THE CHALLENGE OF EMERGING TECHNOLOGIES TO NON-PROLIFERATION EFFORTS

Controlling Additive Manufacturing and Intangible Transfers of Technology

KOLJA BROCKMANN AND ROBERT KELLEY

STOCKHOLM INTERNATIONAL PEACE RESEARCH INSTITUTE

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The information contained in this report builds on past research by the authors on 3D printing and additive manufacturing (AM), and on information collected through interviews and communications with representatives of national licensing authorities, delegates to the technical working groups of the multilateral export control regimes and export control officers and technical experts from both AM companies and companies and research institutes that use AM technology. The respondents and interviewees were asked to outline proliferation concerns in their respective areas of expertise; positions on proposed future controls on AM (where possible for publication); national practices in controls on AM; and the challenges their particular authorities or companies are facing with regard to AM and the associated transfers of data. The authors also greatly benefited from a background briefing provided by Joachim Wahren.

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Abbreviations

AM	Additive manufacturing
CAD	Computer-aided design
CBN	Chemical, biological, nuclear (weapons)
CNC	Computer numerical controlled (machine tools)
CVD	Chemical vapour deposition
DIY	Do-it-yourself
DMLS	Direct Metal Laser Sintering
EBM	Electron beam melting
EU	European Union
ICP	Internal compliance programme
ITAR	International Traffic in Arms Regulations
ITT	Intangible transfers of technology
LBM	Laser beam melting
MTCR	Missile Technology Control Regime
NASA	National Aeronautics and Space Agency
OGEL	Open General Export Licence
PVD	Physical vapour deposition
PZT	Piezoelectric (generators)
R&D	Research and development
SALW	Small arms and light weapons
SLBM	Submarine-launched ballistic missile
SM	Subtractive manufacturing
UAV	Unmanned aerial vehicle
^{235}U	Uranium-235
UF_6	Uranium hexafluoride
WA	Wassenaar Arrangement
3D printing	Three-dimensional printing

Executive summary

3D printing, and additive manufacturing (AM) more broadly, is developing rapidly and taking advantage of the increasing automation and digitalization of production equipment and technical data. AM has the potential to produce any physical object based on technical data in the form of build files. These can be easily transferred using email or other means of electronic communication that are hard for authorities to detect and prevent. AM may therefore enable export control circumvention and contribute to illicit weapon programmes. Export controls currently capture AM machines and the software, technical data and materials they use only to a limited extent. Particularly relevant are the controls on technology in the multilateral export control regimes and in corresponding EU regulations, which cover the transfer of both tangible and intangible items. New control list items have been discussed in recent years. However, the way in which existing controls are being applied differs from state to state and it has proved difficult to agree on whether and how they should be expanded. This SIPRI Research Paper maps the current state and spread of AM technology, the key proliferation challenges linked to AM, and both existing and proposed controls on AM. It outlines national practices and the key challenges experienced by the affected stakeholders, and the steps that could be taken to establish effective controls on AM.

Section 2 summarizes the current state and spread of AM technology by highlighting the differences between traditional additive techniques and newly developed techniques in the areas of 3D printing and metal AM. Most traditional additive manufacturing techniques, such as physical vapour deposition (PVD), chemical vapour deposition (CVD), sputtering and filament winding, require a substrate or a mandrel to provide the basic shape for the object being formed. Production equipment that is 'specially designed' to use these techniques within certain technical parameters is covered by controls. More recent AM techniques, such as 3D printing and metal AM, do not require a substrate or mandrel and are therefore not bound by or limited to specific shapes. Instead, they enable the user to produce objects that can be of virtually any shape. Modern 3D printers and metal AM machines use a variety of different techniques, almost all of which are not covered by export controls.

Section 3 discusses proliferation risks and possible applications of AM to small arms and light weapons (SALW), missiles, nuclear weapons and centrifuges for nuclear enrichment. There are few technical limitations on AM techniques being used to produce SALW, but the current cost of metal AM, the performance characteristics of 3D printed polymer guns, the appeal of conventional alternatives and market saturation limit the potential impact of 3D printing and AM in this area. Applications of AM technology are particularly advanced in the aerospace industry, reflecting the significant utility that AM technology offers to the production of missile components and auxiliary systems, many of which also find applications in nuclear weapons. AM has not yet been developed sufficiently to assist in the proliferation of nuclear weapon cores. It may enable the production of some components, but there is no indication that the necessary processes have been thoroughly explored or certified for nuclear weapons manufacturing. The applications of AM to centrifuges are limited to some components and ancillary equipment, while other possible applications such as using maraging steel will most likely be substantially inferior to easier solutions.

Section 4 outlines both existing controls on AM and proposals for future controls that have been made in the multilateral export control regimes. There are existing list-based controls on AM production equipment and some of its key parts, such as lasers, on certain metallic powders and other feedstock materials, and on transfers of technology, in the form of both technical data and technical assistance. In addition, catch-all controls may apply if an item is not listed, but the exporter or the competent national authorities are aware that it may be used in a chemical, biological or nuclear (CBN) weapon programme, or their delivery systems. The first presentation on AM to a technical expert group of one of the regimes took place in 2010. Since then proposals have focused on possible amendments to and expansions of controls on AM machines and the software they use, and on feedstock materials. Changes to, and the expansion of, existing controls on technology, the effective implementation of ITT controls and non-list-based trade control measures, such as catch-all controls, have also been discussed at regime level.

Section 5 discusses national practices, guidance materials and the challenges facing the main stakeholders. There are few current controls targeted at AM and national practices have therefore only been established to a meaningful extent in a handful of states. In addition, there are no industry associations for AM companies and no targeted guidance material for AM. The main challenges for national governments are balancing proliferation risks with adverse consequences for trade and industry, identifying relevant AM machines, defining technical parameters without falling behind technical standards, and detecting and controlling relevant transfers. For companies, it is important to raise awareness among relevant employees and along their supply chains, and to implement an effective internal compliance programme (ICP) that screens end-use and end-users and complies with catch-all provisions. The main challenge for academia and research institutes is compliance with ITT controls on technical data, and transfers of knowledge and technical assistance.

Section 6 presents conclusions and recommendations, and summarizes the main considerations and criteria that should be taken into account when expanding or devising new controls on AM. It argues for a holistic approach to controls that engages all relevant stakeholders in order to create multiple layers of oversight. Specifically, the EU and the multilateral export control regimes could amend controls on lasers and on AM production equipment for explosives, introduce controls on specialized feedstock materials, facilitate exchanges of national practices and information sharing, link the discussions between the different regimes and develop targeted guidance material. National authorities could increase outreach to—and dialogue with—AM companies, universities and research institutes, coordinate national regime delegations, effectively apply catch-all controls to AM, apply specialized company audit procedures to effectively control ITT and review resourcing of national licensing and enforcement agencies. Companies could facilitate dialogue and share best practices within their industry and improve end-user screening and the information on export controls provided by print-on-demand services. Academia and research institutes could increase awareness raising among their staff and researchers, and develop voluntary codes of conduct on dual-use research of concern in the field of AM and its applications to CBN weapons and their delivery systems.

1. Introduction

It has become standard for the export controls in the multilateral export control regimes and the European Union (EU) export control system to apply to both the transfer of physical items and intangible transfers of associated technologies. The multilateral export control regimes define these technologies as the information required for the development, production or use of a controlled item.[1] While intangible transfers may only provide technology in the form of technical data, software or technical assistance, they can nonetheless enable the recipient to produce conventional arms, chemical, biological or nuclear (CBN) weapons and their delivery systems, and their related components. The extent to which this is the case depends on which other barriers are in place for preventing the acquisition of controlled items. Automation continues to play an increasing role in manufacturing. Technological advances in this field must therefore be monitored in order to assess the potential value of an intangible transfer of technology to an actor seeking to illicitly acquire controlled goods, especially those relevant to weapons of mass destruction and their delivery systems. Three-dimensional printing (3D printing), and additive manufacturing (AM) more broadly, is one such technical development that presents challenges for the traditional export control system by increasing the automation factor, reducing remaining knowledge barriers and avoiding the design specialization of multipurpose manufacturing machines. None of these factors or the related challenges are new, and they are being encountered to different degrees in other types of production machinery. However, recent developments in 3D printing, AM more broadly and related industries exacerbate these challenges and serve as a striking illustration of the multiple dimensions of controlling proliferation-relevant technology.

The additive manufacturing process can be described as creating an object from raw materials, often in microscopic powder or liquid form, where there was no object before. This is analogous to a sculptor taking lumps of clay and adding them together in space to produce an object. By adding layer after layer of clay to the core, the sculptor is able to create a finished product. Much like a sculptor, AM processes deposit layers of material on top of each other and bond these together to form an object. This is a sharp change from most traditional manufacturing processes, which rely on subtractive manufacturing (SM) processes that start with a piece of material larger than the desired object and selectively remove material from the surface until the finished product is created. Naturally, this type of manufacturing produces significant quantities of waste that often cannot be reused, or requires additional processing and energy to be recycled.

AM technologies are not new, they have been around for decades and have many industrial applications, especially in rapid prototyping. They have undergone rapid development in the past decade, however, and several important techniques are worth reviewing in the context of proliferation and export control circumvention risks. In recent years, 3D printing has captured particular attention as a new form of AM that produces three-dimensional objects—usually made from polymers—in a process that functions in a similar way to a common inkjet printer. However, a growing number of more advanced AM processes arguably pose a much greater proliferation risk, such

[1] Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-use Goods and Technologies, 'List of dual-use goods and technologies and munitions list', WA-LIST (16) 1 Corr. 1, 17 Feb. 2017; Missile Technology Control Regime, 'Equipment, software and technology annex', 19 Oct. 2017; Nuclear Suppliers Group, 'Guidelines for nuclear transfers', annexed to IAEA document INFCIRC/254/Rev.13/Part 1, 8 Nov. 2016; Nuclear Suppliers Group, 'Guidelines for transfers of nuclear-related dual-use equipment, materials, software, and related technology', annexed to IAEA document INFCIRC/254/Rev.10/Part 2, 8 Nov. 2016; and Australia Group, 'Australia Group common control lists', [n.d.].

as the AM of explosives, rocket propellants, metals and specialized alloys. These AM processes take advantage of the enormous power of modern computers and the processing capabilities of laser- and electron-beam melting systems, for example, to create complicated objects more quickly and potentially more cheaply than traditional forms of manufacturing. Notably, AM may also produce significantly less waste than traditional SM. The machine-operator adds the material needed to produce the part and the unused starting material can be immediately employed for a new production task. AM machines can now produce a growing variety of products that are subject to dual-use and arms export controls. In addition, the capabilities of AM machines are increasing and larger amounts of information can now be coded into digital build files.[2] To date, objects ranging from basic forms of small arms, to components for drones, rocket motors and engines have been produced using AM machines.[3]

AM has become a non-proliferation challenge for two main reasons. First, it provides an alternative to many existing export-controlled production machines. In particular, it promises to increase material efficiency and reduce personnel costs while at the same time enabling some performance characteristics that cannot be achieved using traditional manufacturing equipment. Second, AM means that a machine can be used to process technical data in the form of build files to produce potentially any physical object. Build files can be easily transferred using email or other means of electronic communication that are hard for authorities to detect and prevent, thereby overcoming knowledge barriers and avoiding the physical controls of the traditional export control system. Concerns have been raised about the possible impact on proliferation of a number of applications of AM for producing export-controlled goods. The case of gun activists in the United States designing, printing and subsequently making available the build files for a polymer gun, for example, initiated a debate in the field of small arms and light weapons (SALW).[4] Advances in missile technology using AM have put a spotlight on the future role of this technology in missile development.[5] The claims for what AM can achieve have even extended into the fields of nuclear weapons and nuclear enrichment technology, although these for the most part overestimate the applicability and accessibility of the appropriate AM technology and thus the resulting proliferation risks.

In the dual-use and arms export control community, these concerns have generated a growing interest in AM machines and the technology and material they use. Controls already exist on a range of tangible goods associated with AM, such as some of the machines themselves, the lasers they employ and the powder feedstocks they commonly use. A number of options have been discussed in recent years for expanding these controls. However, formulating new proposals has proved challenging, given the need to keep pace with rapid technological advances and avoid creating an unnecessary regulatory burden on the wide range of commercial applications of AM. Export controls in accordance with the multilateral export control regimes, including those under the EU's export control system, also control the transfer of build files and the technical assistance required for the design and engineering processes through controls on technology.[6] However, while transfers of technology have been covered by

[2] Stewart, I. J., *Examining Intangible Controls,* Part 2, *Case Studies*, Project Alpha, Centre for Science and Security Studies (King's College, London: London, June 2016), p. 21.

[3] Walther, G., 'Printing insecurity? The security implications of 3D-printing of weapons', *Science and Engineering Ethics*, vol. 21, no. 6 (Dec. 2015), pp. 1435–45; and Aerojet Rocketdyne, 'Aerojet Rocketdyne successfully tests engine made entirely with additive manufacturing', 23 June 2014.

[4] Greenberg, A., 'Meet the "Liberator": Test-firing the world's first fully 3D-printed gun', *Forbes*, 5 May 2013.

[5] Raytheon, 'To print a missile: Raytheon research points to 3-D printing for tomorrow's technology', News feature, 19 Mar. 2015.

[6] Brockmann, K. and Bauer, S., '3D printing and missile technology controls', SIPRI Background Paper, Nov. 2017, p. 2.

export controls for a long time, their implementation and enforcement have proved difficult.[7] In the context of the growing capabilities of AM machines, it has become even more important to further improve both the controls and their implementation by the relevant stakeholders.

Although export controls to a certain extent already apply to AM, and there are discussions about further expansion, there is also a lack of consistency in terms of how existing controls are applied at the national level. In the EU, in particular, trade facilitation through open licences and the implementation of controls on intangible transfers of technology (ITT) vary across states. Moreover, there is a lack of guidance material for governments to use when implementing existing controls and for companies when using or exporting AM machines or providing AM-related services. For example, it is challenging for companies to establish for each transfer whether the complexity and detail of the technical data mean that it is subject to controls. Experience at the national and company levels also highlights some of the particular challenges associated with implementing and complying with the existing controls, as well as some of the potential challenges that could be generated by the implementation of new controls in this area.

This paper explores the state of the art in AM, its ability to produce key dual-use items and military goods, the application of export controls to AM, their implementation at the national level and the challenges that implementation and compliance present for governments, companies and research institutes. This is the second of two papers that SIPRI is producing on the issue of ITT controls. The first paper examines transfers of technology more broadly, the different ways in which transfers of technology occur, the proliferation-related challenges they can generate, the way controls are structured in the regimes and implemented at the national level, and the particular challenges that implementation and compliance present for governments, companies and research institutes.[8]

Section 2 details the current state of the art in AM by briefly discussing traditional additive techniques and comparing these to more recent advances in 3D printing and metal AM. Section 3 examines the opportunities presented by the use of AM techniques in four key areas of concern: (*a*) small arms and light weapons; (*b*) missiles; (*c*) nuclear weapons; and (*d*) centrifuges for nuclear enrichment. The section focuses on established applications of AM, relevant research and development (R&D) efforts and cooperation, and technical limitations. In the light of the alarm generated by certain misrepresentations in the popular media and some academic articles, the subsections on nuclear weapons and enrichment technology provide a more detailed technical discussion of the possible applications of AM with regard to specific sensitive components. Section 4 maps the existing export controls relevant to AM, such as those on lasers, metal powders and technology. It also provides an overview of the different approaches to expanding controls that have been proposed or discussed in the multilateral export control regimes. Section 5 briefly examines how existing controls are being implemented at the national level. The section discusses the challenges facing the effective implementation of existing controls on AM—particularly on the technology used by AM machines—and the challenges of expanding the scope of controls in this area. Section 6 presents conclusions and recommendations, focused on the steps that could be taken by the multilateral export control regimes, the EU, EU member states, companies and research institutes to improve and expand controls,

[7] Bromley, M. and Bauer, S., 'The Dual-use Export Control Policy Review: Balancing security, trade and academic freedom in a changing world', *EU Non-Proliferation Consortium Paper* no. 48 (SIPRI: Stockholm, Mar. 2016), p. 10.

[8] Bromley, M. and Maletta, G., *The Challenge of Software and Technology Transfers to Non-Proliferation Efforts: Implementing and Complying with Export Controls*, SIPRI Research Paper (SIPRI: Stockholm, Apr. 2018).

and to promote their effective implementation. The section pays particular attention to the possibility of adjusting the regime control lists, cooperation between stakeholders and the provision of targeted guidance.

2. The state of the art in additive manufacturing

Additive manufacturing is a rapidly developing technology, the capabilities of which have been both chronically overestimated and underestimated in the literature. In order to improve understanding of the relevance of AM technologies to proliferation, this section summarises the current state and spread of AM technology by highlighting the differences between traditional additive techniques and newly developed techniques in the areas of 3D printing and metal AM.

The current state and spread of AM technology

Traditional additive manufacturing techniques

A number of traditional additive manufacturing techniques with applications relevant to controlled items have been around for much longer than today's 3D printing and AM techniques. For example, physical vapour deposition (PVD) is a process of adding atoms one-at-a-time to form an object. The atoms can be vaporized from a target of source material, which may be a solid target or a gas. The atoms are directed to condense on a substrate by their momentum, chemical reactions or electrical charges.[9] Sputtering, a variation of PVD, is a process of moving a material from a target, through space to a target substrate. The atoms to be moved are driven off the target by a high-energy beam of ions, such as ionized argon gas. Sputtering has been studied in the US nuclear weapon research and production complex for use in many of the processes in the manufacture of nuclear weapon components.[10] A related additive process is chemical vapour deposition (CVD), where material in a gaseous form is placed in a work chamber with a mandrel of the final form. Conditions are chosen such that when the gas touches the mandrel or target, it selectively decomposes, leaving behind a metal layer on the mandrel.[11] This technique was used, for example, to coat the plutonium metal pieces used in the Trinity nuclear test in 1945, to make them safe to handle.[12]

Filament winding is a common proliferation-relevant additive technique that relies on winding fine fibres of very strong material that have been soaked in a strong liquid matrix, such as epoxy, around a mandrel, such as a cylindrical tube, resulting in extremely strong, resilient and ideally lightweight cylindrical parts.[13] This technique can be used to manufacture thin-walled gas centrifuge rotor tubes or missile body casings for strong, highly stressed applications that require minimal weight. In modern military applications, the fibres can be high strength glass fibre, carbon fibre or other material soaked in epoxy resin. The resulting shapes are stronger and much lighter than metal parts produced for the same applications.

These traditional additive manufacturing techniques all require a substrate or a mandrel to provide the basic shape for the object being formed. For each of these techniques, 'specially designed' production equipment within certain parameters is covered by controls under Category 2 of the Wassenaar Arrangement dual-use control

[9] See e.g. chapter 11 on physical vapour deposition in Rockett, A., *The Materials Science of Semiconductors* (Springer: Boston, MA, 2008), pp. 505–72.

[10] US Department of Energy, Office of Energy Research, Office of Basic Energy Sciences and Division of Materials Science, *Energy Materials Coordinating Committee: Annual Technical Report*, Fiscal Year 1986–87.

[11] See e.g. Chandler, D. L., 'Explained: chemical vapor deposition', MIT News, 19 June 2015; and chapter 12 on chemical vapour deposition in Rockett (note 9), pp. 573–609.

[12] Bernstein, J., *Plutonium: A History of the World's Most Dangerous Element* (Joseph Henry Press: Washington, DC, 2009), p. 168.

[13] See e.g. Allnex, 'Filament winding', [n.d.], <http://www.nuplex.com/composites/processes/filament-winding>.

list, and in some cases under Category 6B of the Missile Technology Control Regime (MTCR) control list.[14]

3D printing and 'new' AM techniques

More recent AM techniques do not require a substrate or mandrel and are therefore not bound by or limited to specific shapes. Instead, they enable the user to produce objects that can be not only of virtually any shape, but also solid, hollow or with cavities. In addition, they enable a much greater degree of automation, which significantly alters the skills required by operators. However, production machines using these techniques are largely not covered by export controls. The most prominent of these new AM technologies, 3D printing, owes its name to the similarity in its functioning with a common inkjet printer. However, the image of a rather simple desktop device—as suggested by the term 3D printing—describes a range of techniques that is not clearly defined, and is therefore misleading when used to describe the full range of modern AM techniques and production machines. Forms of AM have been around for many decades, but recently the technology has developed at a phenomenal pace. Once a niche technology for prototyping, artwork and jewellery,[15] there are now many variations of AM technology, some of which are perceived as 'disruptive technologies'. A growing range of AM machines may also pose risks of CBN and conventional weapon proliferation.[16] Among other things, AM is being used to produce complex parts with applications in the aerospace industry where strength and quality control are very important.[17]

The many different versions of AM in industrial use today can be explained using a simplified model of the basic technology. The simplest form of 3D printing can use a modified inkjet printer where the 'ink' has been tailored so that either the dried liquid itself becomes the printed object, or additives to the liquid are the printed material in the dried product. One example of this is the thin films of high explosives used in the detonators and boosters of larger high explosive components, such as in a nuclear weapon. Other AM techniques use a machine with a powder-bed and one or more lasers or electron beams driven by a computer program. To achieve the desired performance characteristics, the operator requires a digital 'build file' that describes the exact shape and properties of the reference object and the parameters for the operation of the printer. These are usually made using computer-aided design (CAD) software.[18]

The basic processes involved in powder-bed AM can best be understood when examining their use in the production of a particular final object, such as a knight in a chess set, which is symmetrical but complex. In the printer, there is a very thin layer of powder. This could, for example, be a low melting point plastic or a special metallic powder. The computer causes a raster beam from a laser or an electron beam to pass over the powder, melting it into a thin layer equivalent to the base of the knight. A second extremely thin layer of powder is then added and the beam scans again with

[14] Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-use Goods and Technologies (note 1), pp. 24–49; and Missile Technology Control Regime (note 1), pp. 39–41.

[15] Fey, M., *3D Printing and International Security: Risks and Challenges of an Emerging Technology*, PRIF Report no. 144 (Peace Research Institute Frankfurt: Frankfurt, 2017), p. 8.

[16] Brimley, S., FitzGerald, B. and Sayler, S., *Game Changers: Disruptive Technology and US Defense Strategy*, Disruptive Defense Papers (Center for a New American Security: Washington, DC, Sep. 2013); and Horowitz, M. C., 'Coming next in military tech', *Bulletin of the Atomic Scientists*, vol. 70, no. 1 (Jan. 2014), pp. 54–62.

[17] Norsk Titanium, 'Norsk Titanium to deliver the world's first FAA-approved, 3D-printed, structural titanium components to Boeing', [n.d.], <http://www.norsktitanium.com/norsk-titanium-to-deliver-the-worlds-first-faa-approved-3d-printed-structural-titanium-components-to-boeing/>.

[18] German Parliamentary Committee on Education, Research and Technology Assessment, 'Technikfolgenabschätzung (TA): Additive Fertigungsverfahren (3-D-Druck)' [Technology assessment (TA): Additive manufacturing (3D printing)], Bundestag Drucksache 18/13455, 29 Aug. 2017, pp. 57–59.

slightly different instructions from the computer. This process is repeated thousands of times, building up layers of the piece until the final layer of powder fashions the tip of the knight's helmet and the chess piece is complete. The resulting object is a copy of the original instruction embedded in the build file.

This process is very flexible. If the programme is changed, other chess pieces can be printed by the same machine. If white powder is substituted for black powder, the colour of the chess piece changes. In the case of chess pieces, 3D printing can be used to relatively quickly and cheaply produce identical parts with a high degree of faithfulness, as long as the build file is designed for the capabilities, the specific AM process and the feedstock material used in the printer. AM is an alternative to perhaps casting the same chess piece out of metal or plastic. It is unlikely that ordinary chess pieces would ever be conventionally machined because of the disproportionately high cost. For some industrial applications, however, AM could eventually be a much more cost-effective alternative to traditional casting and machining processes.

There are now a number of AM techniques that function in a similar fashion. AM manufacturing devices, often still referred to as '3D printers' in the popular media, range from mobile desktop devices that heat-liquefy thermoplastic filaments in 'extrusion processes' and cost as little as $150, to industrial grade, metal AM machines that mainly use laser beam melting (LBM) or electron beam melting (EBM) techniques and can cost several million dollars. The main differences between AM machines are in the materials they can process and the techniques employed to deposit and bond these together.[19] AM machines vary in their specific technical requirements, according to the technique they use and their machine design. For example, virtually all metal AM techniques require an inert atmosphere within the build chamber, while others require high-powered lasers capable of moving on multiple axes. The materials used as feedstock today range from polymers to metals, steels, alloys, high-strength carbon fibres, tissue and even 'superalloys' such as Inconel. These superalloys have advanced characteristics, such as very high corrosion resistance, that are required in many items with aerospace, rocket and nuclear enrichment applications.[20]

AM has been widely embraced by industry, researchers and the military. Many large multinationals are investing strategically in the technology by acquiring pioneering companies. Major companies, such as General Electric and Siemens AG, have acquired specialist Swedish and British AM companies.[21] Substantial R&D efforts have involved cooperation between companies, research institutes, universities and the military. Multiple branches of the US military have adopted AM processes in their R&D efforts, even using them in forward deployment in conflict zones and for repair and replacement part production.[22] The US Army, for example, has been cooperating with the National Aeronautics and Space Administration (NASA) and the University of Alabama on AM applications for missile technology.[23] AM machines are already being incorporated into the production facilities of firms in the defence sector, both for production and to continue R&D efforts.[24] Moreover, AM service providers increasingly offer more advanced products, such as metal AM of special materials,

[19] This is not an exhaustive account of the techniques used in modern AM. For a more comprehensive overview see German Parliamentary Committee on Education, Research and Technology Assessment, (note 18), pp. 69–89.

[20] Christopher, G., '3D printing: Implications for non-proliferation', eds F. Sevini and A. De Luca, *JRC Technical Report: ESARDA 37th Annual Meeting Proceedings*, Report EUR 27342 (Publications Office of the European Union: Luxembourg, 2015), pp. 19–20.

[21] General Electric, 'GE agrees to purchase controlling shares of Arcam AB', Press release, 15 Nov. 2016; and Michaels, D., 'Europe leads as industrial 3-D printing takes shape', *Wall Street Journal*, 5 May 2017.

[22] Hallex, M., 'Digital manufacturing and missile proliferation', *Public Interest Report*, vol. 66, no. 2 (Federation of American Scientists: Washington, DC, Spring 2013).

[23] Keith, R., US Army Aviation and Missile Research, Development and Engineering Center (AMRDEC), 'Army, NASA, university collaboration promotes additive manufacturing', 22 May 2014.

[24] Leonardo, 'Missiles produced with 3D technology', Focus, 15 Jan. 2016.

and post-production finishing, such as machining and heat treatment, for customers in motor racing, among other things.[25] So-called makerspaces provide members with both the software needed to design objects and the hardware to 'print' them. In addition, there is a vibrant community developing both online and with these makerspaces as a forum, similar to and overlapping with the wider do-it-yourself (DIY) community, in which experiences, problems and questions are shared and discussed.[26] While the growth of these communities is indicative of the widespread enthusiasm for the technology, the capabilities of the available hardware and engineering expertise remain below what is required for high-tech applications, at least in missiles or the nuclear field.

With the current state of the technology there are few examples of serial production to the same standard as traditional manufacturing techniques in terms of repeatability and the precision of the production process. In addition, AM cannot replace all the steps in the production process, but provides only an alternative for one or multiple steps in the production of an object. AM machines have unlocked a number of previously unattainable performance characteristics, but the products they produce do not necessarily meet quality and reliability requirements. The speed of production, the relationship between speed and quality, and the reliability of individual pieces still place limits on certified mass production.[27] While AM has proved itself in applications for rapid prototyping, attempts to achieve large-scale industrial manufacture of pieces with high performance requirements are still limited by the small defects that continue to occur in additively manufactured objects. Such impurities and weaknesses are not easy to either predict or detect, and they pose obvious challenges such as the possibility of material fatigue. Finishing and post-processing techniques to mitigate these factors are still being researched and may prolong the development phase of high-performance applications. New quality testing and certification techniques, beyond existing non-destructive testing methods, are still being explored.

AM technology—and especially the industry producing 3D printers and AM machines—is continuously expanding. There are however significant differences between the spread of low-end, consumer level polymer printers and the spread of high-end AM machines that are highly specialized for specific materials, such as metal and alloys, or specific production steps. At the lower end, the USA and China hold significant market shares for polymer printers, but states from a diverse range of regions are entering the market. Even North Korea has shown an interest in the technology and has displayed 3D printers at national trade fairs.[28] The production of high-end metal AM technology and the high-performance feedstock materials required is, however, mostly limited to companies based in Germany, the USA, the United Kingdom, Canada and a few other European states. Japan is an emerging competitor in Asia. The production of advanced machines therefore currently remains largely concentrated in the member states of the multilateral export control regimes.

The development of applications and advances in the technology, as well as in the engineering and design of items to be produced using AM, depend on the contributions of a multiplicity of actors, and often take place in targeted cooperation projects that may take a decade to develop one specific application, such as a certified component for a civilian rocket motor.[29] This means that there are a wide range of relevant

[25] Christopher (note 20), pp. 640–42.

[26] Shaw, R. et al., 'Evaluating WMD proliferation risks at the nexus of 3D printing and Do-It-Yourself (DIY) communities', *CNS Occasional Paper*, no. 33 (Middlebury Institute of International Studies at Monterey: Monterey, CA, Oct. 2017), pp. 15–17.

[27] Brockmann and Bauer (note 6), p. 4.

[28] Byrne, L., '3D printer advertised at North Korean trade fair', *NK News*, 3 June 2016.

[29] Hartmannshenn, J., Customs and export control manager, Electro Optical Systems (EOS) GmbH, Germany, Interview with the authors, 18 Jan. 2018.

actors with regard to R&D—and thus also the transfers of knowledge and the technical data involved. These include research institutes, government agencies, national laboratories, universities and companies. The dissemination of and the provision of access to the technology take place not only through the export of AM machines, but also through the access provided to 3D printers and AM machines in makerspaces and by AM service providers. All these actors in this still new industry therefore need to be accounted for and engaged with when seeking to raise awareness of proliferation challenges and possible export licensing requirements.

3. Key proliferation challenges linked to AM

Additive manufacturing has many applications across different industries. The technology has been shown to be relevant to the proliferation of both conventional weapons, and weapons of mass destruction and their delivery systems. This section discusses four specific possible applications of AM: SALW, missiles, nuclear weapons and centrifuges for nuclear enrichment. The application of AM to produce SALW generated the initial hype that still surrounds 3D printing. This section puts those developments into perspective and analyses their relevance as a proliferation risk. The greatest number of advances in applications of AM have arguably taken place in the field of missiles and engine technology. This section discusses the application of AM to missiles and the AM of components that are relevant to both nuclear weapons and missiles. Discussion of the possible application to either nuclear weapons or centrifuges for nuclear enrichment has often been rather abstract. The analysis below therefore discusses possible applications to key components of nuclear weapons and of centrifuges in more technical depth. The selection of applications in this section however does not reflect the whole range of possible applications of AM. A discussion of possible applications of AM to biological and chemical weapons and systems for their delivery or dispersal, such as special nozzles, biotechnical equipment or munitions, is beyond the scope of this paper.

Small arms and light weapons

In May 2013 US activist Cody Wilson and his company Defense Distributed released and successfully tested the design for the 3D printed ‘Liberator’ gun.[30] This marked the first and arguably most prominent case of 3D printing being used to produce an entire functional gun. Wilson and his associates had initiated their ‘Wiki Weapon Project’ ‘to create and release the files for the world’s first printable handgun’ in 2012.[31] In the process, which was widely covered by popular media outlets,[32] they also developed 3D printable lower receivers and standard magazines for the AR-15 rifle, before releasing the build file for the Liberator.[33]

While 3D printing has been used in the development of SALW since the mid-1990s, this had until recently been limited to prototyping and ergonomics testing. Therefore, very few arms manufacturers operated their own 3D printers, but instead outsourced these tasks to commercial 3D printing companies.[34] Currently, most commercial applications of 3D printing and AM to SALW concentrate on the production of components and accessories for gun customization.[35] These applications benefit from the reduction in material use and ease of production of complicated shapes available from AM machines. The ease of personalization and customization of components and accessories via their build files—without the need to refit machine tools—provides another advantage for producers. The use of 3D printing or AM for structural and/or pres-

[30] Greenberg (note 4); and Defense Distributed, ‘DD history’, [n.d.], <https://defdist.org/dd-history/>.

[31] Defense Distributed (note 30).

[32] See e.g. Hotz, A., ‘Download, print, fire: gun rights initiative harnesses 3D technology’, *The Guardian*, 26 Sep. 2012; and Greenberg, A., ‘I made an untraceable AR-15 “ghost gun” in my office—and it was easy’, WIRED, 3 June 2015.

[33] The receiver is the central part of a gun that typically holds key components, such as the action and the firing mechanism, and joins the other main parts of the weapon. Under US federal law, the receiver is the legally controlled part of a gun, which requires serialization and possibly also background checks before sale. The receiver can consist of two components, one of which is controlled. In the case of the AR-15, this is the lower receiver.

[34] Jenzen-Jones, N. R., ‘Small arms and additive manufacturing: An assessment of 3D-printed firearms, components, and accessories’, eds B. King and G. McDonald, *Behind the Curve: New Technologies, New Control Challenges*, Small Arms Survey Occasional Paper no. 32 (Small Arms Survey: Geneva, Feb. 2015), pp. 45–46.

[35] Jenzen-Jones (note 34), p. 46.

sure-bearing components, however, is much rarer.[36] The US-based company Solid Concepts Inc., part of Stratasys Direct Manufacturing, produced the first and only marketed fully additively manufactured metal pistol in late 2013.[37] While the company does sell a limited edition of the gun, the purpose was explicitly to provide a proof of concept, dispel scepticism about the performance of Direct Metal Laser Sintering (DMLS) and promote the company's products and technology, rather than commercial profit.[38] The parts of the gun were made from stainless steel and Inconel, and received only limited hand finishing and fitting during assembly.[39] Key performance enabling features, such as the rifling of the barrel, were achieved within the build process and did not require any additional machining. Notably, the gun was manufactured using an industrial grade DMLS machine, priced at more than half a million US dollars, and was subsequently sold for the prohibitively high price of $11 900, over 10 times the price of an equivalent weapon produced using traditional manufacturing techniques.[40]

Under the UN Programme of Action, all states have committed to control the manufacture of SALW, and to ensure that all SALW are individually marked at the point of production and that records are maintained on manufacture, holdings and transfers.[41] These measures are aimed at helping to ensure that SALW do not reach illicit markets and enabling illicit weapons to be traced back to their point of origin. States have agreed to implement these marking, tracing and record-keeping requirements for polymer receivers and guns produced using AM in the same way as they would for traditionally produced firearms.[42] However, the main concern about the impact of AM technology on SALW production is that it could provide opportunities for individuals or armed groups to acquire unmarked firearms outside of regulated procurement channels. In addition, AM could be used to modify legal firearms or to produce accessories that alter their performance beyond the originally licensed capabilities.[43] There are also concerns that weapons produced by AM would be able to avoid detection using metal detectors, X-ray scanners and other screening devices.[44] Israeli journalists reportedly 3D printed a plastic polymer gun and smuggled it into the Knesset, albeit without a firing pin or ammunition, on two different occasions, and even covertly aimed it at the prime minister to expose the threats produced by such weapons.[45]

Publication of the digital build files for a gun and the associated information on its assembly is probably a violation of export controls or other regulations on the production of SALW in many states. However, enforcing these controls against small-scale violations will be a challenge even for well-resourced states. In the case of Defense Distributed, US law enforcement reacted swiftly to prohibit the distribution of the build files for the Liberator. However, by that time it had already been downloaded over 100 000 times and uploaded to other illegal file-sharing websites, almost cer-

[36] Jenzen Jones (note 34), pp. 53–54.

[37] Stratasys, 'World's first 3D printed metal gun', Stratasys blog, 7 Nov. 2013.

[38] Stratasys (note 37).

[39] Stratasys, 'How it's made: The 3D printed 1911 pistol', Stratasys blog, 26 June 2014.

[40] Jenzen-Jones (note 34), pp. 52–53.

[41] United Nations, Programme of Action to Prevent, Combat and Eradicate the Illicit Trade in Small Arms and Light Weapons in All Its Aspects, A/CONF.192/15, 20 July 2001; United Nations, General Assembly, Resolution 55/255, Protocol against the Illicit Manufacturing of and Trafficking in Firearms, their Parts and Components and Ammunition, supplementing the UN Convention against Transnational Organized Crime (UN Firearms Protocol), adopted 31 May 2001, entered into force 3 July 2005.

[42] United Nations, General Assembly, 'Report on the Sixth Biennial Meeting of States to Consider the Implementation of the Programme of Action to Prevent, Combat and Eradicate the Illicit Trade in Small Arms and Light Weapons in All Its Aspects', A/CONF.192/BMS/2016/2, 15 June 2016, pp. 14–15.

[43] Jenzen-Jones (note 34), pp. 43–44.

[44] Jenzen-Jones (note 34), p. 66.

[45] Berman, L., 'Journalists print gun, point it at Netanyahu', *Times of Israel*, 4 July 2013.

tainly making it impossible to prevent further distribution.[46] This is illustrative of the problems that the release of sensitive information or data on the Internet may entail for national law enforcement bodies.

Nonetheless, the impact of emerging production technologies such as AM in the field of small arms is limited by a number of factors. First, there are already a significant number of inexpensive, illicit unmarked small arms in circulation worldwide.[47] As the unit cost of traditionally manufactured small arms is typically low, even if the weapons are not marked, serialized or licensed, and thus 'untraceable', the application and the demand for 3D printed guns remains rather limited. Second, the advantages regarding less cost-intensive production and traceability may only apply to simple polymer-based handguns that can easily be printed using an affordable 3D printer and dissolved in commonly available chemicals after use. In addition, while the limits to detectability have been demonstrated for common walk-through metal detectors, the X-ray scanners commonly used for luggage at airports are able to detect polymer guns.[48] Furthermore, the easy detectability of the ammunition required—especially in the case of larger quantities—is another factor that limits their utility and the applicability of the above-mentioned concerns. Finally, any advantages need to be weighed against the operational limitations that most 3D printed or additively manufactured small arms display. Most types of polymer gun are notoriously unreliable and may even pose risks to the user due to the poor pressure-bearing characteristics and durability of these types of materials. As the Chair's summary of the Second Open-ended Meeting of Governmental Experts on the Programme of Action on Small Arms and Light Weapons noted in 2015, the reliability of 3D printed firearms 'is not very high for the moment' and the manufacture of small arms using AM 'requires no small amount of resources and time'.[49] There are few technical limitations on metal AM techniques with regard to the production of SALW, but the current persistently high cost of achieving military standard performance parameters and the various alternatives to achieving the desired characteristics significantly limit the impact of 3D printing and AM in this area.

Missiles

Applications of AM technology are particularly advanced in the aerospace industry, reflecting the significant utility that AM technology offers in the production of aerospace products and components, including missiles and other types of unmanned delivery vehicles. AM machines can produce complicated shapes that are both hollow and stable, which allows for weight reduction and component performance beyond the capabilities of traditional manufacturing techniques.[50] For example, in a 2013 test, NASA demonstrated the abilities of an engine injector for a rocket that was produced using AM. It produced more than ten times the thrust compared to any previous additively manufactured injector and consisted of significantly fewer components than had previously been required.[51] With regard to aerospace applications, metal

[46] Greenberg, A., '3D-printed gun's blueprint downloaded 100 000 times in two days (with some help from Kim Dotcom)', *Forbes*, 8 May 2013, <https://www.forbes.com/sites/andygreenberg/2013/05/08/3d-printed-guns-blueprints-downloaded-100000-times-in-two-days-with-some-help-from-kim-dotcom/>.

[47] Schroeder, M., 'New technologies and small arms control: Preventing unauthorized acquisition and use', eds B. King and G. McDonald, *Behind the Curve: New Technologies, New Control Challenges*, Small Arms Survey Occasional Paper no. 32 (Small Arms Survey: Geneva, Feb. 2015), p. 88.

[48] Programme of Action on Small Arms and Light Weapons, 'Second Open-ended Meeting of Governmental Experts 2015: Chair's summary', 1–5 June 2015, p. 4.

[49] Programme of Action on Small Arms and Light Weapons (note 48), p. 4.

[50] Committee on Education, Research and Technology Assessment (note 18), pp. 39–40.

[51] NASA, 'NASA tests limits of 3-D printing with powerful rocket engine check', Press release 13-260, 27 Aug. 2013, <https://www.nasa.gov/press/2013/august/nasa-tests-limits-of-3-d-printing-with-powerful-rocket-engine-check/#.

AM has proved particularly advantageous in the production of components that require internal voids in bulk pieces, such as cooling channels in engine nozzles or combustion chambers.[52] The defence company Raytheon even went so far as to claim that 'The day is coming when missiles can be printed', after it reportedly manufactured a guided missile with 80 per cent of its parts made using AM.[53] This announcement however did not specify which parts or the exact type of rocket, and therefore did not reveal what kind of mechanical or other stresses the parts could withstand or how far advanced the AM applications used really were. In July 2017 NASA successfully tested the first bimetallic rocket engine igniter produced using AM. The engine igniter was produced from feedstocks of a copper alloy and Inconel, and promises to significantly reduce the cost and production time of engine igniters in the future.[54] Maraging steel is another important high-strength material used in the aerospace and missile industries. Research is under way to produce objects such as rocket motor parts from maraging steel using metal AM. This is particularly relevant because the maraging steel blanks used in subtractive machining and the flow-forming tools used to extrude maraging steel are export controlled, while maraging steel powders that could be used for AM currently are not (see section 4).

There are several key technical areas where advances in the application of AM to missile technology and nuclear technology overlap. These include the manufacture of energetic materials, in the form of pyrotechnics and high explosives, and the manufacture of cylindrical bodies using fibre composites. In recent years, there have been considerable advances in additive techniques for the production of explosives. There are many applications of such pyrotechnics and high explosives in missile technology, especially in the production of the propellants that power missile flight and in many auxiliary systems such as explosive separation bolts, explosively controlled valves and explosive trains. For example, solid rocket propellants can be additively manufactured, allowing for the optimization of the microstructure, the propellant and the bonding to the missile casing, compared to traditional manufacturing techniques.[55] US company Rocket Crafters Inc. was recently awarded multiple patents for 3D printed rocket fuel technology that uses thermoplastic and high-energy nano-scale aluminium particles to safely manufacture propellants for its hybrid rocket engines.[56]

The auxiliary systems of missiles and rockets commonly use explosives to separate stages, but their use in nuclear weapons is less well known. In nuclear weapons, explosively driven valves (squibs) are sometimes needed to open and close gas passages, for example in boost systems for tritium and deuterium. Like missiles, these valves need to function reliably after years of inactivity. Explosively driven cutters and diaphragm bursters are used in such applications. In addition, there may also be applications in a missile or a militarized nuclear weapon system where objects must be moved by force, gas pressure or using preloaded springs. These include parachute deployment, yield select mechanisms and use-denial devices to prevent unauthorized use. Advances in the AM technologies used to produce the energetic materials and explosives needed to carry out similar requirements in missile programmes could be applied equally to nuclear weapons. Explosive trains can also be produced using similar AM techniques to be employed in missile event timers and nuclear weapon firing systems. The time an explosive train takes to burn a given distance can be a highly accurate way of timing

WaFqJHf5xp9>.

[52] Committee on Education, Research and Technology Assessment (note 18), p. 45; Aerojet Rocketdyne (note 3).

[53] Raytheon (note 5).

[54] NASA, 'NASA tests first 3-D printed rocket engine part made with two different alloys', News release, 18 Sep. 2017.

[55] Hutterer, E., Los Alamos National Laboratory, 'Explosiv3Design: 3D-printing could revolutionize the high explosives industry', *1663* (Mar. 2016).

[56] Petch, M., 'Rocket crafters granted new patent for 3D printed rocket fuel', 3D Printing Industry, 15 Dec. 2017.

an event in a weapon. They are also very reliable, and resistant to shocks and electromagnetic interference that could destroy electronic chips or circuits.

Explosively driven piezoelectric (PZT) generators are also essential components of military systems. A military system might sit idle for many years before being armed and used. Conventional batteries are not reliable over a period of years. PZT generators are used because of their long life and reliability. When needed, even after years of inactivity, the PZT uses explosives to compress a material to produce a large, sharp voltage pulse to fire detonators, squib valves or other electromechanically driven devices. Advances in the AM of explosives and detonators allow for a more precise tailoring of explosives, which makes them more reliable, more predictable and thus also safer—in both missiles and nuclear weapons.[57] These technologies are especially relevant in militarily reliable and flexible systems, but may be of less relevance to single-event detonations of the type that would probably be desired by terrorists.

The technologies for producing cylindrical bodies using AM of fibre composites overlap greatly with missile programmes and nuclear materials manufacture. In the missile industry, large, strong and light missile bodies are made from epoxy-reinforced fibres such as fibreglass and carbon fibre. These materials are used in the bodies of missiles ranging in size from the smallest surface-to-air anti-aircraft systems to the largest rocket bodies, such as submarine-launched ballistic missiles (SLBMs). The technology is now decades old and has been subject to constant improvement. The same technology is also used to produce highly stressed rotor tubes for the gas centrifuges used to separate uranium isotopes. The highly enriched uranium produced by gas centrifuges is used in nuclear weapons. The main difference between missile bodies and centrifuges is the angle at which the fibres are wound. A missile body must contain the high pressure of burning for seconds to minutes and the stresses are both circumferential and longitudinal. The rocket body is a pressure container for its short active life. Therefore, for some layers the winding angle must be very large with respect to the axis of the cylinder. In a centrifuge, the forces are largely circumferential because the gas pressure inside is negligible. Centrifuges could theoretically be wound circumferentially to make them very strong to only combat centrifugal force. However, centrifuge rotors also suffer large mechanical stresses when they undergo flexural stresses as a function of rotor speed, and so the flexural strength of the length of the tube cannot be ignored. The art of winding a centrifuge tube to account for these two forces makes them somewhat more difficult to wind than missile bodies. New AM techniques may provide possible alternatives to traditional, export-controlled filament winding procedures, for example, using metal AM to produce rotor tubes for centrifuges.

However, there are still a number of hurdles to be cleared in the development of applications of AM technology to missile production and development. It is especially important to note that current applications of AM to high-tech missile production do not translate into 'at the push of a button' scenarios, in which a proliferator has easy access to the technology and would only need the material and a build file to effectively gain access to an operational component for a missile. Instead, the production of just one component will require additional preparation and finishing procedures, and the engineering expertise to tailor it to a specific missile system. The European missile manufacturer MBDA, for example, has already integrated AM devices into one of its missile production plants, but the AM machines only form part of the design and production process and are still far from replacing the majority, let alone all, of the other manufacturing machines.[58] The parts currently produced by the plant using

[57] Hutterer (note 55), p. 4.
[58] Leonardo (note 24).

AM devices all still require finishing procedures, such as high-precision machining or galvanic processes, to meet the tolerance, quality and durability standards required for military grade missiles.[59]

Hybrid applications allow the producer to exploit the strengths of both AM and subtractive or finishing techniques in one machine centre, and represent an interesting option for some AM techniques.[60] The German Parliamentary Committee for Education, Research and Technology Assessment concluded in a recent report that hybrid applications will contribute to the maturation and steady enhancement of the technology in the next five to ten years.[61] However, such combinations are only possible for a limited range of AM techniques. Nonetheless, hybrid applications—and AM-centred production approaches in particular—still pose significant challenges to traditional approaches to export control, as they increase the emphasis on ITT.

Nuclear weapons

Recent publications have raised the question of whether AM could be an enabling technology for the production of finished nuclear weapons, gas centrifuges or significant related components.[62] These articles and reports in the popular media fail to explicitly discuss the technical details of such alleged applications. This paper argues that AM currently provides very few new or alternative paths to critical components either for nuclear weapons or for gas centrifuges. This section considers the most critical components of nuclear weapons and the prospects and problems for AM to bypass controls on traditional manufacturing methods. While the section finds many areas where the potential for AM to contribute to proliferation remains very limited in the near future, it also identifies some areas where AM is rapidly advancing and which will need to be monitored in the future.

It is therefore worth considering the possible applications of AM technology to nuclear weapons in more technical detail. There have even been concerns published that a state or a non-state actor with a build file for a nuclear weapon could print one in a single pass. These articles are probably referring to the key internal components of the weapon, such as the fissile 'pit' that is encased in high explosives. Certainly, such a project would not try to 'print' electronics or the ordinary structural components as well. In any case, additively manufacturing the explosive primary of a nuclear weapon in one pass is beyond any credible capability of current or future AM machines. It is, however, reasonable to consider whether it would be potentially possible to print the individual components of the explosive core and then assemble them. The weapons portion of this analysis is restricted to the nuclear core because components outside the core—the structure, firing sets, electronics and so on—are similar to aerospace applications and are covered elsewhere (see figure 3.1). The nuclear core is a unique item in modern manufacturing and must be addressed in order to answer the questions posed.

Discussion of the production of nuclear weapon components can reasonably be limited to the key elements of an implosion type nuclear weapon that uses plutonium or uranium as the fissile material, as AM does not offer any advantages or circumvention opportunities regarding the much simpler technology in a gun type nuclear weapon. The components at the core of a nuclear weapon are usually hazardous to health and

[59] Leonardo (note 24).
[60] Fey (note 15), p. 9.
[61] Committee on Education, Research and Technology Assessment (note 18), p. 14.
[62] See e.g. Kroenig, M. and Volpe, T., '3-D printing the bomb? The nuclear non-proliferation challenge', *Washington Quarterly*, vol. 38, no. 3 (Fall 2015), pp. 7–19; and Kelley, R., 'Is three-dimensional (3D) printing a nuclear proliferation tool?', EU Non-proliferation Paper no. 54 (SIPRI: Stockholm, Feb. 2017).

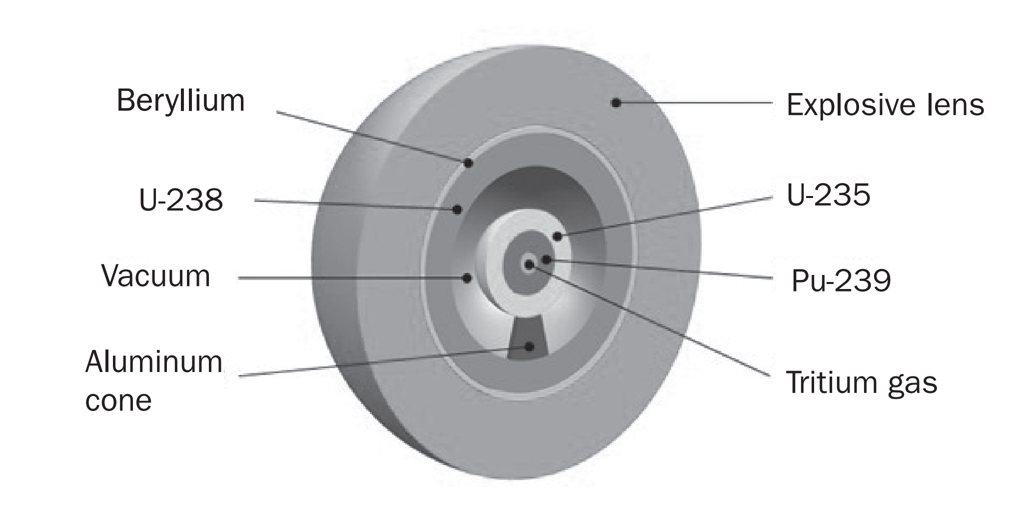

Figure 3.1. Basic components of a nuclear core

Source: Nuclear Knowledge, 'Implosion', [n.d.], <http://nuclear-knowledge.com/implosion.php>.

safety. They require extreme precision and are difficult to produce using traditional subtractive machining and other preparation processes.

Fissile core

The fissile core of a nuclear weapon will be made of plutonium, highly enriched uranium or both. Plutonium, in particular, is highly radiotoxic. Even tiny specks of plutonium penetrating the lungs will lead to cancer and death. The time this takes will be proportionate to the amount inhaled. Unless the proliferator is a suicidal non-state actor, extensive safety precautions must be taken.

AM requires finely divided powders to be melted to form the final object. Finely divided plutonium powder is highly pyrophoric and would ignite spontaneously in air or when heated and melted in an AM process in the presence of oxygen. Therefore, any AM of plutonium must be carried out in a high-vacuum or very pure inert gas environment. Industry has already demonstrated that highly reactive powders can be printed, so this is not necessarily a barrier.[63] Numerous accidents during attempts to print reactive materials such as titanium, however, should serve as a warning.[64] Combined with the extreme level of toxicity, this is a daunting prospect. This is one reason why controlled atmospheres are of particular importance for advanced AM machines.

Plutonium also has a peculiar and complex metallurgical phase diagram. Plutonium behaves very differently from other metals and has challenged metallurgists' attempts to cast it, alloy it and machine it—all in an effort to make parts that are precise and metallurgically stable for many years. For example, plutonium expands and breaks its mould when the molten liquid is cast and when it is solidifying. Water and tin are the only other materials in nature that expand on freezing. Much oversimplified, this presents problems comparable to frozen water pipes.

Using AM as an alternative manufacturing process will require a complete rethink of plutonium metallurgy. This would be an entirely new industrial and scientific environment and it is likely to require years of effort to overcome the challenges posed

[63] Inert Corporation, 'Understanding potential reactions in a 3D printing enclosure', 7 June 2016, <http://www.inerttechnology.com/whats-new/understanding-potential-reactions-3d-printing-enclosure/>.

[64] United States Department of Labor, Occupational Safety and Health Administration, 'After explosion, US Department of Labor's OSHA cites 3-D printing firm for exposing workers to combustible metal powder, electrical hazards', Region 1 News release 14-817-BOS/BOS 2014-073, 20 May 2014.

by the properties of plutonium. It is worth noting that these properties also make the conventional production of plutonium parts a highly challenging activity. At this point, however, it can be concluded that additively manufacturing plutonium is more difficult than using conventional means. It would require the development of entirely new processes that would challenge even a highly developed state with an advanced nuclear industry. It would therefore be a poor choice for a state proliferator and an extremely unlikely one for a non-state actor. Uranium provides for a similar case to plutonium. It is far less toxic and the metallurgy is relatively docile, but it burns readily in air and melts at a much higher temperature. The same conclusion can therefore be drawn about the possibility of a proliferator using AM to produce uranium core parts.

Neutron reflector

The core of a nuclear weapon will probably include a neutron reflector, which also serves as a strong metal container for the highly toxic plutonium inside allowing it to be more easily handled. Some public documents call the reflector a 'tamper' but the tamper is a separate concept and an older technology. The reflector is the first layer outside the fissile material and is used to reflect neutrons back into the exploding core at critical time. The reflected neutrons cause extra fissions, instead of being lost outside the core. This substantially increases the yield.

Neutron reflectors are commonly made of beryllium, which is a toxic material.[65] If inhaled, it can lead to chronic breathing problems or death. It is a difficult material to process because it is not suitable for melting or casting. It is normally produced by pressing fine beryllium powder into a rough metallic shape and machining to final dimensions. Beryllium powder is available for powder pressing but on its own may not be suitable for additive manufacturing.[66]

Beryllium-aluminium powders can be produced for use in AM because the aluminium component can melt and form a matrix with the beryllium.[67] This produces a part that is less effective at reflecting neutrons than a pure beryllium reflector, but in thin shells would be more than adequate as a reflector material. Developing AM processes for beryllium-aluminium powders would be a relatively simple development task. Export controls have therefore been applied to these powders and authorities need to monitor whether printing processes designed around this toxic material are being developed.

High explosives

The 3D printing and AM of high explosives has been researched for more than a decade. Explosives are obviously dangerous, and 3D printing promises to make the production of explosive components safer. The technology is already in use to print the detonators that set off high explosive charges. This can be done in a printing machine as simple as an ink jet printer, where the explosive is in a fluid matrix.[68] When the matrix evaporates an explosive component is left. Objects such as the bridge wires in a detonator, the explosive in the detonator and 'boosters' that increase the tiny explosion of a deto-

[65] Nuclear Knowledge, 'Reflectors', [n.d.], <http://nuclear-knowledge.com/reflectors.php>.

[66] Materion Corporation, 'Nuclear grade Berylium metal for reactors', [n.d.], <https://materion.com/products/beryllium-products/beryllium-metal/s-65-h>.

[67] IBC Advanced Alloys, 'Beryllium aluminium alloys: Beralcast alloys', <https://www.ibcadvancedalloys.com/products-beralcast-alloys-beal-alloys>.

[68] Ihnen, A. et al., 'Inkjet printing of nanocomposite high-explosive materials for direct write fuzing', Presentation at 54th Fuze Conference, Kansas City, Missouri, 13 May 2010, <http://docplayer.net/47391046-Inkjet-printing-of-nanocomposite-high-explosive-materials-for-direct-write-fuzing.html>.

nator to ignite a large mass of kilograms of high explosive can be produced. This technology represents an alternative means of detonator production, but not necessarily a new capability for a proliferator.

Of greater concern is the 3D printing of massive amounts of high explosive, in the order of kilograms, for high explosive lenses.[69] The technology is not yet mature but it is rapidly improving.[70] Early explosive charges for implosion nuclear weapons were generally made by casting high explosives. This is an established technology for conventional explosives throughout the world and a relatively crude technology in modern nuclear weapons. Advanced explosive lenses in modern weapons are made by isostatically pressing explosive powders with a binder such as Teflon powder. This is a complex process that requires much more sophisticated equipment than casting, such as very large, expensive, export-controlled presses. In addition, hot isostatic pressing is very dangerous if done inexpertly. Finished pressed parts normally need to be machined to final shape and drilled for various penetrations. Drilling and machining high explosives are additional dangerous industrial processes that a proliferator would need to master. The 3D printing or AM of precise shapes of high explosive with penetrations and other cut-outs produced in a one-step printing process could be a safer and easier technology in the long run. Printing high explosives at lower temperatures than metal is on a par with printing plastics.

AM has an advantage in many structural applications because it can produce strong, hollow parts that it would be impossible to make by conventional means. In the case of high explosives, the advantage of the 3D printing or AM of nuclear weapons high explosives is different. Explosives pressed by conventional means contain tiny defects and voids. Lawrence Livermore Laboratory has found that the 3D printing of explosives presents opportunities to reduce these imperfections at the microscopic level.[71] This signals a path to better performance, safer explosives and even the ability to produce energy gradients within a massive part—instead of relying on an assembly of precisely calculated and machined discrete individual shells—to improve performance.

This is not particularly relevant to non-state actors, but could be very attractive to a country building a small nuclear weapon stockpile. This is therefore a case that is highly relevant to the future of export controls, as printers for high explosives must of necessity be designed with the appropriate safety features in mind. Specifications for sealed electrical systems, spark-proof features and remote operation would be strong indicators of concern and could therefore form parameters in the control lists or indicators that a machine has been 'specially designed' for the production of high explosives or other energetic materials.

Neutron initiators

Neutron initiators are used to start the chain reaction in a nuclear explosion. When the core is compressed to its maximum, neutrons from an external electronic accelerator or an internal nuclear reaction inject the first neutrons into the core, beginning the extremely rapid chain reaction of fissions that lead to the nuclear explosion. Electronic initiators are small accelerators slightly smaller than an aluminium can. They resemble the vacuum tubes used in 20th century electronics and are not extremely difficult to build. There may be advantages in making glass to metal seals and delicate internal components using 3D printing but it is not obvious that there will be any enabling advantages.

[69] Hansen, R., 'Next generation manufacturing for the stockpile: Additive manufacturing may help transform the nuclear weapons enterprise', *Science & Technology Review* (Jan./Feb. 2015).

[70] Hutterer (note 55).

[71] Hansen (note 69), p. 8.

Internal initiators are largely classified in their design and function. They consist of material at the centre of the core that is squeezed by the conventional explosives and mixed with certain elements to produce a small neutron burst. An unclassified historical example is the crushing of beryllium and polonium together, which produces a strong neutron source for microseconds, enough to start the chain reaction. These internal initiators use toxic materials and demand high precision. As such, existing AM techniques could potentially be a useful alternative to other dangerous conventional manufacturing techniques.

Modern nuclear weapons are often boosted using reactions between tritium and deuterium isotopes to produce high-energy neutrons that greatly enhance fission. It is not clear that AM has much to contribute to producing boosting systems and the details of the engineering design of boosting systems are classified at the level of detail needed for this paper.

The above findings demonstrate that some components of a nuclear core can be produced using AM. There is, however, no indication that the necessary processes have been thoroughly explored or certified for nuclear weapons manufacturing. For example, AM of high explosives is in its infancy and shows great promise, but major research institutes with significant financing and facilities are only beginning to explore the practical problems. For this reason, this papers assesses that AM has not yet been developed sufficiently to assist in the proliferation of nuclear weapon cores.

Centrifuges for nuclear enrichment

Enrichment technology used to produce highly enriched uranium for a weapons core, or as a precursor to producing plutonium, must also be considered as a possible area of application for AM. The analysis in this section is restricted to the gas centrifuge enrichment method. Gas centrifuges are used to separate the isotopes of uranium in order to acquire relatively pure uranium-235 (^{235}U) for use as the fissile material in nuclear weapons. There are many other processes for separating uranium isotopes but gas centrifuges are the modern standard for this industrial process and their proliferation has long been of major concern. In addition, gas centrifuges have played a major role in modern proliferation and other separation methods do not obviously benefit from AM.

Description of a gas centrifuge

A gas centrifuge is a machine designed to separate the isotopes of uranium from each other. A minor constituent, ^{235}U occurs at less than 1 per cent concentration in natural uranium mined from the ground. Its concentration must be enriched from less than 1 per cent to about 3.5 per cent for use in electricity generation and about 90 per cent for use in a nuclear explosive. The gas centrifuge has emerged as the favoured industrial technology for carrying out this task. It is currently in use in around 12 countries and has been linked to nuclear weapons proliferation in several others, notably Iraq in the 1990s.[72]

The gas centrifuge is simply a very strong tube containing uranium hexafluoride (UF_6) gas that spins at tens of thousands of revolutions per minute in an evacuated casing (see figure 3.2). Centrifuges range in size from a large kitchen waste bin to a cylinder almost a metre in diameter and up to 10 metres high. Only the smallest lend themselves to advantages from modern AM, although traditional AM using filament

[72] International Atomic Energy Agency, Nuclear Fuel Cycle Information System, 'Numbers of nuclear fuel cycle facilities', [n.d.].

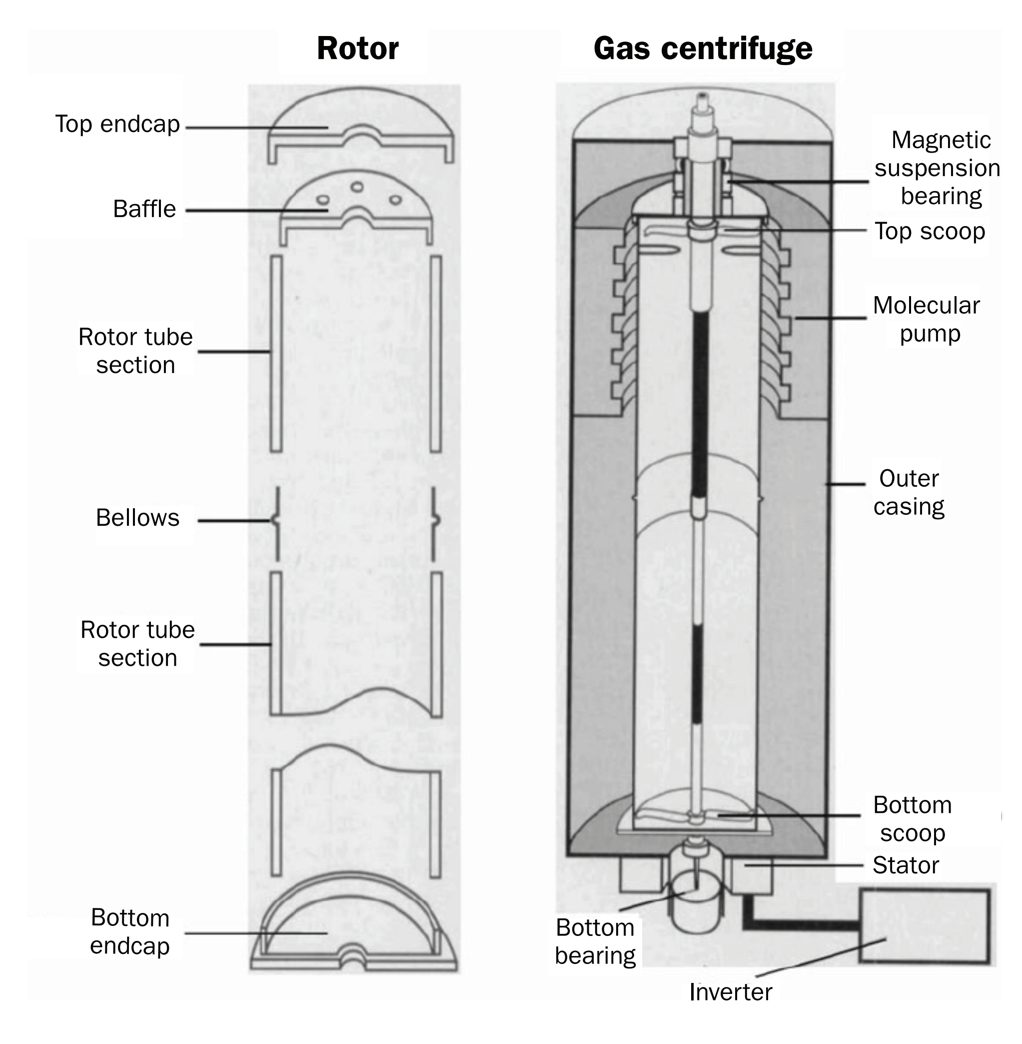

Figure 3.2. Basic gas centrifuge design

Source: Albright, D. and Hibbs, M., 'Iraq's Shop-Till-You-Drop Nuclear Program', *Bulletin of the Atomic Scientists*, vol. 48, no. 3 (1992), pp. 27–37.

winding is still the preferred technology for the most critical parts—such as the rotor tube.

Gas centrifuges require precision components and very good balancing to rotate at such high speeds. Nonetheless, a modern gas centrifuge is far simpler to manufacture than the internal combustion engine in a modern car. The key to the success of the centrifuge is the spinning rotor tube. The faster it can spin, the better the separation of uranium isotopes and the cheaper the process. Early tubes were made of high strength aircraft-grade aluminium alloys. The next generation of spinning tubes was made from very high strength 350- grade maraging steel, an alloy of steel with very high nickel content and other alloying elements such as cobalt and molybdenum.[73] Today, rotor walls made of maraging steel have largely been superseded by rotors made of fibre composites, which are far superior and easier to manufacture. Nonetheless, some recent articles have highlighted AM using maraging steel as a possible

[73] All Metals & Forge Group, 'Metal tidbits: Maraging', [n.d.], <http://www.steelforge.com/literature/metal-tidbits/maraging/>.

route for the manufacture of gas centrifuge components using uncontrolled production equipment.[74]

Maraging steel is conventionally formed by casting followed by carefully designed heat treatment steps. The heat treatment produces age-hardened grains that give the steel very high strength, good machinability and very little distortion from the original shape. In many applications the finished part can be subtractively machined to the final shape and heat treated without losing its precision. It is not clear, however, that this would be true of a carefully balanced spinning rotor tube. AM could, in theory, mimic the casting and heat-treating process. A tube or an endcap for a rotor could be additively manufactured and then heat-treated, although slight machining for precision balancing might still be required.

It should also be noted that a centrifuge plant necessarily consists of thousands or even tens of thousands of centrifuge units connected together, known as a cascade. All of the parts in the centrifuges need to be reproduced for thousands of units. In theory, AM could be a way of making thousands of small parts instead of using traditional methods. These small parts are non-rotating structural components that do not need the extremely high strength required in the stressed spinning tube. It is unlikely that this would be a critical application of AM technology, however, and it is not necessarily a concern for export controls.

Rotor tube

The centrifuge rotor tube needs to be extremely strong because of rotational forces. A minimum length is in the order of half a metre, which would duplicate the earliest crude centrifuges. Some popular articles have postulated that the tube could be printed from maraging steel powder. This raises the question of why a manufacturer would choose this path. Maraging steel centrifuge tubes are a technology of the 1960s, normally made by flow forming (cold working) a thicker blank. This provides significant work-hardening of the final product, giving it great strength. Maraging steel blanks for forging into centrifuge rotors (and small rocket tubes) are already export controlled. Additively manufactured maraging steel parts may have the same chemical composition as centrifuge quality 350-grade maraging steel. They could be subjected to heat treatment that would improve the strength beyond the weak 'as-cast' properties of casting or 'as-build' properties of AM. However, to reach the desired strength, they also require forging or flow forming. Hence, additively manufactured maraging steel would be greatly inferior to cold-worked versions and possibly completely inadequate for centrifuge rotor tubes.

Flow forming maraging steel blanks has long since been superseded by filament winding of material such as carbon fibre, where epoxy-coated fibres are wound on a cylindrical mandrel in a relatively simple carbon fibre manufacturing process. The maximum rotation speed of maraging steel rotors is much lower than of those made from modern carbon fibres. Carbon fibre machines are cheaper and far more efficient. Most western countries have progressed from aluminium to maraging steel to carbon fibre tubes. Some states that were dependent on technology stolen from Europe went through a phase of using maraging steel. Both Pakistan and Iraq used maraging steel but stepped up to the better filament technology. The Russian nuclear programme never used maraging steel. Instead, it went from simple high-strength aluminium tubes to aluminium tubes overwrapped with fiberglass and carbon fibre for additional

[74] Christopher, G., '3D printing: A challenge to nuclear export controls', *Strategic Trade Review*, vol. 1, no. 1 (autumn 2015), p. 20–21.

strength. A substandard additively manufactured rotor tube may not be as capable as an aluminium tube that is much easier to manufacture.

Carbon fibre filament winding technology, such as that used in gas centrifuges and missile bodies, was developed in the 1960s and is far superior to maraging steel. Any country with the capabilities to additively manufacture maraging steel would probably also have the industrial technology and skills to produce far superior filament-wound tubes. As a result, AM of maraging steel rotor tubes presents a theoretically possible, but inadequate engineering approach. Slightly more worrying is the prospect of a country choosing to additively manufacture very high strength aluminium tubes, of a type that the Russian nuclear programme has used in the past. This involves highly specialized alloys developed for the Russian gas centrifuges. Using these alloys in AM would involve considerable process development and ignores the fact that other western countries use carbon fibre alone, without the aluminium inside, which provides even better performance. Nonetheless, the Russian approach to centrifuge design is the exact opposite of the European approach. Russia has relied for decades on small, inexpensive, simple and inefficient centrifuges.[75] The Russian cost model is thus very different from the URENCO Group, for example, but printing high strength rotating components of the most primitive centrifuges in very large quantities could bypass the controls on the much more complex technologies in use in Europe and elsewhere.

Rotor endcaps and baffle

The case for a maraging steel baffle or endcaps is slightly different. The endcaps of a rotor tube need to be made of high-strength steel or aluminium. Carbon fibre filament is not a good solution for making these plate-shaped objects. In addition, the eddy-current motor of a gas centrifuge needs a magnetic susceptor in the rotating tube. Maraging steel can serve both as a high-strength lower endcap and a magnetic eddy current motor plate. However, given that a printed endcap would need to be cold worked and machined, it would make little sense to print it. The same powder, if not export controlled, could be used to cast a superior part using conventional manufacturing. There would need to be an engineering trade-off study to determine whether high-strength aluminium endcaps with an ordinary high-strength steel motor plate would be a better solution. A common steel saw blade without teeth is adequate to be the magnetic susceptor. Forged and machined aluminium endcaps would be an easy conventional manufacturing approach.

Smaller rotating and non-rotating parts

Most of the small rotating parts of the centrifuge rotor are not extremely critical due to their small diameter and the lower stresses than on the rotor tube wall. One key component of a so-called Zippe centrifuge is a ball at the bottom of the rotor shaft. It is not a conventional ball bearing, but simply a ball a few millimetres in diameter sitting in a cup of oil that carries the weight of the rotor tube. The ball has a very carefully designed tiny spiral groove photo-etched on to it. This spiral groove is key to flinging the oil on the ball to lubricate the bearing spinning at thousands of revolutions per minute. Photo-etching has proved to be a difficult technology for developers and proliferators, and additively manufacturing the ball might be an alternative to photo-etching. Partnerships between regulatory authorities or the regimes and the nuclear industry could facilitate the evaluation of the impact of AM on such niche

[75] Bukharin, O., 'Understanding Russia's uranium enrichment complex', *Science and Global Security*, vol. 12, no. 3 (Jan. 2004), pp. 194–98.

technologies. This study has not identified any applications for AM in the remaining non-rotating parts and casing of a centrifuge unit that could not be equally well-served by conventional processes.

Valves and pressure sensors

Certain valves and sensors are included on export control lists because of their high vacuum seals and material resistance to corrosive uranium hexafluoride gas.[76] A centrifuge cascade is designed to run at medium high vacuum and because of the reactive nature of UF_6 gas, needs to be totally free of surface contaminants. The gas also corrodes many materials, notably steel. Nickel-based alloys and aluminium fittings are often preferred in a centrifuge plant and are therefore export controlled.

In theory, a proliferator could circumvent some export controls on high vacuum valves, fittings, bellows and measurement devices by reverse engineering prohibited items and producing them using AM. The nickel-based powders, such as Inconel and Hastelloy, used in such applications should be subject to export control.

A thin diagram capacitance manometer would be a particularly attractive item for reverse engineering and reproduction using AM. This is simply a very precise measurement gauge that operates at low pressures to measure the pressure of UF_6 gas. It consists of a thin foil nickel alloy diaphragm with high vacuum on one side as a reference and a chamber on the other containing an unknown pressure of UF_6 gas. Flexing of the diaphragm is monitored with a capacitance gauge calibrated to indicate pressure. Manufacturing the diaphragm in a way that eliminates a weld between the diaphragm and the chamber wall would be an excellent application of AM and could effectively bypass export controls. These capacitance gauges have figured prominently in several export control cases.[77]

Maraging steel castings are controlled under today's export control regimes. They are controlled by their composition and geometric constraints that make them applicable to restricted uses. This is not the case for amorphous powders. Many articles focus on maraging steel as a production route for gas centrifuge machines. This is very unlikely given the state of existing AM machines, the need for cold working the metal by forging or other means and the fact that the product will be substantially inferior to easier solutions. The main proliferation risks in the AM of centrifuges are therefore mostly limited to ancillary equipment such as valves and sensors.

[76] See Article 3 and Category 0B in Annex I of Council of the European Union, Council Regulation (EC) 428/2009 of 5 May 2009 setting up a Community regime for the control of exports, transfer, brokering and transit of dual-use items (EU Dual-use Regulation), *Official Journal of the European Union*, L 134.

[77] US Department of Justice, 'Summary of major US export enforcement, economic espionage, trade secret and embargo-related criminal cases (January 2010 to the present, updated June 27, 2016)', Washington, DC, June 2016.

4. Current and proposed future export controls on AM

Existing export controls relevant to additive manufacturing

Although AM technology is already being used or showing potential for future use in a number of areas that are commonly covered by arms and dual-use export controls, there are currently very few export controls specifically targeted at AM. The different applications of AM intersect with the areas covered by each of the multilateral export control regimes. This explains why discussions about the potential impact of AM on export controls and the future application of export controls to AM have been taking place within the different technical expert groups of each of the regimes. These discussions on the current coverage of the technology and subsequent proposals for control list amendments have been grappling with the question of which aspects of AM could and should be controlled. In this context, it is therefore useful to disaggregate the different types of export controls that might apply. There are existing controls on: (*a*) AM production equipment and its key parts; (*b*) certain metallic powders and other feedstock materials; and (*c*) transfers of technology, in the form of both technical data and technical assistance.

Controls on AM production equipment and its key parts

Production equipment can be controlled if the specific product it is designed to build is itself export-controlled. The criterion commonly used for control list items to determine whether a machine that can produce a controlled object is covered by controls is the so-called specially designed clause. For example, controls on propulsion subsystems, such as rocket motors, that can be used in missiles and Unmanned Aerial Vehicles (UAVs) covered by Category I and Category II of the Missile Technology Control Regime Annex include related production equipment if the equipment—in this case a 3D printer or other AM machine—is 'specially designed' to produce these subsystems.[78] The MTCR Annex explains the terminology as follows: 'a piece of equipment that is "specially designed" for use in a missile will only be considered so if it has no other function or use. Similarly, a piece of manufacturing equipment that is "specially designed" to produce a certain type of component will only be considered such if it is not capable of producing other types of components'.[79] Less exclusive terminology, such as 'designed or modified' or 'capable of', is less frequently applied to relevant production equipment and the authors are not aware of any cases in which it has been applied to AM machines to date. The main aspiration of AM machine development is to produce general- or multi-purpose machines that produce very high performance characteristics in their products across a multitude of applications. In the highly proliferation-relevant area of the AM of metal objects, for example, the machines capable of utilizing titanium for the production of missile components and the machines used by the civilian aerospace industry for aircraft engine components or by biomedical companies for prosthesis production do not easily lend themselves to unambiguous distinction.[80]

[78] National licensing official, Correspondence with the authors, 1 Nov. 2017.

[79] Missile Technology Control Regime, 'Equipment, Software and Technology Annex', Oct. 2017, <http://mtcr.info/wordpress/wp-content/uploads/2017/10/MTCR-TEM-Technical_Annex_2017-10-19-corr.pdf>, p. 16.

[80] Government Senior Technical Policy Adviser on Export Controls, Interview with the authors, 20 Sep. 2017.

In general, the reach of controls depends on national trade control systems, membership of the regimes or adoption of their control lists without membership, translation of the lists into national regulations, implementation and enforcement. The Wassenaar Arrangement (WA) is currently the only multilateral export control regime that prescribes export controls for a specific type of AM production equipment. In 2016, the participating states agreed to introduce an amendment to its dual-use goods control list to cover 'directional-solidification or single-crystal additive manufacturing equipment' for the production of gas turbine engine blades, vanes and tip shrouds, as well as the associated software, under list items 9B001 c. and 9D004 c.[81] Rather than due to an extraordinary proliferation risk associated with this technology, these controls on a narrowly defined application of AM were introduced to ensure coverage of equivalent technologies to prevent substitution for other already controlled production equipment.

While complete AM machines are hardly covered by existing export controls, some typical components of AM machines are covered and can trigger licensing requirements. AM machines used to produce objects made of metals, alloys or ceramics often rely on high-powered lasers to melt and bond the layers of the metallic feedstock powder. Under Category 6, the WA dual-use control list covers a wide range of lasers where technical parameters might overlap with those used in AM machines.[82] However, the definitions of the technical parameters used in these list items were not developed specifically to cover those used as components of AM machines.[83] The extent to which this overlap provides any meaningful control is therefore unclear, and future changes to the control lists or developments in AM technology would be likely to further diminish the coverage. For example, in December 2017, changes to the WA list of dual-use goods altered the coverage of controls on certain types of lasers currently used in the metal AM systems of several companies, from output powers exceeding 200W to only cover lasers with output powers exceeding 500W.[84] Sales of AM machines often involve the export of spare lasers for repair, which may be covered by controls. However, not by design, the list changes by the WA decontrolled a range of lasers used in AM machines that had previously required an export licence because their output power exceeded the threshold.[85] In addition, AM production equipment could be controlled if it is itself a part of a single machining centre, that is a 'hybrid' that includes both additive and subtractive manufacturing elements, where the subtractive machine meets the performance characteristics of a listed computer numerical controlled (CNC) machine tool or other listed production equipment.[86]

Catch-all provisions provide an additional instrument of control that allows states to apply controls to dual-use items even if they are not listed, but the exporter or the competent national authorities are aware that they may be used in a programme for nuclear, biological or chemical weapons, or their delivery systems.[87] In the case of the EU, a similar catch-all provision applies to items that may be used in connection with military end-use in an embargoed destination, but not generically for conventional

[81] Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies (note 1).

[82] Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies (note 1).

[83] Brockmann and Bauer (note 6), p. 11.

[84] Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies, 'Summary of changes', Dec. 2017, <http://www.wassenaar.org/wp-content/uploads/2017/12/Summary-of-Changes-to-2017-Lists-Website.pdf>.

[85] Hartmannshenn, J., Customs and export control manager, Electro Optical Systems (EOS) GmbH, Germany, Communication with the authors, 1 Feb. 2018.

[86] Government Senior Technical Policy Adviser on Export Controls, Correspondence with the authors, 19 Sep. 2017.

[87] Bromley and Bauer (note 7), p. 6.

military end-use.[88] Catch-all controls are generally seen as an instrument that enables states to balance security-driven control requirements with economically driven trade-facilitation imperatives, by avoiding the introduction of unnecessarily complicated barriers to legitimate, non-sensitive trade while retaining the legal power to impose controls if it is justified by the available information. In the case of AM production equipment, this possibility is frequently highlighted by national officials as a means of controlling trade if necessary, before standards for the capabilities of AM machines emerge. There is no information available in the open source literature, however, on whether catch-all provisions have ever been invoked to control AM machines.

Controls on feedstock for AM machines

Feedstock materials for use in AM machines are inherently of 'dual-use', as they merely determine the material from which an additively manufactured product is made but not necessarily its end-use. Controls on materials have been somewhat limited in order to avoid creating disproportionately negative effects on industry and trade. However, the more specific the requirements for a material are, for example in terms of the purity, composition or gas content of a powder, the clearer it becomes for what type of manufacturing machine and type of product they were made. Some materials can be defined precisely enough to exclude the vast majority of civilian applications while others are used exclusively for components in weapon systems, including nuclear weapons, because they would be too expensive to use, or have no application, in other products. Beryllium metal is an example of a material that has few applications beyond controlled items and is therefore covered by the control lists. Based on this reasoning, over the years, a number of metals, alloys, explosives, propellants and other materials of specific composition have been added to the control lists of the export control regimes.

Each regime covers different materials and powders according to the proliferation relevance they have for the weapons or delivery systems on which it focuses. The MTCR and NSG control lists, for example, cover maraging steels with certain characteristics for use in missiles or centrifuges, although not specifically in powder form, while the WA does not control maraging steels in any way.[89] Category 1C of the WA list of dual-use goods and technologies, however, lists a range of other specific metals and alloys, including in powder form.[90] These controls specifically define these powders according to their chemical and physical properties, composition and other characteristics. These definitions, which are not always very detailed, were devised to fit the production methods available at the time. This has resulted in some overlap with the feedstock materials used in AM machines but as AM technology develops rapidly, a considerable proportion of the currently available feedstock materials that could be used in conventional arms, weapons of mass destruction, missiles and other unmanned delivery systems are not covered by export controls. Currently, purity thresholds are the main criteria that lead to feedstock materials for high-end metal AM being covered by controls.[91] The share of uncontrolled powders could however increase as AM technology advances and more feedstock materials are designed for

[88] See Article 4 of the EU Dual-use Regulation; and Council of the European Union (note 76).

[89] See Missile Technology Control Regime (note 79); Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies (note 1).

[90] Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies (note 1).

[91] Hartmannshenn, J., Customs and export control manager, Electro Optical Systems (EOS) GmbH, Germany, Interview with the authors, 4 Jan. 2018.

use in AM. Catch-all controls might apply to unlisted feedstock materials in the same way as to production equipment.

Controls on transfers of technology

Transfers of technology generate a range of significant proliferation-related risks and are therefore already widely covered by the multilateral export control regimes. They have traditionally been controlled in order to prevent the acquisition of sensitive technology by hostile states or malicious actors more generally. The export controls and other strategic trade control measures employed have evolved, as have the ways in which technology is being transferred, stored and accessed by states, militaries, terrorists, industry, academics and researchers.[92] Controlling transfers of technology has been made particularly challenging by the digitalization of information and data, and as the automation of production processes has been embraced by relevant sectors.[93] As a result, controlled technology is increasingly transferred by digital means, without having to travel physical distances or cross national borders, or transit other physically controllable spaces.

In the multilateral export control regimes, technology is defined as the 'specific information which is required for the "development", "production", or "use"' of a listed item.[94] Transfers of technology are usually differentiated into transfers of 'technical data' (i.e. 'blueprints, plans, diagrams, models, formulae, tables, engineering designs and specifications, manuals and instructions written or recorded on devices such as disk, tape, read-only memories') and 'technical assistance' (i.e. 'instruction, skills, training, working knowledge, consulting services').[95] Transfers of technology can take a physical—tangible—form. This is the case, for example, with published technical manuals, printed drawings or blueprints and training materials. However, they often take a non-physical—intangible—form. In the case of technical data, such intangible transfers can take place via 'email attachments, server uploads or downloads, cloud computing and other Internet-sharing platforms'.[96] In the case of 'knowledge and technical assistance', they can take place either in-person or by telephone or video call in the form of training workshops, lectures or consulting services.[97]

Controls on intangible transfers of technology are generally applied because of the nature of the list item that is the target of controls, rather than because of the type of transfer or the form the technology takes. This applies to controls on both transfers of arms and transfers of dual-use goods. For example, national export control regulations and the Common Military List of the European Union, in line with the WA, control exports of the technical data required for the production of listed conventional weapons.[98] The WA also indicates through the General Technology Note of the dual-use list, as well as list item ML22 in the munitions list, that controls should only apply to the key technologies required to achieve the performance characteristics specified for the controlled items.[99] However, while the definition of technology provides a set

[92] Wahren, J., 'Technical briefing note on Intangible Transfers of Technology (ITT)', Oct. 2017, Unpublished.

[93] Nelson, A., 'The truth about 3-D printing and non-proliferation', War on the Rocks, University of Texas, 14 Dec. 2015, <https://warontherocks.com/2015/12/the-truth-about-3-d-printing-and-nuclear-proliferation/>.

[94] Wahren (note 92).

[95] Wassenaar Arrangement, 'Best practices for implementing Intangible Transfer of Technology Controls', Agreed at the 2006 Plenary, <http://www.wassenaar.org/wp-content/uploads/2015/06/ITT_Best_Practices_for_public_statement_2006.pdf>, p. 1.

[96] Bromley and Bauer (note 7), p. 10.

[97] Wassenaar Arrangement (note 95), p. 1.

[98] Common Military List of the European Union, adopted by the Council on 6 Mar. 2017, *Official Journal of the European Union*, C97, 28 Mar. 2017.

[99] Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-use Goods and Technologies (note 1), p. 207.

of examples and it is relatively clear that both tangible and intangible forms of these manifestations of technology are covered, there is still a degree of ambiguity and scope for national-level differences when determining when controls should be applied to a particular transfer.

ITT controls are therefore particularly relevant to the case of AM, as the specific information required by an AM machine to perform a desired production task is commonly coded into a digital build file that is easily transferrable. Such a build file describes both the geometry of the desired object and the work process that an AM machine needs to execute in order to produce the object in such a way that it meets the desired performance characteristics. As such, if a build file describes the process of producing an item that is subject to dual-use or arms export controls, then such a build file would be covered by controls on transfers of technical data as being 'required' for the production of that product. For example, the transfer or 'making available' of build files for SALW across national borders without a proper export licence can violate existing controls.[100] When the US Government acted to ban the publication of the 'Liberator' design files, it explicitly cited possible International Traffic in Arms Regulations (ITAR) violations based on the making available of controlled technology to parties outside the USA.[101]

In the case of ITT relevant to AM, the specific application of the definition with regard to the information required for the 'production' of a controlled item is an important element. This definition covers for example digital build files, the operational parameters required for a general-purpose AM machine to achieve the desired performance characteristics and training on or other types of technical assistance with the production of controlled items using AM.[102] In addition, the controls on the technology required for the 'development' of controlled items apply specifically to transfers that spread the knowledge required for advanced AM design processes, particularly for items specially designed for missile and nuclear programmes.

However, controls on technical assistance are also particularly relevant in connection with the use of AM. The transfer of technology in the form of a build file can only provide an actor with sufficient information to recreate an object that someone else has previously designed for their specific purposes and needs. Especially in the context of missile programmes and nuclear programmes, however, design and engineering decisions are always tied to the specific circumstances of a programme.[103] These include the availability of materials, machines and specific expertise in certain areas, as well as the desired performance and mission requirements. For any reverse engineering, redesign and other adjustments, additional information—and particularly the tacit knowledge required for sophisticated AM design processes—are likely to be needed.

Proposals to apply controls to additive manufacturing

The first presentation on the topic of additive manufacturing to a technical expert group of one of the multilateral export control regimes took place in 2010. Further briefings on the technology and controls, as well as proposals for control list amendments have followed. Due to the confidential nature of the discussions that take place within the regimes and their respective expert groups, information in the open source

[100] Kukolj, M., *Discussion Paper on 3D Printing and Firearms* (SEESAC: Belgrade, Dec. 2016), <http://www.seesac.org/f/docs/SALW-Marking-and-Tracing-2/Brief02_eng-Web.pdf>, pp. 4–5.

[101] Greenberg, A., 'State Department demands takedown of 3D-printable gun files for possible export control violations', *Forbes*, 9 May 2013.

[102] National licensing official, Correspondence with the authors, 1 Nov. 2017.

[103] National licensing official, Correspondence with the authors, 6 Dec. 2017.

literature on these proposals and the content of deliberations is limited, and the information provided by national officials cannot be attributed. Discussions and concrete proposals to expand controls on AM have been most prominent within the MTCR and the WA. Proposals have focused on possible amendments to and expansions of controls on AM machines and the software they use, and on feedstock materials. Changes to existing controls on technology and additional technology controls have also been discussed. Deliberations have further addressed the means for their effective implementation and the application of non-list-based trade control measures, such as catch-all controls.

Controls on AM production equipment

In February 2014, the MTCR partner states discussed a proposal previously submitted by Australia.[104] The control list amendments proposed the introduction of controls on all 'machine tools for "additive manufacturing"' with controlled atmosphere environments configured for the production of certain listed explosives, propellants, metals, ceramics or alloys 'with greater than 98% theoretical density'.[105] The proposal was not adopted, which in retrospect proved to be a reasonable decision as these specifications are already well behind the current state of the art. Most commercially available AM machines for metal manufacturing now have a controlled atmosphere as a standard feature and with the proper choice of processing parameter applied during the build, are able to produce items with greater than 99 per cent theoretical density.[106] The proposed controls would therefore have resulted in a volume of licensing applications significantly beyond the desired requirements and would have had a negative impact on trade and development. Australia proposed a similar amendment on the control of AM machines to the WA in 2014, which was also rejected, but the subject of controls on AM was made an item of interest to be revisited in subsequent meetings.[107]

In April 2016 a proposal to control AM machines via the dual-use list of the NSG was made by France. The proposed parameters would have controlled AM machines with a build chamber with one dimension larger than 20 centimetres and that use LBM or EBM powder bed techniques.[108] This approach would have put the focus on the maximum build-size and therefore of the size of the build envelope of the machine. However, many parties argued that this choice of parameter would only stay relevant for a limited time and not necessarily allow for meaningful future adjustment within the same choice of parameters. Therefore, this proposal was also rejected.

A number of analyses in the literature have highlighted controls on computer numerical controlled subtractive machine tools as a model, due to their similarities with AM machines. Both are inherently dual-use and can be used to produce non-listed and listed components. This comparison however is only of limited value given the still limited capabilities with regard to accuracy and unidirectional repeatability of AM machines and the past experience of controlling CNC machines. AM machines currently cannot achieve the same accuracy and unidirectional repeatability in the production of objects (as built by the machine), compared to the standards that the parameters for CNC machines control. To achieve these standards, 'AM components for missile applications (or indeed nuclear applications) that require very fine toler-

[104] Finck, R., '3D printing', Presentation at the 20th Anniversary Practical Export Control Workshop of the Wassenaar Arrangement, 27–28 June 2016, <www.wassenaar.org/wp-content/uploads/2016/06/FR-3D-Printing.ppt>.

[105] Finck (note 104).

[106] National licensing official, Correspondence with the authors, 6 Dec. 2017.

[107] Finck (note 104).

[108] Finck (note 104).

ances would always require post-processing by an export-controlled CNC machine'.[109] In addition, the parameters currently applied in the case of CNC machine tools depend on the regime and thus on the possible associated end-use. The NSG uses accuracy as the main parameter while the WA uses unidirectional repeatability, which further complicates licensing for companies and national licensing authorities. These considerations demonstrate that choosing an approach to the development of comparable controls for AM machines has been far from straightforward and still lacks consensus among the participants in the regimes.

Although not formal proposals, other approaches have considered: adding specific controls on AM production equipment specially designed to work with energetic materials such as explosives and rocket propellants, thereby introducing limited controls specifically targeted at the material processing capability of AM machines; or controls on AM machines specially designed for the production of specific items controlled in the MTCR or in the Munitions List of the WA, such as solid rocket motor grains with motor casings.[110]

Controls on feedstock for AM machines

The details of only one proposal to add AM-specific feedstock materials to one of the control lists are openly accessible. In 2015, France proposed adding maraging steel powders for use as AM feedstock to the dual-use control list of the WA. The text proposed that the steel alloy powders be controlled by their particle size and composition, thus specifying the weight share of specific alloying elements such as nickel, cobalt, molybdenum, carbon and hardening elements.[111] This proposal was not adopted at the time, but discussions on the introduction of controls on maraging steel powders have continued and are expected to be turned into new proposals. Discussions are also ongoing on the addition of other control list items, for instance AM feedstock materials for extreme temperature high-strength applications such as in rocket or missile engine and motor components.[112] Proposals have thus taken the approach of trying to specify feedstock materials according to the technical parameters required for specific controlled applications, as there is considerable precedent for introducing these types of controls across the control lists of the various regimes.[113]

Controls on transfers of technology

In 2014 Australia proposed an amendment to the MTCR control list that would have introduced language to explicitly include technology for the 'development' and 'production', using AM techniques, of components for turbofan and turbojet engines covered by list item 3A1 of the MTCR control list. However, the proposal did not include any technical parameters specifying the technology and could have overlapped with technology captured by list item 3E1, while at the same time not contributing to a better differentiation between missile engine technology and civilian aircraft engine technology. Controls on the transfer of the software required for the manufacture of items of a certain quality using specific AM techniques, albeit decoupled from and thus not controlling AM machines, have also been proposed within the MTCR. One approach here could be to control software packages that configure AM machines to

[109] National licensing official, Correspondence with the authors, 6 Dec. 2017.

[110] Government Senior Technical Policy Adviser on Export Controls, Correspondence with the authors, 19 Sep. 2017.

[111] Finck (note 104).

[112] Government Senior Technical Policy Adviser on Export Controls, Correspondence with the authors, 19 Sep. 2017.

[113] National licensing official, Correspondence with the authors, 1 Nov. 2017.

enable the processing of specific controlled high-end feedstock materials. However, no consensus was reached on parameters to sufficiently differentiate specific software capabilities for AM machines, which would be required for such controls. In the light of the rapid evolution of AM technology—which makes the lifespan of relevant standards rather fleeting—the application of other trade control measures, such as catch-all controls, and the need for outreach, engagement and other measures that could be implemented by states in order to make the implementation of ITT controls more effective have also formed part of reports and discussions in the technical expert groups of the different regimes.

These discussions and reports have included calls for rigorous application of national visa screening regulations and outreach to the relevant AM machine producing industries as well as to the academics, companies and research institutes involved in R&D of AM technologies relevant to sensitive applications.[114] The application of catch-all controls to intangible transfers of technology in the form of software, technical data and technical assistance has also been discussed. However, no agreed standards or guidance specific to AM have resulted from these discussions.

[114] National licensing official, Correspondence with the authors, 1 Nov. 2017.

5. National practices and key challenges in applying export controls to AM

National practices in applying controls to AM

National practices on the application of export controls specific to AM only offer limited comparative insights, as few such specifically targeted controls currently exist. The production of proliferation-relevant, high-end AM machines is still limited to a select number of states. National practices have therefore only been established to a meaningful extent in a handful of states and data on such practices is scarce.

National practices on the application of other relevant export controls, which currently cover components, materials or technology, are worth reviewing when considering the challenges facing the implementation of existing and the development of new export controls. National practices on the implementation of existing controls on components, especially lasers, are well established and there is only slight variation in their application. However, in the case of exports of controlled feedstock materials, national practices differ due to the different types of national export licences. The United Kingdom, for example, allows the use of Open General Export Licences (OGELs) for controlled metal feedstock materials for use in AM, while other European countries require an exporter to apply for an individual licence for each export.[115] Such variations affect the tightness of controls and the competitiveness of national industries, due to the range of different waiting periods for licence applications.

In the case of technology transfers, there are different interpretations of when a particular transfer qualifies as being 'required' to develop or produce a controlled item. In the specific case of AM, some states apply a distinction between the transmission of information on the pure geometry of an object and the transmission of information that also includes knowledge on how to produce an object with the specific qualities and characteristics according to which it is controlled. Others again interpret any transfer of build files for controlled objects to be subject to controls, regardless of the complexity of the information. It is not only such transfers of data that are relevant for controlling AM. Controls on transfers of knowledge and skills are especially relevant as the technology and industry continue to spread. Knowledge, especially in the area of design for AM, to a large extent resides in scientific communities that are traditionally averse to the idea of export controls. The implementation of controls, reporting requirements and enforcement measures on ITT varies both in practice and in its effectiveness across states, not least because of a lack of established compliance standards and guidance material for the relevant stakeholders.[116]

Guidance material

To date, no state, industry association or other actor has produced guidance material that specifically addresses the control of AM production equipment, software, feedstock materials or technology. The 'Best Practices for Implementing Intangible Transfer of Technology Controls' document agreed by the participating governments during the 2006 Plenary of the WA points states to a number of broad measures for enforcing controls on intangible transfers of both dual-use and conventional weapons

[115] Hartmannshenn, J., Customs and export control manager, Electro Optical Systems (EOS) GmbH, Germany, Interview with the authors, 4 Jan. 2018.

[116] For a more comprehensive account of national practices on controls on ITT see Bromley and Maletta (note 8).

technology.[117] However, this guidance document does not provide a great level of detail in terms of the measures it proposes, is only directed at states and does not address the challenges faced by the other stakeholders involved. In the AM industry, no industry association or similar type of organization has so far been established that could voice the concerns of the industry and act as a partner in developing standards and guidance materials. While the relevant high-end technology is concentrated in a limited number of companies in states with advanced export control systems, guidance can still be provided through direct contact with the relevant national authorities. In some cases, these contacts have been initiated by governments as part of their efforts to support emerging industries in the sector.[118] However, this level of contact does not apply across all states with AM companies. Nor does it present a sustainable model for the future, if the industry continues to grow and expands worldwide as expected.

Challenges in applying export controls to AM

National authorities

Controlling AM generates a range of particular challenges for national authorities. The multilateral export control regimes—and thus in practice the member states—seek to strike a balance between creating barriers to proliferation and limiting the negative side-effects that controls can have on legal trade. The capabilities of AM machines, however, do not make it easy to distinguish between those that are proliferation-relevant and those that are not. The approach to defining controlled machines based only on the materials they use has limitations, especially if the materials have a variety of applications. Titanium, for example, is used by AM machines to produce dental and other implants, as well as components for the defence and aerospace industry. In the case of explosives, however, non-sensitive applications may be so few that such control parameters could be justified. In general, apart from their size, AM machines are hardly distinguishable by the type of object they are capable of producing—although they may be, to some degree, by their precision and the finishes that they can apply. Thus, there is a natural overlap with many civilian uses that do not require licensing. With regard to SALW, for example, neither the AM machines nor the materials required to produce them (at least in the case of polymer-based guns) are possible to distinguish from those used for other purposes, as they are rather low-tech. Controls would therefore have disproportionate effects on the massive array of civilian applications that rely on the same materials and machines.[119] This is especially significant given the limited impact of and need for action on the use of AM for SALW production. When considering new controls on AM machines, the challenge is therefore to determine whether an element of control can be gained over those high-performance machines that pose the greatest proliferation risk without impeding too much the further development and future profitability of the technology, especially for civilian uses.

Control list items covering high-performance AM machines could define the machines according to technical specifications, such as the lasers used, the ability to process energetic materials, such as explosives and propellants, the size of the build chamber and/or the level of precision or repeatability that the machine achieves.[120]

[117] Wassenaar Arrangement, 'Best Practices for Implementing Intangible Transfer of Technology Controls, Agreed at the 2006 Plenary', <http://www.wassenaar.org/wp-content/uploads/2015/06/ITT_Best_Practices_for_public_statement_2006.pdf>

[118] Hartmannshenn, J., Customs and export control manager, Electro Optical Systems (EOS) GmbH, Germany, Interview with the authors, 4 Jan. 2018.

[119] Kukolj (note 100), pp. 6–7.

[120] Brockmann and Bauer (note 6), p. 11.

However, such an approach would need to avoid introducing parameters that would be quickly overtaken by events, such as the previously proposed parameters of a controlled atmosphere and the theoretical density of the product.[121] Introducing different metrics across the regimes and national control systems would also be problematic, and controls on subtractive CNC machine tools suffer from this problem to some extent today. Initiating a dialogue between the regimes however has been proved difficult in the past, not least because of the highly political nature of these discussions, national economic interests and the different composition of the respective regimes.

The implementation and enforcement of export controls by national authorities on the technical data used in AM face many of the same challenges that confront the implementation of controls on ITT more broadly. These include the significant limitations on the ability to detect unauthorized transfers of technical data and being able to demonstrate that they have occurred.[122] The implementation of audit procedures to regularly check record-keeping on transfers of technical data provides one possible mechanism, but this would require national licensing authorities to devote a considerable amount of resources and capabilities to their implementation.

Companies

Controls on AM and especially on related ITT pose a particular set of problems for company compliance. The more technologically advanced and thus the more sensitive certain build files and technical data are, the tighter the controls on transfers by the company producing them will be, due both to their legal obligations and to their own commercial interests. It is therefore undesirable that this type of data should be released on the Internet. This is the more concerning as the case of Cody Wilson's gun file has demonstrated that once uploaded it is virtually impossible to remove such a file from the various often illegal file-sharing websites.[123] In addition to their own commercial interests, it is therefore necessary to ensure an awareness of the possible proliferation and export control implications among all relevant stakeholders in companies designing sensitive build files and software for AM machines. While the high-tech industry has, for the most part, already developed an understanding of these and included appropriate compliance measures in their internal compliance procedures, the increasing capabilities of online (and therefore remote) printing-on-demand services, and to some extent also of actors from the do-it-yourself community who have access to advanced metal printers in makerspaces, require that these actors should also be included in such discussions.

In cases of attempted acquisition of items for nuclear weapons, centrifuges or delivery systems, interest from a customer and their behaviour may be a strong indicator that the end-use is, in fact, devoted to building weapons. A historical example of this, from decades past, is Pakistan's attempt to buy hemi shells from European suppliers that were unequivocally intended for use in nuclear weapon cores.[124] This applies to compliance by AM companies, be they producing machines, supplying materials or providing AM services, and they should therefore include screening for appropriate 'red flags' in their compliance systems to comply with national catch-all provisions, and exchange information with the national authorities in cases of flagged inquiries or orders, as any other producer of dual-use items should.

[121] National licensing official, Correspondence with the authors, 1 Nov. 2017.
[122] Bromley and Maletta (note 8).
[123] Greenberg (note 100).
[124] Burr, W., 'New documents spotlight Reagan-era tensions over Pakistani nuclear program', Wilson Center, 25 Apr. 2012, <https://www.wilsoncenter.org/publication/new-documents-spotlight-reagan-era-tensions-over-pakistani-nuclear-program>.

Academia and research institutes

Compliance with export controls on AM-related technology by research institutes engaged in R&D and design for AM in sensitive areas generates many of the same challenges that generally apply to research and academia and that are produced by compliance with controls on ITT more specifically. The development of AM, and of its industrial applications, is decisively driven by the work of universities and research institutes. However, for universities and research institutes seeking to comply with export controls, ITT pose a particular set of challenges. To comply with licensing requirements on technical data a university or a research institute may need to keep a record of every transfer of a controlled technology—including in an email, download or upload to a computer server or 'cloud'.[125] Compliance with licensing requirements on transfers of knowledge or technical assistance may involve keeping track of every instance in which controlled technology is included in a presentation and the nationalities of the people in the audience. For a university or a research institution to operate an effective compliance system will therefore involve investing time and money in ensuring that relevant personnel understand their export control-related obligations. It may also involve adopting practices that are contrary to the immediate commercial or academic interests of the university or research institute, existing privacy and data protection standards, or the established practices or 'culture' of its sector. In particular in research and academia there is a culture that values the free exchange of knowledge and ideas, and seeks to foster international scientific collaboration. Therefore, the process of raising awareness and creating an understanding among researchers that the need to comply with export control requirements may involve seeking permission to present their work at a seminar or checking the nationality of their potential project partners has proved highly challenging.

[125] Bromley and Maletta (note 8).

6. Conclusions and recommendations

AM is a rapidly developing technology and there are frequent changes in the techniques and machines used. The list-based approach of the export control regimes is rather rigid, as it relies on definitions that use precise technical parameters and thresholds. It will therefore be a major challenge to find a balance between the precision of the technical parameters required to prevent too great an overlap with legitimate civilian applications and the desire to keep definitions broad enough to cover AM technologies for a meaningful period of time, before the technology develops so far that control list items need to be adjusted again. In this way, the challenges presented by AM are illustrative of many of the wider contemporary challenges to effective implementation of dual-use export controls triggered by technological developments.

Another factor that must be taken into consideration when assessing the relevance of AM technologies as a proliferation risk is the distinction between a state seeking to produce nuclear weapons to a high standard in something approaching an industrial process, and a non-state actor with the goal of producing a small number, or even just one, nuclear explosive device. In the former case, most states will presumably have an industrial and academic base to rely on and will be seeking to engineer a reproducible process. In the latter case, the device may be crude and unpredictable in its performance, being intended for use as a political statement rather than as a militarily reliable weapon that can serve for deterrence purposes. It is also not clear that a non-state actor has much incentive to develop many new processes that take time and money instead of relying on conventional techniques that are known to be crude but adequate. Standards, technical parameters and types of control need to be selected in a way that takes account of the differences in capabilities between these types of proliferating actors—and therefore the proliferation threat they are seeking to counteract.

In the case of gas centrifuge technology for nuclear enrichment purposes, for example, it is highly likely that the proliferator will be a state because the scale and complexity of a complete enrichment enterprise is beyond the capability of smaller, non-state actors. Using 3D printing or AM to produce small arms would probably only be relevant for small terrorist enterprises or assassination attempts, because states have other options and capabilities at their disposal for carrying out similar operations. The case of missile applications is less clear, as states, state-sponsored insurgents and smaller rebel groups have shown an interest in using or used missiles of various origins in the past. The distinction therefore depends on the capability, operational requirements and sophistication of the missile being sought, as they affect the proliferation scenario and whether it warrants expanded controls on a certain technology.

It is essential to have clear criteria when evaluating the relevance of export controls to AM processes. If a proliferator can produce thousands of ordinary parts for a proliferation enterprise using uncontrolled conventional technology, and the only advantage is cost or efficiency, this is not necessarily a sufficient criterion for introducing export controls. If, however, 3D printing or other new AM techniques allow a proliferator to carry out an operation that is either impossible or extremely difficult by traditional means, then export controls need to be considered. Printing high explosives much more safely than conventional processes, or using an uncontrolled raw powder to make a part that would have otherwise been export controlled represent such substantial advantages. If 3D printing or other advanced AM techniques reach a level of maturity that allows them to bypass controls on conventional SM machine tools, especially when their products outperform those produced by conventional SM machines, this could also be a reason to propose new export controls. Therefore, from a security and economic perspective, it is reasonable for AM applications to be assessed as a significant proliferation concern only if they allow the operator to make a part, or carry out a process, that would be difficult or impossible to make without such applications. In addition, AM capabilities could reasonably be judged as presenting a problem if they bypass other critical barriers. Nonetheless, if AM techniques simply provide an engineering alternative to a process that could be done using another uncontrolled conventional manufacturing technique, this does not necessarily require the introduction of new export controls.

Controlling AM technology in a meaningful way will require a holistic approach that engages all relevant stakeholders to the optimum extent, thereby creating multiple layers of control whether through increased awareness, compliance measures, audit procedures, licensing or other regulatory measures. As is outlined above, these already exist to some extent but in order to meet the challenges the various stakeholders will continue to face, a number of steps may need to be considered by each relevant actor.

The EU and the multilateral export control regimes

- *Amend controls on lasers*: Current controls on lasers already cover some of the systems applied in different AM techniques. However, these controls were designed to cover other systems and production equipment available at the time. Adding technical parameters specific to lasers for the use in high-end metal AM machines could ensure continuous coverage of relevant AM techniques and machines. These parameters could be defined in cooperation with industry and should take technical developments in AM into account.
- *Amend controls on AM production equipment for explosives*: The multilateral export control regimes should monitor developments in this technology, particularly due to its relevance to proliferation in the areas of nuclear weapons and missiles. The relevant regimes could explore the possibility of expanding existing controls to explicitly cover AM machines that are specially designed to handle high explosives for use in nuclear weapons and missiles.
- *Introduce controls on specialized feedstock materials*: The multilateral export control regimes could consider new controls on materials that are sufficiently distinguishable for their main use in AM products—especially for missile applications and nuclear weapon or centrifuge applications.
- *Facilitate exchange of national practices and information sharing*: As the AM industry continues to expand, the multilateral export control regimes need to make the most of their information sharing function and provide a forum for the member states to exchange national practices and experiences regarding classification, licensing and enforcement related to AM. This is key to inform both the continuing debate on control list amendments and the production of guidance materials. At the EU level, the appropriate working groups could serve a similar function to increase consistency in the implementation of controls across EU member states.
- *Link the discussions between the different regimes*: Promoting an exchange across the multilateral export control regimes on controls on AM would

enable states to benefit from each other's lessons learned on classification, licensing and enforcement. It would also prevent the unnecessary introduction of different metrics in the respective regimes for technical specifications of the same item, which could lead to additional challenges for implementation by industry and national licensing authorities.

- *Develop targeted guidance material*: Targeted controls on tangible elements such as AM machines, software and feedstock materials are likely to remain limited until clear technical standards have emerged. However, the advances in AM continue to add relevance to the control of ITT.[126] Developing targeted guidance materials on the implementation of controls on relevant intangible technologies could be a step that complements other control efforts and improves the harmonization of control standards across states. To this end, the multilateral export control regimes could develop targeted guidance material on how to apply and effectively implement existing export controls on AM. This would be especially useful with regard to the controls applied to ITT in the form of technical data (e.g. build files and design information) and transfers of knowledge and technical assistance (e.g. knowledge about the application of design for AM to controlled goods). These guidance materials could include sections on the implementation of such measures by states, companies, research institutes and academia, as well as other stakeholders.

National authorities

- *Increase outreach to and dialogue with companies*: National governments and the relevant authorities should increase their outreach efforts and facilitate dialogue with companies from the AM industry on controls on ITT. These efforts should include discussions on licensing requirements, the effective operation of internal compliance programmes (ICPs), record-keeping and data security.
- *Increase outreach to and dialogue with universities and research institutes*: National governments and the relevant authorities should increase their outreach efforts and facilitate dialogue with universities and research institutes. These outreach efforts should raise awareness about licensing requirements and the application of the 'basic scientific research' and 'in the public domain' exemptions.
- *Coordinate national regime delegations*: At the national level, technical experts, licensing and other officials who act as delegates to the regimes do not necessarily discuss specific topics, such as AM, between the respective regime delegations.[127] As an intermediate step to facilitate an effective linking of the discussions on AM between the regimes, nationally, the delegations to the regimes could share information and discuss possible overlaps or inconsistencies in existing and proposed technical parameters and control approaches to AM.

[126] National licensing official, Correspondence with the authors, 6 Dec. 2017.
[127] Anders Lennartsson, Deputy Research Director, Swedish Defence Research Agency (FOI), Correspondence with the authors, 11 Mar. 2018.

- *Effectively apply catch-all controls*: To maintain effective controls despite rapid technological developments, national authorities can make effective use of catch-all controls on non-controlled production equipment, the software it requires, special powders and technology that could knowingly be used for nuclear, chemical or biological weapons and their delivery vehicles, in line with their national legislation and procedures.
- *Apply specialized company audit procedures*: Specialized company audit procedures can help national authorities to verify compliance, review records of digital transfers and certify digital security standards in companies or research institutes that rely heavily on intangible transfers of controlled technology.
- *Adequate resourcing:* The relevant licensing and enforcement agencies need to be funded and staffed sufficiently to perform their increased outreach function and effectively implement specialized audit procedures.

Companies

- *Facilitate dialogue and share best practices*: Companies in the AM industry in Europe are currently not organized in an industry association or comparable organization. The absence of such a forum to facilitate exchange to some extent limits the input companies can provide to deliberations at the EU, national and regime levels. Sharing and improving best practices for customer screening, record-keeping—especially on intra-company transfers and the making available of controlled technology and software—and other relevant compliance procedures could strengthen company ICPs and therefore reduce proliferation and diversion risks, and the possible legal consequences for companies. The focus could be on due diligence by companies and researchers that develop and design dual-use components to be made using AM, as most of the knowledge and technology is resides with them.
- *Improve end-user screening and the information on export controls provided by print-on-demand services*: Print-on-demand services may need to increase the information provided to customers on export controls and possible licensing requirements in order to meet due diligence standards and prevent violations of brokering regulations. End-user and product screening standards could also be explored regarding the printing of firearms or high-end metals.

Academia and research institutes

- *Raise awareness*: Universities and research institutes should raise awareness of existing export control regulations, record-keeping requirements and screening procedures among researchers and relevant staff. This is especially relevant with regard to the transfer, distribution and making available of dual-use technology and research on AM processes that enable the achievement of performance characteristics required for nuclear, chemical or biological weapons and their delivery systems.
- *Voluntary codes of conduct for dual-use research of concern*: Universities and research institutes should explore the development of voluntary codes of conduct for dual-use research of concern in the area of AM.

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