. Terrorist groups could use AM to get access to weapons which were previously out of reach or which they could only obtain with the support of state sponsors.
4. New technologies, such as AM, Artificial Intelligence, nanotechnology etc. could continue to converge and create asymmetrical threats through game changing capabilities we cannot even imagine.

Some of these risks are already materializing. Others are less likely or even speculative. These technological developments must be observed closely, and possible disruptive effects must be identified – if at all possible – before they manifest into threats. That is the purpose of reports such as this one, and of international cooperation in security studies of which this report is a product.

This Report: Structure and Analysis

This report is organized into three distinct sections of analysis:

1) A foundational overview of proliferation-relevant developments in AM from 2015 to 2019, plus an analysis of AM trends, particularly those relevant to nuclear uses.
2) A case study-oriented analysis of AM trends in the US, with a focus on AM use in the aerospace sector and the relevance of this to proliferation of missiles as WMD delivery systems
3) A case study-oriented analysis of the 2019 RapidTech 3D printing tradeshow and conference held June 25-27 in Erfurt, Germany and offering a view into AM developments in Germany as well as a snapshot of the entire AM supply chain.

While the first section emphasizes nuclear-relevant uses of AM, many of the developments surveyed have relevance to other WMD. Additionally, our study includes an Annex describing the potential use of AM to produce chemical- and biological-weapons related equipment on the Australia Group's export control lists.

Regarding the second and third sections, two factors guided the decision to write case studies of AM developments in the US and Germany respectively: 1) actual deployment of AM is especially visible in the US commercial space launch vehicle industry and the US defense industry – both of which are highly relevant to missiles as a WMD delivery systems (thereby offering a clue into how proliferators might use AM in illicit missile development efforts); and 2) the AM supply chain is well-developed in Germany, which is recognized as home to leading manufacturers of 3D printers as well as universities and institutions conducting research on AM technology and its uses. Examining AM development and use cases in the US and Germany also provides a useful and necessary benchmark against which similar developments in other countries – notably China and Russia – can be evaluated in the future.

Key takeaways from these analytical sections are then discussed in this report's Conclusion.

A brief summary of these takeaways is provided in this Executive Summary, in the following sub-section.

Note: With recently published studies covering AM developments relevant to biological weapons nonproliferation, we did not focus on this WMD modality. However, an Annex is included offering a table-based analysis of potential for Australia Group control listed-equipment to be manufactured using AM.

Key Findings

Discussed in more depth in this Report's Conclusion, takeaways identified through this study's analysis are briefly summarized in bulleted format below:

- Delivery systems – namely missiles – remain the WMD proliferation modality most likely to be impacted in the near-term by ongoing developments in AM. This is illustrated by the actual deployment of AM in supply chains used in the aerospace industry, particularly those companies involved in the manufacturing of spacecraft launch vehicles such as Ariane.

- AM is converging with other emerging technologies, most notably AI-oriented tools such as machine learning and generative design. While the actual implications of this convergence is still unclear, these tools are enabling the development of novel structures that can be produced using only AM. Across a variety of applications, such structures have the potential to reduce materials and component costs both for legitimate AM users as well as proliferators engaged in proscribed WMD programs.

- The AM supply chain is becoming increasingly multifaceted featuring niche actors supplying specialized materials (metal powders and plastic resins), 3D printing equipment, 3D printing services, design services, software, and software integration. These actors include both established corporations as well as start-up enterprises. Additionally, industry-university collaborations can be found throughout this supply chain. The result is a wide range of conduits by which proliferators can exploit emerging AM-focused supply chains, in order to access AM capabilities or acquire AM-specific know-how. At the same time, more established actors in the AM supply chain – such as large manufacturers of 3D printers and the aerospace companies using their products – have implemented internal export compliance programs and are aware of the dual-use nature of AM technologies and associated export control requirements. This mitigates the risk to some degree, but not completely as smaller or start-up enterprises entering the AM industry space may be less aware of such requirements.

- Failure of AM start-ups may itself present a risk, in that engineers and software developers attuned to the AM field are forced to re-enter the job market. Accordingly, they may be targeted for recruitment by proliferators seeking sources of know-how.

- The full potential of AM – particularly related to use of multi-materials, layered electronics, and generative design to produce truly novel items that are not substitutes for existing products – may not have yet been realized. Although evaluating proliferation risk in this context is highly speculative, the potential for a 'black swan'-type event involving an AM-centered military program to acquire truly novel unconventional/asymmetric military capabilities cannot be ruled out. "AM-centered" would refer to a scenario in which a proliferating state or non-state actor deliberately approaches the acquisition of such unconventional/asymmetric capabilities by bringing together a team of AM specialists and commission them with the task of "producing something new, powerful and not yet seen before" using AM. It is possible this could even be used by a state otherwise not expected to be a WMD proliferator, in that this effort would be truly below radar and perhaps not in apparent violation of treaties/regimes.

Policy Recommendations

Our hope is that the findings as described above will inform non-proliferation policymakers as they craft strategies to mitigate the potential proliferation risks of AM. With this in mind, and even though some fall beyond the specific task of this study, the contributors offer the following recommendations related to non-proliferation policy regarding AM:

- Closely monitor ongoing AM developments, particularly in the aerospace sector, and engage enterprises and other participants in AM-focused supply chains to develop appropriate proliferation risk management strategies. While developments in other industry sectors should also be monitored, AM deployment in aerospace-related supply chains is particularly advanced.

- Promote effective, informed implementation of regulatory-based national security reviews on cross-border investment activity in AM-related enterprises, as well as provide information and best practices-sharing with international partners implementing similar controls in overseas jurisdictions.

- With respect to export control strategies and AM, multilateral regimes (especially the MTCR and Wassenaar) and national governments should promote the development of AM-specific best practices on Intangible Technology Transfer (ITT) controls and WMD-related ‘catch-all’ (end-use and end-user) controls. These best practices should be crafted for both government officials implementing export controls and for export compliance officials in the industry.

- US and allied governments should explore ‘red-teaming’ simulations, in which specialists play the role of bad actors and are tasked with developing AM exploitation strategies to yield unconventional or asymmetric military capabilities. Exploring “outside-the-box” scenarios in particular should be encouraged, with an aim specifically to develop possible indicators of an emergent ‘black swan’ scenario of AM-driven proliferation. While the red-teaming and its detailed results will need to be handled discretely, the corresponding indicators (‘red flags’ of possible diversion of an AM-focused supply chain to support proliferation) should ideally be shared with industry and other stakeholders in the evolving AM supply chain.

- International cooperation, particularly in the form of information sharing and best practices must be a priority. Strengthening international mechanisms and governance will be key in facilitating this, as AM supply chains are globally distributed, and the relevant export controls (namely ITT controls and catch-all controls) are among the most challenging to implement.

Additive Manufacturing developments from 2015-2019

Introduction

Technological innovations can provide benefits to national defense programs, but they can also present opportunities to an array of threat actors. While we suspect that additive manufacturing (AM) will impact WMD production equipment and WMD delivery systems, we do not know, in 20-30 years' time, what the critical use cases will be.[1] The primary impacts of AM oft cited for security applications are the production of replacement parts in the field[2] and shortening product development cycle. This will be more relevant for military operations than WMD programs. AM's salience for WMD and delivery systems lies in its dual-use nature and flexibility, innovations that could "*lower the technological threshold for countries or non-state actors to independently build complex components of modern weapon systems".*[3] For WMD, the relevant components are not the weapons systems themselves, but production equipment for fissile material, chemical or biological payloads The possibility of undercutting export controls[4] or the use of cyber espionage to acquire sensitive designs both increase the likelihood of proliferation of sensitive military technology.[5]

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[1] "We only have a limited sense of the ultimate potential of new technologies and what lies ahead". (p. 86) "For each innovation we can think of there will be a positive application and a dark side." p. 88. From Klaus Schwab, *The Fourth Industrial Revolution* (Currency, 2017).

[2] Ibid.p.86. Schwab also considers the production of new types of warheads, presumably conventional, that have 'greater control of particle size and detonation.

[3] Deutscher Bundestag, "Technikfolgenabschätzung (Ta) Additive Fertigungsverfahren „3-D-Druck" ", No. Deutscher Bundestag, Deutscher Bundestag, 2017.

[4] Grant Christopher, "Use of 3d Printing to Bypass Nuclear Export Controls," (2016).

[5] "Technikfolgenabschätzung (Ta) Additive Fertigungsverfahren „3-D-Druck" ", 2017. pp. 22-23. Full quote (translated from German): Additive manufacturing processes could also play a role in the military and security context. Due to their pronounced flexibility, the processes are predestined for dual-use applications. They could lower the technological threshold for countries or non-state actors to independently build complex components of modern weapon systems (drones, rocket engines, etc.) and other armaments. Existing export restrictions on sensitive armaments and dual-use goods could be undermined by the highly virtual additive process chain, as digital 3-D models are more likely to illegally cross borders than material goods. At the same time, the risk of technology espionage or theft increases. Overall, additive manufacturing could thus contribute to the proliferation of defense technologies, which is why there are first considerations to make at least the export of particularly high-performance additive manufacturing plants and associated starting materials subject to approval.

Schwab also highlights this risk saying "...regulators in this field will find themselves running behind technological advances due to their speed and multifaceted impact". Schwab, *The Fourth Industrial Revolution*.

A similar point is made in Connor M McNulty, Neyla Arnas, and Thomas A Campbell, "Toward the Printed World: Additive Manufacturing and Implications for National Security (Defense Horizons, Number 73)", National Defense University Fort McNair DC Institute for National Strategic Studies, 2012. Where "...the spread of this technology will

The shared impact of AM with other emerging technologies, or congruence, has not been fully explored in its relevance to WMD. The congruence of AM and AI has been explored in work by Volpe and Hoffman which examined the applicability of distributed ledger technology to provide permissive controls for sensitive digital designs: that is the use of blockchain-like solutions to restrict what a 3D printer is allowed to print. In their 2019 'Bio Plus X' report, Brockmann et al. have examined the convergence of biology with other emerging technologies, including AM..[6] In addition, Christopher has stressed the need to continually assess the role of artificial intelligence in improving AM capabilities.[7] It is concurrent development of technologies that enable 'game changing' in security:[8]

> *"The core elements of a game-changing technology are the technology itself, a concept for its use and a relevant problem. The congruence of these factors provides the opportunity or potential for a new technology to have game-changing impact. Blitzkrieg is a clear example of how such congruence works: integrating fast tanks, aircraft and two-way radios into an operational concept of advanced maneuver warfare obviated the largely defensive technologies of Germany's opponents (most famously, France's Maginot Line). The synergies among these core elements produced a discontinuous shift in the balance of military power in Europe – a truly game-changing innovation"*

Additive Manufacturing is a form of computer-aided manufacturing: the group of processes where the machine tool movements are based on pre-programed instructions relayed by a computer.[9] For decades, standard industry techniques for computer-aided or computer numerically controlled (CNC) manufacturing have relied on so-called subtractive processes, such as lathes, drills and bores. In mass manufacturing, computer-aided processes produce standardized parts using high degree of automation. In contrast, a key attraction of AM is the ability to customize each part.[10]

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make it easier for foreign agents to simply copy a physical component after scanning an original." Note that 'scanning' here I believe is misleading. External scanning will miss all internal features so CT scanning or such must be done to map internal features. The materials (if a custom material is used) and production parameters are also likely to be hard to replicate successfully if not acquired.

[6] Kolja Brockmann, Sibylle Bauer, and Vincent Boulanin, "Bio Plus X: Arms Control and the Convergence of Biology and Emerging Technologies", No. SIPRI, 2019.

[7] Grant Christopher, "Additive Manufacturing: The Future for Safeguards" (paper presented at the IAEA Symposium on International Safeguards, Vienna, 2018).

[8] Shawn Brimley, Ben FitzGerald, and Kelley Sayler, "Game Changers: Disruptive Technology and U.S. Defense Strategy", No. Center for a New American Security, 2013.

[9] Computerised manufacturing is any computer-controlled manufacturing technique that includes CNC (Computer Numerically Controlled) machine tools using traditional, subtractive, manufacturing.

[10] Quote from "Technikfolgenabschätzung (Ta) Additive Fertigungsverfahren „3-D-Druck" ", 2017. P78. "Conventional production processes are generally characterized by an opposing relationship between the criteria of efficiency and flexibility: efficient production processes are characterized by minimal variable costs and fast

Advanced states that have integrated AM into their jobs and growth strategies,[11] will apply it in other areas. The use of AM is being explored in the defense and aerospace industries, and to a more limited extent for nuclear applications, in instances where it provides cost savings or demonstrates a new capability. Would-be proliferators use a different set of criteria for deciding what manufacturing technology to use: that is what technologies and materials are available after export restrictions and can they produce or use an item that is 'good enough'[12] for their purpose.[13]

The future impact of AM is both *"uncertain and ambiguous"..*[14] Studies of the impact of AM on WMD and delivery systems[15] have gone far in addressing the impact of AM, as it is capable today,

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turnaround times and are typically achieved through standardized product forms and a high degree of automation (e.g. assembly line production in the mass production). In contrast, flexible production processes offer a greater variety of designs and variants, as well as a better ability to respond to changes in demand, but also require a high level of labor and personnel for the conversion and operation of the machines and production systems (for example, single or small series production in workshops). A balance must be made between the efficiency and flexibility of a production process, with the range of what is technically feasible limited depending on the available production methods. Although additive manufacturing cannot resolve the trade-off between efficiency and flexibility of production processes, it does expand the scope for design in many ways."

[11] Remarks by Barack Obama at the 2013 State of the Union illustrated the US ambition to bet on AM to add high-tech manufacturing to provide economic opportunity. Barack Obama, "State of the Union," 2013, https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/remarks-president-state-union-address.Many OECD countries have developed AM strategies, and are pumping money into the technology.

[12] This should be understood as being possibly below the level of explicit export control requirements but still able to perform the intended task.

[13] G E Christopher, "3d Printing: A Challenge to Nuclear Export Controls", No. King's College London, Ridgeway Information, 2018.

[14] Daniele Rotolo, Diana Hicks, and Ben R. Martin, "What Is an Emerging Technology?," *Research Policy* 44, no. 10 (2015). "[An emerging technology] is ...a radically novel and relatively fast growing technology characterised by a certain degree of coherence persisting over time and with the potential to exert a considerable impact on the socio-economic domain(s) which is observed in terms of the composition of actors, institutions and patterns of interactions among those, along with the associated knowledge production processes. Its most prominent impact, however, lies in the future and so in the emergence phase is still somewhat uncertain and ambiguous."

[15] See now a rather extensive set of literature, from scoping assessments of the problem in 2015: Grant Christopher, "3d Printing: A Challenge to Nuclear Export Controls," *Strategic Trade Review* 1, no. 1 (2015). Matthew Kroenig and Tristan Volpe, "3-D Printing the Bomb? The Nuclear Nonproliferation Challenge," *The Washington Quarterly* 38, no. 3 (2015).

This was followed by later detailed technology assessments of nuclear and missile use. See: Marco Fey, "Waffen Aus Dem 3d-Drucker: Additives Fertigen Als Sicherheitspolitisches Risiko?", No. PRIF, 2016; Kolja Brockmann and Sibylle Bauer, "3d Printing and Missile Technology Controls", No. SIPRI, SIPRI Background Paper, 2017; Marco Fey, "3d Printing and International Security: Risks and Challenges of an Emerging Technology", No. PRIF, 2017; Robert Kelley, "Is Three-Dimensional (3d) Printing a Nuclear Proliferation Tool?", No. No. 54 SIPRI EU Non-proliferation Paper, 2017; Robert Shaw, "3d Printing: Bringing Missile Production to a Neighborhood near You," 2017, http://nti.org/6801A; "3d Printing: A Challenge to Nuclear Export Controls", 2018.

Finally, some literature has assessed the risk in specific areas such as the use by non-state actors: Robert Shaw et al., "Wmd Proliferation Risks at the Nexus of 3d Printing and Diy Communities", No. CNS, 2017; "3d Printing: A on the nuclear fuel cycle, biological weapons and missile delivery systems. Regarding nuclear weapons, despite concluding that that AM does not provide proliferators with the ability to substitute for conventional manufacturing, especially for enrichment and reprocessing technologies,[16] an array of relevant materials and applications are being developed for stockpile stewardship and civilian power.

This section provides an overview of the future of AM and the likely areas of development. It describes developments in new printing processes, new materials relevant to WMD production equipment and WMD delivery systems.

General challenges, opportunities and developments in AM

Relative to other computer-aided manufacturing technologies[17] AM is limited by:[18]

- Slow process speed
- Small volumes of construction
- Lack of fineness in producible details
- Lack of reproducibility
- Insufficient material properties or surface quality
- A limited range of workable materials.

As will be demonstrated in the following sections, the range of WMD-relevant materials available is expanding, year upon year. The remaining critiques, which essentially constrain the size of a part produced using AM and the ability to mass produce it have been limiting factors up to this point for the adoption of AM by the nuclear and missile industries.

Using AM is difficult. Assessments conducted in 2017 on this topic did not expect a metal printing machine to be able to consistently produce the same part twice in a row.[19] Differences between factory-set printers require individual calibration then months of commissioning prior to production.[20]

Challenge to Nuclear Export Controls", 2018. The convergence of bioprinting and other technologies: "Bio Plus X: Arms Control and the Convergence of Biology and Emerging Technologies", 2019.

[16] Tristan Volpe et al., "Additive Manufacturing and Nuclear Nonproliferation: Shared Perspectives on Security Implications and Governance Options", No. Stanley Foundation, 2018.

[17] Christopher stresses the need, when assessing relevance to nuclear-related developments, to consider digital manufacturing which includes conventional subtractive processes that are digitally controlled alongside AM. Christopher, "Additive Manufacturing: The Future for Safeguards."

[18] "Technikfolgenabschätzung (Ta) Additive Fertigungsverfahren „3-D-Druck“ ", 2017.p. 13.

[19] "Additive Manufacturing and Nuclear Nonproliferation: Shared Perspectives on Security Implications and Governance Options", 2018.

[20] Ibid.

AM provides customization of design for each item: the so-called ‘complexity is free’ mantra that is costly via conventional mass production processes.[21] The ability to use AM to freely customize is ideally suited to areas like dentistry, and surgical implants where parts can be optimized for each user.

For WMD-related production, which typically requires mass production of identical parts, this is not a typical use case. The reasons cited in the literature or stated by practitioners for using AM over other manufacturing processes are multicausal: it can be used to redesign a component, especially those with complex internal geometries, or to consolidate multiple components;[22] it can also be used to work with otherwise impossible materials with more desirable properties;[23] it can be used to reverse engineer parts where the supply chain has been interrupted;[24] or it can also be used to accelerate development cycles by rapid prototyping, which is performed in tandem with computer modelling in each iteration of the part.[25] The benefits for aerospace, and hence missile technology are particularly salient: parts may be redesigned with less weight.

The additive manufacturing industry is seeking to offset its disadvantages by improving speed, size, reliability and the cache of available materials. These disadvantages, which impact adoption of AM in all sectors, have slowed developments relevant to WMD production equipment and WMD delivery systems. Cumulatively, the developments outlined in this section could produce a transformative impact on the technology if coupled with the needed development of industry standards.

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[21] This play off between mass production and small production runs is highlighted in a 2017 German Government report: "Technikfolgenabschätzung (Ta) Additive Fertigungsverfahren „3-D-Druck“ ", 2017. p78.

[22] The most famous example is actually in aerospace with GE’s LEAP fuel nozzle that was redesigned with AM and consolidated over 20 pieces into a single printed component. Jerry Underwood, "Ge Aviation Readies First 3-D Printed Jet Engine Nozzle at Alabama Plant," 2015, Made In Alabama, http://www.madeinalabama.com/2015/06/ge-aviation-readies-first-3-d-printed-jet-engine-nozzle/.

[23] LLNL redesigned the foam used in nuclear warheads for stockpile stewardship using an AM-unique material that had more predictable material properties. "Additive Manufacturing Reshapes Foam Design," 2014, LLNL, https://str.llnl.gov/september-2014/wilson.

[24] Siemens replaced an impeller at a nuclear power plant in Slovenia using a 3D-printed part. The original supplier was no longer available so the existing part was 3D scanned and provided the basis for the design of the new printed part. "Siemens Sets Milestone with First 3d-Printed Part Operating in Nuclear Power Plant," 2017, Siemens, http://www.siemens.com/press/pool/de/pressemitteilungen/2017/powergenerationservices/PR2017030221PSEN.pdf.

[25] Bruce Goodwin, "Additive Manufacturing and High-Performance Computing: A Disruptive Latent Technology" (paper presented at the APS March Meeting 2015, San Antonio, TX, USA, 2015). See also p. 68 "3d Printing: A Challenge to Nuclear Export Controls", 2018.

Process developments

Manufacturers are seeking to integrate AM into their existing computational manufacturing processes by standardizing design files and introducing interoperability between additive and subtractive processes such as in Siemens' so-called 'factory of the future'.[26]

Establishment of standards

The AM industry as a whole has recognized that a lack of unified standards is holding back development and adoption. The civilian nuclear industry is the farthest behind on development of standards, which is reflected in the low number of observed applications.[27] The key bodies for standards development are the ASTM F42 committee[28] and the ISO 261 Technical Committee,[29] which are developing standards from powder to postprocessing.[30] CECIMO, which represents the interests of European machine tools and manufacturing technologies - including AM - is negotiating with the US-based organizations to achieve unified standards.[31] The Metal Powder Industries Federation (MPIF) has also published standards for powder for metal AM.[32] Developing standards are a necessary step for adoption of AM in the nuclear and missile industries.

It has long been clear that the development of standards and material characterization is a bottleneck for applications of AM in harsh environments such as required for the military. America Makes collaborates with the American National Standards Institute (ANSI) to form the Additive Manufacturing Collaborative Standardization Collaborative (AMSC). The goal of AMSC is to work with other standards organizations, such as ISO and ASTM, to prioritize and accelerate standards critical for AM in various industrial sectors and thereby aid the further development of AM. The AMSC has outlined significant gaps in the development of standards and certification according to: 1) design; 2) process and materials (precursor materials, process control, post-processing, and finished material properties); 3) qualification and certification; 4) nondestructive evaluation; and

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[26] Siemens are developing what they are calling the factory of the future: where subtractive CNC and 3D printing machines both are used to mass produce customised parts. Siemens, "Mass Customization: The Factory of the Future," 2018, https://new.siemens.com/global/en/company/stories/industry/the-factory-of-the-future.html.

[27] United States Department of Defense, "Department of Defense Additive Manufacturing Roadmap", No. United States Department of Defense, America Makes, 2016. p.3. This report states that ISO and ASTM have not yet considered nuclear industry applications of AM. ASME have a single code underway. The way forward is being provided by the Nuclear Regulatory Commission (NRC) which has issued a draft action plan.

[28] "Astm F42 Committee on Additive Manufacturing," 2016, https://www.astm.org/COMMITTEE/F42.htm.

[29] Ibid.

[30] See also pp. 54-55, "3d Printing: A Challenge to Nuclear Export Controls", 2018.

[31] Beau Jackson, "Eu Prioritizes Additive Manufacturing in U.S. Trade Talks, Receives Cecimo Support," 2019, 3D Printing Industry, https://3dprintingindustry.com/news/eu-prioritizes-additive-manufacturing-in-u-s-trade-talks-receives-cecimo-support-150403/.

[32] MPIF, "A Collection of Powder Characterization Standards for Metal Additive Manufacturing," 2019, MPIF, https://www.mpif.org/News/PressReleases/TabId/166/ArtMID/1129/ArticleID/230/New-Publication-A-Collection-of-Powder-Characterization-Standards-for-Metal-Additive-Manufacturing.aspx.

5) maintenance. The AMSC recommends 18 high priority items that need to be addressed.[33] Because of how significant these are to future development of AM in defense and nuclear weapon development we discuss some of them here:

1) A standard that focuses on the completeness of the Technical Design Report so that it can be directly provided to a vendor clearly defining the physical and performance specifications.

2) Gaps remain in specifying tolerance and dimension requirements although the existing ASME Y14.41 Digital Product Definition Data Practices do provide some guidance. [34]

3) Machine calibration and preventative maintenance: "There are no known industry standards addressing machine calibration and preventative maintenance for additive manufacturing." The concern is that if this is not standardized then "current users may not have established best practices".

4) The concern addressed is that in the AM materials "can be sensitive to changes in environmental conditions including temperature, humidity, and ultraviolet radiation." Guidance is required to "ensure the environmental conditions in which the material is used and stored remain within acceptable ranges for all material types."

5) Environmental Health and Safety: There is inadequate standards for the protection of machine operators. There is a need for standards to "address environmental health and safety (EHS) in the AM process".

6) Material Properties. Material characteristic values are not "statistically validated and do not have the pedigree required for material design". "Standards for thermal properties and minimum mechanical properties that also contain qualification procedures cannot currently be produced for AM materials, given the current state of knowledge, for the reasons stated above. Testing standards modified for use with AM parts that are designed/built to be inhomogeneous are also not available at this time." This requires a great deal of R&D in the future to acquire data that describe materials especially metals and polymers that currently does not exist. Qualification requirements to establish minimum mechanical properties for AM parts, both homogeneous and deliberately inhomogeneous, need to be developed.

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[33] The roadmap can be downloaded from here after registering for access: https://www.ansi.org/standards_activities/standards_boards_panels/amsc/Default?menuid=3

[34] This standard is the one that applies to CAD drawings and is widely accepted by DoD. http://gost-snip.su/download/asme_y14_412003_digital_product_definition_data_practices

The requirement for these standards must be considered beyond the requirements for WMD production equipment. WMD warheads and WMD delivery systems require operation in extreme environments and as such must satisfy specific requirements to decrease the probability of inadvertent detonation. The term "assured safety" implies that the nuclear weapon is safe "regardless of accident scenario". Another way of expressing the concept is that assured safety is achieved as long as isolation is maintained or if a detonation-critical component becomes irreversibly inoperable before isolation is lost. [35] A series of accidents with nuclear weapons have led to the well-known Walske criteria which led to the Enhanced Nuclear Detonation Safety (ENDS) concept of the three I's: isolation, incompatibility, and inoperability. [36] This is a detailed topic that is discussed in many unclassified reports, but any nuclear weapon components and parts that have been produced with AM need to satisfy the same requirements and be certified to the same standards. All of these requirements must be satisfied without nuclear testing and the same must be true for other states as well.

It is likely that other states that are constructing nuclear weapons also have sealed pits, where the pit is inside the weapon rather than inserted inside before arming. For that reason, it is reasonable that they would have the same concern with quality of the pit, insensitivity of the high explosives in the nuclear weapon and the delivery systems and other applications for which AM can be utilized.

Database of AM Materials/Machines

It is critical to have a database with the characteristics of materials that can be 3D printed. The US company SenVol has provided this service to the AM community in a free database available online. [37] The database at the time of writing contains 2384 different materials and 1230 machines (industrial not desktop) and according to CEO Annie Wang the number of entries increases by 50% each year as new materials, 3D printers and processes come into being. [38]

Front-end Developments

Additive manufacturing can be thought of as divided into a front end and back end with the printing process itself dividing the two. The front end is the design phase where the virtual component is tested for its material properties by computational modelling and converted into a format that retains all this design information. In this stage, the file to instruct the chosen printer on how to construct the part is also developed.

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[35] Alton P. Donnell, "A Robust Approach to Nuclear Weapon Safety", No. SAND 2011-4123 C Sandia National Laboratories, Albuquerque, NM, United States, 2011.

[36] Raymond Wolfgang, "The Enhanced Nuclear Detonation Safety Theme", No. SAND2012-0793C Sandia National Laboratories, Aluquerque, NM, United States, 2012.

[37] The database can be found at: http://senvol.com/database/

[38] Interview with Annie Wang CEO of SenVol at RAPID+TCT 2019. https://www.youtube.com/watch?v=_RcCtg08Ujc&list=PLEjvbhTzaWiFwgCgwQAdJlVmWsGK8WRNd&index=2

Until recently, the industry standard file format was the Standard Tessellation Format (stl), but the new Additive Manufacturing File Format (AMF format) allows additional information to be included such as color and surface texture.[39]

Advances in the quality and quantity of material supply, particularly for the powder metal processes, will improve reliability. A new powder production technique—the plasma atomization process (PAP)—allows more control over particle sizes than previous processes. Powder consistency is a major factor in reliability in AM manufacturing. US company, PyroGenesis use this process and has supplied a non-titanium reactive powder using this process to the US government.[40]

Using AI to improve the printing process

A major goal for the AM industry is to improve the reliability of printed products during printing. Part failure can occur through a variety of modes such as surface roughness which can initiate cracks; voids where powder has not fully melted, or pores created by gas bubbles from the powder production process. Residual stress, caused by uneven cooling rates, can cause distortions and part failure. Significant projects are underway which use machine learning and artificial intelligence to understand how and why parts fail. This is supplemented by investigative science and engineering research to understand the underlying physics in AM, particularly regarding the metal AM processes.

Researchers at US universities, US national labs and partnerships with the military are leading these developments. A Purdue-lead collaboration is seeking to improve algorithms that measure deviations in final part shape from digital design.[41] The first project will use Stereolithographic (SLA)[42] printers with the ultimate goal to transfer to this Powder Bed Fusion (PBF).[43] The University

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[39] "Technikfolgenabschätzung (Ta) Additive Fertigungsverfahren „3-D-Druck“ ", 2017. p.58.

[40] Umair Ifikhar, "Afrl Awards $8.2 Million to Jasr System to Develop Chip-Sized Lidar," 2019, 3D Printing Industry, https://3dprintingindustry.com/news/afrl-awards-8-2-million-to-jasr-system-to-develop-chip-sized-lidar-150504/.

[41] "Purdue and University of Southern California Enhance 3d Printing Quality Control with Machine Learning," 2019, 3D Printing Industry, https://3dprintingindustry.com/news/purdue-and-university-of-southern-california-enhance-3d-printing-quality-control-with-machine-learning-149180/.

[42] Stereolithography is a layer-by-layer process where UV light is used to cure a resin. Advances in this concept have been used to alter the layer-by layer paradigm (Carbon’s CLIP process) or to print metals by embedding metals in resin and then sintering the part to remove the resin. See: "3d Printing: A Challenge to Nuclear Export Controls", 2018.

[43] Powder Bed Fusion (PBF) is a group of technologies where energy (either a laser of electron beam) is directed to a bed of powder in a layer-by layer process. After the powder in each layer has been melted a new layer of powder is added so the part will gradually submerge in a ‘sea’ of loose powder that has not been melted. Some techniques only sinter the powder (i.e. melt the boundaries) rather than fully melt the powder. These are not suitable for high-end applications.

Technologies that fall under PBF include: EOS’ DMLS (Direct Metal Laser Sintering), GE-Arcam’s EBM (Electron Beam Melting) and GE-Concept’s DMLM (Direct Metal Laser Melting). Others terms that may be encountered are LAM (Laser Additive Manufacturing) and SLM (Selective Laser Melting).

of Texas at El Paso's WM Keck Center is working with the US Army Research Laboratory to monitor and auto-correct PBF processes. This approach will eventually use infrared cameras to instrument AM machines.[44] Researchers at LLNL are using high-speed cameras to examine the melting and solidification process and the results will then be applied to improve overall process reliability.[45] Using these cameras, build failures are detected using just 1/100th of a second of footage. This uses an AI method dubbed Convolutional Neural Networks (CNN). In a recent study, an AI algorithm was trained using 2000 videos which were compared to the plans of built parts.[46] LLNL is seeking to deploy this technology in an AM system developed with GE.[47]

Private companies are also conducting leading research. California-based start-up Relativity, famous for their intent to 3D print an entire rocket, has patented a machine learning process for detecting and correcting faults.[48] Leading Directed Energy Deposition (DED)[49] company Sciaky has invented a monitoring and real-time adjustment technology dubbed Interlayer Realtime Imaging & Sensing System which dynamically monitors and changes process parameters and can alter the beam pattern.[50] Work is also ongoing to reduce need for support structures, which are required for a part to maintain integrity during printing, such as that undertaken by VELO3D.[51] Finally,

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Electron beams reach higher powers than lasers, permitting hotter melting temperatures in the powder, which improves the part density – vital to ensure a part does not fail. Electron beam processes use coarser powders, so are less capable of producing finer details and cannot melt ceramic powders. See: ibid.

[44] Beau Jackson, "Real-Time Metal 3d Printer Monitoring at El Paso Awarded in $900k Arl Grant," 2018, 3D Print Industry, https://3dprintingindustry.com/news/real-time-metal-3d-printer-monitoring-el-paso-awarded-900k-arl-grant-129057/.

[45] Sonny Ly et al., "Metal Vapor Micro-Jet Controls Material Redistribution in Laser Powder Bed Fusion Additive Manufacturing," *Scientific Reports* 7, no. 1 (2017).

[46] Bodi Yuan et al., "Machine-Learning-Based Monitoring of Laser Powder Bed Fusion," *Advanced Materials Technologies* 3, no. 12 (2018).

[47] LLNL, "New Multibeam Metal 3d Printer Testbed to Understand Laser-Material Interactions," 2019, LLNL, https://www.llnl.gov/news/new-multibeam-metal-3d-printer-testbed-understand-laser-material-interactions.

[48] This uses Finite Element Analysis (FEA) an industry-standard computational engineering model, in-situ laser interferometry in the AM hardware and stored data from previous printing processes.. There is also 'training data' to train AI/machine learning models. Relativity, "Relativity - Mission," 2019, Relativity, https://www.relativityspace.com/.

[49] Sciaky's proprietary name for the technology is EBAM (Electron Beam Additive Manufacturing). In EBAM/DED processes a laser or electron beam is used to melt powder or wire that is deposited from a nozzle co-located with to the energy beam. This has some advantages over PBF processes – it can be used for repairs as well as new builds and it is straightforward to work with multiple materials. EBAM is open air so the parts built can be meters in size rather than tens of centimeters. The disadvantages are that DED-produced parts produce a coarse finish, so must undergo extensive postprocessing. See: "3d Printing: A Challenge to Nuclear Export Controls", 2018.

[50] Realtime Imaging & Sensing System (IRISS) Beau Jackon, "Interview: How Sciaky Is Overcoming Challenges and Competition of Metal Am," 2019, 3D Printing Industry, https://3dprintingindustry.com/news/interview-how-sciaky-is-overcoming-challenges-and-competition-of-metal-am-152843/.

[51] See VELO3D, "Velo3d Capabilities Summary," 2019, VELO3D, https://www.youtube.com/watch?v=lic79ld7Ml8.

Sigma's PrintRite3D INSPECT 4.0 is an In-Process Quality Assurance (IPQA) tool that uses hardware to collect real-time data.[52]

Developments are not restricted to the United States. For instance, in the UK, AM workflow automation software AFMG company, with the Nottingham Centre for AM (CfAM) is developing AI and machine learning for postprocessing. [53]

Integrated AM-subtractive metal CNC machines

One of the most important trends that will impact the use of AM for WMD and delivery systems is the integration of additive and subtractive systems. This is distinct from Siemens' factory of the future concept[54] where additive and subtractive machines are co-located. In these so-called hybrid machines CNC lathes are combined with an AM machine. Hybrid machines from Japanese company Matsuura have been on the market for some time. New machines are also being developed that expand the range of capabilities such as the LASIMM project (Large Additive Subtractive Integrated Modular Machine), which seeks to integrate AM and subtractive systems.[55]

Faster Machines

The adoption of AM, particularly for the powder metal processes, is being held back by the slow build time: the typical build time for a 10-20-centimeter part is currently 3-4 days. Established hardware manufacturers are lowering build times by using more lasers. Newer entrants to the market are developing more disruptive methods. One process is Australian company Aurora Labs' Rapid Manufacturing Technology (RMT) which claims to achieve metal printing speeds 55x the current rate by laying multiple layers of powder at a time. This process is dubbed Multi Concurrent Printing (MCP).[56]

New Printing Processes

New printing processes may fundamentally alter what it is possible to print – for some processes this is about redefining the printing process; for others it is about lowering cost and time barriers.

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[52] Tia Vialva, "Sigma Labs Receives Contract from Undisclosed Global Additive Manufacturing Company," 2019, 3D Printing Industry, https://3dprintingindustry.com/news/sigma-labs-receives-contract-from-undisclosed-global-additive-manufacturing-company-147347/.

[53] CfAM also launched the manufacturing execution system (MES) in 2018 which is linked to these efforts. Anas Essop, "Interview: Amfg Obtains £350k from Innovate Uk to Spur Development of Ai for Additive Manufacturing," 2019, 3D Printing Industry, https://3dprintingindustry.com/news/interview-amfg-obtains-350k-from-innovate-uk-to-spur-development-of-ai-for-additive-manufacturing-147634/.

[54] "A Print on-Demand Manufacturing Plant," 2016, Siemens, https://www.siemens.com/innovation/en/home/pictures-of-the-future/industry-and-automation/additive-manufacturing-spare-parts-for-the-rail-industry.html.

[55] Matsuura, "Matsuura Lumex Avance-60 and Mx-520 V-8 Engine Block," 2017, Matsuura, https://www.youtube.com/watch?v=mY_hTzO4WzQ.

[56] "Aurora Labs Reveals Ground-Breaking Multi-Level Rapid Manufacturing Technology," 2018, Aurora Labs, https://www.youtube.com/watch?v=Sqh3FM12KVg. They also have a technology call Large Format Technology (LFT).

Rather than seek to improve printing speeds via an existing process the alternative is to invent new, inherently faster, processes. The applications to WMD production equipment and their delivery systems are unclear, given that their nascent nature. This section highlights only some of the many developments in AM as significant developments continue to occur frequently.

Metal Big Area Additive Manufacturing

Oak Ridge National Laboratory's (ORNL) Big Area Additive Manufacturing Process (BAAM) is suitable for printing multi-meter length plastics, such as molds for aircraft wings and vehicles[57] and has produced proof of concept designs for objects such as a 30-foot submarine.[58] This extrusion process is limited by the range of materials available.[59]

To expand the range of materials for large printing processes, ORNL has invented a metal process (mBAAM). It uses a gas metal arc weld and is a fast, low-resolution process. Its completed parts still require extensive subtractive process machining and finishing,[60] but such a process could be applied to production of parts for aerospace, including delivery systems, reactor pressure vessels, steam systems and turbine systems for nuclear power.

Volumetric Additive Manufacturing

A revolutionary technique, Volumetric Additive Manufacturing, has been patented but still is in the conceptual phase. Rather than constructing a part with a layer-by-layer approach, magnetic fields are used to levitate metal powders within volumetric parts (blocks, spheres). The powder is then melted simultaneously from different directions by electron beams, and forms the part when cooled off..[61] A similar approach is being developed by the University of California at Berkeley in collaboration with LLNL using polymers.[62]

Wire-Arc Additive Manufacturing

Wire Arc Additive Manufacturing or WAAM is not a new technique, but it is an adaptive metal production process that has garnered a notable amount of new interest in the past three years. Alongside developers at the UK's Cranfield University, GEFERTEC have developed their 3DMP wire

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[57] Alex Roschli et al., "Designing for Big Area Additive Manufacturing," *Additive Manufacturing* 25 (2019).

[58] Energy.gov, "Navy Partnership Goes to New Depths with First 3d-Printed Submersible," 2017, US Department of Energy Office of Energy Efficiency & Renewable Energy, https://www.energy.gov/eere/articles/navy-partnership-goes-new-depths-first-3d-printed-submersible.

[59] "3d Printing: A Challenge to Nuclear Export Controls", 2018. pp. 8-9.

[60] Clayton Greer et al., "Introduction to the Design Rules for Metal Big Area Additive Manufacturing," *Additive Manufacturing* 27 (2019).

[61] NATAŠA MUŠEVIĆ. Device and Method for Additive Manufacturing of Three-Dimensional Objects. 2018. https://3dprintingindustry.com/news/patent-filed-for-metal-3d-printing-without-layers-147049/

[62] Brett E. Kelly et al., "Volumetric Additive Manufacturing Via Tomographic Reconstruction," *Science* 363, no. 6431 (2019).

arc process that includes 3-axis and 5-axis machines that are like directed energy deposition (DED) in terms of functions and capability.

FDM printing of metals

The Virtual Foundry uses Fused Deposition Modelling (FDM)/Free Form Fabrication (FFF)-type technology[63] to print metals. This can dramatically lower the cost of working with metals (an FDM machine is less than $1000, compared to a metal machine is over $500,000) and thus present new possibilities for printing.[64] This process could be initially used to print one-off tools and non-critical components.

Faster DED processes

Digital Alloys have developed the Joule Printing process, a DED process that reduces cost and increases speed.[65] DED has seen a broad uptake in aerospace; therefore, techniques that improve current processes could further increase adoption.

Electronics

DARPA has funded projects to 3D print sensors, electronics and scanning systems. This permits miniaturization of bulky parts while incorporating the electronics for radars and other sensors into the component.[66] This technology is especially desired by the military for incorporation of electronics into the structure of aircraft and has applications for WMD delivery systems. The Department of Energy has also stated that integrating sensor technology is a reason for pursuing AM applications in the nuclear industry for predictive maintenance,[67] discussed in more detail on p. 377.

Development of electronics printing is widespread, in both global spread and the range of printing technologies that are being pursued. For instance, Nano Dimension, an Israeli company listed on the NASDAQ, is printing radio frequency identification (RFID) chips using the DragonFly Pro, their inkjet-type printer.[68]

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[63] Fused Deposition Modelling (FDM), Stratasys' trademarked term or Free Form Fabrication is the hobbyist's choice of 3D printing processes. In this a thermoplastic wire is melted in a nozzle and deposited layer by layer. The process has proved to be exceptionally flexible, used for printing explosives and magnetic material. See "3d Printing: A Challenge to Nuclear Export Controls", 2018.

[64] "Virtual Foundry," 2019, Virtual Foundry, https://www.thevirtualfoundry.com.

[65] Duncan McCallum, "A Radically Simple New Technology for Fast, Low-Cost Metal Additive Manufacturing," 2018, Digital Alloys, https://www.digitalalloys.com/blog/joule-printing/.

[66] Umair Iftikhar, "Afrl Awards $8.2 Million to Jasr System to Develop Chip-Sized Lidar," 2019, 3D Printing Industry, https://3dprintingindustry.com/news/afrl-awards-8-2-million-to-jasr-system-to-develop-chip-sized-lidar-150504/.

[67] DoE, "4 Major Opportunities for Additive Manufacturing in Nuclear Energy," 2019, US DoE, https://www.energy.gov/ne/articles/4-major-opportunities-additive-manufacturing-nuclear-energy.

[68] Umair Iftikhar, "Nano Dimension Granted Patent for Dielectric Ink," 2019, 3D Printing Industry, https://3dprintingindustry.com/news/nano-dimension-granted-patent-for-dielectric-ink-149841/.

Advances in known materials

AM can only work with some of the key materials for missile and WMD-related parts that conventional manufacturing techniques can utilize. This section describes advances towards these materials being printed in scenarios that are similar to those used for WMD production equipment and delivery vehicles.

Aluminum

Aluminum is used in aerospace for missile casings and the rotating components of gas centrifuges. The 7xxx and 6xxx series alloys of aluminum, using the traditional chemical compositions, are not suitable for AM. This is due to the volatile compounds present that would vaporize in AM's rapid heating-cooling cycles. However recent research has provided a solution to this problem using nanoparticles selected to control the solidification process, which allows Al alloys such as Al 6061 and Al 7075to be printed.[69] This process can also be applied to nickel alloys and superalloys to make them suitable for AM.[70]

This does not mean that aluminum can now be used to print rotating components of gas centrifuges. The showstoppers for printing this material for a gas centrifuge are inherent to the printing process itself. First, the part would have to be printed in the largest available printers. Second, the dimensional tolerances centrifuges require to rotate at 60,000 rpm are too strict for any AM process alone so much of the difficult traditional manufacturing process would have to be replicated to produce a part with the required dimensional tolerances.[71]

Maraging steel

Maraging steel is of interest due to applications in missile casings and rotating centrifuge components. Maraging steel has been well-researched for WMD applications. For use in gas centrifuges, as with suitable alloys of titanium and aluminum, the output of the AM process would require flow forming.[72]

The volume of maraging steel 300 research and interest that has continued indicates that a printed version of the alloy could be developed that could be relevant for gas centrifuge applications, after flow forming, although the same restrictions stemming from the printing process from aluminum – the dimensional tolerances do not meet requirements – apply also to maraging steel.

Carbon fiber

The carbon-fiber filament winding process, used to produce missile casings and rotating components of centrifuges, shares many features with AM: a computer-controlled process is used

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[69] John H. Martin et al., "3d Printing of High-Strength Aluminium Alloys," *Nature* 549 (2017).

[70] Tuan D. Ngo et al., "Additive Manufacturing (3d Printing): A Review of Materials, Methods, Applications and Challenges," *Composites Part B: Engineering* 143 (2018).

[71] "3d Printing: A Challenge to Nuclear Export Controls", 2018. P.30.

[72] Kolja Brockmann and Robert Kelley, "The Challenge of Emerging Technologies to Non-Proliferation Efforts: Controlling Additive Manufacturing and Intangible Transfers of Technology", No. SIPRI, 2018.

to build a 3D structure from a filament. When AM is referred to when discussing carbon fiber, it is in the context of a new technique based on other recognized AM processes. No new AM-process is known that can replicate part quality from the filament winding process.

The carbon fiber AM manufacturing techniques seek to work with new materials such as carbon fiber reinforced thermoplastic (CFRTP). The University of Tokyo has performed research for the Japanese Space Agency (JAXA)[73] producing this material, printing bundles of carbon fiber in resin using an FDM technology.[74] A DuPont partnership with the RepRap printer developers - which is capable of printing the majority of its own components - has produced carbon fiber and glass fiber-reinforced plastics for FDM.[75]

While new methods of AM may not be suitable as winding processes for carbon fiber, other processes are looking to either minimize the amount of fiber that needs to be used or substitute for it altogether. The German company, SGL Carbon, GMBH, for example is using a new process to lessen the need for carbon fiber for prototyping and perhaps ultimate production. To be used in parts carbon fiber textiles normally have to be cut, impregnated with resin, hot pressed, shaped, and coated. The SGL process decreases the number of steps and uses carbon powder and AM instead of carbon fiber. SGL uses a binder-jetting process to print the powder and then infiltrates it with liquid silicon. This could be useful for several types of WMD proliferators. For instance, this material could be useful for handling corrosive chemical weapons precursors and coping with high temperatures. [76]

New materials

New materials that are added to the catalogue of printable materials increase the flexibility of AM to be applied to WMD production equipment and WMD delivery systems. This section describes materials that have not been previously reported being 3D printed and the modifications to materials suitable for AM. The applications and use cases of these new materials are as yet unknown and fit into the uncertain and ambiguous future characterized by emerging technologies.

Functionally Graded Materials

Functionally graded materials (FGMs) are materials that mix two or more materials, varying the overall composition across the material. They can be used to smooth material boundaries or provide parts with varied properties. Notable examples include 2019 research in China to print

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[73] Ryosuke Matsuzaki et al., "Effects of Set Curvature and Fiber Bundle Size on the Printed Radius of Curvature by a Continuous Carbon Fiber Composite 3d Printer," *Additive Manufacturing* 24 (2018).

[74] Used suitable fibres: Toray T800S in an ABS matrix. The technology uses FDM printing technology rather than traditional filament winding.

[75] "Dupont™ Zytel® 3d10c20fl Bk544 ", 2019, DuPont, https://www.dupont.com/content/dam/dupont/products-and-services/plastics-polymers-and-resins/thermoplastics/documents/TDS%20Zytel%203D10C20FL%20BK544.pdf.

[76] Sarah Reiser (SGL Carbon GmbH)—"3D Printing with Carbon and SiC", Rapid Tech+ Falcon 3D Conference, June 26, 2019, Erfurt, Germany

FGM tungsten-copper[77] and adapting 316L stainless steel, which has numerous nuclear applications. [78] This new type of material is enabled by additive manufacturing and after more development may a wide set of applications. It is possible that an FGM may find an application in delivery systems or WMD production equipment by incorporating two or more materials that are already in use.

Beryllium

Beryllium was highlighted by Kelley and Brockman to be a material of interest due to the application as neutron reflectors in explosive devices. The very small quantities used would fit one of the use cases where little material waste is desired.[79]

Notable use-cases of beryllium in AM have been identified. Patents have been filed by the Materion Corporation to use AM for manufacturing with a beryllium layer.[80] The U.S. Department of Defense has granted an award to Grid Logic for AM manufacturing of replacement missile components using beryllium.[81]

AF96 steel alloy

The U.S. Air Force has developed custom high-strength steel alloy powder, AF96, for bunker-busting munitions applications.[82] U.S. Army Combat Capabilities Command (CCCD) has prototype printed an impeller using this powder. This is a key example illustrating the development of a custom alloy developed to be printed for a custom military purpose. Custom alloys may find uses beyond their original purpose.

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[77] C. L. Tan, K. S. Zhou, and T. C. Kuang, "Selective Laser Melting of Tungsten-Copper Functionally Graded Material," *Materials Letters* 237 (2019); ibid.

[78] The paper states that: "An additively manufactured 316L lattice has been infiltrated by molten A356 (with a significantly lower melting temperature). The stress-strain response and the thermal conductivity of the lattice structure were optimised by varying the geometry and density. At the same time, tensile elongation increased by one order of magnitude when compared with the original A356. These results were obtained because the adopted infiltration processing method avoided intermetallic formation, cracking and poor resolution, thereby solving common problems that are encountered in traditional AM techniques for printing metallic composites". Ngo et al., "Additive Manufacturing (3d Printing): A Review of Materials, Methods, Applications and Challenges."

[79] "The Challenge of Emerging Technologies to Non-Proliferation Efforts: Controlling Additive Manufacturing and Intangible Transfers of Technology", 2018.

[80] OH) Yurko; James Andrew; (Maumee. Additive Manufacturing of Articles Comprising Beryllium United States, filed 10 December 2015 2015.

[81] SBIR.gov, "Additive Manufacturing Technology for Production of Beryllium Replacement Missile Components," 2016, Small Business Innovation Research Programme (SBIR) US Government, https://www.sbir.gov/sbirsearch/detail/1469377. The award is, for 'non-critical beryllium replacement components using material specified by Raytheon Missile Systems'.

[82] "Researchers 3-D Print Ultra-Strong Steel Parts from Powder," 2019, ARL Public Affairs, https://www.arl.army.mil/www/default.cfm?article=3371.

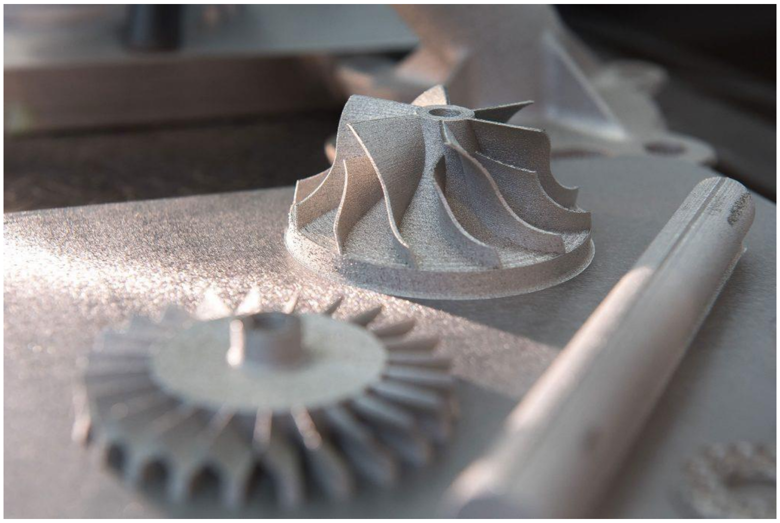

Figure 1: AF96 steel impeller printed by the US Army (credit: US Army).

NASA’s copper alloy: GRCop-42

NASA has been developing a copper-chromium-niobium alloy, GRCop-42, for rocket components such as combustion chamber liners and fuel injector face plates. [83] The appetite to develop AM-specific alloys for aerospace applications is likely to be a continuing trend.

Indeed, the European space firm Ariane is looking to the widespread use of additive manufacturing to dramatically lower the cost of its next generation of rocket engines, including through the use of a copper-Inconel combustion chamber. [84]

Bulk Metallic Glasses

Bulk Metallic Glasses (BMGs) possess unique combinations of metallic, magnetic and chemical properties. The disordered structures, as opposed to crystalline structures of metals, give the materials high tensile strengths, hardness and toughness. The applications of BMGs to WMDs and delivery systems are, as yet, unclear.[85]

High-Entropy Alloys

High-entropy alloys (HEA) are materials where four or five elements are combined.[86] The concept is an older idea that is now being researched in China after 3D printing offered new possibilities of

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[83] K. G. Cooper et al., "Three-Dimensional Printing Grcop-42", No. NASA, NASA Technical Reports Server, 2018.

[84] Steffen Beyer, (Ariane Group, GmbH), “Breakthrough in Industrialization of Additive Manufacturing for Future Launcher Rocket Engine Applications and Devices—Game Changer in Design, Manufacturing, and Functionality”, Rapid Tech+ Falcon 3D Conference, June 27, 2019, Erfurt, Germany

[85] See for instance: Zaynab Mahbooba et al., "Additive Manufacturing of an Iron-Based Bulk Metallic Glass Larger Than the Critical Casting Thickness," *Applied Materials Today* 11 (2018).

[86] Zhaopeng Tong et al., "Laser Additive Manufacturing of Fecrcomnni High-Entropy Alloy: Effect of Heat Treatment on Microstructure, Residual Stress and Mechanical Property," *Journal of Alloys and Compounds* 785 (2019).

using the materials. Applications to delivery systems and WMD production equipment are as yet unclear.

Smart materials[87]

Smart materials or '4D printing' are 3D-printed materials that respond to external stimuli and then change shape. No particular applications relevant to WMD and delivery systems have been identified.

Material coating

Material coating can be performed by powder spay or electroplating. By adapting AM techniques new possibilities for material coating may emerge. For instance, researchers at the University of Texas at El Paso are looking at using AM to provide nitride coating to enhance mechanical properties.[88]

AM is an easier—and cheaper-- technology for working with titanium than previous subtractive techniques, because it avoids a number of intermediary steps in forging and casting. A barrier, however, has been the rough surface material it produces.[89] However, new techniques could alleviate this concern. A German research organization and a leading industrial company in heat and surface treatment, for example, have pioneered the use of post-processing techniques of hot isostatic pressing (HIP) and heat treatment together to remove surface roughness.[90]

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[87] Julien Gardan, "Smart Materials in Additive Manufacturing: State of the Art and Trends," *Virtual and Physical Prototyping* 14, no. 1 (2019).

[88] Jackson, "Real-Time Metal 3d Printer Monitoring at El Paso Awarded in $900k Arl Grant".

[89] Shunyu Liu and Yung C. Shin, Additive manufacturing of Ti6Al4V alloy: A review

www.sciencedirect.com/science/article/pii/S026412751830916X

[90] Viviane Kettermann Fernandes (Aalberts Material Technology; Fraunhofer IAPT), "Industrialization of Post Processing For Additive Manufacturing Parts" Rapid Tech+ Falcon 3D Conference, June 27; 2019, Erfurt, Germany.

Additive manufacturing applications with relevance to WMD: Developments in the United States

Introduction: the concern

This section focuses on U.S. AM technical and policy developments, some of which are in steep competition with those of other nations.

As we consider different AM applications, a few developments stand out. In the past, technical impediments limited the use of AM for the production of WMD or related delivery systems. However, important changes over the last several years require a rethinking of this assumption. For example, previously printers' limited build volume appeared to be a serious impediment. Indeed, it is true that commercial desktop 3D printers still have a small build volume making it difficult to use them to manufacture large components such as nosecones of missiles or successfully manufacture subcomponents.[91] However, now companies such as EOS are now producing printers (EOS M290) that have a large build volume of 40 cubic centimeters.

In addition, 3D printers previously were constrained to producing components using one material at a time and if other materials were used, they would need to be independently loaded. However, as discussed below, this is not likely to pose a future barrier as printers will have multiple heads and can print simultaneously with multiple materials allowing the construction of complex parts. A further future development already underway but not discussed further is to develop 3D printers that can self-replicate, allowing unlimited number of parts to be produced if the source materials are at hand. [92] Some open-source communities have been champions of developing such technology and sharing the details of their manufacture of these technologies openly online. This will make tracking the 3D printers themselves very challenging just as Defense Distributed makes tracking 3D printed guns difficult.

Extending this concern to weapons of mass destruction and their delivery systems is logical in the sense that nefarious actors and states intent on producing these weapons will use advanced manufacturing for efficiency, cost, perhaps to produce equipment that has not been produced before or has increased performance over conventional manufacture, and to overcome export control driven restrictions on other means of production or acquisition.

Additive manufacturing for the US Department of Defense

The United States pioneered AM in the 1980s at the University of Texas with the development of Selective Laser Sintering where metals and polymer powders are melted with powerful lasers. The

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[91] Even if manufactured in components and later assembled, the joints risk failing under the kinds of stress they would experience during deployment. In addition, the cleaning and post processing (finishing) of the pieces composed using AM tend to require a great deal of effort.

[92] "Welcome to Reprap.Org," 2019, RepRap, https://reprap.org/wiki/RepRap.

idea started as an undergraduate honors project, then became a master's and finally a PhD with a working academic 3D printer named "Betsy". At the time the machine was controlled by a Commodore 64 (64k RAM) computer. Multiple funders supported further development of the program including the National Science Foundation and DARPA and others. It was quickly realized that this technology could be used for developing missile technology. In 1998, a pioneering collaboration of Lockheed Martin, DARPA and the Office of Naval Research led to the development of a technique using SLS and HIP (hot isostatic press) to produce the guidance section housing base for the AIM-9 Sidewinder missiles. [93] Decades before Raytheon's 80% 3D printed rocket, the US had already pioneered 3D printing missile components and SLS 3D printing, the grandfather of most present-day 3D printing techniques. [94]

Fast forward to the early 2010's. The Obama Administration realized the potential of 3D printing technology and established several initiatives aimed at establishing the US as a leader in the technology. These efforts included involving AM in the Manufacturing USA initiative which is a network of technological centers of excellence each specializing in testing new manufacturing technologies relevant to the Department of Defense (DoD). The AM focused center is the America Makes facility in Youngstown, Ohio managed and operated by the National Center for Defense Manufacturing and Machining (NCDMM).

The DoD sees AM not only as a means for developing new technology but also for solving the problem of diminishing manufacturing sources (DMS), situations where parts need to be replaced but are no longer manufactured.[95] For example, the US still uses the B2 bomber which is more than 60 years old and would benefit from AM's ability to generate replacement parts quickly and efficiently. [96]

In 2016, various representatives from the services and the Defense Logistics Agency (DLA), including members from America Makes, released a DoD roadmap for AM. The DoD roadmap sets forth 4 priorities aligned with the 4 main agencies representing the effort (see Figure 2): (1) develop application focused new technologies; (2) improve readiness for missions; (3) revolutionize the supply chain; (4) enhance war fighting capabilities.

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[93] Suman Das et al., "Producing Metal Parts with Selective Laser Sintering/Hot Isostatic Pressing," *JoM* 50, no. 12 (1998).

[94] See detailed history of the invention of SLS at the University of Texas at: Ashley Lindstrom, "Selective Laser Sintering, Birth of an Industry," 2012, University of Texas at Austin, https://www.me.utexas.edu/news/news/selective-laser-sintering-birth-of-an-industry.

[95] This often goes by the acronym DMSMS where MS stands for Material Shortages. This is such a significant issue that the DMSMS field has dedicated conferences dealing with the problem.

[96] See video embedded in article by Aaron Mehta (Aaron Mehta, "Payback emerges on Pentagon's Manufacturing USA initiative", Defense News, September 2017. https://www.defensenews.com/smr/equipping-the-warfighter/2017/09/11/payback-emerges-on-pentagons-manufacturing-usa-initiative/). Comments by National Defense Industrial Association President and CEO Hawk Carlisle details the biggest gamechangers in defense manufacturing.

What is striking about the AM Roadmap, as its authors observed, is the overlap there was among the needs and objectives of the various organizations that participated in its development. As emphasized of the "29 objectives identified, 20 were aligned with all four organizations; 26 were aligned with three or more; 28 were aligned with at least 2." [97] This emphasizes the point that these applications overlap many agencies, as well as the need for coordination. It also means that other nations may see the same needs in their development of defense systems – such as nuclear weapon or delivery systems.

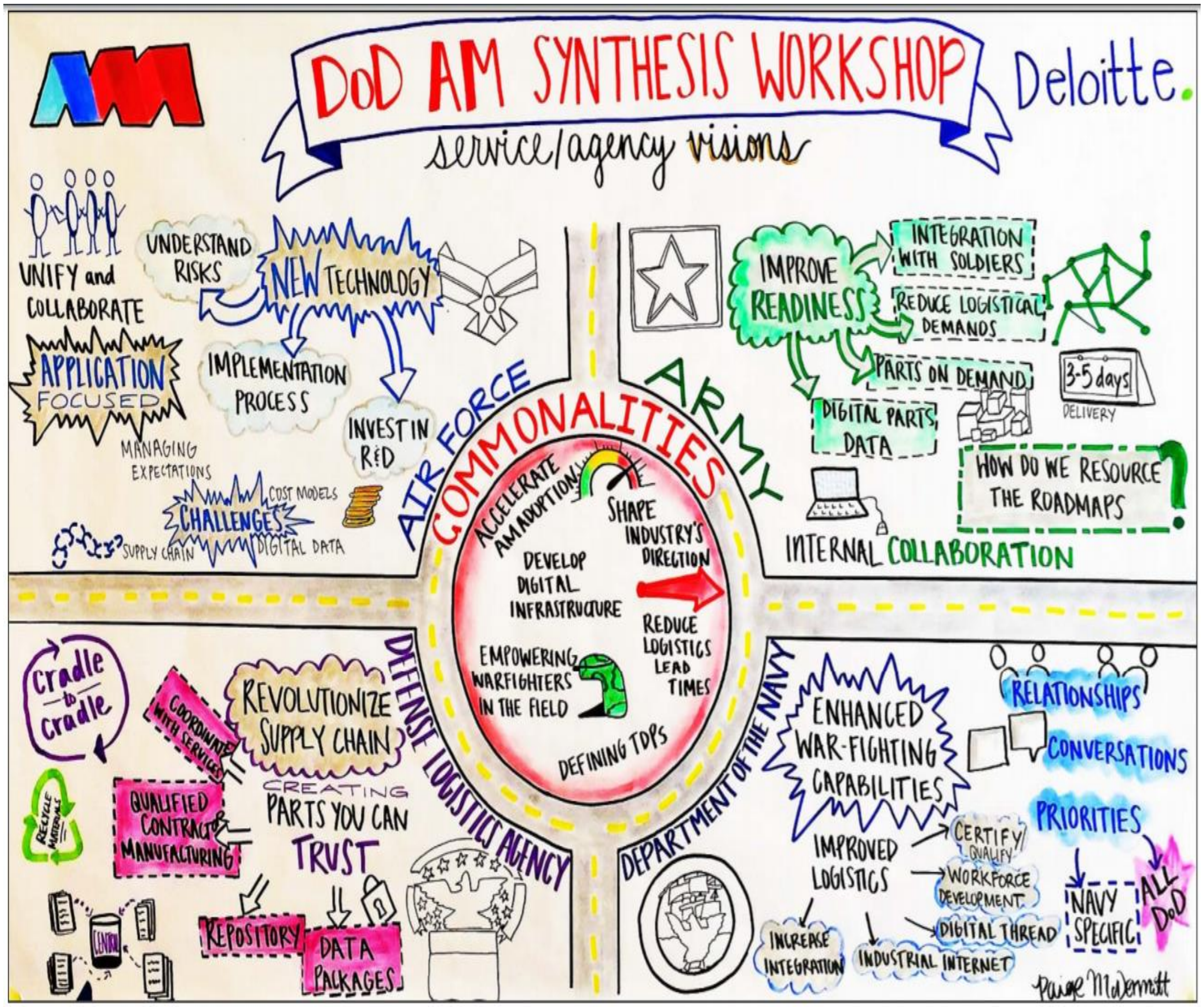

Figure 2: Pictorial characterization of the Department of Defense Roadmap representing various branches of the armed forces and America Makes public-private partnership. [98]

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[97] FY 2017 Additive Manufacturing Report to Congress, Office of the Undersecretary of Defense for Acquisition, Technology and Logistics., December 2017. https://defenseinnovationmarketplace.dtic.mil/wp-content/uploads/2019/05/fy-2017-additive-manufacturing-report-to-congress.pdf

[98] J. Fielding et al, Final Report Department of Defense Additive Manufacturing Roadmap Report, Released 30 November 2016, https://www.americamakes.us/wp-content/uploads/sites/2/2017/05/Final-Report-DoDRoadmapping-FINAL120216.pdf.

The road map effort is further categorized according to specific application needs.

- Manufacture of components that are normally produced using conventional techniques
- Repair of conventional manufactured components
- Manufacturing aids to support conventional manufacturing. Here we mean various tools, masks, fixtures, mounts, patterns, jigs often used in conventional additive and subtractive manufacture.
- New part/system acquisition. New parts and systems designed for AM and manufacturing using AM.
- Rapid part development and prototyping

The Trump Administration has largely continued efforts in AM. [99] A DOD report to Congress described the efforts to employ AM for various applications and across different agencies. Chief among these efforts is America Makes, which coordinates a group of over 180 industry and consortium members "forming the ecosystem for US AM research, production, and workforce training". [100] America Makes has a portfolio of 66 different projects and initiatives and almost 100 million USD in private and public investment and is driving US innovation in AM.

Civilian nuclear applications

Nuclear applications of AM are being developed primarily for limited civilian power applications rather than potential nuclear weapons production equipment (i.e. equipment used for enrichment of uranium, equipment for reprocessing of spent fuel, equipment for the conversion of uranium etc.). Applications of AM in the nuclear sector are behind identified applications in aerospace, defense and automotive sectors, with respect to the maturity of the application. The principal reason is the lack of nuclear-specific industrial standards.[101]

The United States Department of Energy has provided four areas where AM will provide benefits for the nuclear industry.[102] Two of them already have been discussed in the broader context of AM developments in this report: design flexibility and the availability of new materials. The remaining two are not prominent in discussions of the utility of AM as applied to other sectors,

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[99] Dan O'Brien, America Makes Funding Remains Intact; Others' Cut, Business Journal Daily, https://businessjournaldaily.com/america-makes-funding-remains-intact-others-cut/. Also note that the Trump Administration is providing tax incentives and subsidies for companies that want to aid in making components for the DoD supply chain in the United States. See: Richard A. D'Aveni, The Trade War with China Could Accelerate 3-D Printing in the U.S., Harvard Business Review, Oct 18 2018.

[100] Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, FY 2017 Additive Manufacturing Report to Congress, Dec 2017, pg 17. https://defenseinnovationmarketplace.dtic.mil/wp-content/uploads/2019/05/fy-2017-additive-manufacturing-report-to-congress.pdf

[101] Marcus Nichol, "Roadmap for Regulatory Acceptance of Advanced Manufacturing Methods in the Nuclear Energy Industry ", No. Nuclear Energy Institute, Nuclear Energy Institute, 2019. P.3. This report states that ISO and ASTM have not yet considered nuclear industry applications of AM. ASME have a single code underway. The way forward is being provided by the Nuclear Regulatory Commission (NRC) which has issued a draft action plan.

[102] DoE, "4 Major Opportunities for Additive Manufacturing in Nuclear Energy".

which may reflect the differing priorities of the nuclear industry. The first is that as AM parts are built layer by layer, the data collected during the building process can be incorporated into the certification process and thus reduce part certification times. The second is that AM allows the production of parts with integrated sensors, as was discussed on p. 28. This is not for the purpose of weight reduction but communicating operational status and, therefore, permitting predictive maintenance and possibly autonomous operations.

The desire for predictive maintenance is part of a broader trend in advanced manufacturing. The ability to predict when a critical part will break – in order to replace it before it fails - increases reliability of the overall system and reduces disruptions in operation caused by lengthy downtimes for maintenance.[103] This is enabled using an Internet of Things (IoT); i.e. machines that can communicate over an internet. The data collected is used to train machine learning algorithms that can model when parts will fail. Rather than predicting failure on average – i.e. replacing a component or performing a detailed inspection as standard after a number of hours of operation, the individual part can be monitored remotely and replaced before the model predicts its failure. AM expands the reach of this technique by enabling construction of parts that could not be otherwise be instrumented with embedded sensors capable of telemetry. This convergence of machine learning and AM will improve reliability and decrease the likelihood of catastrophic accidents resulting from the failure of critical parts. This feature is cited by the U.S. Department of Energy as a development goal for funding AM research for nuclear applications.[104]

Reverse engineering

The first publicly reported application of AM in the nuclear industry was at Sellafield reprocessing plant in the UK. In 2014, part of the waste and decommissioning program researchers produced a custom metal lid, designed using 3D scanning of the container it was to be affixed to, used to store waste.[105] Reverse engineering of broken parts, where the original supplier is no longer available, is also a prominent application. In March 2017, Siemens produced a 3D printed metal water impeller for the Krško nuclear power plant in Slovenia. The manufacturer of the original part was no longer in business and a replacement was reverse engineered and produced with AM.

Nuclear fuel

National nuclear laboratories have shown interest in manufacturing nuclear fuel with AM. Researchers at Canadian Nuclear Laboratories (CNL) have printed thorium oxide (ThO2) in resin, using stereolithography.[106] Using this process to print metals requires a de-binding and sintering

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[103] Online monitoring is already available via SCADA (supervisory control and data acquisition systems) but systems monitored with SCADA cannot use predictive modelling. See for instance: Science Soft, "A Comprehensive Guide to Iot-Based Predictive Maintenance," 2019, ScienceSoft, https://www.scnsoft.com/blog/iot-predictive-maintenance-guide.

[104] DoE, "4 Major Opportunities for Additive Manufacturing in Nuclear Energy".

[105] Sellafield Press Office, "Sellafield Ltd Leads the Way with Revolutionary 3d Technology," 2014, http://www.sellafieldsites.com/press/sellafield-ltd-leads-the-way-with-revolutionary-3d-technology/.

[106] Andrew Bergeron, Brent Crigger, and Cathy Thiriet, "Early Progress on Additive Manufacturing of Nuclear Fuel Materials," 2018, Canadian Nuclear Laboratories,

stage to fuse the metal and remove the resin. This is preferred to Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) approaches – the processes that directly print metals. Researchers at CNL argue that PBF surface finishing is poor, which can negate any advantage of introducing complex geometries. On the other hand, while DED is preferred to PBF it is a complex process that has difficulty with overhanging parts.[107] Idaho National Laboratory has also performed preparatory research for the development of a printed U3Si2 fuel. No uranium has yet been printed but cerium, zirconium and hafnium are used as surrogate materials.[108]

Fuel Assemblies

Large nuclear companies, such as Westinghouse,[109] Hitachi-GE,[110] Lucideon[111] and BWXT[112] have been investing in printing components for nuclear fuel assemblies.

Novatech, as a supplier for the US nuclear industry, has been developing AM-produced components of fuel assemblies.[113] The philosophy is to first identify parts composed of stainless steel 316L and Inconel 718 where a well-established powder material is available. Using these materials, Novatech has designed four subcomponents of fuel assemblies.[114] Designs for these parts were rapidly prototyped and promising designs were selected. Part testing for nuclear components is extensive and includes full-loop testing, irradiation testing at ORNL, modelling the performance of the part using computational fluid dynamics (CFD) under operational conditions.

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http://www.thoriumenergyworld.com/uploads/6/9/8/7/69878937/thec-18_presentation_-_c._thiriet_2018oct30.pdf.

Andrew Bergeron and JB Crigger, "Early Progress on Additive Manufacturing of Nuclear Fuel Materials," *Journal of Nuclear Materials* 508 (2018).

[107] Greg Hersak, "Additive Manufacturing in the Nuclear Industry," 2018, Canadian Nuclear Laboratories, http://www.nuclearsafety.gc.ca/eng/pdfs/Presentations/Guest-Speakers/2018/Speaker-Series-greg-hersak-additive-manufacturing.pdf.

[108] Jonathan Rosales, Isabella J. van Rooyen, and Clemente J. Parga, "Characterizing Surrogates to Develop an Additive Manufacturing Process for U3si2 Nuclear Fuel," *Journal of Nuclear Materials* 518 (2019).

[109] "Westinghouse to Install First 3d-Printed Reactor Fuel Part in 2018," 2017, Nuclear Energy Insider, https://analysis.nuclearenergyinsider.com/westinghouse-install-first-3d-printed-reactor-fuel-part-2018.

[110] "Gnf2," 2019, GE Hitachi Nuclear Energy, https://nuclear.gepower.com/fuel-a-plant/products/gnf2-advantage.

[111] Lucideon, "Additive Manufactured Parts for the Nuclear Industry," 2019, Lucideon, https://www.lucideon.com/energy/nuclear/additive-manufacturing.

[112] "Bwxt Selected for U.S. Department of Energy Cost-Share Program for Advanced Nuclear Technology Development," 2018, BWXT, https://www.bwxt.com/news/2018/04/30/BWXT-Selected-for-US-Department-of-Energy-Cost-Share-Program-for-Advanced-Nuclear-Technology-Development.

[113] George Pabis and Craig Gramlich, "Additive Manufacturing for Nuclear Components," 2018, NovaTech, https://www.energy.gov/sites/prod/files/2019/02/f59/ne-amm-additive-manufacturing.pdf.

[114] Top and bottom nozzles, lower tier plates for BWRs and hold down springs.

Westinghouse has also been working with printed Inconel and stainless steel 316L to print parts for fuel assemblies.[115] Westinghouse has conducted irradiation tests on printed zircaloy-2, an alloy zirconium developed for cladding.[116]

The University of Pittsburgh was awarded $1 million to develop nuclear power plant components.[117] GE Hitachi Nuclear Energy (GEH) was awarded $2 million to develop sample replacement parts for nuclear power plants.[118] As part of the development the parts will be irradiated at Idaho National Laboratory (INL).

GEH used 3D printing to build rapid prototypes of fuel filters in the GNF2 fuel assembly.[119] 3D printing was also used to rapidly prototype remote uncouplers from the control rod drive in a nuclear power plant reducing the development time of a critical component from months to hours.[120]

Work in this area is also occurring in East Asia. There is interest in using this technology in South Korea, research on fuel assembly components[121] and China's CNNC printed a lower tube socket for the CAP 1400 PWR in 2016.[122]

Small Modular Reactors

National nuclear research in the UK is being pursued at the Nuclear Advanced Manufacturing Research Centre (Nuclear AMRC). This includes a collaboration with Rolls Royce to develop AM

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[115] William Cleary, "Fabrication, Irradiation, and Testing of Zircaloy-2 " 2017, Westinhouse, https://nsuf.inl.gov/documents/Review2017/Cleary%20Fabrication.pdf.

[116] William Cleary and Zeses Karoutas, "Fuelling Additive Manufacturing," 2017, Nuclear Engineering International, https://www.neimagazine.com/features/featurefuelling-additive-manufacturing-5945496/. In 2017 Westinghouse were developing designs for a thimble plugging device, placed at the bottom of the fuel assembly, as well as a bottom nozzle and grid spacers. The thimble plugging device was scheduled to be deployed in a commercial reactor in 2018. MCTR, "Mctr Annex Handbook", No. MCTR, MCTR, 2017. See also presentation by William Cleary, "Current Westinghouse Efforts," 2017, Westinghouse, https://www.nrc.gov/docs/ML1733/ML17338A894.pdf.

[117] "3d Printed Parts for Us Nuclear," 2018, Materials Today, https://www.materialstoday.com/additive-manufacturing/news/3d-printed-parts-for-us-nuclear/.

[118] "Energy Department Invests $82 Million to Advanced Nuclear Technology ", 2016, Department of Energy, https://www.energy.gov/technologytransitions/articles/energy-department-invests-82-million-advanced-nuclear-technology.

[119] Ibid.

[120] Rosales, van Rooyen, and Parga, "Characterizing Surrogates to Develop an Additive Manufacturing Process for U3si2 Nuclear Fuel."

[121] See for instance: Suk Hoon Kang et al., "Additive Manufacture of Nuclear Fuel Supports and Valve Items" (paper presented at the Korea Nuclear Society Spring Conference, 2019).

[122] "Department of Defense Additive Manufacturing Roadmap", 2016.

parts for its Small Modular Reactor (SMR).[123] The printing of Reactor Pressure Vessels and nozzles are also being researched by these institutions.[124] [125]

Research and development using AM for radioisotope production

As part of a program to provide alternative production methods for radioisotopes without the use of highly enriched uranium (HEU), additive manufacturing has been used by researchers at ORNL to great effect in solving a complex engineering problem. Molybdenum-99 (Mo-99), is used in nuclear medicine and the most common production process involves irradiating a HEU target in a nuclear reactor to produce Mo-99. Teams at ORNL explored a variety of approaches to produce Mo-99 without the use of HEU. One proposed solution used an accelerator production process to generate Mo-99 from the enriched Molybdenum isotope Mo-100 (which itself is produced by a separate process). Mo-100 is an expensive material to produce so for this alternative Mo-99 production process to be viable it must use as little of it as possible. The new process additively manufactured both the Mo-100 target and the target assembly in a single process using laser metal printing, in order to overcome the tendency of the targets to be distorted after being placed in the accelerator, wasting valuable Mo-100.[126] This case highlights the adaptability of the AM process to conserve as much material as possible, even when working with exotic materials.

Using AM in US nuclear weapons

The average age of a US Air Force aircraft is 27 years. The companies that produce the parts that service these aircraft have either dissolved or the parts are not manufactured anymore. [127] The same is true for legacy parts of nuclear weapons which need to be replaced, revamped or refurbished. Therefore, in order to understand the non-proliferation risks of AM, it is prudent to understand how DOD uses AM to deal with the DMS/MS issue.

AM of warhead components

Details have not been divulged in the open source literature, but AM has been used by the company Orbital ATK to produce prototype warheads for hypersonic vehicles (likely the X51A Waverider). The 50-pound warhead was detonated at a facility in Texas surrounded by thin metal sheets for post-detonation diagnostics.

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[123] "Nuclear Amrc to Support Rolls-Royce Smr Development," 2017, Nuclear AMRC, http://namrc.co.uk/centre/rolls-royce-smr-support/.

[124] "Printing Nuclear Parts," 2017, Nuclear Engineering International, http://www.neimagazine.com/features/featureprinting-nuclear-parts-5861118/.

[125] Nigel Trenwick, "3d Printing at the Nnl," 2015, National Nuclear Laboratory, http://www.nnl.co.uk/media/1889/nnl-tech-conference-15-poster-fcs-3d-printing-nigel-trewick.pdf.

[126] DoE, "4 Major Opportunities for Additive Manufacturing in Nuclear Energy".

[127] The Air Force has established a strategy called MAMLS (Maturation of Advanced Manufacturing for Low Cost Sustainment) to establish programs for rapid part replacement for legacy aircraft. https://3Dprintingindustry.com/news/america-makes-air-force-3D-printing-project-soars-to-new-heights-142306/

The company was operating according to a compressed schedule and within the space of two months was able to design and produce the warhead. The technology uses Lethality Enhanced Ordinance which it claims expands the radius of destruction and decreases unexploded ordnance to as low as 1%. Some of the advantages of using AM cited by the company were: 1) decreasing the manufacturing time; 2) reduction in expected cost both in funds but also in labor; 3) a general advantage in "terms of positioning in the global arms race". [128] As stated by Richard Truitt, the Orbital ATK's program manager for warhead development programs "Additive manufacturing allows us to make complicated geometries, which would benefit a hypersonics application, without the nasty, long schedule". [129]

Warhead components have also been constructed using AM for the W80-4 life extension program (LEP) which includes adding improved detonators and enhanced safety features. In addition, the main explosive material used in the warhead needs to be replaced but the problem is that "the original high-explosive constituents are not available and therefore must be reconstituted." [130] [131] The warhead also needs to be certified to be compatible with its use in the long-range stand-off (LRSO) delivery system which must be shown not to detonate the warhead if it fails. The design must be certified to be safe (no accidental launches), secure (formal permissions in place) and effective (will operate as designed) without ever conducting a full-scale explosive nuclear test of the system. AM is being used in some of the components and a great deal of effort is being done to verify that the warhead with AM produced components is performing as expected. One technique in the absence of nuclear testing is to do hydrodynamic (non-nuclear) testing and to feed the data obtained from the test into supercomputers to compare the results to simulations. These non-nuclear tests were conducted in 2016. Also, material-aging experiments are done to ensure that the materials and parts can meet their performance requirements throughout the expected lifetime of the warhead.

AM of high explosives

The United States only uses the insensitive high-explosive TATB for its nuclear weapons. This explosive is insensitive to detonation from external stimuli such as heat and shock which is why it is useful for nuclear weapon safety. "An IHE can be dropped, run over, hit with a hammer, or engulfed in flames, and it won't detonate—but it is also more difficult to detonate intentionally

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[128] "Orbital Atk Successfully Demonstrates New Advanced Missile Warhead for High Temperatures and Velocities," 2018, Business Wire, https://www.businesswire.com/news/home/20180426005137/en/Orbital-ATK-Successfully-Demonstrates-New-Advanced-Missile.

[129] Jen Judson, "Orbital Atk Tests Partially 3d Printed Warhead for Hypersonic Weapons," 2018, Defense News, https://www.defensenews.com/land/2018/04/09/orbital-atk-tests-partially-3d-printed-warhead-for-hypersonic-weapons/.

[130] "W80-4 Life Extension Program," 2018, National Nuclear Security Administration (NNSA), https://web.archive.org/web/20190109144055/https://www.energy.gov/sites/prod/files/2018/05/f51/W80-4%20LEP%20factsheet%202018.pdf.

[131] "Warhead Life Extension Passes Key Milestone," 2018, Lawrence Livermore National Laboratory, https://www.llnl.gov/news/warhead-life-extension-passes-key-milestone.

and can lack the power of conventional high explosives." [132] In the 1980's nuclear weapons production slowed, and TATB production stopped. However, after 9/11, the wars that followed, and the increasing interest in safer explosives, DoD increased production of TATB.

Los Alamos National Lab is pioneering 3D printing of explosives such as TATB which has several advantages. First, the explosives themselves can be produced in any configuration necessary. For example, if a hollow sphere is required within another sphere, normally two half hemispheres are produced and then fused together. However, in this case a hollow sphere can be produced layer-by-layer "So it could whip out a hollow ball in no time without hidden holes or seams." [133] The other advantage is that 3D printing explosives allows for better control of the voids inside the explosives which otherwise can make the explosives more susceptible to detonation.

Conventional high explosives (CHE) tend to be more effective explosives then insensitive high explosives (IHE). However, CHEs are also much easier to detonate than IHEs which makes TATB the explosive of choice for nuclear weapons. The sensitivity of explosives is related to the voids inside the materials that in the detonation process produces local hot spots at the microscopic scale. A team at Los Alamos is pioneering a technique to not only 3D print conventional explosives but do so with hotspots tailored to have the "energy release be 'tuned'" – while maintaining safety benefits.[134]

We can speculate that states like North Korea may be interested in manufacturing TATB to produce safer explosives for the same reason the Unites States does. North Korea appears to use unsymmetrical di-methyl-hydrazine (UDMH) as propellant in its Hwasong-12 missiles intermediate-range ballistic missile (IRBM) and Hwasong-14 intercontinental ballistic missile (ICBM) systems and may use it in future missiles. [135] UDMH can also be used as a material to produce TATB. [136] We do not suspect that North Korea is using AM to produce TATB in specific configurations but consider the possibility that it might in the future.

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[132] Explosiv3Design: 3D-printing technology is booming and could revolutionize the design of high explosives, 1663 Magazine, Los Alamos National Laboratory, March 8 2016. https://www.lanl.gov/discover/publications/1663/2016-march/explosive-3D-design.php

[133] Explosiv3Design: 3D-printing technology is booming and could revolutionize the design of high explosives, 1663 Magazine, Los Alamos National Laboratory, March 8 2016. https://www.lanl.gov/discover/publications/1663/2016-march/_assets/docs/1663_26_explosive-3d-design.pdf

[134] Ibid.

[135] Propellant is the chemical mixture burned to produce thrust in rockets and consists of a fuel and an oxidizer.

[136] Mitchell, Alexander R., Philip F. Pagoria, and Robert D. Schmidt. A new synthesis of TATB using inexpensive starting materials and mild reaction conditions. No. UCRL-JC-122917; CONF-9606189-1. Lawrence Livermore National Lab., CA (United States), 1996.

AM of electronics

Exploding foil initiators (EFIs), which are used in a nuclear device, are being researched at the FLEGOMAN program in collaboration with the Army's Armament Research, Development and Engineering Center (ARDEC) at Picatinny Arsenal, New Jersey.[137]

AM of foams

The makeup of the inter-stage material in thermonuclear weapons known as FOGBANK has been cloaked in secrecy. This material absorbs X-rays and re-emits them in any direction therefore changing erasing the direction of the initial X-rays from the initial primary fission explosion and causing uniform compression for the secondary fusion explosion. Details about the plastic foam are classified but is likely an aerogel or a light solid material. The material was produced via a multi-step production process in the 1980s, but production ceased in the 1990s and the facility was dismantled. Recently the production of the material was successfully re-established. It is highly unlikely that the US can 3D print these foams that form the inter-stage of a nuclear weapon although the US has established how to print aerogels.

Instead nuclear weapons currently use 3D printing to produce "hundreds of parts made from polymers, such as foam cushions, O-rings, gaskets, seals, and washers. The parts fill gaps, transmit loads, dampen vibration, and provide cushioning and thermal insulation. Polymers are of particular concern to stockpile scientists because they tend to be reactive. Polymers can change chemically and physically when subjected to radiation, temperature swings, and physical loads." [138] [139]

AM of pressure vessels

Components that can likely be 3D printed are the tritium gas reservoirs used to hold the boost gas for modern nuclear weapons. [140]

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[137] Amanda M. Schrand, "Additive Manufacturing: From Form to Function," *Strategic Studies Quarterly* 10, no. 3 (2016).

[138] "Additive Manufacturing Reshapes Foam Design".

[139] Three 3 materials needed to be replaced: Silastic S-5370, Kerimid 601 is a polyimide resin used as the binder for the syntactic foam used as a support material in the W76. Urethane Encapsulant 7200. See: Sandoval, Cynthia W., Gary M. Gladysz, Thomas S. Stephens, Seth S. Gleiman, Daniel Mendoza, G. Keith Baker, Jon R. Schoonover, Jim Schneider, Brian Perry, and J. W. Lula. Polymeric materials replacement issues for the LANL stockpile. No. LA-UR-02-1470. Los Alamos National Laboratory, 2002. https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-02-1470

[140] Boost gas is added in the plutonium pit if a nuclear weapon which greatly increases the TNT yield of the bomb.

Figure 3: A gas reservoir for boost gas used in the primary of a nuclear weapon. The details and design of these canisters are classified. [141]

In US nuclear weapons the gas reservoirs are emptied and filled at the Savanah River Site, Savannah River Tritium Enterprise (SRTE). [142]

At the Sigma Complex at Los Alamos National Laboratory AM has been used to produce small pressure vessels from stainless steel powders.

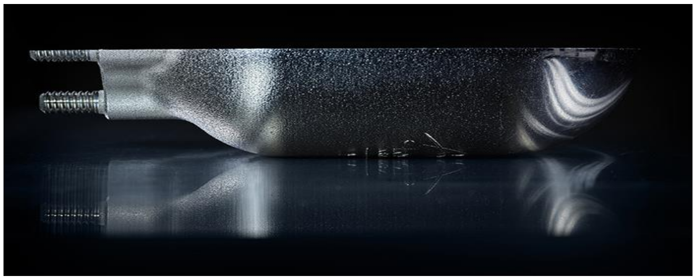

Figure 4: A partially (half) produced pressure vessel produced by Sigma Labs at Los Alamos National Laboratory. [143]

The process is similar to that of the other applications discussed. The focus is on controlling the process-product feedback loop to understand the production process at the microscale so that the microstructure produced through AM can be used to be predictive of properties of the material. The process variables can be modified in order to change the performance characteristics of the material. This is what is called *science-based qualification*, and it “gives the

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[141] "Savannah River Site Defense Programs," 2012, National Nuclear Security Administration (NNSA), https://www.srs.gov/general/programs/dp/index.htm.

[142] "Savannah River Tritium Enterprise," 2018, Savannah River Nuclear Solutions https://www.srs.gov/general/news/factsheets/srs_srte.pdf.

[143] "Additive Manufacturing: The Power of Powder," 2019, Bradbury Science Museum, https://www.lanl.gov/museum/news/newsletter/2019/5/lanl-1.php.

scientists greater control over the product. Science-based qualification is not a guess-and-check process; rather, it is a fundamentally different way of qualifying components. By linking structure to properties, a component can be qualified based on whether it has the right microstructure, regardless of the synthesis or production route.” [144] The Pressure Vessel Project funded by the NNSA is a project to test powder-bed AM for parts manufacture and refurbishment. One such component could be the gas reservoirs used to hold the boost gas for the primary.

AM of conventional explosives

Several independent groups have started initiatives in the United States to 3D print explosives with conventional 3D printers. The idea is that explosives can be combined with other polymers used in 3D printing or the polymer itself acts as the oxidizer for a propellant. Usually, extra materials are added to the polymer for added strength, but here they are exploited to produce explosives themselves as part of the 3D printed material.

The first group, an offshoot from the University of Tennessee is a company EG&G is exploring using Commercial-off-the-Shelf (COTS) 3D Printers to produce explosives. In particular, they are using an HP Multi-Jet 3D Printer to print explosives, with HMX explicitly mentioned.[145] The 3D printer requires the input material to be a powder and EG&G plans to produce explosives powder by first using spray drying. This is a process often used in the food industry where a liquid is atomized and then rapidly dried with hot gas which turns the droplets into a fine powder. [146] The company uses nylon infused explosive material as the source material. The project is to support the US Navy that would like to see if COTS 3D printers can be used to produce explosives instead of dedicated 3D printers.

A team at Purdue University has taken a different approach. Instead of using powders they are producing filaments that can be used in the MakerBot Replicator 2X commercial 3D printer which can be purchased for less than $3,000. The technique produces thermite material by combining Al fuel powder (20% by mass) and a polyvinylidene fluoride (PVDF) oxidizer. This material is known to be a reactive substance and can be used as a propellant. [147] [148] Aluminum itself is very reactive with other materials and is frequently used as an additive in propellants or as the fuel itself. The combined material is cut into pellets and extruded into 1.75 mm diameter filaments appropriate for the Makerbot Replicator using a filament extruder. [149] Since, the filament extruder itself uses high temperatures, care must be taken not to cause the material to react inadvertently. The 3D

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[144] Ibid.

[145] "Development of Explosive Feedstock for Commercial-Off-the-Shelf (Cots) 3d Printers," 2017, SBIR, https://www.sbir.gov/sbirsearch/detail/1472543.

[146] HMX is an insensitive explosive also called octogen similar to the explosive RDX.

[147] Hongtao Yang, Chuan Huang, and Houhe Chen, "Tuning Reactivity of Nanoaluminum with Fluoropolymer Via Electrospray Deposition," *Journal of Thermal Analysis and Calorimetry* 127, no. 3 (2017).

[148] Jeffery B DeLisio et al., "Ignition and Reaction Analysis of High Loading Nano-Al/Fluoropolymer Energetic Composite Films" (paper presented at the 52nd Aerospace Sciences Meeting, 2014).

[149] The filament extruder is a Filabot which can be purchased for less than $3,000.

printer prints at 230 C which is much lower than the temperature of the onset of the deflagration reaction which is at 500 C.

Still another technique from Purdue University is exploring 3D printing nano-thermite materials using a technique known as Reactive Inkjet Printing which essentially uses an ordinary inject printer but instead of using inks, two or more chemical components are used, and combined which droplet-by-droplet react and produce a hardened substrate. The next layer can then be printed on top of the previous to build up the material as with other AM techniques. [150] The technique is essentially a form of photolithography but instead of curing the material with UV light it is done through the drying process (in this case) or through reactions between the droplets. [151] Nano-thermite was produced using colloidal suspensions of nano-Al and nano-copper oxide in a mixture similar to inkjet inks. The two chemicals were then printed in small droplets adjacent and overlapping with each other. Several layers of this matrix are produced one on top of the other. The final solid substrate can then be ignited like other explosives.

Other countries are also exploring 3D printing of explosives. In fact, the Dutch research organization TNO (Netherlands Organization for Applied Scientific Research) successfully 3D printed TNT high explosives using a FDM printer. According to a report “They succeeded in printing multi-perforated gun propellants containing up to 75 wt% of energetic material by using a stereolithography (SLA) based printer.” [152] According to the video posted online TNO has been 3D printing gun propellant with a COTS ASIGA Max 3D printer. [153] As well a research wing of the Department of Defense (DST) of Australia is collaborating with the company DefendTex and academia to explore 3D printing of explosive materials in more detail.

AM of solid propellants

An obvious extension of using AM for high and low explosives is whether AM could be used to produce solid propellants. Solid propellants are preferred over liquid propellants because they can be quickly and directly fired not unlike a firecracker. In contrast, since liquid propellants are often corrosive the oxidizer and the fuel need to be kept separate and loaded into tanks before launch and cannot be immediately fired. [154] Solid propellants can come in many configurations, but a common one is simply a thick cylindrical shell with a hollow perforation at the center. Normally the solid propellant in the form of a slurry is directly poured inside a cylindrical housing with a

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[150] For a general description see: https://3Dprint.com/181892/reactive-inkjet-printing/. A more detailed explanation of the technique is in: Patrick J Smith and Aoife Morrin, "Reactive Inkjet Printing," *Journal of Materials Chemistry* 22, no. 22 (2012).

[151].Ibid.

[152] Chiroli, M., F. Ciszek, and B. Baschung. "Additive Manufacturing of Energetic Materials." In 29th Annual International Solid Freeform Fabrication Symposium–An Additive Manufacturing Conference, Austin, USA, p. 1003. 2018.

[153] "Asiga: The Max Lcd," 2019, ASIGA, https://www.asiga.com/products/printers/max_series/max_lcd/.

[154] A fuel is a substance which burns when combined with oxygen producing gas for propulsion. An oxidizer is an agent that releases oxygen for combination with a fuel. Both are needed in explosives and propellants.

mandrel that is removed after the material is cured. Alternatively, the material is cured inside a cylindrical housing and the perforation (void) removed (subtractive manufacturing).

Additive manufacturing allows grains to be constructed which vary as a function of lengths along the body of the missile housing allowing the thrust produced to optimized. Studies have shown that gas permeable and porous grains may afford a faster burn rate. [155] Previously, the complexity of manufacturing prevented these features from being added. [156] Another motivation for using AM to produce solid propellants is because the process allows very precise ratios of the components of the fuel and oxidizer to be controlled. That composition is critical for determining the burn rate of the solid fuel inside its rocket casing. Nowadays, the thrust profile is controlled by the shape of the solid propellant (grain). However, with 3D printing the concentration of the oxidizer/fuel can be varied throughout the grain giving an extra variable to use to modify the thrust for specific missions. For example, for particular missions the acceleration may need to change throughout the mission. Therefore, there is a strong motivation for companies to use AM to produce solid propellants.

Several companies are pioneering this technology. In the United States the company Rocket Crafters has filed several patents focusing on 3D printing solid propellant using FDM. [157] The basic idea is to build up concentric layers of a compound of a polymer which contains an aluminum additive. Nano-sized particles of Al are desired because the higher surface area makes them higher in reactivity compared to if larger pieces are used. The goal is to employ 3D printed solid propellant into hybrid rockets which do not have the complication of liquid propellant rockets and can be throttled. [158] [159]

Raytheon has also filed a patent for additive manufacture of solid propellants which is based on a 5 step process: (1) mixing together the fuel, oxidizer and a binder to form a propellant mixture (2) mixing well in an acoustic mixer (3) adding a curative and partially curing (4) then dispensing through nozzles to build up the grain of the solid propellant (5) heating the propellant to fully cure it. The patent also describes a list of possible fuels (metal-based fuels), oxidizers (percholorate or nitrate-based oxidizers) and binders are the primary resin materials (such as HTPB or CTPB) and bonding agents, curing catalysts etc.

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[155] KK Kuo and M Summerfield, "Theory of Steady-State Burning of Gas-Permeable Propellants," *AIAA Journal* 12, no. 1 (1974).

[156] Chandru, R. Arun, Nikhil Balasubramanian, Charlie Oommen, and B. N. Raghunandan. "Additive Manufacturing of Solid Rocket Propellant Grains." Journal of Propulsion and Power 34, no. 4 (2018): 1090-1093.

[157] The patent can be found here: https://patents.google.com/patent/US20170073280A1/en

[158] "Rocketcrafters," 2019, Rocketcrafters, http://www.rocketcrafters.com/.

[159] Recently, the company has split up and formed a competing company known as Firehawk Aerospace. It is not clear what the status is of this company in terms of meeting their goals.

US companies using AI in AM

Generative design in AM for delivery systems

US companies Autodesk,[160] nTopology[161] and Frustum[162] utilize AI to optimize parts according to a set of user parameters.[163] These parameters can be relevant to designing and building parts for delivery systems to optimize variables such as strength, weight, and cost.[164] For example, the user enters specific design parameters and the algorithm generates multiple versions of the design using AI each with different functional parameters optimized. The programs can also call Functional Element Analysis packages into the codes to optimize for stress, heat etc. This accelerates the design process and cuts down the time it takes to make the design. [165] It may also mean that less skill is needed in designing the part a general concern about AM for proliferation given that it decreases the barrier for production of WMD and delivery systems. As expressed by Brad Rothenberg CEO nTopology's software creates a workflow to tie in the physics, geometry and design to produce a part. It is not a CAD program to just simply produce and STL file, it incorporates many other aspects of design. The technology can lead to designs that may not have been thought of before. A salient example: nTopology was used to design an engine block. The project designers realized that through the process of making the part more lightweight they could integrate a lattice structure into the part that allowed the engine to be cooled and act as a heat exchanger which was not a function conceived of before. [166] The generative design process is a different way of thinking about the part from conventional manufacturing in the sense that complexity in the part can be used as an advantage to bring new features to the part that could not have been possible without AM. An important trend that will aid in generative design is that more sensors are embedded in 3D printers. [167] At least one company Additive Rocket Corporation (ARC) is using generative design to produce engines for SLV (space launch vehicles).

Using AI to optimize material parameters

The American company Senvol is working with the Navy's Office of Naval Research (ONR) to develop software to use AI to address a key issue: "analyze the relationships between AM process

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[160] Autodesk has a powerful program called Dreamcatcher which uses AI as described. See: https://www.autodeskresearch.com/projects/dreamcatcher

[161] Ntopology software is nTop: https://ntopology.com/

[162] Frustum has now been bought by another company PTC: https://www.ptc.com/en/about/history/frustum

[163] Other companies that are using functional generative design are Dassault Systems in France.

[164] Other companies such as Dassault Systems also use generative design in AM systems.

[165] Tia Vialva, "Autodesk University: How Is Generative Design Used within Additive Manufacturing?," 2018, 3D Printing Industry, https://3dprintingindustry.com/news/autodesk-university-how-is-generative-design-used-within-additive-manufacturing-134963/.

[166] Interview with Brad Rothenberg of nToplogy at RAPID+TCT 2019 on May 27 2019. https://www.youtube.com/watch?v=xr6Y94Zx1Ds&list=PLEjvbhTzaWiFwgCgwQAdJlVmWsGK8WRNd&index=26

[167] Annie Wang at RAPID 2019 interviewed by John Wilczynski, Executive Director of America Makes. https://www.youtube.com/watch?v=8xOgt4qx4hE

parameters and material performance". The goal of this technology for the Navy is to develop validated material properties to decrease the need for material characterization and testing. So that AI can be used to set particular process parameters in AM to meet specific target performance of a part. The main motivation is to decrease the need for trial and error that is often required when producing a part with AM. This will allow parts to be produced quicker as well as decrease costs.

An example from the Senvol website is to optimize a part according to a specific density by modifying the 3D printer process parameters: laser power, laser dwell time, and point distance for a specific laser power bed fusion AM machine.

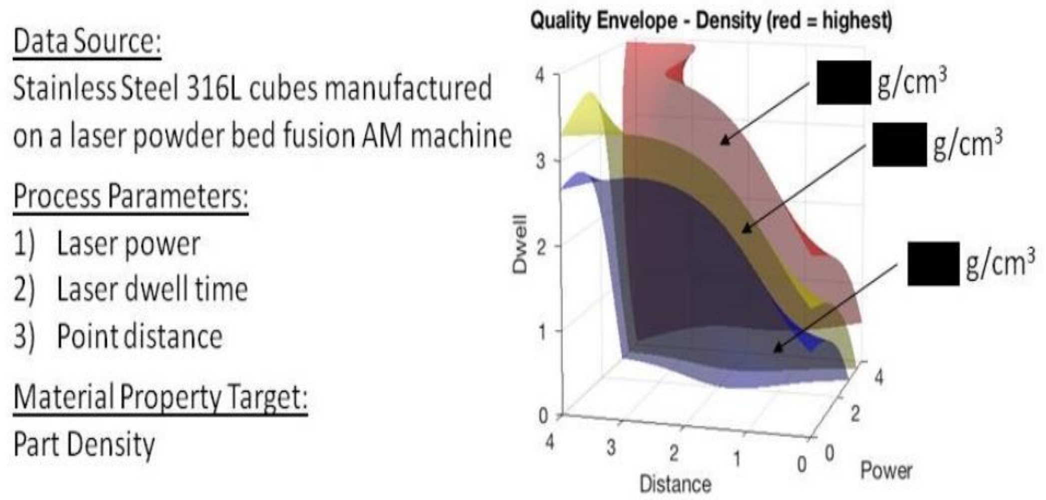

Figure 5: Example analysis from Senvol's software: the three quality envelopes (red, yellow, purple) indicate what process parameters should be used in order to achieve a target material density. All points on the quality envelope surface would allow the build to achieve the target material density (Note: Density values have been redacted). Note: Caption verbatim from the Senvol website. [168]

US success in AM-produced parts for aerospace

There are over 115 companies around the world all vying to place satellites in orbit. [169] With such a large set of competitors, AM is taking a leading role. In the United States alone there are many companies but in this section, we focus on some that have expressly emphasized using AM in their workflow. The challenge is to design components that must be able to withstand high environmental conditions such as "high pressures and temperature gradients that range from -423°F to more than 5,000°F". [170]

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[168] "Senvol Developing Machine Learning Software of Us Navy for Additive Manufacturing," 2018, Senvol, http://senvol.com/2018/03/13/senvol-developing-machine-learning-software-u-s-navy-additive-manufacturing/.

[169] Interview with CEO Andy Kieatiwong at Space Tech Expo 2019. https://www.youtube.com/watch?v=R-FLS_N-_uk&list=PLihnJB3AnlZyAoOUxjEElIgzOQVAfHBc-&index=9

[170] https://www.rocket.com/article/3-d-printed-rl10c-x-prototype-rocket-engine-soars-through-initial-round-testing

Relativity Space: Build SLV from scratch in two months

Relativity Space has developed their dedicated 3D printer Stargate to produce their Terran 1 Space Launch Vehicle (SLV). The company's aim is to produce a rocket that can deploy 1,250 kg payload into low earth orbit (LEO) or a 700 kg payload to height of 1,200 km. The company also claims that they can build a rocket from "scratch" in 2 months. If this SLV were modified to produce a missile instead of an SLV, a payload of 700 kg could be delivered to a range exceeding 2,400 km. The company claims that by using AM to construct the missile engine dubbed Aeon 1 they could decrease the number of parts for their engine from 100,000 to 1,000 components.

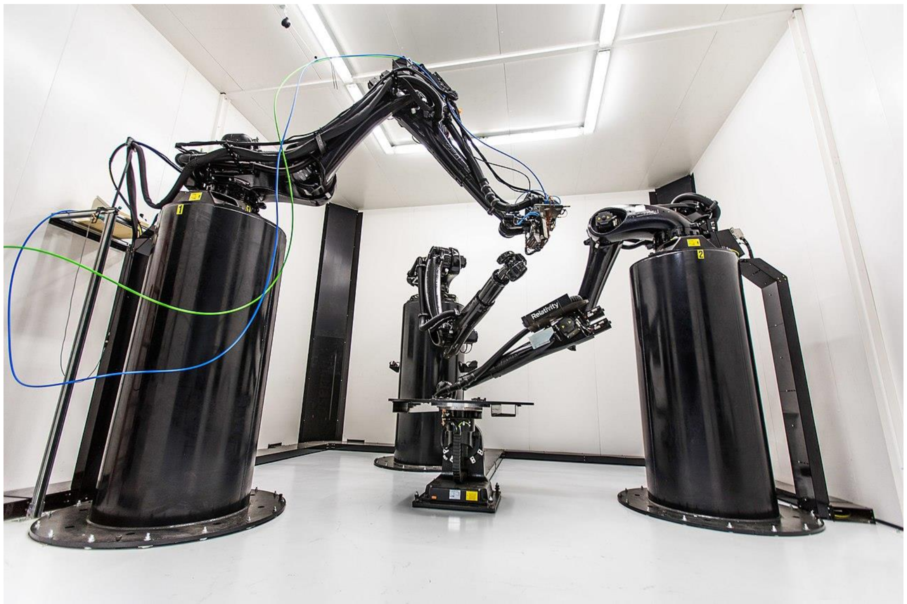

Figure 6: Relativity Space's custom designed SLS 3D printer Stargate. [171] Image courtesy of Relativity Space.

Additive Rocket Corporation: use generative design to build engines

A American company Additive Rocket Corporation is specifically using functional generative design to produce rocket engines. The company design SLV engines using Inconel and Direct Metal Laser Sintering (DMLS). The company claims that through their approach they have been able to decrease the weight by a factor of two. [172] [173] They use the EOS M290 3D printer that can print various alloys such as Inconel, titanium etc. Their latest product is the generative design constructed Hades Engine which can have 2,000 pounds of thrust and because they used generative design is much lighter than similar engines.

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[171] Relativity Space, Inc. - www.relativityspace.com, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=76334077

[172] "Additive Manufacturing in Launch Vehicles," 2018, ARC Engines, https://arc-engines.com/media.html.

[173] Raman Ponnappan, "Additive Manufacturing in Launch Vehicles," 2019, Space Tech Asia, http://www.spacetechasia.com/additive-manufacturing-in-launch-vehicles/.

Launcher: The largest AM produced one-piece engine

The American company Launcher based in Brooklyn, N, is a startup that claims to build the largest 3D printed engine in a single piece in the world.[174] In fact, the engine dubbed E2, is printed by the German company AMCM with their M4K printer in about a week. The goal of the company to produce a rocket that can send a 300 kg to a 200 km LEO. The company has recently partnered with EOS to 3D print alloys like CuCrZr (copper-chromium-zirconium) that are used for regenerative cooling. [175]

NASA Marshall Space Flight Center

NASA is not new to including AM in their projects. In 2013 they used SLM to print a SLV engine and reduced the number of parts from 115 to only 2. They also used AM to print a nickel-alloy liner for a copper combustion chamber as well as print nozzles for engines. They have used AM to produce turbo-pumps and claim a reduction of parts of 45% compared to conventional fabrication.

Aerojet Rocketdyne

The American company Aerojet Rocketdyne used AM to manufacture the RL10C-X engine which will be used in many SLV applications. They 3D printed components critical for the successful operation of the engine such as the injector and thrust chamber. The engine was recently hot tested at their Long Beach, CA facility. [176] The company predicts that "95% of the components that make up an RL10 could ultimately be built using additive manufacturing technology." [177] This emphasizes the importance that AM has for established companies involved in manufacturing aerospace components

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[174] 2019, http://launcherspace.com

[175] Interview with Max Haot, CEO of Launcher at EXPO 2019: https://www.youtube.com/watch?v=4eB_3hbEwno&list=PLihnJB3AnlZyAoOUxjEEIlgzOQVAfHBc-&index=5

[176] "Rl10c X Prototype Engine Hot Fire Test," 2019, Aerojet Rocketdyne, https://www.youtube.com/watch?v=DLb9Gpxm3n8&feature=youtu.be.

[177] S. Erwin, New version of Aerojet's RL10 upper-stage engine to be almost entirely 3D printed, Spacenews.com. https://spacenews.com/new-version-of-aerojets-rl10-upper-stage-engine-to-be-almost-entirely-3D-printed/

RapidTech2019: A snapshot of AM trends in Germany and the AM supply chain

The Rapid Tech/Fabcon 3D conference is not the biggest additive manufacturing trade show—in fact, it's not even the biggest one in Germany, with a larger show held each fall in Frankfurt. However, the three-day gathering and its associated conference is one of the most representative in the field as it brings together companies and experts from all parts of the industry supply chain—from printer manufacturers to software engineers and from materials producers to system integrators and service companies—as well as outside experts. It also comes in a country whose recent industrial strategy document designated "additive production" as one of its key industries.[178] Therefore, a few days spent at this year's June show in Erfurt, a small city in the former East Germany, provides a useful snapshot on the state and future of the industry, particularly in Europe.

Figure 7: Messe Erfurt Exhibit Hall, Site of RapidTech 2019 (photo: Robert Shaw)

The trade show featured a conference with sessions primarily featuring key industries in which use of AM has made inroads. These industries included the aerospace, automotive, and medical sectors, and speakers from both established multinational corporations as well as start-up enterprises described the impact of AM in technical and business contexts. The show also included

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[178] Federal Ministry for Economic Affairs and Energy, *National Industrial Strategy 2030: Strategic Guidelines for a German and European Industrial Policy*, February 19, 2019, p. 5. https://www.bmwi.de/Redaktion/EN/Publikationen/Industry/national-industry-strategy-2030.pdf?__blob=publicationFile&v=9

a mini-conference featuring only start-up enterprises focused on AM (mainly AM-related services), in which each could present its typical "pitch" on the unique value offered by their product or service. The exhibit floor itself was organized according to the AM supply chain, with materials suppliers, 3d printing service providers, design service providers, and printer manufacturers themselves each having their own district section of the show floor.

Figure 8: Show floor of RapidTech 2019 (Photo: Robert Shaw)

Below is a summary of observations from attending the trade show and various conference panels relevant to nonproliferation. The clear picture that emerges from this snapshot of the AM field and its supply chain is that of an industry whose product development is proceeding fitfully but unevenly yet making considerable progress.

Leading Adopters of AM: Aerospace and Automotive Industries

Leading the pack of industries embracing and using AM are the aerospace and automobile sectors. While aerospace worldwide has been receptive to a shift to additive manufacturing, the process in Europe has gained further impetus because of the competitive pressure European manufacturing giants such as the rocket-maker Ariane face from entrepreneurial U.S. start-ups. Ariane, for example, hopes to use AM to lower the cost of a rocket engine from 10 million euros to 1 million euros. [179] Likewise, engineer Gunter Wilfert says AM will allow General Electric to reduce inventory by 95% and to increase fuel efficiency substantially in its rocket engines—decreasing fuel burn by one-fifth.[180] And these changes have come even though the pace of progress in the industry has been slowed by the need to meet the Nadcap standard for aerospace parts, a considerable challenge for many smaller companies.[181]

Like those in the aerospace industry, Germany's luxury automakers—Mercedes, BWM, Porsche—look to AM to dramatically reduce inventories of spare parts. Similarly, they're beginning to use the technology to develop innovative designs that could not be produced by subtractive methods and that reduce product weight and resources by using fewer materials and parts. And they and other manufacturers find AM to be a more useful process for producing some industrial tools than current methods. [182]

An Emerging Area of Possibility: AM and Electronics

The simultaneous conference indicated that the biggest change may come with the growing ability to use 3D printing to quickly design, prototype, and manufacture electronics. This was illustrated by the conference program itself, in which the electronics field had its own distinct set of sessions, featuring firms such as Nano Dimension and Hensoldt Sensors. A key development that was highlighted in these sessions is the unique design possibilities and shape freedom that AM provides, allowing manufacturers to embed electronics (without separate circuit boards) in many other systems, increasing the reach and extent of this technology. Additive manufacturing can also encapsulate electronics within another system to avoid heat and moisture and improve reliability [183] One industry which already appears to be taking advantage of this technology is small satellite manufacturers, given the intense drive to reduce satellite weights to save launching costs. [184]

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[179] Steffen Beyer, (Ariane Group, GmbH), "Breakthrough in Industrialization of Additive Manufacturing for Future Launcher Rocket Engine Applications and Devices—Game Changer in Design, Manufacturing, and Functionality", Rapid Tech+ Falcon 3D Conference, June 27, 2019, Erfurt, Germany

[180] Gunter Wilfert, GE Aviation Munich, "Additive Parts from GE Aviation in Mass Production", Rapid Tech+ Falcon 3D Conference, June 27, 2019, Erfurt, Germany

[181] Nadcap (National Aerospace and Defense Contractors Accreditation Program) is an industry-managed approach that brings together technical experts from prime contractors, suppliers and representatives from government to work together and establish requirements for approval of suppliers using a standardized approach. Generally, suppliers must be accredited for specific parts and processes under Nadcap to be able to sell them to commercial or government buyers.

[182] Uli Klenk, Siemens AG, Industrial Additive Manufacturing: A User Perspective" Rapid Tech+ Falcon 3D Conference, June 26, 2019, Erfurt, Germany

[183] Apparently the electronics can even be designed with embedded cooling. Stefan van Waalwijk van Doorn, Holst Center TNO, "Integrated Electronic Functionalities in 3D printed Products," Rapid Tech+ Falcon 3D Conference, June 25, 2019, Erfurt, Germany

[184] For example, by using RFID chips produced by AM for satellite antennas. Valentin Storz, Nano Dimension, "What is Additive Manufacturing of Electronics: What Can be Done Today? How does it Enable the Electronics of Tomorrow?", Rapid Tech+ Falcon 3D Conference, June 25, 2019, Erfurt, Germany.

Rapid Prototyping

As adoption of AM into development and manufacturing processes has advanced, rapid prototyping quickly emerged as a near-term benefit of the technology. Both in electronics and aerospace, this trend was evinced in the conference sessions by the desire of some manufacturers to use AM to bring in-house aspects of the product cycle that are currently outsourced. For example, rapid prototyping not only would such a system shorten the product cycle for commercial manufacturers, it would also permit them to improve protection of their intellectual property which is put at risk now when they typically outsource production of prototypes. Likewise, the aerospace industry is eager to break the grip of the few companies involved in the cast forging of rocket engines, a process that can be bypassed through AM.[185]

The AM Supply Chain: Increasing in Complexity and in the Variety of Actors

The trade show exhibit hall in particular provided a view into the current AM supply chain, and notable was the variety of actors within or connecting with the use of AM in manufacturing.

At the center of the AM supply chain are the 3D printer manufacturers themselves. As the heir to a long industrial and metalworking tradition, German companies continue to lead in producing various types of industrial 3D printers. Still, experts warn that most of these companies will fail. The industry sector is led by two firms, EOS and Trumpf (both of which had prominent displays in the exhibit floor space) and is likely to remain so given the tendency for a few designs to dominate.[186] Yet, that sector accounts for the largest number of start-ups—more than one-third of all AM-related technologies, according to one survey.[187]

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[185] Gunter Wilfert, GE Aviation Munich, "Additive Parts from GE Aviation in Mass Production", Rapid Tech+ Falcon 3D Conference, June 27, 2019, Erfurt, Germany.

[186] Arno Held (AM Ventures), Presentation: "Survival Rate of AM Printing Start-Ups" Rapid Tech+ Falcon 3D Conference, June 25, 2019, Erfurt, Germany.

[187] Ibid. 36% of start-ups surveyed were involved with hardware, 28% with materials, 31% with applications, and 5% with software.

Figure 9: Display in exhibit booth of EOS, German manufacturer of 3d printers, at RapidTech 2019 (Photo: Robert Shaw)

Additionally, companies offering 3D printing services such as Stratasys were present at the show, with significant floor space as well. Based on discussions with representatives of both 3D printer manufacturers and 3d printing service providers, the delineation between the two company types is somewhat blurred, as both may offer original-design 3D printers as well as printing services.

The trade show indicated that materials suppliers continue to increase the range and quality of the materials they are producing for use in AM. These include materials typically export-controlled such as maraging steel and stainless steel. Displays featured powders of various metal types in clear canisters or examples of printed industrial parts using the materials. Additionally, suppliers of lightweight materials were also present at the show. One interesting example was Orion, which suppliers PEEK – a material used in AM and marketed to manufacturers of cubesats – yet another example where AM is converging with other new technologies.

Figure 10: Metal powders on display at RapidTech 2019 (Photo: Robert Shaw)

Figure 11: Display at RapidTech 2019 promoting maraging steel powder for 3d printers (objects on display are examples of components made of maraging steel and produced by AM) (Photo: Robert Shaw)

Software is a particularly dynamic part of the AM supply chain. This appeared to be an outgrowth of a complaint heard consistently throughout the conference: the inadequacy and incompatibility of current software programs, slowing product cycle and requiring multiple file transfers. Sensing an opportunity, start-up enterprises attempt to address this challenging, offering solutions for connecting software running AM processes with other software used in traditional manufacturing settings.

From a nonproliferation risk perspective, the increased complexity of the AM supply chain might seemingly offer a barrier to realizing the most advanced aspects of the technology. Additionally, the established companies that play a key role in this supply chain, such as the major 3D printer manufacturers, have well-developed export control compliance programs – and are based in countries (such as Germany and the US) with mature export control regulatory frameworks that can further mitigate this risk. However, at the same time, the increased number and variety of actors in this supply chain offer “nodes” by which proliferators might enter the supply chain and acquire either know-how or access to services.

A Special Actor in the AM Supply Chain: Universities and Research Institutions

The advanced state of the AM industry in Germany has been fostered by a strong network of technical and other universities and research institutions, backed by government and working closely with industry to overcome the obstacles to greater use of AM produced technologies. These institutes are scattered throughout Germany in places such as Hamburg, Frankfurt, Paderbon, and Duisberg-Essen and experts from these centers gave nearly half the talks at the conference. One example is the Direct Manufacturing Research Center (DMRC), based at Paderborn University, which conducts research into AM processes and applications and supports key industry partners such as Siemens, Porsche and EOS (whose booth on the trade show floor was next to DMRCs). DMRC also offers courses in AM as well as workshops for industrial partners.[188]

The relevance for nonproliferation relates specific to increased range of actors connecting with the AM supply chain. Universities and research institutions' activities related to AM may offer a convenient conduit by which proliferators could:1) acquire basic AM skills, and then 2) gain further access to AM capabilities via institutions' collaborations with companies.

Other Observations of Note

- The German logistics company DB Schenker presented at the conference session on Contract Manufacturing. In addition to its more traditional freight forwarding and transport services, the company is now offering 3D printing services. This appears to be a hedge against the possibility of AM potentially supplanting the need for cargo to be moved from port to port (or airport to airport), with finished goods being potentially printed at a customer's site.
- The exhibit hall included a display of products that had won awards for innovative use of AM. These included outdoor jackets, boots and an extensive structure for apparent use in remote locations. While the items may have had a certain fashion or design-focused element to them, they also suggest AM's potential value for more prosaic aspects of a WMD proliferation program: the need for basic materials and structures in remote locations where WMD may be developed or tested.

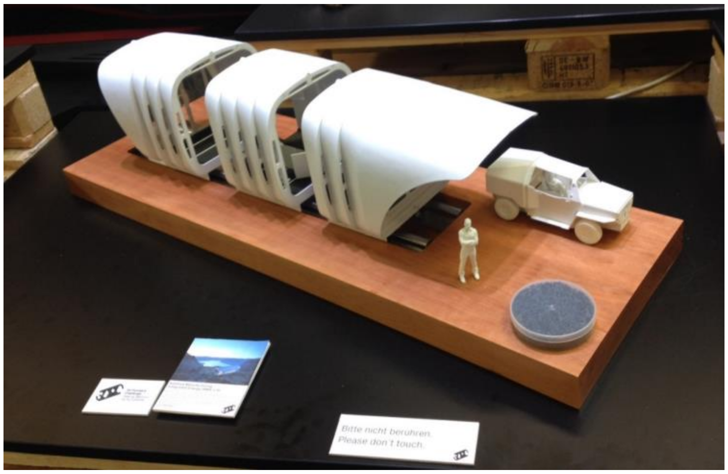

Figure 12: Display at 3D Pioneers Challenge Awards section of RapidTech 2019 show floor; display features a concept building, 3d printable via Big Area Additive Manufacturing Technology (BAAM), developed by a University of Tennessee team and titled "Additive Manufacturing Integrated Energy (AMIE 1.0)" (Photo: Robert Shaw)

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[188] DMRC (Direct Manufacturing Research Center) distributed at RapidTech 2019, Erfurt Germany, June 27, 2019

Figure 13: Display at 3D Pioneers Challenge Awards section of RapidTech 2019 show floor; display featuring a 3d-printable outdoor jacket titled "WearPure" (Photo: Robert Shaw)

Figure 14: Display at 3D Pioneers Challenge Awards section of RapidTech 2019 show floor; display featuring 3d- printable outdoor boot by TailoredFits.com (Photo: Robert Shaw)

Untapped Potential: A Key Theme

One notable theme continuously emerged at the trade show is that the real potential of AM has yet to be tapped. According to this view, AM tends to be used simply as a substitute method for an existing manufacturing processes to produce an item with an existing design and with the potential for cost benefits driving the substitution. This approach in turn suggests that users of AM have yet to really begin taking advantage of the power of the technology to reimagine products and production cycles. This is further accentuated by AM's potential for manufacturing electronics – and embedding electronics in printed forms – and the potential for AI and generative design to yield even newer forms. The perspective also suggests that nonproliferation analysts and policymakers may need to consider the "black swan" potential of innovative use of AM offering a path toward truly new asymmetric and unconventional weapons capabilities.

Conclusion

How might a proliferator seek to use AM to advance a WMD program? When AM is used, in OECD states, it is to reduce process costs or to provide a distinct capability. Proliferators will make a different calculation. They may be limited by the availability of machine tools or materials due to effective enforcement of sanctions or export controls. New opportunities to procure sensitive designs may also be provided by cyber-espionage. We must avoid the temptation to mirror-image when predicting how a proliferator will use AM. Caution applies in any evaluation of proliferation risks associated with future AM trends – especially when these trends themselves are difficult to predict. However, the three major sections of this report captured key developments since 2015, an in-depth look at the use of AM in the U.S. with a focus on missile-relevant aerospace applications, and a snapshot of the evolving AM supply chain in Germany. Clear, ongoing trends in AM emerged, and when considering how these trends might progress across the next decade, the project team could identify key developments as proliferation-relevant. Below is a summary of these key takeaways:

*Delivery Systems: The WMD Modality Most Likely to Be Impacted Near-Term by AM Development*s

AM is used in the nuclear sector for a variety of purposes, including to produce replacement parts where supply chains have collapsed or components with complex internal geometries. At present, AM cannot substitute for conventional manufacturing techniques to print critical WMD production equipment such as centrifuges or reprocessing plants. Gains in using AM for WMD delivery systems are more identifiable and immediate.

Convergence of AM with Other Emerging Technologies Could Accelerate WMD Programs

The promise of AM to print anything, anywhere, must be caveated by the realities of 3D printing. Yet, inevitably, technological progress will allow work with ever more materials and printing processes. Recent trends in AM development, such as the race to master printing electronics and unlocking improvements with machine learning, if mastered, could dramatically increase the demand for AM.

Related to machine learning specifically and our project's examination of the AM sector in the U.S., trends in AI are beginning to impact and influence trends in AM. Many U.S. aerospace companies big and small are also using AI to both save materials, cut down cost and consolidate number of parts. But the big story is how AM can go past transcend traditional manufacturing and produce parts that have never been produced before using generative design. The American company Senvol is using AI to optimize 3D printer parameters in order to print materials that meet certain specifications. Additionally, the American companies Autodesk, nTopology and Frustum utilize AI to optimize parts according to a set of user parameters. These parameters can be relevant to designing and building parts for delivery systems to optimize variables such as strength, weight, and cost. The objects produced by the algorithms tend to have biomorphic shapes that are not easy to manufacture with conventional manufacturing. It is only since the advent of AM where an object's complexity is not a serious impediment that it is possible to use generative design.

The implications for proliferation pathways are unclear, but potential quality and cost benefits and associated accelerated drafting of designs and introduction of novel product forms could in theory speed up and augment a WMD development program.

The AM Supply Chain Is Increasingly Multi-Faceted, Offering More Conduits for Access to Capabilities and Acquisition of Know-How

Illustrated by the variety of exhibitors and featured speakers at the RapidTech 2019 trade show, AM-focused supply chains continue to evolve in complexity. At the same time, the contemporary AM industry remains close to its experimental roots. As a result, there are an increasing number of enterprises involved in industrial/commercial AM supply chain at a time when industry-university collaboration in AM remains extensive (presumably to distribute both R&D costs and associated risks). Each aspect of this evolving AM supply chain may offer conduits that WMD proliferators could exploit to: a) gain access to 3D printing capabilities and services; and/or b) acquire AM-specific know-how. At the same time, mitigating this risk is the presence in the AM supply chain of large companies producing or using 3D printers, particularly in the aerospace and defense sectors, that have well-developed export control compliance programs. In our discussions with such companies exhibiting 3D printers and AM-produced products at the RapidTech2019 trade show, the project team found that these firms were aware of the dual-use nature of 3D printing and the importance of following the associated export control regulatory requirements. While the presence of such established actors in the AM supply chain provides opportunities for further awareness-building (among their suppliers and customers), the general risk of more and a wider variety of actors (especially start-ups that may not be familiar with export controls) offering conduits for proliferators to access AM capabilities is still notable. This risk is discussed in further detail below.

"Niche" Actors in AM Supply Chain

The emergence of several niche actors in 3D printing supply chains – materials (powders, plastic resin) suppliers, 3D printing equipment manufacturers (who offer 3D printing services as well), 3D printing service providers, software providers, and start-ups providing software integration and design support – may offer further access points for proliferators interested in exploiting or acquiring AM capabilities and know-how. The presence of these actors in part relates to the lack of standards, particularly with software used in or connected to the 3D printing supply chain (a reality that seems to be acting as a limiter on pace of growth in the industry).

Industry-University Collaboration in AM Development

RapidTech 2019 featured a conference, with parallel sessions held across each of the three days and focused on particular industry sectors (such as aerospace and electronics). Well-established corporations such as Siemens and Ariane were among the presenters, but several of the presentations delivered by industry representatives featured collaborative projects with universities. Academic and research institutions were also prominent on the trade show's exhibit floor, and these highlighted both collaborations and educational paths available to engineers interested in specializing in AM.

Extensive collaboration between industry and universities in the AM field – and the growth of AM-focused engineering programs within universities -- may offer additional conduits by which proliferators could access AM supply chains and/or know-how. The exemption of "basic" or "fundamental" research from export controls in the EU and US respective underscores this potential.

Start-Up Enterprises and Implications

Start-up enterprises are also driving the emergence of additional actors in the AM supply chain, as discussed in the sub-section above on niche actors. However, the majority of these enterprises are likely to fail. Nonetheless, while such failures are common and even celebrated as a necessary learning tool among venture capitalists and start-ups in Silicon Valley, failure in the additive manufacturing industry could open an overlooked pathway to proliferation. Laid off workers and entrepreneurs could be lured to countries seeking to take advantage of this expertise for their WMD programs; unsold inventory or production lines could follow a parallel path.

After all, a recent survey indicated that of start-up additive manufacturing firms had failed within a four-year period and only a little more than half of those firms could be described as truly "successful" rather than merely surviving hand-to-mouth. [189]

A particular concern could lie within the specific AM industry sector of printer manufacturers. That industry sector, primarily located in Germany is dominated by two firms, EOS and Trumpf, and is likely to remain so given the tendency for a few designs to dominate. [190] Yet, that sector accounts for the largest number of start-ups—more than one-third of all AM-related technologies.

A "Known Unknown"? The Possibility of Untapped Potential in AM and Its Attractiveness for Unconventional Military Programs

More than one practitioner at RapidTech 2019 commented that the real potential for additive manufacturing has yet to be realized. A key factor is that, in general, AM is being seen as a substitute manufacturing method for existing components/products. Rarer are truly new products, enabled only by AM. The introduction of "layered" electronics in 3D printed objects -- and multi-materials in such objects -- may be a game changer looking for someone to realize new products achievable only through this manufacturing method. "Layered" electronics are PCB-like circuits embedded in and printed as part of a 3D-printed object. The use of generative design carries a similar potential.

There is a cadre of engineers graduating from Germany engineering programs with skills in AM, and AM-focused projects are visible activities among US engineering students. However, a revolution driving use of AM may still be awaiting the proverbial 'spark'. Although highly speculative, this raises questions about a possible might be a 'black swan' event waiting to happen, in which a proliferating state or non-state actor deliberately approaches seeking unconventional/asymmetric military capabilities by bringing together a team of AM specialists and

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[189] Arno Held (AM Ventures), Presentation: "Survival Rate of AM Printing Start-Ups" Rapid Tech+ Falcon 3D Conference, June 25, 2019, Erfurt, Germany. The analysis examined 777 start-ups which had sought funding: 23% survived after 4 years. 14% of those seeking funds were declared "successful" at that time—for instance by receiving additional and enlarged funding; 9% of the told were listed as merely surviving.

[190] Ibid. 36% of start-ups were involved with hardware, 28% with materials, 31% with applications, and 5% with software.

commissioning them with the task of "producing something new, powerful and not yet seen before" using AM. It's possible that this could even be used by a state otherwise not expected to be a WMD proliferator, in that this effort would be truly below radar and perhaps not in apparent violation of treaties/regimes.

To be sure, as China has increased its investments in Europe, Germany has become more conscious of the risks of foreign acquisition of technology, recently lowering the trigger for national security review of investments in critical industries from 25 to 10 percent.[191] German Economic Minister Peter Altmaier has also recently indicated that Berlin could purchase stakes in critical domestic industries in order to prevent them being acquired by foreign companies. While it is not clear if that designation of critical industries includes additive manufacturing.[192] Such reviews are also likely to overlook the proliferation risk that could be posed by countries that do not represent a direct national security risk to Germany but are at risk for proliferation (for example, South Korea or Japan).

The actual potential for an unconventional military program centering itself around AM is highly unclear. Use of AM in a proscribed missile program, such as North Korea's, is a more concrete scenario and perhaps more probable. Nonetheless, one recommendation for the US government and its allies to consider would be 'red-teaming' to try to evaluate the potential for such a 'black swan'-like development occurring – and improve the chances of its detection.

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[191] Tobias Buck, Germany Toughens Investment Rules as China Concerns Build, Financial Times, December 19, 2018. https://www.ft.com/content/568183Dc-038e-11e9-99df-6183D3002ee1

[192] Paul Carrel and Michelle Martin, "German State Ready to Buy Company Stakes to Protect Core Industry" Reuters, February 5, 2019, https://www.reuters.com/article/us-germany-industry/german-state-ready-to-buy-company-stakes-to-protect-core-industry-idUSKCN1PU11D; Skadden Arps Slate Meagher & Flom LLP, "Foreign Investment Control Reforms in Europe", Lexology, January 17, 2019, https://www.lexology.com/library/detail.aspx?g=57b9ac72-92b6-49f2-b24a-fb374a12ba27.

Annex: Export-controlled Chem-Bio Equipment and Potential Use of AM

AG Control Lists

The following identify items from the Australia Group Common Control Lists (CCL) that would be suitable for additive manufacturing of production equipment. Items are identified from two lists: the list for dual use biological production equipment and related technology[193] and the list for chemical manufacturing facilities and related technology.[194]

The materials used in the chemical facilities list are common to chemical weapons production equipment, and some biological weapons production equipment. The notation adopted in the list consists of the following items:

a. nickel or alloys with more than 40% nickel by weight;
b. alloys with more than 25% nickel and 20% chromium by weight;
c. fluoropolymers (polymeric or elastomeric materials with more than 35% fluorine by weight);
d. glass or glass-lined (including vitrified or enameled coating);
e. graphite or carbon-graphite; (carbon-graphite is a composition consisting of amorphous carbon and graphite, in which the graphite content is eight percent or more by weight.)
f. tantalum or tantalum alloys;
g. titanium or titanium alloys;
h. zirconium or zirconium alloys;
i. silicon carbide;
j. titanium carbide; or
k. niobium (columbium) or niobium alloys.

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[193] "Control List of Dual-Use Biological Equipment and Related Technology and Software," Common Control Lists (2017).

[194] "Control List of Dual-Use Chemical Manufacturing Facilities and Equipment and Related Technology and Software," Common Control Lists (2017).

	Material type	Possible printed materials	AM processes	AM applications
a.	Nickel or alloys with than 40% nickel by weight	Many materials (>20) meet this requirement[195] including: Inconel 625 Inconel 718 Monel	PBF, DED, binder jetting	Nickel printing is common for applications in aerospace and other sectors. Nickel-based materials printed include Inconel 718, Monel
b.	alloys with more than 25% nickel and 20% chromium by weight;	Several alloys (>20) meet this criterion[196] including: NiCoCrMo Inconel 625 Hastelloy C-2000 Hastelloy C-22HS Hastelloy G-35 Inconel 718	See above	See above
c.	fluoropolymers (polymeric or elastomeric materials with more than 35% fluorine by weight);	PTFE (teflon) 3M have invented an STL technique for printing PTFE that they have taken to market.[197] The maximum dimensions are currently 12 cm x 8 cm x 8 cm.	Stereolithography (STL)	The 3M process will be used for consumer products and parts for industry.
d.	glass or glass-lined (including vitrified or enameled coating);	MIT has developed an optically transparent glass-printing process.[198]	Specifically modified extrusion	
e.	graphite or carbon-graphite; (carbon-graphite is a composition consisting of amorphous carbon and graphite, in which the graphite content is eight percent or more by weight.)	See carbon fiber printing in the main section.		
f.	tantalum or tantalum alloys;	A large number of papers from 2017 onwards. Tantalum powder development printed using Trumpf TruPrint 1000	PBF, DED, binder jetting may be possible	Tantalum has printed for use in orthopaedic

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[195] "Matweb - Online Materials Information Resource," 2019, Matweb, matweb.com.

[196] Ibid.

[197] 3M, "Design Guidelines: Printing with Ptfe," 2019, https://multimedia.3m.com/mws/media/1653754O/3d-printing-design-guide-final.pdf.

[198] John Klein et al., "Additive Manufacturing of Optically Transparent Glass," *3D Printing and Additive Manufacturing* 2, no. 3 (2015).

		(PBF).[199] Printed at Los Alamos using EOS M 280 (PBF).[200]		implants, due to its biocompatibility.[201]
g.	titanium or titanium alloys;	Ti-6Al-4V is the highest developed alloy for printing and more limited work has been performed with Ti-6Al-2Sn-4Zr-6Mo Ti-6Al-2Sn-4Zr-2Mo And commercially pure Ti[202]	PBF, DED	Titanium Ti-6Al-4V is used in aerospace.[203]
h.	zirconium or zirconium alloys;	Zircaloy-2 has been printed and irradiation tested by Westinghouse[204]	PBF	
i.	silicon carbide;	Carbon-reinforced ceramics: Si2C with carbon fiber have been printed[205]	Extrusion (FDM)	
j.	titanium carbide; or	Powder has been developed for PBF printing.[206]	PBF, should be suitable for DED	
k.	niobium (columbium) or niobium alloys.	Uranium-niobium alloy powder has been printed by Lawrence Livermore National Laboratory[207]	PBF	

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[199] Craig Sungail and Aamir Abid, "Spherical Tantalum Feed Powder for Metal Additive Manufacturing," *Metal Powder Report* 73, no. 6 (2018).

[200] Veronica Livescu et al., "Additively Manufactured Tantalum Microstructures," *Materialia* 1 (2018).

[201] Sungail and Abid, "Spherical Tantalum Feed Powder for Metal Additive Manufacturing."; Livescu et al., "Additively Manufactured Tantalum Microstructures."

[202] Bhaskar Dutta and Francis H Froes, *Additive Manufacturing of Titanium Alloys: State of the Art, Challenges and Opportunities* (Butterworth-Heinemann, 2016). P. 45.

[203] Francis Froes, Rodney Boyer, and B. Dutta, "1 - Introduction to Aerospace Materials Requirements and the Role of Additive Manufacturing," in *Additive Manufacturing for the Aerospace Industry*, ed. Francis Froes and Rodney Boyer (Elsevier, 2019). See also: Dutta and Froes, *Additive Manufacturing of Titanium Alloys: State of the Art, Challenges and Opportunities*.

[204] Cleary, "Current Westinghouse Efforts".

[205] Monique S McClain, Ibrahim E Gunduz, and Steven F Son, "Additive Manufacturing of Carbon Fiber Reinforced Silicon Carbide Solid Rocket Nozzles" (paper presented at the AIAA Scitech 2019 Forum, 2019).

[206] GA Pribytkov, MG Krinitcyn, and AV Baranovskiy, "Additive Manufacturing of Parts from “Titanium Carbide–Titanium” Mechanically Activated Powder" (paper presented at the AIP Conference Proceedings, 2018).

[207] LLNL, "Next-Generation Manufacturing for the Stockpile," 2015, LLNL, https://str.llnl.gov/january-2015/marrgraff.

Control List Of Dual-Use Chemical Manufacturing Facilities And Equipment And Related Technology And Software			
Item	AG Reference	Materials	Notes
Reaction vessels or agitators	I.1	a-d, f-h, k	Reactor vessels with total internal (geometric) volume greater than 0.1 m^3 (100 l) and less than 20 m^3 (20000 l) Agitators and impellers, blades or shafts designed for such agitators Prefabricated repair assemblies and their specially designed components, that: iii. are designed for mechanical attachment to glass-lined reaction vessels or reactors that meet the parameters above; and iv. have metallic surfaces that come in direct contact with the chemical(s) being processed which are made from tantalum or tantalum alloys.
Storage Tanks, containers or receivers	I.2	a-d, f-h, k	Total internal (geometric) volume greater than 0.1 m^3 (100 l)
Heat exchanges or condensers	I.3	a-k	heat transfer surface area of greater than 0.15 m^2, and less than 20 m^2; and tubes, plates, coils or blocks (cores) designed for such heat exchangers or condensers
Distillation or absorption columns	I.4	a-h, k	Distillation or absorption columns of internal diameter greater than 0.1 m; and liquid distributors, vapor distributors or liquid collectors designed for such distillation or absorption columns
Filling equipment	I.5	a-b	Remotely operated filling equipment
Valves	I.6	a-d, f-i, k aluminum oxide (alumina) w. purity >99% by wt. zirconium oxide (zirconia)	a. Valves, having both of the following: i. A nominal size greater than 1.0 cm (3/8"), and ii. All surfaces that come in direct contact with the chemical(s) being produced, processed, or contained are made from the materials of construction in Technical Note 1 of this entry b. Valves, not already identified in paragraph 6.a., having all of the following:

			i. A nominal size equal to or greater than 2.54 cm (1") and equal to or less than 10.16 cm (4") ii. Casings (valve bodies) or preformed casing liners, iii. A closure element designed to be interchangeable, and iv. All surfaces of the casing (valve body) or preformed case liner that come in direct contact with the chemical(s) being produced, processed, or contained are made from the materials of construction in Technical Note 1 of this entry c. Components, as follows: i. Casings (valve bodies) designed for valves in paragraphs 6.a. or 6.b., in which all surfaces that come in direct contact with the chemical(s) being produced, processed, or contained are made from the materials of construction in Technical Note 1 of this entry; ii. Preformed casing liners designed for valves in paragraphs 6.a. or 6.b., in which all surfaces that come in direct contact with the chemical(s) being produced, processed, or contained are made from the materials of construction in Technical Note 1 of this entry.
Multi-walled piping	I.7	a-h, k	Multi-walled piping incorporating a leak detection port
Pumps	I.8	a-h, k, ceramics, ferrosilicon	Multiple-seal and seal-less pumps with manufacturer's specified maximum flow-rate greater than 0.6 m3/h, or vacuum pumps with manufacturer's specified maximum flow-rate greater than 5 m^3/h (under standard temperature (273 K (0^{o}C)) and pressure (101.3 kPa) conditions), and casings (pump bodies), preformed casing liners, impellers, rotors or jet pump nozzles designed for such pumps
Incinerators	I.9	a-b, ceramics	

Control List of Dual-use Biological Equipment and Related Technology and Software		
Item	AG Reference	Notes
Containment facilities – double-door pass through decontamination autoclaves	I.1.a	
Containment facilities – mechanical seal walk-through doors	I.1.c	
Fermenter cultivation chambers	I.2.a	Fermenters capable of cultivation of micro-organisms or of live cells to produce viruses or toxins, without the propagation of aerosols, having a total internal volume of 20 liters or greater. cultivation chambers designed to be sterilized or disinfected in situ
Fermenter cultivation chamber holding devices	I.2.b	
Centrifugal separators	I.3	Centrifugal separators capable of the continuous separation of pathogenic micro-organisms, without the propagation of aerosols, and having all the following characteristics: a. one or more sealing joints within the steam containment area; b. a flow rate greater than 100 liters per hour; c. components of polished stainless steel or titanium; d. capable of in-situ steam sterilization in a closed state. Technical note: Centrifugal separators include decanters.
Cross (tangential) Flow Filtration Equipment	I.4	Cross (tangential) flow filtration equipment capable of separation of micro-organisms, viruses, toxins or cell cultures having all the following characteristics: a. total filtration area equal to or greater than 1 square meter; and b. having any of the following characteristics: i. capable of being sterilized or disinfected in-situ; or ii. using disposable or single-use filtration components. (Note – This control excludes reverse osmosis and haemodialysis equipment, as specified by the manufacturer.) Cross (tangential) flow filtration components (e.g. modules, elements, cassettes, cartridges, units or plates) with filtration area equal to or greater than 0.2 square meters for each component and designed for use in cross (tangential) flow filtration equipment as specified above. Technical note: In this control, 'sterilized' denotes the elimination of all viable microbes from the equipment through the use of either physical (ego steam) or chemical agents. 'Disinfected' denotes the destruction of potential microbial infectivity in the equipment through the use of

		chemical agents with a germicidal effect. 'Disinfection' and 'sterilization' are distinct from 'sanitization', the latter referring to cleaning procedures designed to lower the microbial content of equipment without necessarily achieving elimination of all microbial infectivity or viability.
Freeze-drying Equipment	I.5	Steam, gas or vapor sterilizable freeze-drying equipment with a condenser capacity of 10 kg of ice or greater in 24 hours and less than 1000 kg of ice in 24 hours.
Spray-drying equipment	I.6	Spray drying equipment capable of drying toxins or pathogenic microorganisms having all of the following characteristics: i. a water evaporation capacity of ≥ 0.4 kg/h and ≤ 400 kg/h ii. the ability to generate a typical mean product particle size of ≤10 micrometers with existing fittings or by minimal modification of the spray-dryer with atomization nozzles enabling generation of the required particle size; and iii. capable of being sterilized or disinfected in situ.
Protective and containment equipment	I.7	a. protective full or half suits, or hoods dependent upon a tethered external air supply and operating under positive pressure; Technical note: This does not control suits designed to be worn with self-contained breathing apparatus. b. biocontainment chambers, isolators, or biological safety cabinets having all of the following characteristics, for normal operation: i. fully enclosed workspace where the operator is separated from the work by a physical barrier; ii. able to operate at negative pressure; iii. means to safely manipulate items in the workspace; iv. supply and exhaust air to and from the workspace is HEPA filtered. Note 1 - this control includes class III biosafety cabinets, as described in the latest edition of the WHO Laboratory Biosafety Manual or constructed in accordance with national standards, regulations or guidance. Note 2 - this control does not include isolators specially designed for barrier nursing or transportation of infected patients.
Aerosol Inhalation Equipment	I.8	Aerosol inhalation equipment designed for aerosol challenge testing with micro-organisms, viruses or toxins as follows: a. Whole-body exposure chambers having a capacity of 1 cubic meter or greater.

		b. Nose-only exposure apparatus utilizing directed aerosol flow and having capacity for exposure of 12 or more rodents, or 2 or more animals other than rodents; and, closed animal restraint tubes designed for use with such apparatus.
Spraying or fogging systems and components therefor	I.9	Spraying or fogging systems, specially designed or modified for fitting to aircraft, lighter than air vehicles or UAVs, capable of delivering, from a liquid suspension, an initial droplet "VMD" of less than 50 microns at a flow rate of greater than two liters per minute. Aerosol generating units are devices specially designed or modified for fitting to aircraft such as nozzles, rotary drum atomizers and similar devices.
Nucleic acid assemblers and synthesizers	I.10	Nucleic acid assemblers and synthesizers, which are partly or entirely automated, and designed to generate continuous nucleic acids greater than 1.5 kilobases in length with error rates less than 5% in a single run.

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