Showcasing examples of the capabilities that National Nuclear Security Administration national laboratories and sites bring to the Stockpile Stewardship Program (SSP) is one of the key intents of the Stockpile Stewardship Quarterly (SSQ). SSQ articles celebrate representative successes of our programs that are made possible by the incredibly talented staff that contributes to these efforts. This issue of SSQ highlights some major diagnostics which enable important SSP experiments and also discusses the role and impact of Laboratory Directed Research and Development (LDRD) on SSP.

The first article in this issue summarizes a major diagnostic on the National Ignition Facility (NIF), the Advanced Radiographic Capability (ARC). ARC is able to produce a bright source of penetrating high energy x-rays for target backlighting that is not possible with current NIF x-ray sources and sources at other high energy density experimental facilities. The second article describes a next-generation diagnostic for experiments at the Nevada National Security Site. It diagnoses the behavior of materials under highly explosive dynamic shock conditions and has been transformative for U1a Complex experiments. The next article highlights representative University of Rochester Laboratory for Laser Energetics diagnostics from the 160 diagnostics on OMEGA. It will focus on diagnosing the burn averaged hot spot pressure and other key performance metrics for layered deuterium-tritium implosions on OMEGA. These diagnostics have served as a basis for NIF diagnostics. The final article in this issue highlights select LDRD projects from the program’s more than 25-year history, which have had a significant effect on the SSP and, in general, have had a significant scientific impact within the high technology industries.

This year’s SSAP Annual Review Symposium, held February 17-18 at the Bethesda North Marriott in Bethesda, Maryland, hosted more than 300 academic partners, NNSA national laboratories staff, and NNSA staff. Geared toward NNSA-supported researchers with grants and cooperative agreements, the work of students and postdoctoral researchers, and university faculty was highlighted in the more than 120 posters on display during the poster reception.

Comments
The Stockpile Stewardship Quarterly is produced by the U.S. Department of Energy/National Nuclear Security Administration (DOE/NNSA) Office of Research, Development, Test, and Evaluation. Questions and comments regarding this publication should be directed to Terri Stone at terri.stone@nnsa.doe.gov.

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The National Ignition Facility (NIF) is a megajoule (million joule)-class laser and experimental facility built for stockpile stewardship and high energy density (HED) science research.1,2 Up to several times a day, 192 laser pulses from NIF’s 1.92 laser beamlines converge on a millimeter-scale target located at the center of the facility’s 10-meter-target chamber. The carefully synchronized pulses, typically a few nanoseconds (billions of a second) in duration and co-timed to better than 20 picoseconds (trillions of a second), deliver a combined energy of up to 1.8 megajoules and a peak power of 500 terawatts (trillion watts). This drives temperatures inside the target to tens of millions of degrees and pressures to many billion times greater than Earth’s atmosphere.

The need to better understand the physics occurring in NIF experiments over time scales measured in picoseconds has required researchers to develop a new generation of ultraviolet, ultrahigh-resolution diagnostic capabilities.1,2 One such capability, the Advanced Radiographic Capabilities (ARC), enhances the suite of detectors, spectrometers, interferometers, streak cameras, and other diagnostics already deployed on NIF. ARC is a kilojoule petawatt-class laser—that is, it can deliver more than 1 terawatt of pulse power at a peak power of energy at a peak power levels exceeding a quadrillion (10^15) watts. Following in the footsteps and building on the capabilities of successful petawatt systems built at other HED experimental facilities,3-9 ARC is able to produce a focused x-ray beam with sub-picosecond temporal resolution, high spatial resolution, high brightness, and a broad energy range. The ARC, specifically the installation of the high-power focal spot quality, precision pointing, and block using a silver micro-wire heated by evaporation of the grid was obtained (see Figure 4).

The integrated performance of the ARC system with the new front end was tested during the fourth quarter of fiscal year 2015 in a carefully coordinated campaign that addressed diagnostic calibration, focal spot quality, precision pointing, precision timing, energetics, and backscatter isolation.36 (For the focal spot quality of each beamlet is achieved by firing low-energy regenerative amplifier pulses (one beam at a time) to a sensor located at the center of the target chamber and “dithering” the active area of the master oscillator in the main laser cavity to optimize the focal spot by maximizing the intensity in the central lobe of each spot. The resulting mirror figure is then offset to add the pre-figure needed to cancel the prompt wavefront distortion that propagates between the main amplifiers are fired. Direct measurement of the high-power focal spot at the target plane is not practical, so this procedure has been validated by executing it to an equivalent focal plane camera in the ARC diagnostic package at the output of the ARC compressor. The results show that the focal spot varies among the four commissioned beamlets, but is consistent shot to shot, with the best beamlets performing very well in agreement with the optimized focal spot quality measured during NIF commissioning.14,15,19 Upon which the ARC specifications were based. Additionally, x-ray images of the individual beamlets incident on the gold foil targets showed x-ray spots that were similar in size and shape, and were well focused. Operation up to one kilojoule per beamlet in a sequence of shots on gold foil targets demonstrated the pulse energy was increased incrementally while monitoring diagnostics in the front end comprised of a grid and resolution grid. The resulting shadow image was recorded on a film plate. A series of filter steps were used to diagnose the backlighter spectrum (magnification of the system is 15.75). After it was demonstrated that ARC could be fired on a target with up to one kilojoule per beamlet, the first diagnostic test was performed. The test target consisted of a 10-micron-diameter silver wire mounted on a 500-micron square flag and oriented along the line of sight to a resolution grid located 28 mm away (see Figure 3). This configuration provides a near-point-source of x rays projected through the resolution grid onto a image plate located 553 mm away. The four ARC beamlets were co-pointed with the wire micro-wires and each 30-picosecond delay applied between pairs of beamlets to create a 60-ps random x-ray pulse. A high-resolution shadow image of the grid was obtained (see Figure 4). The signal level recorded in sufficient spatial resolution of approximately 22 microns

The National Ignition Facility (NIF) is a megajoule (million joule)-class laser and experimental facility built for stockpile stewardship and high energy density (HED) science research.1 Up to several times a day, 192 laser pulses from NIF’s 192 laser beamlines converge on a millimeter-scale target located at the center of the facility’s 10-meter-diameter target chamber. The carefully synchronized pulses, typically a few nanoseconds (hundreds of a second) in duration and co-timed to better than 20 picoseconds (milliseconds of a second), deliver a combined energy of up to 1.8 megajoules and a peak power of 500 terawatts (trillion watts). This drives temperatures inside the target to tens of millions of degrees and pressures to many billion times greater than Earth’s atmosphere.

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ARC achieves its extreme laser intensities through chirped-pulse amplification, a common architecture for high-energy lasers.1 In this process, an ultrashort laser pulse, only picoseconds or femtoseconds (10^-15 seconds) long, is first stretched in time to reduce its intensity. The frequency content of the ultrashort pulse is distributed in time to create a nanosecond-long, frequency-swept (chirped) pulse that can be amplified without generating intensities above the damage limit of laser glass and optics. After amplification, the chirped pulse is passed through an arrangement of diffraction gratings called a pulse compressor to undo the frequency sweep and re-create the initial short pulse, thus producing a high-energy, high-power laser pulse.

Multi-frame radiography employing x-ray backlights has been a standard diagnostic technique on NIF, but to date it has lacked the image quality, penetration levels, speed, and flexibility of the ARC design. ARC splits each of its 192 laser beams in one NIF can into two apertures (beamlets), producing up to eight petawatt-class laser pulses that can be used to create high-energy x-ray images of the target (only four of which are planned to be implemented). When fully implemented, each of the 192 beamlets will be capable of producing energy ranging from 0.4 to 1.7 kilojoules at pulse durations between one and 50 picoseconds with delays up to 80 nanoseconds. A single beam of NIF (one beamlet) will deliver up to 500 terawatts of power—the same level of power NIF generates with 192 beams.

This past year saw the completion of several important milestones in the development and commissioning of the ARC, specifically the installation of a new “high contrast” front end, the ramping of the first two ARC beamlines (four beamlets) to a total energy of four kilojoules on simple foil targets, and the acquisition of the first ARC radiograph. The ARC front end is the section of the system responsible for producing the low energy (<1 milljoules) chirped pulses that are injected into the NIF amplifier. One of its many stringent performance requirements concerns pre-pulse, or the amount of laser light that can arrive at the target ahead of the compressed pulse. Too much pre-pulse adversely affects x-ray conversion efficiency and increases the apparent size of the backlighter source through plasma blow-off and target motion.11 For the ARC, the allowable pre-pulse levels at the target flow back to a requirement for the allowable pre-pulse power at the output of the front end of ≤ 10^13 W (40-80) of the peak power in the compressed pulse. To ensure this high level of temporal pulse “cleanliness,” the front end was upgraded this past year to employ a state-of-the-art short-pulse optical parametric amplifier (OPA) architecture similar to that developed for the OMEGA EP laser at the University of Rochester.12 In this scheme, a 3,053-micrometer wavelength sub-picosecond pulse selected from a commercial mode-locked neodymium (Nd:glass optical amplifier) is amplified by a few billionths of a joule up to a few microjoules in a single beta-barium borate (BBO) crystal. The amplified pulse for the OPA is derived from a second pulse from the same oscillator that is first passed through a regenerative amplifier to increase its energy to a few millijoules and broaden its pulse duration to about 10 picoseconds. It then frequency-converted to the second harmonic wavelength of 0.5265 microns in a BBO crystal (see Figure 1). This architecture has the advantage of being inherently low on noise time scales important for pre-pulse, because any parametric fluorescence that occurs during the amplification process is confined to the 10-picosecond duration of the pump pulse. The chirped signal pulse exiting the OPA is stretched in time (chirped) and then split two ways to form the seed pulses that drive the ARC beamlets that make up each ARC beam. A parallel set of “twistor” compressors allow the chirped pulse to be adjusted relative to the dispersion of the compressor for optimum pulse width with the arc. A set of delay lines, tritium and spectral filters ensure independent timing and pulse shape control. Amplification to the millijoule level is accomplished in a parallel set of Nd:glass regenerative amplifiers.

A single beam of ARC (two beamlets) will deliver up to 500 terawatts of power—the same level of power NIF generates with 192 beams.

The integrated performance of the ARC system with the new front end was tested during the fourth quarter of fiscal year 2015 in a carefully coordinated campaign that addressed diagnostic calibration, focal spot quality, precision pointing, precision timing, energetic, and backscatter isolation. Optimally, the focal spot quality of each beamlet is achieved by firing low-energy regenerative amplifier pulses (one beam at a time) to a sensor located at the center of the target chamber and “dithering” the actuator of the deflection mirror in the main laser cavity to optimize the focal spot by maximizing the intensity in the central lobe of each spot. The resulting mirror figure is then offset to add the pre-figure needed to cancel the prompt waveform distortion that happens when the main amplifiers are fired. Direct measurement of the high-power focal spots at the target is not possible, so this procedure has been validated by executing it to an equivalent focal plane camera in the ARC diagnostic package at the output of the ARC compressor. The results show that the focal point varies among the four commissioned beamlets, but is consistent shot to shot, with the best beamlets performing in concert with the optimized focal spot quality measured during NIF commissioning13 upon which the ARC specifications were based. Additionally, x-ray images of the individual beamlets incident on the gold foil targets showed x-ray spots that were similar in size to the optimized focal spot size. Precision timing of beamlets has been established to better than 10 picoseconds rms using standard timing techniques,13 and validated with the SPIDER diagnostic,14 a fast x-ray streak camera that records hard x-ray emission vs. time from the ARC interaction with the target. The pointing accuracies required to meet requirements by imaging the locations of the soft x-ray emission produced by a few hundred joules per beamlet focused onto special pointing targets, including geometries that simulate aligning to a wave-irregularity-distributed grid. Operation up to one kilojoule per beamlet in a sequence of shots on gold foil targets, where the pulse energy was increased incrementally while monitoring diagnostics in the front end confirmed that spatial quantities levels remain negligible. The tests were conducted with the compressed pulse duration limited to ≤ 200 femtoseconds. However, consistent shot to shot, variations among the four commissioned beamlets were similar in size to the optimized focal spot size, and consistent with specifications for the first planned physics experiments (see Figure 2).

After it was demonstrated that ARC could be fired onto a target with up to one kilojoule per beamlet, the first radiographic test was performed. This test target consisted of a 16-micron-diameter silver wire mounted on a 500-micron square flag and oriented along the line of sight to a resolution grid located 28 mm away (see Figure 3). This configuration provides a near-point-source x-rays to backlight a grid with a hot spot and resolution grid. The resulting shadow image was recorded on an image plate. A series of filter sets were used to diagnose the backlighter spectrum (magnification of the system is 157.5x).

Figure 3. Schematic of the backlighter (BL) experimental configuration. The 10-micron silver wire produced a near-point-source x-rays to backlight a grid with a hot spot and resolution grid. The resulting shadow image was recorded on an image plate. A series of filter sets were used to diagnose the backlighter spectrum (magnification of the system is 157.5x).

Figure 4. Image plate radiograph of a grid and backing shot using a micro-wire-beamed by four ARC beamlets. The color scale is shown in Photo-Stimulated Luminescence (PSL) and the spatial ruler represents the scale at the target. Exposure of the image plate to transmission through the filter sets was used to estimate the backlighter spectrum.

Figure 2. The ARC can produce energies above 1.5 kilojoules per beamlet and powes above 400 terawatts per beamlet, depending on pulse duration. The plotted points show beamlet data obtained during commissioning of four ARC beamlets at 30 picoseconds pulse duration.
Shocked Surface Stereo Imaging with Fiber-Optic Imaging Probes: A Next-Generation Diagnostic for Subcritical and Other Experiments by Stuart Baker, Brent Froggatt, and Abel Diaz (National Security Technologies, LLC)

Introduction and Motivation
A picture tells a thousand words—this is a concept that captivates everyone, from the casual observer to the experimental physicists. To bring this concept to light in support of Stockpile Stewardship subcritical experiments conducted at the Nevada National Security Site (NNSS), we have developed a new diagnostic tool to investigate the behavior of materials under high-explosive dynamic shock conditions. For the Leda subcritical experiment executed in August 2014, a single-line-of-sight imaging system was designed and fielded as a stretch diagnostic goal for National Security Technologies, LLC (NSTec). For the Lyra series, beginning with the Orpheus experiment in September 2015, a newly created dynamic stereo surface imaging (DSSI) capacity was deployed. The DSSI diagnostic records a high-speed image sequence that allows scientists to peer inside an imploding hydrodynamic test object. Early versions of this diagnostic were fielded in single-line-of-sight borescope experiments with the Atomic Weapons Establishment (United Kingdom) in 2005. A borescope is an instrument used to inspect the inside of a structure through a small hole. The borescope system was expanded to stereo imaging by the addition of another small probe and small optical wedges to make the two views overlap. To accommodate the wedges, a narrowband (laser) light was used to avoid a chromatic ‘rainbow’ effect of prism. Laser light has the added flexibility of increased power and multiplex shaping. For this system, laser speckle noise is negligible.

Challenges and Solutions
Projecting a bright image through a very small hole is no small task. During the Leda experiment, we were able to use a small probe through the glide plane to achieve this. For Lyra, the method was expanded to stereo imaging by the addition of another small probe and small optical wedges to make the two views overlap. To accommodate the wedges, a narrowband (laser) light was used to avoid a chromatic ‘rainbow’ effect of prism. Laser light has the added flexibility of increased power and multiplex shaping. For this system, laser speckle noise is negligible.

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Acknowledgements

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References


For each view, a small lens focuses light from the surface to a small-diameter, high-speed imaging detector. The GRIN lens directs the image out of the experimental package. Once out of the package, the image is expanded by a small magnifier lens relay for transmission by coherent fiber-optic bundles and pressure containment fiber-plugs to cameras outside the chamber. A larger image results in high-speed resolution through the coherent fiber-optic bundles. Views of the GRIN probe assembly are shown in Figure 2.

Stereo correlation is the process of recovering depth information from stereoscopic camera images by quantifying the relationship between multiple views. The idea is to calibrate a stereo camera system by taking multiple images of a calibration target, such as a checkerboard pattern, at multiple orientations to map the three-dimensional (3D) image space. From correlating these images, estimates of the intrinsic properties of the camera system, such as focal length, relative pose, and the cameras, and lens distortions can be determined. By applying the intrinsic properties to a set of data images taken by the same system, a 3D visualization of the scene in real-world coordinates can be produced. By taking a number of stereo images at various times during an experiment, a 3D movie can be created allowing for a unique perspective. Stereo views of a test object are shown in Figure 3.

The stereo images are processed to provide a relief surface map. The DSSI field-of-view overlapping MPDV points are shown in Figure 4 (left).

For Lyra-2, the DSSI diagnostic is an expandable field-of-view, 3D imaging camera system designed to observe large structures created by the dynamic shock. The DSSI diagnostic integrates high speed imaging, high resolution x-ray radiography, and MPDV data to observe the interaction of the shocked surface to supplement the dye gas probing data. The DSSI diagnostic is designed to observe the changes in the shocked surface due to dynamic shock heating on materials that have a small optical wedge, such as the Chapman-Jouguet region.

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Los Alamos National Laboratory
National Security Technologies, LLC.
An Overview of Diagnostic Systems Used on OMEGA

Before focusing on our array of diagnostics dedicated to Laser Energetics (LEE), we introduce the facility and context for the broad array of diagnostics discussed in this article. The Omega Laser System at LLNL consists of a 60-beam, 30-kJ, symmetric illumination facility, OMEGA, and a 4-beam, 30-kJ (National Ignition Facility (NIF) architecture) planar illumination facility, OMEGA EP (EP). Two of the EP beams can be compressed in time for high intensity (in excess of $10^{19}$ W/cm$^2$) high energy density physics (HEDP) and basic science applications. One of the high intensity EP beams can be directed into the Omega target chamber for backlighting and is often used to image the deuterium–tritium (DT) shell of an ignition hydro-advanced direct-drive implosion as it nears stagnation. A plan is being developed to bring a long-pulse EP beam into this Omega target chamber. The Omega facility has the most comprehensive set of experimental tools of any HEDP diagnostic facility in the world and has been a staging/ development facility for NIF. The EP facility has access to dedicated HEDP-relevant materials science, laser pre-heating studies for the Magnetized Inertial Fusion (MIF) concept, and ultra-high-intensity physics; EP is dedicated to the diagnostic capability of OMEGA.

The cessation of operations at the LNL Nova facility in 1999 and the beginning of the National Ignition Campaign (NKC) in 2009, the Omega Laser Facility performed approximately 15,000 experiments for the Stockpile Stewardship Program and Basic Science (via the National Laser Users’ Facility and the Laboratory Directed Research and Development Program). During that same time, the facility encountered crucial shortfalls in diagnostics materials, in particular, the absence of matched diagnostics for tests of the Laser Inertial Fusion (LIF) concept, and ultra-high-intensity physics; EP was also dedicated to the diagnostic capability of OMEGA.

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before focusing on our array of diagnostics used to investigate Laser Energy (LLE), we introduce the facility and context for the broad array of diagnostics discussed in this article. The Omega Laser Facility at LLE consists of a 60-beam, 30-kJ, symmetric illuminating facility, OMEGA, and a 4-beam, 30-kJ (National Ignition Facility (NIF) architecture) planar illuminating facility, OMEGA EP (EP). Two of the EP beams can be compressed in time for high intensity (in excess of 10^15 W/cm^2) high energy density physics (HEDP) and basic science applications. One of the high intensity EP beams can be directed into the OMEGA target chamber for backlighting and is often used to image the deuterium-tritium (D-T) shell of an ignition hydro-scaled direct-drive implosion as it nears stagnation. A plan is being developed to bring a long-pulse EP beam into the OMEGA target chamber. The OMEGA facility has the most comprehensive set of optical, X-ray, and neutron diagnostics in the world and has been a staging/development facility for NIF. The EP facility has the ability to perform heating experiments with HEDP-relevant materials science, laser pre-heating studies for the Magnetized Laser Inertial Fusion (MLIF) concept, and ultra-high energy physics; EP shares the advantages of the diagnostic capability of OMEGA.

Between the cessation of operations at the LLNL Nova facility in 1999 and the beginning of the National Ignition Campaign (NIF) in 2009, the Omega Laser Facility performed approximately 15,000 experiments for the Stockpile Stewardship Program and Basic Science (via the National Lasers User’s Facility, and since 2008, the Laboratory Directed Research and Development Program). During that decade, much of the diagnostic and component technologies for NIF were developed and tested using an array of shots on both OMEGA and EP Examples include 1) the widespread use of CR-39, a plastic polymer that when exposed to high energy charged particles in the focal region of the laser, can be developed to reveal the location and energy of incident charged particles; 2) Chemical Vapor Deposited (CVD) diamond used to monitor the time-of-flight (TOF) spectroscopy; 3) temporally-gated multichannelion time-of-flight (PMT) for low energy neutron spectroscopy; 4) Chernikov radiation for γ-ray spectroscopy and burn history measurements (non-ideal) image plate and high energy x-ray imaging; 6) neutron imaging systems; 8) recent scintillator blankets with materials designed for specific applications; 9) the development of new optical and x-ray staring cameras with extended dynamic range and ultra-fast sweep speeds (2 ps) and 9) a new generation of x-ray framing cameras. A full accounting of this work is beyond the scope of this report but is captured in the included references.

While OMEGA and EP have many optical and X-ray diagnostics to measure laser-plasma coupling, this report will describe the diagnostic systems used to infer the burned-averaged hot-spot pressure (P_HS) and other key performance metrics for layered DT implosions on OMEGA. The P_HS is calculated using the formula below assuming an isobaric hot spot:

\[ P_{\text{HS}} = \frac{R_y}{2} \left[ \frac{M_{\text{FWHM}}^{2}}{\pi} \right] \left( \frac{\Delta V}{\Delta t} \right) \]

where \( R_y \) is the primary DT yield, the D_T neutron line is the fusion burn width, the integral over the hot-spot volume is (A/3)B, where A is inferred from x-ray core images, and \( \rho \) is the ion temperature. Other important performance metrics described in the document "Priority Research Directions for the National Inertial Ignition Fusion Program" (2016) include the fuel adiabat (inferred using shock-timing measurements and the areal density) and the implosion velocity.

Neutron Yield, Ion Temperature, and Areal Density

Neutron time-of-flight spectroscopy is used to measure the primary neutron yield, the fuel ion temperature (\( T_{\text{Fi}} \)) and the fuel areal density (\( \rho_f \)) in ICF implosions. The temperature of the burning plasma is encoded in the distribution of the emitted neutron energies (the energy gap due to the thermal distribution of ion velocities in the plasma). Long flight paths to the various TOF detectors ensure that the spread in neutron arrival times is comparable to or larger than the impulse response of the detectors. The instrument uses a set of turbulent and collective fuel motion, the thermal temperature is then the quasiequilibrium difference in the measured neutron line width (in time) and the measured impulse response. The integral of the signal from an ATOF detector can be calibrated (e.g., against standard activation diagnostics) to provide the absolute neutron yield. If the inferred fuel areal density, one of the OMEGA ATOF detectors uses gated PMTs to measure the neutron backscatter from the dense tritium. The e(nT) backscatter edge is shown in the green shaded area of Figure 1; the tritium edge in this edge region is proportional to the fuel areal density7 2 the ratio of the T/HD backscattered neutron spectrum found using a sapphire monitor and the red line is the fit based on the known signal (the neutron backscatter cross section is quite well known) and background components in the neutron spectrum (explicitly shown in the figure). The peak at 2.45 MeV is the DD fusion line (the energy scale is at the top of the figure). The gated PMT ensures that the signal has at least a few times larger signal from the primary DD fusion line is not recorded; this signal would overwhelm the backscatter edge and the DD line in the recording system.

Fuel Areal Density

The areal density is also measured using a magnetic recoil spectrometer (MRS) with the active detector being CR-39. The MRS was originally developed by the Massachusetts Institute of Technology and LLE for OMEGA2 7 Layered DT implosions (first data in 2008) and was later duplicated for the NIF during the National Ignition Campaign. The MRS records the portion of the forward scattered neutron spectrum (from the DT fuel) between 10 and 12 MeV. Since this neutron is elastic scatter from the deuterium and tritium nuclei, the yield between 10-12 MeV is proportional to the areal density of the DT fuel provided the DT fuel is homogeneously distributed. MRS works by momentum analyzing deuterons (using a dipole magnet) forward scattered by the neutron spectrometer from a thin DT foil placed near the target. The deuterons are detected with unity efficiency by PMTs placed on a re-entrant tube approximately 20 cm from the target. Each image is relaid onto unique positions of the four strips of a fast x-ray framing camera. The integration time of each image is approximately 38 ps and the image-to-image timing of the strips can be as short as 15 ps. This means that when properly timed all sixteen images are arranged across the roughly 100 μm wide illuminated layered DT implosion. Figure 3 shows a sequential set of images (each is 100 μm x 100 μm) from a recent implosion (note that the core structure is visibly changing on a 20-ps time scale). These images are analyzed using the MRS software to determine the horizontal core radius which is used to calculate the hot-spot volume for the determination of the hot-spot temperature. The dot-dash curve is the fitted to the scattered neutron spectrum based on a uniform density model for the fuel distribution. With direct-drive implosions, both the forward and backscatter measurements of the \( \rho_f \) are used to infer the core density and carbon in the ablator; the ablator is completely removed during the laser irradiation, and the core density of the DT fuel is 4.3 ± 0.3 x 10^21 cm^-3 and the yield was 169 ± 13 mg/cm^2.

Shock Timing

The stability and performance of an ICF experiment depends on the design adiabat and the implosion velocity. In the absence of electron x-ray preheating, the adiabat is set by a series of shock waves that successively and

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An Overview of Diagnostic Systems Used on OMEGA by Craig Sangster (Laboratory for Laser Energetics, University of Rochester)
incrementally compress the fuel while adding the desired amount of entropy. The shocks travel the NP-shell and fuel in a tight sequence designed so that they merge very near the inner surface of the fuel. LLE, in collaboration with LLNL and Sandia, developed the technique to measure the shock strength and timing using velocity interferometry with “cone-in-shell” targets. This concept, shown in Figure 5a, is applicable for both direct and indirect-drive. The shell and cone are filled with liquid D₂ (an optically transparent surrogate for layered DT) and the shell is driven by the desired laser pulse (or x-ray pulse from a laser-driven hohlraum). The VISAR diagnostic, (Velocity Interferometer System for Any Reflector) records laser light reflected from the leading shock using an interferometer to create time shifts as the trailing shocks overtake and strengthen the leading shock. Figure 5b shows the VISAR traces for a direct drive experiment where three 100-ps pulses and a main drive pulse (the blue trace at the bottom of the figure) drove four shocks into the D₂ filled capsule. The VISAR fringes, whose vertical position is proportional to velocity, are streaked in time and show the jumps at 0.3, 1.6, and 2.3 ns due to shock mergers. At 3.1 ns, the fourth shock produced by the main pulse overtakes the third shock. This technique is used routinely on the NIF at LLE to confirm design prediction of laser energy coupling and the fuel ablation following shock transit and coalescence.

Radiography

A short pulse (typically 10 ps), high energy (1,500 J), high intensity (typically a few 10¹⁲ W/cm²) beam from the EP laser is routinely used in the OMEGA target chamber to radiograph the dense fuel of an imploding DT shell (in flight) (after the laser is off and before the onset of core self-emission). Radiographs⁴⁷ such as the one shown in Figure 6 are acquired using 1.865 keV x-rays from the Si-He (transition (the configuration is area backlighting so the short pulse beam is focused to a much larger spot which reduces the on-target intensity and maximizes the brightness of the He line). The 10-ps x-ray burst ensures minimal motional blurring as the velocity of the shell in-flight exceeds 350 km/s. Soft x-rays are required to provide adequate contrast as the fuel density in-flight is much lower than at stagnation. During the fusion burn, the core self-emission is photometrically brighter than the Si-He emission. Stagnation images of the compressed fuel shell may be possible using 50-100 keV x-rays to generate a low-background Compton radiograph.⁴⁸ Photometric estimates of the Compton count are marginal for OMEGA implosions given the relatively low areal densities but look quite promising for layered DT implosions on the NIF using the Advanced Radiographic Capability (ARC).⁴⁹,⁵⁰ The dark circle in Figure 6 is the extent of the DT shell approximately 300 ps before peak compression. The contrast provides a measure of ablator material, the length of the conduction zone, and the shape of the ablation surface during the acceleration phase via self-emission radiography.⁵¹ Figure 7 shows a series of ablation surface self-emission images from a recent D₂ filled CH capsule implosion. The trajectory (radius as a function of time) of the ablation surface is a sensitive measure of the time-dependent coupling of the laser energy to the shell kinetic energy. Simulations and a separate ablation measurement with shell radiography confirm that the ablation surface trajectory (and velocity) is an excellent surrogate for the shell motion.

Summary

The OMEGA and EP lasers will continue to serve as the test bed for new ICF/HEDP diagnostics and experimental platforms. The high shot rate (> 2,000 per day) and configuration flexibility ensure that platforms and instrumentation...
incrementally compress the fuel while adding the desired amount of entropy. The shocks transit the DT shell and fuel in a tight sequence designed so that they merge very near the inner surface of the fuel. LLE, in collaboration with LANL and Sandia, developed the technique to measure the shock strength and timing using velocity interferometry with “cone-in-shell” targets. This target concept, shown in Figure 5a, is applicable for both direct and indirect-drive. The shell and cone are filled with liquid D₂ (an optically transparent surrogate for layered DT) and the shell is driven by the desired laser pulse (or x-ray pulse from a laser-driven hohlraum). The VISAR diagnostic (Variable Interferometer System for Any Reflector) records laser light reflected from the leading shock wave passing an interferometer to create a fringe shift as the trailing shocks overtake and strengthen the leading shock. Figure 5b shows the VISAR fringes for a direct drive experiment where three 100 ps pulses and a main drive pulse (the blue trace at the bottom center of the figure) drove four shocks into the D₂ filled capsule. The VISAR fringes, whose vertical position is proportional to velocity, are streaked in time and show the jumps at 0.3, 1.6, and 2.3 ns due to shock mergers. At 3.1 ns, the fourth shock produced by the main pulse overtakes the third shock. This technique is used routinely on the NIF at LLE to measure the velocity of the OMERA to confirm design prediction of laser energy coupling and the fuel ablation following shock transit and coalescence.

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**Implosion Velocity**

The Sydor Framing Camera (SFC) was developed for LLE several years ago by Sydor Instruments. The head design for development on OMERA and EP is programmatically cost-effective and can be transitioned to the NIF quickly and effectively. Instrument development was governed under the National Diagnostic Plans such as deep UV (~ 200 nm) Thomson Scattering and advanced Single-Line-Of-Sight framing cameras based on hybrid CMOS technology will be thoroughly tested on OMERA (and likely be added to the list of qualified facility diagnostics available to all users). References

**Laboratory Directed Research and Development: A Pathway from Idea to Impact**

The U.S. Department of Energy has charged the Laboratory Directed Research and Development (LDRD) program with reporting high-risk, potentially high-value research at the national laboratories. That LDRD is a program of the Laboratory’s mission to trace their roots to research that began to another, and it provides data to help the U.S. Army improve the penetration resistance of armor for our troops on the battlefield.

"Early on, LDRD provided the resources to develop the proof of principle that is foundational to pRad. Now a key capability for maintaining the Nation’s nuclear stockpile, pRad is the direct result of the synergy between the Laboratory’s defense mission and basic scientists.”

— Chris Morris

Muon Tomography Team Leader

Los Alamos National Laboratory
Accelerated Aging of Plutonium

In 1997, NNSA launched a comprehensive study at Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL) to examine in detail how plutonium (Pu) pits age and provide a firmer scientific basis for estimating the service life of these components. Experiments at the national laboratories produced the equivalent of 60-year-old Pu in a period of only four years. The work benefited greatly from capabilities that already existed because of LDRD. For example, at LLNL, the first direct measurement of helium bubble formation in aged Pu was based on LDRD investments in positron annihilation lifetime spectroscopy (PALS). This capability was developed and sustained through LDRD investment in the 1990s. Results from the NNSA study were used as the foundation for the 2006 Pit Lifetime Assessment and influenced the decision not to build a large capacity Modern Pit Facility—a multi-billion dollar savings. A current LLRD project at LANL to watch aging on a daily basis will form the basis for pit lifetime estimates that are physically sound and advance the understanding of the fundamental radiogenic processes in delta-Pu.

"LDRD investment in radiation damage and PALS laid the foundation for using high-resolution transmission electron microscopy imaging to directly measure Pu aging for the stockpile." — Patrick G. Allen  
Plutonium Aging Program Lead Lawrence Livermore National Laboratory

Optical Damage Reduction for Fused Silica Optics

Reducing optical damage to fused silica optics has been central to meeting the National Ignition Facility’s (NIF) stockpile stewardship mission. A decade of LDRD investments had enabled a series of fundamental discoveries and innovations in optical finishing science, the mechanisms of optical damage, and the discovery and mitigation of important damage precursors, which were key to reducing damage by a factor of over 10,000 from pre-2007 levels. These improvements have been implemented as production processes (Advanced Mitigation Processes 2 and 3) for large silica optics on all of NIF’s 192 beamlines, allowing an increase in operation from below 1 MJ to routine operation at 1.8-MJ levels.

"Investing early and building a long-term program in the basic material science underlying optical processing was essential in moving NIF down the pathway to mission-relevant energies. There are 384 large custom UV silica optics installed on NIF at a time, some of which are replaced every year. Without the improvements enabled by this research, NIF would have to replace more than five times more of these per year which exceeds the world-wide optical finishing capacity by more than a factor of two." — Jeffrey Bude  
Associate Program Manager in Optics and Material S&T Lawrence Livermore National Laboratory

Safe, Secure Nuclear Weapons Architecture

Traditionally, nuclear weapon interfaces tended to be discrete and dedicated in nature with little flexibility, making it difficult and costly to modify existing systems without extensive redesign. An LLRD-developed “communications backbone” bus-based architecture now simplifies weapons electronic system communications and interconnections, while ensuring system and component reliability and allowing for simpler upgrades in the future. Via two additional Early Career LDRD projects, formal verification methods were implemented into the architecture, thereby increasing safety and security of the system. The “foundation bus communications architecture” has been selected as a baseline for all current Life Extension programs.

"These LDRD efforts have had significant impact on our nuclear weapons missions. The end product from this LDRD investment is now being used on all of the current life extension programs for both mission and instrumentation functions.” — Perry Molley  
Digital Design & Verification Manager Sandia National Laboratories

Multiplexed Photonic Doppler Velocimetry

For nearly 50 years, weapons designers could only see “time snapshots” of an imploding cavity. With the emergence of fiber-optic velocimetry, and later, photonic Doppler velocimetry (PDV), surface motion could be continuously recorded. Utilizing advanced, low-cost, commercially available digitizers, the Site Directed Research and Development program at National Security Technologies, LLC enabled velocimetry at 10,000 frames per second. Using a method called multiplexing, tuned and optimized oscillators are added to each digitizer signal. Multiple time-delayed PDV signals can be recorded on a single channel, meaning 32 signals can now be recorded on one four-times-delayed PDV signals can be recorded on a single channel, meaning 32 signals can now be recorded on one four-channel digitizer. With multiple tests and integrated experiments now complete, multiplexed PDV (MPDV) has transformed the weapons hydrodynamics program, providing designers with a wealth of information.

"Without the Site Directed Research and Development (SDRD) program, this capability would not exist today. The ramifications of this technology have gone well beyond anything envisioned when the SDRD proposal was first written.” — E. Daykin  
Principal Investigator National Security Technologies, LLC

Electronics for Hostile Environments

Radiation-hardened electronics are critical to the performance of nuclear weapons and for systems that operate in space, high altitude, defense systems, or in close proximity to nuclear reactors. Unfortunately, standard components and processes common for commercial microchip production are vulnerable to ionizing radiation from natural or deliberate sources (in hostile environments). Multiple LDRD projects developed special materials and processing technologies that enable the design of radiation protection right into the chip. This LDRD-developed capability is now being utilized in the 861 and W76 modernization programs, with Sandia National Laboratories scheduled to provide more than 25,000 radiation-hardened application-specific integrated circuits (ASICs) for both programs starting in 2016.

"Sandia’s LDRD program has funded fundamental radiation-hardened ASIC technologies, and because of that investment, Sandia’s Microsystems and Engineering Sciences Applications (MESA) Complex is able to provide radiation-hardened technology required by our nuclear weapons programs.” — René Sanchez  
Microsystems S&T Sandia National Laboratories

Massively Parallel Molecular Dynamics Simulation

Stockpile stewardship applications require a deep understanding of matter (specifically, plasmas) at a wide range of extreme conditions, which is a considerable coding challenge for computational physicists, who rely on theoretical plasma physics at Lawrence Livermore National Laboratory’s (LLNL’s) Cimarron LDRD project developed a world-class, massively parallel molecular dynamics code to model warm dense and hot dense matter. Research-based molecular dynamics can create a virtual representation of matter at extreme conditions (plasmas), which was then used to probe various physical properties. This research has addressed critical plasma physics model uncertainties for stockpile stewardship; the resulting capability was instrumental in completing a level-2 NNSA milestone. In addition, it is contributing to key uncertainties related to fusion ignition.

"The Cimarron project has provided an entry point for many early career[ New hires] into LLNL, and has created a high-energy-density computational capability as well as a scientific community for hot dense matter that did not exist before." — Frank Graziani  
Cimarron Project Lead Lawrence Livermore National Laboratory

This research has addressed critical plasma physics model uncertainties of importance to stockpile stewardship. The image shows the plasma wake produced as an ion slowed by the plasmas in the stopping process.

Office of Research, Development, Test, and Evaluation
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Dr. Eric Machorro has been employed within DOE/ NNSA’s RDT&E for the past 10 years. She was recently appointed the Program Manager for Secondary Assessment Technologies (C4) in the Office of Research and Development. Previously, she worked in the Office of Inertial Confinement Fusion and was Program Manager for the Laboratory for Laser Energetics and for the National Laser Users’ Facility Program. Her duties included programmatic leadership, in addition to contractual activities. Prior to joining NNSA, she worked on the design and development of the new US $20, $50, $10, and $100 banknotes and on the technical evaluation of new counterfeit deterrence features for U.S. currency at the Bureau of Engraving and Printing. Before, she spent 18 years as a Senior Research Scientist at Eastman Kodak Company in Rochester, New York and holds 21 U.S. patents in silver halide photographic technology. She completed the Council for Excellence in Government Executive Leadership Development Program in 2008 and the Grants Management Certificate Program in 2015. She has a bachelor’s degree from the University of Massachusetts Lowell and a master’s degree from the University of Rochester, both in Chemical Engineering.

For the past eight years, Dr. Eric Machorro has been at the Nevada National Security Site (NNSS). For the early part of most of his tenure there, he developed mathematics and algorithms for analyzing both legacy reaction history data and photonic Doppler velocimetry data collected on recent subcritical experiments. He was also a part of the Site Directed Research and Development program, and now manages NSTec’s Diagnostic Development and Materials Studies group in North Las Vegas. For several years prior to that, he worked on algorithms for solving neutron transport problems for Lawrence Livermore National Laboratory.

Previous positions include a brief position at WaMu as Lead Quantitative Analyst and a 13-year career as a watershed manager for the City of Portland directing environmental salmon-habitat and floodplain restoration projects. Eric received a bachelor’s degree from Reed College in Mathematics and his doctorate in Applied Mathematics from the University of Washington. He also holds master’s degrees in Environmental Science and Engineering from the Oregon Graduate Institute.

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Tiberius Morán-López
Program Manager
J. Tiberius Morán-López has been a member of the Office of Defense Programs since 2013, during which he has worked with the offices of RDT&E and Stockpile Management. His managerial responsibilities have encompassed weapon engineering and defense sciences, academic alliance programs, contract administration, and collaborative agreements with the Department of State and the Commissariat à l’Energie Atomique (CEA) of France. Prior to joining RDT&E, Tiberius was awarded the Defense Programs Award of Excellence in 2015 for his contributions to Integrated Surety Architectures. In addition to his responsibilities at NNSA, Tiberius also continues collaborative research with the Lawrence Livermore National Laboratory on predictive methods for shock-driven hydrodynamic instabilities and turbulent mixing for high-energy-density physics applications. As such, he remains active in publishing peer-reviewed work and presenting at scientific conferences.

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National Security Technologies, LLC/ NNSA Details
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Tiberius earned his doctorate and master’s degrees from the University of Michigan in Nuclear Engineering and Radiological Sciences, and earned dual bachelor’s degrees from Texas A&M University in Nuclear Engineering and Theoretical Physics. Tiberius has worked with the Lawrence Livermore and Los Alamos National Laboratories, General Atomics, and has served as a physics and mathematics civilian instructor for the Navy. Lastly, Tiberius is also fluent in Spanish, proficient in Korean, and has studied elementary Russia.

SSAA Center of Excellence Principal Investigator Receives Prestigious Rutgers University Award
Congratulations to Dr. Jolie Cizewski on being named the 2016 recipient of Rutgers University’s Daniel Gorenstein Memorial Award. This award is given to an outstanding member of the faculty and includes a stipend and the honor of presenting the annual Gorenstein Memorial Lecture to the university and wider community on a topic of the winner’s choice. Dr. Cizewski is the Principal Investigator of the Stewardship Science Academic Alliances Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science.

2016 Summer School: Foundations of High Energy Density Physics (HEDP)
To promote the spread of fundamental knowledge in the field of HEDP, the University of Michigan offers an intensive summer school course. Registrants will receive 40 hours of lectures based primarily on the book High-Energy-Density Physics by Professor R.P. Drake. The course, scheduled for June 12-25, 2016, is aimed at graduate students, young scientists, and experienced scientists seeking an HEDP foundation. For more information, visit http://clasp-research.engin.umich.edu/workshops/hedss/.

8th OMEGA Laser Users Group (OLUG) Workshop
The 8th OLUG Workshop will be held on April 27-29, 2016 at the University of Rochester Laboratory for Laser Energetics. The annual workshop explores ways to enhance and extend current research and collaborations at OMEGA as well as to help formulate further improvements to, and novel operating regimes for, the OMEGA facilities. To register, visit http://ouw. rochester.edu/. U.S. citizens must register by April 15; the deadline for foreign nationals to register was March 7. Registration is limited.