ADDITIVE MANUFACTURING FOR MISSILES AND OTHER UNCREWED DELIVERY SYSTEMS

Challenges for the Missile Technology Control Regime

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October 2021

Contents

Acknowledgements

The author would like to thank the German Federal Foreign Office and the Swiss Federal Department of Foreign Affairs for their generous funding, which enabled the production of this paper as part of the research project 'Quo Vadis MTCR: The Missile Technology Control Regime at a Crossroads'. The information contained in this report builds on past research by the author on additive manufacturing, and on information collected through a series of background interviews and communications with representatives of national licensing authorities, delegates to the multilateral export control regimes, compliance officers and missile technology experts.

The author would like to thank his colleague, SIPRI Distinguished Associate Fellow Robert E. Kelley, for providing a technical background briefing and his support and valuable input and feedback throughout the production of this paper. The author would also like to thank his SIPRI colleagues and two external reviewers for their detailed comments on a previous version of the paper. The author would finally like to thank the SIPRI Editorial Department for its excellent work.

Kolja Brockmann, October 2021

Abbreviations

3D	three-dimensional
AM	Additive manufacturing
CAD	computer-aided design
CBN	chemical, biological or nuclear
CNC	(subtractive) computer numerical-controlled
DED	directed energy deposition
EBM	electron beam melting
EOS	Electro Optical Systems
EU	European Union
G7	Group of Seven
HALE	high altitude long endurance
IEM	information exchange meeting
ITT	intangible transfers of technology
LBM	laser beam melting
LEEM	licensing and enforcement experts meeting
MALE	medium altitude long endurance
MTCR	Missile Technology Control Regime
NASA	National Aeronautics and Space Administration
NSG	Nuclear Suppliers Group
POC	point of contact
R&D	research and development
RPOC	reinforced point of contact
TEM	technical experts meeting
UAVs	uncrewed aerial vehicles
WMD	weapon(s) of mass destruction

Executive summary

Additive manufacturing (AM) has become an attractive production technology for the aerospace sector, particularly in the area of missiles, space launch vehicles and uncrewed aerial vehicles (UAVs). Modern AM techniques, often referred to as 3D printing, create objects from feedstock materials such as metallic powders, by building them up from the first to the last layer in an iterative process of depositing and fusing layers of material. AM has seen significant increases in performance, speed, versatility and precision. Therefore, AM has been recognized to pose a growing proliferation threat and a challenge to existing export controls. The Missile Technology Control Regime (MTCR) is the multilateral export control regime that aims to prevent the proliferation of missiles and other uncrewed delivery systems capable of delivering chemical, biological or nuclear (CBN) weapons. The MTCR has been discussing AM since at least 2013 and seeks to update and harmonize the export controls of the participating states (MTCR partners) to mitigate the risks posed by AM and ensure the effectiveness of export controls prescribed by the MTCR.

AM is being used to produce a growing range of components for missiles and UAVs, both by civilian and military aerospace companies. AM can produce many complex parts—for example ones with internal voids, such as cooling channels—or particular geometries that could not otherwise be produced in one piece using subtractive manufacturing techniques. Its applications in the development of key components with new performance characteristics for rocket propulsion systems, including combustion chambers, injector heads, turbo-pumps and nozzles, are of particular interest in the context of the MTCR. Advances in AM of energetic materials are increasingly used for solid propellants and could enable new characteristics of rocket motor grains. AM is also increasingly used to produce components of re-entry vehicles, new warhead designs and lightweight aerodynamic components for air vehicle structures, such as rocket bodies or structural components of UAVs. The ability of AM to produce very complex shapes potentially also lends itself to design applications for stealth and other low observability technology.

However, the increasing technical capability of AM to produce highly sophisticated missile or UAV components does not necessarily mean that a state or non-state actor seeking to acquire missiles or other uncrewed CBN delivery systems will choose to use AM. This decision is highly dependent on the circumstances of the individual missile or UAV programme, including its objectives, the available aerospace industrial base and the ability to access the required items and AM-specific know-how and technology. There are also still a range of technical limitations to AM and challenges associated with non-destructive testing and certification that influence specific engineering decisions. AM poses a significant challenge to export controls, particularly because of its use of intangible transfers of technology (ITT), and the difficulty of detecting and preventing such transfers. Feedstock materials and AM machines are often multipurpose and are therefore difficult to regulate and will require a comprehensive and layered approach to export controls on AM.

The export controls prescribed by the MTCR and some of the other regimes already create controls on AM, including on transfers of certain AM production equipment and key components, hybrid machine tools, feedstock materials, software for AM machines, and technical data and technical assistance. Catch-all controls on unlisted items with possible CBN end-uses also contribute to mitigating the proliferation risks posed by AM. However, many of these controls are based on overlaps rather than control list items that cover AM by design and the multipurpose nature of many AM machines, materials and software means they are not covered by ‘specially designed’ clauses. Identifying appropriate technical parameters and standards continues to be difficult and a barrier to the introduction of new dedicated control list items.

The MTCR could take a range of measures to help address the missile proliferation risks posed by AM and ensure the effective application of export controls. The MTCR partners need to follow technical developments in AM and the proliferation of AM-specific know-how. Based on a continuous technical assessment, the partners should further explore and eventually introduce changes to the MTCR annex. The development of new list items should be supported by targeted inter-regime dialogue and coordination on AM. The MTCR could also enhance information sharing on the application of catch-all controls to AM, and on related denials and procurement attempts. As ITT continues to present a key challenge in the context of AM, the MTCR should consider issuing best practice documents on implementing ITT controls in the context of AM. Finally, more work needs to be done to better understand the ecosystem of stakeholders involved in AM and strengthen outreach, engagement and awareness raising.

1. Introduction

Additive manufacturing (AM) has become an attractive technology for the aerospace sector, particularly in the area of missiles and space launch vehicles.[1] AM is a category of manufacturing techniques that produce objects by depositing and fusing successive layers of material, as opposed to subtractive manufacturing techniques, which remove material from a larger block to achieve a desired shape. Traditional AM techniques such as filament winding or physical vapour deposition have long been used, for example, to produce rocket casings or to apply coatings to rocket engine components. These techniques require a mandrel or substrate and are therefore bound by or limited in the materials they can use and the shapes they can produce.[2] Modern AM techniques, often referred to as three-dimensional (3D) printing, can produce objects with virtually any geometry, from a wide range of materials, including high-strength metals and alloys, ceramics and energetic materials.[3] Additively manufactured objects allow for significant weight reduction and enable and simplify the production of objects with internal voids, such as cooling channels.

Since at least 2013, it has been widely recognized that modern AM machines, such as 3D printers, are increasingly capable of producing a range of items that are subject to states' dual-use and arms export controls. AM poses a proliferation risk, as AM machines can increasingly substitute for controlled production equipment and enable new performance characteristics. However, the objects produced by AM are typically 'near net-shape' components and still require machining and other finishing procedures to meet demanding tolerances or precision requirements.[4] AM enables new ways of manufacturing items and highly desirable performance characteristics that can surpass those of traditional manufacturing techniques. For example, additive metal printing techniques enable entirely new ways of producing highly complex rocket engine components with integrated cooling channels in one piece, and deposition techniques for energetic materials could potentially enable new ways of producing solid propellant motor grains with graded composition or in complex shapes.

In addition to offering specific capabilities, AM also poses particular challenges associated with the application and enforcement of export controls. First, the machines and materials involved are multipurpose and have a wide range of civilian applications which are not subject to export controls. This means machines and materials of concern are difficult to distinctly define with technical parameters. Second, the technical data needed to enable an AM machine to produce a controlled item is encoded into digital build files which can easily be transferred undetected. These types of so-called intangible transfers of technology (ITT) have been recognised as a longstanding challenge to export control enforcement that AM only exacerbates.[5] Third, transfer recipients benefit not only from the high degree of automation of AM but potentially also from a reduced need for different types of technical expertise required for other traditional manufacturing techniques.[6] AM shares many of these

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[1] Leonardo, 'Missiles produced with 3D technology', Focus, 15 Jan. 2016; and Launcher, 'Launcher Engine-2', [n.d.].

[2] Brockmann, K. and Kelley, R. E., *The Challenge of Emerging Technologies to Non-proliferation Efforts: Controlling Additive Manufacturing and Intangible Transfers of Technology* (SIPRI: Stockholm, Apr. 2018), pp. 5–6.

[3] 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 no. 18/13455, 29 Aug. 2017, pp. 69–89.

[4] Christopher, G., '3D printing: a challenge to nuclear export controls', *Strategic Trade Review*, vol. 1, no. 1 (2015).

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

[6] Shaw, R., '3D printing: bringing missile production to a neighborhood near you', Nuclear Threat Initiative, 22 Feb. 2017.

Box 1.1. The Missile Technology Control Regime

The Missile Technology Control Regime (MTCR) is an informal political understanding among a group of 35 supplier states that aims to limit the proliferation of missiles and other uncrewed delivery systems capable of delivering chemical, biological or nuclear (CBN) weapons. It was established by the Group of Seven (G7) largest industrialized states in 1987, originally as an instrument to help prevent the proliferation of nuclear weapons by controlling missiles capable of delivering them. The scope of the MTCR has since expanded to include ballistic and cruise missiles capable of delivering CBN weapons. Through the MTCR, the participating states (MTCR partners) harmonize their export controls, following the MTCR Guidelines for sensitive missile-relevant transfers (MTCR guidelines) and by maintaining a control list (MTCR Equipment, Software, and Technology Annex) that covers missiles and certain uncrewed aerial vehicles (UAVs) and relevant dual-use goods and technologies. The annex divides the items it covers into two categories:

Category I includes any complete missile or UAV 'capable of delivering a payload of at least 500 kg to a range of at least 300 km' (e.g. ballistic missiles, space launch vehicles, cruise missiles and reconnaissance drones); complete major subsystems (e.g. rocket stages and engines, guidance systems and re-entry vehicles); related software and technology; and specially designed production facilities. For all Category I items, the partners commit to exercising an 'unconditional strong presumption of denial', meaning that no licences for exports of such items should be issued under all but the most exceptional circumstances. The export of Category I production facilities is prohibited without exception.

Category II includes dual-use missile- and UAV-related components, and complete missile and UAV systems with a range of at least 300 km, regardless of their payload capability. Exports of such systems destined for any weapons of mass destruction delivery end-use are also subject to a strong presumption of denial. All other exports of Category II items are subject to licensing procedures and are to be assessed with consideration of the criteria outlined in the guidelines.

The MTCR takes decisions, for example on admitting new partners or making amendments to the annex, by consensus and these decisions are politically rather than legally binding. The main decision-making body of the MTCR is the plenary that is convened every year, usually in October, and is hosted by the annually rotating chair. The MTCR has several subsidiary bodies which cover different topical areas and operational functions: the technical experts meeting (TEM), the information exchange meeting (IEM), the licensing and enforcement experts meeting (LEEM), point of contact (POC) meetings, and reinforced point of contact (RPOC) meetings.

Sources: MTCR, 'Objectives of the MTCR', [n.d.]; and MTCR, 'Frequently asked questions (FAQs)', [n.d.].

characteristics with traditional subtractive computer numerical-controlled (CNC) machine tools; however, by contrast, many of those machine tools and the materials they process are already subject to controls agreed in several of the multilateral export control regimes.

The Missile Technology Control Regime (MTCR) is one of the four main multilateral export control regimes.[7] It aims to prevent the proliferation of missiles and other uncrewed delivery systems capable of delivering chemical, biological or nuclear (CBN) weapons.[8] The states participating in the MTCR (MTCR partners) have agreed on common guidelines for missile technology exports and maintain a control list of complete missile and other uncrewed delivery systems and relevant dual-use items (MTCR annex) to which they extend controls through licensing requirements (see box 1.1).[9] The MTCR has an important function as a forum for the exchange of information on denials and procurement attempts, for licensing and enforcement experts to share experiences and good practices, and for technical deliberations to maintain the control list and stay up to date on relevant technological developments.[10]

The MTCR partners recognized the proliferation risks and challenges to export controls posed by AM and in 2013 concrete discussions on potential loopholes created by AM began within the technical experts meeting (TEM). In 2014 and 2015 the TEM continued the work on AM by additionally convening technical working groups on the

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[7] The other multilateral export control regimes are the Australia Group (AG), the Nuclear Suppliers Group (NSG) and the Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-use Goods and Technologies (Wassenaar Arrangement, WA).

[8] Missile Technology Control Regime (MTCR), 'Objectives of the MTCR', [n.d.].

[9] MTCR, 'Equipment, Software and Technology Annex', 11 Oct. 2019.

[10] See the most recent MTCR newsletter on current work in these areas. MTCR, *Missile Technology Control Regime Newsletter*, 3 Sep. 2020.

topic, and discussed AM in a joint MTCR experts meeting.[11] The 2016 MTCR plenary in South Korea explicitly acknowledged in its public statement that ‘3D printing technology poses a major challenge to international export control efforts’ and indicated that the topic would continue to be on the agenda of MTCR meetings in the following years.[12] In 2018 the MTCR participated in an inter-regime dialogue meeting with the Wassenaar Arrangement at the technical experts level and exchanged information about their respective assessments of the technology and approaches to controls.[13] The discussion on AM within the MTCR has matured and the MTCR partners have to date not agreed on the introduction of any new list-based controls on AM—but technical deliberations continue.

The wider adoption of AM by the aerospace industry progresses and more and more critical components for missiles and UAVs can be produced using various AM techniques. This calls for continuous assessment that takes into account both technical advances and capabilities, and proliferation risks and scenarios. This paper seeks to combine this type of assessment with a detailed analysis of the applicability of the export controls prescribed by the MTCR and related instruments and regimes. It seeks to inform the ongoing technical discussions within the MTCR, and increase awareness among policy-makers, licensing and enforcement officers, and to promote compliance and vigilance among stakeholders in industry, research and academia.

Chapter 2 provides an introduction to modern AM techniques that are particularly relevant for the aerospace industry and describes a range of specific applications of AM in missiles and other delivery systems. Chapter 3 discusses the proliferation risks posed by AM and the engineering and organizational considerations that have to be weighed against the technical capabilities of AM. Chapter 4 analyses in depth the application of export controls to AM, primarily under the MTCR, by discussing controls on AM production equipment, feedstock materials, transfers of technology and technical assistance, and catch-all controls. Chapter 5 concludes by outlining key measures through which the MTCR could strengthen its efforts to address AM and the proliferation risks and challenges to export controls it poses.

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[11] National regime delegate, Interview with the author, 10 Sep. 2021. A joint MTCR experts meeting brings together its technical experts meeting (TEM), information exchange meeting (IEM) and licensing and enforcement experts meeting (LEEM), which usually only convene separately, to present and discuss issues of mutual interest.

[12] MTCR, Public statement from the plenary meeting of the MTCR, Busan, 21 Oct. 2016.

[13] Wassenaar Arrangement, Statement issued by the plenary chair on 2018 outcomes of the Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-use Goods and Technologies, Vienna, 6 Dec. 2018; and Brockmann, K., *Challenges to Multilateral Export Controls: The Case for Inter-regime Dialogue and Coordination* (SIPRI: Stockholm, Dec. 2019), p. 23.

2. Additive manufacturing in the aerospace sector

AM is a rapidly developing manufacturing technology. After years of considerable hype over both the capabilities of the technology and its potential misuse by nefarious actors in weapons programmes, discussions have more recently focused on specific applications of the technology in areas where it enables specific new performance characteristics.[14] Many of the performance characteristics it enables are particularly valuable for applications in the aerospace sector, specifically in missile technology.[15] Rather than providing an account of the state of the AM industry as a whole, this chapter provides a short introduction to modern AM technology before discussing specific applications in the area of missiles and other uncrewed delivery systems that are particularly relevant in the context of the MTCR.

I. What is additive manufacturing?

AM processes create objects from feedstock materials, often fine metallic powders or filaments in wire form, by building them up from the first to the last layer in an iterative process of depositing and fusing layers of material. An often-used analogy is that of a potter who combines lumps of clay in a successive process to form an object, as opposed to a sculptor who chips away bits of material from a large block of marble. As a result, AM makes much more efficient use of materials than most traditional manufacturing processes and produces very little waste. In addition, compared to many high-precision subtractive machine tools, AM machines are often less reliant on highly skilled and experienced machinists and other technical personnel, and enable faster prototyping and testing cycles. The ability to produce objects with precise internal voids or in bionic design that would have been extremely laborious or even impossible using traditional production techniques is perhaps the most significant new capability that AM provides. Significantly, AM technology also lends itself both to reverse engineering and to innovative design of objects with very specific performance characteristics or novel design features.

AM technology, including what is commonly described as 3D printing, is not new, but has frequently been employed since the 1980s in rapid prototyping, mainly using plastics.[16] However, it has undergone rapid development since the mid-2000s and has seen significant increases in the performance, speed, versatility and precision of machines and the range of high-performance materials that a growing variety of different AM techniques can process.[17] Modern AM techniques range from relatively simple extrusion processes that heat-liquefy thermoplastic filaments, to laser beam melting (LBM) or electron beam melting (EBM) techniques that successively scan extremely thin layers of metal powder to selectively melt and fuse them until the final object is formed. An AM machine produces an object based on the information encoded in a digital build file, based on a model created using computer-aided design (CAD) software.[18] The CAD file (or similar formats) encode the dimensions of the desired object which are then, based on machine-specific parameters, turned into a sliced model that includes the operating parameters and commands to print each successive layer

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[14] Shaw, R. et al., *Evaluating WMD Proliferation Risks at the Nexus of 3D Printing and Do-It-Yourself (DIY) Communities*, James Martin Center for Non-proliferation Studies (CNS) Occasional Paper no. 33 (CNS, Middlebury Institute of International Studies at Monterey: Monterey, CA, Oct. 2017); and Daase, C. et al., *WMD Capabilities Enabled by Additive Manufacturing*, Negotiation Design and Strategy (NDS) Report no. 1908 (NDS: Jupiter, FL, 2019).

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

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

[17] Brockmann and Kelley (note 2), p. 1.

[18] Fey (note 16), p. 3.

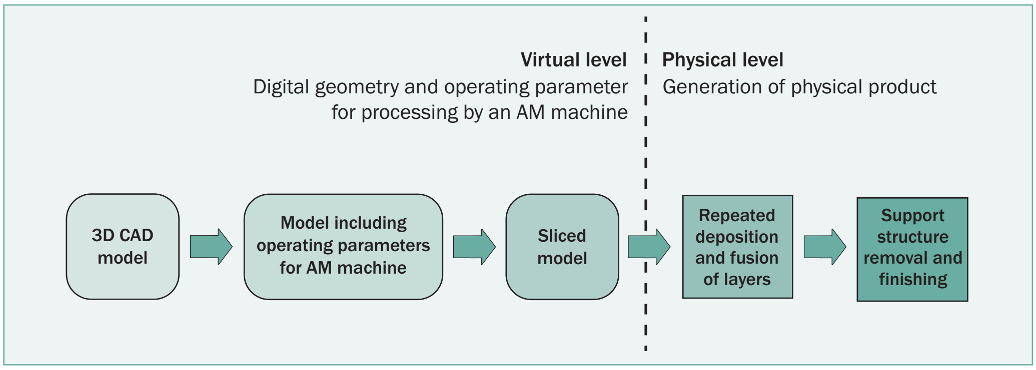

Figure 2.1. The additive manufacturing process

AM = additive manufacturing; 3D = three-dimensional; CAD = computer-aided design.

Source: Adapted from Heil, J. E., 'Quantitative, modellbasierte Analyse der Wirkungen generativer Fertigungsverfahren auf die Wertschöpfungskette des deutschen Maschinen- und Anlagenbaus' [Quantitative model-based analysis of the effects of additive manufacturing processes on the value chain of German mechanical and plant engineering], Master's thesis, Institute of Production Science, Karlsruhe Institute of Technology, 2014, as reproduced in German Parliamentary Committee on Education, Research and Technology Assessment, 'Technikfolgenabschätzung: Additive Fertigungsverfahren' [Technology assessment: Additive manufacturing], Bundestag Drucksache no. 18/13455, 29 Aug. 2017, p. 57.

to reach the object's desired performance characteristics (see figure 2.1). Depending on the AM technique chosen and the required tolerances or characteristics, leftover powder and support structures need to be removed and finishing procedures, such as precision machining, hot isostatic pressing or heat treatment, need to be applied. For comparison, these finishing procedures can take as much as 75 per cent of the total processing time required to complete an AM component with specific desired performance characteristics.[19]

There continue to be a number of technical limitations on what AM technology can achieve. AM processes generate an inherent surface roughness due to the application of successive layers and can produce small defects, such as microscopic cracks, that can result from the continuous melting and fusion processes (somewhat similar to a continuous welding process), particularly in larger objects. The speed–quality relationship and the repeatability and resulting reliability of individual pieces still somewhat limits the utility and productivity of AM.[20] The techniques and standards for non-destructive testing and validation of parts are evolving, but they continue to be a specific challenge in achieving and certifying parts with very specific performance requirements. This is particularly relevant for specific applications in rockets which often require hot-fire testing in relevant environments, including extreme structural, thermal and dynamic load.[21] In addition, while the physical manipulation in AM machines is completely automated, the operating, handling and cleaning of advanced AM machines, as well as removal of support structures, all require know-how and experience—as they can affect the properties of the product. As a result, AM does not provide a manufacturing capability 'at a push of a button' but requires significant know-how, particularly for designing parts and processes specific to AM, in order to be utilised to its fullest potential. This includes specialized skills and experience in engineering and material science, often in the form of tacit knowledge that needs to be acquired through practice or apprenticeship.[22]

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[19] Government senior adviser on export controls, Correspondence with the author, 27 Sep. 2021.

[20] *Spiez Convergence: Report on the Second Workshop, 5–8 September 2016* (Spiez Laboratory: Spiez, Oct. 2016), pp. 19–20.

[21] Gradl, P., Senior Propulsion Engineer at the NASA Marshall Space Flight Center, 'Advancement of metal additive manufacturing techniques and materials for rocket propulsion applications', Webinar presentation at Digital Additive Manufacturing Marathon, 27 Apr. 2020.

[22] Stewart, I., 'The contribution of intangible technology controls in controlling the spread of strategic technologies', *Strategic Trade Review*, vol. 1, no. 1 (2015).

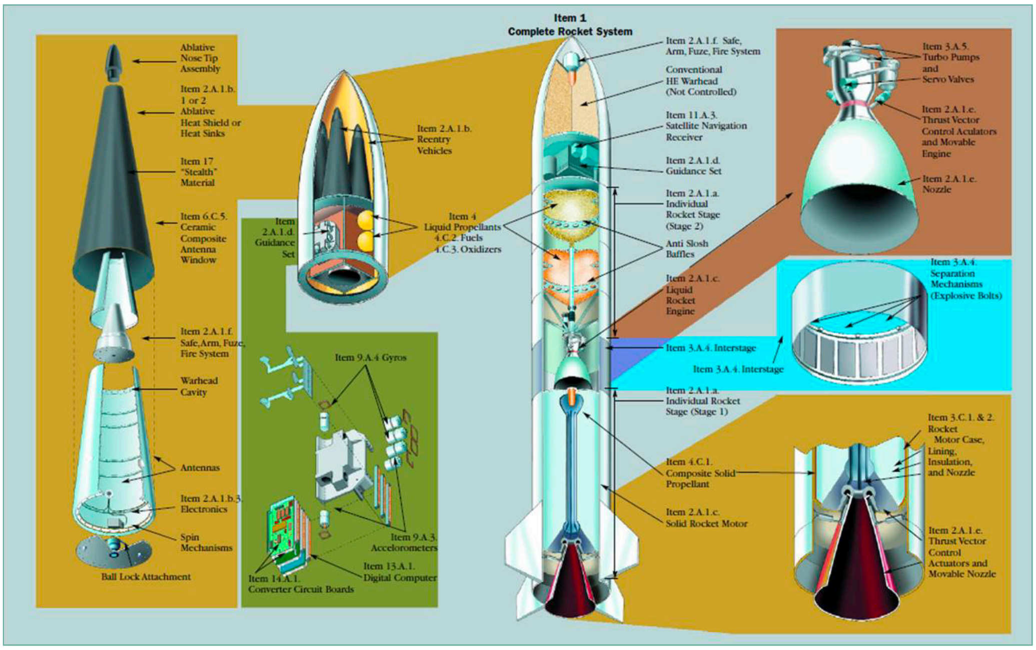

Figure 2.2. Expanded view of a notional ballistic missile showing MTCR annex items

HE = High explosive.

Source: Missile Technology Control Regime, *MTCR Annex Handbook 2017* (2017), p. 6, figure 4.

II. Applications in missiles and rockets

All missiles and rockets capable of delivering CBN weapons are covered by the MTCR annex and therefore subject to export controls. The annex further covers many of the key components that are required and the acquisition or production of which typically pose a barrier to a potential proliferator.[23] Many of these components are complex and require specific machine tools, engineering knowledge and materials to produce. AM can produce many of these types of complex parts—for example ones with internal voids, such as cooling channels—or particular geometries that could not otherwise be produced in one piece using subtractive manufacturing techniques. The reductions in weight, waste and the time required for development and testing cycles make AM technologies very desirable from a commercial perspective—one of the key reasons for its continued growth and adoption by the wider aerospace industry and, in particular, companies developing and producing rockets, missiles, space launch vehicles and UAVs.

An exhaustive account of applications of different AM techniques to all components of different types of missiles and UAVs is beyond the scope of this paper. Instead, the focus is on a selection of applications relevant to specific components for the main subsystems of ballistic missiles (see figure 2.2), cruise missiles, and other delivery systems where there is overlap with the set of items covered by the MTCR annex.

Rocket propulsion systems

There are a range of rocket propulsion systems that different types of rockets, or individual rocket stages, commonly use. The main categories are solid propellant and hybrid rocket motors and liquid propellant rocket engines. Solid propellant rocket motors require fewer parts, as they contain a heterogeneous solid mixture containing both fuel and oxidizer within their motor casing. The airframe, including the casing,

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[23] MTCR, 'Equipment, Software and Technology Annex' (note 9).

usually also acts as the pressure vessel within which the solid propellant grain is ignited, and the expanding hot gases exhausting through the nozzle at high speeds create thrust. Hybrid rocket motors usually use a solid fuel and a liquid oxidizer, enabling throttling, shutdown and reignition during flight, thus often allowing for more controllability than in a solid motor design. Liquid propellant rocket engines feed fuel and oxidizer through a complex set of pipes, valves and an injector head into a combustion chamber where they are mixed and, upon ignition, vaporize and burn as hot gases which then pass out through the nozzle, creating thrust. Therefore, liquid propellant rocket engines require more individual components, most of which can demonstrably be produced using AM.[24]

Combustion chambers are a prime example of a key component of liquid propellant rocket engines where metal AM has had a profound impact and where its application as the primary manufacturing technology for developing and producing new designs may become an industry standard.[25] The National Aeronautics and Space Administration (NASA) has conducted a significant amount of research and development (R&D) since the mid-2010s on AM of copper alloys for regeneratively cooled combustion chambers with integral cooling channels. The production processes for such combustion chambers traditionally took many months but can now be achieved in a matter of weeks using AM.[26] The Launcher space company cooperated with Electro Optical Systems (EOS) and AMCM, leading producers of advanced metal AM machines, to produce a combustion chamber in a single piece for its E-2 liquid rocket engine, claiming reductions in 'cost, complexity and manufacturing lead time for most parts, including the combustion chamber'.[27]

Injector heads are another example where AM has demonstrated its inherent strengths. AM production processes allow for the redesign of injector heads that previously had to be welded or otherwise fused together, often from several hundred precision parts, and were therefore prone to containing small defects. The Ariane Group redesigned an injector that was previously made from 248 individual parts into one single piece and can now produce injectors using AM in approximately 35 hours, rather than the previously required three months.[28] Similarly, NASA reduced the individual components of a subscale injector head from 115 parts to just two, thereby enabling significant cost saving.

Turbo-pumps are responsible for pumping the liquid fuel from the tanks through the injector head into the combustion chamber. They consist of precise turbines with impellers that drive the pump to achieve the desired pressure, enabling the engine to produce and maintain thrust after ignition. In 2015, NASA reported that switching from a traditional design to an AM design turbo pump reduced the number of required parts by 45 per cent.[29]

Nozzles are key components of both liquid- and solid-fuelled rockets. The design of a nozzle determines the direction and velocity of the hot exhaust gases exiting the rocket and thus how much thrust is generated. They are usually conical or hourglass-shaped with a throat to maximize velocity of the exhaust gases.[30] Nozzles have to withstand extreme structural, thermal and dynamic loads. Size limitations, for example of

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[24] MTCR, *Annex Handbook 2017* (2017), pp. 29–35.

[25] National Aeronautics and Space Agency (NASA), 'NASA advances additive manufacturing for rocket propulsion', 9 May 2018.

[26] Gradl (note 21).

[27] Launcher (note 1).

[28] Electro Optical Systems (EOS), 'Future Ariane propulsion module: simplified by additive manufacturing', Feb. 2019.

[29] NASA, 'Successful NASA rocket fuel pump tests pave way for 3-D printed demonstrator engine', 26 Aug. 2015; and MetalAM, 'Additive manufactured fuel pump tested for liquid methane NASA rocket in Mars project', 5 May 2016.

[30] MTCR (note 24), pp. 69–70.

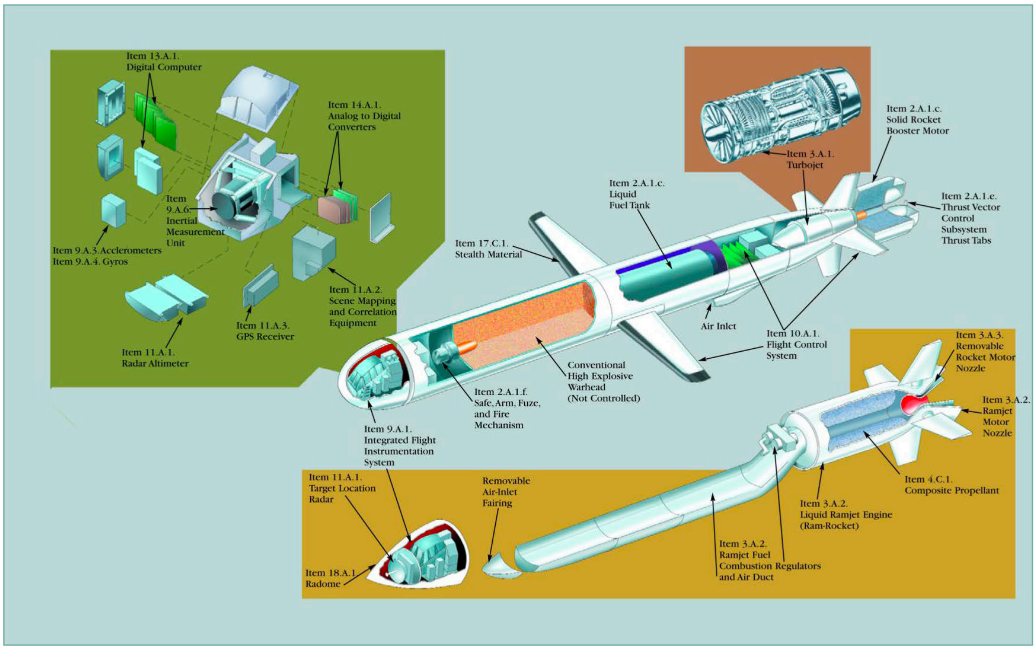

Figure 2.3. Expanded view of a notional cruise missile showing MTCR annex items

GPS = global positioning system.

Source: Missile Technology Control Regime, *MTCR Annex Handbook 2017* (2017), p. 6, figure 4.

the build envelopes of AM machines using powder-bed fusion techniques, can make certain techniques less suitable for application to larger components, including for many large-scale rocket propulsion units, particularly their nozzles. A range of other AM techniques in the area of directed energy deposition (DED)—including laser DED, blown powder DED, and arc DED processing feedstock in wire form—are able to 'free form' objects, largely without the constraints of a build envelope, and have started being used to print, for example, large-scale rocket nozzles.[31]

Solid propellants

Additive manufacturing of energetic materials, such as rocket propellants, using a variety of AM techniques is the subject of targeted R&D processes.[32] It seeks to overcome challenges that are commonly associated with established techniques and processes for production of solid rocket propellant motors, such as casting and curing of solid propellants.[33] In particular, additive layering of propellants could reduce the risk of voids in the grain and enable different grain designs that include burning tubes of different shapes and forms that allow tailoring of the propellant composition, for example by introducing gradients, and thus of the rocket burn to specific mission requirements.[34]

The use of AM to process energetic materials is still in development and most applications developed to date have produced grains that are significantly smaller than those used in solid propellant rocket motors for missiles covered by the MTCR. Notably, applications of AM technology in military items include many other fields,

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[31] Gradl (note 21).

[32] European Defence Agency, 'Additive manufacturing techniques for energetic materials: new opportunities for defense applications', [n.d.].

[33] Muravyev, N. V. et al., 'Progress in additive manufacturing of energetic materials: creating the reactive microstructures with high potential of applications', *Propellants Explosives Pyrotechnics*, vol. 44, no. 8 (2019), pp. 942–55.

[34] McClain, M. S., 'Additive manufacturing of 3D-printed energetic structures', Defense Systems Information Analysis Center (DSIAC) Seminar, 5 May 2021.

in particular ammunition, propellants and explosive munitions, which is why there have also been technical exchanges on this technology in the Wassenaar Arrangement experts group.

Re-entry vehicles and warheads

Advanced metal AM is increasingly able to produce intricate designs with a low mass that possess high compressive strength and can withstand high loads.[35] These properties may particularly lend themselves to application in hypersonic glide vehicles. In 2018, Orbital ATK tested a warhead design for application on a hypersonic missile, relying on AM 'to build a large portion of the components' of the warhead.[36] Aerojet Rocketdyne also relies on AM in the development of hypersonic boost glide systems and hypersonic scramjet-powered cruise missiles.[37] Previous analyses have also pointed to the possible applications of AM to produce key components of re-entry vehicles, such as ablative heat shields.[38]

Rocket bodies and other structural components

AM has also seen increasing application in lightweight aerodynamic components for air vehicle structures, such as rocket bodies for cruise missiles (see figure 2.3). While rocket bodies are often produced from traditional additive techniques, such as filament winding, others are made from aluminium alloys and coated, for example using physical vapour deposition, or PVD, coating processes. US company Relativity Space uses its proprietary Stargate printer—claimed to be the largest AM printer in the world—to produce fuel tanks and entire rocket bodies for space launch vehicles using AM.[39] Notably, there are hardly any machines which could produce objects of the required size for them to be able to build a complete rocket airframe using one AM machine. Relativity Space is an outlier and it is questionable if their printer and approach would be applicable for a military programme, as it follows a unique pathway of designing and producing their entire space launch rockets using AM, using their proprietary materials and printer. This type of pathway of building an entire programme around AM technology is highly dependent on the specific 'new space' industry eco-system where there is arguably easier access to the technology and know-how, and which places a premium on innovative approaches rather than proven reliability—and is unlikely to be replicated by any state's missile programme.

Other components

Because of its versatility, AM can further be used to produce a whole range of small components that can be used in different parts of a rocket. For example, advances in printing of energetic materials (see 'Solid propellants' above) means that AM could be used to produce many small pyrotechnic devices in a missile system, such as actuators, squib valves, explosive cutters and separation bolts.[40]

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[35] Government senior adviser on export controls, Interview with the author, 26 Aug. 2021.

[36] Judson, J., 'Orbital ATK tests partially 3D printed warhead for hypersonic weapons', *Defense News*, 9 Apr. 2018.

[37] Aerojet Rocketdyne, 'Hypersonics', [n.d.].

[38] Shaw et al. (note 14), annex, pp. 19–24.

[39] Relativity Space, 'The factory of the future', [n.d.].

[40] Brockmann and Kelley (note 2), p. 13.

II. Applications in uncrewed aerial vehicles

The MTCR annex covers 'unmanned aerial vehicles' based on the same two parameters as it does for ballistic and cruise missiles. It also controls a specific subset of UAVs that particularly lends itself to delivery of biological or chemical weapons.[41] Since the expansion of MTCR controls to cover UAVs, the nature and missions of military UAVs, also referred to as drones, have evolved significantly and become more like those of crewed aircraft.[42] The MTCR's control parameters mean that many high altitude long endurance (HALE) UAVs, which are now commonly both surveillance and strike platforms, fall within Category I, while many other medium altitude long endurance (MALE) UAVs are covered by Category II.[43] Most of these UAVs are air-breathing vehicles often powered by small turbine engines that drive propellers, while only some newer types rely on jet engines. AM can be used to produce components for both types of engines but, for the time being, is arguably not a key enabling technology in this context. The requirements on the airframe of these types of UAV differ considerably from those of missiles and the advantages of using AM for the production of components is less clear. However, the need for lightweight components to increase efficiency and the desirability of low observability point to potential applications of AM for components of these types of UAVs.

Structural components

While most applications of AM in UAVs are in small systems that are well below the MTCR's 300 km range threshold, some of the applications and capabilities of AM demonstrated in structural components may still be relevant for larger systems, particularly as the size of printable components continues to increase.[44] The ability to produce lattice or honeycomb structure designs or other light but high-strength structural parts with relative ease enables the manufacture of components that could in the future also become more applicable in larger UAV designs that are more relevant to the MTCR, for example in the internal structures of wings.

Stealth and other low observability technology

While low observability is often less relevant in the context of ballistic missiles, it is very desirable for delivery systems using air-breathing engines, such as UAVs and certain types of cruise missiles. 'Stealth' technology describes different approaches to reducing observables, such as radar reflectivity, ultraviolet or infrared signatures, and acoustic signatures.[45] To achieve such effects, the design features of surfaces, inlets and airfoils are adapted to reduce or scatter such signatures as much as possible. The other side of this is inherent in the material science behind 'the choice of materials and the details of geometry of layers and voids that can reduce reflections and absorb incident energy'.[46] Publicly available information on the specifics of stealth technology is limited and it is not clear whether AM has to date played any significant role in stealth-related R&D or any concrete applications. However, the ability of AM to produce very complex shapes lends itself to possible designs, such as absorbing honeycomb, that can be loaded with conductive fillers.[47] Therefore, it may be relevant for the MTCR to monitor technical developments and applications of AM in this area.

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[41] MTCR, 'Equipment, Software and Technology Annex' (note 9), item 19.A.3.

[42] Horowitz, M. C., 'Drones aren't missiles, so don't regulate them like they are', *Bulletin of the Atomic Scientist*, 26 June 2017; and Schörnig, N., *Preserve Past Achievements! Why Drones Should Stay within the Missile Technology Control Regime (for the Time Being)*, PRIF Report no. 149 (PRIF: Frankfurt, 2017).

[43] MTCR, *Annex Handbook 2017* (note 24), pp. 331–33.

[44] For an account of the wider applications of AM to UAVs see Shaw et al. (note 14), annex, pp. 26–45.

[45] MTCR, *Annex Handbook 2017* (note 24), p. 309.

[46] Kelley, R. E., SIPRI Distinguished Associate Fellow, Background briefing provided to the author, 15 Sep. 2021.

[47] MTCR, *Annex Handbook 2017* (note 24), p. 311.

3. The proliferation risks of additive manufacturing and challenges to export controls

Developments in the field of AM have raised concerns over new proliferation risks resulting from the spread and use of AM. However, many analyses have either been too focused on the specific technical capabilities of novel AM techniques, or failed to take into account the considerations and 'soft' factors that influence any actor's decision to use AM and the obstacles they may face in adopting AM technology.

I. Proliferation scenarios and engineering decisions

The material efficiency and potential reduction in personnel cost and lead times in development cycles, as well as the new performance characteristics it can enable, make AM a particularly viable alternative to much of the production equipment that is already explicitly covered by the control lists of the MTCR or the other export control regimes.[48] However, the technical capability to produce a highly sophisticated missile or UAV component using AM does not necessarily mean that an actor will choose to use AM. A key factor here is that despite its significant capabilities, technical limitations on AM techniques persist and significant process development is required. As mentioned above, AM machines are still behind on accuracy and repeatability in the production of objects, compared to established but advanced CNC machine tools.

Whether a specific actor chooses to adopt AM as a significant tool in pursuing a missile programme or other relevant delivery systems is highly dependent on the circumstances of their individual programme. The development of applications and advances in AM technology, including the engineering and design of items to be produced using AM, depend on the contributions of a multiplicity of actors.[49] Often, aerospace companies, research institutions and AM machine producers collaborate in targeted projects that may take many years to develop a single application, such as a certified component for a rocket engine.[50]

Understanding the proliferation risk posed by AM means trying to understand or at least model when such a decision may be more or less likely. This is dependent on both the circumstances of the proliferation scenario in which AM might be adopted and the more specific decisions as to why AM would be chosen as the production technology used for one or a range of specific missile components. In any case, it could enable states and non-state actors that previously did not have access to missile technology to circumvent controls and more easily acquire missiles (horizontal proliferation). In addition, the ability of AM to enable new performance characteristics in key components of missiles and other delivery systems raises proliferation concerns where missile-possessor states are seeking to increase the capabilities of their missile arsenals (vertical proliferation).

There are significant differences in and implications for the proliferation scenario—whether, for example, a nuclear-armed state seeks to produce a highly sophisticated intercontinental-range ballistic missile, or whether a non-state actor seeks to produce a small arsenal of shorter-range cruise missiles for a specific attack. In the former case, such states will presumably have a significant industrial and scientific base to rely on and will be seeking to engineer a reproducible process that may be adaptable for several generations of missiles. For a non-state actor, less accurate and less

[48] Brockmann and Kelley (note 2).

[49] Brockmann and Kelley (note 2), p. 8.

[50] Electro Optical Systems (EOS) (note 28).

reliable missiles may be more acceptable if they are intended largely for signalling or as a political statement. Part of the consideration therefore depends on 'the capability, operational requirements and sophistication' of the missile or delivery system being sought.[51] A state with a very limited industrial base or a non-state actor may not have much incentive to develop new tailored manufacturing processes and invest in AM capabilities instead of relying on more established manufacturing technology that could still produce adequate parts.

Thus, the circumstances of a proliferation scenario differ considerably depending on whether a state is (*a*) starting a national missile programme from scratch, (*b*) seeking to indigenize the development and production capabilities to support a national missile programme that has been heavily reliant on outside assistance, or (*c*) seeking to use AM to circumvent or break through a specific bottleneck, for example when it has been unable to procure certain key items. Particularly relevant for a decision to adopt AM as a key technology used in a state's missile or UAV programme is the ability to access the required items and the specific know-how. Experience with AM residing in national industry, state research facilities or space programmes, and even in the start-up scene (e.g. in 'new space' companies or the micro-launcher community) could put a state in a better position to take advantage of AM technology.[52]

Beyond the immediate decisions and considerations, several factors relate to more long-term trends that may affect these decisions in the future and may thus potentially increase proliferation risks. As AM becomes more established as a standard technology within the aerospace industry and particularly in rocketry, the knowledge base will grow and the hurdles to pursue, or at least explore, the use of AM will gradually lower. Notably, there is also a growing number of AM service providers that offer AM production, including collaboration in design processes and post-processing, on demand. In areas where AM becomes the industry standard for producing key components of rockets and missiles, vertical proliferation efforts to increase capabilities of national missile arsenals, in particular, may have a higher likelihood of states choosing to pursue the technology as relevant know-how becomes more readily available. The growing use of AM to produce combustion chambers and injector heads by a wide range of actors across the civilian and military aerospace industry may be an early example of such trends.

II. Challenges to the application of export controls

AM poses a significant challenge to existing export control systems. Transfers of technical data in the form of build files provide a recipient with considerable capabilities if they have access to a capable AM machine. Electronic transfers of this type of technical data are difficult—if not impossible—to prevent using the physical controls of the traditional customs and export control systems.[53] Moreover, materials and AM machines are often multipurpose and are therefore difficult to regulate using list-based controls. Nevertheless, a considerable range of export controls already apply to AM machines, feedstock materials and technology, and on end-uses in CBN weapons and their delivery systems (see chapter 4). Therefore, export controls still create significant barriers and enable additional oversight of potentially sensitive transfers by states. In order to make best use of existing export controls and enable them to help address the proliferation challenges posed by AM, it is key that the MTCR partners continue to monitor technical developments, assess possible proliferation scenarios, and improve the applicability and effectiveness of export controls on AM.

[51] Brockmann and Kelley (note 2), p. 38.

[52] The author is indebted to Markus Schiller of ST Analytics for an illuminating discussion on decision-making, constraints and implications of different technology acquisition and indigenization efforts in missile programmes.

[53] Nelson, A., 'The truth about 3-D printing and non-proliferation', *War on the Rocks*, 14 Dec. 2015.

4. Applying MTCR export controls to additive manufacturing

The export controls prescribed by the MTCR and several of the other multilateral export control regimes already create controls on AM in several ways. The current coverage of the control lists means that licensing requirements may apply to transfers of certain AM production equipment and its key components, feedstock materials, software for AM machines, and technology. In addition, catch-all controls enable states to impose licensing requirements on unlisted items if their end-use is in connection with uncrewed delivery systems for weapons of mass destruction (WMD). Other export controls cover machine tools required to apply the finish to additively printed products, hybrid machine tools (combining AM machines and controlled subtractive machine tools in one machine) and key components, thus contributing to mitigating the proliferation risks posed by AM.

Regime members have introduced a range of proposals, including in the MTCR, for possible new control list items covering different aspects of AM, or for adjusting existing list items to strengthen controls, but hardly any list changes have been agreed upon to date because of a lack of consensus both on the specific nature of the proliferation risk posed and on suitable technical parameters that would sufficiently distinguish items. State practice in applying list-based controls and catch-all controls varies considerably.

I. Controls on additive manufacturing production equipment and key components

‘Specially designed’ production equipment

A range of AM production equipment—particularly AM machines—is already within the scope of the MTCR annex. Many of the control list items in the MTCR annex that define a specific item extend controls to production equipment that is ‘specially designed’ or ‘modified for’ the production of that item. For example, list items on propulsion subsystems for use in both Category I and II delivery systems include controls on ‘production equipment’ that is specially designed or modified for these subsystems.[54] However, determining whether an AM machine is ‘specially designed’ or ‘modified for’ such a purpose can be difficult, as most are multipurpose manufacturing machines. The criterion defined by the annex states that ‘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’.[55] In contrast, most leading AM machine producers develop and market general- or multipurpose machines which are able to achieve certain performance characteristics in their products independent of what type of component they print. For example, many of the advanced powder-bed fusion type AM machines that produce objects made from metal alloys are restricted by the size of their build envelope and the mechanical properties of the objects they print, but those capabilities still commonly lend themselves to producing many different types of components. MTCR technical experts have identified several examples where specially designed AM production equipment could be controlled, including, in particular, specialized machines used to produce solid propellant rocket motors and key components of air-breathing engines that are

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[54] MTCR, ‘Equipment, Software and Technology Annex’ (note 9), items 2 and 20.

[55] MTCR, ‘Equipment, Software and Technology Annex’ (note 9), p. 16.

the main propulsion system for Category I and II delivery systems, particularly cruise missiles. Notably, some companies increasingly offer custom-made AM machines to their customers, particularly to those in the aerospace sector. Some start-ups, research institutions, national space programme enterprises and companies have developed their own custom printers—often, but not always, in collaboration with AM machine companies as development partners. In those cases, AM machines are more likely to fall under the 'specially designed' clause and trigger a licensing requirement if they are to be exported.

Hybrid machines

Controls can also apply to AM production equipment if it is part of a so-called hybrid machine—one that combines additive and subtractive manufacturing equipment in one machine. Notably, there are some additional technical limitations to hybrid machines that result, for example, from the need to ensure the removal of all excess powder from the workpiece and working space within the machining centre before subtractive machining to ensure that high accuracies can be achieved. The hybrid machine as a whole is subject to controls if the performance characteristics of the subtractive machine part—particularly its accuracy—fall under the controls on machine tools established by the Wassenaar Arrangement or those established by the Nuclear Suppliers Group (NSG).[56] The applicability of these controls is particularly important as the objects produced by AM machines typically require machining and other finishing procedures because of their inherently uneven surface structures and to meet precision requirements.[57]

Key components of additive manufacturing machines

Similar to controls on hybrid machines, controls can also apply to AM machines if their key components are controlled in their own right. This particularly applies in the case of high-powered lasers that are commonly incorporated in AM machines that make use of, for example, selective laser melting techniques to precisely melt and bond layers of feedstock powder or wire. Certain lasers are covered by controls of the Wassenaar Arrangement and the NSG. Category 6 of the dual-use control list of the Wassenaar Arrangement and item 3.A.2. on the NSG list specify several relevant types of lasers.[58]

However, there are a range of limitations to the effectiveness and sustainability of controls based on key components, particularly if these components are controlled by other regimes. Whether the transfer of an AM machine in its entirety could be controlled based on the laser it uses depends on national rules that usually specify, for example, what percentage of the whole item a component represents, or if the component is the main element of the machine.[59] The applicable rules vary across states and whether they result in controls depends on the characteristics of the AM machine in question. If component controls originate from an application in a different context, they are usually neither designed to specifically cover a component's use in an AM

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[56] Government senior adviser on export controls, Correspondence with the author, 19 Sep. 2017.

[57] Swiss State Secretariat for Economic Affairs, 'Overview of the basic principles of export control', Fact sheet, [n.d.], pp. 14–15.

[58] See Category 6 in Wassenaar Arrangement, 'List of dual-use goods and technologies and munitions list', WA-LIST (19)1, 5 Dec. 2019; and Nuclear Suppliers Group, 'Guidelines for transfers of nuclear-related dual-use equipment, materials, software, and related technology', annexed to International Atomic Energy Agency, INFCIRC/254/Rev.11/Part 2, 18 Oct. 2019.

[59] Swiss State Secretariat for Economic Affairs (note 57).

machine, nor are their technical parameters adjusted with those applications in mind.[60] Therefore, future list changes can diminish the applicability of such controls over time, as the example of laser controls by the Wassenaar Arrangement demonstrates. In December 2017, the WA introduced a change to a list item controlling certain types of lasers, lifting the output power threshold of certain controlled lasers from 200W to exceeding 500W.[61] As a result, the lasers used in a range of advanced metal AM machines that had previously been subject to a licensing requirement because of their incorporated lasers (and spare lasers included in exports as replacement parts), were no longer controlled.[62]

Controls resulting from other regimes' controls

The Wassenaar Arrangement is the only multilateral export control regime that has introduced list-based controls that specifically mention AM production equipment. In 2016, the WA amended its dual-use goods control list to include two list items extending controls to 'directional-solidification or single-crystal additive manufacturing equipment' for the production of gas turbine engine blades, vanes, tip shrouds and associated software.[63] These controls on AM machines for a highly specific application were introduced to prevent substitution for other already controlled production equipment, rather than to address a specific proliferation risk that had caught the WA's attention.[64] To the knowledge of the author, based on consulting several licensing officials, these specific controls have never been used, as the application of this technique for the specified purpose has not materialized to date. Agreeing on control parameters 'pre-emptively' (i.e. before an item or production technology becomes widely adopted by industry, including for military end-uses) can be an asset, particularly if it limits proliferation and raises awareness among industry and research institutions, early on. However, in this case the lack of impact of these early controls may have resulted in some regime members taking a step back from this pre-emptive approach and choosing instead to wait for more tangible examples of production equipment being used for relevant missile or UAV end-uses before adopting additional controls on AM machines.[65]

Many of the controls on AM machines, including those resulting from controls on their key components and on hybrid machines (see above), result from controls that are only codified in the control lists of regimes other than the MTCR, in particular of the Wassenaar Arrangement. While 33 of the 35 MTCR partners are also members of the WA (Brazil and Iceland being the two exceptions), it is important to keep in mind that the applicability of each set of controls depends on each individual state's national control system and whether their control lists follow those of the MTCR and other relevant regimes. Adoption of the respective control lists is considerably widespread, either through participation in or adherence to the respective regimes, states adopting the combined dual-use list of the European Union (EU) (or of others), or states consulting the regimes' control lists in creating and maintaining their own control lists.[66] However, these different adoption models result in possible delays, inconsistencies and different levels of awareness of the reasons and technical

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[60] Brockmann and Bauer (note 15), p. 11.

[61] Wassenaar Arrangement, 'Summary of changes', Dec. 2017.

[62] Brockmann and Kelley (note 2), p. 25.

[63] See items 9B001 c. and 9D004 c. in Wassenaar Arrangement, 'List of dual-use goods and technologies and munitions list' (note 58), pp. 162, 164.

[64] Brockmann and Kelley (note 2), p. 25.

[65] Government senior adviser on export controls, Interview with the author, 26 Aug. 2021.

[66] The European Union maintains a control list of dual-use items that combines the control lists of the four multilateral export control regimes.

discussions that form the basis of any changes to the different regimes' control lists. Furthermore, the respective regimes' decisions are taken based on the criteria and in the context of each regime's objectives, procedures and principles. As exemplified by the amendment of controls on lasers in the Wassenaar Arrangement, a regime's ability to rely on controls established by another regime to reduce the proliferation risk of an emergent technology like AM in their area of concern, for example missiles and UAVs, is limited and may not be sustainable. Therefore, introducing specific controls through the MTCR control lists to address missile technology–specific proliferation risks posed by AM machines may still be necessary in the medium to long term.

Proposed controls on additive manufacturing production equipment

Because of the confidential nature of the discussions in the MTCR and in the other regimes, few details are available in public sources about concrete proposals for list changes that have been introduced by the MTCR partners and states participating in the other regimes. Information on past proposals shared by national officials can generally not be attributed.

In February 2014, Australia submitted a proposal to the MTCR that it introduce controls on 'machine tools for "additive manufacturing"' that have controlled-atmosphere environments configured for the production of listed explosives, propellants, metals, ceramics or alloys 'with greater than 98% theoretical density'.[67] Later in 2014, Australia introduced a proposal for a similar amendment in the Wassenaar Arrangement.[68] In April 2016, France proposed amending the NSG dual-use control list to include controls on LBM and EBM AM machines using powder-bed techniques with a build envelope having 'one dimension larger than 20 centimetres'.[69] Each set of the technical parameters proposed was ultimately rejected because they would have quickly become obsolete, resulted in large volumes of licensing applications, and possibly created an undue burden on competitiveness and technological innovation.

The continued lack of international technical standards for AM machines and feedstocks that would lend themselves to control list parameters, as well as a certain hesitation after the early list-based controls introduced in the Wassenaar Arrangement remained unused, has meant that no new controls have been introduced. Nevertheless, discussions of technical proposals in the TEM continue. The author and Robert E. Kelley have previously argued for specific controls on AM production equipment designed for the production of propellants for rocket motor grains.[70] As this type of specialized machine may lend itself more to clear definition by technical parameters, the possibility of such controls should continue to be considered as more mature examples of this application of AM emerge.

II. Controls on feedstock materials

Materials that in a certain form or in combination with other materials can be used as feedstock materials in AM machines are inherently dual-use. The material used and its composition and parameters determine specific characteristics of an object produced by an AM process, but they do not determine its end-use. The more specific the requirements of a particular item, for example a component of a rocket motor, the more specific may be the AM machine used to process it and the narrower the

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[67] Finck, R., '3D printing', Presentation at the 20th Anniversary Practical Export Control Workshop of the Wassenaar Arrangement, 27–28 June 2016.

[68] Finck (note 67).

[69] Finck (note 67).

[70] Brockmann and Kelley (note 2), p. 37.

possible end-uses of products manufactured using the material. Developing technical definitions of materials, particularly of powders used in AM of metals, with meaningful parameters that are sufficiently distinct from those used in common civilian applications, and that would not be soon overtaken by technical developments, is inherently difficult.

The control lists of the export control regimes already cover a range of metal powders and alloys that can be used in AM. For example, the MTCR and the NSG control lists cover maraging steel because of its applications in structural components of missiles and gas centrifuges. However, the parameters chosen to characterise the controlled material do not include the powder or wire form used by many AM machines. Other control list items, for example in Category 1C of the WA list of dual-use goods and technologies, control certain metals and alloys in powder form according to their chemical and physical properties, composition and other characteristics.[71] The purity parameters in the list items covering some of the relevant metal and alloy powders mean that a range of feedstock materials for high-end metal AM are already controlled.

Category II, item 4 of the MTCR annex controls a wide range of chemicals, fuel substances and metal powders that are commonly used for the production of propellants, including solid-fuel grains.[72] These controls will in many cases also control the materials and substances used as feedstock in AM machines for the production of propellants and explosives. The technical thresholds used to characterize the metal powders (i.e. particle volume, weight, shape, composition, gas content and purity) mean that in many cases the most potent materials that could be used by such AM machines are already controlled. However, because these parameters were chosen based on different applications, in some cases the parameters will not cover AM feedstock materials. Notably, an actor with the required expertise who is willing to accept sufficient rather than optimal characteristics of some of these materials, for example concerning the spherical shape of aluminium powders, would likely still be able to produce a functional fuel grain using unlisted powders, albeit with a somewhat lower fuel-burn efficiency.[73] Notably, MTCR controls also extend to 'metal powder "production equipment"' used to achieve desired powder characteristics, adding another layer of control to mitigate proliferation risks.[74]

One consideration to note is that the existing definitions—which in some list items are quite broad—were devised to cover materials that could be used by the production equipment available at the time and have generally not been designed with today's AM technology in mind. Systematic review and potential adaptation of control parameters will likely be necessary to maintain the desired coverage of AM feedstock materials that could be used in missiles and other uncrewed delivery systems. Some states, notably the United Kingdom, have chosen to apply catch-all controls where possible—and where there are serious concerns—to require authorizations for exports of unlisted AM feedstock materials (and other AM technologies).[75]

III. Controls on transfers of technology and technical assistance

In many cases general-purpose AM machines, rather than 'specially designed' machines, may be sufficient to produce controlled missile components. However, in order to produce these items, AM machines require detailed instructions, commonly in the form of digital build files that are easily transferable. These digital files are

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[71] Wassenaar Arrangement, 'List of dual-use goods and technologies and munitions list' (note 58).

[72] MTCR, 'Equipment, Software and Technology Annex' (note 9), pp. 29–36.

[73] Markus Schiller, ST Analytics, Interview with the author, 9 Sep. 2021.

[74] MTCR, 'Equipment, Software and Technology Annex' (note 9), pp. 28–29.

[75] Government senior adviser on export controls, Interview with the author, 26 Aug. 2021.

subject to controls on transfers of 'technology', based on the item whose production they enable. Controls on transfers of technology are therefore particularly important in the context of AM in the area of missiles.

Transfers of technical data

The MTCR annex defines 'technology' as 'specific information which is required for the "development", "production" or "use" of a product' and distinguishes between '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').[76] Technology can take a tangible, physical form, such as a printed blueprint, or be intangible, for example training on specific manufacturing skills. Technology can be transferred physically, for example by shipping a physical item, or in an intangible form, such as through an electronic transfer method such as email or by transferring knowledge through training and apprenticeship.[77] These types of intangible transfers of technology pose significant challenges to the effectiveness of export controls because those transfers can no longer be physically observed, controlled and stopped at national borders or in transit. Moreover, despite the definitions provided by the MTCR and a range of public guidance material from other regimes and national governments, there are differences in national implementation of these controls and a certain ambiguity over when and how controls apply in practice, including in the context of AM.[78]

The digital build files processed by the operating software of AM machines usually describe both the geometry of the product and encode the specific parameters for the work process applied to achieve sufficiently high performance characteristics in the manufactured product. The files are thus clearly 'required' for the process to meet the listed performance characteristics and therefore clearly controlled as technical data if the item itself is controlled. Digital build files can easily be transferred using email, or made available using common file-sharing systems or cloud services.

Controls also extend to the technology required for the 'development' and 'production' of controlled items. They can apply specifically to transfers that spread the know-how or process parameters required for advanced AM design processes or controlled production technologies where these are sought to be applied in the context of controlled missiles and other delivery vehicles.

Technical assistance

Technical assistance can be provided by means of training and consulting services or through academic courses, transferring knowledge that may be subject to export controls to a recipient in another state or of another nationality. While controls on technology in the form of technical data are both important and challenging in the context of AM, the provision of technical assistance and the ability of states to control it is perhaps equally significant, particularly as AM technology is still very specialized and requires a combination of know-how and practical experience in engineering and material science. Specifically designing components for AM, rather than copying the design of a traditional component (where using AM may be sub-optimal), enables new performance characteristics but is highly reliant on specific expertise. A digital

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[76] MTCR, 'Equipment, Software and Technology Annex' (note 9), pp. 13–14.

[77] Bromley and Maletta (note 5).

[78] Brockmann and Kelley (note 2), pp. 27–28.

build file for a specific type of AM machine may enable another actor with access to such a machine to reproduce an item previously designed for a specific application and within the context of, for example, a specific rocket design. However, especially in the context of missile programmes for the delivery of WMD, the design and engineering decisions inherently depend on the circumstance of that programme and its goals (see chapter 3).[79] The machines, materials, know-how, resources and personnel available to such a programme each influence the utility that can be derived from acquired technology and the 'success' of the programme in reproducing, reverse engineering, redesigning or adjusting, for example, a rocket design for a desired missile application. Therefore, controls on technical assistance to limit the acquisition of know-how, particularly tacit knowledge, required for sophisticated AM design and engineering are an important component of a holistic approach to controls on AM.[80]

However, while the MTCR's definition of technology includes technical assistance, the application and implementation is not specified and varies considerably across states, both in terms of their coverage and the mechanisms used to control technical assistance.[81] For example, the United States imposes controls on 'deemed exports' (i.e. the release of controlled technology to a national of another country), while other states rely much more on visa screening procedures.[82] The EU recently expanded its common rules on controlling technical assistance as part of the recast of the EU dual-use regulation, clarifying to some extent its controls on the provision of 'training' and the 'transmission of working knowledge and skills'.[83]

IV. Catch-all controls

Catch-all controls enable states to impose controls on items that do not appear in their control lists but which are likely to be used for a proscribed end-use. Catch-all controls are a common export control instrument, with provisions included in each of the regimes, the EU's regulations and most national export control systems. The MTCR guidelines provide that each partner will 'require an authorisation for the transfer of non-listed items if the exporter has been informed by the competent authorities of the Government that the items may be intended, in their entirety or part, for use in connection with delivery systems for weapons of mass destruction other than manned aircraft'.[84] If the exporter is 'aware that non-listed items are intended to contribute to such activities, in their entirety or part', the exporter is obliged to notify the relevant national licensing authority, which then determines if a licensing requirement applies.[85] This type of control has increasingly been applied to impose licensing requirements—and in some cases issue denials—on transfers of unlisted AM machines, feedstock materials and technology.

Catch-all controls are a versatile tool because they enable a state to control sensitive trade solely on the basis of a possible end-use in WMD delivery systems and require exporters to exercise due-diligence concerning the end-use of their exports. Catch-all controls can be particularly useful where there is a lack of international standards for items—such as AM machines and feedstock materials—that could readily be used as parameters in list items. Notably, triggering a catch-all control does not neces-

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[79] Brockmann and Kelley (note 2), p. 28.

[80] Brockmann and Kelley (note 2), pp. 28, 37.

[81] For a more comprehensive analysis of controls on technical assistance see Bromley and Maletta (note 5).

[82] Bromley and Maletta (note 5), p. 21.

[83] Bromley, M. and Brockmann, K., 'Implementing the 2021 recast of the EU Dual-use Regulation: challenges and opportunities', EU Non-Proliferation and Disarmament Consortium, Non-proliferation and Disarmament Paper no. 77 (Sep. 2021), p. 5.

[84] MTCR, 'Guidelines for sensitive missile-relevant transfers', [n.d.].

[85] MTCR, 'Guidelines for sensitive missile-relevant transfers' (note 84).

sarily entail the denial of the export in question, but rather enables the state to require additional information and end-use assurances concerning a specific transfer, thus better informing its licensing decision. The extent to which states use catch-all controls varies considerably, with some using them widely to impose licensing requirements on certain items, others only when they have the intention to deny a specific transfer. Catch-all controls enable states to balance security-driven control requirements with economically driven trade-facilitation imperatives, by avoiding the introduction of broad list-based controls while retaining the ability to impose controls based on available intelligence.[86]

However, the effective use of catch-all controls is highly dependent on access to relevant intelligence and analysis, through intelligence sharing or collection, and the strength of exporters' due-diligence and compliance procedures. Catch-all controls arguably result in a smaller number of licence applications, when compared to the introduction of broad list-based controls. However, industry, research and academia frequently criticize their heavy use for the unpredictability it can create for businesses, for example, concerning timelines of exports.[87] Long-term reliance on catch-all controls can be difficult because of the considerable resources they can require and the negative impact they may have on scientific and industrial R&D, including in the emergent AM industry. It is therefore important for the MTCR partners to continually assess where frequent use of catch-all controls might be better replaced by sufficiently targeted list-based controls.

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[86] Brockmann and Kelley (note 2), p. 26.

[87] Brockmann, K., 'Drafting, implementing, and complying with export controls: the challenge presented by emerging technologies', *Strategic Trade Review*, vol. 4, no. 6 (2018), pp. 22–23.

5. Strengthening the MTCR's efforts to address proliferation risks posed by additive manufacturing

There are a range of measures that the MTCR could take in order to address the proliferation risks posed by AM.

I. Key measures

Follow technical developments and proliferation of know-how in additive manufacturing

The continuing advances in AM technology and the ongoing R&D across civilian and military applications of AM in rockets, space launch vehicles, missiles and UAVs make it necessary that the MTCR partners, particularly through the TEM, continue to follow technical developments in AM and what technical expertise is built up in the commercial spaceflight sector. Of particular relevance to the MTCR will be the further development of rocket, missile and UAV–specific applications of AM and any AM machines that could be identified as specially designed for that purpose.

In addition, AM becoming the production technology of choice for key missile components could have implications for the likelihood of its adoption by missile aspirants and their ability to access and procure the technology and required know-how. The further development of specialized AM machines for printing of energetic materials—particularly concrete applications and deployment of such machines to produce solid-fuel grains for rockets and missiles—should be monitored closely.

Despite the ongoing discussions on AM machines for energetic materials in the Wassenaar Arrangement, the MTCR partners need to stay abreast of significant developments in this area and further explore whether they need to introduce separate targeted controls on AM machines through the MTCR. The development of international standards, such as ISO standards, and other robust industry standards for AM machines and feedstock materials—in particular metallic powders—present another important technical reference point for the MTCR to continuously monitor, as these standards will be key to any potential new list items targeting AM machines or feedstock materials.

Explore and introduce changes to the MTCR annex

The MTRC partners should continue to explore possible control list amendments to explicitly cover AM machines and feedstock materials, based on their monitoring of technical developments in AM. A targeted review of whether the existing controls on materials still cover a sufficient range of AM feedstock and, in particular, new materials for AM applications in rockets, could be an important step to ensure the effectiveness of this aspect of controls. The partners may also want to revisit the changes to controls on lasers in other regimes and the impact this has on whether many of the metal AM machines of the current generation are still affected by these component controls. New controls on energetic materials for applications in solid-propellant rocket motor grains should be considered as more concrete use cases and technical specifications emerge.

Enhance information sharing

A significant share of export controls on AM continues to be the result of the application of catch-all controls. However, unless information on denials issued are shared, the MTCR partners will not necessarily know to what extent catch-all controls are being used and how prevalent sensitive transfers of AM-related items are. Therefore, the information exchange between the partners is of increasing importance in this context. In particular, the partners would benefit from sharing more data and in-depth case studies of instances in which information available to a licensing authority led to the imposition of a licensing requirement using a catch-all control and where denials were issued that prevented transfers of AM machines, feedstock materials, software and technology. This would both improve the awareness among the partners of the use of catch-all mechanisms and contribute to a better understanding of possible proliferation scenarios. More dedicated research and information sharing about actual or potential cases of horizontal and vertical proliferation could better inform where the MTCR partners focus their efforts. As the debate on the sufficiency of catch-all controls in the area of AM (but also more broadly in the context of emerging technologies) continues, increased information sharing and a targeted analysis in this area could inform decisions on whether and when list-based controls might be preferrable.

Engage in targeted inter-regime dialogue and coordination on additive manufacturing

As the review of current controls, proposals and ongoing discussions on AM has shown, many of the key deliberations take place not only—and in the case of AM machines for energetic materials not even primarily—in the MTCR, but also in the Wassenaar Arrangement and to a lesser extent in the NSG. Many of the cross-cutting challenges related to AM, such as ITT controls, are also relevant for and have been discussed separately over years in multiple regimes.[88] For the regimes to avoid problematic control list overlaps with diverging technical parameters, a certain level of inter-regime dialogue and coordination would be desirable. Since the 2018 plenary, the MTCR TEM has a mandate to set up a more structured process for arranging inter-regime informal meetings of experts.[89]

The recent experience with inter-regime dialogue activities has shown that careful planning and formulation of concrete objectives are key to reaching a successful outcome from such dialogues. However, exchanges among smaller groups of technical experts from interested states' delegations across the regimes could in some circumstances be more effective in advancing very targeted discussions in the AM context. They could help select the most relevant topics, formulate goals and identify opportune times for pursuing more inclusive engagements at inter-regime level. The expertise on specialized topics such as AM is often concentrated in individual technical experts and dependant on the experts' background. There is a risk that if this expertise becomes unavailable, for example due to staff rotation or absence of that delegation or expert from a meeting, progress in technical discussions is slowed or even set back.[90] The use of dedicated technical working groups within a regime, or well-planned inter-regime dialogue meetings with concrete goals could be measures to address these challenges. Considering the relevance for both the MTCR and the Wassenaar Arrangement of potential future controls on AM machines capable of

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[88] Brockmann, *Challenges to Multilateral Export Controls* (note 13), pp. 13–15.

[89] Government senior adviser on export controls, Interview with the author, 26 Aug. 2021.

[90] Brockmann, *Challenges to Multilateral Export Controls* (note 13), p. 23; and National regime delegate, Interview with the author, 10 Sep. 2021.

printing energetic materials, a targeted inter-regime dialogue on this topic with the goal of exploring ways to devise mechanisms that effectively control both applications in munitions and in solid-propellant motor grains, could be pursued in the next years.

Issue best practice documents on controls on intangible transfers of technology

Continued advances in AM technology add relevance to the effective implementations of controls on ITT. The MTCR should have a dedicated discussion on how to apply and implement existing ITT controls effectively in the specific context of AM and consider publication of a good practice guide. This could then be used in the formulation of good practices concerning the application of controls in the case of 'making available' controlled technology and the use of cloud computing. Such discussions could draw and build on the significant efforts undertaken by some of the other regimes, the EU and at the national level, to clarify and help stakeholders apply, enforce and comply with ITT controls. Such a guide would also be valuable in ensuring the use of common language, or at least compatibility between the guidance documents provided, to prevent disadvantages from diverging applications and risks arising from a lack of effective implementation and enforcement.

Strengthen stakeholder engagement and awareness raising

The MTCR partners should actively reach out to all relevant stakeholders in the AM ecosystem, including industry, research, academia and service providers. In many cases, this may require an additional mapping effort to identify all relevant stakeholder groups and which of them operate in each state's jurisdiction. This effort could be extremely valuable in creating or ensuring the functioning of engagement channels between national authorities and the different stakeholder groups. The partners could benefit from additional sharing of national experiences and approaches in their outreach to national industry, research institutes and other stakeholders in the AM ecosystem.

About the author

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