Additive Manufacturing and Nuclear Security
CALIBRATING REWARDS AND RISKS

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CENTER FOR GLOBAL SECURITY RESEARCH

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The image of the additively manufactured prosthetic hand is courtesy of Oak Ridge National Laboratory.

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About the Author

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Executive Summary

In a security environment marked by a high degree of technological dynamism, additive manufacturing (AM) stands out for its special significance. The AM field has emerged from infancy, with many new and potential applications in the commercial and military sectors. Its potential impact on nuclear security is a matter of rising debate, with some emphasizing the disruptive consequences of AM competition for international stability and others emphasizing the disruptive benefits for the United States. This essay addresses both aspects and draws on a technical analysis to inform the further development of U.S. policy.

From a nuclear-security perspective, additive manufacturing offers both rewards and risks for the United States and its allies. The rewards are primarily (1) reduced scale of effort and cost in maintaining weapons-production infrastructure and (2) greatly increased responsiveness and agility in production infrastructure. Both these benefits are long-standing U.S. policy goals.

The risks derive from the potential impact of AM on foreign nuclear weapons programs and are of three kinds. Those impacts will likely be a function of the degree of technical sophistication of the foreign actor. Non-state actors and entry-level proliferants pose modest AM risks relative to more advanced states, including both existing nuclear-weapon-states and those developed countries with a high degree of nuclear latency. A critical factor in predicting the impact of AM is current uncertainty as to the utility of AM techniques in the fabrication of special nuclear materials.

To meet the emerging challenges of AM, U.S. policy makers face a number of decisions regarding which benefits to seek, how much risk to accept, and how to reduce that risk. The basic strategic approach of the United States to the AM problem is sound, but some fine-tuning is necessary and appropriate at this time. The good news is that we have time to act; the bad news is that the time to act decisively may be shorter than we would wish.

Introduction

In the introduction to his 2018 book *Beyond Disruption: Technology's Challenge to Governance*, George Shultz argues that "The world ahead of us is not going to be anything like the world behind us…This profound change is driven not by the humanities, but by technology."[1] In Shultz's analysis, technological change will drive far-reaching changes in economics, politics, society, and of course also security. Hence his use of the term "disruptive" to capture the impact of the technologies. And hence his effort to shift focus from the technologies themselves to their implications for what we do to cope.

The current National Security Strategy (NSS) and National Defense Strategy (NDS) echo these assessments. In the words of the NSS, "the drive to develop new technologies is relentless, expanding to more actors with lower barriers to entry and moving at accelerating speed."[2] It highlights the potential impact of such technologies on the security environment and character of war. In the words of the NDS, "the United States will prioritize emerging technologies critical to economic growth and security."[3] It highlights an urgent need to renew a competitive mindset so that we can out-think and out-innovate our strategic competitors.

This essay focuses on one such technology: additive manufacturing (AM). In fact, AM is not one technology; it is many. AM is a combination of robotics, directed energy, and advanced software built on a foundation of advanced material and computational sciences. Its impact is already being felt in small ways with limited applications that might best be described as boutique. Often described as an emerging technology, a more accurate characterization would be as a maturing technology. The various technologies associated with AM have been in development and use for more than a decade, although new applications and new techniques continue to emerge, driving further changes to the technologies themselves. It has proliferated widely and is making in-roads in many manufacturing sectors.

As with all such disruptive technologies, there is a debate about whether and how to try to gain disruptive benefits for the United States along with a debate about whether and how to try to minimize the disruptive costs to the security environment. The National Security Strategy's emphasis on out-innovating adversaries clearly suggests that the nation move toward a more competitive AM posture. But the desire to minimize the costs and risks of intensified military competition with AM clearly suggests caution in competing. These twin imperatives point to a need to clearly understand the potential benefits and risks of AM. This is not possible without a sound grasp of the technologies themselves.

To better understand these issues this paper proceeds as follows. It begins with a technical review of AM technologies. This includes a discussion of their potential applications to nuclear weapons development and production and the associated proliferation risks. It then examines the potential benefits to the United States for its stockpile stewardship activities. The paper then explores the implications of this technical analysis for U.S. policy. It concludes with a small set of policy recommendations aimed at balancing benefits and risks.

Defining Additive Manufacturing

Additive manufacturing or "printing" makes objects by adding rather than subtracting material. Subtractive manufacturing, by contrast, discards material—picture Michelangelo chiseling away a marble block to reveal the David within. Subtractive manufacturing has been performed throughout human history, most notably since the industrial age, and may generate huge waste flows, as in milling and machining. AM creates shapes by adding material, hence the name. Picture a sculpture steadily taking shape as pieces of clay are added and worked. Because it does not subtract material from a large mass, material requirements, waste, and energy cost are greatly reduced under AM, and new horizons in design are opening as these AM techniques allow the manufacture of hitherto impossible to manufacture shapes.

Unlike subtractive machines, which are specialized for a particular product, AM machines are general purpose. The specifications that define a given product are contained in a digital build file that drives the machine, containing not only design details, but the distilled know-how (the "tacit knowledge") of the expert technicians who would have operated the machine were it (for example) a traditional drill press, lathe, grinder, or welding machine. By removing human operators and human error, AM greatly increases throughput yields for an application. AM machines are becoming capable of in-line process control, that is, inspection and error correction/avoidance to make real-time product certification possible. This capability is a big data, high-performance computing (HPC) function, which, combined with uncertainty-quantification (UQ) methods, is driving a revolution in product design and development.

Examples of newly possible AM objects include mini-octet-truss meshes (Figure 1) with the density of plastic foams yet the rigidity of metal structures. Even simple objects can be enhanced through AM. For example, a tripod support (Figure 2) that would have

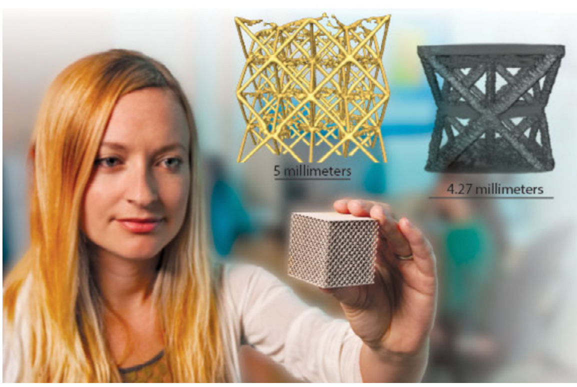

Figure 1. Mini-octet-truss structures.

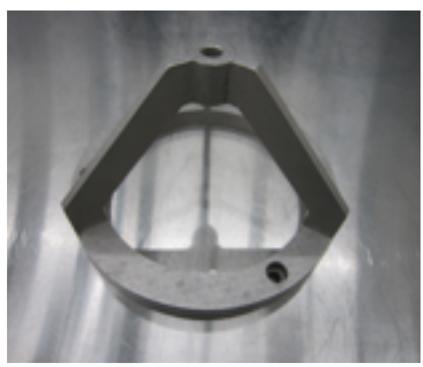

Figure 2. Tripod support manufactured monolithically.

required at least four processes on four machines, not to mention many welds for assembly, can be produced monolithically in a single step with AM.

Once loaded with a digital build file and material, AM machines can operate autonomously, twenty-four hours a day, seven days a week, greatly reducing the demand for skilled workers. Where multiple specialized machines were needed, each requiring the training and tacit knowledge of technicians and operators, now an operator less skilled than a machinist can load, start, attend, and unload many autonomous machines alone.

Combining the fact that one AM machine replaces multiple conventional machines with the relatively small size of an AM machine means that factory footprints can be reduced by a factor of 50 to 90 percent. A typical AM machine replaces many subtractive machines and would fit in the bay of a one-car garage with space to spare.

Logistics trains and warehousing needs are dramatically reduced under AM—you make what you need, when you need it, where you need it. There is now a "MakerBot" aboard the International Space Station; few facilities have a more difficult logistics train. Because digital build files obviate the need for expertise, logistics problems are reduced or eliminated, along with part rejection, and throughput is increased. For the military, there is no need to ship and store a part if you can make it on demand in theater or aboard ship. This is why the DoD, NASA, Boeing, Airbus, and GE are moving quickly to reap these benefits.

AM reduces or eliminates repetitive and costly "production prove-in" (PPI) processes. In traditional production, complex products require a proving in of the production line to assure a certified product. Once proved, the line is run to make a product lot, the lot is warehoused for future use, and the expensive-to-operate production line shuts down. When the production lot has been expended and more product is needed, the PPI must be repeated with all the costs of the initial startup. This is why production lines for major defense items are often kept open. By contrast, because AM digital files contain all product information, there is no need to do large production runs. The build files enable certified products to be made and supplied as needed, greatly reducing repetitive PPI work, product warehousing, and logistics-train costs.

These advantages are revolutionizing manufacturing. The Wohlers Report 2019[4] forecasts for 2020 is $15.8 billion for all AM products and services worldwide. The company expects that revenue forecast to climb to $23.9 billion in 2022, and $35.6 billion in 2024.

A Survey of Techniques

AM is a collection of technologies and technical solutions to manufacturing problems, most of which are subject to further development. AM innovation is spread across public and private institutions in the United States and overseas, and U.S. national nuclear laboratories. Lawrence Livermore National Laboratory (LLNL) has played a leading role developing a number of ambitious techniques.

Certification of Products

While some major AM methods are of special interest, all methods have the possibility of achieving piece-by-piece, real-time certification of a product. Continuous, high-resolution images of the production "weld pool" (see description below) are available on many AM machines. Harnessing this massive data stream to a real-time material-analysis capability could, in principle, enable in-line process control, error avoidance (not just correction), and ultimately, production quality certified on a by-component basis.

This multiscale (i.e., micro- to part-scale) simulation and big-data/data-mining problem demands large-scale HPC. The computers necessary are commercially available. Programs such as the Accelerated Certification of Additively Manufactured Metals (ACAMM)[5] initiative at LLNL could enable AM machines to produce in-process certified products with certification documented at the micro-scale throughout the item produced, all in real time. The ultimate objective of these efforts is to achieve "feed-forward" rather than feedback control of the manufacturing process, so that material behavior during a build is understood and anticipated such that no defects are produced. The approach is error avoidance rather than detection and correction.

Selective Laser Melting (SLM) and Selective Laser Sintering (SLS) Powder-Bed Technology

In the SLM and SLS processes, a digital representation of a complex metal part is "salami sliced" into thousands of paper-thin digital layers. These slices are used to produce patterns that direct a laser beam to selectively melt a thin layer of metal powder in the image of the slice. The weld pool referenced above is the place in the build process where the laser melts the powder. The process starts in a machine with a build platform that can be precisely indexed (i.e., moved precisely) down (see Figure 3). A sweeping re-coater arm lays a thin layer of metal powder across the build platform. The laser beam is directed to draw the first salami slice into the powder layer by melting it in the image of the slice. The build platform then indexes down by the thickness of the

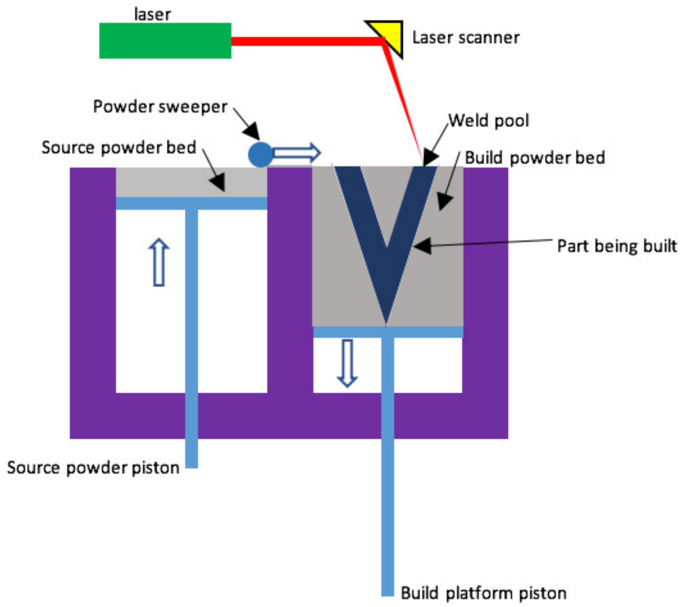

Figure 3. Typical selective laser melting/sintering process (SLM/SLS) commercially available from companies around the world.

next slice, the sweeper sweeps the next layer of powder across the build platform, and the laser melts the new powder in the image of the next slice.

This process is repeated over and over, with each slice slightly different from the last to build the cumulative whole. SLM and SLS is perhaps the most common form of metal AM manufacturing, available from a number of commercial suppliers.

Laser Direct-Metal-Deposition Technology (LDMD)

LDMD is a development in SLM technology that eliminates the need for a powder bed. Instead of being swept as thin layers of metal powder across a build platform, the powder is delivered through a nozzle as a fine spray, directly into the weld pool of the laser on the build platform. Here the build platform is more complex. Besides being able to index down by the thickness of a given digital slice, the platform can also index left and right, spin, and tilt. This is called a five-degree-of-freedom mount: it can move a part three ways in translation and two in rotation. The method affords a continuous build whereby the part seems to appear out of nowhere as the powder emerges from the nozzle into the weld pool to write the part upon the build platform (see Figure 4).

LDMD eliminates the extra powder needed in the SLM/SLS method to fill the build platform, reducing the total amount of powder required to make a part.

Some metals already demonstrated in SLM/SLS and LDMD processes are various stainless and tool steels, aluminum, titanium, copper, tungsten, and nickel-based alloys. An issue with powder-based AM, whether SLS, SLM, or LDMD, is that powders introduce purity and safety problems. Of particular concern are metals like aluminum or titanium alloys whose powders are flammable or even explosive when heated in the presence of oxygen; they must be worked in an inert atmosphere to avoid oxidation and possibly

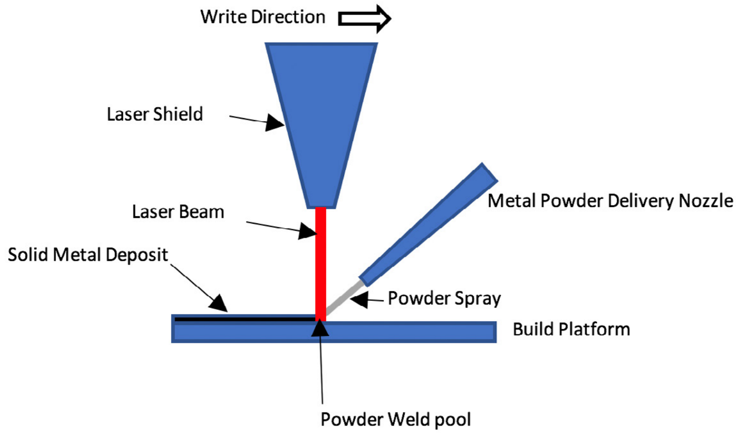

Figure 4. Laser direct-metal-deposition (LDMD).

explosive fires for the more reactive metals. The laser's intense heating of the powder may splash particles out of the weld pool, leaving voids and density irregularities. The intense heat in a small pool leads to high cooling rates, leading in turn to very small grain sizes and increased strength with decreased ductility. The complex build pattern and high cooling rates may induce high, nonuniform residual stresses that cause parts to warp. The smoothness of the surface finish is limited with this technique, and methods involving intricate laser-scan patterns have been developed to partly mitigate these problems.

Direct-Ink Writing (DIW) of various materials

Many are familiar with direct-ink writing, rapid-prototyping machines that heat and extrude plastics through a nozzle to write plastic models of various objects.

Analogous machines use the unique flow and gel properties of various materials to create products. An extreme example of the DIW of difficult materials is the creation of manufactured glass (e.g., a crystal vase) by MIT. LLNL recently demonstrated the DIW printing of precision-glass optical components,[6] and carbon-fiber materials have also been printed via DIW techniques. Materials in carbon-fiber resin and carbon–carbon composites have been DIW printed in a single step for extremely stressing aerospace applications like rocket-motor technology.

The cutting edge of DIW is direct metal write (DMW) technology. DMW starts with a metal ingot heated in a reservoir to a semisolid state consisting of solid metal particles surrounded by liquid metal. The metal emulsion is then pressurized and forced through a nozzle. The metal exhibits shear-thinning behavior: at rest, the solid particles clump, making it act like a solid. When the material is sheared, as through

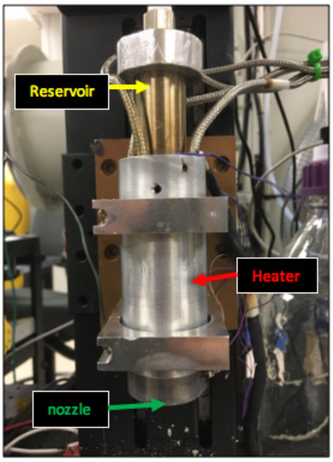

Figure 5. Direct-metal-write (DMW) apparatus. Image courtesy of Jason Jeffries, LLNL.

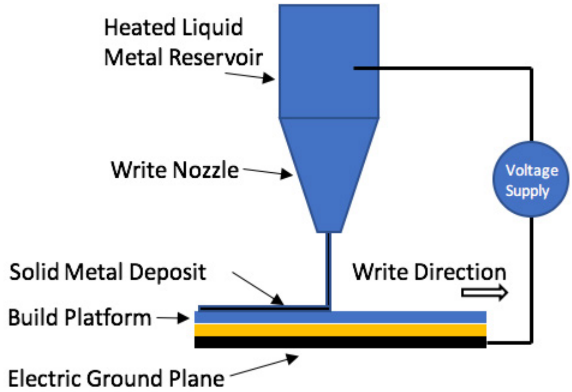

Figure 6. EHD-DMW schematic.

a nozzle, the particles break up and the system acts like a liquid matrix. Toothpaste is an everyday example of shear-thinning behavior. These systems need no powder, are minimally susceptible to incorporating oxide, and leave less residual stress in the final part as compared to laser-melting methods. A DMW apparatus is shown in Figure 5.[7] The molten metal would be written from the nozzle to the platform. These machines use pressure to push the partially molten metal through the nozzle. While useful for many manufactured objects, the relatively indirect control and inherent hysteresis in a pressure-driven system may be problematic in the production of precision components, and the issues of control and safety under pressure make this technique unsuitable for molten fissile metals.

Electrohydrodynamic (EHD-DMW) and Magnetohydrodynamic (MHD-DMW) Methods for DIW

A recent development in DIW technology is the electrohydrodynamic and magnetohydrodynamic control of molten metal within a DIW machine (for EHD-DMW, see Figure 6).[8] By placing an electric potential between the build platform and the molten-metal reservoir, the emission of metal from the nozzle can be precisely controlled by varying the voltage. By increasing the voltage, the flow of metal can be controlled from full stop to single droplets to a stream of droplets to a full stream of metal. Similarly, in MHD-DMW,[9] a precisely oscillating magnetic field at the nozzle can control the emission of metal droplets from the nozzle. Pressurization of the liquid metal is minimized, eliminating that hazard from the system. The cooling rate of the metal is manipulated by controlling the temperature of the build platform, thereby controlling grain structure and strength while avoiding residual stresses in the final part. In principle, one could go from ingot to part in a single step. Some minor final machining may be beneficial, but the bulk of the build is done in a single process.

Some Additional Methods

Physical vapor deposition (e.g., sputtering) and chemical vapor deposition are additive methods used for decades to place thin layers of metals on supporting substrates or mandrels. This old, relatively slow technique has limited application. Electrophoretic deposition (EPD) uses electrical fields to transport and order nanoparticles, layer by layer, to attain very special properties in applications such as ultralightweight armor and metalo-ceramic material creation. Projection micro-stereolithography is an additive method for creating microstructural materials on a large scale. It is used, for example, to make ultra-low-density structures— think structural smoke.[10] Continuous and chopped carbon fiber is also additively manufactured by DIW, for example, by Markforged Co. and LLNL.[11, 12]

Commercially available AM machines use electron beams (E-beams) to melt metal in powder beds or as wire fed into the beam. E-beam, wire-fed machines work much like SLM or DMW machines, substituting E-beams for lasers and wire for the powder bed or spray. They require that the E-beam be in a vacuum. Additionally, the metal must be in wire form, which presents a disadvantage, especially for fissile materials. The wire is fed into the weld pool of an electron beam (instead of a laser) for melting into a slice of the part to be printed.

Finally, volumetric 3D printing (tomographic or holographic printing) uses transparent liquid photoreactive polymers to solidify materials inside the liquid via a high dose of light energy that solidifies the liquid into a 3D shape.[13]

As noted, though many of these technologies are widely available, the more cutting-edge technologies, e.g., EHD and MHD DMW methods, are either in R&D or just recently commercialized. These technologies should be out in a few years as the advantages of ingot to product in a single box supplant powder and wire-based technologies. But as Yogi Berra said, “It’s tough to make predictions, especially about the future.”

What is clear is that AM is a very dynamic, rapidly developing set of technologies—so much so that this synopsis may well be out of date before it is published.

The Global Diffusion of AM

The United States is not the major player in AM and no longer has a monopoly on HPC leadership. The spread of commercial AM manufacturing and indigenous AM-machine production is worldwide. Most machine design and production, in fact, is offshore, in Germany, Japan, China, and the U.K., and part sourcing currently enables indigenous machine production.

In Turkey, for example, a sea turtle with a jaw broken by a propeller was rescued and brought to Pamukkale University's sea-turtle rehabilitation center in Denizli. The Turkish company Btech Innovation scanned the turtle to create a 3D model, designed and 3D-printed a titanium jaw, and mailed it to the rescue center, where surgeons attached the prosthetic (see Figure 7).[14]

Technology as challenging as the AM of titanium alloys is now marketed by an MIT startup called Desktop Metal, which boasts it will put titanium printers on engineers' desks.[15]

The ability to capture design for AM is readily available. The Australian publication Small Wars Journal notes:

> Though state and non-state actors will most likely continue to invest in traditional and contemporary methods of kinetic and non-kinetic engagement, digital fabrication represents a threat to state security due to its ability to provide those actors with rapidly produced and potentially untraceable means to achieve their desired end states.[16]

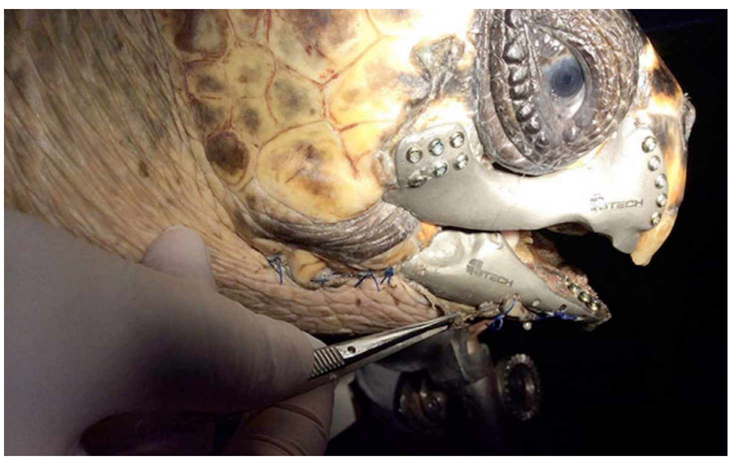

Figure 7. An AM titanium prosthetic turtle jaw made by scanning and AM fabrication. Image courtesy of Btech.

One way to achieve these ends is illustrated by the 3/10th-scale stainless-steel copy of a bust of E. O. Lawrence displayed in the LLNL administration building (Figure 8). This replica was made by scanning the bronze original to create an AM build file and reproducing it in a powder-bed machine. One could more easily use an iPhone to take pictures for the build file.

The Times of Israel notes that 3D printing could influence foreign policy by undermining sanctions:

> The U.S. has sanctioned everything from fighter jet spare parts to oil equipment. 3D printing could turn sanctions—which have been a crucial part of foreign policy for a generation or more—into an antiquated notion.[17]

Figure 8. A 3/10th-scale digital AM stainless-steel copy of the E.O. Lawrence bronze at LLNL.

If one can appropriate technology simply by photographing it, the theft of designs and other intellectual property becomes trivial. The implications of simple duplication with commercially available AM technology are evident.

In fact, many local AM-machine manufacturers are springing up across the globe. Three Iranian AM experts, combining knowledge and experience gained in England,

Figure 9. Iran's first indigenous SLM metal 3D printer. Image from NILI.

the United States, Canada, and Belgium, have launched the first selective laser-melting metal (SLM) 3D-printer in Iran (see Figure 9), claiming that:

> …the SLM-M100 3D-printer, developed by Noura Imprinting Layers Industry (NILI) is suited both for research and industrial applications in aerospace and military sectors, and will help to promote the scientific and technical industries of Iran while commercializing 3D-printing technology within the country.[18]

Pakistan is also developing an indigenous 3D printing industry. In discussing locally produced, low cost 3D printers, Luavut Zahid, writing in Pakistan Today,[19] observes that all future engineers will be trained to think additive first. Though prescient when published in 2014, this is common practice today.

A striking example of foreign AM development is an enormous powder-fed laser machine from China (see machine produced part in Figure 10). It is claimed that:

> …the primary force-bearing structure of the J-15 [fighter], including its landing gear, was formed by high-tensile titanium powder sprayed [LDMD] from a 3-D printer…. Lockheed Martin Aeronautics… needed 2,796 kg of titanium alloy to produce a F-22 fighter jet. According to Wang, only 144 kg of the material was actually present on the plane.[20]

Figure 10. Titanium force-bearing structure of J15 fighter, powder sprayed (DMD) from 3-D printer. Image from tiananmenstremendousachievements.

The Important Synergy Between High-Performance Computing and AM

To understand the power of HPC in additive manufacturing, it is important to look beyond the role of build files in guiding the machinery. As already noted, AM accelerates the fabrication cycle by as much as an order of magnitude; to this may be added the advantages of uncertainty-quantified, high-performance computing (UQ/HPC), which also accelerates engineering design. By combining AM and UQ/HPC, the iterative engineering design/prototyping cycle time can be slashed, cutting time to market and costs. This matters in commercial production, defense manufacturing, the nuclear security enterprise, and, unfortunately, in nuclear proliferation. In principle, under these combined technologies, the first prototype is the first production unit. In practice, the first prototype is often the 95-percent solution, but the 95-percent solution is often more than good enough.

What is UQ/HPC? UQ is essentially engineering safety factors on steroids. Since 2000, UQ has been the common Livermore and Los Alamos methodology for stewarding the nuclear-weapons stockpile without the need for nuclear tests.[21] UQ is used to establish nuclear-program priorities and provides the basis for certifying nuclear-stockpile decisions.

While it may appear that fielding complex engineered systems without full-scale testing is an unprecedented engineering feat, in fact many complex systems can be fielded without testing at scale by using adequate engineering safety factors.

Suspension bridges are a prime example—no one builds a suspension bridge and tests it to failure. Full-scale testing of a suspension bridge begins the day it is opened to traffic. Full confidence in the bridge's integrity is assured by building it to greatly withstand the worst combination of insults it may endure in its service life.

The example illustrated in Figure 11 is for a notional suspension bridge. The point at which the red line crosses out of the yellow box at the left of "normal daily conditions"

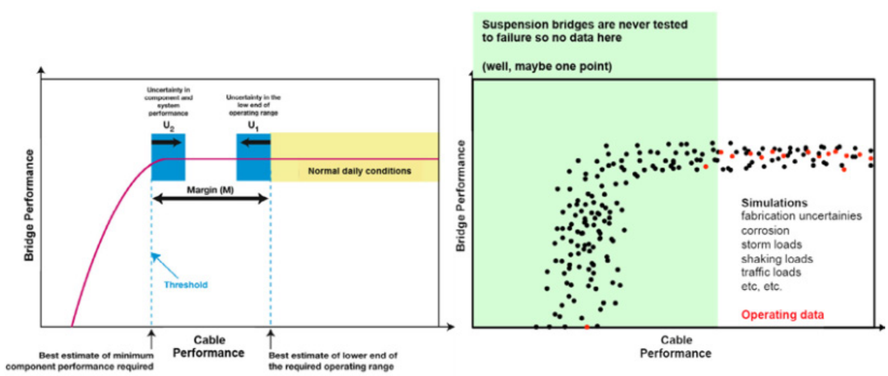

Figure 11. UQ as applied to a notional suspension bridge.

is the design engineer's best estimate of the worst-case load/stress condition for the bridge. The designer may anticipate the bridge at one hundred years of age, for example, suffering maximal corrosion, fully loaded tractor-trailer trucks halted nose to tail in traffic from both directions, and hurricane-force winds—when a major earthquake strikes. The bridge should be built to withstand these combined stresses. Hence, the crossing point on the red performance curve is far from the knee in the curve, the threshold where failure begins. A good engineer is humble, aware that some stresses will not be accounted for or adequately estimated. Hence, uncertainty (shown as blue blocks) is added to the margin estimates, and there is plenty of white space, i.e., extra margin, between the uncertainty blocks. The red points in the scatter graph illustrate notional daily operating data from this and other bridges. The red point near the bottom of the graph represents a singular failure of a bridge, such as the 1940 failure of the Tacoma Narrows Bridge under unstable aerodynamic oscillations caused by 40-knot winds.

Uncertainty quantification teaches engineering humility. Figure 12 depicts the effect on the span of the fiftieth-anniversary celebration of the Golden Gate Bridge. The bridge was closed to traffic for a day and the public was invited to walk it. It was not anticipated that 300,000 people would crowd the Golden Gate Bridge, creating the largest bridge load ever and causing it to sag between the towers. It sagged seven feet at mid-span and the tower tops moved in 6 inches. The span that day was concave up where it is normally concave down. The bridge withstood this extraordinary load because engineering safety factors for uncertainty were baked into the design process.

Returning to issues of stewardship, the illustrations in Figure 11 also apply to weapons performance. In this case, the black dots in the scatter graph may notionally represent the results of nuclear tests that the United States conducted. Cable performance (the x-axis) may be replaced by the performance of the weapon's first-stage trigger. Bridge performance (the y-axis) may be replaced by the full performance of the weapon. The principles of uncertainty quantification analogously apply. The normal operating range of the weapon must have its worst case represented by the left side of the yellow block, with a large margin to failure between that case and where weapons are likely to begin failing (i.e., the knee of the curve). By accounting for uncertainty, we can certify nuclear weapons without resort to nuclear testing.

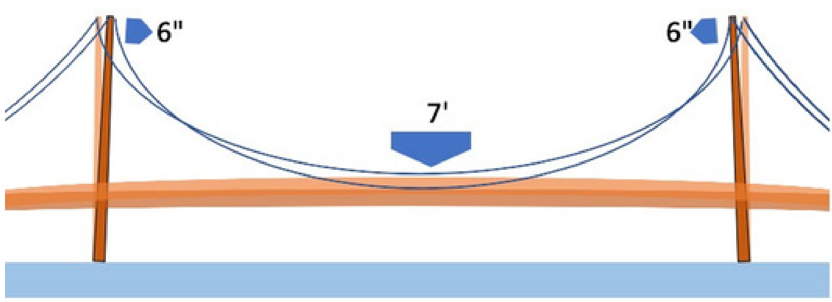

Figure 12. Pedestrian overloading on the fiftieth anniversary of the Golden Gate Bridge's opening.

AM and Nuclear Weapons

Over the last decade, additive manufacturing has matured in many significant ways. Technical barriers have been overcome. Technical approaches have also diversified, each tailored to a new manufacturing challenge. AM techniques have been widely embraced and the associated technologies are now available in a global market in which the United States is far from the dominant factor.

From the perspective of nuclear security, the technology raises a number of concerns. The principal components of a nuclear device are the core of fissile material, the surrounding chemical explosive lenses that start the spherical detonation of the main-charge chemical high explosive, and the casing.

For production of the casing, additive manufacturing would add the efficiencies already noted for commercial AM to the process but should not be expected to have a revolutionary effect.

For production of the chemical explosive lenses, the printing of energetic materials must be mastered. Work toward this end is underway at many laboratories around the world. Some progress is evident. Some laboratories have gone beyond printing homogeneous, monolithic energetic components and are using AM to print special energetic-materials architectures (see Figure 13). As one paper put it: "The researchers found that by creating the reactive material architectures, or RMAs, they could direct and manipulate the energy released by the material in ways never before possible."[22]

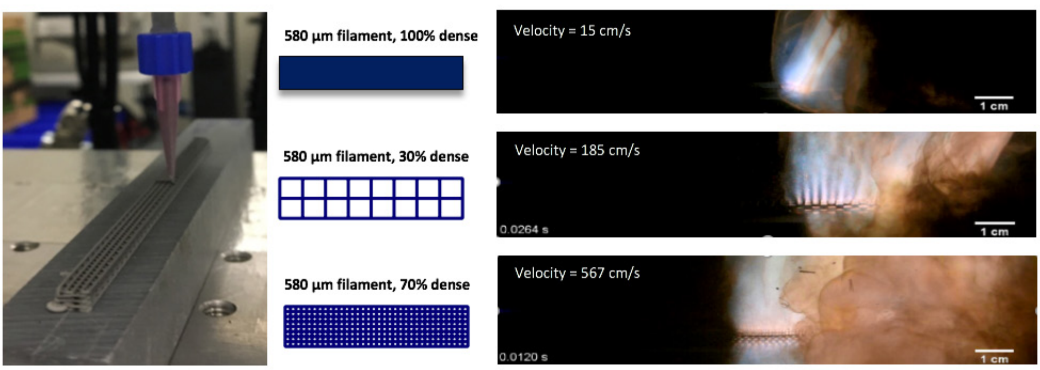

Figure 13. Directional reaction control via architected 3D-printed energetic materials. Direct ink writing of energetic material shown in left Image. Material architectures shown in center images. Reacting materials in right images. Images courtesy of Kyle Sullivan, LLNL.

For production of the fissile material core, the potential utility of AM is a matter of conjecture and deep debate. There is no reason to worry that powder-bed technology (SLS and SLM) will be used to manufacture nuclear-weapon fissile cores. This would not be safe. The problem is that as the slices of a part are built up layer by layer, the void surrounding the component on the build platform is progressively filled with metal powder thus creating the powder bed. In producing a fissile component, the powder bed would fill with fissile-metal powder and rapidly reach a critical mass of fissile material, such that a criticality accident is triggered, rendering the technique unsuitable for fissile-component production.

While the elimination of a powder bed in LDMD technology might seem an advantage in writing fissile-metal parts, the spraying of the powder into the weld pool by an aerodynamic nozzle causes overspray that delivers hot metal powder beyond the part under construction. The overspray sticks all over the build platform, the part, and the interior of the AM machine. While not a problem for ordinary metals, the contamination and buildup of fissile material in the machine and build platform is dangerous and wastes precious fissile powder—unacceptable results. While potentially useful in non-fissile component production, LDMD is not useful for fissile production.

EHD and MHD DMW technologies are the most interesting from a nuclear enterprise and proliferation viewpoint; they may avoid the fissile-material problems in the preceding methods. Though their applicability to fissile materials is uncertain, their potential cannot be ignored.

Potential AM Benefits for the U.S. Nuclear Enterprise

From the U.S. nuclear-security perspective, AM promises some important benefits. These benefits relate directly to high-level policy priorities set out by each presidential administration since the end of the Cold War. In the Nuclear Posture Reviews of each administration, leaders have expressed the commitment to maintain a safe, secure, and credible nuclear deterrent and to reduce nuclear risks and dangers where possible. They have also expressed their commitment to reduce the cost of these activities (a priority that has become more urgent as modernization of the weapons and delivery systems has begun) and to increase the agility of the weapons complex to deal with technical and/or geopolitical surprises. These latter two goals have gone unmet for decades. AM can be part of the solution.

The adoption of AM technologies to fabricate nuclear-weapons components would reduce the cost of stockpile sustainment, in part by freeing it from archaic original practices. Up to a 90-percent reduction in production floor space in a nuclear manufacturing facility may be possible. This is good news for these facilities, where new floor space is running ~$100K per square foot. Billions of dollars in cost avoidance may be possible if AM is developed for nuclear-component production.

Adoption would also increase infrastructure agility, strengthening the U.S. hedge against geopolitical and technical surprise and reducing reliance on a large stockpile of up-loadable weapons. Both goals have been long contemplated by political leaders and appear prominently in the nuclear-posture reviews of 1994, 2001, 2010, and 2017. A related benefit is reduction of waste streams and their deleterious effects on the environment.

AM provides needed flexibility in a security environment certain to bring unexpected technical and military problems. The ability to design, make, deploy, and employ weapons against new tactical and strategic challenges during a conflict is exceptionally important. Here, Admiral Alfred Mahan's observation in his seminal work, "The Influence of Sea Power Upon History: 1660–1783," is on point:

> Changes in tactics have not only taken place after changes in weapons, which is necessarily the case, but the interval between such changes has been unduly long. This doubtless arises from the fact that an improvement in weapons is due to one or two men, while changes in tactics have to overcome the inertia of a conservative class; but it is a great evil. It can be remedied only by a candid recognition of each change, by careful study of the powers and limitations of the new ship or weapon, and by a consequent adaptation of the method and using it to the qualities it possesses, which constitutes its tactics. History shows that it is vain to hope that military men generally will be at the pains to do this, but that the one who does will go into battle with a great advantage—a lesson in itself of no mean value.[23]

AM thus has value in strengthening the ability of the complex to deliver new nuclear military capabilities in a timely and efficient way when and if a future president and Congress call for them.

But to seize these advantages, the United States must overcome the prevailing culture of technical conservatism in the U.S. government and nuclear complex. Today's efforts to strengthen U.S. nuclear-weapons production capacity look more to the past than the future, resorting to old technologies to recreate old production approaches.

This Luddite approach leads to stratospheric and needless costs, which should be no surprise—imagine if an auto maker had to build a 1948 sedan by resurrecting the old assembly lines. The costs and daunting effort in recreating PPI processes for vintage technology are unsustainable. Similarly, decision makers in the nuclear enterprise strive to recreate lost capabilities, such that the enterprise and deterrent may cost an order of magnitude more than it might were AM broadly adopted. In their drive towards traditional methods, the same technical leaders forget that all salient manufacturing techniques have been nuclear tested and show no preference as to manufacturing method.

Future success depends upon the next generation of nuclear-weapons scientists and engineers using the full range of available technologies to sustain the deterrent and renew it with new designs. The best way to make the nuclear complex forward-thinking is to empower it with the best available technologies to fulfill its missions.

International Risk Factors

The risks associated with AM and nuclear weapons fall into five categories. The first is the risk that non-state actors might acquire an appropriate AM machine, the necessary software, the associated materials, and the necessary operational expertise to create weapons components. The odds of a non-state actor being successful in all of these endeavors is extremely small. But the risk merits a watchful eye.

The second is the risk that major powers with advanced nuclear-weapons programs might acquire and utilize AM technologies. Such states might seek the benefits catalogued above for the United States (cost reduction, agility). Their successful integration of AM would render their weapons programs even more difficult to monitor, reducing our confidence in our ability to assess and predict potential breakout capabilities and capacities. Accordingly, confidence would decrease in our assessments of the adequacy of the U.S. hedge and optimism that adversary ambitions for future weapons will be constrained by economic factors.

The third is the risk that entry-level proliferators (as opposed to those with significant nuclear latency) might attempt to integrate AM into their illicit efforts to develop an initial weapons capability or to develop more advanced capabilities. Their adoption of AM would have all of the consequences identified above for major powers. A proliferator program without a conspicuous industrial footprint or waste stream, with most work conducted via encrypted data, could generate huge proliferation surprises in the international system, including the sudden emergence of entire new arsenals and the empowerment of non-state actors in the manufacture of nuclear weapons.

The fourth is the risk that advanced non-nuclear weapon states might incorporate AM into their latent nuclear postures, readying themselves for breakout in reaction to a dramatic erosion of their security environment. Generally speaking, these states have high scientific and engineering capabilities and will be integrating AM into their economies for other purposes, which will greatly reduce the barriers to rapid and successful military application of AM. For those seeking a hedge, AM provides a low-cost, low-profile ability to break out without first developing the large industrial infrastructure typical of the P-5 states (i.e., U.S., U.K., France, Russia, and China). Costs, evidence of construction, material requirements, and general activities would be reduced and so more easily concealed, dramatically reducing breakout indicators and warnings. These states, too, will be influenced by AM's potential utility for the production of special nuclear materials.

The fifth risk is that the United States will compromise its position through delay and inaction. Its position today is one of technical advantage in applying AM to its stockpile sustainment requirements. It has done excellent exploratory work and can now "out-think" its competitors to useful applications. Proliferators appear to be in a less competitive position. Based on interviews with technical experts, I estimate that it would take a proliferator roughly three or four times longer to stand up an AM-based component production capability than it would take the United States.[24] If proliferators have already launched on this project, then our cushion of comfort is even smaller.

Conspicuously, none of these potential AM benefits to states seeking nuclear weapons or improvements to their nuclear postures enables them to overcome the fundamental challenge of gaining access to the requisite quantities of special nuclear materials. Uranium must be mined and enriched in a large-scale, time-consuming process detectable by various means, though AM techniques may help conceal some of the indicators of a centrifuge enrichment program. Plutonium must be harvested from reactors—also time-consuming and detectable.

Policy Implications

The fundamentals of U.S. policy vis-à-vis AM and nuclear security are sound. But some fine-tuning is necessary and appropriate at this time. The fundamentals are the following:

1. Monitor and assess the development and diffusion of additive manufacturing technologies and their impact on foreign nuclear weapons programs.
2. Severely constrain access to fissile materials through effective implementation of existing nonproliferation mechanisms, both formal and ad hoc.
3. Explore AM for its potential benefits for the U.S. stockpile sustainment program.

The fine-tuning that's necessary and appropriate at this time includes the following:

1. To support the monitoring and assessment work, determine whether AM techniques can be used to produce reliable fissile nuclear components. This is a place where the United States can and should be in the leading position. A reasonable reading of U.S. history and of the technology leads me to the conclusion that there is indeed a technical path to nuclear component production—which we must understand if we are to effectively monitor and assess. Only with this technical knowledge in hand can we anticipate possible future proliferation pathways, understand their signatures, and identify the potential opportunities to disrupt them.
2. In implementing nonproliferation mechanisms, resist the temptation to try to extend them into the AM realm. The players in the technical market are different from those in the nuclear market and the norms are as yet unformed.
3. The exploration of AM for potential U.S. benefits must move onto the next phase. Exploratory work is the basis of innovation, but it is not the innovation itself, which must be evident in changed practices. It's time to transition some of these technologies into the stockpile sustainment program and to make meaningful progress toward the goals of affordability and agility for an uncertain security environment. This is what out-competing our strategic adversaries requires.

This agenda reflects my assessment that the United States can seize the benefits while effectively managing the risks of AM. The counter-hypothesis is that risk reduction requires significant restraint by the United States—that is, that the United States should not more aggressively pursue AM for stockpile sustainment as a way to disincentivize others from doing so. This counter-hypothesis has its roots in a time when proliferation technologies and the associated know-how were controlled by a powerful few. Today's AM landscape is entirely different, with the technologies and know-how widely dispersed and the United States not in the leading industrial position. U.S. rejection of AM as a tool of stockpile stewardship is unlikely to have any significant effect on the efforts by other states to acquire, understand, and integrate AM into their nuclear and other military programs. The National Security Strategy is right to emphasize the need to strengthen our competitive position.

Closing Observations

Following the advice of George Shultz, we should look beyond the disruption caused by advancing technologies to their implications and our responses. And as the National Security Strategy argues, we must strengthen our competitive posture. Our national approach to AM and nuclear security should seek the benefits of AM while minimizing its risks. The potential benefits for the United States of integrating AM into the stockpile sustainment program are significant, by helping us to achieve long-term policy goals related to affordability and agility. The potential risks of AM are numerous and include heightened proliferation risks and new proliferation pathways that will be more difficult to detect and monitor. But these risks will exist regardless of how aggressively the United States pursues AM, as all the technologies necessary to additively manufacture a nuclear explosive are, at this time, either commercially available or under development at research institutions around the world. It is essential that the U.S. push the boundaries of AM technology to demonstrate whether fissile-material components can be fabricated. If they can, new steps must be taken to strengthen nonproliferation. If they cannot, we can breathe a collective sigh of relief that additive manufacturing will be less disruptive to nuclear security than we have feared.

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