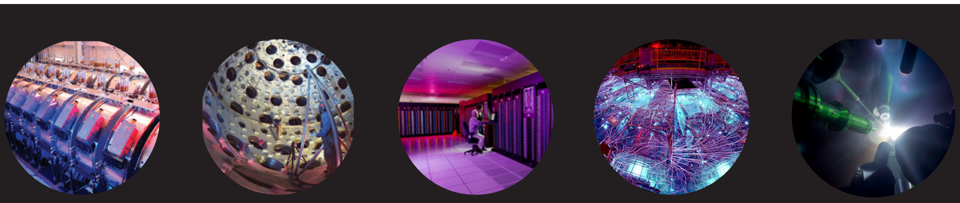

DOE/NA-0028

National Nuclear Security Administration

Office of Research, Development, Test, and Evaluation

# Stockpile Stewardship Quarterly

VOLUME 5 | NUMBER 1 | MARCH 2015

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

The Poster Session on the first evening of this year's Stewardship Science Academic Programs (SSAP) Annual Review Symposium, held in Santa Fe, New Mexico on March 11-12, 2015, generated enthusiasm and excitement among attendees. Read about the symposium on page 12.

I have had many opportunities over the last few months to highlight the major accomplishments of our programs to leadership at the Department of Energy and National Nuclear Security Administration (NNSA) as well as to our stakeholders. Showcasing examples of the tremendous capabilities that our NNSA national laboratories and sites bring to bear on the Stockpile Stewardship Program is one of the best aspects of my job.

One of our focus areas over the last three years has been on the subcritical experiments conducted using the U1a Complex at the National Nuclear Security Site. In early 2011, Dr. Donald Cook, NNSA Deputy Administrator for Defense Programs, challenged us to develop a near-term effort to conduct experiments on scaled plutonium pits which remain subcritical. The first article summarizes the progress of this high priority activity.

The next article describes how the Laboratory Directed Research and Development (LDRD) program attracts and challenges the next generation of stockpile stewards. LDRD is an important element to ensuring that creative and innovative ideas at the laboratories are pursued—providing a proven recruiting and retention tool while simultaneously providing direct benefit to NNSA as technologies initially developed on LDRD transition to our programs. The materials/manufacturing career of an accomplished young researcher, who began her work at one of the national laboratories on LDRD funding, is featured. In addition, the careers of four other award-winning young scientists, who also joined the NNSA national laboratories through LDRD opportunities, are highlighted.

The next two articles are written by former students who were, in part, supported by NNSA prior to receiving their PhDs. Both articles describe how the NNSA academic program support lead to their appointments at NNSA national laboratories. One former student, now at Lawrence Livermore National Laboratory (LLNL), did PhD research on materials at extremely high pressure, and his work at LLNL has him doing high pressure materials research supporting stockpile stewardship. The next article highlights a former student, now at Sandia National Laboratories (SNL), trained in high energy density plasma physics, who spent time at both Los Alamos National Laboratory and SNL. He is now a key laboratory experimentalist in the area of magnetized liner inertial fusion. Our final article provides highlights from this year's SSAP Annual Review Symposium.

### Inside

**Comments**

The *Stockpile Stewardship Quarterly* is produced by the 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. | Technical Editor: Dr. Joseph Kindel | Publication Editor: Millicent Mischo

# Science Campaign Subcritical Experiments

*by Jeffrey A. Paisner (Los Alamos National Laboratory) and Robert Hanrahan and Paul Ross (National Nuclear Security Administration)*

## Overview

At the beginning of the test moratorium in 1992, the U.S. nuclear weapons stockpile was certified based on the best science tools of the time—tested and validated by past underground testing. Science Based Stockpile Stewardship (SBSS) was established as the approach to maintaining the deterrent capabilities of the United States without the need to return to underground testing. The essential capabilities of SBSS were laid out in an executive order, Presidential Decision Directive-15 Stockpile Stewardship, signed by President William J. Clinton on November 3, 1993 and established in law by the 1994 National Defense Authorization Act. Among these were the execution of hydrodynamic and hydronuclear experiments to evaluate the properties of plutonium (Pu) driven with high explosives. It was recognized then (and now) that these experimental capabilities would be required "to retain and exercise weapon design and engineering skills and to examine safety modifications in existing nuclear warhead designs that could be introduced into the stockpile without nuclear testing."

During subsequent negotiations of the Comprehensive Test Ban Treaty, the United States decided to draw a line at zero yield from all nuclear experiments. Consequently, the United States does not conduct hydronuclear experiments. Nuclear experiments are undertaken in which special nuclear materials such as Pu are limited to subcritical experiments, which are experiments whose size preclude a criticality event. One example of a subcritical experiment, called a scaled experiment, is reducing the size of the assembly so that the trajectory of the material follows that of a real primary as closely as possible while remaining subcritical at all times. Scaled experiments have been part of the Dynamic Plutonium Experiments plan since 2007. Indeed, "scaled experiments" have been a technique for conducting subcritical experiments investigating primary performance, boost physics, and certification issues for decades. Integral subcritical experiments provide the link between hydrodynamic experiments (using surrogate materials) to nuclear tests (using Pu) without producing any nuclear yield.

Typically, subcritical experiments take several years to complete and involve a myriad of state-of-the-art diagnostics. A typical life cycle is composed of several overlapping phases: physics design, engineering, fabrication, assembly, fielding and execution, post-shot diagnostic data analysis, and documentation. Since 2007, Los Alamos National Laboratory (LANL), in collaboration with National Security Technologies, LLC (NSTec) and supported by Sandia National Laboratories, has performed focused and integral subcritical experiments in the U1a.05 drift 'zero' room at the Nevada National Security Site (NNSS). All experiments in U1a.05 are conducted behind a sealed bulkhead containment barrier in specially designed and manufactured high-strength steel 3-foot-diameter (eventually 6-foot-diameter) confinement vessels engineered with tensile strength and fracture resistance when impulsively loaded. This arrangement provides a defense-in-depth safety envelope against dispersal of the material being studied in the experiment. After execution of a given Pu-containing experiment, the confinement vessel is entombed within the experiment room, allowing for re-use of the U1a.05 facility. The National Nuclear Security Administration (NNSA) Nevada Field Office formally reviews Criticality and Containment before granting authority to execute a subcritical experiment.

LANL has concentrated on integral 'scaled' subcritical experiments since the completion of the Barolo/Bacchus Series of focused subcritical experiments in 2011. These focused experiments investigated specific physics and material properties important to the dynamic behavior of Pu in weapons designs and systems. The remainder of this article describes the recent series of integral subcritical experiments.

## Integral Subcritical Experiments

Integral subcritical experiments involve Pu implosions in weapon-like configurations. They are a component of an evolving advanced certification methodology, called scaling & surrogacy, being investigated by the weapons primary design community. The goal of this methodology is to provide new data and direct information on device performance using implosions of scaled Pu pits which remain subcritical. The measurements provide essential validation data for weapons simulation codes. These scaled implosions also allow inferences about the performance of full-scale devices, building confidence in stockpile assessments.

## Gemini Series (FY 2011 – FY 2013)

Gemini was the first series of experiments executed by LANL supporting scaling & surrogacy. Gemini was conceived in response to a directive from the NNSA Deputy Administrator for Defense Programs, Dr. Donald Cook, to execute a "scaled experiment" within two years (February 2011). The series included six engineering development and qualification tests at LANL firing sites, as well as hydrotest H4080 at the Dual-Axis Radiographic Hydrotest Facility (DARHT) using a surrogate pit to prove-in the scaled blast pipe hardware. At NNSS's U1a.05 Castor, the confirmatory hydrotest using a surrogate pit was followed by the Pollux subcritical experiment using a scaled Pu pit.

Gemini exercised and integrated many special skills and capabilities that span LANL—ones that were envisioned in the earliest days of stockpile stewardship to be critical to the future Weapons Complex, including high-performance primary design, supercomputing, physics and engineering modeling,

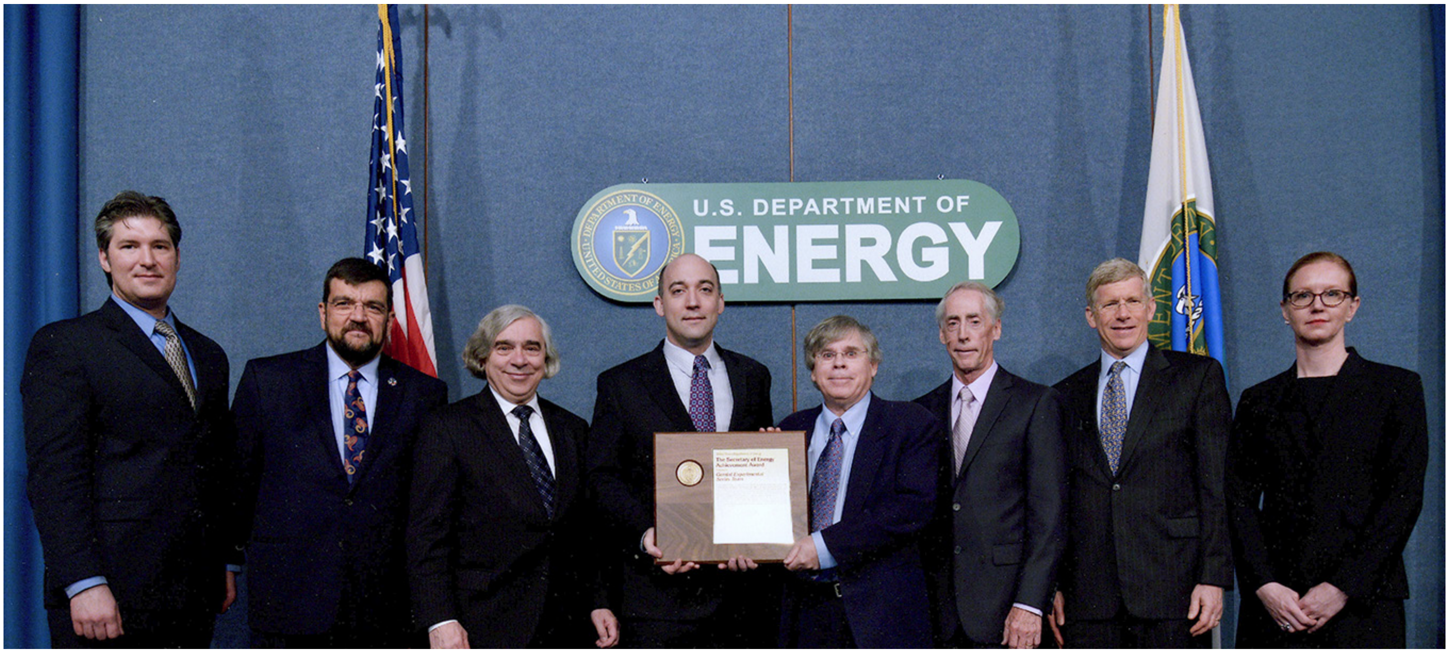

Figure 1. The Gemini Series received a 2013 Secretary of Energy Achievement Award. Pictured (L-R) are Jeffrey E. Hylok (LANL), Ghazar Papazian (NSTec), Secretary of Energy Ernest Moniz (DOE), Garry R. Maskaly, Jeffrey A. Paisner, and Gary Wall (LANL), Deputy Secretary of Energy Daniel Poneman (DOE), and Debra Johnson (LANL).

materials science, high explosives, hydrodynamic experiments, chemistry, prototype fabrication, Pu manufacturing, other manufacturing, quality control, environment, safety and health, state-of-the-art diagnostics, data analysis, and purchasing and shipping. Examples of results and accomplishments of Gemini follow:

- Physics Modeling: Advanced Simulation and Computing (ASC) codes to design the Gemini experimental series, informed the design requirements for the diagnostic systems, and prepared for pre-shot and post-shot analyses of previously unattainable data; three-dimensional (3D) code analyses to design blast-pipe hardware and perform realistic safety calculations; and invention of a transformational multi-dimensional technique named Composite Velocimetric Comparison Approach (CVC) for analyzing data. The CVC technique allowed the deluge of data to be assimilated rapidly by the weapon design community.
- Diagnostics: Novel and transformational high-density and high-bandwidth multiplexed photon Doppler velocimetry (MPDV) optical dome probes using 21st century metrology and telecommunications technologies; and high-fidelity hydrotest H4080 at DARHT at LANL to validate 3D physics modeling of blast-pipe design. Implementation of the MPDV diagnostic produced several thousand times more data, and of higher-fidelity, than previously possible.
- Fabrication: ASC fluid flow code to understand Pu casting and to design the Pu molds; development of processing and modeling for high-precision fabrication, and handling and inspection of scaled components at LANL and at the Plants (in particular 'new' detonator components of LANL design at the Kansas City Plant).
- Engineering: Construction methodology based on the ASME Code Case first developed by the LANL DynEx Program for impulse-loaded vessels; and establishment of a commercial vendor for confinement vessels fabricated to rigorous requirements.

## Leda (FY 2013 – FY 2015)

Leda was a scaled integral experiment using the Gemini platform with a new surrogate material. It was successfully executed on August 12, 2014. The goal of the experiment was to further inform the LANL scaling and surrogacy methodology. Leda also enhanced the pit material database used by the LANL Weapons Program and provided a rigorous test of advanced diagnostic suites for future subcritical experiments. Leda involved two engineering development and qualification tests at LANL firing sites. In particular, Leda accomplishments include the following:

- Leveraged existing systems and hardware, in combination with key material substitutions to record unique experimental data used to broaden understanding of material behavior.
- Maintained subcritical experiment formality of nuclear operations in the Device Assembly Facility, onsite transportation, and U1a.05 at the NNSS maintaining personnel, facilities, and processes via the surrogate experiment.
- Demonstrated safe and secure execution of a complex experiment.

- Advanced and expanded experimental diagnostics in U1a.05:

  –Utilized, as in Gemini, Dual-Axis Cygnus Radiography but with shielding and Zoom Lens System enhancements;

  –Demonstrated Dynamic Surface Imaging capability for subcritical experiments; and

  –Incorporated additional MPDV channels (as a next generation 5th MPDV system) to add flexibility, redundancy, and capability to the current subcritical experiment diagnostic suite.

### Lyra Series (FY 2014 – FY 2016)

Lyra is a series of three scaled-integral implosion experiments: 3667, a blast pipe hydrotest at DARHT using a surrogate pit; Orpheus, a confirmatory experiment in U1a using a surrogate pit; and Vega, a subcritical experiment in U1a using a Pu pit. The Lyra Series will use the Gemini platform to investigate a reuse concept, and requires one engineering development and two qualification tests at LANL firing sites.

### The Future (Post – FY 2016)

Gemini and its successor series, Leda and Lyra, pioneered by the Office of Research, Development, Test, and Evaluation's Science Campaign, have spawned a renaissance in the NNSA Defense Programs' subcritical experiment activities. The weapon physics data from the 21st century diagnostic suites obtained in these series have driven a mission need for enhanced radiographic and diagnostic capability in the U1a facility. In addition, these experiments underground at the NNSS contribute to maintenance of a modest level of nuclear test readiness should the Nation need to resume such activities. Both physics design laboratories, LANL and Lawrence Livermore National Laboratory, now envision a broad ranging strategy of focused and integral subcritical experiments that support their respective weapon system responsibilities into the next decade and beyond. •

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## Securing the Talent to Secure the Future *by Craig Tyler (Los Alamos National Laboratory) and Arnie Heller (Lawrence Livermore National Laboratory)*

The National Nuclear Security Administration (NNSA) national laboratories are responsible for solving some of the toughest technical problems facing the United States. Maintaining the nuclear weapons stockpile without testing, preventing nuclear smuggling, and addressing environmental contamination spanning thousands of years—these tasks demand technical expertise from the frontier across science.

Yet by its very nature, frontier-advancing science is not necessarily applied, and comparatively few frontier-advancing scientists enter national security research directly. Rather, their focus and devotion must be fostered through opportunities for cutting-edge research in the Nation's service. Long-term specialization must be complemented by the latest tools, techniques, and talent. In this regard, the Laboratory Directed Research and Development (LDRD) program has proven particularly successful.

Established by Congress in 1991 to maintain the health and technical vitality of the Department of Energy's (DOE's) national laboratories, LDRD is currently the largest single source of capability investment in each of the three NNSA national laboratories, i.e., Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and Sandia National Laboratories (SNL). Through highly competitive proposal processes, it promotes high-risk, high-reward research designed to advance the frontier of basic science in support of laboratory missions. Indeed, LDRD-funded projects have made seminal contributions to every facet of national security, including stockpile stewardship, high-energy-density matter, high-performance computing and simulation, materials science, chemistry, information systems, biosecurity, cybersecurity, and energy. Additionally, many key NNSA programs (and personnel) trace their roots to research that began under LDRD sponsorship. For example, the LDRD program invested in research advancing biosecurity and biodetection long before they became indispensible tenets of national security.

> *"This LDRD project has helped me become an independent researcher and has provided an important first step in my career."*
>
> *— Miguel Morales-Silva, LLNL*

"Without the LDRD program, for someone such as myself who is interested in basic science, the Laboratory would be much less attractive," says LLNL physicist Miguel Morales-Silva (see *Faces of the LDRD National Security Pipeline* on page 6), who expects that his calculation methods to analyze the behavior of liquid-metal hydrogen will ultimately improve the accuracy of stockpile stewardship codes. "This LDRD project has helped me become an independent researcher and has provided an important first step in my career."

To be sure, LDRD has been a major vehicle for attracting, training, and retaining new technical staff, thus filling the talent pipeline to support the broad generational turnover of national security staff currently underway. It allows the top young scientists to work on fundamental science and then bring the skills they develop to bear on critical national security applications.

## A Career Takes Shape...

Amy Clarke

Amy Clarke came to LANL in 2006 on a prestigious Seaborg Institute Postdoctoral Fellowship, which is supported in part by LDRD. She had previously studied steel metallurgy in both her undergraduate and graduate education and, during the latter, worked within an industry-university cooperative research center exploring novel alloying and heat-treating strategies to create advanced high-strength steels designed to reduce automobile weights and improve fuel efficiency and crashworthiness. LANL was among the center's participating sponsors, and it was through contacts made in that partnership that she received her fellowship—to perform research on uranium.

"The physical metallurgy of uranium and uranium alloys shares many similarities with that of steel," says Clarke. "I was able to leverage my experience with steel to learn about phase transformations, microstructural evolution, thermal and deformation processing, properties, and advanced characterization of a uranium alloy." That alloy, uranium-6 wt.% niobium (a uranium alloy that's 6 percent niobium by weight, or U-6wt.%Nb for short), is a material of interest for the nuclear weapons program (see Figure 1); in particular, its metallurgical and aging characteristics are of engineering interest.

Clarke and her postdoctoral mentor, Robert Field, were particularly focused on the alloy's shape-memory behavior. After a deformation, shape-memory materials can be restored to their original shape by reheating them beyond a critical temperature. Clarke and Field worked to experimentally uncover the alloy's complex microstructure after deformation within the shape-memory regime and compare their results with single-crystal model predictions. Using electron microscopy, they identified the preferred martensite variants (collective atomic shifts in crystal structure) and twins (symmetric splits in crystal structure) after deformation in tension or compression. They then machined single-crystal U-6wt.%Nb pillars with a focused ion beam and tested them to nail down the material's mechanical properties in its distinct orientations. In so doing, they obtained that holy grail of predictive materials science: experimental agreement with model predictions.

*Clarke's LDRD support provided the seed results that ultimately led to a five-year Early Career Award from the DOE and a Presidential Early Career Award for Scientists and Engineers (PECASE), considered the highest honor of its type bestowed by the U.S. government, both in 2012.*

## ... and Solidifies

Clarke's unique work within LANL was complemented by external opportunities within her field. "I am grateful that during this fellowship I was encouraged by my colleagues to become more involved in the Minerals, Metals & Materials Society (TMS)," says Clarke. "It really expanded my international exposure and influence." Clarke also joined the Association for Iron and Steel Technology (AIST) and currently serves on the board of directors of both professional societies. Along the way she had the opportunity to chair committees within both TMS and AIST and was recognized with three TMS Young Leader awards.

Clarke casts her career as a series of such fortunate opportunities. Upon achieving conversion from postdoc to scientific staff at LANL, she took the opportunity to join the Lab's foundry team and learn a whole new subfield. "After years of delving into solid-state phase transformations and microstructural evolution in metal alloys," she says, "I found myself learning more about liquid-solid phase transformations. The solidification of metal alloys is critical to their manufacture, from cast aluminum alloy engine blocks to components in the U.S. nuclear stockpile."

In 2011 and 2012, she successfully proposed for LDRD funding to perform the first real-time imaging of metal alloy melting and solidification inside large volumes (see Figure 2), using proton radiography (pRad) at LANL and x-rays from the Advanced Photon Source at Argonne National Laboratory—her success demonstrating the potential of these in-situ characterization techniques for materials-processing studies more generally. Her LDRD support provided the seed results that ultimately led to a five-year Early Career Award from the DOE and a Presidential Early Career

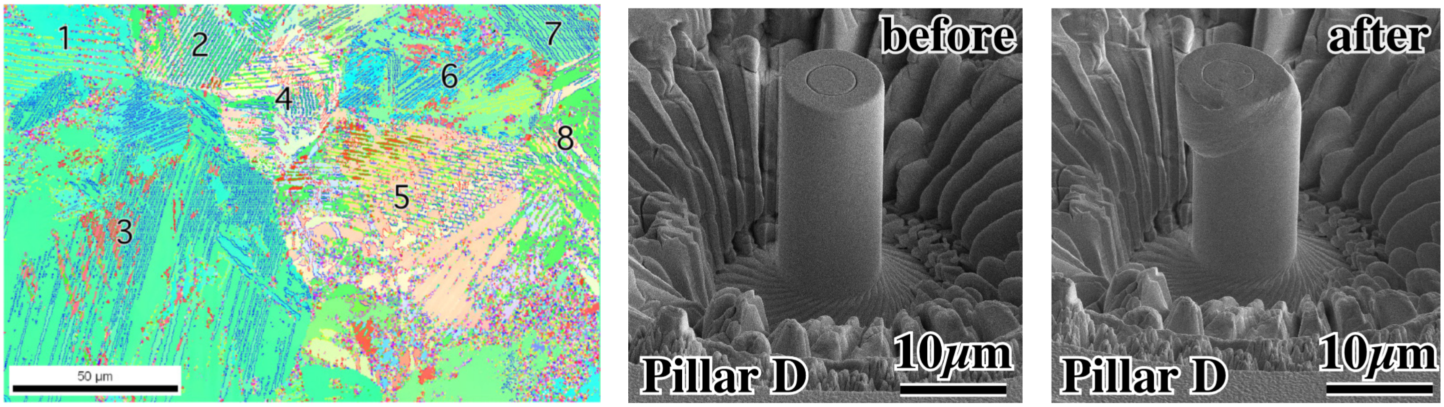
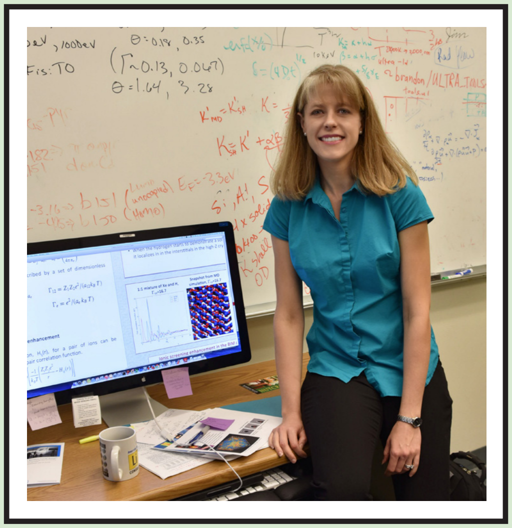


Figure 1. (Left) Electron backscatter diffraction of uranium-6wt.% niobium after straining compression within the shape memory regime, showing internal microstructural variations. (Right) Single-crystal U-6wt.%Nb pillars before and after deformation.

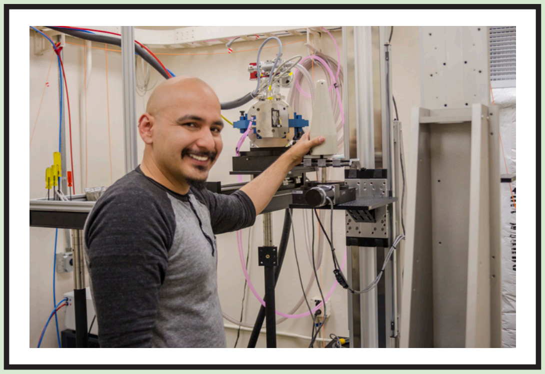
# Faces of the LDRD National Security Pipeline

Physicist **Miguel Morales-Silva** (LLNL) was first funded by LDRD as a graduate student and is currently the principal investigator for an LDRD project using quantum Monte Carlo calculations to analyze the behavior of hydrogen at extreme temperatures and pressures, when it exhibits metal-like behavior. This work has earned him a Presidential Early Career Award for Scientists and Engineers award. He is also a coinvestigator with physicist Randolph Hood on an LDRD project determining the electronic properties of heavier elements.

**Stephanie Hansen** (SNL) has participated in five LDRD projects. She was recently awarded a $2.5 million, five-year Early Career Research Program award for 2014 from DOE's Office of Science to improve existing atomic-scale models for high-energy-density matter and is confident that her experience with LDRD increased her competitiveness for the current award.



Theoretical chemist and Presidential Early Career Award for Scientists and Engineers award recipient **Heather Whitley** (LLNL) uses supercomputer simulations to expand understanding of dense plasmas. After initially working on semiconductor nanomaterials that could be applicable to solar cells and other clean-energy technologies, she began working on LDRD-sponsored simulations of dense plasmas. She has since been the coinvestigator on two LDRD materials-science projects with applications for the physics of aging nuclear weapons and experiments at the National Ignition Facility.



Applied mathematician **Edward Jiminez** (SNL) started there as an intern and was subsequently hired after completing his PhD, As an early career LDRD principal investigator, his work— which generated four pending patents—allows large-scale computed tomography reconstructions at rates 2,000 times faster than what was previously possible.

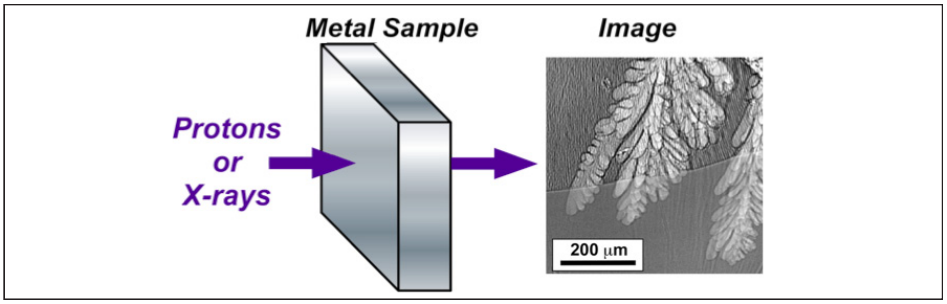


Figure 2. Real-time imaging of metal alloy microstructure during solidification.

Award for Scientists and Engineers, considered the highest honor of its type bestowed by the U.S. government, both in 2012.

Today, Clarke's team continues to make, measure, and model metal alloys. Her x-ray and proton real-time interrogations produce movies that feed into multi-scale computational models for metal solidification, enabling key new predictive capabilities. With additional LDRD support, she is also working to make Truchas—a LANL continuum-scale casting simulation code—microstructure-aware. The sequence of fortunate opportunities that characterize her career were made possible in no small degree by the LDRD program.

Those opportunities have resulted in considerable scientific contributions to the Nation and the world. Clarke's experimental and computational visualization of solidification, coupled with controlled processing, are likely to result in the creation of metal alloys with designed structures, properties, and performance—and the rapid deployment of advanced manufacturing technologies. Her work also demonstrates how advanced materials-interrogation tools can enable process-aware stockpile stewardship and advanced manufacturing of actinides, such as uranium and plutonium. Indeed, because such revolutionary predictive capability in materials design and manufacture is on the line, its LDRD support buys down the national security risk of being caught by surprise if it is first developed outside the United States. And Clarke's seminal contributions, like those of many others, have emerged from that support.

"I choose to build my career at Los Alamos because Los Alamos has made and continues to make investments in my professional development," she says. "I also choose to build my career here because of the amazing people I get to work with each and every day." ●

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## **Parallel Paths in Building Habitable Planets and Stockpile Stewardship** *by Richard G. Kraus (Lawrence Livermore National Laboratory)*

Squeezing polymers between diamonds, pressures of tens of thousands of atmospheres, and pepperoni pizza from Papa Murphy's—these were the thoughts of my undergraduate self, I'll admit, at a time when the implications of science-based stockpile stewardship weren't yet quite clear to me. I was first introduced to the Stockpile Stewardship Program (SSP) at the University of Nevada, Reno and, with the help of my research advisors, I started to learn—and then build an interest in how my research might be relevant to science being done at the National Nuclear Security Adminstration (NNSA) national laboratories. Back then, when the real world still seemed far away, I didn't know that I would eventually work as a scientist at a national laboratory, but it was the sense of utility and relevance, coupled with a keen interest in dynamic material properties that propelled me to focus my graduate research on the behavior of materials at extreme conditions.

Of course, recognizing your interests in a field of research, and finding the path are completely different stories (mainly because as undergraduates we were sheltered from the pains of writing grant proposals). Fortunately, there was an NNSA program in place to fund graduate students interested in the areas relevant to science-based stockpile stewardship. With the support of the NNSA's Stewardship Science Graduate Fellowship, I began my graduate research in shock physics and planetary science at Harvard University.

The importance of shock physics to SSP has recently been described better than I ever could by Neil Holmes in the *Stockpile Stewardship Quarterly*.[1] In that article, Neil also describes the importance of shock physics to Earth science and why laboratory scientists should also work on Earth science problems. In short, there is strong critical peer review of the techniques. My interest in applying shock physics techniques to planetary science problems represented another important aspect of science-based stockpile stewardship, a "farm to table" scientific program. In this science model, a problem in our predictive capability is recognized,

Figure 1. Giant impact origin of the Moon after an original painting by W.K. Hartmann.

experimental data is taken, that data is used to constrain and inform the theory, and the improved theoretical models are used in complex, integrated, and hopefully more predictive simulations.

For planetary scientists, one of the most important and complex research areas

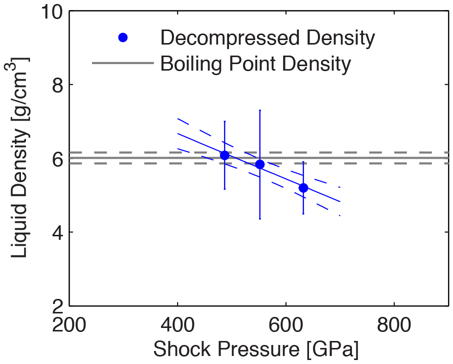

Figure 2. Shown in blue are the densities we measured upon decompression from the high-pressure shock state in three different experiments. The gray horizontal line represents the density at the boiling point. The shock pressure at the intersection of the boiling point density and the decompressed densities determines the shock pressure required to reach the entropy at the boiling point of iron.[5]

is predicting how planets form and evolve to their current state. Generally, planets form by a series of impacts, with the speed of the impacts being slow at first, tens of meters per second, but then faster as the planets grow larger, tens of kilometers per second (see example impact in Figure 1). Consequently, the range of conditions important to understanding how Earth and the other planets formed and evolved is broad and extreme, from pressures and temperatures like those at the bottom of the ocean to many times those at the center of the Earth.

A major gap in our understanding lay at conditions in planetary materials beyond what could be achieved using a two-stage gas gun (i.e., above ~8 km/s impact velocity), and in particular, our understanding of impact vaporization. Here, I use impact vaporization to describe the process where a high velocity impact causes strong shock waves to form in the colliding materials. These shock waves compress the material but also dissipate a tremendous amount of the kinetic energy of the impact as heat, causing the temperature and entropy of the colliding materials to increase dramatically. And while the increase in temperature may be more familiar, it is the increase in entropy where focus should be given. One way to think about entropy is that it is a measure of the disorder in the system; this shock-induced increase in entropy describes the transformation of a highly ordered crystalline solid to a disordered compressed fluid. But as the shock wave passes on by and the material begins to decompress back to the ambient pressure condition (e.g., 1 atmosphere), there is no time for the heat to leave the material, the entropy remains constant, and the stable thermodynamic state for material with such high entropy is a vapor or boiling liquid. And while using entropy to understand phase transitions is not new,[2] it is often ignored because of our inability to directly measure the entropy.

> *Fortunately, there was an NNSA program in place to fund graduate students interested in the areas relevant to science-based stockpile stewardship. With the support of the NNSA's Stewardship Science Graduate Fellowship, I began my graduate research in shock physics and planetary science at Harvard University.*
>
> *— Rick Kraus, LLNL*

One path that we have taken in the past is to calculate the entropy gain during shock compression using the first law of thermodynamics.[3] However, this requires a tremendous amount of thermodynamic data, principally high accuracy shock temperature measurements. Yet, it is critical to our understanding of planet formation that we know how the iron cores of the impacting bodies behave during high velocity impacts. And while it is tough to measure the temperature of transparent silicates such as quartz, it is much more difficult to measure the temperature of opaque solids like iron. Without accurate shock temperatures we cannot calculate the entropy increase during shock compression. We need something new.

That novel approach is to use the fact that we know the entropy and density of liquid iron at its boiling point.[4] We then developed a technique to determine the density of liquid iron upon decompression from the high-pressure shocked state (see the supplement of Reference 6). The Sandia National Laboratories Z Machine was then used to shock iron to extremely high pressures (up to twice that at the center of the Earth) and for each shock pressure, we measured the density upon decompression (see Figure 2). We were then able to pinpoint the shock pressure that it takes for iron to decompress to the density at the boiling point. As the decompression process does not change the entropy of the material, the entropy at the boiling point is the same as that of the shocked iron, thereby making this the first measurement of the entropy of shocked iron at just over 5 Mbar.

By comparison with the equation of state models used in the planetary science community, we found that for the same impact conditions, the shock-induced entropy gain is significantly greater than would be predicted. Or another way to think about it is that the critical shock pressure to vaporize iron is ~5 Mbar instead of 9 Mbar. Consequently, there will be significantly more of the incoming iron cores vaporized during planet formation than would be predicted. This result has two important implications. First, significant vaporization of the incoming iron cores will cause the iron to easily disperse over the surface of the growing Earth, which enhances chemical equilibration with the mantle and alters our interpretation of the timing of Earth's core formation. Second, because of the Moon's lower gravity, significant impact vaporization reduces the amount of iron being retained on the Moon, relative to the Earth, which helps to solve a long-standing problem in the low abundance of iron-loving (i.e., siderophile) elements on the Moon.[6]

Aside from the applications to planet formation, understanding the shock-induced entropy gain actually simplifies how we think about complex experiments. This realization leads me to one of the many exciting research topics at Lawrence Livermore National Laboratory, using dynamic compression techniques to determine ultra-high pressure melting curves. In 2016, we will use the National Ignition Facility (NIF) to shock melt iron, thereby setting the initial entropy state, and then re-compress the iron along an isentropic path in an attempt to detect pressure-driven re-solidification using in-situ x-ray diffraction. Because of the tremendous laser energy at the NIF, we will be able to access conditions that exist naturally within the cores of super-

Earths and answer questions about the types of exoplanets that can have a stable magnetosphere and possibly a habitable surface environment. Due to its importance to the planetary science community, this project will draw a great deal of scrutiny, and thereby also validate this technique for answering important NNSA questions about how materials behave at extreme pressures and temperatures.

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## Experimental Studies of Instability Development in Magnetically Driven Systems

*by Thomas J. Awe (Sandia National Laboratories)*

My research in National Nuclear Security Administration (NNSA)-supported programs began in 2003, when I started a year-long post-baccalaureate internship in X-1 at Los Alamos National Laboratory (LANL). There, I carried out magnetohydrodynamic (MHD) simulations in support of Atlas Facility imploding liner experiments, and joined a community that was passionate about pulsed power and magneto-inertial fusion (MIF).

As a graduate student at the University of Nevada, Reno (UNR), my research remained pertinent to imploding liners for MIF, as I ran experiments on the Zebra Facility to study how intensely Ohmically heated metals transition to plasma. Next, as a postdoctoral scholar in P-24 at LANL, I ran experiments and simulations to understand the utility of using plasma liners to compress MIF plasmas. All of this work prepared me well for my current position as a Staff Scientist at Sandia National Laboratories (SNL). Below, I highlight results from a variety of experiments on the Z Machine, for which I've served as the lead experimentalist. All experiments on Z take dedicated effort from a large collaboration of scientists, engineers, and technicians. I feel fortunate that my NNSA-supported experiences as a student have put me in a position to contribute to this very exciting and impactful work.

The Z Machine at SNL is the world's most powerful pulsed power accelerator and is capable of delivering ~25 million amps of current in about 100 billionths of a second. Z generates massive magnetic fields and forces, which are used to produce extreme temperatures and pressures in a variety of experimental samples. For example, when imploding wire arrays driven by Z stagnate on axis, they generate the world's most powerful x-ray source. Z assembles material into high-energy-density states, enabling world-class experimental capabilities to study dynamic material properties, radiation effects, and the physics of inertial confinement fusion (ICF).

ICF is a process in which a deuterium-tritium plasma target is compressed to high temperature and pressure, allowing the plasma to burn. If the internal heating from the fusing plasma exceeds the energy losses, the target will ignite, releasing energy in the form of high energy neutrons, charged particles, and radiation. Demonstration of ignition in the laboratory is a top priority of the NNSA Stockpile Stewardship Program for the validation of nuclear weapons performance.

While a variety of ICF concepts exist, all must bring the fusion fuel to an extreme high-energy-density state. For example, in traditional hot-spot ignition, the fuel is compressed to ~1,000 times solid density, and reaches temperatures of order 100 million Kelvin. This is typically pursued using intense lasers to accelerate a spherical pellet of fusion fuel (slightly smaller than a pea) radially inward at a velocity of several hundred km/s. During the implosion, the fuel pressures can exceed 1 billion times that of the Earth's atmosphere. The implosion must be highly symmetric; if it is only slightly perturbed, the perturbation will grow rapidly and tear the implosion apart. Implosion asymmetries resulting from hydrodynamic (or other) instabilities plague all ICF concepts. Therefore, methods which reduce the difficult-to-achieve fuel conditions required for ignition are sought.

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>
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A relatively new approach to ICF, called magnetized liner inertial fusion[1] (MagLIF) is being explored at the Z Facility. Designed to reduce the fuel requirements of traditional ICF, MagLIF uses a magnetically driven implosion to compress and inertially confine

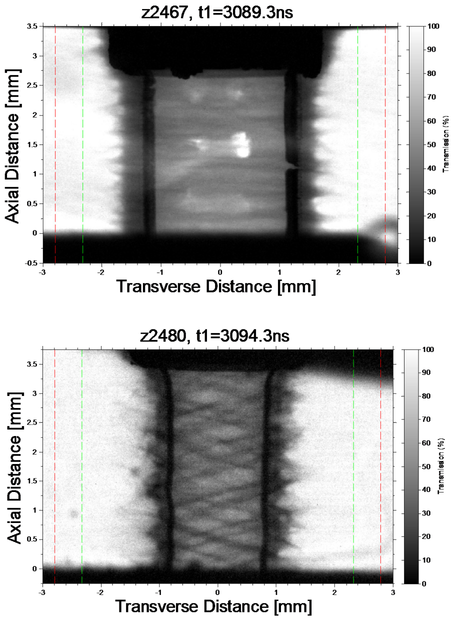

Figure 1. X-ray radiographs (6.1 keV) of beryllium liners imploded on the Z Facility. Green and red dashed lines indicate the liner's initial inner and outer radii, respectively. (a) $B_{z,0}$=0 T, with azimuthally correlated MRT structure. (b) $B_{z,0}$=7 T with helix-like instability structure.

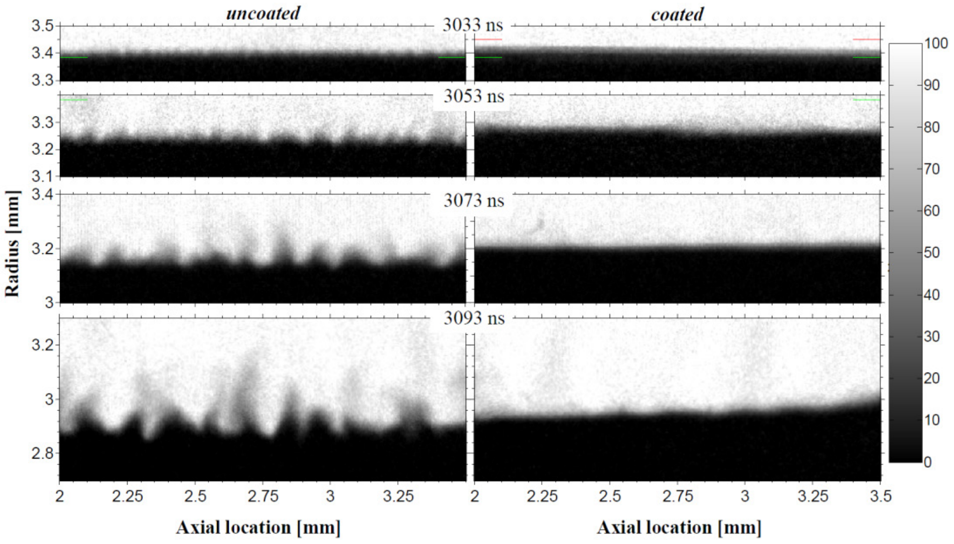

Figure 2. Radiographs demonstrating instability growth on solid aluminum rods driven by the Z accelerator. Bare aluminum is shown on the left. Aluminum coated with 60 to 70 microns of dielectric is shown on the right.

pre-magnetized and pre-heated fusion fuel. In MagLIF, a 3- to 5-mm radius, ~1-cm-long cylindrical liner (tube) is filled with deuterium-tritium gas. The liner and fuel are pre-magnetized with an axial field $B_{z,0}$~30 T. The field is compressed (along with the fuel) by the metallic liner to $B_{z,fuel}$ >1,000 T, which reduces heat loss, allowing a much slower implosion ($v_{imp}$~100 km/s) to adequately heat the fuel. The fuel is pre-heated to 10 to 300 eV to ease liner-convergence requirements, yet ~30-fold radial convergence is still necessary; meeting symmetry requirements at such convergence has yet to be confirmed.

The integrity of magnetically imploded liners is compromised by the magneto-Rayleigh Taylor (MRT) instability.[2] MRT instabilities occur whenever an electrically conducting fluid (e.g., a metal or plasma) is accelerated by a magnetic field. While MagLIF, by design, incorporates techniques to reduce implosion-velocity and liner-convergence requirements, instabilities may still grow disastrously large from very small perturbations on the liner surface. On Z, we are actively exploring MagLIF liner dynamics, and using what is learned to develop instability mitigation techniques. The primary liner-dynamics diagnostic is a two-frame, monochromatic, 6.1 keV x-ray radiographic capability (resolution: 1 ns, 15μm). Radiographs of the liner provide a wealth of information on symmetry, including the wavelength and amplitude of liner instabilities, the location of shock fronts in the material, and the density of the liner wall.

Time-resolved x-ray radiographs of beryllium liners accelerated to ~70 km/s are show in Figure 1. First, Figure 1(a) shows a standard MagLIF-style liner ($R_{in,0}$=2.325 mm, $R_{out,0}$=2.79 mm) which develops the commonly-observed azimuthally-symmetric "bubble-spike" MRT structure. Figure 2(b) displays a liner nominally identical to that in Figure 1(a), but we pre-imposed a $B_{z,0}$=7 T axial magnetic field. The pre-magnetized liner developed a three-dimensional (3D) helix-like instability structure that persisted at a large angle to the pinch axis (z) throughout the implosion.[3] We believe the helical structure may result in enhanced liner stability during the implosion. For example, the white regions near the central axis of Figure 1(a) are due to "time integrated self-emission" that is commonly produced when imploded liners stagnate. The emissions are likely due to MRT bubbles breaking through the liner surface and generating x-rays from associated hot spots. This emission, which is imaged by the radiography optics, is atypically absent in Figure 1(b), which may signify enhanced uniformity.

To minimize the initial seed for MRT, we employ single-point diamond turning techniques to fabricate liners with astonishingly smooth surfaces (e.g., root mean square roughness below 50 nm); this small initial perturbation is not expected to generate the level of MRT growth we observe in experiments. However, early in the implosion, an electrothermal instability (ETI) may provide a seed perturbation which exceeds the initial surface roughness. For a condensed metal, resistivity increases with temperature ($\partial\eta/\partial T>0$). Regions of locally higher resistivity undergo increased Ohmic heating, resulting in locally higher temperature, and thus still higher resistivity. Such unstable temperature growth produces density perturbations which can seed MRT growth. We recently experimentally demonstrated that ETI-driven density perturbations can be mitigated by coating the metal surface with a dielectric tamper.

Z experiments have validated pre-shot simulations that predicted that the nonlinear growth of ETI would be mitigated by the hydrodynamic tamping effect of a relatively massive dielectric coating. The effect on instability growth was dramatic (see Figure 2). For example, when we coated aluminum (Al) rods with 60 to 70 microns of dielectric, the amplitude of those MRT modes with wavelengths ranging from 100 to 200 microns was reduced by a factor of 10

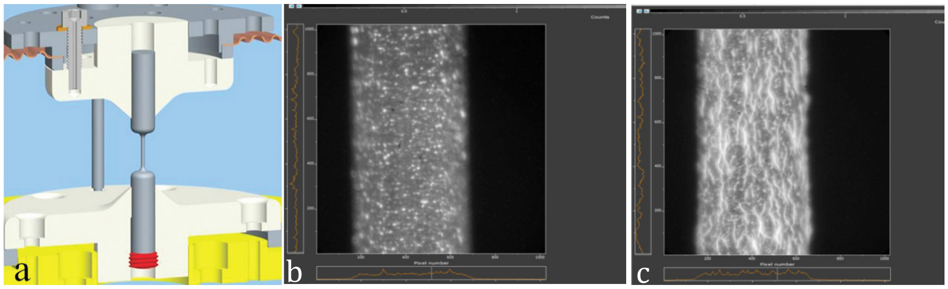

Figure 3. (a) Specialized “barbell” load hardware to mitigate non-thermal plasma production. (b) Emission from hot spots as the 1.0 mm diameter rod first forms plasma. (c) Image of self-emission at higher current, when axial plasma filaments form.

to 20.[4] We’ve also recently compared coated and uncoated imploding liners and obtained similarly dramatic results; publications detailing those experimental results are in progress.

ETI seeding of MRT on liners has thus far only been inferred by evaluating the MRT amplitude late in experiments; a direct observation of ETI is vital to verify the accuracy of this theory. In early 2014, I obtained Laboratory Directed Research and Development funding to support a SNL and UNR collaboration where we’re attempting to directly measure ETI growth in experiments on UNR’s Zebra generator. Zebra is well suited for such ETI studies for a number of reasons, including a current rise time similar to Z (~100 ns) and a full suite of low temperature diagnostics. Furthermore, and perhaps most importantly, during my graduate research at UNR, we developed and characterized an experimental hardware configuration (see Figure 3(a)) that is capable of avoiding several non-thermal plasma formation mechanisms that are common to high-voltage generators.[5,6] Such performance is required to enable the study of relatively low-temperature phenomena.

Our experiments on the Zebra generator have examined ETI growth from solid aluminum rods. Rods of initial diameter $D_0$~1.0 mm are Ohmically heated by intense current. ETI, caused by the dependence of the local resistivity on the local temperature, amplifies temperature variation in the metal, and these temperature variations can be observed directly through high resolution gated optical imaging. The images in Figures 3(b-c), which have ~10-micron-spatial, and 2-ns-temporal resolution, show visible-light self-emission from an electropolished 1.0-mm-diameter 6061-alloy Al rod. As plasma first forms, hot spot emission dominates (see Figure 3(b)). As the surface is further Ohmically heated, plasma filaments form and align mostly axially (to the direction of current flow). The observed plasma hot spots may originate from silicon/copper/magnesium inclusions that remain embedded in the aluminum after electropolishing. In fact, the scale size and surface number density of plasma hot spots (from imaging) and inclusions (from pre-shot SEM characterization) are quite similar. In upcoming experiments, we’ll examine inclusion-free 99.999%-pure Al rods to test the hypothesis that inclusions seed hot-spot plasma formation.

Ongoing research on the SNL Z Machine and on smaller facilities has enhanced our understanding of liner implosion dynamics, and has enabled the advancement of various instability mitigation techniques. This work not only informs ICF concepts such as MagLIF, but can enhance the performance of magnetically driven platforms for Dynamic Materials and Radiation Effects Sciences research in support of NNSA stockpile stewardship missions.

## References

[1]S.A. Slutz, M.C. Herrmann, R.A. Vesey et al., Phys. Plasmas 17, 056303, 2010.

[2]E.G. Harris, Phys. Fluids 5, 1057 (1962).

[3]T.J. Awe, R.D. McBride, C.A. Jennings et al., Phys. Rev. Lett. 111, 235005, 2013.

[4]K.J. Peterson, T.J. Awe, E.P. Yu et al., Phys. Rev. Lett. 112, 135002, 2014.

[5]T.J. Awe, B.S. Bauer, S. Fuelling, and R.E. Siemon, Phys. Rev. Lett. 104, 035001, 2010.

[6]T.J. Awe, B.S. Bauer, S. Fuelling, and R.E. Siemon, Phys. Plasmas 18, 056304, 2011. ●

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## Highlights

### Los Alamos National Laboratory (LANL) Physicist Honored for Leadership in Nuclear Security

Mary Hockaday, Associate Director for Experimental Physical Sciences at LANL, received a 2014 fellowship from the American Association for the Advancement of Science on February 14, 2015. She was recognized for her “exemplary leadership at Los Alamos National Laboratory in support of the Nation’s nuclear security and in realizing the technologies to foster that security.”

### *Physics of Plasmas* Celebrates the International Year of Light and Light-Based Technologies

The United Nations General Assembly proclaimed 2015 the International Year of Light and Light-based Technologies. The journal *Physics of Plasmas* has joined this celebration, focused on the topics of light science and its applications, by presenting a two-part series of high impact papers in these areas published in their journal within the past 40 years or so. These highlighted papers encompass the areas of laser-plasma interactions, inertial confinement fusion, and high energy density physics. There were several papers by staff at National Nuclear Security Administration (NNSA) national laboratories and funding recipients to receive this high impact honor. Those papers can be downloaded for a limited time at no cost. One recipient is physicist Joseph Kindel, long-time NNSA consultant and Technical Editor of the *Stockpile Stewardship Quarterly* for his paper, with co-authors David Forslund and Erick Lindman, entitled “Theory of Stimulated Scattering Processes in Laser-irradiated Plasmas,” Physics of Fluids 18, 1002, August 1975. To view this paper and others, visit http://aip-info.org/1XPS-37348-36C9T5GA9E/cr.aspx. ●

## Massachusetts Institute of Technology (MIT) Graduate Students Receive Lawrence Postdoctoral Fellowships

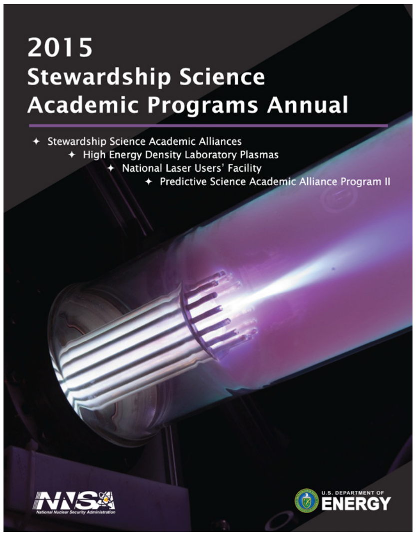
Lawrence Livermore National Laboratory (LLNL) awarded two of this year's Lawrence Postdoctoral Fellowships to Massachusetts Institute of Technology (MIT) graduate students Hans Rinderknecht and Alex Zylstra. The three-year fellowship is given to candidates with exceptional talent, scientific track records, and potential for significant achievements. Both students received other prestigious fellowship award offers. Zylstra, who received NNSA support via a Stewardship Science Graduate Fellowship during much of his PhD, also received the Fredrick Reines Fellowship from Los Alamos National Laboratory. Rinderknecht received the Harry S. Truman Fellowship in National Security Science and Engineering from Sandia National Laboratories. They have tough choices to make.


MIT-NIF Neutron Spectrometer

At the National Ignition Facility (NIF), MIT High-Energy-Density (HED) Physics Division students and staff build and utilize nuclear diagnostics for advancing ignition and HED science. MIT graduate students and alumni pictured (L to R): Hans Rinderknecht (Physics), Dan Casey (Nuclear Science and Engineering), Alex Zylstra (Physics), and Mike Rosenberg (Physics). Casey and Rosenberg are now scientists at LLNL and the University of Rochester Laboratory for Laser Energetics, respectively.

## 2015 Stewardship Science Academic Programs Annual Review Symposium

More than 275 individuals from the National Nuclear Security Administration (NNSA), NNSA national laboratories, and academia attended this year's annual review symposium held in Santa Fe, New Mexico on March 11-12, 2015. The symposium featured overviews of work to date from ongoing grants and cooperative agreements from the Stewardship Science Academic Alliances Program; the NNSA-supported grants from the Joint Program for High Energy Density Laboratory Plasmas; and grants awarded under the National Laser Users' Facility.


2015
Stewardship Science
Academic Programs Annual

- Stewardship Science Academic Alliances
- High Energy Density Laboratory Plasmas
- National Laser Users' Facility
- Predictive Science Academic Alliance Program II

Keynote speaker Scott Doebling from Los Alamos National Laboratory spoke to attendees about Verification & Validation: Uniting Simulations, Theory, and Experiments. The Poster Session and reception followed. There were approximately 100 posters on view during this year's session on topics including low energy nuclear science, properties of materials under extreme conditions, high energy density physics, and predictive science. The winners of the Poster Session follow.

- ***Patricia Kalita***, University of Nevada, Las Vegas, *High Pressure Behavior of Mullite-Type Oxides: Phase Transitions, Amorphization and Microstructural Implications*
- ***Keith Loebner***, Stanford University, *Plume Characterization of a High Directed Energy Plasma Source for Material Interaction Studies*
- ***Mindy Lorance***, University of Nevada, Reno, *Spectroscopic Modeling of the First Planar Wire Array Experiments on the LTD Generator at the University of Michigan*
- ***Amy Lovell***, National Superconducting Cyclotron Laboratory/Michigan State University, *Reaction Theory/VANDLE Simulations*
- ***Mark Mikhaeil***, Georgia Tech, *Dynamics of Rayleigh-Taylor Driven Flows*
- ***Tane Remington***, University of California, San Diego, *Spall Strength Dependence on Strain Rate and Grain Size in Tantalum*
- ***Nathan Riley***, University of Texas at Austin, *Magnetized Radiative Blast Waves*
- ***Daniel Sneed***, University of Nevada, Las Vegas, *Forcing Cesium into Higher Oxidation States Using X-Ray Induced Photochemistry at Extreme Pressures*
- ***Bryan Wiggins***, Indiana University, *Measuring the Position Resolution of Low Intensity Signals Using a Resistive Anode Microchannel Plate Detector*
- ***Willow Wan***, University of Michigan, *Observation of Single-Mode, Kelvin-Hemholtz Instability in a Supersonic Flow*
- ***Eloisa Zepeda-Alarcon***, University of California, Berkeley, *Visco-plastic Modeling of MgSi03 + Periclase Aggregates*

To view the 2015 SSAP Annual online, visit http://www.nnsa.energy.gov/stockpilestewardship.