Stockpile Stewardship *Quarterly*

Defense Programs *Stockpile Stewardship in Action* Volume 3, Number 1

Message from the Assistant Deputy Administrator for Research, Development, Test Capability and Evaluation, Chris Deeney

I want to share some thoughts about the recent reorganization. Why now? As you know, there is a decade or two of stockpile modernization on the horizon and although we remain committed to our prime directive—stewarding the stockpile without recourse to underground nuclear tests, it was time to better align for the future. As such, we are now the Office of Research, Development, Test Capabilities and Evaluation (RDT&E).

Hopefully, *Research* and *Development* are self-explanatory. *Test Capabilities* represents the fact that our stewardship tools are the same ones that enable stockpile modernization (e.g., the Dual Axis Radiographic Hydrodynamic Test Facility, Advanced Simulation and Computing platforms, the Omega Laser Facility, National Ignition Facility, and U1a Complex come to mind.) *Evaluation* refers to the process of annual assessments, and surveillance requirements. As we move to the future, we should demand more of assessments, and we must ensure the best linkage of stewardship tools with core surveillance plus the plans for enhanced surveillance for a modern stockpile. We will do this and, in a future issue of the *Stockpile Stewardship Quarterly*, Roger Lewis, the acting director for Test Capabilities and Evaluation will describe his team's vision.

Obviously, the most important thing to our deterrent and to successful modernization is the great work you all do, every day, to move us forward. From an NNSA Headquarters' perspective, I like to think of our new organization in the following way regarding the Quantification of Margins and Uncertainties (QMU).

- Test Capabilities — Tools to improve QMU.
- R&D — The activities to improve QMU.
- Evaluation — Pushing those improvements into our products, the stockpile, and annual assessments.

Please enjoy this issue of the *Stockpile Stewardship Quarterly* and see how your great work is making RDT&E happen!

Office of Stockpile Stewardship Reorganization

Effective April 8, 2013, the Office of Stockpile Stewardship became the Office of Research, Development, Test Capabilities and Evaluation. The following four offices comprise the new organization:

- Office of Inertial Confinement Fusion, NA-112, Christopher Deeney, Director (Acting);
- Office of Research and Development, NA-113, Ralph Schneider, Director;
- Office of Advanced Simulation and Computing and Institutional Research and Development, NA-114, Robert Meisner, Director; and
- Office of Test Capabilities and Evaluation, NA-115, Roger Lewis, Director (Acting).

The Office of Test Capabilities and Evaluation includes our new colleagues from the Stockpile Assessment organization. Please join us in welcoming our new team members. You'll be able to read about their work in future issues of the *Stockpile Stewardship Quarterly.*

Inside this Issue

Comments
Questions or comments regarding the *Stockpile Stewardship Quarterly* should be directed to Terri.Stone@nnsa.doe.gov
Technical Editor: Dr. Joseph Kindel, Publication Editor: Millicent Mischo

Obtaining Record Ramp Pressures on Z Using Cylindrical Geometrical Convergence

by Thomas R. Mattsson, Dawn G. Flicker, Dan H. Dolan, Raymond W. Lemke, Ryan D. McBride, Matthew R. Martin, and Mark C. Herrmann (Sandia National Laboratories)

Understanding how matter behaves under strong compression is of utmost importance for the Stockpile Stewardship Program. Consequently, scientists at the NNSA laboratories have worked on techniques to drive materials to ever higher pressure using guns, high explosives, and lasers for many decades. The community's approach has traditionally exploited shock waves to reach high pressures. It has recently been recognized that many applications are actually quite sensitive to shockless compression properties. For the last decade, Sandia National Laboratories (SNL) in Albuquerque, New Mexico, has employed the unique Z Machine[1] in this mission. Z is the world's most powerful pulsed-power accelerator, capable of delivering power-plant sized currents, up to 25 million amperes (MA), over a mere 100 billionths of a second (ns), a timescale normally associated with nano-physics. The short timescale and high current together create a very strong magnetic field; the magnetic field in turn affects the material. Pulsed power, which enables delicate shaping of the pressure drive is a natural way to conduct ramp or shockless compression experiments.

Using magnetic fields to drive material to high pressure is efficacious due to the marriage of hydrodynamics (the theory of how material flows and changes temperature as it is subject to pressure and heat) and electrodynamics (the theory of how electromagnetic fields change with time as currents generate them). The joint theory is called magnetohydrodynamics (MHD); in which the square of the magnetic field contributes to the hydrodynamic pressure, directly increasing the pressure in the material. The pressure is decoupled from temperature and heat, so it is possible to create high pressures in cold materials, a condition particularly relevant to problems in stockpile stewardship. The phenomena is illustrated in Figure 1: the high current (J) generated by Z is taken in a loop, creating a magnetic field (B), equivalent to a material pressure (P), in turn driving strong pressure waves in the sample.

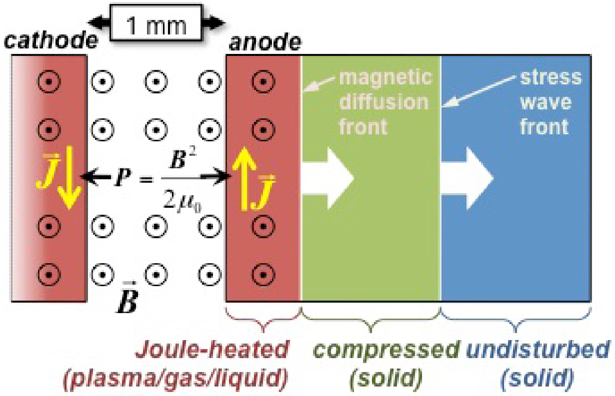

Figure 1. Using a strong current loop (J) to create a magnetic field (B) symbolized by the dots, which in turn creates a high pressure (P) driving a compression/stress wave into the sample. The volume of planar experiments increases with time, limiting the pressure.

This very technique—planar high-pressure drive on Z—has been extraordinarily successful in obtaining shock data with exquisite precision for many different materials[2-7] in the 1-25 Mbar range and ramp data in the range of 4 Mbar. (1 Mbar is 1 million times atmospheric pressure; the pressure at the core of the earth is about 4.5 Mbar.) While successful, Figure 1 also reveals the limitation of a planar experimental design: with time, the volume of the experiment increases, thus reducing the magnetic field/pressure available to continue driving the experiment. The experiment diverges geometrically with time. Creating the maximum possible pressure in the sample comes down to a design competition between increasing the current as fast as possible without destroying the sample prematurely.

A solution to the problem of divergence in planar geometry is to utilize a convergent geometry, like a cylindrical shell/liner, as shown in Figure 2. In this experiment, the current flows in a sheath outside the cylindrical shell, the magnetic field is generated on the outside, and the pressure compresses the cylinder towards the symmetry axis. Simulations indicate that Z should be able to reach pressures of 15 Mbar in ramp experiments and even higher in shock experiments. While conceptually simple, employing a cylindrical geometry is not without complications. In the planar design, laser interferometry is used to measure the different velocities and diagnostic access is straightforward from outside the experiment. In cylindrical experiments, the interesting dynamics occur inside the cylindrical shell, creating severe challenges in diagnosing the experiment. Creating extremely high pressures is of little benefit unless we are able to diagnose the conditions and draw conclusions regarding how the material behaves.

Over the last two years, we have made two significant breakthroughs in the diagnostics arena for this problem. First, we were able to use quantitative radiography to image the density profile of an imploding beryllium cylindrical shell and directly extract the pressure from a hydrodynamic analysis.[8] The pioneering results for beryllium

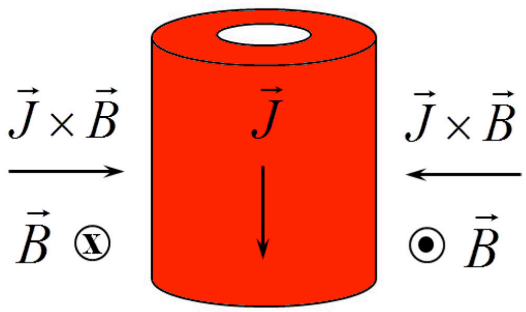

Figure 2. Experiment in a cylindrical converging geometry. With time, the volume of the experiment decreases, resulting in a tremendously strong compression. The force on the cylinder is depicted as JxB, the mathematical description of the force generated as a current (J) runs in a magnetic field (B).

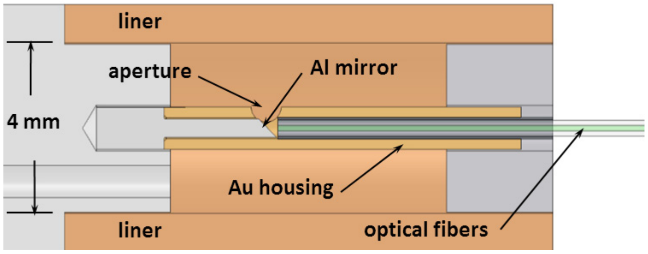

Figure 3. A cylindrical liner target with internal radial PDV diagnostic. Notice the dimensions, the diameter of the probe is no more than 1 mm in diameter, housing optical fibers and a mirror.

were more than a proof-of-principle of the concept; the new method provided the highest recorded pressures ever for shockless compression of beryllium, almost 6 Mbar. In fact, the cylindrical method exceeded the pressure from previous planar beryllium ramp experiments on Z by a factor of two. Analysis with radiography, however, becomes difficult for heavy elements like tantalum, gold, or tungsten since the photon energy required for penetrating the samples increases dramatically. The radiograph-based beryllium work nevertheless led the way towards a cylindrical platform since it demonstrated that symmetry and radial convergence were not impediments for obtaining data. For the cylindrical concept to be applicable to any material, including high Z metals, however, it was necessary to develop a new concept.

The second breakthrough came in that we were very recently able to diagnose the inside cylinder wall of a converging shell using Photon Doppler Velocimetry (PDV). Conceptually simple, the PDV technique measures the Doppler shift in frequency of laser light reflected off a surface; the higher the velocity of the object, the larger the Doppler frequency shift. In practice, the method is state-of-the-art and requires very high-speed digitizer equipment and an advanced signal processing capability. The experimental assembly is shown in Figure 3. The PDV development was made in a partnership between SNL and National Security Technologies, LLC. The targets were fabricated by General Atomics (GA). We have now successfully measured the internal implosion velocity on four shots on Z for two different liner materials: aluminum and beryllium. Preliminary results from the latest experiment are shown in Figure 4; the data quality was excellent and we were able to track the velocity of the inside beryllium cylinder wall to over 45 km/s. Simulations of these experiments show that velocities in this range correspond to ramp compression pressures in the range 10-20 Mbar.

The future is very exciting as we work on turning the new cylindrical convergent geometry concept into a production platform for reaching unprecedentedly high ramp compression pressures in a broad range of materials and compounds. This new capability will play an important role in investigating materials of direct importance for the safety, security, and effectiveness of the nuclear stockpile. Design, execution, and analysis of experiments on SNL's Z Machine are collaborative efforts involving several large teams; we sincerely thank the Z-operations and target fabrication and assembly teams.

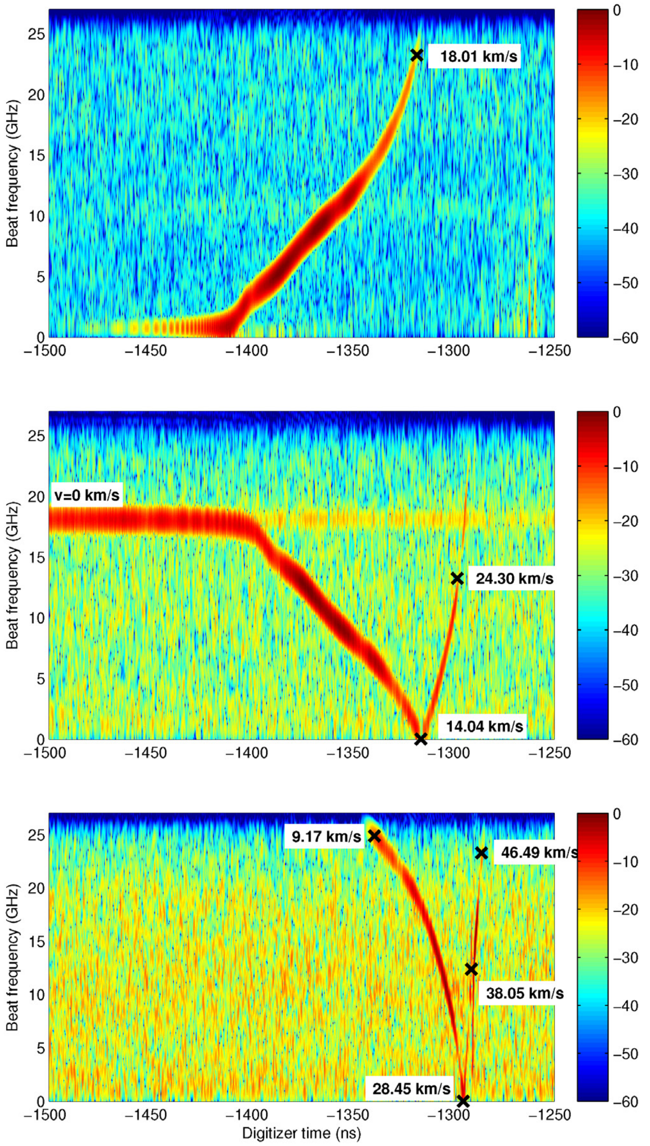

Figure 4. Velocimetry data from a beryllium liner experiment. The panels show results analyzed for three beat-frequencies, targeting different velocity ranges.

References

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National Ignition Campaign Closure and the Path Forward for Ignition by Kirk Levedahl (National Nuclear Security Administration)

The End of the Beginning

The end of the National Ignition Campaign (NIC) at the close of FY 2012 marked the end of the beginning of the quest to achieve thermonuclear burn in the laboratory. With the end of the construction of the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) in March 2009, the NIC team began an intense two-and-a-half year period of commissioning the laser, bringing the facility to full operations, installing diagnostics, and developing the experimental capabilities and techniques that would give the inertial confinement fusion (ICF) community the first real look at where the challenges lie in achieving ignition in the laboratory. Achieving energies on target at the NIF of over 2 megajoules (above the 1.8 megajoule design specification of the NIF) provided the ICF community the first facility with energies that are believed capable of achieving ignition conditions.

Whereas bringing the experimental platforms to full operations was in and of itself a challenge, it was during the last year that the program was able to execute a campaign of well-diagnosed, layered, cryogenic implosions and surrogate implosions that have enabled a detailed investigation into the target conditions that have been achieved to date at the NIF (see Figure 1).

So how did we do? Whereas we did not achieve our goal of laboratory ignition by the end of FY 2012, those who participated in the May 22-24, 2012 *Science of Fusion Ignition on NIF* workshop chaired by Dr. William Goldstein and Professor Robert Rosner were able to look back on the stunning wealth of data that was produced during the NIC. That data is of a superior quality never before seen, and the scientific community has been able to assess and respond that, as scientists, the results are not bad, not bad at all! In fact, the results are compelling, and the NIC partners who worked so hard to make the facility, the laser, and the targets all function superbly and the scientists who worked to design and analyze experiments should be congratulated for a job very well done indeed.

What we have achieved are experiments that put us right at the boundary of demonstrating thermonuclear burn in the laboratory. Yields of 6×10^{14} neutrons, ion temperatures of above 3.5 keV, and inferred hot-spot pressures above 30 Gbar puts these ignition capsules at a point that is very close to the goal, and some argue that we have indubitably achieved a small level of self-heating through alpha-particle deposition. Simply put, pressures are a factor of 2 to 3 below what is believed to be needed for ignition. Now the challenge is to understand why that is so.

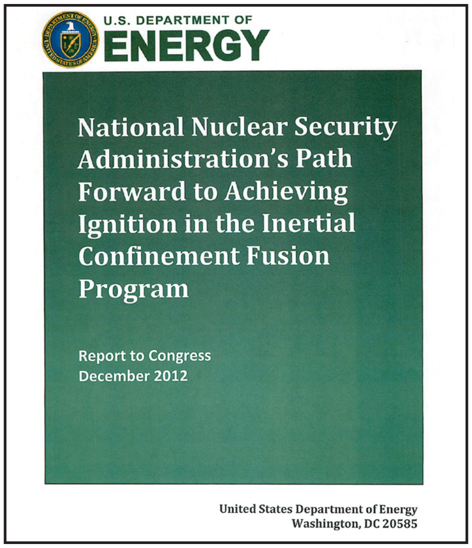
Of course the really remarkable achievements are the precision in laser performance, target fabrication, and diagnostics development that made all this possible. Any statement about the present capability of the NIF will turn out to be an understatement in a program that is making stunning progress on energy, space, and time resolution on a daily basis.

What we have learned is that there is a lot we do not understand about target performance—from opacities and equations of state, to hohlraum performance, to the importance of laser plasma instabilities, to symmetry effects. Computational models that used to be sufficient now have been shown to require improvements because of the experimental precision that was achieved during the NIC. This is not a failure, but the success of good experimental science informing good theoretical and computational efforts and provides plenty of good challenges in all the related areas of specialization. Effects of mix and asymmetry are challenges, particularly at the 30-40 convergence ratios pertinent to ignition targets. These are not surprises, as the uncertainties at high convergence ratios long have been anticipated. NIF is the first facility that offers the opportunity to investigate these effects with superior precision so that we can test various models of the underlying phenomena.

Figure 1. Top - View of the National Ignition Facility at Lawrence Livermore National Laboratory in Livermore, California. Bottom - NIF Laser Bay 2, a 96-beam bay. The yellow dots are hard hats worn by workers.

The Middle Game – the Path Forward

So where do we go next? Over the course of the last several months of 2012, Dr. Jeffrey Quintenz, the NNSA ICF Program Director, led an effort of senior scientists and program managers from the principal ICF Program laboratories to develop a path forward that was reported to Congress


U.S. DEPARTMENT OF
ENERGY

National Nuclear Security Administration's Path Forward to Achieving Ignition in the Inertial Confinement Fusion Program

Report to Congress
December 2012

United States Department of Energy
Washington, DC 20585

Figure 2. Requested in the Senate Energy and Water Development Appropriations Report for FY 2012 (112-164) and in Section 3119 of the House Armed Services Committee Report for the FY 2013 National Defense Authoriation Act (112-479), this report discusses the path forward for ignition and the impact of not achieving ignition on the Stockpile Stewardship Program.

in December 2012, entitled the *National Nuclear Security Administration's Path Forward to Achieiving Ignition in the Inertial Confinement Fusion Program* (see Figure 2). Recognizing the enormous strides that had been made in developing experimental capabilities at the NIF as well as at the Omega Laser Facility at the University of Rochester's Laboratory for Laser Energetics and at the Z Facility at Sandia National Laboratories, the path forward recommended refocusing the ignition effort to provide more focus on exploring the underlying physics issues to better understand, from a scientific perspective, the challenges to achieving ignition that have occurred to date. The goal, of course, is to make progress towards ignition and, in particular, towards the intermediate milestone of demonstrating alpha-heating. But just as important from the stockpile stewardship perspective is deepening our scientific understanding of phenomena in this regime of physics. Not only is this vital to the mission of the Stockpile Stewardship Program, but it also is vital to attracting and training qualified scientific and technical staff and to providing a vigorous research program for the NNSA mission.

Another prong to the path forward is the effort to develop alternative approaches to ignition by both the polar direct drive approach (primarily at Omega) and by the magnetically-driven fusion approach (primarily at Z). This is in addition to pursuing the integrated experiments and *single effects* experiments for the mainline indirect drive approach that is being conducted on the NIF.

NNSA has created five Working Groups to flush out detailed plans and to oversee the execution of the program:

- Indirect Drive Working Group;
- Polar Direct Drive Working Group;
- Magnetically-Driven Fusion Working Group;
- Target Fabrication Working Group; and
- Diagnostics Working Group.

Expert representatives from each of the ICF Program laboratories serve on these Working Groups.

In addition to developing the path forward report, the National Research Council (NRC) of the National Academy of Sciences (NAS) completed its assessment report on inertial fusion energy entitled *An Assessment of the Prospects for Inertial Fusion Energy.* The findings of the report are consistent with NNSA's ignition path forward.

A key conclusion of the NRC report states: "The appropriate time for the establishment of a national, coordinated, broad-based inertial fusion energy program within DOE is when ignition is achieved [Conclusion 4-13]." The path forward focuses NNSA on achieving ignition as part of a balanced approach to best utilizing NNSA's ICF facilities, such as the NIF, for the immediate and long-term needs of the nuclear stockpile.

The NNSA's ignition path forward focuses on continuing the quest to achieve ignition with the present indirect drive scheme on the NIF while also attempting to understand the reasons for not having yet achieved ignition. This approach is consistent with key conclusions of the NRC's subcommittee report entitled *Assessment of Inertial Confinement Fusion Targets* that accompanied the aforementioned NAS report assessing the prospects for inertial fusion energy. The subcommittee report noted that "[t]he national program to achieve ignition using indirect laser drive has several physics issues that must be resolved if it is to achieve ignition [Conclusion 4-1]." This subcommittee report further predicts that it will take a significant effort to resolve these issues: "Based on its analysis of the gaps in current understanding of target physics and the remaining disparities between simulations and experimental results, the panel assesses that ignition using laser indirect drive is not likely in the next several years [Conclusion 4-2]."

The End Game – Ignition and High Yield in the Laboratory

NNSA is committed to achieving ignition; however, the path forward does not attempt to set a date by which ignition will be achieved. Instead, it is developing metrics to understand and to measure progress towards the ignition goal. These metrics will measure improvements in performance, experimental productivity for stockpile stewardship and, most importantly, improvements in the understanding of physics models as related to both ignition and to the broader Stockpile Stewardship Program.

The next assessment of the ignition effort is scheduled for FY 2015 when the program will assess the current progress, current understanding, and the prospects for ignition under the mainline indirect drive and alternative (polar direct drive and magnetically-driven fusion) approaches. We hope that at that time either to have achieved ignition or to have a clear trajectory for the FY 2018 predictive capability pegpost to have a high yield capability in place on the NIF.

Gemini Experimental Series by Robert J. Hanrahan, Paul Ross (National Nuclear Security Administration), and Jeff Paisner (Los Alamos National Laboratory)

On December 5, 2012, a team from the Nevada National Security Site (NNSS), Los Alamos National Laboratory (LANL), and Sandia National Laboratories (SNL) successfully executed Pollux, the subcritical experiment at the culmination of the Gemini Experimental Series. Pollux marked a number of firsts as well as provided a link to historic experiments. Pollux also marked the successful completion of a challenge Dr. Donald Cook, NNSA Deputy Administrator for Defense Programs laid out for the NNSA laboratories in 2010: to execute a scaled experiment in U1a within 2 years from a standing start. The purpose of the Cook Challenge was to "develop improved scientific understanding of plutonium [Pu] behavior, provide data to evaluate integrated models, and challenge the design and production capabilities of the Nuclear Security Enterprise." In the end, Gemini was even more successful than Dr. Cook had expected. Not only was the experiment conducted on schedule and under budget, but it also resulted in the following accomplishments among its other successes:

- Lead to the development and first deployment of a new diagnostic technique, i.e., Multiplexed Photon Doppler Velocimetry (MPDV), a novel fiber-optic probe which measures the velocity distribution of an imploding surface. This technique replaces the traditional more limited electrical pin technique.
- Marked the development of a new partnership with a vendor for vessels meeting ASTM standards for explosive containment;
- Lead to new capabilities for rapid design and production of near-net-shape Pu castings; and
- Broke new ground for the use of modern precision manufacturing and inspection techniques at PF-4 at LANL.

Lawrence Livermore National Laboratory conducted 973IS, a scaled experiment with 60 channels of PDV (both single channel and multiplexed) on October 27, 2011. The results of the experiment revealed behavior in materials and high explosives (HE) that had not been resolved in any previous work. Hydro experiment H4080 followed on December 16, 2011 and was conducted in front of the Dual Axis Radiographic Hydrodynamic Test facility (DARHT). H4080 used the new all-MPDV probe head with over 100 possible channels of data. H4080 used surrogate materials for the metals that would be used in the final Gemini experiment. Results from H4080 gave the designers the same and additional hints of material behavior under the pressure of HE-driven experiments that were seen in 973IS.

Following H4080, Castor, a confirmatory experiment, was conducted on August 29, 2012. Castor had all of the final diagnostics, setup, procedures and safety restraints in place that would be used for the final Pu experiment of the series. To a greater extent than either 973IS or H4080, Castor provided more than 100 channels of data and gave the designers a glimpse into the behavior of materials that had not been resolved, or in some cases even predicted in any previous experiments. The fidelity and number of data points returned enabled codes to more closely match experimental results. Pollux, the full system experiment conducted December 5, 2012 is still being studied for the wealth of data it produced on the behavior of Pu when driven by HE.

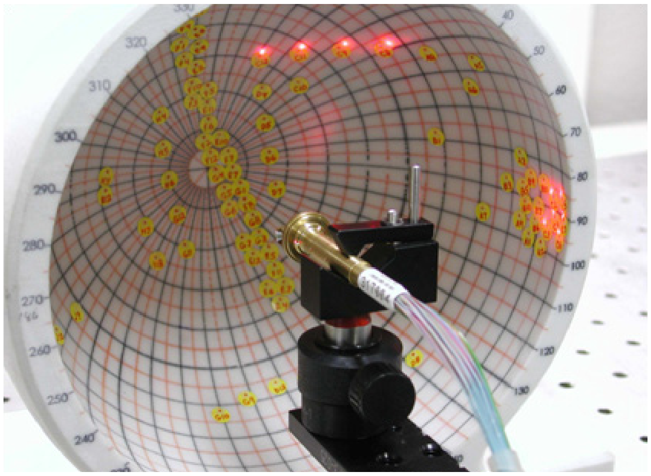


Figure 1. PDV probe head being aligned.

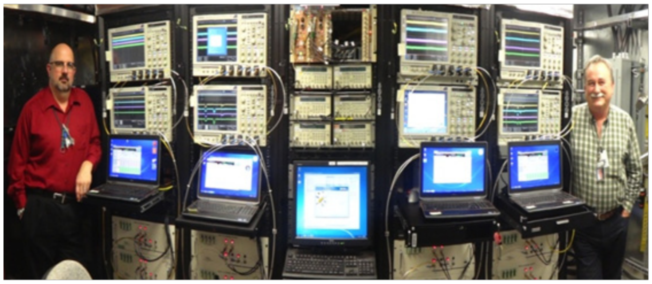


Figure 2. Multiplexed velocimetry system to capture over 100 data channels per experiment.

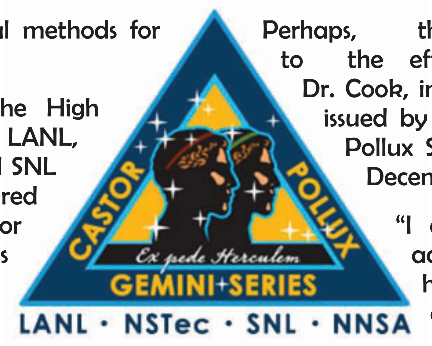
Gemini also demonstrated the application of modern Stewardship tools. Examples are presented in the table on the next page.

The transformational technologies, i.e., Advanced Optical Domes, MPDV and Composite Velocimetric Comparison (CVC), above, developed by the Project—and unexpected when Gemini was first formulated in 2011, will have an enduring impact on the design, data quantity, quality and analyses of all future weapons experiments. Furthermore, the data from the three integral experiments in the Gemini Experimental Series (H4080 in DARHT at LANL, and Castor and Pollux in U1a at the NNSS) have already informed weapons codes and provided extraordinarily important data for the Predictive Capability Framework (PCF) community. The PCF is a planning methodology that coordinates the complex array of performance requirements that constitute stockpile assessment, with the

Modern Stewardship Tools	Gemini Experimental Series Activities
Physics Modeling	• ASC codes to design the Gemini Experimental Series, inform the design requirements for the diagnostic systems, and prepare for pre-shot and post-shot analyses of previously unattainable data output by these codes • 3D codes to design scaled blast-pipe hardware and safety analyses • Composite Velocimetric Comparison approach for analyzing data. This is a transformational technology when combined with MPDV, which is already starting to revolutionize planning and execution of hydrodynamic experiments on DARHT
Diagnostics	• Novel high-density and high-bandwidth PDV optical dome probes using 21st century metrology (or Advanced Optical Domes) and multiplexing technologies (or MPDV. Using this technique Pollux was able to provide approximately 1.3 million points of data compared to four to five hundred points of data captured in earlier underground tests and hydro tests.) • High-fidelity DARHT hydrotest to validate 3D physics modeling of blast-pipe design
Fabrication	• The ASC fluid flow code Truces is used to understand Pu casting and to design the Pu mold • Development of processing and modeling for high-precision fabrication, handling and inspection of scaled components at LANL (in particular, Pu and surrogates of interest to the Hydrotest Program) and at Kansas City Plant (in particular, 'new' detonator components)
Engineering	• Construction methodology and ASME Code Case first developed by the LANL DynEx Program for impulse-loaded vessels • Establishment of a commercial vendor for confinement vessels fabricated to the rigorous weapon experiment requirements

development of advanced calculational methods for evaluating this performance.

To meet the schedule imperative, the High Performance Project Team from LANL, National Security Technologies, LLC and SNL also demonstrated the discipline required to maintain the Authorization Bases for Hazard Category III nuclear operations in the Device Assembly Facility and U1a Complex at the NNSS. In addition to all of the above, Gemini brought the United Kingdom's Atomic Weapons Establishment on board as partner in the physics design and analysis, and diagnostics areas.



Perhaps, the most eloquent testament to the efforts of the Gemini team is from Dr. Cook, in his e-mail response to the Flash Report issued by the Test Director a few hours after the Pollux Sub-Critical Experiment was executed on December 5, 2012:

"I am already certain that the technical achievements in H-4080, Castor, and Pollux have demonstrated a new and important capability put into place for the Nation's Stockpile Stewardship Program. My heartfelt congratulations go to you and the Gemini team for your leadership, your hard work, and your success. Well done, indeed."

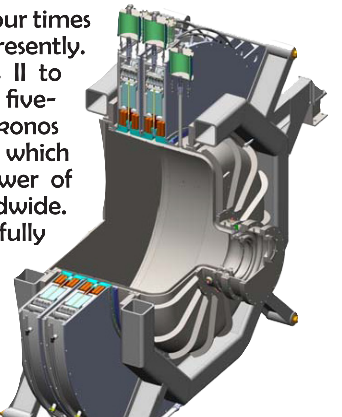
2013 Stewardship Science Academic Programs (SSAP) Annual Review Symposium

This year's Symposium will be held at the Sheraton Albuquerque Uptown Hotel in Albuquerque, New Mexico on June 27-28, 2013. It will feature overviews of work to date from ongoing grants and cooperative agreements in the areas of Low Energy Nuclear Science, Properties of Materials Under Extreme Conditions, High Energy Density Physics and grants awarded under the National Laser Users' Facility Program and the Predictive Science Academic Alliances Program. Presentations on topics of general interest will also be given by National Laboratory and NNSA personnel.

The goals of this symposium are to: (1) Highlight accomplishments of the academic programs (these presentations are part of the periodic reviews of the program); (2) Promote interaction and help build user communities in areas of physical science relevant to stockpile stewardship; (3) Foster ties between participants, sponsors, and the NNSA National Laboratories and identify areas for future collaboration; and (4) Encourage student and postdoctoral researcher involvement and interaction with the scientific community. For more information, visit http://www.orau.gov/ssaa2013/.

Successful Operation of the World's Most Powerful Megaampere-Class LTD

A linear-transformer-driver (LTD) module is an induction voltage adder that consists of two or more LTD cavities connected electrically in series. Sandia National Laboratories (SNL) demonstrated successful operation of Mykonos II, a two-cavity 3-meter-diameter module, on 2,000 shots. At a charge voltage of 90 kilovolts, Mykonos II generates a peak electrical power of 160 gigawatts (GW) with a standard deviation of 1% and a switch prefire rate of < 0.003%. The peak current achieved is 775 kiloamperes. An automated control system operates Mykonos II at the rate of one shot every 33 seconds. Mykonos II generates more power than any other megaampere-class (> 0.3 MA) LTD module in the world today. Mykonos II also generates more than twice as much current as any other module. In addition, Mykonos II is the only module that drives an internal water-insulated transmission line, which is substantially more efficient than a magnetically insulated transmission line. These results demonstrate that liquid-insulated LTDs can be used as the prime power source for next-generation pulsed-power accelerators, such as Z-300, a proposed 300-terawatt machine that will produce four times as much power as Z does presently. SNL is upgrading Mykonos II to Mykonos V, which will be a five-cavity LTD module. Mykonos V will generate 400 GW, which is more than twice the power of any other module worldwide. Mykonos V is expected to be fully operational before the end of FY 2013. — B. Stoltzfus, B. Hutsel, W. Stygar, E. Breden, W. Fowler, R. Hohlfelder, D. Jaramillo, M. Jones, P. Jones, D. Justus (SNL), K. LeChien (NNSA), A. Lombrozo, F. Long, M. Lopez, D. Lucero, K. MacRunnels, K. Matzen, M. Mazarakis, R. McKee, J. Moore, T. Mulville, G. Olivas, J. Porter, S. Radovich, S. Roznowski, M. Savage, M. Sceiford, T. Schweitzer, K. Seals, M. Sullivan, M.A. Sweeney, A. York (SNL), and our colleagues at the High Current Electronics Institute (Tomsk, Russia)



Mykonos II

PhD Thesis Research at the National Ignition Facility

by R. Petrasso (Massachusettes Institute of Technology)

Four Massachusettes Institute of Technology (MIT) PhD students played an important role in the highly successful implosion at the National Ignition Facility (NIF) on March 12, 2013, in which a record deuterium-deuterium (D-D) fusion yield ($5\text{x}10^{12}$) was achieved. The four students, Hans Rinderknecht, Mike Rosenberg, Alex Zylstra, and Hong Sio, all from the MIT Physics Department and the MIT Plasma Science and Fusion Center, were part of the team responsible for fielding nuclear spectrometers that revealed critical internal plasma conditions of the implosion.

For this deuterium-fueled implosion, the D-D fusion reaction has the following two equally probable branches.

$$D + D \rightarrow n\,(2.5\ \text{MeV}) + {}^{3}\text{He}\,(0.8\ \text{MeV}) \tag{1a}$$

$$\rightarrow p\,(3.0\ \text{MeV}) + T\,(1.0\ \text{MeV}) \tag{1b}$$

As the very energetic ^{3}He or T fusion products slow down in the background D plasma, they have a probability of about $1\text{x}10^{-3}$ of undergoing *in-flight* fusion with the plasma D, thus generating the following fusion products:

$$^{3}\text{He}\,(0.8\ \text{MeV}) \quad +D \rightarrow P\,(12\ \text{MeV}\text{-}17.6\ \text{MeV}) + \text{alpha} \tag{2a}$$

$$T\,(1.0\ \text{MeV}) \quad +D \rightarrow n\,(12 - 17\ \text{MeV}) + \text{alpha} \tag{2b}$$

By carefully analyzing the spectra of both the energetic protons and neutrons from these latter reactions, and doing such in a novel and integrated fashion, the MIT PhD students were able to infer the D fuel areal density (15 mg/cm^2) and electron temperature (1.8 keV), and the total (fuel and shell) areal density (45 mg/cm^2). Figure 1 shows a high-quality proton spectrum from this implosion. Figure 2 shows a recent photo of the four MIT PhD students at the NIF facility, together with the former director of the NIF facility, Dr. Ed Moses.

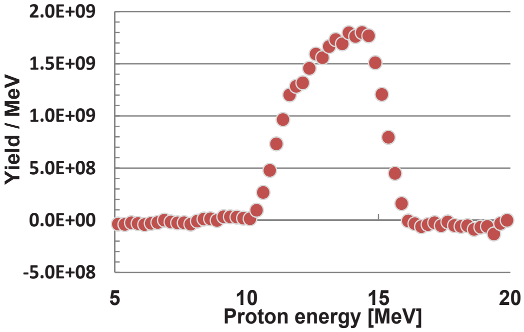


Figure 1. The spectrum of protons resulting from the in-flight fusion of the primary ^{3}He fusion product with the background deuterium (Eq 2a), from the record 12 March 2013 NIF implosion, measured using the MIT-developed proton spectrometer.

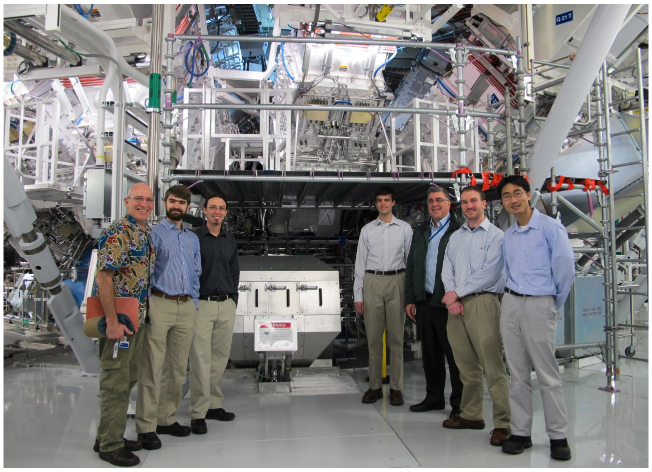


Figure 2. Four current MIT PhD students (2nd from left, Rinderknecht; 4th, Zylstra; 6th, Rosenberg; and 7th, Sio), with their advisor, Dr. Richard Petrasso (far left), former MIT PhD student Dr. Dan Casey (3rd from left), and Dr. Ed Moses, former Director of the NIF (5th from left). Dr. Casey was the first student to use NIF data in his PhD thesis, and recently joined LLNL as a staff scientist. The NIF target chamber is in the background. The MIT-LLE-LLNL designed high resolution neutron spectrometer, used by Dr. Casey in his thesis research, is in the middle.