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POLICY dialogue BRIEF

Additive Manufacturing and Nuclear Nonproliferation

Shared Perspectives on Security Implications and Governance Options

The capabilities that make additive manufacturing (AM) technology so promising for agile and efficient production could also be used by actors trying to evade export controls. Being able to 3-D "print" components on demand, locally, from digital files, along with a shift in specialized labor, could open new pathways for proliferators developing nuclear weapons and the means of their delivery. In this way, AM technology could intensify challenges for arms control regimes. But the risks are mostly theoretical at this point.

Export control regimes and member states appear to be ahead of the curve in considering the potential risks of AM technology for nuclear proliferation. This assessment reflects three general observations. First, regime and member state technical discussions and proposals on AM technology are already raising awareness of potential issues with controlling it. Second, it is not clear that AM has yet provided alternative proliferation pathways and strategies that are technically and economically advantageous. Third, there is limited data on whether or how AM has been integrated into countries' nuclear production processes. Lacking such data, the current risks of AM for nuclear proliferation appear low.

Given the assessed level of risk, export control regimes and member states still have time to consider how to design controls on AM technology before developments might warrant issuing them. There are a number of ways stakeholders can promote awareness and information sharing in order to detect any emerging risks and be more responsive with governance measures to mitigate them.

This policy dialogue brief summarizes the major themes from a workshop that brought together European and US experts, including technical experts, researchers, industry stakeholders, and government officials dealing with export controls and nonproliferation regimes, to assess the risks and opportunities posed by AM technology and to consider governance approaches.

The brief describes the state of play with advancements in AM technology. It examines how AM might affect nuclear proliferation pathways and strategies. It then explores how export control regimes and other stakeholders can respond

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to the rapid pace of AM development and promote governance measures that mitigate the risks of AM for nuclear proliferation.

Advantages, Limitations, and Applications of Additive Manufacturing

Additive manufacturing is a disruptive technology that is entering a new phase of maturation.

Broadly defined, AM is a "process of joining materials to make objects from 3-D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies."[1] Conventional, subtractive manufacturing often produces an object by removing material through cutting, drilling, and milling to achieve a desired shape. AM machines work from a digital build file to print that object in three-dimensional space. In AM, the properties and material used to make an item are dependent on the process used. For industrial manufacturing metals, there are two principle methods: powder bed fusion and directed energy deposition. In contrast, stereolithography and fused deposition modeling typically use plastics. The full range of materials that can be used across AM machines is staggering. AM processes have been developed that use materials including metals, ceramics, polymers, composites, biological tissue, and energetic materials (e.g., explosives or propellants).[2]

AM ultimately will cause a shift, not elimination, of necessary tacit knowledge and skills for manufacturing.

This technology provides significant advantages for efficient production and supply chains. An AM machine can print a vast range of geometries within its build space, allowing one machine or facility to replace several custom production lines. This enables rapid prototyping by reducing tooling requirements. Users can also print components on demand, locally, and with less wasted raw material, thereby potentially reducing warehousing and transportation requirements. Employed throughout a supply chain, AM can reduce the number of suppliers involved in production and decrease the associated labor market pull. These advantages represent the technology's promise and disruptive economic potential.

Currently, however, applications are somewhat limited. Uptake of AM is driven by areas where it is thought to be cost competitive such as prototyping, small production runs, and for products with complex geometries. It is also a potential solution for supply chain atrophy, as AM can reproduce replacement parts for heritage systems after an original supplier ceases operation.[3] The range of AM applications is expected to quickly grow as AM processes and machines improve, machines print with new materials, and costs decrease.

Firms are already seizing the advantages of developing and employing AM technology. Aerospace and defense industries are using AM to fabricate components for jet engines, missiles, satellites, and other hardware.[4] Civil nuclear industry is at an early stage of investing in the technology.[5] Firms are also producing certified parts for aerospace and medical uses.[6] Investment in research and development is increasing, as industry seeks to scale up the uses of AM and reduce associated costs.[7] Over the next ten years, one workshop participant described AM development goals to include a 90 percent price reduction in integrated controls, development of in-situ quality control, and the ability to print with more materials.

Discussing the market disruption potential of AM technology, workshop participants assessed that AM ultimately will cause a shift, not elimination, of necessary tacit knowledge and skills for manufacturing. As AM use increases in some industries, demand might diminish for certain skills associated with conventional manufacturing. Demand would likely rise for skills involved in computer-aided design, production of AM powders, and operation of AM machines.[8] Participants noted, however, that such labor shifts would be gradual and unlikely within the next five years.

Despite the hype, AM technology does not mean anyone can print anything, anytime, anywhere. The required technical expertise, skill, sunk costs, and access to machines and materials remain considerable barriers to entry. AM processes require skilled engineers and technicians to create the designs, program instructions into a build file, and operate the machines. One workshop participant remarked that developing a new, printed, metal part can be a multiyear research and development project. Given current limitations with the technology, using the same machine to consistently produce the intended component is also challenging. Importantly, there remain significant requirements for postproduction processing like removal of support structures, milling, thermal treating, polishing, and cleaning. These limitations weigh considerably in assessing the proliferation risks from AM technology.

Additive Manufacturing and Nuclear Proliferation

The current risks of AM for nuclear proliferation appear low. There is limited evidence from publicly available sources on whether or how AM has been integrated into countries' nuclear production processes.

Initial discussions of the proliferation potential of AM examined how an actor seeking to acquire nuclear weapons could use AM as a substitute for conventional manufacturing processes. This could, in theory, allow an actor to evade export controls by domestically printing controlled items.[9] Subsequent studies have examined in detail the potential of AM for the manufacture of specific critical components for nuclear weapons and their means of delivery. Such studies examined the utility of AM for the production of:

Uranium Gas Centrifuge Components

- **Uranium gas centrifuge vacuum pumps or rotor tubes, baffles, and end caps.** While feasible, it is unclear if such AM components would meet performance requirements.[10] For these components, studies observe that AM techniques would not be competitive on cost compared to conventional manufacturing techniques that can produce parts at scales necessary for most enrichment facilities. AM might therefore not be an attractive alternative for would-be proliferators.

Nuclear Warhead Components

- **Fissile material cores.** It appears unlikely that a proliferator would use AM to manufacture weapons cores because of the hazardous and difficult radiochemical and metallurgical properties of plutonium and uranium.[11]
- **Neutron reflectors**. It may be possible to produce beryllium-aluminum powders for use in AM processes to manufacture an adequate neutron reflector.[12]
- **High-explosive lenses.** It is possible to use AM to produce shaped high explosives for use in nuclear warheads. Researchers at Lawrence Livermore National Laboratory are using this technology to improve the efficiency of programs to sustain and qualitatively improve warheads in the US nuclear stockpile.[13]

Missile Components

- **Rocket propulsion systems.** AM is attractive for the production of rocket motors because of the complex internal geometry and potential weight savings.[14] NASA, the Department of Defense, and several private firms are actively developing, test firing, and flying rocket engines made with additively manufactured components.[15]

Actors considering using AM technology to produce critical parts for nuclear weapons would need to assess if such processes provide them with a viable acquisitions path. Is the technology good enough for their goals and needs? Secondarily, they would need to consider if AM processes are technically and economically advantageous. Workshop participants noted that for most studied components, current AM processes and machines tend to not be competitive on cost, speed, safety, or performance. A proliferator might see AM as too risky or not an attractive alternative to conventional techniques for acquiring critical components for nuclear weapons. Where AM is competitive, as with rocket-propulsion systems and high explosives, users are quickly integrating AM into production processes. This creates some urgency for controls on AM for the production of missile technology.[16]

Workshop participants briefly discussed the possibility that AM could enable entirely new processes that could circumvent control regimes. Due to the speculative nature of the discussion, participants noted such possibilities as known unknowns.

Recurring Challenges for Strategic Trade Controls

Export control regimes—involving an array of international, multilateral, bilateral, regional, and national mechanisms—exist to prevent the proliferation of weapons of mass destruction (WMD) and the accumulation of armaments by controlling the export of certain technologies and their means of production. AM technology presents concerns for several regimes, particularly the Nuclear Suppliers Group (NSG), the Wassenaar Arrangement (WA), and the Missile Technology Control Regime (MTCR).

Workshop participants discussed how AM technology magnifies existing challenges for these multilateral export control regimes. This conversation drew on several common themes:

Intangible Technology Transfer

The digital nature of AM raises challenges associated with intangible technology transfer. In addition to controlling export of physical goods, regimes work to control the spread of knowledge of how to manufacture control-listed items. This can include technical data (e.g., designs, instructions, and manuals) and technical assistance (e.g., education and skills).[17] AM technology presents challenges for both. Explicit knowledge can be easily transferred as digital design files. Because AM also captures some knowledge and skill in design files and automated tools, tacit knowledge can increasingly be digitally transferred as well.[18] These intangible aspects of AM pose significant challenges for export monitoring, detection, and compliance.

Regime Responsivity to Rapidly Developing Technologies

There is a significant time lag between a regime considering a control and national implementation of it. With the NSG, for example, it can take several years—involving consideration of member state proposals, expert group and member state consultations, annual plenaries, codification of amended control lists under a revised IAEA INFCIRC 254, and issuance of national regulations—between proposal and implementation. Given the pace of innovation with AM and other digital technologies, it seems likely that AM applications and risks could change faster than the NSG could process guidelines on the technology. Other regimes like WA and MTCR face similar time lags, allowing gaps in governance of developing technologies like AM.

Regime Coherence and Harmonization

Dual-use technologies like AM can have relevance for concerns over the proliferation of more than one category of weapons-of-mass-destruction, bringing them under consideration for controls by more than one export control regime. This can create confusion in national implementation if, as recently happened with controls on cryptography technology, a control itself lacks coherence or the major regimes offer different guidelines on what is or is not controlled.[19] If the NSG, WA, and MTCR consider whether or how to control AM, it would be advantageous to promote regime harmonization through issuance of similar guidelines regarding any controlled AM technology.

Equilibrium Between Control and Innovation

In considering controls on emerging technologies, as with AM, regimes must balance goals of controlling proliferation risks while not stifling innovation.

State of Play With Export Control Regimes

The potential proliferation risks of AM are not yet clear enough for regimes to issue new controls covering the technology. In creating a new guideline, regimes try to keep the global costs of imposing control proportionate to the proliferation risks of the controlled technology. For most member states and regimes, the costs of control likely still outweigh the risks for AM. Existing controls and catchall controls have served as viable stopgap measures so far.

AM machines themselves, with one exception, are not presently listed by export control regimes.[20] There are overlaps with existing controls, however, that can apply to AM technology:[21]

- **Production equipment and components.** Industrial metal manufacturing AM machines use high-powered lasers and electron beams to melt and join materials. The WA currently covers some lasers with technical parameters similar to those used in AM machines. Such machines, and any spare lasers to repair them, might be subject to control through existing listings. Controls could also be considered for electron beams.
- **Powders and feedstock materials.** Proliferation-relevant AM processes use powders or wire feedstock as print material. Some proliferation-sensitive materials that could be used in AM—including maraging steel, titanium, high-strength aluminum alloys, carbon fiber, beryllium metal, explosives, and propellants—are included in the control lists of export control regimes. These controls are generally set according to a material's chemical or physical characteristics and can apply whether the material is in powder form or not.
- **Specially designed applications.** Equipment that is specially designed for the production of a control-listed item may itself be subject to regime or national-level controls. In this way, an AM machine that is customized for specific applications could be controlled.
- **Technology transfers.** The information required to produce a controlled item is also controlled. This could include AM build files, operator instructions, and training.

Within the last eight years, regimes and member states have advanced proposals on potential parameters for controls on AM technology. Workshop participants cited example parameters, including those on printable materials and AM machine laser numbers, laser strength, build envelope, build environments, and ambient temperature. These parameters have thus far not been sufficient for designing specific and appropriate controls, and regimes have not agreed on such proposals. Workshop participants noted the difficulty of defining parameters and control levels that would be specific enough to address proliferation concerns without creating expansive export licensing requirements and while being responsive to AM technology development.

Workshop participants discussed how, for items not subject to control or where there is ambiguity in existing controls, catchall controls serve as a flexible solution. Such controls, implemented by the exporter and based on assessments of end use and end user, allow a state to block export of a nonlisted item where the state suspects that the item could be used in an illicit WMD program. For emerging technologies, catchall controls can be preferable to new controls that might be premature, overtaken by technology development, indiscriminate, or stifling for innovation. Given the state of play with AM technology and regime considerations, catchall controls will play a significant role in mitigating proliferation concerns with AM for the foreseeable future. Workshop participants noted that there is need for more analysis on how effective catchall controls are for risks with AM.

Firms have incentives–on intellectual property rights, cybersecurity, brand reputation, and liability–to ensure that AM technology is not diverted or misused for proliferation. They also have incentives to avoid new or reactionary controls that might stifle innovation and competitiveness.

Governance Options: Export Control Regimes

How can export control regimes respond to the rapid pace of development with additive manufacturing technology? Regimes are not yet prepared to formulate controls. Workshop participants suggested that before formulating controls, regimes could use more-detailed assessments of the proliferation risks associated with AM. It would also be easier to formulate controls once ISO and ASTM provide standards defining the technology.

Given the rapid development of AM, regimes appear focused on how to be responsive to any emerging concerns. Workshop participants noted regime interest in:

- Increasing outreach to AM industry stakeholders in order to sensitize them to proliferation considerations with the technology.
- Raising awareness of AM risks with government officials and the expert community. This could include greater outreach, technical exchanges, and information sharing between governments, industry, researchers, and do-it-yourself (DIY) communities to build awareness of any emerging concerns.[22]
- Preparing to fast-track a control listing if the need were to arise.

Workshop participants emphasized the importance of coordination and harmonization between export control regimes if they issue new controls on AM technology. This could include improved information sharing, technical exchanges, and timing coordination between regimes. It might be useful if information on export denials, already shared within regimes, could also be shared between regimes. By improving harmonization between regimes, stakeholders could also create greater coherence or congruence with control listings between regimes such that compliance is more efficient and effective.

Governance Options: Industry

Industry can play a constructive role in promoting responsible use of AM technology and mitigating proliferation concerns. Firms have incentives—on intellectual property rights, cybersecurity, brand reputation, and liability—to ensure that AM technology is not diverted or misused for proliferation. They also have incentives to avoid new or reactionary controls that might stifle innovation and competitiveness.

Workshop participants emphasized the importance of sensitizing industry stakeholders to concerns about intangible technology transfer and any consumer behaviors that raise suspicion. Outreach and exchanges could be useful for raising such awareness. Additionally, while firms do not share customer risk profiles or denials, they could share best practices of how they screen potential customers for compliance risk.

There may be a governance gap with small- and medium-sized enterprises (SME). These companies may lack the resources to stay current on compliance requirements and emerging concerns with AM and proliferation. Workshop participants suggested that larger industry players could share compliance expertise with each other and with SME. As one participant remarked, companies coordinate—not compete—on compliance. Industry associations could also help raise awareness among SME. Workshop participants asked for more clarity on who is in the best position to lead with outreach on compliance with SME.

This governance gap might be a particular concern for AM service bureaus. These are companies that provide on-demand additive manufacturing as a service, allowing customers to print components without the necessary upfront costs or skills.[23] Workshop participants remarked that it might be feasible for a proliferator to contract with a service bureau to print and deliver a controlled item without the bureau being aware of its compliance violation. Outreach to and compliance coordination with these bureaus could be valuable for raising awareness of and being responsive to emerging proliferation concerns.

Workshop participants also discussed whether the interconnectivity of AM technology and cyberphysical manufacturing, more generally, could create new means for detecting and deterring proliferation. Participants discussed how GPS-based "kill switches" in AM machines could help deter diversion of the machines themselves. Some firms have used such disabling features in other machines. A digital thread approach to AM—by which companies maintain a single strand of data from design through end use and product lifecycle—could allow for improved quality control, intellectual property security, nondiversion, and end-use monitoring.[24]

Conclusion

The number of stakeholders involved in the governance of AM technology is expansive. Export control regimes, states, firms, researchers, and DIY communities have constructive roles to play in ensuring that AM is not misused for WMD proliferation. The governance challenge going forward is how to best raise awareness and improve coordination among these stakeholders such that governance solutions can be responsive to this rapidly developing technology. Particular consideration should be given to how stakeholders can play leadership roles within these processes.

The workshop that informed this brief was organized, in part, to open up questions on this governance challenge. It did not arrive at direct answers. It did, however, demonstrate significant demand among participants for more technical exchanges, policy dialogue, and outreach on AM and governance.

This brief is intended to help inform and encourage those activities by capturing expert assessments of the risks of AM for nuclear proliferation, describing the state of play in export controls on AM, and offering perspectives on governance options for regimes and industry.

It is not a complete build file for the kinds of efforts necessary to produce governance options for AM technology. By laying out the dimensions of the conversation, however, this brief attempts to make it easier for others to innovate on these ideas and fuse together the right stakeholders.

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