

3D Printing: A Challenge to Nuclear Export Controls

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Abstract

This paper examines the possibility of manufacturing critical nuclear-fuel cycle technology using 3D printers in order to circumvent export controls. In particular, it examines the possibility that it may soon be possible to 3D-print maraging steel for use in a centrifuge to enrich uranium. The paper finds that while significant technological challenges remain, an expert with access to an off-the-shelf 3D printer, advanced quality control technology and knowledge of centrifuges should be able to achieve this. Using these results the paper discusses the need for export controls of 3D printing technology and provides export control recommendations for printers on the basis of their specifications.

Keywords

Additive manufacturing, 3D printing, nuclear, export controls

Introduction

Additive manufacturing has been hailed as a revolutionary technology that promises to begin a second industrial revolution, transforming supply chains and allowing the manufacture of items of great complexity at the same cost as more simple items.² Whatever the effect on economies may be, the effect on export control regimes may be profound: a digital file transfer, such as an email attachment, may provide the complete information to produce a physical item, provided one has the 3D printer and the material.³ Published work in security studies up to this point has not systematically compared current export controlled items with the technical specifications of today's 3D printers, with the exception of a single overview.⁴

The reasons that current export control regimes have not included 3D printing technology to this point are unclear. The most likely explanation is that the technology is not considered to be mature and that it is

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² "The Third Industrial Revolution," *The Economist*, April 21, 2012.

³ Stewart, Ian. "Export Controls and 3D Printing," Project Alpha, June 7, 2013. <https://www.acsss.info/news/item/236-export-controls-and-3d-printing>.

⁴ Christopher, G.E. "3D Printing: Implications for Non-Proliferation," Paper delivered at the Proceedings of the ESARDA 37th Annual Meeting, Manchester, UK, 18-21 May, 2015, pp. 636-644.

assumed to be some years away from being a viable alternative to traditional, or subtractive, manufacturing. Yet, a number of developments suggest that the technology could be viable earlier than anticipated.

3D printing is already being used in the nuclear industry: at Sellafield, 3D scanning and printing technologies have been used to manufacture metal lids for low-level waste containers in order to move waste around the site.⁵ In India, at the Raja Ramanna Centre for Advanced Technology of the Department of Atomic Energy, using their Laser Additive Manufacturing System, nuclear components have been fabricated for the reprocessing plant and the Prototype Fast Breeder Reactor at IGCAR.⁶ In addition, the aerospace industry is already using the technology; Boeing, in 2014, patented the first 3D-printed part, a housing for a compressor inlet temperature sensor, which will be used in the BE90-94B jet engine on Boeing 777 aircraft.⁷ Finally, in May 2015, details emerged of a miniature 3D printed jet engine from GE that can rotate at 33,000 rpm—a similar magnitude to that required for uranium-enriching centrifuges.⁸ Both the nuclear and aerospace industries demand high-quality, high-strength parts; the parallel provides a strong indication that 3D printing technology could soon be applicable to the production of export controlled items used in the nuclear fuel cycle.

Additive Manufacturing

Additive manufacturing (AM) is the catchall phrase for 3D printing and associated technologies. This includes scanning technologies, which create digital copies of physical objects that can be used for 3D printing. The digital design files, or Computer Aided Design (CAD) files are created in a standard format and various software packages can then be used to alter the designs. Software packages are also used to slice the files into a series of layers to prepare for printing. The production part of the technology, 3D printing, is in fact a ‘big tent’ of different technologies that includes plastics and metal, along with biological tissue, chemicals and food. Most of this is not relevant to any discussion of nuclear export controls and the only interesting technologies in this case are those that use metals and plastics.

The most flexible technologies are the metal printing technologies of Selective Laser Sintering (SLS) and Selective Laser Melting (SLM). Direct Metal Laser Sintering (DMLS) is also referred to in the literature and is similar to SLS.⁹ In these technologies, metal powder is printed in layers and a Computer Numerically Controlled (CNC) multi-axis laser with high power fuses the particles within each layer together, along with fusing each new layer to the previous one. In SLS, only the boundaries of the powder are melted and fused together; whereas in SLM the powder is completely melted, allowing for more dense material.

The layers themselves are formed by two different methods. In the first method, each layer is a ‘bed’ of powder and, after each layer has been scanned by the laser, the platform lowers and a roller places a new bed of powder which acts as a supporting structure. In the second technique, the structure is ‘constructed’ from the ground up in the manner of a building.

⁵ Powley, Tanya. “Sellafield Hopes to Allay Cost Fears with 3D Printing,” *Financial Times*, May 11, 2014.

⁶ Adora, Amit D. “DR. R. Chidambaram Indian’s Premier Nuclear Scientist Talks About 3d Printing in India,” *Smart Printing*, last modified February 22, 2015, <http://www.smartprinting.co/3d-printing-india/dr-r-chidambaram-indians-premier-nuclear-scientist-talks-about-3d-printing-in-india/>.

⁷ Koreis, Rocke Robert. “Three Dimensional Printing of Parts,” United States Patent: 51625781, September 5, 2013

⁸ Szondy, David. “GE Fires Up Fully 3D-printed Jet Engine,” *Gizmag*, last modified May 13, 2015, <http://www.gizmag.com/ge-fires-up-all-3d-printed-jet-einge/37448/>.

⁹ Grünberger, Thomas and Domröse, Robert. “Direct Metal Laser Sintering,” *Laser Technik Journal 12:1*, (January 2015): p. 45-48.

A large number of metals are available for 3D printing, including: stainless steel, titanium, Inconel (a nickel-chromium alloy) and maraging steel: a class of low carbon, high-nickel, stainless steel in the ‘martensic’ phase that has been precipitation hardened or ‘aged’; hence the term maraging, from martensic aging. Of these, maraging steel is the most relevant material to the nuclear fuel cycle as it has the required properties for use as components in a centrifuge to enrich uranium; specifically, the rotor, baffles and endcaps. Of these, the rotor is the most difficult to produce and has the most stringent requirements for material properties. Concerning high-strength materials, only high-strength aluminium, maraging steel and carbon fibre are currently export-controlled for their potential for use in centrifuges.

3D Printing of Maraging Steel

Printing high strength materials that have similar characteristics to those traditionally produced for nuclear purposes requires a detailed understanding of the manufacturing process. It is not quite as simple as clicking ‘print’ after one has obtained a CAD file with the required geometry. The printing material, maraging steel powder, has the same bulk chemical composition as traditionally manufactured maraging steel. This corresponds to US 18% Ni Maraging 300, European 1.2709 and German X3NiCoMoTi 18-9-5; these are typically grades that would be export controlled when traditionally manufactured. For both traditionally manufactured and printed steel, in a post-processing stage, the material must be held at a high temperature for two to three hours whilst the metal undergoes the transition from the more brittle and less hard austenite phase to the stronger martensite phase.

Independent of the post-processing steps, there are many reasons why the mechanical properties of 3D-printed maraging steel would differ from that traditionally manufactured. A large volume of technical literature dedicated to understanding the causes of these differences has emerged. Advances in understanding the 3D printing process have led to production of high-quality maraging steel with comparable characteristics to the traditionally manufactured material.^{10,11} Yet, there remain key questions over the properties of 3D-printed maraging steel. The 3D printing process involves the use of a high-powered laser to melt or partially melt the powder, which in turn involves high thermal gradients—meaning heat from the laser will dissipate rapidly. This can introduce residual stresses into the material.¹²

For the 3D-printed material, however, the single most important parameter for macro-mechanical properties is the relative density.¹³ A density close to 100%, where few pores have formed in the printing process, provides the best thermal conductivity, ductility, yield strength and fracture toughness. This is determined by the processing parameters: powder feed rate, laser scan speed, laser power, scan spacing, beam diameter as well as scanning sequence, scanning atmosphere and the parameters chosen in re-melting completed surfaces.¹⁴ The high thermal gradient can also influence this. The initial powder quality (size distribution, elemental composition and temperature-dependent powder properties) also has a significant effect on the material properties.¹⁵ Another outstanding issue is the noted reversion of

¹⁰ Yasa, Evren; Deckers, Jan; Kruth, Jean-Pierre; Rombouts, Marleen and Luyten, Jan. “Charpy Impact Testing of Metallic Selective Laser Melting Parts,” *Virtual and Physical Prototyping* 5:2, (June 2010): pp. 89-98.

¹¹ Casalino, G; Campanelli, S.L.; Contuzzi, N. and Ludovico, A.D. “Experimental Investigation and Statistical Optimisation of the Selective Laser Melting Process of a Maraging Steel,” *Optics & Laser Technology*, Vol. 65, January, (2015): pp. 151-158.

¹² C. Casavola, S. L. Campanelli, and C. Pappalettere, “Preliminary investigation on distribution of residual stress generated by the selective laser melting process,” *C, J. Strain Analysis* 44:1, (January 2009): pp. 93-104.

¹³ Kruth, J.P. et al. “Part and Material Properties in Selective Laser Melting of Metals,” 16th International Symposium on Electromachining (ISEM XVI), Shanghai, China, April 19-23, 2010.

¹⁴ Ibid.

¹⁵ T. B. Sercombe, “Sintering of Freeformed Maraging Steel with Boron Additions,” *Materials Science and Engineering: A* 363, 1-2, (December 2003): pp. 242-252.

3D-printed maraging steel into the austenite phase from the martensite after age hardening;¹⁶ this undermines a material's strength and is not seen to occur in traditional manufactured maraging steel.¹⁷ Considering the time it would take to print a typical centrifuge rotor with current technology is an important benchmark for current applicability to the technology. An estimate of building rate for a typical metal printer is between 2-20 mm³/s.¹⁸ Using an open source estimate of a centrifuge volume¹⁹ it would take about between 1.5 to 15 days to produce a centrifuge rotor at this rate of printing. Neglecting machine handling time and maintenance etc., ten machines working in parallel would take a time between two weeks to half a year to produce 100 centrifuge rotors, with estimates likely to be on the conservative side due to the quality requirements of the product. Efforts are being made, however, to design multi-laser printers that significantly reduce these build times.²⁰

Challenges to producing 3D printed maraging steel with properties comparable to traditionally manufactured maraging steel are being gradually overcome. Not only that, but these problems are being solved by understanding the 3D printing process, by parametric refinement of existing procedures, not the introduction of new hardware. It is entirely conceivable that the current generation of 3D printers could be used to manufacture key components of one of the sensitive and controlled technologies in the nuclear fuel cycle. Yet, developing production of beyond-the-state-of-the-art materials requires a detailed understanding of the laser-powder interaction that involves software simulation and increased expert proficiency in knowledge of the process. Would 3D-printed components be fit-for-purpose and are we likely to ever see 3D-printed centrifuges?

Illicit procurement by states has always been a flexible process and states have shown a willingness to adapt, as has been shown in a study on Iranian nuclear technology procurement practices.²¹ However, with centrifuges, it must be stressed that the mechanical requirements of the materials are quite strict. To be able to print parts that are fit-for-purpose, access to advanced quality control machinery, such as scanning electron microscopes, is required. This places a high threshold on the knowledge and advanced machinery needed to print centrifuge rotors from an off-the-shelf printer.

It is worth discussing what other items from the Nuclear Supplier's Group (NSG) trigger list and dual use list are suitable for 3D printing. Not any item that is of interest due to its chemical composition is a suitable candidate for 3D printing; this includes various materials such as uranium, plutonium, nuclear grade graphite, zirconium and beryllium. Items with many components, including some parts with special materials or complex moving parts with electronics are also not (currently) suitable: this includes items such as frequency inverters, pressure transducers, lasers, hot cells and remote manipulators. We are therefore left to examine other materials to use for centrifuge manufacturing including carbon fibre and aluminium, as well as plastics that are resistant to the highly corrosive UF6.

For what concerns aluminium, it can be 3D printed, although the ultimate tensile strength, the only criterion other than geometry that has export-control limits, is well below the specification for use in

¹⁶ Yasa, Evren; Deckers, Jan; Kruth, Jean-Pierre; Rombouts, Marleen and Luyten, Jan. "Charpy Impact Testing of Metallic Selective Laser Melting Parts," *Virtual and Physical Prototyping* 5:2, (June 2010): pp. 89-98.

¹⁷ Ibid.

¹⁸ "EOSINT M 270," EOS, last modified August 2, 2012. http://dmlstechnology.com/images/pdf/EOSINT_M_270.pdf.

¹⁹ United States Senate, "Report of the Select Committee on Intelligence on the U.S. Intelligence Community's prewar Intelligence Assessments on Iraq", U.S. Senate, July 9, 2004. See page 109 for specifications of the Beams centrifuge rotor which has a volume of about 2600 cm³.

²⁰ Hipolite, "Borealis Project Looks to Create Large, Super Fast 3D Metal Printers With Multiple Laser Technologies in One," 3dprint.com, last modified July 1, 2015, <http://3dprint.com/77915/borealis-project-3d-printers/>.

²¹ Stewart, Ian. J., Gillard, Nick and Druce, John. "Iran's Illicit Procurement Activities: Past, Present and Future," Project Alpha, July 24, 2015, <https://www.acsss.info/proliferation/item/428-iran-s-illicit-procurement-past-present-and-future>.

centrifuges.²²

Printing Carbon Fibre

Carbon fibre, a material commonly used for centrifuge rotors, has recently been 3D-printed. The Mark One printer, available from the 3D printing company Markforged for around \$6,000, can print carbon fibre, fiberglass, Kevlar and nylon.²³ Carbon fibre rotors are traditionally manufactured using filament winding machines, which are currently export controlled, as are the fibres themselves. Unlike maraging steel therefore, the material used by the machine to print is in this case export controlled. The filament winding machines, used to make centrifuge rotors, are designed for cylindrical geometries. Carbon fibre 3D printers may be used to print this geometry, but it is unclear if the printed material will meet the strict geometric quality requirements. It is also not clear if “printed” carbon fibre would meet mechanical requirements. As carbon fibre rotors are difficult to manufacture, it is unlikely that printing technology presents a viable manufacturing option. Nevertheless, development of this technology should also be monitored.

Corrosion Resistant Plastics

The interest in plastics, rather than stemming from use in the moving parts of centrifuges, stems from the corrosion resistance of Fully Fluorinated Materials (FFM). Fluoropolymers, such as polytetrafluorethylene (PTFE), polythene where the hydrogen is replaced with fluorine, are common examples of such materials. However, PTFE and other fluoropolymers do not melt when heated so would not be suitable for 3D printing using the Fused Deposition Modelling (FDM) technology, which is commonly used for plastics. Other FFM such as FEP, PFA, PCTFE and Vinydene fluoridehexafluoropropylene suffer from the same problem. No plastic FFM exists at the moment that would be suitable for 3D printing. Consequently, any 3D-printed UF6-resistant plastic would have to be developed.

Manufacturing items with the current generation of printers is both expensive and time consuming; a metal printer costs around \$750,000 and printing large items such as centrifuge rotors with high quality specifications could take 1-2 days. Expensive additional hardware would also need to be purchased for quality control. The minimum diagnostics set-up for basic metallurgical analysis of test materials produced by SLS or SLM, and assessment in their range of application includes: morphological analysis by means of scanning electron microscopy, elemental analysis by means of X-ray spectroscopy and mechanical analysis by means of an indenter and stress strain curves. To traditionally manufacture using a flow forming machine costs around \$1m for the machine itself and takes a few minutes.²⁴ Obtaining the pre-form tubes and providing sufficient quality control will take a lot longer, but similar steps would be required for printed parts.

Relevance of 3D-printing to Weaponisation

To what extent should we be concerned about 3D printing of delivery systems? An extensive amount of open-source work has already been performed on the technical dimensions of the little-boy gun type device, even by members of the public.²⁵ However, any large explosive device is a clear security threat

²² “EOS Aluminium AlSi10Mg Data Sheet,” EOS, last modified June 18, 2014. https://ip-saas-eos-cms.s3-eu-west-1.amazonaws.com/public/8837de942d78d3b3/4e099c3a857fdddca4be9d59fbb1cd74/EOS_Aluminium_AlSi10Mg_en.pdf.

²³ “The Mark One,” Markforged, accessed July 22, 2015. <https://markforged.com/mark-one/>.

²⁴ “Economics of Light Weighting Steel Wheels Through Flow Forming”, Auto Steel, last modified 10 October 2011. <http://www.autosteel.org/~media/Files/Autosteel/Great%20Designs%20in%20Steel/GDIS%202010/14%20-%20Economics%20of%20Light%20Weighting%20Steel%20Wheels%20through%20Flow%20Forming.pdf>.

²⁵ Samuels, David. “Atomic John,” *New Yorker*, December 15, 2008.

and should be controlled as strictly as possible. Special nuclear materials are under export controls and cannot be 3D printed. We can take comfort from the fact that any nuclear device serves no purpose without fissile material.

A similar argument can be made for missile systems: to what extent is it realistically possible to use 3D printing to bypass missile export controls? Raytheon has recently manufactured most parts of a guided missile through 3D printing.²⁶ This indicates that the Missile Technology Control Regime (MTCR) may benefit from a similar analysis to that performed in this paper: to look at components in critical areas of ballistic missile technology that may be manufactured using 3D printers in order to circumvent export controls.

From the legal perspective, the framework is still being put in place to cope with a world in which 3D printing is common.²⁷ Copyright may be placed on the written word, and ideas may be patented, but you cannot copyright objects unless they have an individual design. US copyright does not extend to "...any idea, procedure, process, system, method of operation, concept, principle, or discovery, regardless of the form in which it is described, explained, illustrated, or embodied in such work."²⁸ Therefore, it would not be possible to copyright a design such as a cylinder. The implication of this for non-proliferation, where this paper envisages an illicit procurement channel of centrifuges via maraging steel printing, is unclear.

Existing Hardware

It seems increasingly clear that 3D printing of maraging steel using the current generation of printers, for use in a uranium-enrichment centrifuge is plausible. Export controls for high-precision multi-axis CNC machinery are already in place in WMD export controls, but these do not yet cover 3D printers. Printers that are currently maraging-steel-capable are limited to a small number, including: the EOS M series²⁹, the Matsuura Lumex Avance-25,³⁰ Renishaw AM250,³¹ SLM 280 or SLM 500³² and Concept Laser machines.³³ Any export controls for 3D printers should be constructed to include these models, whilst excluding others that are not capable of printing high-strength maraging steel. All of the above machines are 5-axis tools operating 200 W or 400 W fibre lasers. The build volumes are all similar: around 250 x 250 x 325 mm³. The thickness of each powder layer varies, but the upper limit is 100-200 μm . The laser focus diameters, the size of the beam that fuses the powder together, are in the range 50-200 μm . All these machines are capable of operating the build chamber in an inert atmosphere, which is also a requirement to print maraging steel.

Towards Export Controlling 3D Printers

Further examination of 3D printing technology is clearly required to completely understand the class of

²⁶ "To Print a Missile: Raytheon Research points to 3-D printing for tomorrow's technology," Raytheon, last modified July 13, 2015. http://www.raytheon.com/news/feature/3d_printing.html.

²⁷ Mendis, D.; Secchi, D and Reeves, P.A. "Legal and Empirical Study into the Intellectual Property Implications of 3D Printing," Project Report. (London: Intellectual Property Office, 2015).

²⁸ Herzfeld, Oliver. "Protecting 3D Printing Designs and Objects," *Forbes*, May 5, 2013. <http://www.forbes.com/sites/oliverherzfeld/2013/05/29/protecting-3d-printing-designs-and-objects/>.

²⁹ "EOSINT M 270", EOS, last modified August 2, 2012. http://dmlstechnology.com/images/pdf/EOSINT_M_270.pdf.

³⁰ Matsuura, "Matsuura Lumex 25 - Additive Manufacturing Machine", innovatetec, last modified 2015. <http://innovatetec.com/matsuura-lumex-avance-25-additive-manufacturing-machine/>.

³¹ "Renishaw AM250", Renishaw, accessed July 22, 2015. <http://www.renishaw.com/en/am250-metal-additive-manufacturing-3d-printing-system--15253>.

³² "SLM 500", SLM Solutions, accessed July 22, 2015. http://www.stage.slm-solutions.com/index.php?slm-500_en.

³³ "Concept M3 Linear Technical Data", Concept Laser, last modified March 21, 2012. http://www.yingfeng.com.hk/image/RP-CL/101120_M3_English_view.pdf.

printers that are maraging-steel-capable. However, comparison with the export controls guidelines for multi-axis machine tools for cutting³⁴ under the NSG dual use list for “Test and Production Equipment” is useful. These guidelines control machines with two or more axes within specified positioning accuracy, specifically covering various types of machines.

Laser technology encompasses an enormous variety of instruments with a wide range of uses. However, all lasers used in 3D printers are fibre lasers, which significantly narrows the range of focus when discussing applicable laser technology in 3D printers. To define precise specifications for export control of 3D printers yet more information is required. We can discuss the key parameters and likely ranges to consider controlling. We suggest the key parameters to consider are: laser power, number of positioning laser axes, laser positioning accuracy, laser beam focus diameter, laser scan speed, layer thickness, machine build volume and the ability to print in an inert atmosphere.

Export controls are already in place for lasers that could be used to enrich uranium by laser isotope separation techniques such as AVLIS, MLIS and CRISLA. These laser enrichment techniques include the use of multiple lasers operating at specific wavelengths, pulse durations and powers. The export control provision that covers these lasers could perhaps be extended to cover lasers that could be used in 3D printers. However, this would essentially amount to export controlling the key components of 3D printers to be built. The current generation of 3D printers that print maraging steel are an expensive advanced technology that may prove difficult to construct.

Laser power for printers discussed earlier is consistently 200/400W. It is not clear whether a lower-power laser would have sufficient energy density to melt the metal, but the industry choices certainly show a common design preference. The number of laser axes to control would likely be lower than five; manufacturing a cylindrical geometry should be possible with two axes only. The technical literature indicates that lower laser accuracy would produce parts below required mechanical specifications due to the lower material density.³⁵ Control over the scan speed is also a key parameter required to produce high-strength stainless steels. The build volume issue is far simpler to understand as it would be controlled on the basis of being able to produce useful parts. Maraging steel is export controlled if material exceeds the mechanical strength specification where all dimensions are above 75 mm; this would likely cover all commercially available printers.

Current Export Controls

Knowledge of how to print quality high-strength metals is continually advancing and available from open sources.³⁶ The literature on manufacturing maraging steel using subtractive manufacturing is also open source.³⁷ Tacit knowledge also plays an important role in the manufacturing process for maraging steel, as is the case for nuclear weapons-related technology.³⁸ However, access to this technology is limited: the flow forming machines required to manufacture by this method are export-controlled, as are multi-axis milling machines.

The export control of multi-axis subtractive manufacturing machinery sets a precedent for export control of 3D printers that similarly use multi-axis lasers to print high-strength materials. Any export

³⁴ “NSG Guidelines Dual Use List, June 2013,” Nuclear Suppliers Group, last modified June 2013, Paragraph 1.B.2.

³⁵ Yasa, Evren; Deckers, Jan; Kruth, Jean-Pierre; Rombouts, Marleen and Luyten, Jan. “Charpy Impact Testing of Metallic Selective Laser Melting Parts,” *Virtual and Physical Prototyping* 5:2, (June 2010): pp. 89-98.

³⁶ Casalino, G; Campanelli, S.L.; Contuzzi, N. and Ludovico, A.D. “Experimental Investigation and Statistical Optimisation of the Selective Laser Melting Process of a Maraging Steel,” *Optics & Laser Technology*, Vol. 65, January, (2015): 151-158.

³⁷ Hirschhorn Joel S. and Westphal, David A. “A New Approach for the Production of Maraging Steel P/M Parts,” *Modern Developments in Powder Metallurgy*, (1971), pp. 481-490.

³⁸ MacKenzie, Donald and Spinardi, Graham. “Tacit Knowledge, Weapons Design and the Unvention of Nuclear Weapons,” *American Journal of Sociology* 100:1, (July 1995): pp. 44-99.

control guidelines should be based at least partially on the laser system, including on the following criteria: number of axes, laser power, and precision which govern the complexity, precision and strength of the manufactured item. These parameters should be specified as to restrict the final quality of materials that can be printed.

As for the control of the associated technology, it may be thought prudent to export control CAD files that fulfill particular requirements. If the product that one is trying to protect is a centrifuge rotor then this results in attempting to export control CAD with cylindrical geometries; an obvious non-starter. Other more complicated geometries where 3D printing could be applicable would be more suitable for export control.

To consider previous attempts to control 3D printed designs the printed gun is an illustrative case. To control CAD files for 3D-printed guns has been a huge challenge for US law enforcement. When the first handgun from Defense Distributed, dubbed “The Liberator”, was designed, the CAD files were made available through the company’s website. Before the US Department of Defense ordered their removal, the designs were downloaded over 100,000 times³⁹. The CAD file could then easily be shared privately via email or posted on numerous file-sharing websites, including those on the dark web. Whilst the level of interest in this handgun CAD represents the popularity of firearms and resistance to government regulation in the United States, it also highlights the challenge in controlling any CAD file. A nuclear fuel cycle related CAD would not likely have such a high level of popularity. Yet even if control over sensitive designs could be obtained, it is worth considering the likelihood of our being able to protect designs from cyber-crime⁴⁰, insider threat⁴¹ or state-sponsored cyber-attack.⁴² However, we can again point to the fact that, at least for the nuclear fuel cycle, the items that are most likely to be 3D-printed have simple geometries so controls over the CAD are impractical. Export controlling weaponisation is a different matter however.

Conclusion

We are currently in an unconstrained era of export controls on 3D printing technology. The manufacturing base for advanced additive manufacturing, for now, is in North America, Europe and Japan. It seems that the difficulties in printing maraging steel to meet the requirements for use in centrifuges are gradually being overcome. It should therefore be in the interests of the EU and its Member States, the United States and Japan to introduce export controls for 3D printers based on the parameters discussed above. The NSG should also introduce corresponding controls. At present, 3D printing constitutes an unmanaged potential proliferation pathway. The technical community should work together with policy makers and the wider non-proliferation community to address this issue as soon as possible.

Acknowledgments

Thanks to Nick Gillard and Dominic Williams for a discussion on flow forming machines.

³⁹ Preston, J. “Printable-Gun Instructions Spread Online After State Dept. Orders their Removal,” *New York Times*, May 10, 2013.

⁴⁰ “Former U.S. Nuclear Regulatory Commission Employee Charged with Attempted Spear-Phishing Cyber-Attack on Department of Energy Computers,” FBI, May 8, 2015. <https://www.fbi.gov/washingtondc/press-releases/2015/former-u.s.-nuclear-regulatory-commission-employee-charged-with-attempted-spear-phishing-cyber-attack-on-department-of-energy-computers>.

⁴¹ Warren, Mark. “Modern IP Theft and the Insider Threat,” *Computer Fraud & Security* 2015:6, (June 2015), pp. 5-10.

⁴² Walker, Paul. “Law of the Horse to Law of the Submarine: The Future of State Behavior in Cyberspace,” *Cyber Conflict: Architectures in Cyberspace (CyCon)*, 7th International Conference, Geneva, Switzerland, 2015, pp. 93-104.