


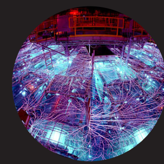
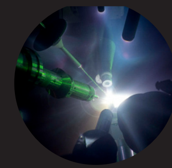

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Stockpile Stewardship *Quarterly*

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

It is with great pleasure that I craft my first message for the *Stockpile Stewardship Quarterly*. I am honored to lead this organization that performs work crucial to the success of the Defense Programs' mission. I have confidence in the ability of the enterprise to deliver the best science, technology, and engineering solutions to the mission challenges before us. I will be focusing a lot of my time on improving communications with our stakeholders regarding the importance and impact of the NNSA Office of Research, Development, Test and Evaluation (RDT&E) on our core mission. In addition, I am committed to ensuring the health and vitality of the RDT&E enterprise.

In this issue, you will find articles which span the breadth of activities in the RDT&E portfolio—from computing to the experimental science performed at our national laboratories and at an affiliated university facility. The computing article describes the critical role of computing throughout the history of the Stockpile Stewardship Program.

Validation of our modeling and simulation capabilities is performed on a wide range of experimental platforms. A key experimental capability for stockpile stewardship is the 40-mm Impact Test Facility at Los Alamos National Laboratory for measuring the dynamic properties of plutonium. This facility has provided plutonium data for more than 18 years. The technical article on the high-foot implosion campaign on the National Ignition Facility (NIF) describes exciting recent experiments designed to better understand key physical phenomena occurring in the NIF indirect-drive capsules. The final technical article describes recent polar-drive experiments on OMEGA at the University of Rochester Laboratory for Laser Energetics and on NIF, which were designed to understand the physics occurring in direct-drive implosions at facilities configured for x-ray drive.

One of the most rewarding elements of our program is to provide opportunities to students through the Stewardship Science Academic Alliances (SSAA) program and to high energy density physics researchers through the High Energy Density Laboratory Plasmas grant program. Information on those opportunities can be found on the final page of this issue of the *Stockpile Stewardship Quarterly*. Of particular note is that one of our past SSAA participants, Seth Root of Sandia National Laboratories (SNL), was awarded a Presidential Early Career Award in Science and Engineering; SNL researcher Stephanie Hansen received an Early Career Research Program award from DOE's Office of Science; and two of our Carnegie-DOE Alliance Center Academic Partners, Professors Steven Jackson (Northwestern University) and Eva Zurek (University at Buffalo, State University of New York) have received prestigious awards as well.

Finally, to all members of the NNSA RDT&E community: I look forward to working with all of you and leading this organization as we take on the exciting challenges before us.

Inside

Comments

The *Stockpile Stewardship Quarterly* is produced by the NNSA Office of Research, Development, Test, and Evaluation. Questions and comments regarding this publication should be directed to Terri Stone at terri.stone@nnsa.doe.gov. | Technical Editor: Dr. Joseph Kindel | Publication Editor: Millicent Mischo

The Role of Computing in Stockpile Stewardship *by Bill Archer, Robert Webster, Mark Anderson, Jon Boettger, and Fred Wysocki (Los Alamos National Laboratory); Christopher Clouse (Lawrence Livermore National Laboratory); and Kenneth Alvin and David Womble (Sandia National Laboratories)*

Why Simulations?

The Stockpile Stewardship Program (SSP) has been developed to avoid the need for nuclear testing as a means to ensure the safety and performance of the enduring stockpile. As described in the *Stockpile Stewardship Quarterly* Volume 4, Number 1 (May 2014) issue, it is based on a set of new experimental facilities for understanding dynamic performance of materials and a simulation capability considerably more predictive and higher fidelity than the simulation tools available during nuclear testing.

With the end of nuclear testing, it was realized that computer simulation would have to, in essence, form a numerical test base that, along with focused non-nuclear experiments, would allow us to avoid a return to nuclear testing. The SSP uses simulations to help weapons stewards make decisions about the stockpile. These decisions span the full lifetime of a nuclear weapon; from performance impacts of a refurbishment, to the performance impact of aging parts, to the one-point safety of tooling configurations for dismantlement.

Since the introduction of punch card accounting machines in the Manhattan Project in 1944, simulations have been used to assist in making weapon performance decisions because the stockpile was only tested in a very limited regime of the stockpile-to-target sequence. Today without nuclear testing, the only way to evaluate the performance impact of a change to the device is through simulation. Without nuclear tests, it is not possible to experimentally explore the entire range of physical conditions that exist in a nuclear weapon. The temperatures, pressures, and scale experienced by material in a nuclear explosion, for example, cannot be simultaneously accessed by any experimental facility.

Even where tests are possible, simulation plays an important role in reducing costs and improving the performance and safety of weapons systems. Costs limit the manufacturability and availability of experiments involving the use of special nuclear material. Costs also limit the number of tests that can be performed for re-entry systems and for the safety and security of systems in abnormal environments, e.g., crash, fire, lightning, or blast. In all of these cases, simulation plays a strong role in exploring the design space and reducing build-and-test cycles, assessing performance, designing tests, and assuring the safety and security of the stockpile.

The use of simulation also helps sustain the knowledge-based deterrence called for in the 2010 Nuclear Posture Review. Simulation capability is a major tool that is used to recruit, educate, and retain new nuclear weapon designers. Today, stewards are trained, in part, by using simulations to carry out what-if scenarios to see how changes affect performance and to gain physical insight into the impact of changes to the performance of a device. The integrated design codes (IDCs) (see the ***What is a Code?*** sidebar) developed under the Advanced Simulation and Computing (ASC) program for use by stewards are complex tools requiring complex input, and a mastery of the use of these tools

What Is a Code?

The term "code" refers to a collection of instructions that tell a computer what to do, as shown in the code snippet (see Figure 1). An integrated design code is the collection of instructions to solve the many different types of physics involved in a nuclear weapon. Many of our codes work by breaking the problem down into small spatial pieces, called mesh cells, as shown in the setup of a shape charge (see Figure 2). The simulation time is also subdivided into pieces, called time steps. Each piece of physics is solved within each cell during each time step. The code numerically follows the physics through time to solve the simulation. Some types of codes are more accurate for simulating solid materials while other types of codes are more accurate for simulating the turbulent flow of liquids and gases. The numeric methods used to solve the physics also introduces different types of errors. For example when applied to a particular type of physics, one code method will introduce statistical noise into the solution, whereas another method will cause spatial hot spots. The codes supported by the ASC program provide a complementary set of methods to allow us to understand the strengths and weaknesses of different types of codes and methods on each particular problem. This is definitely a situation where one size does not fit all!

```
!
!      -----convert total energy to internal
!

!$omp do private(ipoint) schedule(static)
!
    do ipoint = 1, mesh%npoint
      point_data%point_state%unknowns(5, ipoint) = &
           point_data%point_state%unknowns(5, ipoint) - 0.5e0_real_kind * &
           dot_product(point_data%point_state%unknowns(2:4, ipoint), &
           point_data%point_state%unknowns(2:4, ipoint))
    enddo
!
!$omp end parallel
```

Figure 1. Snippet of code instructions to calculate internal energy in each cell over an entire mesh.

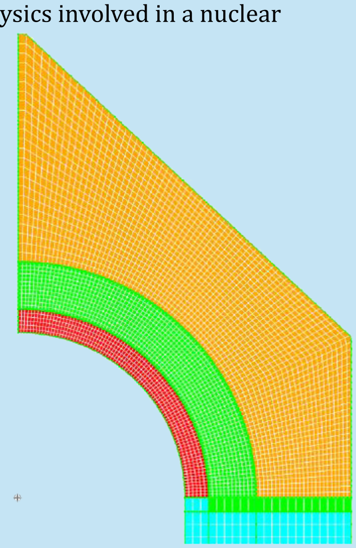


Figure 2. Setup of a shaped charge, showing the simulation mesh (By Daniel Ingraham).

requires both hard work on the part of the steward and adequate peer review by other stewards. In addition, many of the basic algorithms developed within the SSP are employed in unclassified codes for use on unclassified problems where results can be published and internationally peer reviewed, thus providing additional scientific credibility, and a critical test of the capabilities of our stewards.

Equation-of-State (EOS) Modeling

Simulations of nuclear devices require tabular EOSs that represent all materials in the system. The reliability of such simulations is sensitive to the fidelity of those EOSs. The challenge is to produce tabular EOSs that are accurate and well-behaved over a wide range of compression (10^4) and temperature (10^9). To this end, the EOS models used are tuned to match experimental data and results from atomistic simulations. Until recently, a well studied material might have data along the room temperature isotherm up to 1 Mbar (purple in Figure 1), the principal Hugoniot to a few 10s of Mbar (solid black line in Figure 1), and some Hugoniot data on porous samples. None of this data can be used to constrain an EOS in the high pressure, low temperature region probed by an imploding shell of material. This led the laboratories to depend on tuning the most important EOSs to match Nevada Test Site events. Such tuning was a reasonable expedient during the era of testing, but is impractical today. Over the last decade, however, this picture has been altered by the introduction of techniques for generating data along isentropes, dashed lines in the Figure 1 (data from Z Machine, laser drive), quasi-isentropes (data from graded flyer gas gun) or in an imploding shell which do probe that region. These new capabilities, along with atomistic simulations, have played an important role in creating a new multi-phase EOS for Pu at LANL that compares well with multiplexed photon Doppler velocimetry data from recent subcritical experiments at U1a.

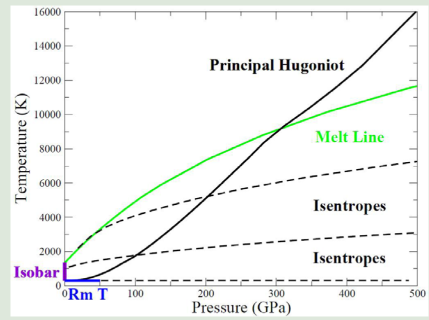


Figure1. EOS of gold, showing the EOS regions that can be measured experimentally.

How Do We Simulate?

Simulations are the end result of a large scientific enterprise. The IDCs couple together many different pieces of physics to provide the simulation capability that decades of experience shows are needed to simulate a nuclear weapon system. This integration makes the IDCs different from most scientific codes that focus on doing only one or two types of physics. The IDC infrastructure is designed to support physics model evolution, over time adding more detailed physics to the models, resulting in improved predictive models.

The IDCs are very general codes that are used to simulate the entire range of nuclear security questions asked of the laboratories. For example, on any given day the same IDC can be used to simulate issues for Significant Finding Investigations, for the Annual Assessment of all stockpile systems, for ongoing Lifetime Extension Projects (LEPs), and for non-stockpile applications like disablement of a proliferant nuclear weapon, foreign weapon design assessment, or nuclear forensics, in which a design is inferred from post explosion data.

There are also science codes that specialize in a particular physics problem such as particle transport, material properties at the quantum level, or high explosive burn. These codes are used in the development of theory, models, and computed properties that are needed within the SSP. In addition, these specialized codes provide a framework for incorporating experimental data and extending our knowledge to conditions beyond what can be reached with current experimental facilities. Data on the properties of materials is a particularly important area where theory and specialty codes, in addition to experiments, underpin all of the integrated design simulations (see the ***Equation-of-state (EOS) Modeling*** sidebar above).

The SSQ March 2014 issue discussed the role of experiments. The experiments are used to inform physics theory and models, and then to calibrate the models. Computational physicists turn the models into numerical methods that are implemented in the IDCs. Experimental data is used to validate the models, producing, in the end, a validated simulation tool for use by stewards.

In the end, confidence in the simulation results is vital. Building that confidence requires rigorous comparison of relevant simulations to ongoing experiments, and historical nuclear tests.

Are We Done?

At the end of nuclear testing in 1992, a broad understanding of the functioning of a nuclear weapon existed. However, questions remained about the details of some physical interactions. The lack of understanding of these details was handled by incorporating expert designer judgment with the IDC through the use of empirical calibrations, colloquially known as knobs. Traditionally, the calibrations were set to a small number of nuclear tests and were only valid for closely related tests. Each family of devices had its own calibrations that were valid for the nominal range of performance. The lack of a universal set of empirical calibrations was acceptable because changes to devices could be tested.

With the end of nuclear testing, the lack of predictive capability by the IDC became a problem. For example, the knobs were calibrated to nominal performance, but with the end of testing the question of where the failure point is for each type of weapon became very important. Yet, this is exactly where nuclear test experience shows that the calibrations are least reliable. In addition, there were many nuclear tests whose behavior was never understood, either by experiments or simulations; these tests are labeled anomalies. In general, the presence of the empirical calibrations causes uncertainty when simulations are

What Is Fidelity?

Fidelity means accuracy, exactness, or adherence to fact or detail. High fidelity simulations are necessary to predict the safety and reliability of the nation's nuclear stockpile. Simulation fidelity can be measured in at least three ways: 1) the correctness of the physics included in the simulation, 2) the detail and precision of the geometric representation of the system being modeled, and 3) the accuracy of the numerical algorithms used to solve the approximate equations.

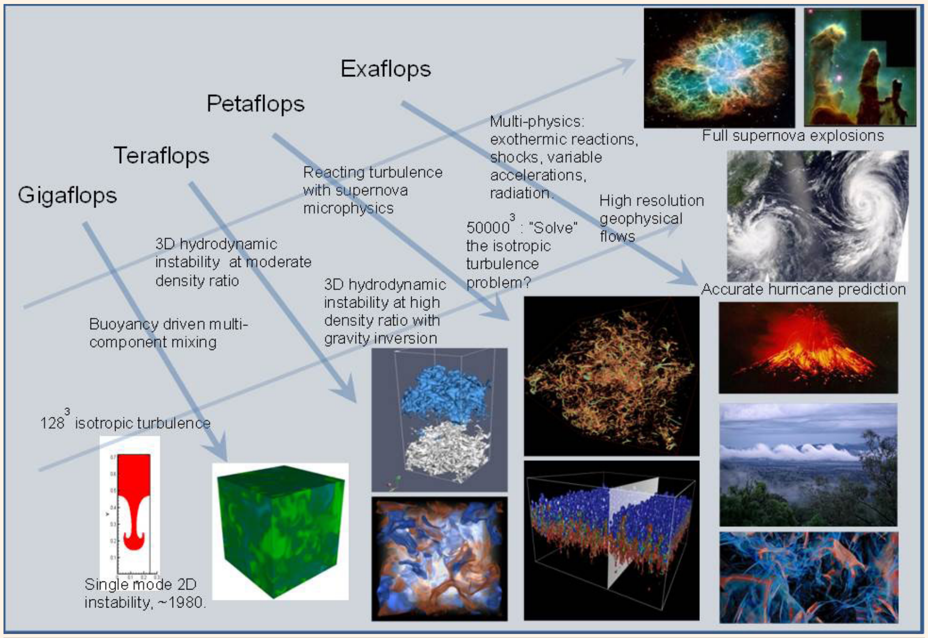
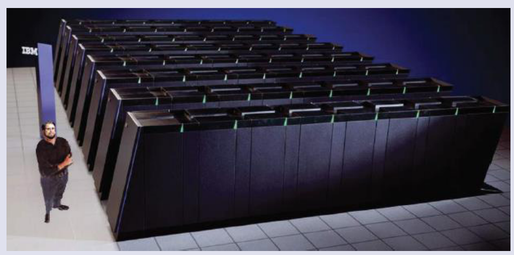


Figure 1. Turbulent flows highlight the need for higher fidelity simulations to address problems of interest (By David Livescu).

High performance computing has enabled much higher fidelity simulations by addressing all three of these aspects of fidelity. Obviously, resolution can be increased by the use of more spatial zones to represent a system on a larger computer. This also allows for a more accurate geometric description. Similarly, faster computers permit smaller time steps or more iteration in approximate solution, thereby increasing their accuracy. Perhaps the most promising of the fidelity enhancements afforded by high performance computing is the ability to support more complete and correct representation of the physics associated with simulation of nuclear weapons.

Next Generation Systems and Codes

The high performance computing industry has seen many changes since its inception following the Second World War. From switches to punch cards to data centers to supercomputers, change has occurred both gradually and suddenly. During the modern supercomputer era, at least two instances of sudden change have already occurred: the introduction of vector computers in the 1970s, and the appearance of massively parallel clusters in the 1990s. The industry is now on the brink of another such change in processor technologies as computer chips reach physical limits on size and voltage.



Roadrunner

The coming paradigm shift is expected to involve many processing elements on a single die and, possibly, heterogeneous processing elements, e.g., general purpose graphics processors in addition to general purpose central processing units. Such technologies challenge the ability of the IDCs to deliver timely simulations for the stewards. To prepare for the future, the ASC program at NNSA is investing in exploring technologies such as these for application to stockpile stewardship.

The Roadrunner supercomputer at Los Alamos National Laboratory was an exploration of heterogeneous computing architecture. The Sequoia supercomputer at Lawrence Livermore National Laboratory is a current experiment in many homogeneous cores computing. Both computers are harbingers of the challenges facing computer scientists and application programmers in the future.

Sequoia

Other challenges are beginning to appear, such as power requirements and lower available memory per core. ASC has created a new program element, Advanced Technology Development and Mitigation to address these issues. The intent of this program element is to respond to the shifting technology landscape to insure that NNSA will continue to have leading edge supercomputers and critical simulation software to support stockpile stewardship.

pushed beyond the calibration regime. The further the extrapolation, the more uncertain results become.

Additionally, the questions being asked of stockpile stewardship are evolving from those asked during the Cold War. One reason for this is that stockpile weapons have been in service well beyond their designed lifetimes ranging from 10 to 30 years and aging effects that were never tested are now becoming prevalent. This drives stewards to understand the aging of materials in the devices to determine when an LEP is required. Further complicating the simulations are the frequent three-dimensional (3D) effects associated with component aging. Due to aging, LEPs have been required to rework both the nuclear and the non-nuclear components of the weapon systems. During LEPs, simulations must be used to understand the effect on performance of replacement materials and new technology such as redesigned arming, fusing, and firing subsystems, and to determine if redesigned components meet reliability requirements in now-untestable radiation environments. The continuing desire to improve safety and security, such as by replacing conventional high explosives with insensitive high explosives, also stresses the ability of simulations to predict performance.

The SSP has made great progress in improving our simulation capability. Improved fidelity weapon codes (see the ***What Is Fidelity?*** sidebar) running on computers with greatly increased capability, combined with data from experimental facilities such as the Dual Axis Radiographic Hydrodynamic Test Facility and Proton Radiography Facility at Los Alamos National Laboratory (LANL), Z at Sandia National Laboratories (SNL), Omega Laser Facility at the University of Rochester Laboratory for Laser Energetics, and the National Ignition Facility at Lawrence Livermore National Laboratory (LLNL) have allowed the stewards to understand the cause of one major knob and to make progress on others. The modern codes combined with science-based physics models have enabled the development of common models for simulating the stockpile. These common models use one set of empirical calibrations to successfully model an increasing number and a very

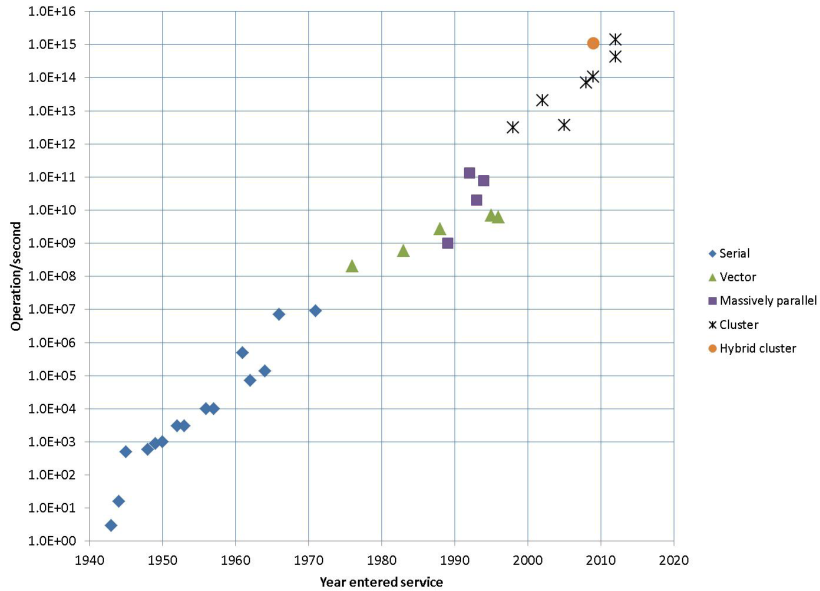


Figure 1. Computing power of LANL computers since 1944.

broad set of the stockpile devices. This gives the stewards increased confidence in the predictive capability of their tools when they are applied to analysis and certification of LEPs. Modern simulation capabilities have also solved a growing list of historic anomalies, again increasing the confidence the stewards have in their tools.

Improving the fidelity of the weapon codes increases the amount of computational work and memory in each simulation. Providing the stewards with acceptable execution times for higher fidelity simulations requires increased capacity of the computers that the simulations run on. This drive for increased simulation fidelity has driven the 10^{15} increase in computer speed shown in Figure 1, since the beginning of the Manhattan Project. Currently the ASC program provides computers for stockpile stewardship at two main facilities: the 253,000-square-foot Terascale Simulation Facility (TSF) at LLNL and the 300,000-square-foot Strategic Computing Complex (SCC) at LANL. Sequoia, an IBM BlueGene/Q 20-petaflops supercomputer, is located at the TSF and operated for the tri-lab (i.e., LLNL, LANL, and SNL) by LLNL. Sequoia, the first computer to have over one million compute cores, is currently the third largest supercomputer in the world, and is optimized for suites of jobs such as those required for common models or uncertainty quantification.

Cielo, a Cray XE6 1.4-petaflops supercomputer is located at the SCC and is operated for the tri-lab by LANL and SNL staff. Cielo is routinely used for 3D simulations that push the edge of predictive science. Both the TSF and SCC also house smaller computers that are used for the routine stewardship work. The next generation of high performance computers that will replace Cielo and Sequoia are expected to have significantly different internal architectures, which will impact the IDC (see the ***Next Generation Systems and Codes*** sidebar).

The integrated weapon codes that run on these massive computers embody the work of a wide range of scientists working on experiments, theory, and modeling. The improved ability to simulate nuclear weapon performance without nuclear tests has been an outstanding achievement of the SSP. Going forward, there are continuing demands to improve the simulation capability so that ever harder questions regarding the weapons can be answered, and decisions can be made. This challenges the laboratory staff to improve the codes, and all the experiments, theory, modeling, and computers that support them. To date, this scientific infrastructure has succeeded in meeting the challenges of stockpile stewardship, and we are confident it will meet the future challenges as well. •

250 Shots and Counting! The 40-mm Impact Test Facility at Los Alamos National Laboratory's TA-55

by William Anderson, William Blumenthal, Paul Contreras, Paula Crawford, Charles Owens, Chris Adams, and George Gray III (Los Alamos National Laboratory)

The 40-mm Impact Test Facility, located in the plutonium facility at Los Alamos National Laboratory's TA-55, is one of the nation's key experimental capabilities for measuring fundamental material properties of plutonium under dynamic loading conditions. It has been a workhorse for the last 18 years, completing more than 250 nuclear weapons-related experiments on programmatic materials (primarily plutonium) requiring accountability, safeguarding, and safety protection against release of radiological and airborne hazards.

An important goal of the Stockpile Stewardship Program (SSP) is to develop a predictive understanding of nuclear weapons behavior in support of annual and lifetime assessments that ensure the performance, safety, and reliability of our nation's nuclear weapons stockpile. Improvements in our modeling and computational assessment capabilities are made possible by incorporating advanced, physics-based material models into weapons simulation codes. A challenging part of this task is to understand how fissile materials, such as plutonium, behave under the extreme pressure, strain-rate, and temperature conditions of actual devices. The properties of these materials are strongly dependent on their crystal structure (e.g., plutonium exists in six different crystallographic phases before it melts at ambient pressure), the kinetics of transitions between the different phases, materials processing conditions (e.g., impurity and microstructural variability), and aging due to self-irradiation from alpha/beta decay. The dynamic property measurements obtained using the 40-mm launcher are essential for studying these effects and developing, constraining, and validating the advanced material models required to meet the goals of the SSP mission.

Figure 1. The 40-mm glovebox at TA-55. The breech end is in the foreground and the catch tank is located at the far end of the glovebox.

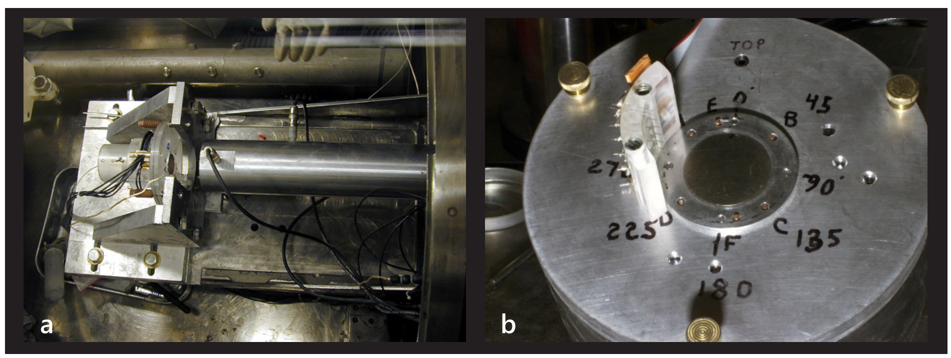


Figure 2. (a) The 40-mm muzzle with a target, window, and diagnostic hardware; (b) Front side of a 40-mm target containing a plutonium sample in the center surrounded by impact velocity and tilt diagnostic pins.

How Does It Work?

The 40-mm launcher consists of a smooth-bore gun comprising a breech and barrel, a target and catch tank, and measurement diagnostics, all contained in a protective glovebox (see Figure 1).

The launcher fires a projectile that consists of a body ("sabot") carrying a flat, disc-shaped impactor. During a shot, the projectile is propelled down the barrel and impacts a target mounted in a target holder. Depending on the desired impact velocity, which may be up to 1.7 km/s, the gun can be fired using either compressed helium or propellant (e.g., gunpowder). The barrel is precisely aligned with the target to produce one-dimensional shock-loading conditions. The velocity, tilt of the projectile, and time of impact at the target are measured using electrical pins mounted on the target. A massive steel "catch tank" is located directly behind the target and is designed to stop the projectile and the fragments of the target and impactor resulting from the intense impact event. Nuclear material (e.g., plutonium) is accountable and is recovered and recycled from the post-impact debris.

Experimental Configurations

Two critical aspects of material models are the equation-of-state (EOS), which describes the response of a material to variations in pressure and temperature, including phase changes such as melting, and the properties of each individual phase; and the phase-dependent constitutive behavior, including material strength and how damage forms and grows as a material is deformed. Different experimental configurations are used depending on the information being sought, including normal-impact EOS, spall, shock recovery, and reverse-impact EOS.

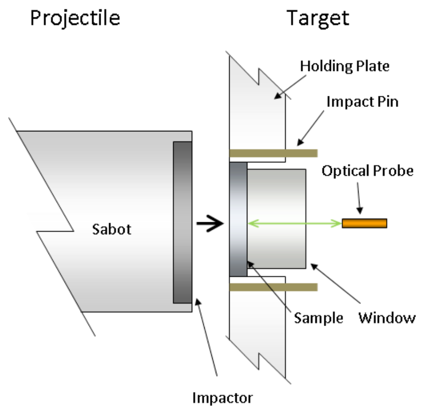


Figure 3. Schematic of the Normal-Impact EOS test configuration. The Spall test configuration is similar, but with a thinner impactor and no window. In the Reverse-Impact EOS configuration, the sample serves as the impactor and impacts the window directly.

Normal-Impact EOS

EOS is the most fundamental aspect of a material model and is the goal of the most common experiment performed with the 40-mm Impact Test Facility at TA-55 using the normal-impact EOS test configuration. The target consists of a sample mounted in a holding plate such that the sample surface will be directly impacted by the impactor (see Figure 2). A transparent window, such as lithium fluoride (LiF) or c-cut sapphire, is placed in contact with the opposite surface of the sample and the velocity of the sample-window interface is observed by optical diagnostics, called Velocity Interferometer System for Any Reflector (VISAR) and photon Doppler velocimetry (PDV), that measure velocity by changes in the wavelength of reflected laser light. The impact generates a shock wave that propagates forward into the sample and one that propagates backward into the impactor. The shock wave in the sample causes motion of the sample-window interface as it passes. This motion, combined with knowledge of the impact time and speed of the projectile, is used to determine the pressure, density, and energy in the shocked sample. Complex behavior, such as material strength or phase changes, can cause the shock wave to exhibit structure that allows such quantities as compressive yield strength and phase transition pressure to be obtained. After passage of the shock wave, a release wave is generated from the reflection of the shock wave off the back of the impactor.

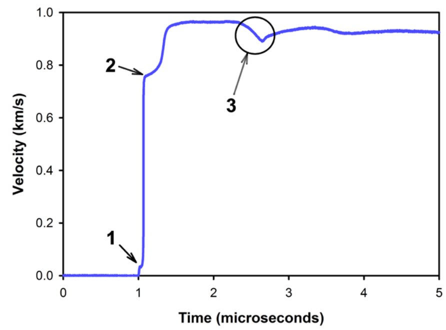


Figure 4. Example of a VISAR surface velocity record from a spall experiment on tin showing features associated with: (1) material strength, (2) a phase transition during compression, and (3) spall. Velocity records provide a wealth of information on dynamic material properties.

The timing and structure of the release wave provide additional information on the properties of the sample at high pressure. The purpose of the window is to keep the sample at high pressure for as long as possible before release to avoid complications in the velocity measurement.

Spall

In a spall experiment, the primary goal is to measure the stress required to dynamically fracture the sample, known as the spall strength. The experimental configuration is similar to the normal-impact EOS experiment, except that the impactor is usually thinner and no window is used, leaving the sample surface uncovered or "free" (see Figure 3). Shock waves produced in the impact reflect as release waves off this free surface and the rear of the impactor, interacting inside the sample and placing it in tension. If the tensile stress is high enough, it will generate damage in the form of voids and/or cracks in the sample until the sample fails and separates into two or more pieces, producing a characteristic set of waves that can be observed as they arrive at the sample-free surface. The shapes and amplitudes of the waves provide information on the type of the damage (i.e., brittle or ductile) and the stress required to cause fracture (see Figure 4). In some cases, the sample may be surrounded by concentric rings that carry away radial motions, allowing the central portion of the sample to be captured by impacting a low-density material, so that it can be recovered and studied.

Shock Recovery

A shock recovery experiment is used to subject a sample to a compressive shock pulse and release to zero pressure without tension, and then allows the sample to be recovered for later analysis. In this configuration, the sample is encapsulated in a specially-designed recovery assembly consisting of a "spall plate" that removes the axial loading pulse and concentric rings that surround the sample and dissipate radial release waves. After the initial shock-loading impact, the target is "soft-recovered" to minimize extraneous damage using low-density materials that act as a "catcher's mitt".

Reverse-Impact EOS

A capability unique to the 40-mm Impact Test Facility at TA-55 is that the sample can be mounted in the projectile as an impactor, rather than being the target—a test configuration known as the reverse-impact EOS geometry. In this type of experiment, the target is a transparent window that is impacted by the sample and the motion of the impact surface is observed. This technique mitigates complications that occur due to wave interactions in the sample and is particularly useful for precisely measuring the high-pressure sound speed in the sample.

New Capabilities for the Future

Capability upgrades and new diagnostics will expand the range of conditions probed with the gun, allowing important questions concerning weapons materials to be addressed. Recently, a capability to preheat targets was installed, which allows the effects of temperature to be directly measured, as well as allowing samples to be heated into different crystal structures prior to the experiment. An optical pyrometer will soon be added for direct measurement of temperatures generated by shock waves in the samples. Additionally, new impactor designs will allow samples to be subjected to complicated loading histories that are designed to replicate or probe unique physical regimes of the device. These new capabilities, combined with the ongoing need for better understanding of how weapons materials behave under high-pressure dynamic loading, will keep the 40-mm Impact Test Facility at TA-55 busy well into the future. •

The High-foot Implosion Campaign on the National Ignition Facility *by O.A. Hurricane (Lawrence Livermore National Laboratory)*

If you could identify only one key skill that a primary or secondary designer should possess, it would be the ability to design an implosion that works reliably and as advertised. Being able to harness an implosion is a key skill because of what an implosion does—an implosion is a "pressure amplifier" that takes absorbed energy and turns that energy, with significant energy loss, into pressure. The pressure generated in implosions is used to compress materials to high densities in the primary designer's case, and high densities and temperatures in the secondary designer's case. While primary designers and their simulation tools can be tested against experiments at scale fielded at high-explosive facilities around the NNSA complex, secondary designers are much more limited in the experimental facilities that can access relevant conditions. Facilities such as the Omega Laser Facility at the University of Rochester Laboratory for Laser Energetics, the Z machine at Sandia National Laboratories in Albuquerque, New Mexico, and the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) are more or less it. Ignition conditions are the highest pressure and, therefore, the hardest conditions to access with facility levels of energy, but the struggle to obtain ignition has been an illuminating test of the stockpile stewardship model.

While the road to ignition has been rocky, recently progress has been made on NIF by our team and collaborators that has energized researchers around the world. We have achieved the highest inertial confinement fusion (ICF) yields to date (i.e., 9.6e15 neutrons equivalent to 27 kJ of energy), "fuel gain," and most excitingly, the first laboratory indications of the key fusion process called "self-heating" which is a critical step on the path to ignition.

A fusion plasma ignites when the power produced by the fusing region exceeds the rate at which energy is lost from the fusing region due to x-ray radiation processes and heat conduction processes—a state that has yet to have been achieved in the laboratory. This simple statement about fusion power and rates of energy loss leads to a quantitative criterion for ignition that is known as the Lawson criterion,[1,2] and it's important to understand what this means.

The Lawson criteria is a statement that relates the plasma pressure (P) and plasma confinement time (t) to a criterion that defines ignition. In its simplest form, the Lawson criteria for ignition of deuterium-tritium (DT) fusion fuel is $P\ t > 30$ atm-s (atmospheres x seconds); although, the exact number can vary somewhat, depending upon plasma density and temperature (e.g., for lower density but hotter magnetic fusion plasmas, the criteria is about 1/3 of the above value). The Lawson criterion suggests why obtaining ignition is so challenging. For modest plasma pressures of atmospheres, the plasma confinement time must be many 10s of seconds (the magnetic fusion case). For small confinement times of less than a nanosecond, the plasma pressures must be enormous and on the order of many hundreds of billions of atmospheres (the ICF case).

Achieving high pressures in an ICF implosion requires finessed control over implosion shape,[3,4] DT fuel compressibility (adiabat), while at the same time obtaining very high implosion velocities (several hundreds of kilometers per second).[5] Obtaining high implosion velocities risks introducing instabilities that can tear apart an implosion, and those instabilities can generate mix that can be quite damaging to an implosion.

While it is not the only problem with the National Ignition Campaign (NIC) point design implosion (the "low-foot" implosion), it appears that ablator-DT mix was a major contributor to it not performing as desired for the higher velocity NIC implosions.[6-8] Recently, a "high-foot" implosion[9-11] has been developed with the specific goals of testing a high-performance implosion that is more robust against ablation-front Rayleigh-Taylor (A-RT) instability,[12] has less convergence, and is generally less sensitive to modeling uncertainties. The modeling and assertions of less instability growth with the high-foot pulse-shape were directly tested and verified in radiography experiments[13,14] while the integrated implosions themselves continue to express no indications of mix as inferred from hot-spot emission measurements.[15]

While our high-foot implosion scales back from the goal of high gain ignition by giving up some potential compression of the DT fuel, its performance has greatly exceeded past implosion performance as demonstrated by recent implosions obtaining "fuel gain" (where the fusion yield exceeds the energy delivered to the fusion fuel), more than a yield doubling due to alpha-particle self-heating, and the highest levels of Lawson criteria to date (see Figure 1).

The data shown in the upper right hand side of Figure 1 show that much progress towards ignition has been made, but the points also belie the challenges that remain in order to push further towards the ignition regime. While high performing, most high-foot implosions exhibit hot-spots (the DT yield-producing region in a non-igniting ICF implosion) that are oblate in shape and can even verge on toroidal (see Figure 2). This "low-mode" shape control problem becomes worse as the laser power, and to a lesser extent laser energy, is increased. However, an increase in laser power is the easiest way to access higher implosion speeds, and remember higher implosion speeds are how an ICF implosion's fusion performance is most directly increased. An alternate way to increase implosion speed with a given laser power and energy is to use a more efficient ablator like high-density carbon (HDC), and work along these lines is presently going forward.[16,17] Colleagues at Los Alamos National Laboratory (LANL) are leading the beryllium (Be) ablator effort.[18,19]

Another avenue to higher fusion performance in the high-foot is to back off somewhat on the DT fuel stiffness (adiabat) generated by the strength of

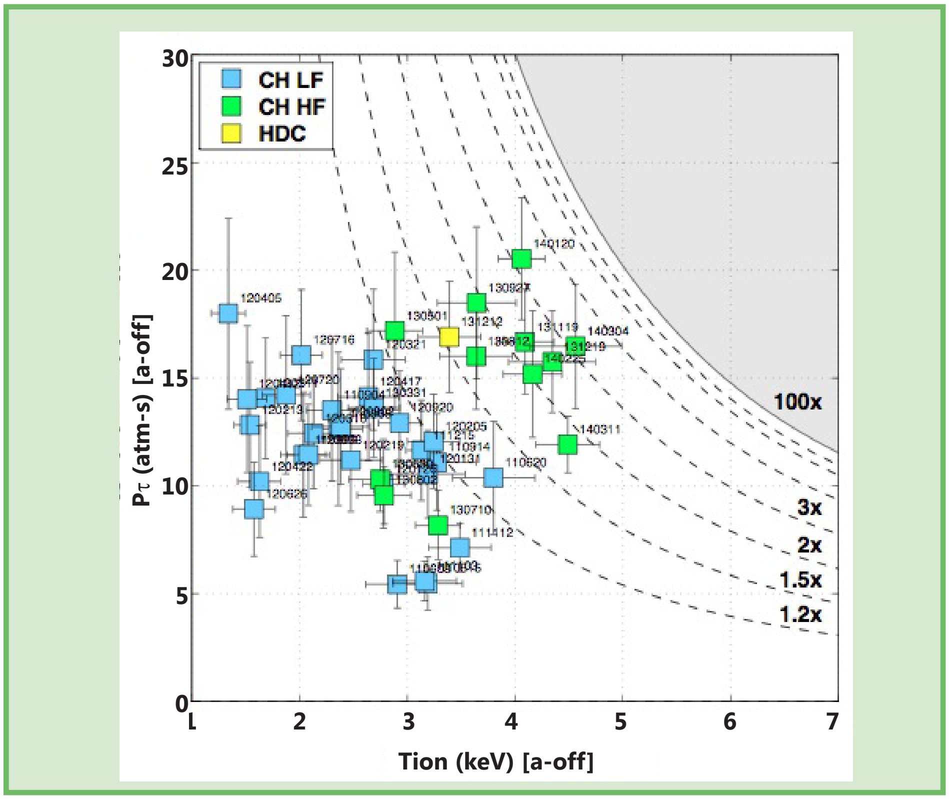


Figure 1. Lawson criteria (DT plasma pressure x confinement time in atmospheres x seconds) is plotted against inferred ion temperature (in kiloelectron volts). The data are DT experiments on NIF for low-foot NIC implosions (CH LF, in blue), high-foot implosions (CH HF, in green), and high-density carbon 2-shock implosion (HDC, in yellow). The contours show the degree of yield increase due to alpha-particle self-heating. The high-foot implosions essentially have closed half the "distance" between the NIC implosions and ignition—the grey region on the upper right. (Data plot courtesy of P. Patel of LLNL).

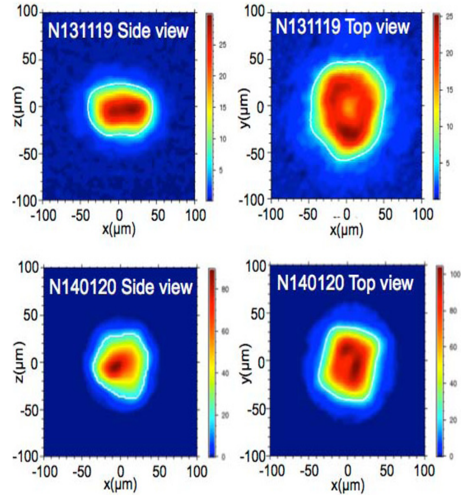


Figure 2. Hot-spot shape for two high performing high-foot implosions is shown in time-integrated x-ray imaging. Image spatial units are in microns. Shot N131119 (NIF year-month-day format NYYMMDD) was the highest performing DT shot in a gold hohlraum obtaining total DT yield of 6.1e15 neutrons while shot N140120 was designed to have the same implosion speed and bang-time of N131119 but was performed in a depleted-uranium hohlraum isolating the effect of improved shape. N140120 obtained a total DT yield of 9.3e15 neutrons (not shown, shot N140304 yielded 9.6e15 DT neutrons). The shape of N131119 was characteristic of many of the high energy high-foot shots. Clearly, the depleted-uranium hohlraum was effective at improving the hot-spot shape. (X-ray image analysis[20] courtesy of N. Izumi, S. Khan, T. Ma, A. Pak, L.R. Benedetti, R. Town, and D. Bradley of the NIF Shape working group.)

the high-foot's first shock—the trade-off that was made to obtain the improved high-foot stability. This "medium-foot" or "adiabat shaping" tactic seeks an optimum between the low-foot NIC implosion and the high-foot implosion, but it will be a matter of research to see if a tolerable amount of A-RT instability with higher DT fuel compressions can actually be achieved on the NIF.

With the benefit of a working and repeatable implosion, effectively the high-foot is a "base camp" from which we can explore different directions in parameter space. The desire is to evolve the high-foot design as we press it to higher performance. In doing so, we will explore failure cliffs that test our designer judgment and the veracity of our simulation predictions. This is a key experience for those entrusted with the stewardship mission, especially for the generation without any underground test experience.

Acknowledgments

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Polar-drive Implosions—Results from OMEGA and the National Ignition Facility

by P.B. Radha, M. Hohenberger, F.J. Marshall, R.S. Craxton, D.H. Edgell, D.H. Froula, V.N. Goncharov, J.A. Marozas, R.L. McCrory, P.W. McKenty, D.D. Meyerhofer, D.T. Michel, J.F. Myatt, T.C. Sangster, W. Seka, and S. Skupsky (Laboratory for Laser Energetics, University of Rochester)

Results from polar-drive experiments on OMEGA and the National Ignition Facility (NIF) are described. These experiments elucidate the physics of direct-drive implosions irradiated by a laser configured for x-ray drive. Implosion velocity, symmetry, and adiabat are important hydrodynamic parameters for inertial confinement fusion implosions. Symmetry in OMEGA polar-drive experiments can be controlled by beam repointing and contouring the target locally near the equator. NIF implosions are used to identify the effect of laser–plasma interactions on hydrodynamic parameters. Measured velocities on the NIF are ~8% lower than those in simulations that include the effect of cross-beam energy transfer (CBET). Simulations indicate that symmetry is influenced by CBET; implosions become more oblate when a CBET model is included in the simulations in agreement with observations.

Introduction

Polar drive (PD)[1] makes it possible to conduct direct-drive–implosion experiments at laser facilities like the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory that are configured for x-ray drive. To achieve nearly spherical drive, beams closer to the poles of the target are repointed toward the equator. Higher energies for the beams near the equator compensate for the oblique angle of incidence of the repointed beams. As with spherical direct drive, target implosion performance is characterized by the peak velocity attained by the imploding shell, the implosion velocity V_{imp}, and the adiabat α (defined as the ratio of the shell pressure to the Fermi-degenerate pressure at peak shell density). The challenge is that PD is multidimensional. It is important to drive the implosions with adequate symmetry while achieving the desired V_{imp} and α.

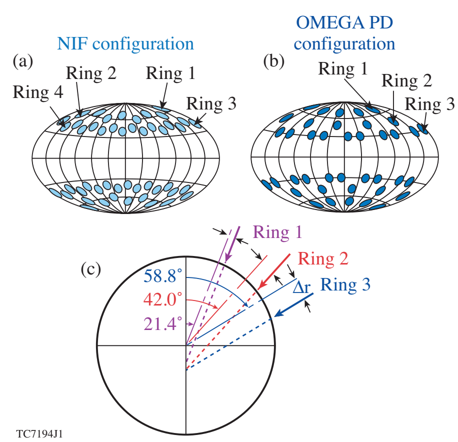

Figure 1. Beam configuration for (a) the NIF and (b) OMEGA. (c) Schematic of beams repointing from higher latitudes toward the equator.

Experiments on the OMEGA[2] laser and the NIF are used to study implosion physics.[3–6] In PD geometry, 20 of the 60 OMEGA beams nearest the equator are eliminated from driving the target to emulate the NIF geometry (see Figure 1). The polar beams are repointed to the equator (see Figure 1c). A subset of the remaining 20 beams is used to create x-rays that backlight the imploding

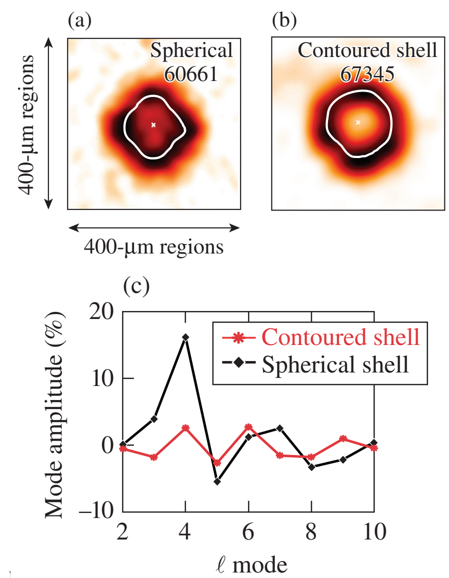

Figure 2. Backlit images from an OMEGA implosion: (a) employing only beam repointing to improve symmetry and (b) employing both beam repointing and shell contouring to improve uniformity. (c) Modal decomposition at the convergence ratio shown on the left for the two cases.

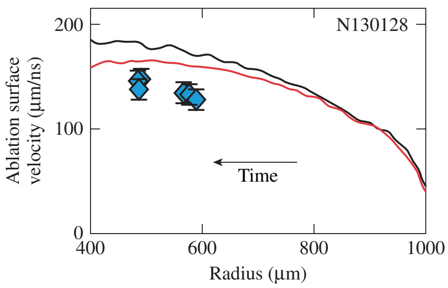

Figure 3. Inferred velocity from self-emission, gated x-ray framing camera images from experiment (symbols) compared to a DRACO simulation with only collisional absorption (black) and a simulation that also includes the effects of CBET (red).

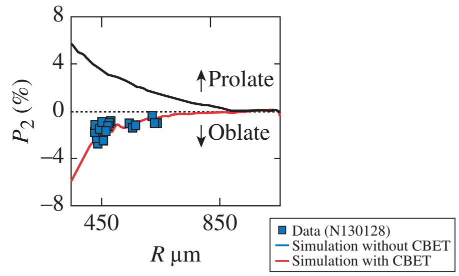

Figure 4. Comparison of the experimentally inferred P_2 Legendre mode for N130128 (symbols) to DRACO simulations with only collisional absorption (black) and DRACO simulations that also include the effect CBET (red).

plastic shell.[3] With relatively low velocities, the implosions do not scale to hot-spot ignition, but provide a platform to test modeling and devise ways to improve symmetry.

Laser–plasma interactions (LPIs) can reduce the implosion velocity by reducing absorbed energy through processes such as simulated Brillouin scattering,[7] cross-beam energy transfer (CBET),[8] etc., and increase the adiabat through preheat from energetic electrons caused by two-plasmon decay[9] or radiation in the corona. The deleterious effects of LPI typically increase with increasing coronal density scale lengths. Since longer-density scale lengths are characteristic of the direct-drive corona on the NIF compared to OMEGA, experiments examining the effect of LPI on hydrodynamic parameters are critical to gaining confidence in implosion modeling.

OMEGA Results

Room-temperature 27-μm-thick plastic (CH) shells filled with 10 atm of deuterium are imploded with a variety of pulse shapes and varying adiabats.[3,4,6] Nearly one-dimensional (1D) areal densities, measured through the energy loss of secondary protons,[10] are obtained.[4] Shell shapes are inferred by fitting the peak absorption in the backlit images obtained using a Ti backlighter.[3] Beam repointing is used to vary the implosion shapes. The best symmetry obtained with only pointing variations is shown in Figure 2a when the shell has converged by a factor of ~6. A residual $\ell = 4$ Legendre mode dominates the asymmetry at this radius (see Figure 2b).

Further improvement in symmetry has been obtained by contouring the shell. Here, a functional form for the contouring was chosen where nearly 2 μm of the CH was removed from the equator, while the region below the polar angle of ~30° was left untouched. Beam pointing was optimized using the 2D radiation–hydrodynamics code DRACO.[11] Significantly improved symmetry was obtained at approximately the same convergence as shown in Figure 2c. This improved symmetry is seen across all the Legendre modes resolved by experiment.

NIF Results

Implosion experiments on the NIF are primarily designed to study the effect of LPI on hydrodynamic parameters.[6] High-compression experiments are precluded because existing indirect-drive phase plates and beam smoothing are used. These implosions can be used to identify and mitigate the effect of LPI on hydrodynamic parameters and to demonstrate techniques to improve uniformity through symmetry and reduction of imprint. Low-adiabat ($\alpha \sim 3$), room-temperature implosions are performed with a pulse shape that has a low-intensity foot rising to a flattop pulse shape. The phase plates are defocused to improve the on-target, low-mode symmetry. The trajectory is measured through gated x-ray self-emission images.[12] Simulations indicate that the steepest gradient in these images tracks a location close to the ablation surface of the imploding shell. Figure 3 shows the inferred velocity versus this radius. DRACO simulations with and without the CBET effect were post-processed with the x-ray tracking code Spect3D.[13] Velocities were extracted from the radius in these images, similar to the measured images. As Figure 3 indicates, CBET accounts for approximately half of the reduction in the velocity measured relative to collisional absorption. Further improvements to the CBET model in DRACO, particularly in the techniques to obtain convergence in the energy transfer between beams in the CBET model, may improve agreement with experiment. Another plausible hypothesis is the decoupling of the ablation surface from the shell resulting from either nonuniformity or preheat from the corona. To investigate this, backlit implosions (where the fuel–shell interface position is tracked) will be performed.

Preliminary simulations with the CBET model in DRACO[14] indicate that most of the loss from CBET occurs over the equator. This equator is thus under driven relative to the pole, resulting in an overall reduction in velocity and an oblate imploding shell. Figure 4 compares the nonuniformity between simulation and experiment. The inclusion of CBET in the simulation results in a more-oblate implosion, which is in good agreement with observations.

Conclusions

Polar-drive-implosion experiments on OMEGA and the NIF have been described. Excellent symmetry and the predicted areal density were obtained when a contoured shell was imploded on OMEGA. Room-temperature NIF PD implosions with indirect-drive phase plates and the existing NIF beam smoothing suggest slower shells by ~8% relative to the DRACO simulations that include the effect of CBET. The velocity measurement will be verified with backlighting measurements in upcoming NIF experiments. Symmetry can be controlled in these experiments by varying the pointing and beam energies. Symmetry is well modeled with DRACO; the change in phase of the $\ell = 2$ Legendre mode is reproduced by the model. Improving hydrodynamic efficiency by using alternate ablators and mitigating CBET through wavelength detuning will be examined in future experiments.

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Highlights and Awards

Upcoming Funding Opportunity Announcements

The Stewardship Science Academic Alliances Funding Opportunity Announcement (FOA) is currently scheduled to be posted on the Grants.gov website in July. This FOA will be for grants only in the research areas of Properties of Materials Under Extreme Conditions and/or Hydrodynamics, Low Energy Nuclear Science, and Radiochemistry.

Also in July, an FOA for the High Energy Density Laboratory Plasmas grant program is scheduled to be posted. This program is a joint effort with DOE's Office of Fusion Energy Sciences and NNSA's Office of Inertial Confinement Fusion. The specific areas of interest are as follows:

- HED Hydrodynamics,
- Radiation-Dominated Dynamics and Material Properties,
- Magnetized HED Plasma Physics,
- Nonlinear Optics of Plasmas and Laser-Plasma Interactions,
- Relativistic HED Plasmas and Intense Beam Physics,
- Warm Dense Matter,
- High-Z, Multiply Ionized HED Atomic Physics, and
- Diagnostics for HED Laboratory Plasmas.

Former Academic Alliances Program Graduate Receives 2014 PECASE

Seth Root of Sandia National Laboratories received a 2014 Presidential Early Career Award for Science and Engineering on April 14. Root was selected for his leading edge research in condensed matter physics. His work on the Z machine is focused on understanding the high-pressure behavior of noble gases cryogenically cooled to an initial liquid state. Root participated in the Stewardship Science Academic Alliances program from 2002 to 2007.

2014 DOE Early Career Research Program Award

Researcher **Stephanie Hansen** of Sandia National Laboratories received a $2.5 million five-year Early Career Research Program award from the Department of Energy Office of Science. Hansen's winning submission, entitled "Non-Equilibrium Atomic Physics in High Energy Density Material," describes an approach to improve simulation tools used to design high-energy experiments in dense hot plasmas, as well as the diagnostic tools used to interpret data from them.

Bessel Award Recipient

Professor **Steven Jacobsen**, a Carnegie-DOE Alliance Center Academic Partner from Northwestern University, received a 2014 Friedrich Wilhelm Bessel Research Award. Granted by the Alexander von Humbolt Foundation, this award allows the recipient to spend a year working at a research institution in Germany. Jacobsen will spend the coming year at the Bayeriches Geoinstitut in Bayreuth, Germany, where he was a Humboldt Postdoctoral Fellow from 2002 to 2004.

2014 Young Leaders Professional Development Award

Professor **Eva Zurek**, a Carnegie-DOE Alliance Center Academic Partner from the University at Buffalo, State University of New York, has received the 2014 Young Leaders Professional Development Award of The Minerals, Metals and Materials Society (TMS). Professor Zurek was presented with the award at the TMS Annual meeting held recently in San Diego, California. Zurek's research focuses on the use of quantum chemical techniques to explore the electronic structures of molecules and solids. In her work as part of CDAC, she uses an evolutionary algorithm method to predict the structures of materials at very high pressures. Professor Zurek joined the CDAC program in 2013.

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