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IS THREE-DIMENSIONAL (3D) PRINTING A NUCLEAR PROLIFERATION TOOL?

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I. INTRODUCTION

Three-dimensional (3D) printing is one of the most exciting new manufacturing technologies of the last three decades. It has moved quickly from a niche technology to a serious and important manufacturing process. Many industries are beginning to rely on 3D printing, especially those producing large numbers of identical parts. On an industrial scale, it can be economical to carry out hundreds or thousands of repetitive operations with little skilled human input. Alternatively, 3D printing can be used to make detailed models of complex industrial or architectural shapes for planning and quality purposes, for example, a printed version of a large building in great detail. Most of the applications are peaceful and ordinary in scope, but a tiny fraction of reports has mentioned applications such as plastic firearms, which can be produced in readily available printing systems and may be difficult to detect in airport scanners, for example.[1]

The possibility of misuse of 3D printing has led to the serious question of whether 3D printing could be exploited to aid the proliferation of nuclear weapons, either by making fissile materials or the weapons themselves. Some of the articles are pure fantasy, only for popular consumption.[2] However, there have been some very in-depth and technically rigorous papers

[1] Tirone, D. C. and Gilley, J., 'You can print your own guns at home. Next it will be nuclear weapons. Really', 7 Sep. 2015, Monkey Cage (blog), *Washington Post*, <https://www.washingtonpost.com/blogs/monkey-cage/wp/2015/09/07/you-can-print-your-own-guns-at-home-next-it-will-be-nuclear-weapons-really/>.

[2] 'Could 3D printing trigger World War 3? Expert warns technology could allow rogue states to manufacture nuclear weapons', *Daily Mail*, 21 July 2016, <http://www.dailymail.co.uk/sciencetech/article-3698033/Could-3D-printing-trigger-World-War-3-Expert-warns-technology-allow-rogue-states-manufacture-nuclear-weapons.html>.

SUMMARY

Three-dimensional (3D) printing is an evolving technology that can produce objects from plastics and metals. It works by building up layers of material hardened by a laser. The process is driven by computers that generate the enabling laser beams from highly detailed computer drawings and models. The parts that can be produced can be accurate copies of the enabling drawings, but they will have different material properties from items produced by traditional manufacturing such as casting, forging and machining.

Popular press and more serious analysts have speculated that a complete nuclear weapon or gas centrifuge could be built using a 3D printer, detailed and accurate computer drawings, and appropriate materials. However, very specialized starting materials such as plutonium powder or high explosives would be required and are not readily available. In fact, there are many barriers to successfully manufacturing a complete nuclear weapon and in most cases 3D printing gives no advantage to a non-state proliferator, or even a state, trying to clandestinely build a weapon. This paper examines the technical limitations of the technology and makes suggestions for how European export regimes can build up and maintain an awareness of cases where it could enable the bypassing of nuclear proliferation barriers.

ABOUT THE AUTHOR

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on the subject, such as one by Christopher Grant from King's College London.[3]

The current paper examines the possibilities of either a state or non-state actor using 3D printing in nuclear proliferation. The main conclusion is that it may have a role in producing miscellaneous supporting parts in nuclear industrial systems, but the idea of 3D printing a complete nuclear weapon is not credible in any way. There are several places, however, where 3D printing could provide an alternative way to build nuclear weapon components and these are described below. The possibility of producing components for specialized machines such as gas centrifuges is certainly possible, but at best it is an alternative way of producing non-critical components and not an enabling technology that bypasses normal export controls. Printing of important components in the uranium production process is a possible enabling capability.

There is also a difference between state and non-state actors. Many states that might wish to produce nuclear weapons clandestinely may have significant financial and industrial resources. 3D printing will be only one of the many tools available to them versus traditional manufacturing technologies and it may offer no advantages. In the case of nuclear weapons, the number of units to be produced is likely to be small—perhaps a dozen units, such as North Korea is assessed to have today. On the other hand, a uranium enrichment plant, such as a centrifuge plant, requires thousands of duplicate components. It could be that economy of scale makes an examination of 3D printing interesting, especially to establish capabilities limited by export control regulations.

Non-proliferation policy does not usually credit non-state actors with being interested in the massive industrial enterprise of producing nuclear materials: plutonium or uranium. Normally theft or diversion of small amounts of nuclear material is assumed. Non-state actors are also expected to have limited goals in assembling a nuclear stockpile. For example, a single nuclear weapon may be adequate to achieve terrorist goals. Substituting a new technology—3D printing—and developing it to make one or a few units greatly complicates the process rather than helping it. Nevertheless, this paper considers one case where 3D printing could offer an advantage to a non-state actor.

[3] Christopher, G., '3D printing: a challenge to nuclear export controls', *Strategic Trade Review*, vol. 1, no. 1 (Autumn 2015), <http://www.str.ulg.ac.be/wp-content/uploads/2016/01/STR_01_full.pdf>.

II. 3D PRINTING

3D printing is a complex and rapidly evolving technology. It is already widely used in low-technology activities such as jewellery manufacture, toys and plastic components for consumer and industrial goods. Initially, 3D printing was developed for producing items from plastics and resins but it has advanced to making parts from metals. Today, 3D printing is increasingly used to make sophisticated metal parts for industrial and aerospace applications. It is often used to produce items of complex shape and material. In some cases it can even print multiple parts at the same time that are not physically connected, for example, printing a removable screw in a threaded hole. Within this technology, the production of metal parts for nuclear proliferation is the primary cause for concern.

3D printing is an alternative to traditional subtractive manufacturing. In subtractive manufacturing, the operator begins a project with a work piece that is reduced in size by machining with lathes, mills, grinders and other removal techniques, until enough material has been removed to produce the final shape. If the goal is to produce a gear, for example, the starting piece would be a disk into which teeth are cut and ground, a central hole for a shaft is drilled and other cuts may be made. There may be numerous industrial steps, such as forging and heat treatment, before actual shaping begins. Subtractive manufacturing produces potentially large amounts of scrap and waste that need to be recycled or thrown away. An artwork analogy is that an artist starts with a block of marble and chips away at it until there is a finished piece.

The opposite analogy is clay sculpture, where the desired piece is built up by adding layers of clay until the desired shape is produced. This is correctly referred to as additive manufacturing. 3D printing is much more analogous to this type of manufacturing. In 3D printing, a part is produced by adding layer after layer of the desired material, until a finished part emerges. As such, 3D printing should not produce as much waste as subtractive manufacturing, because the operator only adds the material necessary to the piece.

The way this is done is simple in concept. The operator begins with a thin layer of powdered material in the work chamber. A laser beam, controlled by a computer, scans across the powder and melts the powder into a solid. The beam turns on and off as it scans across the powder so that the solid is only

produced at the desired point. The beam passes over the powder bed repeatedly, from one side of the bed to the other, until it has passed over every point on the tray. Next, another thin layer of powder is added and the laser process is repeated, turning on and off at different times so that the solid object takes a 3D form.

In the gear analogy, the 3D printing laser scans across a bed of powder roughly the size of the finished product. The laser beam is only turned on when a gear tooth or central disk is desired and turns off for the empty space beyond the teeth or the central shaft hole. The general form of the gear is produced by thousands of passes, back and forth over the bed, in vertical and horizontal directions. This rasterizing process is the same as in a television cathode ray tube, where the beam scans across the television screen. In printing, the laser melts and adds a tiny amount of new material in each pass. The thickness of the gear piece is produced as layer after layer of powder is added and melted in repeated passes.

This is all made possible by the power of computers and computer-aided design. For industrial use, the operator will design the desired part in a computer using Computer Assisted Design (CAD) programmes. The part can be very complex and not just the simple disk-shaped gear considered above. If the part is made of a low-melting point material, the laser does not need very high power.

For other applications, such as artwork, a computer model of the desired part can be made by hand or by techniques such as laser scanning a prototype object. The shape and features of the model are stored in the computer and are used to drive the laser to turn on and off during its thousands of passes over the layers.

A good example of this is the production of chess pieces. Scanning layer after layer of powder, driven by the computer, the printer can be used to produce a chess piece as complicated and asymmetrical as a knight. This can be done cheaply and quickly using low melting point plastics. The part can be printed hollow to save on weight and cost. The system can also be extremely flexible. By changing the computer programme, the 3D printer can print knights and then switch to rooks very quickly. By changing the powder, the operator can easily change the colours from black to white or vice versa. Clearly this is a useful facet of the technology in low-technology applications.

Rapid prototyping

A very important application of 3D printing is making prototypes rapidly. Before engineers build expensive components using metals and subtractive manufacturing, they can use 3D printing to produce trial parts to study physical aspects of the prototype. Are all the dimensions correct? Do multiple parts fit together properly and can they be reasonably assembled? The finished part can also be displayed to potential investors to help them understand the features of the end product. Furthermore, 3D printed models can be used as training devices.

This capability is very useful to engineers or amateurs with little real experience. In theory, an entire model of a gas centrifuge and all its components could be made and assembled with prototype metal parts, but it would not survive the rotational stresses of a real centrifuge. It could even be made of plastic parts in order to study assembly and fit.

For example, in the 1990s Los Alamos National Laboratory in the United States printed a complete nuclear warhead using only plastic parts of different colours. Key components were programmed to be removable. The model was intended for showing decision makers how the final warhead would appear. It could also be used to train workers to assemble and disassemble the components. Of paramount importance was having a safe and lightweight model, so that it was easy to transport and display. However, this example does not suggest in any way that a real warhead could be printed in one step from metal, plutonium and high explosives. As discussed below, this is not feasible.

III. 3D PRINTING NUCLEAR WEAPON COMPONENTS

Explosives

Interestingly, the best and only public reference to 3D printing of explosives comes from the Los Alamos National Laboratory in a public relations article.[4] Los Alamos designed and built the world's first nuclear weapons and maintains a large part

[4] 'Explosiv3Design: 3D Printing could revolutionize the high-explosives industry', *1663*, Los Alamos Science and Technology Magazine, Mar. 2016, <http://www.lanl.gov/discover/publications/1663/2016-march/explosive-3d-design.php>.

of the USA's nuclear weapon stockpile today. The article is a technical discussion of how to improve and diagnose the performance of explosives used in nuclear weapons, such as trinitrotoluene (TNT) or triaminotrinitrobenzene (TATB). The key importance of this article is that it is apparently the only reference found in the literature to the utility of using 3D printing to produce nuclear weapon-scale explosive components. This has clear non-proliferation implications.

High explosives are a key element of any nuclear weapon. They provide the chemical energy to compress a mass of plutonium or uranium into a critical mass that explodes. By their very nature, chemical explosives are dangerous and difficult to process. Casting explosives is a process that involves the least risk, but produces parts of relatively poor quality. A preferred method is to press powders of high explosive, held together with binders such as wax or Teflon®, into a rough shape. The shape is then machined to a precise final shape for the weapon. However, this traditional method of manufacturing is essentially limited to state actors for a variety of reasons: (*a*) the pressing apparatus is highly specialized and only likely to be available in developed countries; (*b*) the powders may be difficult to produce; and (*c*) the machining operations involved, such as lathe turning, milling and drilling, are extremely dangerous and are preferably done remotely behind blast walls.

3D printing, on the other hand, could allow an unsophisticated operator to produce the precision parts needed for a nuclear weapon more safely and easily. The key ingredient would be the powder. If the powders available had the proper shape (rounded or sharp makes a difference) and appropriate particle size, the process could become as simple as many of the plastic or resin shapes that are being produced by the millions in other commercial ventures—if explosive safety issues could be solved.

Los Alamos is interested in producing safer explosives and determining how they behave. Although at an early stage, its work is advanced for the field, but the focus is on science rather than manufacturing. The work demonstrates that explosive powders can be handled safely by experienced personnel and that laser melting of explosive powders in additive manufacturing is possible. This is more sophisticated than a non-state actor needs. Cast explosive shapes, such as were used in the early nuclear weapons of the 1950s, would be adequate and simpler to build than inventing a cutting-edge technology that even Los Alamos is just beginning to explore.

This is one of the few areas where 3D printing could eventually provide a state or even a non-state actor with a capability that they might not otherwise have. European exporters need to be aware of end-user requirements and be especially alert for clues and specifications, such as advanced safety requirements and remote operation, which would be required for such processes.

Fissile materials

Plutonium

It is beyond any possibility that a nuclear core containing plutonium, a tamper such as beryllium and high explosives could be printed as one operation. Yet it is conceivable, if very difficult to believe, that a plutonium (or uranium) metal shell or sphere could be printed. There are a number of difficulties to overcome.

Plutonium is highly radiotoxic and only someone with a death wish would handle it carelessly. A milligram in the lungs would eventually cause cancer and larger doses could bring on immediate symptoms. Plutonium is also highly pyrophoric. Large pieces of metal do not readily burn, but chips of plutonium from conventional subtractive machining regularly catch fire in air. However, the fires are normally small and easily contained if the workplace is kept clean and chips kept to a minimum. Plutonium is normally cast in a vacuum because molten plutonium would burn violently in air. Plutonium powders, such as used in 3D printing, are highly pyrophoric. There is a great danger of them igniting in air and producing chemical explosions. Any such printing would have to be done in a high vacuum or very pure argon atmosphere. Industrial experience with, for example, titanium would be good background. Titanium is similar in reactivity in powdered form and has been the source of numerous industrial accidents involving 3D printing.[5]

Plutonium has an extremely complex and unusual metallurgy; it melts at a fairly low temperature of 640 degrees Celsius (°C). Metallurgists have worked for years to produce adequate alloys to make usable, reliable castings. Gallium is frequently used in alloying

[5] '3D Printing Safety', Environmental Health and Safety (EHS) fact sheet, Carnegie Mellow University, <http://www.cmu.edu/ehs/fact-sheets/3D-Printing-Safety.pdf>.

plutonium, beginning with the very first nuclear test in 1945.[6] It is likely that a great deal of research would also be necessary to achieve the same results in a completely new environment of alloys in 3D printing.

Modern nuclear weapons do not normally use cast plutonium directly. Castings are often rolled and hydroformed to strengthen them, then they are machined by traditional turning and milling processes. This results in strong, well-characterized, stable components with a long history and with technology vetted through nuclear testing. 3D-printed plutonium would have properties similar to a cast material, but would produce new challenges for designers of militarily reliable weapons. For example, 3D printing does not produce extremely smooth surfaces, whereas modern weapons require extremely tight tolerance and smoothness, particularly on internal surfaces. It is possible that a 3D-printed plutonium part might require a simple machining of the inside surface to meet the weapon quality standards for a state programme. A non-state actor would have far less concern about military reliability and accurate prediction of performance. A proliferation nuclear weapon is more a violent political statement than a destructive military weapon. In that case, crude components are adequate without the huge investment required to develop 3D printing of plutonium. One exception to this assertion is covered below.

Uranium

The cautions above all apply to uranium but to varying degrees. Uranium is not very radiotoxic and can be handled safely with far less radiological protection than plutonium. Like plutonium, uranium is highly pyrophoric. Once powders are produced, they need to be handled in a vacuum or extremely dry argon. Uranium melts at a much higher temperature than plutonium (1132°C), which makes 3D printing somewhat more difficult, but the metallurgy of uranium is much simpler than for plutonium and alloying is not essential.

Reconstructing damaged parts

A proliferation-related application of 3D printing is the reconstruction of damaged parts. In the event of an accident or military incursion, non-state actors could come across a damaged nuclear weapon. This was the story line in the popular novel 'Sum of all Fears' by Tom Clancy: Palestinians found an Israeli nuclear weapon damaged in a plane crash and tried to rebuild it.[7] This is an interesting hypothesis. Whether the weapon has been lost in an accident or intentionally disabled is largely irrelevant. A retreating force may destroy its nuclear weapons if there is not enough time to remove them.

Imagine, for example, that US B-61 weapons deployed in Europe are disabled in a crisis where they cannot be removed. Nuclear weapons are reported to have self-destruct mechanisms if the system detects tampering or attempts to make unauthorized use. Yet a quote taken from a review of the fictional Sum of All Fears says 'A nuclear weapon is not destroyed during disablement and its special nuclear material contents could (in concept) be recovered'.[8] It emphasizes that a damaged weapon still contains the necessary amount of plutonium to create the desired nuclear explosion. As long as the high explosive in the weapon has not detonated and scattered the nuclear material, that material can be recovered and reshaped into its original dimensions.

This raises interesting concerns. If only one weapon is recovered, it has exactly as much special nuclear material in it as the designers believed gave a high confidence it would produce an acceptable nuclear yield. Clearly there must be some margin, but there is no open-source information on what that margin is.

If the material, plutonium or uranium, is recovered and melted it could be used to cast a replacement part. However, normal casting processes produce large amounts of waste due to losses in the melting crucibles and casting systems. 3D printing could possibly overcome this problem. If the recovered fissile material is reduced to a fine powder, which is easily done with certain chemical reactions, it could be used in an additive material process to reconstruct the destroyed fissile part. By carefully using the plutonium powder and recovering it regularly during the printing process, the losses might be small enough to reconstruct the part to within the margin of material that would reliably produce a nuclear yield.

[6] Baker, R. D., Hecker, S. S. and Harbur, D. R., 'Plutonium: a wartime nightmare but a metallurgist's dream', *Los Alamos Science* (Winter/Spring 1983), <http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-83-5074>.

[7] Clancy, T., *The Sum of All Fears* (Putnam: New York, NY, 1991), <http://www.publishersweekly.com/978-0-399-13615-3>.

[8] Angelo, J. A., *Nuclear Technology* (Greenwood Publishing Group: Westport, CT, 2004), p. 499.

The dangers of working with highly radioactive material have already been discussed. Therefore, in addition, there is the fact that plutonium and uranium fine powders are extremely pyrophoric and must be handled in an atmosphere completely without moisture or oxygen. This demands that the operators choosing this method have access to high vacuum equipment, glove boxes and a sophisticated printer that will fit inside them and can be maintained and operated remotely.

This example describes a very remote possibility: that a non-state actor recovers the plutonium from a damaged weapon and wants to recreate a plutonium core. In this very special case, 3D printing of nuclear material, difficult and unproven as it will be, gives the actor an incentive to consider this technology. The assessment is that the actor will be unsuccessful but may be highly motivated.

Beryllium and aluminium

An important part of a nuclear weapon core is the material immediately outside the fissile core. Beryllium is often used for this layer because it is a strong neutron reflector. Reflecting neutrons back into the exploding core reduces the critical mass of plutonium required and gives the explosion a greater yield. Beryllium is highly toxic in powder form, especially if inhaled. In metal form, however, it is not a particular health risk; when it surrounds the fissile core it makes the plutonium contained inside safe to handle from a radiological point-of-view.

The scientific literature is largely devoid of articles on 3D printing beryllium. This is probably because beryllium is a brittle metal that is essentially impossible to melt and cast. It is normally produced in metallic shape by making a powder and hot pressing it. Because of its tendency to not coagulate into solid metal pieces when heated to melting, it is likely it would also be a very poor candidate for 3D printing as a heated powder.

A possible compromise to overcome this is to alloy beryllium with aluminium. Beryllium and aluminium do form alloys, which suggests that a beryllium (Be)–aluminium (Al) alloy made from mixed Be–Al powders would also be suitable for 3D printing. Commercial alloys of Be–Al typically contain high weight percentages of Be: 60–70 per cent. Although this is a compromise from a neutron reflector standpoint, it is a very good way to use beryllium in a ductile, machinable, castable and weldable form.

If a state nuclear weapon developer wanted to use 3D printing, this would be a good alternative. However, while aluminium powder is commonly available, there are only a few suppliers of printing-grade beryllium. Export controls on beryllium could raise acquisition difficulties and generate intelligence indicators. The toxicity of beryllium powder in the 3D printer would also need to be addressed because of the very serious health risks.

IV. 3D PRINTING FISSILE MATERIAL PRODUCTION CAPABILITY

Uranium enrichment

Uranium as found in nature cannot be used to produce a nuclear explosion. It consists of two nuclear isotopes, uranium 235 (U235) and uranium 238 (U238). Over 99 per cent of natural uranium is U238, which cannot produce a nuclear explosion. The very rare isotope, U235, must be separated out and purified to make a nuclear explosive device. This process is known as ‘uranium enrichment’ or alternatively ‘uranium isotope separation’.

Many processes have been invented to separate uranium isotopes. The majority are large industrial processes using gas flow though filters, chemical separation columns or very large magnetic field chambers, three to four metres in diameter. All of these are large, brute force industrial processes involving large equipment, big pumps or blowers and kilometres of piping. There are few or no applications of 3D printing likely in these techniques.

An important and particular concern regarding 3D printing in enrichment relates to gas centrifuges.[9] These are precision machines with many small parts. They range in size from roughly a residential waste bin to a two-storey tall tube. Gas centrifuges are considered a challenging mechanical engineering technology, but they are nowhere near as complex as a modern internal combustion automobile engine or an aircraft gas turbine. There are some potential applications of 3D printing in gas centrifuges to consider.

[9] Christopher, G., ‘Can you 3D print a centrifuge to enrich uranium?’, Blog post, International Centre for Security Analysis (ICSA), King’s College London, 20 May 2015, <https://blogs.kcl.ac.uk/icsa/2015/05/20/can-you-3d-print-a-centrifuge-to-enrich-uranium/>.

Gas centrifuges

A gas centrifuge is a mechanical device built to high precision and strength. Its key feature is a rotor spinning at hypersonic speed inside a vacuum housing. The rotor must be extremely strong to withstand the huge G-forces of rotation. A small amount of a uranium gaseous compound, uranium hexafluoride (UF_6), is introduced into the rotor through a pipe. The thermal gradients and centrifugal forces inside the rotor cause the two uranium isotopes to separate slightly and the two streams are withdrawn through two other tubes.

Because no one centrifuge separates out a large fraction of the U235 in one pass, thousands of centrifuges are connected to each other in an enrichment factory. This series of machines is known as a cascade. Slightly enriched U235 is passed on to the next machine in the cascade where it is enriched slightly more and, after many stages, an enriched stream of U235 emerges. For weapons this enrichment needs to be about 90 per cent U235. For nuclear power plants it is much lower, typically around 5 per cent.

The rotor itself consists of four major rotating components plus the bearing, shaft, connections that support it and a magnetic steel motor plate. The most difficult component to engineer is the rotor tube wall.

Rotor tube walls

Rotor tube walls have been made of several high-strength materials in decades of gas centrifuge development: aluminium alloy and maraging steel (considered to be very old technology) and carbon fibre (the modern standard). It is extremely unlikely that 3D printing could duplicate the necessary strength for a metal tube wall, and it is completely inappropriate for the carbon fibre application. For the metallic materials, the strength of a printed material is virtually the same as for a cast material, which is far below the required strength for this application. Any attempt to compensate by other strengthening processes is counterproductive and essentially a waste of time, given that most of these processes could be used to make far better tubes by conventional subtractive manufacturing methods.

End caps and baffle

The end caps and baffle, three rotating parts, are also required to be very high strength, although they benefit by being constrained at the rims by the strong rotor wall. Ordinary materials such as aluminium and maraging steel are preferred for these applications, and 3D printing offers no advantages. 3D printing could produce materials with the required alloy composition, but these parts would not have the strength provided by tradition casting, forging, heat treatment and subtractive machining.

Shaft, bearing and motor susceptor

The shaft, bearing and motor susceptor require exceptional strength both in carrying weight and resisting vibrations. They would normally be made of steel, in some cases magnetically suscepting for the eddy current (non-contact) motor in the base.

The important conclusion is that it would be impossible to 3D print a complete gas centrifuge, particularly not in one operation involving multiple materials. It is unlikely that this conclusion will be different for decades to come, given the material science issues involved. The difficulty with manufacturing a gas centrifuge is entirely associated with the highly stressed rotor itself and not with the non-rotating parts. Because it is impossible to print the rotor itself, 3D printing does not give a potential centrifuge manufacturer any new capabilities.

Other mechanical components

There are a number of other components that might be 3D printed. An important one is the outer vacuum casing. This component needs to be strong and contain debris in the case of a rotor flying apart, which it can do with tremendous destructive energy. Therefore, 3D printing would not be useful in this application.

However, certain internal components, such as the stationary scoops that remove the gas, would be ideal for 3D printing. They may have complex shapes that are difficult to machine and virtually no material strength issues. The molecular pump inside the vacuum housing has complex spiral grooves to machine. It has no strength issues and would be an ideal candidate for printing. Small pieces of the upper centrifuge magnetic

bearing and damper could also be printed. Because they do not rotate, they have minimal strength issues.

The conclusion for these components is simply that they could be 3D printed and the cost of doing so might be attractive. Yet producing the components does not provide a state actor operator with a new or substantial advantage over conventional manufacturing techniques. Hence there is little to fear from 3D printing. It is not an enabling technology for the gas centrifuge itself. The only advantage could be a small economic one and it does not make the production of centrifuges more or less likely. It is the rotor—that cannot be adequately 3D printed—that would be an enabling technology.

V. PLANT PROCESSES AND INSTRUMENTATION

For a state actor building an industrial plant, 3D printing does give a substantial capability advantage when it comes to the balance of the plant and instrumentation.

Valves and fittings

Uranium hexafluoride (UF_6) is an extremely reactive and dangerous gas. It reacts violently with many metals and destroys them. Steel is a marginal choice for working with UF_6 gas and at low pressures; aluminium and nickel-based alloys are excellent. In a centrifuge plant, UF_6 is handled as a liquid and as a gas at a pressure of around one atmosphere in the areas where gas is supplied to the plant and where it is removed from the centrifuge cascade. In the actual centrifuge machine and cascade piping, the pressures are much lower at around 1 per cent of an atmosphere. Corrosion is less of an issue at this pressure and at room temperatures, but material selection is still important. UF_6 also reacts strongly with moisture and air. The fabrication of components in a gas centrifuge plant uses high-vacuum components such as are used in industries like semi-conductor manufacturing. In the low-pressure parts of the plant, aluminium piping is often adequate. For high-vacuum fittings, components made of nickel-based alloys are preferable.

Nuclear export controls recognize this as an area where illicit or undeclared centrifuge enrichment can be thwarted. The specialty metals used in producing UF_6 and for other nuclear applications are subject to controls.[10] There are significant controls on valves and fittings that are designed for use with UF_6. For example, the detailed US Department of Commerce control list is an indication of the restrictions on UF_6-resistant materials.[11]

3D printing is an excellent way to bypass many of these export controls. All that is needed is an accurate CAD representation of the part to be made and the correct material powder. It is not difficult to obtain a single prototype of a valve or an instrument to be copied. Detailed dimensions are often available in sales catalogues. The CAD design can also be created using well-known engineering modelling and measurement systems, including modern 3D laser measuring systems.

3D printing of valve bodies, seats, bellows and shafts would give a proliferator a new capability. The opportunity to evade export controls on these sensitive items is important. It gives the proliferator an added capability and it reduces the ability of export control organizations in the European Union (EU) to spot large quantities of prohibited items being sought or procured.

Pressure transducers and manometers

One of the most sought-after specialty items is the single-sided diaphragm capacitance absolute pressure transducer. Gauges of this type are typically used to measure UF_6 pressure in UF_6 handling facilities at pressures close to an atmosphere and in centrifuge cascades at a fraction of an atmosphere. The best gauges have diaphragms made of Inconel, a nickel alloy.[12] Inconel powder is available for 3D printing.[13] The ability to 3D print a capacitance manometer of this type would be a major bypass of export controls. Therefore, strict control of Inconel powder and other nickel-based powders for export is essential.

[10] Handbook of Alloys Significant to Export Control Commodities, USDOE Pacific Northwest Laboratory (PNNL-SA-60719), Mar. 2012, <http://www.upravacarina.rs/cyr/Zakoni/Корелационе%20табеле%20за%20метале%20које%20подлежу%20контроли.pdf>.

[11] US Department of Commerce Control List, <https://www.bis.doc.gov/index.php/forms-documents/doc_view/734-ccl2>, e.g. see pp. 37–38.

[12] Inconel® is a registered trademark of Inco Alloys International, Huntington, WV, USA.

[13] 'Spherical Inconel 600 (UNS N06600) Powder (3D Printing Additive)', Stanford Advanced Materials, <http://www.samaterials.com/3d-printing-powder/1323-spherical-inconel-600-uns-n06600-powder-3d-printing-additive.html>.

Plutonium separation by spent fuel reprocessing

Plutonium is produced in a nuclear reactor. For reactors large enough to produce a significant amount of plutonium in a reasonable time, there are large vessels, pipes, pumps and valves. The reprocessing plant for chemical separation of plutonium from spent fuel is also an industrial process using large chemical industrial equipment. This is all large hardware that is not appropriate for 3D printing applications, so there does not appear to be any advantage to a nuclear operator or state actor to use 3D printing to acquire plutonium.

VI. THE SUITABILITY OF 3D PRINTING FOR NUCLEAR APPLICATIONS

Strength

3D printing is more analogous to casting than other metalwork processes. Cast materials are usually weaker than wrought materials that are rolled, pressed, hydroformed and heat-treated. The advantage of 3D printing is that products are produced to their final shape and therefore carrying out forging operations to modify grain boundaries to increase strength and other material properties is not possible. 3D-printed objects can be heat-treated, which can improve material properties, but if they undergo dimensional changes from heating and cooling, the advantages of 3D printing to exact shape will be lost. Final machining would then be required.

An example of this would be the famous Samurai sword of Japan. The secret to the sword's great strength is that it is cast and then repeatedly forged into a superstrong piece of hardened steel. It would be possible to print a copy of a Samurai sword, but it would have to be repeatedly forged to give it strength. The initial step of 3D printing therefore proves unimportant and irrelevant.

In general, as seen in the centrifuge example, rotating parts subject to extreme stress are not suitable for 3D printing and it is those parts that are of critical interest. A stationary part, such as a molecular pump, has no strength requirements and its complex shape might be printed more cheaply than a machined part. Yet this does not give an operator a new capability, only an economical choice.

Neither is 3D printing suitable with regard to surface finish. 3D-printed parts do not generally have the fine surface finish associated with fine machining and grinding, which is important in many nuclear weapon components.

The importance of powders

Clearly 3D printing relies on appropriate powders to succeed. The powders need to be of the right size and shape, typically a few microns in size and round in shape. If the goal of using 3D printing instead of other methods is to save material, the powder needs to be recycled constantly and remain oxide-free. For metals, in particular, this would require oxygen-free enclosures with either vacuum or argon atmospheres, which increases complexity and cost.

Many of the critical materials needed for nuclear weapons, such as beryllium, plutonium, uranium and high explosives, are tightly export-controlled. The nickel-based alloys needed for high-vacuum valves and instrumentation are also on trigger lists for export. Using 3D printing to make the components instead of buying them or making them by conventional means still requires powders of materials that are subject to export control. 3D printing does not solve that problem. It is important, therefore, that export control authorities put as much effort into controlling these important raw materials as they do finished parts.

Toxicity and safety

Many of the examples of items to be printed involve materials that are inherently very dangerous or toxic, such as beryllium, high explosives and plutonium. As such, special handling enclosures and procedures are necessary. For example, printing plutonium would require alpha-radiation safety in glove boxes with controlled airflow as well as an inert environment for steps where powder is handled.

All fine metal powders tend to be explosive in air when they are finely dispersed. The additional danger of finely divided plutonium powder as an explosive source is extremely challenging. Experience of 3D printing explosive powders like TNT is extremely limited.

VII. CONCLUSIONS

3D printing is an exciting new technology. It has become an option of serious choice in the manufacturing industries, first in plastics and now in metals. 3D printing is known to be a dangerous capability for manufacturing items such as small arms. It makes precision manufacture of parts possible for lawbreakers. It can also produce items such as guns made of hard plastics that could evade a metal detector.

This has led to some serious questions that can be applied to non-state actors or to state programmes: Can 3D printing be a path to nuclear weapon production? Can someone print an entire nuclear bomb? Can they print a whole gas centrifuge?

The conclusion of this paper is that the technology is not yet ready to do any of those things. Printing a highly dangerous material such as plutonium is a serious challenge. Printing plutonium and high explosives in one operation is beyond any technology available today and likely to be unobtainable for decades, if ever.

However, there are several places where printing an individual component could give a manufacturing advantage. It could eventually become a safer way to produce high explosive parts. Printing beryllium–aluminium alloys could be a way to produce a good neutron reflector, of lower quality but with adequate properties, for use in a bomb core. 3D printing might also be a way to reconstruct damaged parts from a captured damaged nuclear device. However, this presumes a major research and development programme to develop the necessary processes.

For fissile material production, 3D printing is very unlikely to print an entire gas centrifuge. It is not well developed enough to produce highly stressed rotating parts, but it could provide some cost savings in less critical parts of the centrifuge unit.

3D printing could be used very profitably to manufacture critical valves, fittings and instrumentation out of specialized nickel-based alloys in a UF_6 handling facility. Export control regulators need to be alert to this evasion path.

In general, the managers of export control regulations in the EU do not need to be greatly concerned about '3D printing an entire nuclear weapon'. Key processes have not been developed to anywhere near the level needed to print a complete weapon in one pass, and probably never will be. Hence the claims that policymakers might hear in casual media can be quickly refuted. It would be prudent, however, to monitor scientific progress in the fields of 3D printing explosives and highly toxic materials, and to make suppliers of 3D-printing machines alert to unusual safety, high vacuum or remote handling specifications. Particular attention should be paid to beryllium and beryllium–aluminium powder transactions.

A similar conclusion can be reached about centrifuges. It would be foolish to try to 3D print a marginal or even non-functioning centrifuge using substandard materials. Printing ancillary equipment, such as valves and pressure transducers, is a way to bypass export regulations. One of the best indicators of such activity would be unusual purchases of nickel-based alloy powders.

Field personnel who sell and maintain 3D printers should be aware of the dimensions and general characteristics of centrifuges and weapons. This could enable them to spot unusual prototyping activities, where non-functional materials are used to generate prototype components for nuclear research and development.

3D printing is a technology that is rapidly growing and may eventually create serious non-proliferation problems. Yet the claim that someone can simply print a nuclear weapon given the drawings and some plutonium is not valid—and will not be a problem for years to come.

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A EUROPEAN NETWORK

In July 2010 the Council of the European Union decided to create a network bringing together foreign policy institutions and research centres from across the EU to encourage political and security-related dialogue and the long-term discussion of measures to combat the proliferation of weapons of mass destruction (WMD) and their delivery systems.

STRUCTURE

The EU Non-Proliferation Consortium is managed jointly by four institutes entrusted with the project, in close cooperation with the representative of the High Representative of the Union for Foreign Affairs and Security Policy. The four institutes are the Fondation pour la recherche stratégique (FRS) in Paris, the Peace Research Institute in Frankfurt (PRIF), the International Institute for Strategic Studies (IISS) in London, and Stockholm International Peace Research Institute (SIPRI). The Consortium began its work in January 2011 and forms the core of a wider network of European non-proliferation think tanks and research centres which will be closely associated with the activities of the Consortium.

MISSION

The main aim of the network of independent non-proliferation think tanks is to encourage discussion of measures to combat the proliferation of weapons of mass destruction and their delivery systems within civil society, particularly among experts, researchers and academics. The scope of activities shall also cover issues related to conventional weapons. The fruits of the network discussions can be submitted in the form of reports and recommendations to the responsible officials within the European Union.

It is expected that this network will support EU action to counter proliferation. To that end, the network can also establish cooperation with specialized institutions and research centres in third countries, in particular in those with which the EU is conducting specific non-proliferation dialogues.

http://www.nonproliferation.eu

EU NON-PROLIFERATION CONSORTIUM

The European network of independent non-proliferation think tanks

FONDATION pour la RECHERCHE STRATÉGIQUE

FOUNDATION FOR STRATEGIC RESEARCH

FRS is an independent research centre and the leading French think tank on defence and security issues. Its team of experts in a variety of fields contributes to the strategic debate in France and abroad, and provides unique expertise across the board of defence and security studies.
http://www.frstrategie.org

PRIF Peace Research Institute Frankfurt — HSFK Hessische Stiftung Friedens- und Konfliktforschung

PEACE RESEARCH INSTITUTE IN FRANKFURT

PRIF is the largest as well as the oldest peace research institute in Germany. PRIF's work is directed towards carrying out research on peace and conflict, with a special emphasis on issues of arms control, non-proliferation and disarmament.
http://www.hsfk.de

IISS

INTERNATIONAL INSTITUTE FOR STRATEGIC STUDIES

IISS is an independent centre for research, information and debate on the problems of conflict, however caused, that have, or potentially have, an important military content. It aims to provide the best possible analysis on strategic trends and to facilitate contacts.
http://www.iiss.org/

sipri

STOCKHOLM INTERNATIONAL PEACE RESEARCH INSTITUTE

SIPRI is an independent international institute dedicated to research into conflict, armaments, arms control and disarmament. Established in 1966, SIPRI provides data, analysis and recommendations, based on open sources, to policymakers, researchers, media and the interested public.
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