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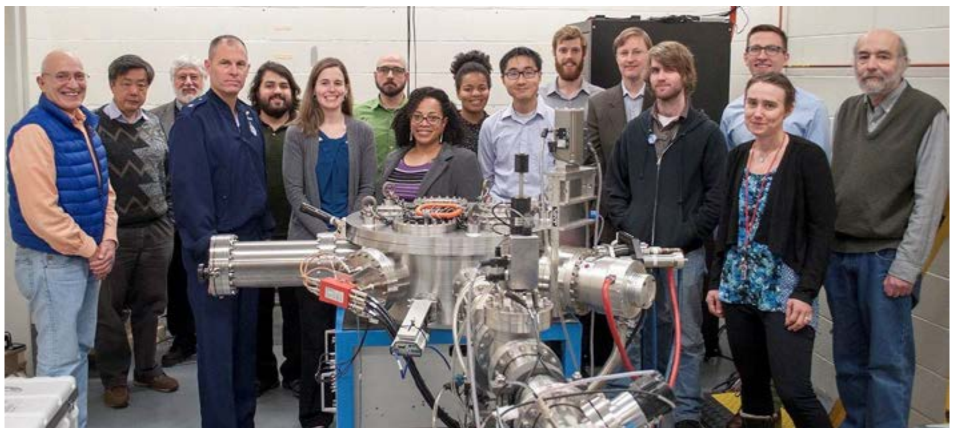
Message from the Assistant Deputy Administrator for Research, Development, Test, and Evaluation, Dr. Kathleen Alexander

This issue of the *Stockpile Stewardship Quarterly* focuses on additive manufacturing (AM), or three-dimensional (3D) printing from digital models. To significantly reduce cost and schedule risk associated with the development and production of components, the National Nuclear Security Administration (NNSA) laboratories and sites are exploring the development of an array of advanced technologies, including AM and 3D printing. This issue introduces representative work on AM at the NNSA national laboratories and Kansas City National Security Campus (KCNSC).

Los Alamos National Laboratory provides us with an introduction to AM and describes the key challenge of qualification of an AM material for an application using this innovative new approach. The article also describes the latest work with AM metal processing using advanced diagnostics. The next article from Lawrence Livermore National Laboratory (LLNL) describes the history of AM and current programs. LLNL is combining materials in new ways, creating materials with properties not found in nature. Specifically, LLNL is pursuing a comprehensive modeling and simulations strategy for accelerating parts qualification based on a successful multiscale modeling framework. Sandia National Laboratories (Sandia) is transforming the way that non-nuclear components are developed and produced using AM. The article, written in close collaboration with KCNSC, details the extensive material testing and characterization that has been performed to quantify material properties and process variations. KCNSC closes the quarterly with an article describing the interesting history of how Honeywell encouraged the adoption of AM. It also takes us through the detailed methodical process that KCNSC uses to create AM parts.



Academic Partnerships. Brigadier General Michael J. Lutton, NNSA Principal Assistant Deputy Administrator, and Dr. Njema Frazier, Acting Director, Office of Inertial Confinement Fusion, toured the Massachusetts Institute of Technology HED/ICF Division's laboratory in January. For more information, see page 12.

As you can see from this issue, exciting things are happening within the nuclear security enterprise. We also highlight two Sandia Presidential Early Career Awards for Scientists and Engineers recipients, as well as our university partnerships (see photo above). Continue to do great work.

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The *Stockpile Stewardship Quarterly* is produced by the National Nuclear Security Administration (NNSA) Office of Research, Development, Test, and Evaluation. Questions and comments regarding this publication should be directed to Terri Stone at terri.stone@nnsa.doe.gov.
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Additive Manufacturing at Los Alamos National Laboratory: Using Advanced Characterization to Explore the Science of a New Manufacturing Method

by John S. Carpenter, Donald W. Brown, Bjørn Clausen, Jason C. Cooley, David F. Teter, and Mark A.M. Bourke (Los Alamos National Laboratory)

Additive manufacturing (AM), or three-dimensional (3D) printing as it is more commonly known, is defined as the process of joining materials and creating objects by melting, sintering, or fusing material in a layer-by-layer fashion coordinated via 3D model data.[1] Subtractive, or traditional, manufacturing methodologies often consist of machining/removing material—like a sculptor—or forming material through the application of pressure—like a potter. Conversely, in an AM process, material is added in individual volume elements and built up in a way similar to interlocking building blocks, but with volume elements that are typically the size of a grain of sand. The additive process often involves less waste when compared to subtractive techniques because material is only added when and where it is needed. Adjustments to the final structure are relatively straightforward and can be simply achieved by adjusting the 3D computer model. This makes the technology much more flexible than traditional, subtractive techniques where new tooling or forming equipment is usually needed to accommodate design changes. Also, the AM processes are beneficial because they permit the fabrication of unique geometries, such as miniaturized metal lattice structures, that cannot be achieved using traditional techniques. An example of a metal lattice structure is the Eiffel Tower with its geometric, interconnecting struts that reduce the overall weight of the tower while maintaining strength. In AM, the size of the struts can be made smaller than the diameter of a human hair, which further reduces weight while maintaining strength—a combination of properties that can benefit many applications.

Although AM shows great promise in reducing time needed for fabrication, cost, and waste, there are challenges. Qualification of AM material is a key challenge that must be overcome before widespread introduction of AM-produced parts in property-critical applications. Historically, manufactured parts have been qualified for use through a process-based strategy. In this strategy, strict guidelines in manufacturing are imposed which, when followed, guarantee that the part will meet performance requirements. Such process-based strategies have been successful but were developed over decades or even centuries of iterative 'trial and error' experiments where the effects of small variations in processing on performance were noted. An example is ancient Arabic metalsmiths and their ultra-tough Damascus steel sword blades. The outstanding performance was due to carbon nanotubes—a potent, nanoscale metal strengthener understood only recently.[2,3] The ancient metalsmiths could not know why their blades were tougher, but they did know that by following a specific manufacturing process, their swords would outperform their rivals.

As seen in the previous example, with modern technology there is a maturing understanding of how traditional processing approaches lead to microstructure (what the material looks like under a microscope), which dictates the properties (like strength or density) which, in turn, controls performance. These interconnected relationships are called process-structure-property-performance (PSPP) relationships. Despite this new knowledge, the process-based qualification strategy is still nearly exclusively used in all industrial manufacturing processes.

The challenge for qualifying AM parts is the lack of experience in this innovative new approach. Decades and centuries of experimental results on AM materials are not available. The potential solution is to qualify a product rather than a process. By connecting targeted experiments with advanced simulation tools, a predictive modeling architecture can be developed for AM PSPP relationships. The simulations would then provide processing conditions based on performance requirements. This approach is opposite to a process-based strategy and can be termed science-based qualification (SBQ). It is a new way of doing business and is a large, multi-disciplinary problem, exactly the type of problem at which national laboratories, such as Los Alamos National Laboratory (Los Alamos), excel. Figure 1 provides a schematic outlining some of the current metal AM projects and how they are developing the critical linkages needed for SBQ between experiments and simulations.

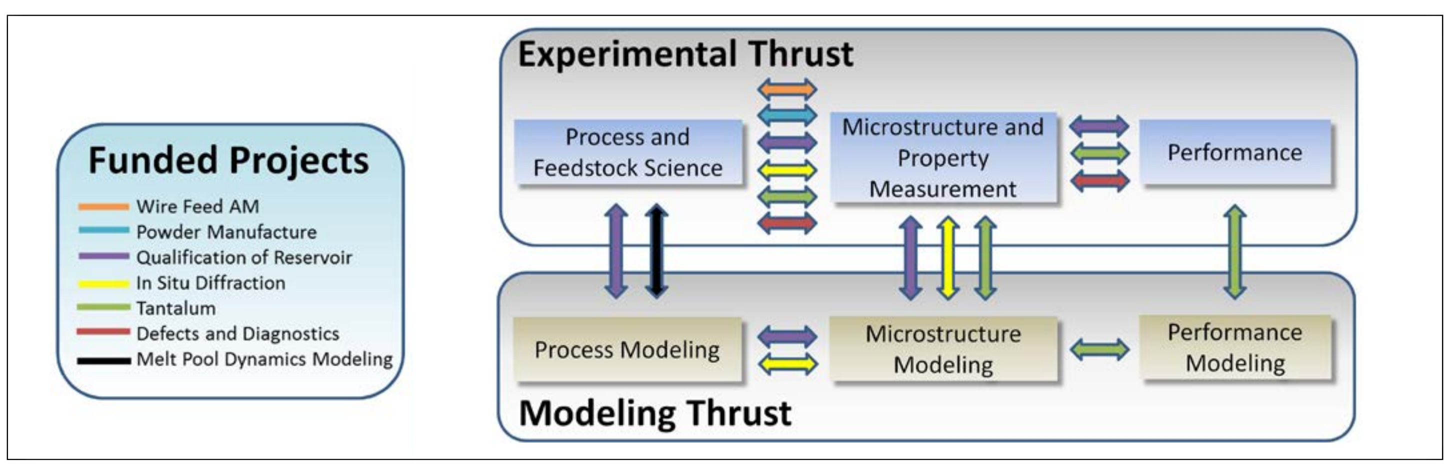

Figure 1. Schematic showing required linkages between experimental and modeling thrusts in order to achieve science-based qualification. Arrows showing linkages are color-coded according to the funded projects listed.

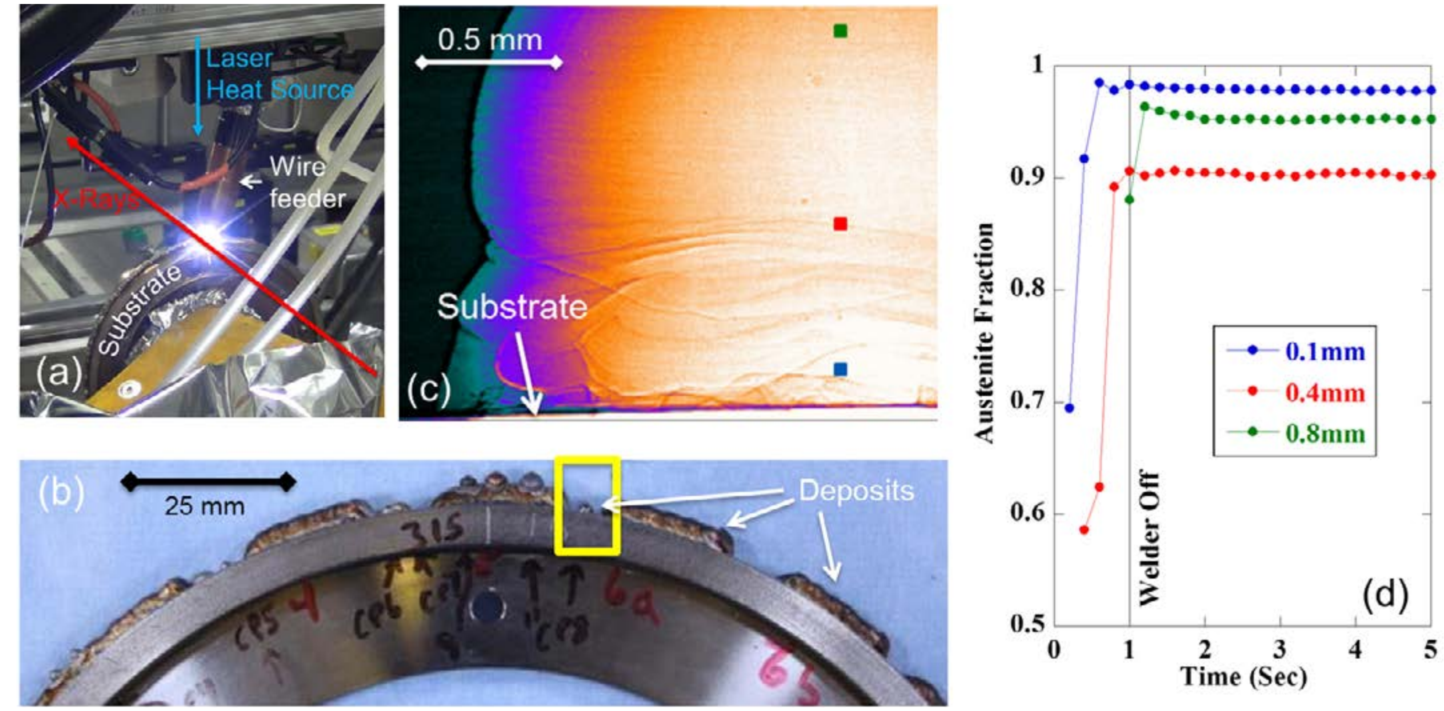

Figure 2. (a) The wire feed AM device deployed in a beamline at Argonne National Laboratory. The wire feeder deposits stainless steel on the rotating substrate while x-ray data are collected. (b) Substrate with various depositions. The yellow box marks the deposit of interest. (c) X-ray radiographic image of the marked deposition from (b) with diffraction collection locations marked by colored dots. (d) Plot showing the fraction of austenite present at each location in (c) as a function of time. The plot indicates that evolution of austenite fraction during cooling and final austenite fraction is location dependent.

The yellow arrows in Figure 1 indicate the specific project (In Situ Diffraction) that will be discussed in greater detail in the remainder of this paper. It should be noted that a similar diagram could be constructed for the various non-metal projects currently underway at Los Alamos.

A critical linkage depicted in Figure 1 is the relationship between process and microstructural modeling. In metal additive manufacturing, the process modeling captures the time period where the heat source has created a molten pool of new material. As the heat source moves away, the metal cools and solidifies. The rate at which the material solidifies determines the microstructure which, in turn, dictates the material properties. AM metal materials cool at rates of 10^3-10^5 °C/sec, which is a million times faster than traditional casting processes. For these rapid cooling rates, models predicting the evolution of metal materials from a liquid to the final, solid microstructure are either unavailable or have not been validated. To understand and control materials under such extreme conditions, new models informed by experiments that link the process science to the microstructure are needed.

To that end, Los Alamos has constructed a unique device (see Figure 2a) that allows for x-ray diffraction data to be collected *in situ* during additive manufacture in order to provide unique data needed to link process science to material and property characterization, as seen in Figure 1. The remainder of this paper will focus on a specific experiment performed with this rig using stainless steel.

At a high level, as stainless steel solidifies and cools, atoms of material organize into one of two configurations. The two configurations, or phases, are called austenite and ferrite with each having a distinct set of properties. Austenite, for instance, is magnetic while ferrite is non-magnetic. The fraction of each phase in the final microstructure will determine properties and, therefore, performance of the final part. The diffraction results seen in Figure 2d were collected to assess the phase evolution of the stainless steel both during cooling and at room temperature.

A molten drop of material was probed in three locations as seen in Figure 2c with the blue, red, and green dots representing data collection locations at 0.1, 0.4, and 0.8 mm from the substrate, respectively. The size of the dots in Figure 2c provides an accurate representation of the x-ray spot size (0.05 mm) as compared to the point deposition of material which was 3 mm in diameter.

Figure 2d provides the quantified phase fraction results for each of the three locations as a function of time with diffraction data collected every 0.1 second. To the left of the black line labeled 'Welder Off,' the diffraction results record the austenite fractions for the solidified material as it cools. To the right of the black line, after the heat source has been turned off, the evolution of austenite phase fraction decreases quickly and the microstructure saturates. These results indicate that ferrite transforms to austenite at different rates depending on position within the point deposition. Additionally, the results provide a unique window into the location-specific nature of the microstructure with the amount of austenite varying as a function of distance from the substrate. Accurate microstructural models will need to be able to predict the non-linear variation in phase evolution as a function of position within the AM material.

With these data in hand, simulations can now select from various proposed pathways of getting from the liquid state to the final solid state and create an accurate model. Further experiments are underway that will provide a finer time resolution to collect more data points during the critical time where the solidified microstructure is evolving. An increase in number of data points will translate into simulations with reduced uncertainty. In addition, the effect of process parameter variation on phase evolution will be studied in both the initial layer deposited and the subsequent layers. With more data in hand, a predictive simulation is foreseen where the final microstructure (and, therefore, the properties and performance) can be known *a priori*. This is an important step in turning the promise of AM into reality.

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Metal Additive Manufacturing *by Wayne E. King, Andy Anderson, Jean Luc Fattebert, Rishi Ganeriwala, Neil Hodge, Saad Khairallah, Manyalibo Matthews, Alexander Rubenchik, Otis Walton, and Morris Wang (Lawrence Livermore National Laboratory)*

Additive manufacturing (AM), the layer-by-layer creation of three-dimensional (3D) parts and components from digital models, is sparking a worldwide revolution in manufacturing. Described and defined in this article is AM and the unique role of Lawrence Livermore National Laboratory (LLNL) in this rapidly expanding research and development area.

Additive Manufacturing History

AM, better known as 3D printing, is not new; in fact, one of the longest-running technical conferences on the topic just held its 27th annual meeting. For much of its history, most additively manufactured objects were made from polymers. Additively-manufactured metal parts were first demonstrated in the 1990s,[1] but were slow to catch on, as the poor coupling of carbon dioxide laser light with metals made the manufacture of full-density parts difficult to achieve. A significant step forward came with the introduction of the fiber laser in 2005. With this new laser, improved part quality was achieved—the 1-micrometer-wavelength light generated by the fiber laser is much more effective in melting metals than the 10.6-micrometer light from a carbon dioxide laser. The first commercial machine with a fiber laser was delivered in 2006, and the first production part was manufactured for the aerospace industry in 2012. Since then, metal AM has grown exponentially.

LLNL is presently playing a leading role in AM by advancing the science of AM, combining materials in new ways, and creating materials with properties not found in nature.

LLNL's Emerging Role

LLNL is presently playing a leading role in AM by advancing the science of AM, combining materials in new ways, and creating materials with properties not found in nature. At LLNL, deep experience in precision engineering, materials science, and high-performance computing combines with a dedicated research and development program to enhance and advance this technology and its applications.

LLNL has been using AM for years to make scale models with acrylonitrile butadiene styrene (ABS) plastic. The more recent move—since 2011—into metals, ceramics, semiconductors, and other materials, opens new opportunities.

Advantages, Disadvantages, and Costs

AM provides a number of advantages compared with traditional subtractive manufacturing, including access to new levels of complexity, reduced need for tooling, weight reduction, part consolidation, and reduction in production steps. Disadvantages, however, include slow build rates, relatively high production costs, high cost of process optimization, relatively poor surface finish and dimensional accuracy, and limited part size.[2] Given these tradeoffs, AM is particularly appealing for manufacturing involving low-volume, high-value parts, including parts that simply cannot be made by other methods. An example of such a part is a lattice, which is a type of cellular periodic structure with dimensions in the range of a few millimeters.

Generally speaking, AM will be cost effective for low volume, high complexity production. The cross-over point where conventional manufacturing will become more cost effective than AM is a function of the recurring cost of the manufacturing process.[3] A driver for cost is the slow build rate in powder bed fusion systems. An important, but perhaps less tangible, consideration is AM's versatility. Small lots of high-value, complex parts can be produced very quickly, and if a change is needed (assuming that the part can be qualified), only the computer-aided design need be changed before building the new parts. Thus, the lifecycle cost advantages of AM may in many instances be more significant than any potential production cost disadvantages.

LLNL's Role in Ensuring Fulfillment of Qualification Requirements

Part qualification for any industry can be costly and take a long time (up to a decade)—attributes that offset the speed, versatility, and adaptability of AM. Thirty-two percent of manufacturers surveyed indicated that uncertain quality of the final product was a barrier to adoption of AM.[4] Most road maps for AM suggest that modeling and simulation will play a key role in accelerating qualification.[5,6]

LLNL is pursuing a comprehensive modeling and simulations strategy for accelerating parts qualification based on the successful multiscale modeling framework illustrated in Figure 1. This strategy includes:

- **Powder dynamics.** A discrete element model of the spreading of the powder layer.
- **Powder model.** A finite element model of the interaction of the laser with the powder bed, melting of the powder, flow of the molten metal, and solidification.[7]
- **Microstructure model.** A phase field model of the solidification of the liquid and development and evolution of the grain structure.[8]
- **Effective medium model.** A finite element model based on a LLNL code that models the building of a complete part and predicts residual stress and distortion.[9]
- **Intelligent feed forward algorithms.** A new methodology focused on improving part quality using advanced models.

The multiscale modeling strategy employs an information-passing methodology with critical information shown in the arrows being passed between scales. The output of our process models can feed into models that are used for prediction of material properties and performance of materials.

Because simulations are only as useful as the models and the input data, our simulations are underpinned by validating experiments. Over the last four years, our experimental work has provided important insights into how the laser interacts with the metal powder.[10] High-speed imaging of the melting process has revealed missing physics in the powder model that is now being added.[11] Extensive material characterization, including density measurements, metallography, x-ray diffraction, electron backscatter diffraction imaging, transmission electron microscopy, focused-ion-beam microscopy, and mechanical testing play a critical role in understanding the role of processing parameters in controlling part properties and performance.

LLNL has demonstrated a significant improvement in part quality compared with the current approach using an early version of model-based intelligent feed forward. Following is a discussion of the critical need for part qualification and how model-based intelligent feed forward can help.

Qualification has three major components: physics and engineering qualification, production qualification, and materials qualification. Because with AM the material is being created at the same time as the part, materials qualification becomes an issue. The experimentally validated models describe what can be expected from a build carried out with specific input parameters, but such predictions alone do not provide the accelerated qualification that is required. Today (Figure 2a), LLNL uses extensive, iterative experimentation to optimize input parameters such as the laser power, speed, and beam size for the process. However, because the thermal boundary conditions change as a function of the part geometry, the parameters required to achieve desired part quality will also be a function of geometry. In current powder bed fusion systems, geometry-specific parameters can be entered only for simple geometries such as overhangs or thin vertical walls. During the build, data are collected from *in situ* process sensors. *In situ* sensors and feedback schemes aid

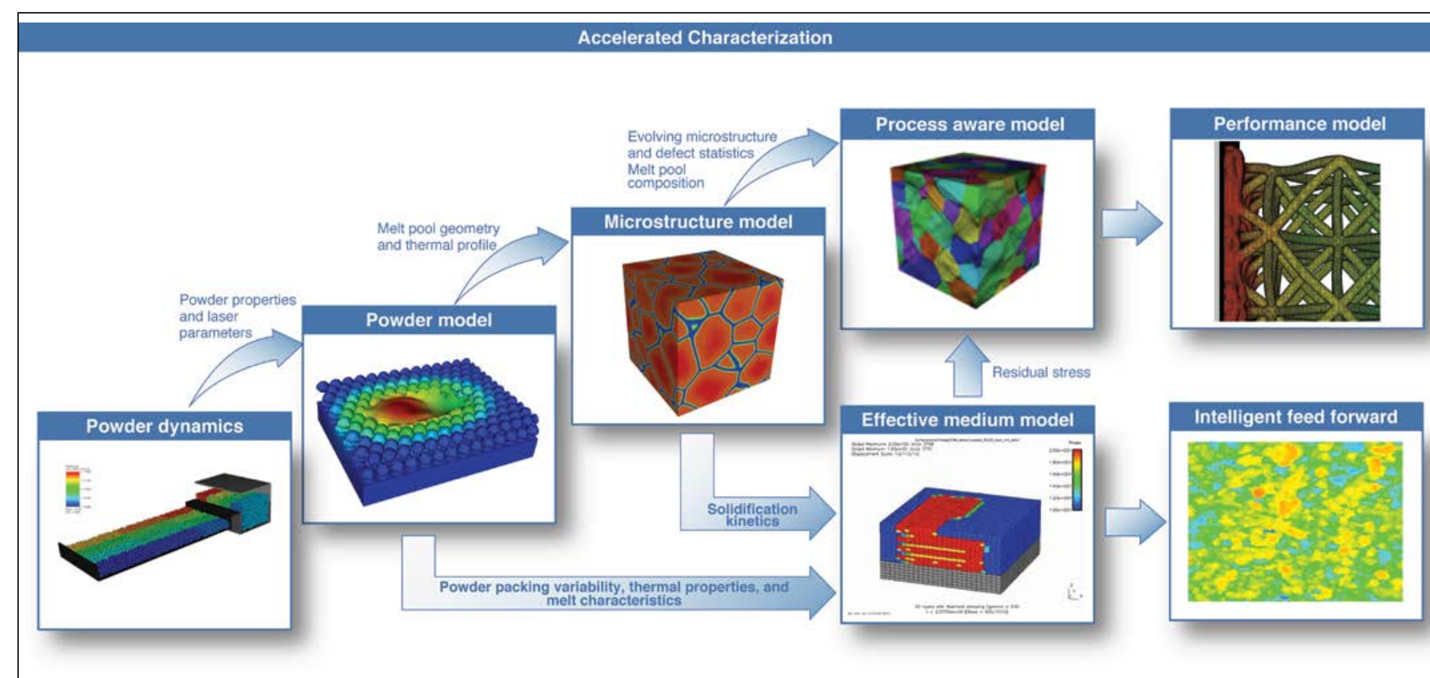

Figure 1. Multiscale modeling framework employed at LLNL as part of the accelerated qualification of additively manufactured metals project.

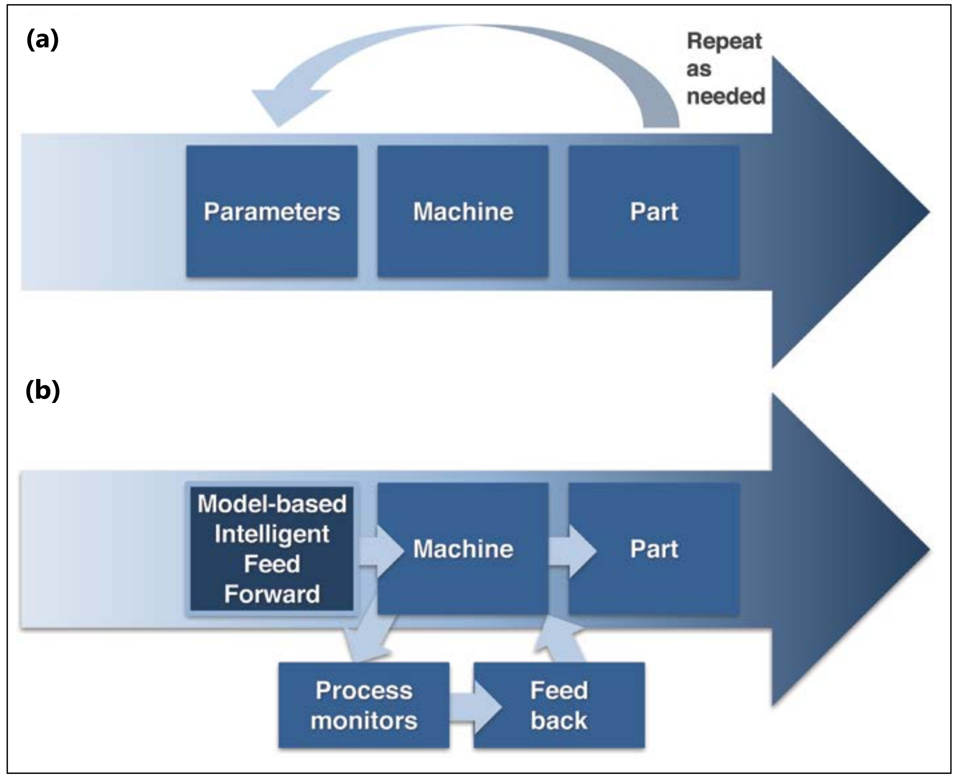

Figure 2. Work flows for the material qualification process. (a) The iterative process used today to develop optimized manufacturing parameters and (b) our vision for model-based intelligent feed forward where simulation is used to teach the machine how to build the part and process monitoring is used.

with process control. Feedback works best when the input parameters are close to optimal for the given geometry. Achieving the needed control throughout a part build requires point-by-point control of the input parameters. The vision of achieving precise, optimized input parameters is referred to as *a priori*[12] or "intelligent feed forward"[3,13] control, Figure 2b.

Modeling and simulation, combined with high-performance computing optimization and targeted layer-by-layer diagnostic monitoring, have the potential to move LLNL to the next stage in controlling the process. Using this approach, the simulation will be used to *teach* the machine how to build the part on a point-by-point basis and at the same time predict the output of the sensors. Because simulations cannot be expected to be perfect, feedback control will be used to correct the simulation-based build. After the build is complete, the sensor data will be compared with the simulation's prediction. If the prediction and the experiment agree within some specified uncertainty, it likely will be possible to establish confidence with product engineers that the material is of the required quality to fulfill mission requirements.

When the desired accelerated qualification is achieved using the process models described above, AM will provide unprecedented flexibility and agility. A fully developed AM capability enables components and features not available through current manufacturing processes and makes more likely the adaptation of AM technologies. The feed-forward approach, when successfully implemented, will ensure "right every time" production or early automated rejection, thus buying down risk. The approach is meant to be independent of feedstock, machine, and geometry.

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Transforming the Development of Non-Nuclear Components Using Additive Manufacturing

by Bradley H. Jared (Sandia National Laboratories)

Additive Manufacturing's Benefits for Product Development

Sandia National Laboratories (Sandia) is using additive manufacturing (AM), or as sometimes called three-dimensional (3D) printing, to transform the way that components are developed and produced. The ability of AM to rapidly generate complex parts directly from a computer model provides agility that is invaluable to product design and development. Small lot quantities of prototypes, test hardware, tooling and fixtures can often be fabricated more quickly and less expensively than through traditional manufacturing methods. Therefore, risks are reduced since designs can be conceptualized, manufactured, evaluated, and improved quickly and cost effectively. The number of 3D printers in use at Sandia is growing due to their benefit for rapid prototyping.

Sandia has a rich history of pioneering AM technologies to impact engineering design as it developed two of the first processes to print metals and ceramics, Laser Engineered Net Shaping (LENS®)[1] and Robocasting™,[2] respectively. These and other processes have been used since for prototypes to shorten development schedules. Recent efforts are addressing barriers associated with AM material quality and reliability. Researchers are also developing new capabilities to increase Sandia's ability to quickly and reliably respond to new requirements.

Two examples are representative of the impact AM has provided to our efforts. Recently, Sandia and Los Alamos National Laboratories collaborated to fabricate a prototype that was cheaper and faster than prior prototypes by roughly 75%. The unit was assembled using printed plastic parts, was the earliest ever realized in a design cycle, and allowed engineers to accurately evaluate assembly. Similarly, Sandia rapidly adopted AM to support tooling, molds, and fixtures for development and production activities, resulting in reduced costs.

Producing Stockpile Components Using Additive Manufacturing

Since AM has routinely provided reductions in development costs and schedules, there is motivation to realize similar gains for other parts, not just support hardware. Multiple parts have been explored for the recent development programs to evaluate opportunities and challenges associated with AM. Opportunities for metal parts have focused on housings with geometries that can only be fabricated by AM. This work is also being leveraged by other programs to explore AM to realize cost, schedule, and performance gains.

A critical challenge in applying AM to parts is to ensure that printed parts and materials satisfy requirements. Material and part geometry are formed simultaneously in AM. While this presents revolutionary opportunities, it introduces the potential to generate defects during fabrication and/or unacceptable material variations. Additive materials also exhibit behavior that differs from traditional forms with equivalent chemical composition since they are different at the microscopic level. Such behavior, particularly as it relates to material reliability and performance under extreme environments, must be quantified and optimized before Sandia can assure that a part meets requirements.

The exploration of additively manufactured parts has involved close collaboration with production. Extensive material testing and characterization has been performed to quantify material properties and process variations. Coupling these results with part tests and performance simulations provides a methodology to establish performance. Part acceptance is a critical hurdle for additively manufactured parts. Potential paths to part acceptance have also been explored that combine destructive testing of parts and material samples, inspection using computed tomography, and strict definition and control of input material and machine operating parameters. There is still work to be done in all of these areas, but significant progress has been made.

AM's ability to rapidly generate parts and materials is a benefit for development engineers, but it presents a unique problem to material scientists since material characterization techniques are time consuming and can slow progress. Sandia engineers are addressing this challenge by generating

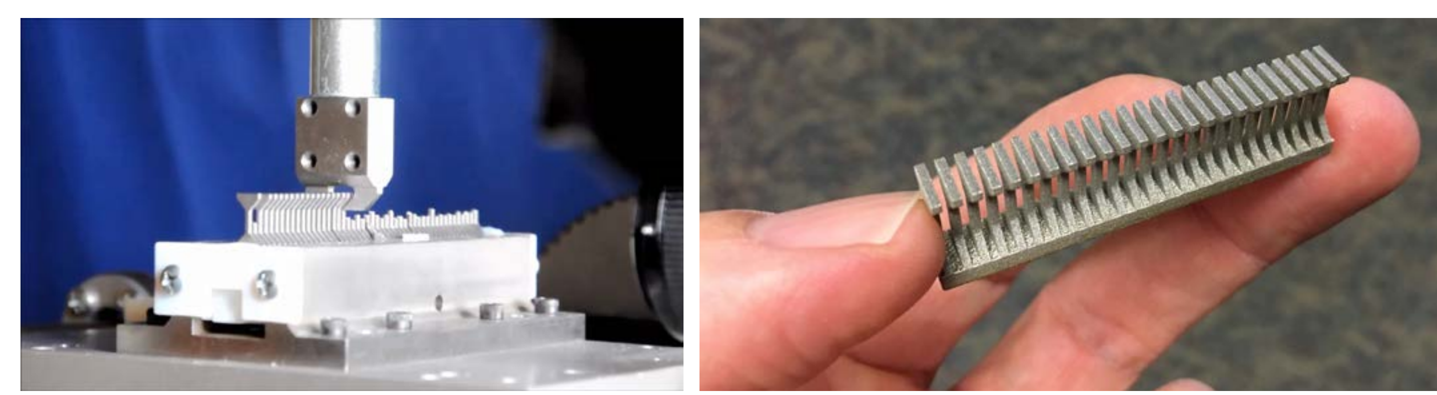

Figure 1. A test platform for automated high-throughput tensile testing of AM materials (left). A test "cartridge" with 25 samples printed in stainless steel (right).

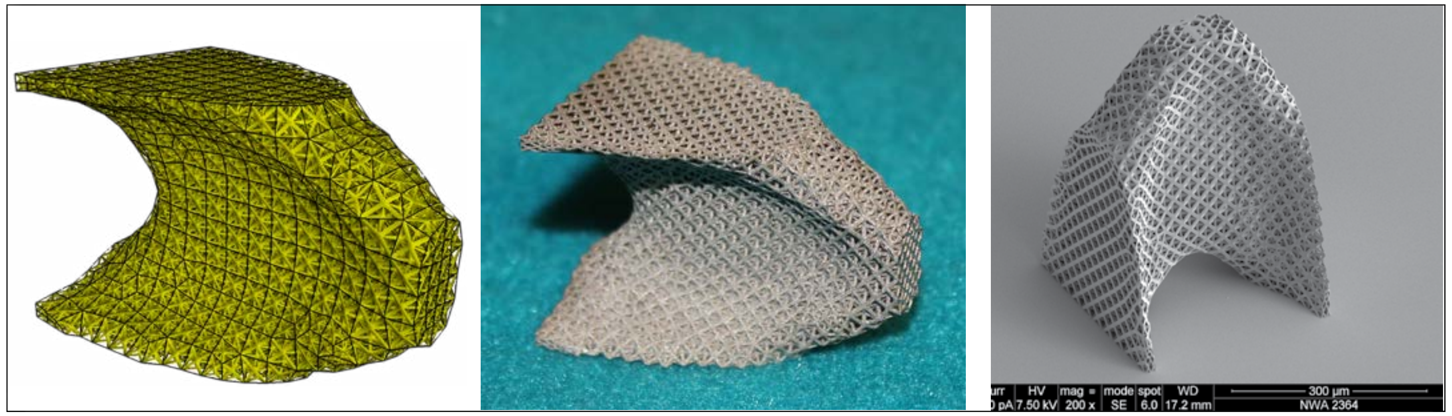

Figure 2. A structure (left) designed in PLATO with tetrahedron lattices[4] that was fabricated in stainless steel (center) and photosensitive polymer (right).

high-throughput techniques for material characterization.[3] Figure 1 shows an automated tester and subsequent test "cartridge" with 25 material samples that measures the strength of structural materials with test times of one to two minutes per sample, compared to one to two hours for traditional techniques. As a result, the statistical variations in additive materials can be captured quickly and cost effectively.

Changing the Engineering Paradigm Using Additive Manufacturing

Although improvements to experimental methods are necessary and invaluable, a new paradigm is being explored at Sandia to further accelerate the development cycle. This vision will couple high-throughput measurement techniques, knowledge of process physics, sophisticated computer models, real-time process sensors and data analysis tools to optimize, predict, and control the performance of additive processes and materials. Process models are in development for metal and ceramic processes that describe the physics at multiple size scales.

Work on material models is capturing the influence of internal, microscopic material structures which is crucial for predicting part performance and variability. Since AM machines provide minimal information during fabrication, researchers are also investigating various sensor technologies combined with data analysis techniques to detect, control, and/or eliminate performance-degrading part defects. When realized, this vision will provide an unparalleled capacity to rapidly ensure that AM products will reliably meet performance requirements.

While AM provides the ability to generate complex geometries and materials that cannot be realized using traditional manufacturing techniques, existing design tools are incapable of fully exploiting this potential. Therefore, Sandia is working to develop analysis-driven design tools that capture and leverage the full potential of AM. PLAtform for Topology Optimization (better known as PLATO) is a design environment that has been developed at Sandia and recently licensed for no-fee U.S. government use. It provides a user interface similar to traditional design software, but optimizes designs based on material properties, geometry boundaries, loads and performance requirements (e.g., weight or strength). Figure 2 demonstrates a lattice structure designed in PLATO which is roughly 70% stiffer than a fully dense part with the same weight.[4] Figure 2 also shows a 38-mm-tall structure printed in stainless steel and a 0.5-mm-tall version printed in a photosensitive polymer. PLATO currently does not process abilities or limits, but coupling it with other advances will provide a powerful platform for integrating process capabilities, material property variations and predictive performance models. When realized, a radically new design paradigm will become available, whereby processes and designs will be optimized simultaneously to more quickly and cost-efficiently realize the full potential of AM.

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Your Opinion Matters!

What do you think about this issue of the *Stockpile Stewardship Quarterly*? We want to know. Please send your comments and suggestions for future issues to Terri Stone at terri.stone@nnsa.doe.gov. Requests to be added to our mailing list should include your full name, email address, and affiliation/organization.

Digital Manufacturing at the Kansas City National Security Campus *by Daniel E. Bowen III and David C. McMindes (Kansas City National Security Campus)*

Digital manufacturing is paying huge dividends for the NNSA's Kansas City National Security Campus (KCNSC). Digital Manufacturing includes additive manufacturing (AM) or three-dimensional (3D) printing, as its central element, but also includes design, simulation, validation, and analysis. At its highest level, AM may be defined as manufacturing by creating objects from melting, sintering, or fusing material by layers following a 3D computer model. In 2016, the KCNSC celebrated its 25,000th 3D-printed development article created within the Digital Manufacturing Initiative, providing more than $45 million in cost benefit.

The KCNSC, managed by Honeywell, first started rigorously exploring the use of 3D printing, or AM, in 2013 as a way to accelerate the fabrication of development articles and parts in support of NNSA's national security mission. This effort produced the Digital Manufacturing Initiative. Digital manufacturing has significantly reduced cycle times for development articles, capitalized on new design processes like computer-aided organic design, and provided better ergonomic and technical solutions to transform nuclear weapons manufacturing. All of the technologies that encompass Digital manufacturing and the systematic approach to their use are necessary for AM to be successfully implemented and maximally effective at the KCNSC. These technologies have far reaching and rapidly increasing implications for the nuclear security enterprise.

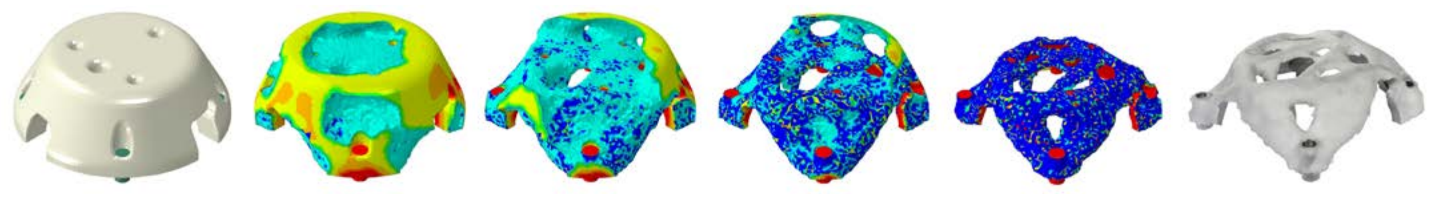
Digital Manufacturing

Digital manufacturing is a systematic approach that takes the concept of rapid prototyping and all of the advantages AM provides, including speed, highly specific geometry, evaluation of fit and function, visualization, increased cycles of learning, and low cost, among others, and supports it with all of the technologies necessary for success. Practically, this includes a change in thinking, and simulation and inspection technologies. The goal of digital manufacturing is the ability to turn an idea or concept for a fixture, mold, tool, or part into something tangible that a partner, collaborator, or customer can reliably use, as fast and efficiently as possible. At the KCNSC, digital manufacturing consists of the five concepts of "Think it," "Simulate it," "Print it," "Validate it," and "Use it" (see Figure 1).

Think it. It is often stated that with AM "complexity is free." The statement is meant to imply that many of the restrictions imposed by traditional subtractive manufacturing on part shape and geometry no longer apply. However, subtractive manufacturing was what the initial practitioners were used to, so early additive designs tended to look a lot like subtractive ones. Parts and assemblies that could be combined into a single article were not, and designs tended to maintain a familiar rectilinear look. A change not just in thinking, but in culture was needed. To speed that change, the KCNSC purchased approximately 30 Makerbots (desktop 3D printers) with the goal of making them available for everyone to use and to explore. This approach was highly successful in expanding the our collective, internal thought processes, while promoting the use of AM. The concept of "complexity is free" is tailor-made for a host of computational design techniques, including topology optimization (TO) (see "Simulate it." below), which goes beyond the capability of the human mind. As a result, some of the designs have an alien look, and for many who may adopt, use, and rely upon parts designed in such a way, the required change in thinking is a work in progress.

Simulate it. If complexity is truly free, then with few limitations, designs that could not easily be manufactured or not manufactured at all, are suddenly possible. This includes what can be imagined, but potentially more significantly what can be derived computationally. Computational science, specifically simulation and modeling, have been important tools in the manufacturing toolbox at the KCNSC for some time. TO is a newer technique that combines simulation and design. With TO, an article or part can be rendered in a simulated environment and have the stresses that the part might see in processing or use applied to it. Simultaneously, the design can be optimized in a variety of ways, individually or even in combination. For example, design can be optimized for weight, strength, load, center of gravity, harmonic frequency, or any of a variety of other constraints, through the selective elimination of material. In many cases, the final designs derived this way could only be made additively (see Figure 2).

Figure 1. Digital manufacturing at the Kansas City National Security Campus operated by Honeywell.



Original part

TO part

Figure 2. The topology optimization process as applied to a testing fixture. The part was optimized for weight and harmonic frequency.

The ability to so deeply integrate simulation and design further compounds all of the advantages of AM. As the design process migrates in this direction, it also begins to make sense to adopt a model-based, rather than paper document-based definition. Practically, a move in this direction eliminates potential translational errors in going from paper to code, but also opens up a host of opportunities and potential efficiencies.

Print it. At the KCNSC, "Print it" is increasingly the method of choice, especially for tools, fixtures, assembly aids, molds, and housings in development. AM has been strategically divided into polymer and metal. As polymer AM is more mature, stereolithographic techniques have been available for rapid prototyping at the KCNSC for more than 25 years, the advances that will be made in this area will be chemistry and material focused. Although a number of thermoplastics are currently able to be printed with commercial machines, many more are not and few thermosets are available, with the notable exception of silicones. With metal AM, applications are viewed as the primary driver; although, deep knowledge of AM machine capability and metallurgy will be required. The original equipment manufacturers (OEMs) of many commercial metal AM machines limit machine capability to the few parameter sets needed for the known metal alloys that can be printed. Early commercial metal AM machines catered specifically to the medical device and implant industry which was reflected in the metal alloys available. In some situations, going beyond these parameter sets requires close collaboration and agreement with the OEMs. The KCNSC is also engaging in strategic, long-term academic partnerships to help develop new alloys with new properties.

Validate it. Traditional non-destructive and destructive analysis and inspection tools are adequate for traditional subtractive manufacturing. However, with AM designs that are derived computationally, these traditional methods for determining tolerances, and properties and performance *a priori* are no longer adequate or no longer apply. The inspection and characterization tools necessary for AM parts will include computed tomography and other x-ray techniques, and 3D light scanning. Commercial machines and associated software allow x-ray and 3D-scanned AM objects to be rendered computationally and compared to the model-based rendering of the article or part, and ultimately highlighting where the object is out of dimensional tolerance, and even the location of certain voids and imperfections. The accuracy of the different scanning processes is an area of continued research and development.

Use it. "Use it" for development, prototypes, evaluation of fit and function, visualization, and non-critical tooling. For critical tooling and War Reserve (WR), more research, development, evaluation, and characterization is needed before such articles and parts can be certified and qualified for these applications. Realistically, even the comfort level of potential customers and end users of AM articles and parts must, and will, grow as the scientific evidence and financial cases for AM use grows.

Implications

There are a number of practical and positive implications for manufacturing with respect to AM. The production environment within the nuclear security enterprise is ideal for the early adoption of AM and the support technologies needed to make it work. The KCNSC is no exception where the mix of work could generally be described as consisting of high quality, low volume, and high diversity development and production manufacturing. Much of the work involves the research and development associated with preparing for production. The area where AM was applied early and continues to have significant impact is development tooling. When tooling, fixtures, assembly aids, molds, housings, and the like are being developed for production, AM accelerates development and cycles of learning by enabling rapid evaluation and testing at low cost. Tools made this way may not ultimately be used in production. The next area where AM is being applied is associated with critical tooling, tooling that will be used in production. Finally, the ultimate goal is to use AM to produce parts additively.

Impact

The impact of AM at the KCNSC has been significant. Over the last three fiscal years (FYs), FY 2014 to FY 2016, the KCNSC has printed approximately 34,000 AM articles and derived approximately $64M in total cost benefit. AM now touches nearly every aspect of development at the KCNSC. The rapid adoption of new technology and close collaboration and cooperation with federal agency counterparts, academia, and industry to derive benefits for customers are the hallmarks of the KCNSC. Along with the Digital Manufacturing initiative comes other technology strategies that have proven successful in generating new and exciting technology breakthroughs in support of national security missions. •

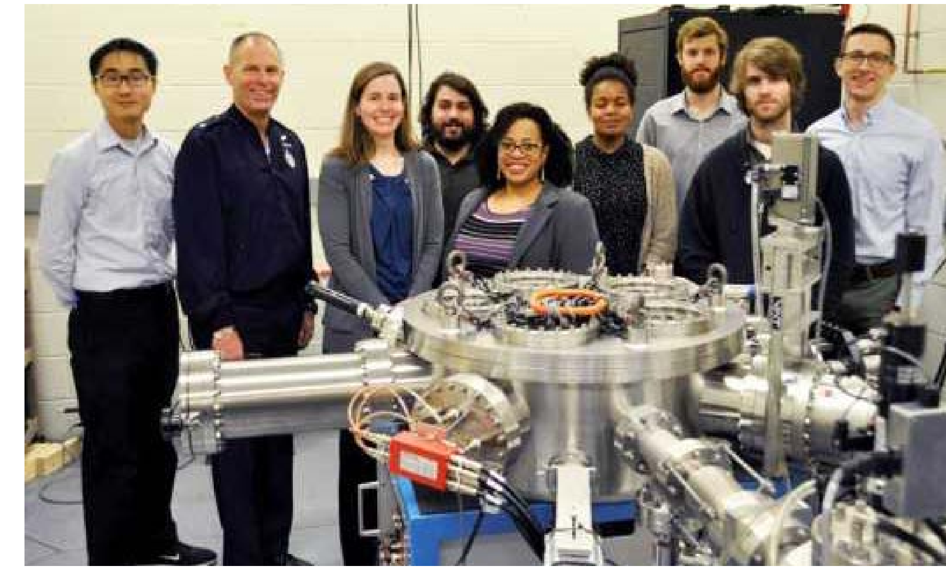
Highlights

Brig. General Lutton and Dr. Njema Frazier Tour Massachusetts Institute of Technology (MIT) HED/ICF Division

While visiting MIT in January, Brigadier General Michael J. Lutton, NNSA Principal Assistant Deputy Administrator, and Dr. Njema Frazier, Acting Director, Office of Inertial Confinement Fusion, were shown the scope of student and staff research at:

- the National Ignition Facility (Lawrence Livermore National Laboratory [LLNL]);
- Omega Laser Facility (University of Rochester Laboratory for Laser Energetics [LLE]);
- Z machine (Sandia National Laboratories); and
- MIT High Energy Density/Inertial Confinement Fusion (HED/ICF) laboratory.

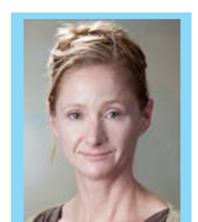
The outstanding PhD work of the students was highlighted. Two recent NNSA-supported MIT PhD graduates were awarded the 2016 and 2014 Rosenbluth Outstanding Thesis in Plasma Physics: Mike Rosenberg and Mario Manuel, respectively. At the heart of MIT's program has been its multi-year collaboration with LLE, LLNL, and the National Nuclear Security Administration (NNSA), the latter of which funded critical major components of large diagnostics that MIT built and interfaced with its many collaborators at LLE and LLNL. The MIT HED/ICF graduate students were able to present their thesis material and engage in wide-ranging discussions with Brig. General Lutton and Dr. Frazier.



At the MIT HED Experimental Facility (left to right): NNSA Stewardship Science Graduate Fellowship awardee Hong Sio, General Lutton, Postdoctoral Associate Dr. Cody Parker, graduate student Neel Kabadi, Dr. Frazier, and graduate students Raspberry Simpson, Graeme Sutcliffe, Brandon Lahmann, and Chris Wink. Hong Sio will be presenting his PhD research at NNSA Headquarters on May 9, 2017.

Dr. Frazier and General Lutton met with the students and Postdoctoral Associate for extended discussions about their research in HED Physics. This was a wonderful opportunity for them to talk informally and exchange ideas and questions, as well as an occasion for these young researchers to understand how important they and their research are to the strategic goals of NNSA.

Two Sandia National Laboratories Scientists to Receive Top Award



Hansen

Kruizenga

The Office of Research, Development, Test, and Evaluation congratulates Sandia National Laboratories researchers Stephanie Hansen and Alan Kruizenga on being selected to receive Presidential Early Career Awards for Scientists and Engineers (PECASE). Hansen studies the behavior of atoms in extreme environments and is working under a five-year Early Career Award from the Department of Energy (DOE) Office of Science. Her work contributes to the tools used to model and interpret data from high-energy-density experiments and astrophysical plasmas. Kruizenga currently leads investigations into materials compatibility, materials selection, and efficiency-generating technology for solar power systems and advanced reactor concepts. His research, funded by DOE, provides fundamental understanding of corrosion mechanisms and associated data for design and use of molten salt and liquid metal-based materials in high temperature solar thermal and nuclear reactor systems. Hansen and Kruizenga are among the 102 individuals selected to receive the 2017 PECASE award. Each recipient of the once-in-a-career award will receive a citation and plaque and will continue to receive DOE funding for up to five years to advance his or her research.

JOULE AWARD 2017

Oak Ridge National Laboratory
Idaho National Laboratory
Lawrence Livermore National Laboratory

The DOE/NNSA Office of International Nuclear Safeguards presents this Joule Award in recognition of outstanding contributions made for transferring:

^{19}F(α,n)^{22} Na Cross Section for Uranium Enrichment to international partners.

Joule Award 2017. The National Nuclear Security Administration's Office of International Nuclear Safeguards presented this year's Joule Award "in recognition of outstanding contributions made for transferring: ^{19}F(α,n) Na Cross Section for Uranium Enrichment to international partners." The Versatile Array of Neutron Detectors at Low Energy, also known as VANDLE, array of plastic scintillators, developed with Stewardship Science Academic Alliances funds, was critical to the success of this project. Also important were the students and postdoctoral associates supported in part by the Rutgers University Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science, an NNSA academic partner, who helped take the data. The final report for this exciting work, entitled "A Kinematically Complete, Interdisciplinary, and Co-Institutional Measurement of the ^{19}F(α,n) Cross Section for Nuclear Safeguards Science" is available online at http://www.osti.gov/scitech/servlets/purl/1263500. Currently, the data are being processed by researchers in the Nuclear Data Section of the International Atomic Energy Agency for use in nuclear safeguards work.