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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* features recent research which encompasses ignition approaches, opacity measurements, laser shock experiments, a Laboratory Directed Research and Development (LDRD) project of relevance to weapon system testing, and an example of our international collaboration.

The first article, about double-shell capsules, introduces an alternative approach to achieving ignition. Three double-shell campaigns on OMEGA have agreed with the designing models. The second article about opacity summarizes work on the Z pulsed power facility which is of interest to stockpile stewardship and provides a new venue to study stellar systems. The third article on shock waves created by high power lasers describes the extreme response of materials by rapidly generating immense pressures and their release. The next article summarizes LDRD research of codes modeling vibrational environments. This research has resulted in the development of an ability to simulate ground-based acoustics tests of weapon systems. In this issue, you'll also read about the recent General Working Meeting for the International Agreement Between France and the United States of America for Cooperation on Fundamental Science Supporting Stockpile Stewardship.

There are several new members of the RDT&E team that are introduced in this issue. The Deputy for RDT&E Military Applications, Colonel Thomas Summers, comes to us most recently from the Pentagon where he played a key role in nuclear weapons policy. The Office of Research and Development welcomes Mr. Willie Ward III and Dr. Staci Brown. Both Mr. Ward and Dr. Brown began working for Defense Programs as Fellows in the DOE/NNSA Graduate Fellowship Program (NGFP). They joined the RDT&E team in June after their fellowships concluded. Ms. Krystal Kasal and Mr. Brian Sims come to the team as new Fellows in the NGFP. This successful program immerses NGFP Fellows in the DOE/NNSA complex in the areas of nuclear security, nonproliferation, and stockpile stewardship.

We are coming to the conclusion of an extremely successful fiscal year. Due to the efforts of the entire team at headquarters, the labs, sites, and plants, we have many successes to celebrate—from new scientific discoveries, to new capabilities at the laboratories, to improved efficiencies in our operations. Congratulations to all for those efforts.

DOE/NNSA Graduate Fellowship Program (NGFP)

Sponsored by DOE, the NGFP is designed for highly motivated graduate-level students interested in a career in nuclear security. The full-time, salaried fellowship program lasts one year and offers Fellows hands-on experience in nuclear security and nonproliferation, career development, professional networkworking opportunities. and the opportunity to contribute to the Nation's nuclear security missions. Applications for the Class of 2016 will be accepted through October 19, 2015. For information about the program and to apply, visit http://ngp.pnnl.gov.

Save the Date

We are pleased to announce that the 2016 Stewardship Science Academic Programs Annual Review Symposium will be held on February 17-18, 2016 at the Bethesda North Marriott in Bethesda, Maryland. Please join us!

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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

A Testable Ignition Path on the National Ignition Facility Using Double-Shell Targets

by Peter Amendt, Alex Hamza, and Jose Milovich (Lawrence Livermore National Laboratory) and Bill Daughton, Mark Gunderson, David Montgomery, Andrei Simakov, and Doug Wilson (Los Alamos National Laboratory)

Introduction and Motivation

The understanding of burning plasmas or alpha particle self-heating across a broad range of parameter space is a key goal of high energy density science and stockpile stewardship. To this end, double-shell targets could significantly impact both ignition and high energy density research. As a path towards ignition, double shells rely on volume ignition, which is a complementary alternative to the mainline and tested approach of cryogenic hot-spot ignition. As a high energy density platform, double shells provide a candidate tunable test bed for assessing the degrading effects of material mixing between the thermonuclear fuel and the pusher shell. The pursuit of demonstrating thermonuclear ignition and energy gain has singularly relied on single-shell targets on the National Ignition Facility (NIF) since 2009.[1] These targets rely on the formation of a high-temperature (~12 keV) spark in the deuterium-tritium (DT) fuel near capsule center that triggers an outwardly propagating self-sustaining burn or deflagration wave to the surrounding higher density fuel for realizing high energy gain (see Figure 1a). This mode of thermonuclear burn is known as hot-spot ignition. Recent experiments with high-foot laser drive histories have demonstrated (~2x) net energy gain from the hot spot, but with no appreciable burn propagation into the dense fuel.[2] Identifying the principal physical mechanism responsible for the inhibited energy output or neutron [D+T→^{4}He(3.5 MeV)+n(14.1 MeV)] yield (<10^{16}) remains an active area of investigation.

Hot-spot ignition efforts on the NIF have relied on converting the incident <1.9 MJ of available laser light (at 0.35 μm wavelength) into soft x-rays from the walls of a high-Z enclosure or hohlraum that bathe a centrally located low-Z capsule ablator, e.g., plastic (CH), beryllium, or high-density carbon (HDC), surrounding the DT fuel. This approach to coupling laser light to a capsule using a hohlraum is known as indirect drive—in contrast to direct laser illumination of

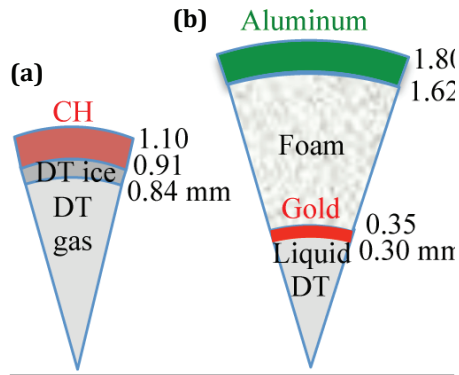

Figure 1. Generic (a) hot-spot single-shell capsule and (b) double-shell target.

the capsule (or direct drive). To date, indirect drive has served as the main ignition platform for the NIF owing to its potential for suppressing inflight shell asymmetries that can otherwise degrade the needed high fuel convergence (~30-35) of the implosion. A variety of hohlraums to assess the best path for efficient and uniform coupling of laser energy to absorbed capsule x-ray energy without incurring excessive preheat of the main DT fuel from hard (>2 keV) x-rays and fast electrons have been studied. Preheat control is important for achieving a final peak DT density of ~1,000 g/cm^3 for efficient fuel self-heating by ^{4}He ions. These hohlraums can be generally classed in terms of shape, composition, and gas fill. The standard hohlraums are cylindrical in shape, but recent experiments with "rugbys" have explored the energetics and drive-symmetry benefits of using rounded hohlraums.[3] Efficient soft x-ray production requires the use of a high-Z hohlraum composition such as gold or depleted uranium (DU). Depending on the ablator choice, the duration of the laser pulse indirectly driving the capsule may require the use of a low-density gas fill to retard the inward motion of the ablating hohlraum walls for x-ray drive symmetry control. The most energetically efficient hohlraums have been found to correlate with minimal gas fills and laser pulse lengths less than 10 ns for (indirectly) driving HDC capsule ablators.[4] These near-vacuum (0.032 mg/cc ^{4}He-filled) hohlraums, however, are challenged by anomalous capsule implosion symmetry compared with mainline simulation predictions.[5] On the other hand, recent high-foot experiments with CH ablators used high density (1.6 mg/cc) gas fills for symmetry control, but showed appreciable amounts of inferred "missing" drive energy even after accounting for laser backscatter.[6] Efforts are underway to identify an intermediate gas-fill regime (~0.6 mg/cc) that delivers both high efficiency and calculable drive uniformity without the need for ad hoc drive degradation factors in the simulations to represent any missing drive energy.[7] The most successful hohlraum platform from the standpoint of agreement with modeling is the indirect-drive exploding pusher (IDEP) that uses an HDC ablator.[8] Although this target type leads to a low fuel-convergence (~5) implosion, the benefit of a short laser pulse (~4.5 ns) in terms of calculable symmetry and indirect drive conditions without using phenomenological drive multipliers was demonstrated. The challenge is to find a potential ignition path with benign hohlraum conditions that are similar to the IDEP platform. This strategy would allow for more accurate capsule modeling that is largely immune to hohlraum physics modeling uncertainties.

An attractive candidate target type is the double shell consisting of a high-Z inner shell supported by an annular foam within a low-Z outer shell (see Figure 1b) that is impulsively hohlraum-driven by a short duration laser power history.[9-11] The mode of ignition (volumetric) for a double shell relies on "*PdV*" compressional work done on the DT fuel by the converging inner shell, in marked contrast to hot-spot ignition. The distinguishing features of volumetric ignition are a low threshold ignition temperature (~4-5 keV) due to efficient radiation trapping within a high-Z shell, low fuel convergence (~10), less need for fuel preheat or entropy (adiabat) control, high fuel burn fraction (~50%), and higher margin to drive asymmetry.[12] The potentially benign hohlraum conditions resulting from

a short duration IDEP-like laser pulse (~5 ns) can also lead to efficient laser-hohlraum coupling and easier control of implosion symmetry. The envisioned challenges to achieving double-shell ignition are adequately controlling hydrodynamic instability growth on the inner shell and the inherently complex target fabrication. Previous work has suggested that instability growth on the outer surface of the inner shell after the instant of shell collision may be controlled with the use of engineered composition gradients to effect a material match with the intra-shell foam.[13] For the interior interface, the uncontrolled mix of high atomic number inner-shell material with the DT fuel can thwart ignition, requiring corrective measures as well. Target fabrication of ignition-scale double shells is complex owing, in part, to the shell concentricity requirements (~5 microns) and need for hemispherical joints on the aluminum outer shell. However, past experimental campaigns at the Laboratory of Laser Energetics, University of Rochester Omega Laser Facility[14-16]—along with nanomaterials research and development—have established a realistic and promising pathway. In addition, recent progress in additive manufacturing techniques may greatly accelerate and improve the process of double-shell target fabrication.

Double-shell Target Design:

(1) The Hohlraum

The first step in developing an integrated target design is assessing and satisfying the requisite hohlraum x-ray flux and symmetry conditions for driving a candidate implosion target. Figure 2 shows the proposed rugby-shaped hohlraum geometry. The hohlraum scale is ~60% larger than for the standard cylinders used in high-foot experiments to date,[2] owing to the need to accommodate the comparatively large outer shell while preserving enough laser beam clearances. Figure 3a shows the requested laser power history for a nearly 2 MJ total laser energy budget. This high-drive energy is readily achievable on the NIF owing to the reversed-ramp nature and short duration of the requested pulse shape, according to laser performance model predictions.[11] The time-varying split between inner (23°, 30°) and outer (44°, 50°) cone powers is also shown, providing a key degree of freedom for helping to control time-dependent drive

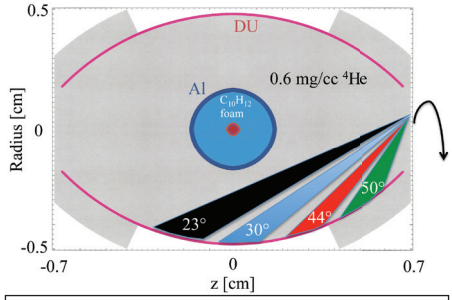

Figure 2. Sketch of depleted uranium (DU) rugby hohlraum geometry with NIF laser cones (shown in only one quadrant for illustrative ease).

flux asymmetry on the outer shell. The predicted radiation temperature history is depicted in Figure 3b, enabling a peak value of ~270 eV. Due to the combined large rugby hohlraum scale, the low-density gas fill and an IDEP-like short laser pulse, the risk of laser backscatter from plasma-mediated instabilities, e.g., Raman and Brillouin, is deemed to be low since the hohlraum has little time to fill with risk-prone high-density plasma.

(2) The Capsule

The proposed hohlraum design is intended to deliver almost 1 MJ of absorbed x-ray energy to the outer shell. The relatively massive outer shell then inelastically collides with the inner shell to deliver a modest degree of velocity multiplication (~0-20%) and to achieve a peak implosion velocity of the inner shell in the optimal range ~250-300 mm/ns, by design. In order to effectively guard against the effects of hard x-ray preheat (on the outside of the inner shell) generated near the regions of laser deposition on the hohlraum wall, a pure aluminum outer shell is proposed. Besides efficiently screening out >2 keV x-rays, the advantages of aluminum are that its equation of state has been extensively studied and it is a relatively easy material to fabricate. The purpose of the intra-shell low-density foam is to concentrically support the inner shell. A fill tube for delivering liquid DT fuel inside the inner shell would make use of the proven and mature cryogenic capability on the NIF for solid DT fuel layering. The design challenge for the inner shell is that it be made thick enough to guard against appreciable hydrodynamic instability feed-through from the outside to the inside, resulting in shell breakup. Even if the shell stays intact, there is still little margin for mix of high-Z shell material with the DT fuel,

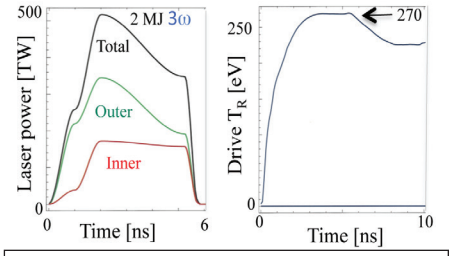

Figure 3. Laser power history (a) and simulated radiation temperature history in hohlraum channel (b), based on design shown in Figure 2.

owing to the high heat capacity of gold or lead (Pb). The interface between the DT fuel and inner shell is classically unstable to surface perturbations that may grow exponentially in time and lead to destructive mix of fuel and shell material. To help gauge and minimize this risk, a "fall line" metric is used as a convenient design tool. A fall line is the straight-line trajectory of inner shell material starting at the instant of maximum implosion speed (or deceleration onset). The physical reasoning is that causality should keep all infalling shell material behind the fall line. By delaying the arrival of the fall line at the origin (r=0) as late as possible, the effects of mix can be minimized. The fall-line model is not parameter free but depends on a "penetration fraction" of the distance between the fall line and interface trajectory that can be constrained by experiments. An improved fall-line model goes beyond this strictly geometrical construction to also include the evolution of the normalized density jump at the interface, $[(d_2-d_1)/(d_2+d_1)]$ or Atwood number $0<At<1$, thereby constraining the penetration fraction with time. The Atwood number is a key parameter in describing linear fluid perturbation growth rates, which generally vary linearly with At. Figures 4a and 4b show two double-shell designs with optimized fall-line behavior that have been assessed for robustness to mix. A third target shown (see Figure 4c) is the low-foot "Rev. 5.0" cryogenic single-shell design[17] for comparison. The first target has the Pb inner shell in contact with the DT fuel, whereas the second uses a "mix buffer" layer of low-Z plastic to help shield the fuel from destructive penetration by Pb. The arrows show on which interface the fall-line mix model is applied in one-dimensional (1D) radiation-hydrodynamic simulations. The non-buffered design (4a) is on the verge of

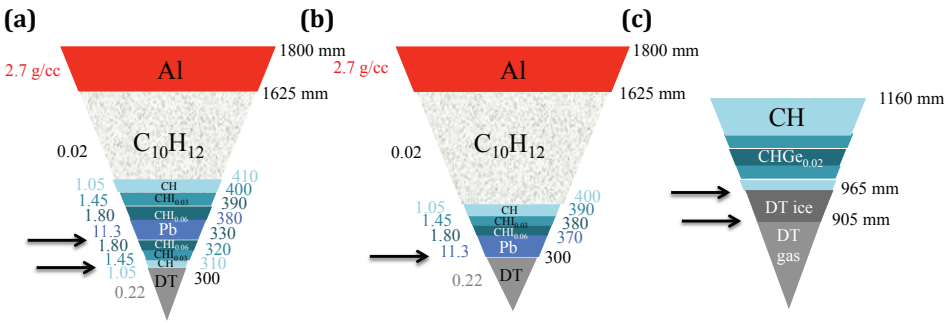

Figure 4. Double-shell designs (4a-b) and Rev. 5.0 single-shell design15 (4c), showing "clean" or no-mix 1D simulated yields and simulated yields with fall-line mix model applied to selected interfaces as indicated by arrows.

igniting, but eventually fails due to mix. The buffered design (4b), however, ignites to give in excess of 1 MJ of yield with mix, meeting the threshold standard for ignition. By contrast, the single-shell design (4c) fails to ignite when subject to the same fall-line mix prescription. Other designs using a beryllium outer shell and reduced inner-shell layering for adequate stability control are also being pursued for early testing on the NIF.

Prospects for Fielding Double Shells on the NIF

The choice of a Pb layer sandwiched in a CH inner shell was chosen to leverage well-established target fabrication capabilities for accelerated fielding on the NIF over a one-year time scale. Similarly, an all-aluminum outer shell was chosen to simplify the fabrication and machining process for short-term delivery. A prototype double-shell target has precedent: three successful hohlraum-driven double-shell campaigns on the Omega Laser Facility were conducted in 1999, 2003, and 2006,[14-16] yielding results in good agreement with modeling. The nearly 4x larger scale for a NIF-relevant double shell would simplify target fabrication for meeting various ignition tolerances, e.g., shell concentricity and outer-shell hemispherical joint offsets. The advances in simulation techniques, recent developments with nanomaterials research, and a successful experimental precedent at smaller scale all point to a timely investment on the NIF in a novel ignition target type for near-term testing.

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Measuring Opacities for High Energy Density Matter *by J.E. Bailey,* Sandia National Laboratories (SNL)*

How does energy propagate from the solar core to the surface of the Sun, where it emerges to warm the Earth? How old are the stellar systems that host the numerous exoplanets that have now been discovered outside our solar system? How does radiation penetrate and heat an inertial fusion capsule? The answers to these seemingly disparate questions hinge on knowledge of the fundamental material property that controls the absorption of radiation: opacity. Opacity plays a critical role for many high energy density (HED) systems and is highly important for the DOE/NNSA stewardship mission. In addition, laboratory astrophysics research serves as a conduit for establishing collaborations between the DOE/NNSA laboratories, between the DOE/NNSA laboratories and universities, and between the DOE/NNSA laboratories and our international partners. Exposure to open peer review sharpens the research capabilities and interactions of DOE/NNSA scientists with students and professors as a natural path for recruiting the next generation of stockpile stewards.

In his seminal 1926 book[1], *The Internal Constitution of the Stars*, Sir Arthur Eddington recognized the importance of opacity for modeling stellar interiors.

*This research was performed in collaboration with G.A. Rochau, T. Nagayama, G. Loisel, and S.B. Hansen (Sandia National Laboratories); A.K. Pradhan, S.N. Nahar, and C. Orban (Ohio State University); M. Sherrill, J. Colgan, C.J. Fontes, and D.P. Kilcrease (Los Alamos National Laboratory); C.A. Iglesias, and B.G. Wilson (Lawrence Livermore National Laboratory); R.C. Mancini (University of Nevada, Reno); and C. Blancard, Ph. Cossé, G. Faussurier, F. Gilleron, J.C. Pain (Commissariat à l'énergie atomique et aux énergies alternatives, France).

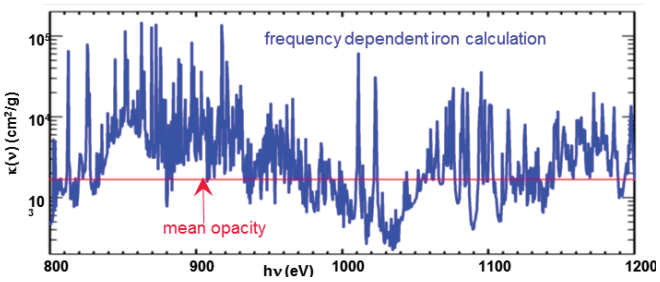

Figure 1. Iron opacity at conditions ($T_e = 2.17\times10^6$ K, $n_e = 9\times10^{22}$ cm^{-3}) corresponding to the boundary of the radiation and convection zones in the Sun, calculated using the Opacity Project model.[6] The opacity variation as a function of wavelength has encoded information about the multiple physical processes that control photon attenuation in matter. Applications such as modeling the inside of a star require knowledge of the Rosseland opacity, a harmonic average over frequency. However, benchmarking opacity models requires detailed knowledge of the different contributing processes. This knowledge can be obtained by first measuring the wavelength- (or frequency-) dependent opacity and then decoding the information contained within the opacity spectrum.

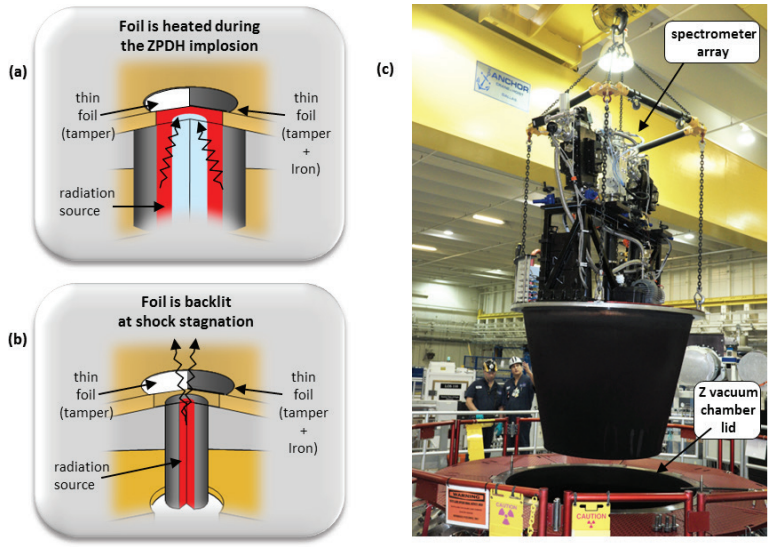

Figure 2. The Z opacity platform uses the z-pinch dynamic hohlraum (ZPDH) radiation source to volumetrically heat a sample over a roughly 7-nsec initial phase (a). Upon stagnation, the source emits a short intense x-ray burst that backlights the sample (b). The sample is split into two halves, with and without iron, to enable determination of the transmission with spectrometers through the sample by backlighting. An array of four spectrometers is used for the Z opacity measurements (c).

Even more remarkable was Eddington's conclusion that some energy-producing process such as fusion must exist, more than a decade before Hans Bethe's landmark paper[2] established that fusion was the energy production mechanism in the stars. Science is a description of nature founded in experiments that reveal which theoretical ideas are the most accurate. Thus, it was obvious that scientists should measure opacity, but opacity measurements at stellar interior conditions were not possible until megaJoule-class HED facilities such as the Z pulsed power facility at Sandia National Laboratories (SNL) and the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL), were built by DOE/NNSA for the stockpile stewardship mission. Now it is finally possible to create and diagnose the radiative properties of matter in stellar interiors, nearly a century after Eddington's book was published.

Opacity experiments are typically conducted[3,4] in the laboratory by volumetrically heating a sample to the desired temperature and density and measuring the transmission of a bright backlight source through the sample. The information required for input into simulations is often the Rosseland mean opacity,[5] a harmonic average over the photon energy. However, it is impractical to measure the mean opacity values for all the temperatures, densities, and elements that laboratory and astrophysical applications require. Consequently, our goal must be to perform measurements that test the physical approximations made in opacity models, so that we can employ those models with confidence. The models must cope with a variety of intermingled and complex physical issues. These include accurate and complete descriptions of the electronic energy level structure, contributions of roughly 1 billion bound-bound transitions, plasma effects that broaden the spectral lines and cause merging of energy levels into the continuum, and a host of excited and autoionizing levels. Our strategy is therefore to measure the wavelength-dependent opacity (see Figure 1), since the variations in the opacity with wavelength have encoded information about the relevant physical processes.

The experimental methods have been developed over the last 30 years,[3,4] but the requirements remain exceedingly challenging. Volumetric heating to temperatures above 2 million Kelvin requires a high-energy x-ray source and the backlighting source must have an equivalent temperature that is even higher, in order to overwhelm the self emission of the sample. The sample must be uniform and its temperature and density must be experimentally determined. Local thermodynamic equilibrium (LTE) measurements at solar conditions require a radiation field that drives the populations into equilibrium. A notable challenge is that the experiments require access to a megaJoule-class HED facility, but the experimental time on these facilities is extremely limited because of the large demand. Furthermore, opacity experiments require many shots because of a number of factors. First, the range of accurate opacity information that can be obtained from a single transmission measurement is approximately a factor of 5-10. Consequently, experiments must be conducted with different sample thicknesses to span the opacity range of interest. Second, experiments are needed over a range of temperatures, densities, and elements in order to unravel the information encoded in the wavelength-dependent opacity spectrum. Third, reliable measurements require multiple experiments to ensure reproducibility.

Experiments at SNL's Z facility can meet these requirements using the z-pinch dynamic hohlraum x-ray source to heat a thin sample over a roughly 7-nsec period (see Figure 2a). The spectral radiance at the center of the source sharply spikes near the end of the pulse and this sharp x-ray burst is used to backlight the sample (see Figure 2b). The transmitted backlit x-rays are recorded on a large array of spectrometers (see Figure 2c). Four spectrometers, which each record six spatially-resolved spectra, are used on each Z shot. Averaging these spectra greatly enhances the measurement accuracy. The measurement accuracy is also increased by using a split sample design. Half the sample is coated with

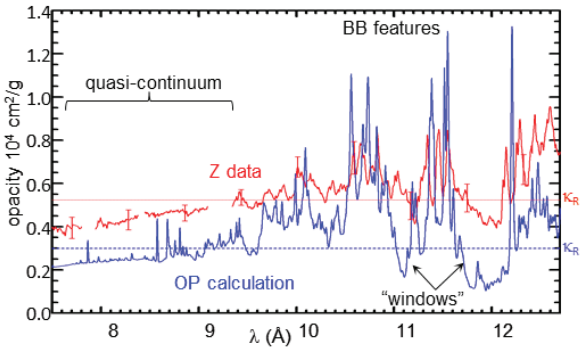

Figure 3. Comparison of iron opacity measured on Z with calculations from the OP opacity model. Both the experiment and calculation correspond to a 2.1×10^6 K electron temperature and a $3.1 \times 10^{22}/cm^3$ electron density. The calculated bound-bound (BB) features, opacity windows, and quasi-continuum are all different from the measurement.

the material to be studied, in this case iron, encapsulated in a low-Z tamper material such as plastic. The other half of the sample consists only of the tamper. This design enables us to record the unattenuated spectrum on each experiment and provides us with multiple independent analysis procedures to infer the transmission of the radiation. The sample coating is typically iron mixed with magnesium. Magnesium spectra are relatively well understood and provide independent measurements of the plasma conditions.[7]

Comparisons of iron opacity measured on Z[8] with calculations performed using the OP model, which is widely used in astrophysics, show that the calculated opacity is generally lower than the data (see Figure 3). In particular, the calculated wavelengths of the sharp spectral features that arise from bound-bound electronic transitions do not match the measurements, indicating inaccuracies in the calculated energy level structure. The calculated peak intensities and widths of the sharp features are also different; the peak-to-valley contrast is much larger in the calculations than in the data. Furthermore, the calculations predict wavelength "windows" with low opacity through which photons would be readily transported. These windows are nearly closed in the experiment, leading to higher average attenuation. Finally, the quasi-continuum opacity at the highest photon energies is nearly two times lower in the calculations.

These differences imply that, if the experimental data are correct, our understanding of photon absorption in HED plasma is different than previously believed. This would impact what we believe about many astrophysical and laboratory plasmas as well as about the Sun. In fact, the measured iron opacity accounts for approximately half the opacity increase needed to resolve an ongoing controversy in solar physics.[8,9] Consequently, we have invested several years of effort in examining the data for possible systematic errors. This process has benefitted from the extensive peer review available from the international community, but no systematic errors have been found yet. Therefore, we are now turning our focus to new experiments that can test hypotheses for what might be the cause of the discrepancy. These hypotheses include the following items. (1) The experiments might be flawed, despite many years of scrutiny and extensive peer review. (2) The models do not correctly account for open L-shell atomic systems with a high fraction of excited state populations. (3) The photoionization processes are not accurately calculated in existing opacity models. Experiments to test these ideas are aimed at measuring the opacity of three different elements at multiple temperature and density conditions. The elements that we have chosen for this study are chromium (Z=24), iron (Z=26), and nickel (Z=28). All three are important in astrophysical applications. Changing the elements in the experimental samples will help us ensure that the discrepancy between the model and the data is not caused by some unknown property of the as-fabricated iron samples. Furthermore, such a collection of unprecedented systematic opacity data will enable us to examine how the discrepancy depends on both the charge state distribution and the excited state populations.

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Highlights

SSAA Solicitation Award

The Office of Research, Development, Test, and Evaluation is pleased to announce that 34 of the 112 applications submitted for Funding Opportunity Announcement DE-FOA-0001067 for the Stewardship Science Academic Alliances Program were recommended for funding. These grants are in the topical research areas of Properties of Materials Under Extreme Conditions and Hydrodynamics, Low Energy Nuclear Science, and Radiochemistry. Visithttp://nnsa.energy.gov/aboutus/ourprograms/defenseprograms/stockpilestewardship/upaa/ssaa/ssaaawards to view the list of awards.

HEDLP Solicitation Award

The Office of Inertial Confinement Fusion, within the Office of Research, Development, Test, and Evaluation, and DOE's Office of Science received 94 proposals for the jointly sponsored High Energy Density Laboratory Plasmas Program's Funding Opportunity Announcement DE-FOA-0001153. NNSA will support 10 new awards. Visit nnsa.energy.gov/aboutus/our programs/defenseprograms/stockpile stewardship/upaa/hedlp/hedlpawards to view the list of awards.

University of California San Diego (UCSD) and California Institute of Technology (Caltech) Probe the Extreme Response of Materials to Laser Shock*

by Eric N. Hahn, Shiteng Zhao, Tane P. Remington, and Marc A. Meyers (UCSD); Zach M. Sternberger and Guruswami Ravichandran (Caltech); Chris Wehrenberg, Bruce A. Remington, and Brian R. Maddox (Lawrence Livermore National Laboratory); and Greg Randall and Mike Farrell (General Atomics)

Introduction

High power laser facilities allow us to probe the extreme response of materials by rapidly generating immense pressures through pulsed laser shock compression and release. The combination of very high pressures and ultrahigh strain rates makes this frontier regime of material science fascinating, exceedingly challenging, and potentially of very high impact to the world-wide inertial confinement fusion/inertial fusion energy (ICF/IFE) effort, basic high energy density (HED) science, astrophysics, and planetary science.[1]

When a material has a stress applied to it, it produces a strain, the amount of deformation in the direction of the applied stress divided by the initial length of the material. The rate at which this stress is applied and strain develops is the strain-rate. Experiments persist for only 10s of nanoseconds and results are often inferred from before and after microscopy or rely entirely on indirect measures of stress such as x-ray diffraction or the Doppler shift in a laser beam to measure velocities. Such extreme stresses and strain-rates reveal unique deformation mechanisms (plasticity) and phase transformations that challenge us to reconsider conventional materials concepts.[2] Massive computer simulations enable us to bridge this knowledge gap by evaluating extreme environments with multi-scale models that originate from molecular dynamics simulations with atomic resolution.[3] Here we will discuss an ongoing campaign to elucidate viscous plasticity, i.e., the deformation of a material undergoing non-reversible changes of shape in response to applied forces and failure of tantalum and silicon at pressures in excess of 10 GPa and strain rates above 10^7 s^{-1}.

On the Janus laser (see Figure 2), we aimed to simultaneously measure the flow stress of tantalum in both compression and tension at very high strain-rates, as a function of sample grain size and texture. We used the Richtmyer-Meshkov (RM) instability, which occurs when the interface between two materials of different density is accelerated, to infer compressive strength of the samples in the plastic flow regime. Driving a shock wave through an interface results in the rapid growth of local perturbations at the interface, i.e., RM hydrodynamic instabilities. If the shock is sufficiently strong, the instability leads to plastic flow at the interface. Material strength will reduce plastic flow and suppress growth. The surface of tantalum was seeded with two types of initial perturbations: two-dimensional (2D) hills and valleys as well as 3D egg crate patterns. The RM instability experiment uses thick targets that can be recovered post-shot to determine peak growth factors by characterization on the bench, obviating the need for, and complexity of, in-flight radiography. The recovered targets show that the 3D initial perturbations grew more than the 2D initial perturbations at the same shock strength.

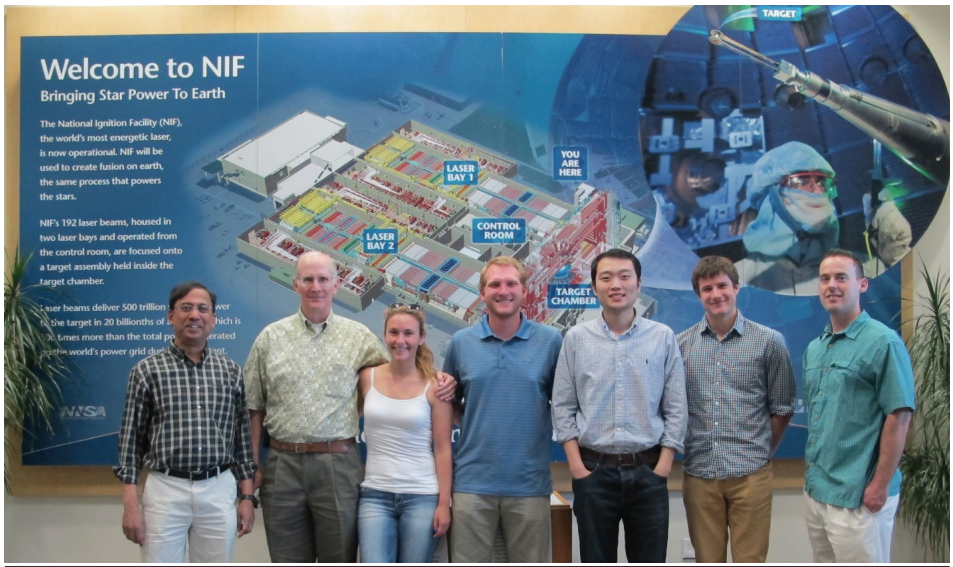

Figure 1. Group photo taken at National Ignition Facility. From left to right: Guruswami Ravichandran, Bruce Remington, Tane Remington, Eric Hahn, Shiteng Zhao, Zach Sternberger, Greg Randall.

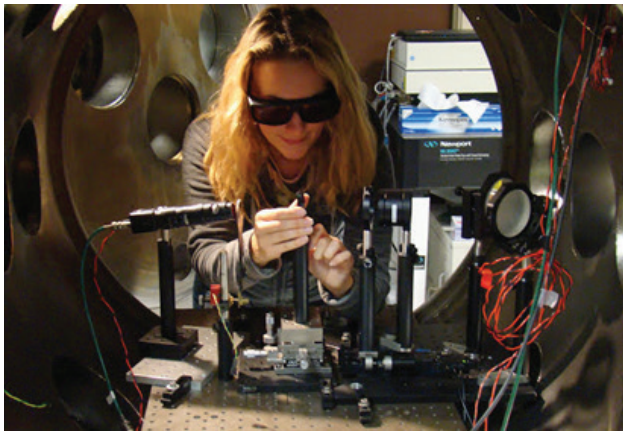

Figure 2. Tane Remington, a PhD candidate from UC San Diego, working inside the Chamber of Janus laser facility at Lawrence Livermore National Laboratory.

Shock pressures ranged from 10 to 200 GPa, and were calibrated using VISAR experiments. Shock compression of monocrystalline Ta reveals dislocations at low pressures and crystal twinning at higher pressures (above 24 GPa). Crystal twinning occurs when two separate crystals share some of the same crystal lattice points, i.e., share a twin boundary. Results are compared with predictions from homogeneous dislocation generation and multiplication and the

*This research was performed, in part, through a Department of Energy Stewardship Science Academic Alliances grant under principal investigator Marc A. Meyers. Supplemental funding sources: National Laser Users' Facility Grant and University of California Research Laboratories Grant.

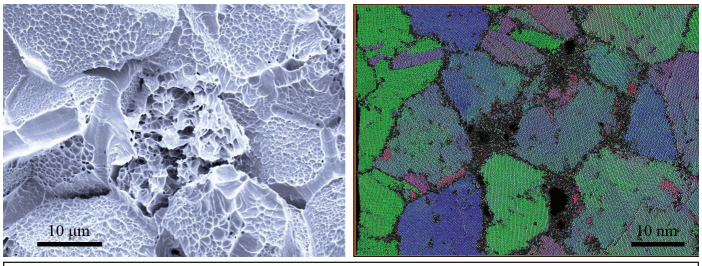

Figure 3. Left, recovered incipient spall sample of grain size 50 µm. Right, simulated spall in a 20 nm nanocrystal. Both illustrate void nucleation occurs at grain boundaries.

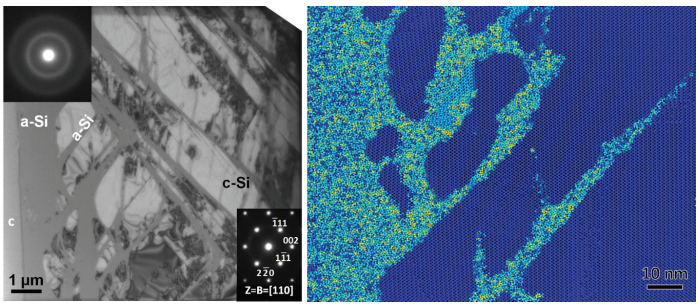

Figure 4. Left, Laser shock recovered silicon monocrystal. Right, simulated recovery of silicon. Both images show directional amorphous bands and a small bulk amorphous layer near the impact surface.

latter mechanism is dominant. The formation of a hexagonal phase was observed in monocrystalline tantalum at shock amplitude of approximately 70 GPa and it is likely that shear stresses may play a role in the transformation.

Using the Omega Laser Facility at the University of Rochester, we have carried out laser shock compression on monocrystalline silicon. The samples are recovered from high pressures using specially designed aluminum capsules that match the impedance of silicon. A detailed transmission electron microscopy (TEM) analysis was carried out. TEM is a microscopy technique in which a beam of electrons is transmitted through an ultra-thin specimen, interacting with the specimen as it passes through. Our preliminary results show that silicon undergoes amorphization, the conversion of the crystalline lattice into an amorphous/glassy state, above a certain shock pressure threshold. The amorphous domains are preceded by stacking fault propagation. As shock energy increases, the following structural changes in monocrystalline silicon are observed: dislocations and stacking faults; bands of amorphized silicon forming on crystallographic orientations consistent with plastic slip; broad regions of amorphized silicon; and nanocrystalline silicon resulting from re-crystallization. Molecular dynamics simulations also show directional amorphization as a result of slip defect avalanches, possibly relating to a metastable phase change associated with partial slip. A comparison between experimentally recovered silicon and simulated recovery is shown in Figure 4.

Future experiments are planned across multiple laser facilities to further explore the extreme response of model metals (Cu and Ta) and application-driven materials (B_4C and SiC) of national interest.

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From Idea to Innovation: The Role of LDRD Investments in Sandia National Laboratories' Recent Successful B61 Experiments *by Marie D. Arrowsmith (Sandia National Laboratories)*

The Laboratory Directed Research and Development (LDRD) program, authorized by Congress in 1991, enables Department of Energy (DOE) laboratories to devote a small portion of their research funding to high-risk and potentially high-payoff research. Because it is high risk, LDRD-supported research may not lead to immediate mission impacts; however, many successes at DOE labs can be traced back to investments in LDRD. LDRD investments have a history of enabling significant payoffs for long-running DOE/NNSA missions and for providing anticipatory new technologies that ultimately become critical to future missions. Many successes of Sandia National Laboratories (SNL) can be traced back to investments in LDRD. Capabilities from three LDRD projects were critical to recent tests of the B61-12 gravity bomb—tests enabled by the advanced computational projects discussed below.

Ensuring the safety, reliability, and performance of the U.S. nuclear weapons stockpile, given a moratorium on underground testing and increased constraints on non-nuclear testing, was one objective of the DOE Accelerated Strategic Computing Initiative (ASCI), announced in 1996. Computationally based solutions were needed to quickly simulate the response of complex structures in extreme environments. With the installation of ASCI Red at SNL in 1997, researchers had access to massively parallel (MP) supercomputing power that enabled the processing of programs over thousands of processors utilizing distributed memory. However, no commercial application existed that could perform simulations of weapons under stress utilizing this new architecture.

In anticipation of this need, researcher Garth Reese (computational sciences) led an LDRD project (1996-1999) to develop an algorithm to solve highly complex

structural dynamics equations, taking advantage of MP platforms. This algorithm, an MP eigensolver, was integrated with existing general purpose SNL parallel computing software. The result, Salinas, was capable of performing structural dynamics finite element analysis on MP systems, and represented a fundamental advance in Sandia's capabilities to model responses of weapons and other systems under stress at high fidelity.

The development of Salinas during this period provided a critical engineering modeling tool. As model complexity grew, so did the computational burden due to increasing numbers of equations to be solved in order to generate results. The ability to obtain solutions to modeling (and other) problems quickly, even on ASCI Red, was of interest to researcher Clark Dohrmann (computational sciences). Leading an LDRD project (2001-2003), Dohrmann developed two linear solvers that were subsequently integrated into Salinas. This work greatly improved the speed at which structural dynamics equations could be solved, enabling the solution of problems that were not solvable with commercial software. The capability developed through this LDRD project was used in 2002 to simulate structural dynamic responses to mechanical excitation in the W76-1 Arming, Fuzing, and Firing system—a significant milestone in the qualification of the W76-1.

To broaden the scenarios that Salinas could model, early career researcher Tim Walsh, experienced in acoustical engineering, led a one-year LDRD project in 2003 to develop a fully coupled structural acoustics capability that could be integrated into Salinas. This would allow users to quantify how acoustic effects impacted components (e.g., vibration of internal components due to the acoustic properties of the respective environment). The research focused on designing an algorithm (domain decomposition) to solve the coupled structural acoustic problem in a parallel environment. Users could now simulate the effects of mechanical excitation on complex structures, including MEMS (micro-electromechanical systems), SAWS (surface acoustical-wave systems), re-entry vehicles, buried bunkers and caves, acoustical weapons, and submarines. Additionally, it has led to spin-off technologies used by industry and other government agencies.

Following these LDRD projects that greatly improved Salinas, mission programs began utilizing the code for weapons simulations, integrating it into Sierra, SNL's engineering mechanics code suite, as a structural dynamics and acoustic module (Sierra/SD). The researchers who had worked on developing the LDRD-funded enhancements to structural modeling continued to test and improve the software, with a focus on scaling to account for improvements in computational capabilities. One such improvement came in 2011, with the introduction of a forward/inverse acoustics computational simulation capability into Sierra/SD. Prior to this enhancement, the models created in Salinas would be used to predict component responses. Now, experimental measurements could be used in Salinas to predict source inputs and material properties.

Figure 1. Microphones placed on a B61-12 system for an acoustic test. The unit is surrounded by banks of speakers that expose it to an acoustic field. The sound pressure reaches 131 decibles, similar to a jet engine.

In 2013, the forward/inverse capability was expanded to include coupled structural acoustics; by performing inverse simulations, the desired experimental conditions could be computed to create complex spatially varying environments. For example, Sierra/SD could now simulate under wing captive carry vibration conditions for the B61 and vibrational environments for reentry vehicles. Sierra/SD enabled the numerical simulation of ground-based acoustic tests of weapons systems at Sandia for the first time in 2014. Measurements were taken from subscale experiments on the B61 to replicate acoustics and vibration inputs for various environments (see Figure 1). These were then used by Sierra/SD to model the input forces on the whole weapon. In the past, this result could have only been achieved experimentally. The successful tests completed on the B61 are a realization of the goals of the ASCI program and critical to continued verification and validation of the U.S. stockpile. They also illustrate the important role that LDRD played in contributing to this vital nuclear weapons mission capability. ●

General Working Meeting of the International Agreement Between France and the United States of America for Cooperation on Fundamental Science Supporting Stockpile Stewardship *by Michael Kreisler (Contractor to the National Nuclear Security Administration)*

In late May 2015, the General Working Meeting of the International Agreement Between France and the United States of America for Cooperation on Fundamental Science Supporting Stockpile Stewardship was held in Bruyeres-le-Chatel, the French weapons laboratory near Paris. Meeting participants are shown in Figure 1. Since 2002, scientists from the nuclear weapons laboratories of both countries have collaborated under this agreement on many unclassified research projects in areas such as Materials Under Extreme Conditions, Nuclear Physics, and Atomic and Plasma Physics. The results of their efforts have not only been published in the open literature but have enhanced the physics base of the computer codes essential to the mission of ensuring that the nuclear stockpiles are safe, secure, and effective.

Over the past decade, a number of distinguished individuals have worked very hard to help manage the Agreement. At this time, the Co-Chairs are Thierry Massard, Scientific Director of CEA/DAM and Ralph Schneider, NNSA Director of the Office of Research and Development. The Management Points of Contact are Catherine Cherfils, CEA/DAM and Michael Kreisler, contractor to DOE/NNSA with Technical Coordinators John Porter (jlporte@sandia.gov), Sandia National Laboratories; Jason Burke (jtburke@llnl.gov), Lawrence Livermore National Laboratory; and Paul Dotson (dotson@lanl.gov), Los Alamos National Laboratory.

During the meeting, a new program was initiated to encourage recent PhD recipients from each country to take one- or two-year postdoctoral research positions at a laboratory in the other country. Candidates presented posters on their thesis work and submitted resumes for review. In addition to the three-day review of all the active projects, participants toured the accelerators and the high performance computing center at Bruyeres-le-Chatel. Scientists interested in collaborative research are encouraged to contact a Technical Coordinator; their email addresses are provided in the previous paragraph.

Figure 1. Participants of the General Working Meeting of the International Agreement Between France and the United States of America held in late May 2015.

History of the International Agreement Between France and the United States of America for Cooperation on Fundamental Science Supporting Stockpile Stewardship

1998: France and the United States seek to "reinforce the collaboration" between the scientists at the weapons laboratories in each country. To that end, Jacques Bouchard, then the Director of CEA/DAM, sent Daniel Gogny to Lawrence Livermore National Laboratory (LLNL) to explore the possibilities of collaborative efforts in unclassified research.

2000: In *January*, Bouchard wrote to the Directors of LLNL and Los Alamos National Laboratory (LANL) suggesting a formal collaboration be established driven by the realization that the "spectacular advances in computational technology offer new prospects in the use of more fundamental physics than in the past." Bouchard proposed meetings between representatives of the U.S. Laboratories and Jean Lachkar, of CEA/DAM – Île-de-France and Gogny to discuss physics areas appropriate for collaborative efforts. In *March*, Brigadier General Thomas Gioconda, then Acting Deputy Administrator for Defense Programs, answered Bouchard saying that the "DOE and the laboratories would value such an interchange" and suggested that an unclassified basic science cooperative agreement be established covering such topics as nuclear science, condensed matter physics and materials science and atomic and plasma physics. Meetings ensued to ascertain what specific areas of research held the most promise, including a seminal meeting held at Bruyeres-le-Chatel in *October* involving almost 30 leaders from CEA/DAM and the DOE/NNSA weapons laboratories.

2001: In February, a Workshop on Potential Collaborations in Nuclear Physics was held.

2002: Workshops on Materials Science, and Atomic and Plasma Physics were held in *February* and *April*, respectively. The Agreement was written, approved, and formally signed on *March 13, 2002* by Alain Delpuech, then Director of CEA/DAM, and John Gordon, then Administrator of the DOE/NNSA. The Agreement covers Cooperation on Fundamental Science Supporting Stockpile Stewardship and is managed by a Steering Committee with two Co-Chairs, two Management Points of Contact, and Technical Coordinators at LLNL, LANL, and SNL.

The following are facts about the Agreement:

- There have been approximately 80 proposals for collaborations.
- Many projects have been completed and 30 projects are active.
- Over 125 joint publications have appeared in the open literature.
- The Steering Committee meets annually. A General Working Meeting is held every two years at which time each active project presents the status of and results from their research. These meetings alternate between sites in each country.

Work on these collaborations is extremely important. Not only does such joint work bring more brilliant minds to work on pressing research problems for both countries but also the collaborative effort sharpens the scientific skills of and presents scientific challenges to the scientific and technical staff of the laboratories. ●

RDT&E Welcomes New Team Members

The Office of Research, Development, Test, and Evaluation (RDT&E) is pleased to announce our newest team members. They include Colonel Thomas Summers, Dr. Staci Brown, Mr. Willie Ward III, and National Nuclear Security Administration (NNSA) Graduate Fellowship Program (NGFP) Fellows Ms. Krystal Kasal and Mr. Bryan Sims.

Colonel Thomas Summers

Deputy for RDT&E Military Applications

Prior to arriving at NNSA, Colonel Tom Summers was the Chief of Strategic Stability and Countering Weapons of Mass Destruction Policy, Assistant Chief of Staff, Strategic Deterrence & Nuclear Integration, Pentagon, Washington DC. He led a division and managed the Air Force's $40 million per year arms control program budget. He ensured Air Force compliance with over 30 U.S. Treaties and International Agreements, managed air sovereignty, administered the Department of Defense (DoD) foreign clearance program for the Secretary of the Air Force, and provided warfighter support and strategy for deterrence and countering weapons of mass destruction (C-WMD) by developing operations and doctrine concepts; providing operations analysis, conducting interservice/DoD and interagency C-WMD talks, and leading the Chief of Staff's C-WMD Master Plan.

Colonel Summers has served in a variety of command, teaching, and staff positions. He received his commission through Officer Training School at Lackland Air Force Base, Texas in 1988. In addition to teaching physics to officer candidates, he also commanded a missile flight, a U.S. Air Force Academy (USAFA) cadet squadron, an operational ICBM squadron, and a joint agency division. The majority of his command and staff experiences in space/missile operations, education and arms control & nonproliferation implementation were at Minot Air Force Base, North Dakota, the USAFA, Colorado, the Pentagon, and Fort Belvoir, Virginia. He also served as the Deputy Inspector General, Headquarters Air Force Global Strike Command, Barksdale Air Force Base, Louisiana, where he conducted independent, impartial, and professional unit inspections. Prior to his current Pentagon assignment, he was the Vice Commander of the ICBM wing at Minot Air Force Base, North Dakota.

Dr. Staci Brown

Program Manager, Dynamic Materials Properties, Office of Research and Development

Dr. Brown followed her physics degree from Florida A&M University in 2006 with her master's degree studies in physics, completed in 2009 at Rutgers University. She returned to Florida A&M where she completed a doctorate degree in physics in May 2015. She was one of 50 outstanding undergraduate students chosen from across the country to participate in the faculty-mentored Research in Science and Engineering program at Rutgers in 2004. From 2005 through 2007, she worked as a summer intern at Corning, Inc., where she investigated the damage thresholds for silica, among other materials science research. While pursuing her master's degree at Rutgers, Brown conducted research under two separate traineeships from the National Science Foundation's Integrative Graduate Education and Traineeship program in 2007 through 2009. Her studies focused on patterning biomolecules to investigate cell behavior, as well as differentiation of stem cells to support the regenerative treatment of Parkinson's disease.

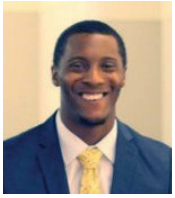
Brown also worked in the Plasma Physics Division of the Naval Research Laboratory as a 2012 summer intern, surveying the composition and monitoring the evolution of underwater plasma generated from high-powered pulsed lasers using laser-induced breakdown spectroscopy (LIBS). This work was conducted to improve naval communications, and other maritime applications. In her doctoral research at Florida A&M, she applied the same analysis technology toward the study of organic materials and isotope-enriched materials in order to develop LIBS as a stand-off detection method for explosives and to determine the relative abundance of enriched materials for non-proliferation applications. In addition, she has been a mentor within the Florida-Georgia Louis Stokes Alliance Minority Program to support minorities pursuing science, technology, engineering, and mathematics (STEM) careers.

Brown first joined NNSA as part of the NGFP where she worked in the Office of Research & Development supporting multiple initiatives within the Science portfolio. She is now an NNSA Federal staff member supporting the Office

of Research and Development as the Program Manager for the Dynamic Materials Properties portfolio (Campaign 2) and providing collaborative support to the Stewardship Science Academic Programs. She continues to support STEM education and help students achieve success in STEM career fields. Brown is from the South Side of Chicago.

Mr. Willie Ward III

Program Analyst, Office of Research and Development



Mr. Ward's current responsibilities include providing program analysis for the Offices of Research and Development and Inertial Confinement Fusion programs as they prepare for the upcoming fiscal year and close out FY 2015. In addition to working on program analyses, Ward also works on collaborative teams for other projects, including the Open Collaboration and Research Capabilities for the Collaboration in Research and Engineering in Advanced Technology and Education, and High-Performance Computing Innovation Center on the Livermore Valley Open Campus and Subcritical Experiments portfolio within the Nuclear Security Enterprise.

Ward will also pilot new program initiatives to support the Stewardship Science Academic Programs, specifically the Stewardship Science Academic Alliances. He will conduct critical skills assessments and establish an analytic framework and metrics to examine the increased need for program participants. In addition to this new initiative, he will focus on the Corporate Performance Evaluation Process, a quarterly assessment of the program's collaborating entities, tasks related to the Enterprise Portfolio Analysis Tool, and tasks related to fulfilling the role of a program Contracting Officer's Representative.

Ward attained a Bachelor's of Science degree in Business Management from Norfolk State University, followed by a Master's of Business Administration from Radford University. During his tenure at Norfolk State University, he interned at Northrop Grumman Shipbuilding and the U.S. Treasury Department, and his participation in the university's Minority Serving Institutions program allowed him to become an intern at Los Alamos National Laboratory through the NNSA Summer Intern Program.

Ms. Krystal Kasal

NGFP Fellow, Office of Research and Development

As an NGFP Fellow in the Office of Research and Development, Ms. Kasal serves as a technical expert in the area of materials physics. She provides support to international collaborations and the materials science programs. She is a member of the team working on the Matter-Radiation Interactions in Extremes (MaRIE) experimental facility project, assists with the Science Campaign monthly reports, and participated in the review of the Lujan Neutron Scattering Center at the Los Alamos Neutron Science Center.

Kasal earned her master's degree in physics from Washington State University and her bachelor's degree in physics, with an emphasis in astrophysics, from the University of Missouri in St. Louis in 2012. During her years in school, she taught several different physics and astronomy labs and participated in research in both undergraduate and graduate school. Her undergraduate research involved using spectroscopic methods to study the formation of stars in the Serpens Molecular Cloud by determining the ages, masses, and spectral types of the stars. In graduate school, she began working as a research assistant at Washington State University studying the diffusion of solute atoms in metal alloys using perturbed angular correlation spectroscopy. In this research, she gained specific and applicable expertise in the detection of nuclear radiation in intermetallics using scintillation detectors and time-coincidence methods as well as in alloy sample fabrication and data analysis of time-series spectra. Krystal also received the Washington NASA Space Grant for her graduate research and the Missouri NASA Space Grant for her undergraduate research. It was radiation safety training and working with radioactive isotopes required for her research in metals diffusion that drew Kasal to the nuclear industry.

Mr. Bryan Sims

NGFP Fellow, Office of Inertial Confinement Fusion

Here at DOE/NNSA headquarters, Mr. Sims is working with Dr. Keith LeChien and the rest of the Inertial Confinement Fusion team to conduct a three-year review of the national Inertial Confinement Fusion Program and to use these findings to prioritize essential research directions.

Mr. Sims received both his master's and bachelor's degrees from the School of Nuclear Engineering at Purdue University and will complete his Ph.D. later this year. Nonproliferation was Sims' primary concentration throughout his graduate studies. He first developed computer simulations for the identification of special nuclear materials arriving in the United States via cargo containers. Building on this, in a partnership with the International Safeguards and Security Group at the Idaho National Laboratory, Bryan established a nonproliferation course for freshman students to promote the field at an early stage of career development. In part because of his success in this initiative, he received Purdue's Magoon Award for Excellence in Teaching. For his doctoral dissertation, he is examining the use of Russian fusion technology to meet U.S. treaty obligations concerning plutonium disposition. His early-career experience with Los Alamos National Laboratory's Advanced Reactor Design Team has been instrumental in this most recent effort.

Having worked in both Senator Richard Lugar's Personal Office and the Senate Foreign Relations Committee Office, Bryan appreciates the integral role policy plays in furthering the nonproliferation mission. He refined this skill set through involvement with Purdue's Global Policy Research Institute. As part of this involvement, Bryan took a leadership role in a collaboration between Purdue University and a consortium of Colombian universities to introduce photovoltaic power systems into impoverished communities. Drawing on these experiences, Sims has pursued a regional expertise in East Asia through education, travel, and cultural immersion to provide local perspectives about nonproliferation issues. •