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# How I Learned to Stop Worrying and Love 3D Printing

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Cassandra Pate, Sean Morrell, Jillian Maloney

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Idaho National Laboratory

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Cassandra Pate, Sean Morrell, Jillian Maloney
*Idaho National Laboratory*

ABSTRACT

The nuclear nonproliferation regime has many robust measures in place to prevent the acquisition of a nuclear weapon, a key pillar of which is denying or preventing the transfer of technology to specific actors. Additive manufacturing (AM) is a rapidly advancing technology that could dramatically alter the landscape of the safeguarded fuel cycle. However, many of the benefits of AM could also be used to circumvent or defeat current safeguard practices and controls. Because the AM capability is not fully understood, research and integration is necessary early in the technology development stages in order for nonproliferation to remain on the leading edge of discovery and not the tail end of technology deployment.

1. INTRODUCTION

The successful prevention of illicit nuclear proliferation has long relied on technology denial regimes—denying or preventing technological transfer to certain actors—as opposed to technology governance. Under this type of regime a bi-polar system of "have" and "have not" actors was created (e.g. "Nuclear Weapon States" and "Non-nuclear Weapon States" under the NPT). As technology has progressed the denial regime has struggled with the legitimate peaceful transfer of technology considered dual-use. The rise of non-state actors an immense departure from the Cold War landscape many non-proliferation agreements were created under, has again challenged the reliance on technology denial. Additive manufacturing (AM) specifically could pose a significant challenge for non-proliferation regimes. The AM industry has progressed at a rapid pace over the last few years as a result of the commercialization of the technology and seemingly small technical advances such as increased precision, lowered cost of metal printing systems, increase in viable materials, and improved open source programs. Industrial 3D Printers (>$5,000) have seen a 26% increase in sales over the last year, marking the second year in a row with more than $1billion increase in growth [1]. The materials and machines for AM are not considered dual-use technology and the required knowledge base to construct complex geometries is low. Technology transfer in the AM field is as simple as emailing or downloading a file—a difficult process to control or prevent

*Overview Of Additive Manufacturing*

Unlike tradition manufacturing where excess material is removed by drilling or machining to create a final part, AM builds each component layer by layer from a computer-aided design (CAD) file. The defense, aerospace, and automotive industries have devoted extensive research and development (R&D) efforts to AM as a way to accelerating innovation though compressed supply chains, minimized materials and energy usage, and waste reduction [2]. Proven benefits of AM include:

- Reduction of manufacturing footprint: Layer by layer building instead of machining away excess material can reduce material costs up to 90% [3].

- Additionally, the consolidation of parts in an assembly and reduction of tools and dies reduces the "cradle-to-gate" environmental footprint and overhead costs [3] [4].
- Reduction of energy consumption: Elimination of steps in the manufacturing process, creation of lighter parts, and repairing end-of-life components instead of producing new ones can reduce energy consumption 2-25% [1] [5].
- Rapid prototyping: Designing and creating new ideas can be accomplished quicker resulting in more time for innovation and testing and less time implementing a manufacturing process. Changes can be made to designs quickly and easily.
- Novel geometries and material innovation:  Shapes considered too intricate or complex for traditional processes can be created. Characteristics such as microstructure, conductivity, or density can be controlled by the printing parameters and materials can be blended together in ways not possible with traditional manufacturing.

2. ADDITIVE MANUFACTURING AND THE SAFEGUARDED FUEL CYCLE
While the aerospace, defense, and dental industries have become early adopters to AM, it is still relatively unexplored for the nuclear industry. A unique opportunity exists for the development of new manufacturing techniques that may overcome current challenges (e.g. aging and degradation of nuclear power plant parts, improved accident tolerance of fuel) and alter the landscape of the safeguarding the fuel cycle (Figure 1).

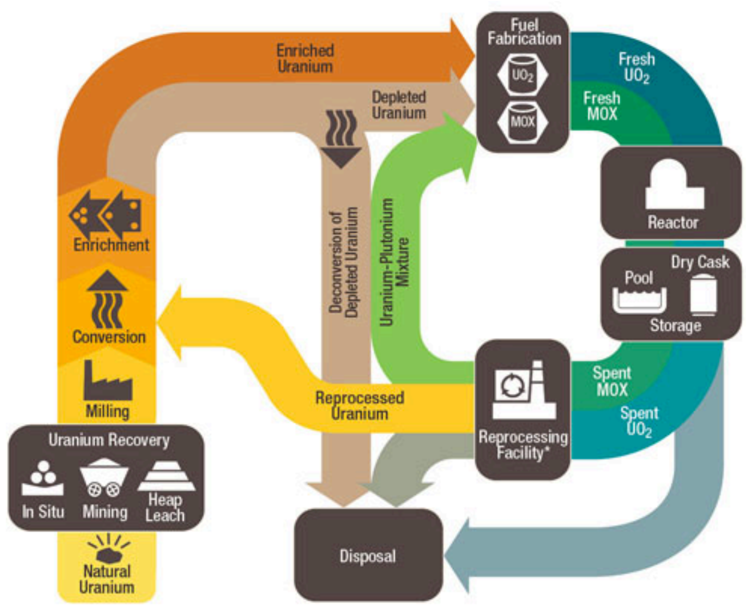


**Figure 1: The Nuclear Fuel Cycle [6]**

*Enrichment*
Additive manufacturing enables the creation of lighter-weight parts with complex geometries that were not previously possible with traditional manufacturing. This could drastically change heat-transfer related components such as heat exchangers. A collaboration between 3D Systems, University of Maryland, the United States Department of Energy produced a new 3D printed air-to-refrigerant heat exchanger that is 20% lighter, 20% more efficient, and quicker to produce, and at a cost equal to that of a traditional heat exchanger [3] [7].

*Fuel Fabrication*
The microstructure of AM components is strongly dependent on process parameters (e.g. scan speed, particulate size, power density, powder porosity and shape) hence why optimization of the process is required to obtain desirable results. Combining the ability to create complex geometries, blend or gradient materials, and control microstructure could allow for the creation of a new fuel design that is not currently available. This range of potential design variables possible will have significant implications on fuel performance, safety, utilization, and cost of nuclear energy.

*Power Plants and Operations*
A challenge to extending the operations of nuclear power plants is the safety margin and life-limiting degradation and aging of materials that can limit the structural response of materials. Replacing entire large components (such as steam generators) may be possible but economically prohibitive [2]. Smaller components may be more practical to replace but offline time for replacement of parts can still be costly, therefor the management and mitigation of aging a degradation of components is key including the research and development of new materials and construction methods for reactor components. A unique opportunity for innovation exists in the development of a new manufacturing technique that may overcome challenges current nuclear power plant components face e.g. minimizing failure rates in parts and components by better controlling structural characteristics.

AM techniques such as LMD and Laser Melting (LM) have been proven to be a rather easily controllable process compared to other techniques such as sintering which may only partially melt the material [8]. They have also been significantly researched and proven for their viability in producing full density parts. The controlled build of microstructures has become a rapidly growing R&D field as more applications for the AM parts have been identified. LMD and Laser Sintering (LS) have also shown potential for metal matrix composites with ceramic reinforcement.

In addition to additive manufacturing of new parts, there is a possibility of repairing smaller, frequently replaced components, which has already been demonstrated and adopted as practice in the dental and aerospace industries. Siemens uses selective laser melting (SLM) for repair of gas turbine components (e.g. SGT-700, SGT-800 burner tips, and turbine blades) that is ten times quicker than conventional repair procedures [8]. The AM repair processes also allows for small modifications in parts to the latest designs at a reduced cost.

*Waste Disposal and Decommissioning*
A common problem within the nuclear industry is the age at which some power plants and related parts were created. Sellafield Ltd., the company responsible for cleanup and decommissioning at one of Europe's largest nuclear waste sites, has begun to 3D print "one-off" parts from 50 years ago such as stainless steel container lids for storing waste as a cost reduction mechanism [9]. Other smaller parts, that are also no longer in production, will be scanned and printed in materials such as titanium and plastics.

By combining 3D printing technology and unmanned aerial vehicles (UAV), a robotics team at Imperial College has created UAVs that can help with moving up to 40kg of nuclear waste [10]. Two vehicles work in tandem; the first prints polyurethane foam so that another UAV can stick itself to the object and move it. The end goal of the UAVs is use in nuclear facilities to aid with hazardous waste disposal by an ALARA-type approach that reduces human handling and involvement.

3. POTENTIAL FOR UNDETECTED PRODUCTION OF CONROLLED ITEMS
Several beneficial characteristics of AM, particularly the ability to quickly produce highly customized precision components, could enable the technology to defeat aspects of the current layered approach to safeguards.

*Reduced footprint*
Many of the processes needed for proliferation purposes require a combination of furtive exports and significant manufacturing capabilities. As 3D-priting of metal improves, the need for large manufacturing facilities decreases and the ability to produce parts in smaller less easily detected facilities increases.

*Reduced Barriers to Entry*
Reduction of cost associated with manufacturing also reduced the cost to manufacture controlled components. While the materials for production of such items (e.g. nickel or zirconium alloys or maraging steel) are controlled under international agreements in addition to national export regimes, they are only controlled in certain shapes for direct use or traditional manufacturing methods. For example, nickel, zirconium, or aluminum alloys and some steels and plastics, all appear on export control lists. However the powder forms of materials are only mentioned in the context of gaseous diffusion barrier production. From INFCIRC/209 and INFCIRC/540:

> *5.3.1.(b) Especially prepared compounds or powders for the manufacture of such filters. Such compounds and powders include nickel or alloys containing 60% or more nickel, aluminium oxide, or UF6-resistant fully fluorinated hydrocarbon polymers having a purity of 99.9% by weight or more, a particle size less than 10 μm, and a high degree of particle size uniformity, which are especially prepared for the manufacture of gaseous diffusion barriers.*

A similar definition is found in the INFCIRC/254/Rev9/Part2 on dual-use equipment. Most of these powders are readily available commercially for additive manufacturing.

Powder forms can also be more easily concealed for avoiding export controls that controlled shapes such as bars or tubes.

Additive manufacturing also reduced the knowledge base required to begin production of parts. Blueprints can easily be created in computer aided design (CAD) software or downloaded and simply printed with only limited knowledge of the printer and material constraints.

*Agility*

While sophisticated AM machines for metal applications are large, they require only the movement of a single machine as opposed to an entire manufacturing facility. Detection could be avoided by creating a small or even mobile facility and sourcing materials locally, thereby eliminating the need for a complex supply chain, material stockpiles and significant infrastructure.

*Time Sensitivity*

Design testing and implementing changes for a traditional manufacturing facility require modifications or change out of large and expensive equipment, resulting in an expensive and time consuming development phase. With AM the design can be modified with little to no change in equipment, providing for a rapid prototyping capability and a compressed development phase. This reduced development phase aids a rapid component deployment and it allows for a greater amount of component enhancement or fine-tuning that would otherwise be prohibitive in a traditional manufacturing setting.

*Challenges to the Current Nonproliferation Regime*

There are three primary means of technology transfers for AM–the sale or acquisition of a machine, the materials compatible with the machine, and the CAD files for the object to be printed. Controlling the transfer or dissemination of electronic documents is an impossible task faced by many industries and fields from Intellectual Property (IP) to diplomatic relations and national security. This has been demonstrated repeatedly by leaked documents, file sharing networks, and "dark net" forums. AM has already been at the forefront of concerns with the spread of CAD files to print gun components, even after the original company removed the files from their website [11].

As the AM industry grows commercially, so do the opportunities to "shop" around and have components printed quickly and easily. While the majority of products will be unrelated to proliferation, there is the possibility of reaching out to countries or 'mom-and-pop' local companies, who many not be familiar with the intricacies of nuclear export controls, to manufacture controlled items from commonly available (and uncontrolled) powder stocks. Little more is needed than mid-range computer, and Internet connection, and a credit card. As the case of the 3D printed gun components highlights, finding a premade file or place to host a file to continue to share with others is relatively easy. Numerous sites[1] specialize in connecting CAD creators to clients with marketplaces for exchanging files. Other sites, such as Yeggi.com and STLFinder, aggregate results across marketplaces to make finding a specific file quicker and easier.

[1] Popular websites include: Pinshapes, Gambody, Treatstock, Shapeways, and Thingverse

Locating a person or company locally or in another country to print the file is just as simple. Websites such as 3DHubs.com specialize in connected clients with commercial print shops (or households with printers) and boast an average turnaround time of two days for orders. If a specific material is desired, a basic Internet search for the material in conjunction with “3D printing” or a specific AM process yields results for companies around the world.

Maraging steel, for example, is controlled under 5.1.1 of INFCIRC/254/Rev12/Part1:

> *The materials used for centrifuge rotating components include the following:*
> *(a) Maraging steel capable of an ultimate tensile strength of 1.95 GPa or more;*

For traditionally manufacturing parts, Grade 300 or 350 18Ni maraging steel most commonly meets these tensile strength requirements. In powder form for additive manufacturing, only grade 300 is presently available commercially. For comparison, characteristics of both the powder form and traditionally manufactured grade 300 maraging steel are shown in Table 1.

**Table 1: Maraging Steel Specifications [12] [13]**

| Maraging Steel Specifications | | |
|---|---|---|
| | AMS 6514/MS1 (Powder) | 18Ni (300 C) |
| Min layer thickness | 40 µm | n/a |
| Large part accuracy | ± 0.2% | n/a |
| Age hardening shrinkage* | 0.08% | up tp 47% |
| Density (g/cm^3) | 8.0 -8.1 | 7.99 |
| Relative density | 100% | n/a |
| Ult. tensile strength (MPa) | 1100 ± 100 | |
| (after age hardening) | 1950 ± 100 | 2169 |
| Yield strength (MPa) | 1000 ± 100 | |
| (after age hardening) | 1900 ± 100 | 1930 |
| Young's modulus (GPa) | 180 ± 20 | 190 |
| Hardness (Rc) | 33-37 | |
| (after age hardening) | 50-54 | 50-55 |
| Maximum operating temp | 400 C | |

* Aged, sheet, tested transverse, 6 mm

Using 3DHub.com and a basic internet search gave a handful of companies outside the United States in Lithuania, the United Kingdom, and Canada offering Selective Laser Melting (SLM) services with maraging steel powder. These international companies were contacted with a file for quotes. Within three weeks, a finished reproduction of a gear (Figure 2) was shipped to Idaho National Laboratory. The density of the part was found to be approximately 8.05 g/cm$^3$, affirming that a full density part is possible. The hardness was found to be 55 HRC (620HV).

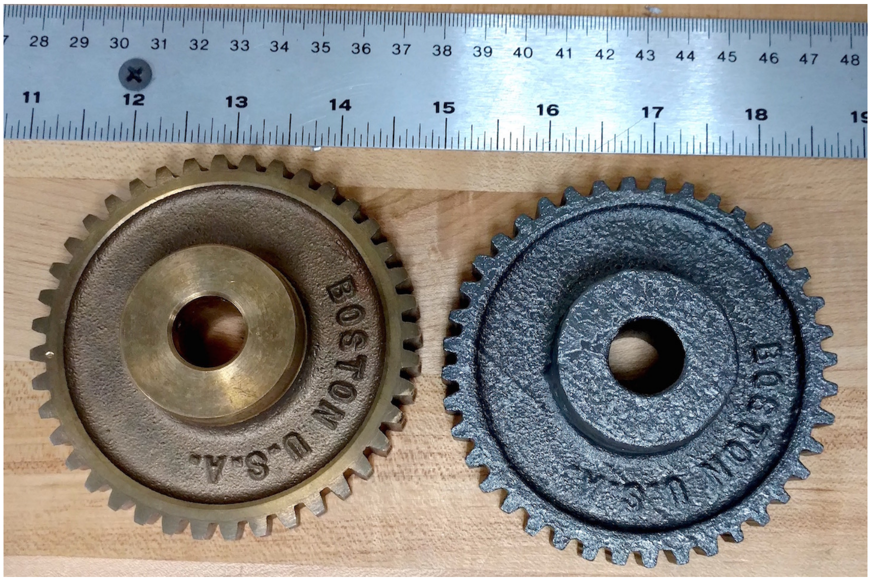

Figure 2: Original part (left) and Additive Manufactured Maraging Steel part (right)

The reproduction gear CAD file was created from reverse engineering the original gear using free, open source software and a camera on an older Android phone [14].

## CONCLUSION

The nuclear nonproliferation regime is built with a series of robust measures to prevent the acquisition of a nuclear weapon. Technological advances require that existing nonproliferation measures be continuously reevaluated for applicability and effectiveness. This unremitting process is further exacerbated by AM's rapid growth and potential. Attempting to control the sale and transfer of AM technology would be impractical. Limiting or slowing the technological advances in this field is impossible. Rather, it is absolutely imperative that the nonproliferation community embraces additive manufacturing and adapts as necessary to remain as effective. Because the AM capability is neither fully mature nor well understood, research and integration is necessary early in the technology development stages. Nonproliferation should be on the leading edge of discovery and not the tail end of technology deployment.

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