OFFICE OF DEFENSE PROGRAMS

2015 Review of the Inertial Confinement Fusion and High Energy Density Science Portfolio: Volume I

May 2016

DEPARTMENT OF ENERGY | NATIONAL NUCLEAR SECURITY ADMINISTRATION | DEFENSE PROGRAMS [NA-10]

DOE/NA-0040
Initial release: **May 3, 2016**
Second release: **June 8, 2016 –** Minor technical edits

EXECUTIVE SUMMARY

In September 2012, at the conclusion of the National Ignition Campaign (NIC), the NNSA committed itself to conducting a review of the progress toward ignition three years later. NNSA called upon twenty subject matter experts to independently review and comprehensively assess the progress and program plans for the Inertial Confinement Fusion (ICF) and High Energy Density (HED) science portfolio within the Stockpile Stewardship Program (SSP). A review that included all major program elements of this portfolio had not been conducted in more than 15 years.

This effort covered three main topics:

1. *ICF and Ignition.* An assessment of the scientific hypotheses that guide the ICF Program, the prospects of achieving ignition with existing scientific facilities, and an evaluation of program balance between the three main ICF approaches.
2. *The ICF/HED Portfolio and Long-Term SSP Goals.* An assessment of the alignment of the ICF/HED portfolio with SSP requirements; the contribution to the SSP in the science portfolio in the near, medium, and long term; the scientific and programmatic progress and plans in the ICF Program to meet the goals of the SSP; and, the long-term requirements for "high-yield" capabilities at laboratory scale.
3. *Improving Scientific Foundations in ICF/HED Physics.* The identification of opportunities to improve the underlying physics and the impact of simulations, models, and codes; to increase the integrated rate of progress of ICF/HED programmatic deliverables through new experimental capabilities (including targets and diagnostics); and, to identify areas where partnerships with academia, industry, and other government partners may be strengthened to support these opportunities.

This report summarizes the reviewers' comments and includes a series of conclusions that were assembled by the Office of Inertial Confinement Fusion and the Office of Research and Development, the authors of this report.

An overview of the reviewer comments follows.

ICF and Ignition

- The ICF Program has achieved the milestones set forth in the "Path Forward" report published in 2012. In particular, the program has: (1) identified leading candidates for impediments to ignition on the National Ignition Facility (NIF); (2) nearly doubled the shot rate on the NIF; (3) improved diagnostics capabilities on all its key facilities; (4) made progress in laser-driven direct drive ICF efforts at the University of Rochester's Omega Laser Facility (Omega), and; (5) made progress in magnetically driven fusion at Sandia National Laboratories' Z Facility (Z).

- There are clear SSP drivers to study the properties of robust thermonuclear burning plasmas, to pursue multi-megajoule fusion yields (which requires ignition), and to ultimately pursue high yield.
- Barring an unforeseen technical breakthrough and given today's configuration of the NIF laser, achieving ignition on the NIF in the near term (one to two years) is unlikely and is uncertain over the next five years. Although performance of NIF ignition targets continues to improve and simultaneously making contributions to the SSP, currently there is no known configuration, specific target design, or approach that will guarantee ignition on the NIF.
- The ICF Program has identified and begun exploration of key hypotheses to explain gaps between calculated and measured performance of NIF implosions, however, the present approach is too broad and diverse, and needs better focus. Neither Z nor Omega were designed to achieve ignition, however, they both may be used along with the NIF to understand limitations in NNSA's understanding of physics of ICF implosions, particularly during hot-spot assembly and stagnation. While efforts are improving, there is currently no published "roadmap" to coordinate cross-platform activities.
- Collaboration between researchers and institutions has improved since the conclusion of the NIC. Priorities for further collaborations include: (1) transformative diagnostics, including spatially, spectrally, and temporally-resolved imaging and spectroscopic diagnostics to observe "stagnation" at low, medium, and high convergence; (2) obtaining cross-platform data for fundamental physics validation of models/codes while improving access to codes/models, where appropriate; (3) reviving development efforts for codes to model Laser-Plasma Interactions (LPI); (4) increasing the number of designers and experimentalists working on magnetically-driven implosions and laser-driven direct drive programs; and, (5) enhancing peer review by academia and other institutions.
- There are areas where program direction should be reassessed, including: (1) pursuing the study of long length-scale LPI using partial Polar Direct-Drive (PDD) configuration on the NIF versus pursuing PDD ignition; (2) revising the charter for the laboratory-staffed ICF Council, which is composed of laboratory researchers; and, (3) reviewing the balance of focused versus integrated experiments.

ICF/HED Portfolio and Long-Term SSP Goals

- The ICF Program is well aligned with the weapons program. The HED science portfolio has delivered important data to the SSP, demonstrated the validity of theoretical, computational, and experimental methods important to evaluating the safety, security, and reliability of the stockpile in HED regimes, and demonstrated the competence and credibility of technical staff to work in these regimes without additional nuclear weapons testing.

- There is a strategic plan that describes how research efforts will evolve over the next decade from radiation transport, to boost science, and eventually, to outputs and effects.
- Applications for fusion yields produced on existing platforms are under development. Higher yields (those approaching ~100 kilojoules) are needed for burn physics relevant experiments.
- The long-term requirements case for “high yield” has not been revisited in nearly twenty years. It is not clear how this case has evolved for enhancing predictive capabilities for nuclear weapons performance or for nuclear survivability qualification of components.
- While there are presently no clear drivers for new major (>$100 million) facility investments, support is needed for diagnostics and facility improvements over the next five years.

Scientific Foundations in ICF/HED Physics

- The United States (U.S.) leads the world in HED science. Internationally, a number of facilities are being developed that exceed some U.S. capabilities, such as the high intensity ultrashort pulse laser being developed at the ELI Facility in the Czech Republic, the existing FLASH X-ray Free Electron Laser (XFEL) at the DESY Facility in Hamburg, Germany, and the follow-on European XFEL, scheduled to come online in 2017, also at DESY.
- All HED capabilities (domestic and international) must be considered as NNSA defines the means by which it will execute SSP-related experiments.
- Cross-platform validation experiments (experiments to elucidate similar physics executed on different platforms such as Z and NIF, for example), are instrumental to advances in HED physics. These efforts should take priority.
- Special attention over the next five years should be given to developing a robust cadre of top researchers in key areas of atomic physics, spectroscopy, laser plasma instabilities, and low-energy nuclear physics. NNSA must shape its’ academic programs to ensure resources are optimally deployed.

Reviewers were not asked to consider resource constraints when providing comments or recommendations. To affect all recommendations contained herein would exceed current budget profiles. The principal next step is for NNSA to identify specific resource requirements to prioritize these recommendations within existing budgets. This prioritization process will begin in FY 2016.

CONTENTS

Department of Energy
National Nuclear Security Administration
Washington, DC 20585

Inertial Confinement Fusion (ICF) and High Energy Density (HED) science are core technical competencies within NNSA's Stockpile Stewardship Program (SSP). The overwhelming majority of the yield from a nuclear weapon is produced in the high energy density state with temperatures and pressures rivaling that of the sun. Understanding these fields is critical to ensuring current and future stockpiles are safe and reliable.

The ICF effort has the unique challenge of achieving fusion "ignition" and developing corresponding HED experimental platforms while, at the same time, regularly delivering short-term contributions to support stockpile Annual Assessments, Significant Finding Investigations, and stockpile modernization. In 2012, the ICF Program outlined its three-year path forward toward the development of an ignition capability and committed itself to conduct a review of the Program at its conclusion. What follows in the report fulfills that commitment and, in fact, expands its scope to encompass the full ICF/HED portfolio.

This review process led to the identification of nearly 40 recommendations that cover management, technical, and programmatic issues. These recommendations vary in scope and urgency. One area already identified as being of immediate importance for the ICF effort is the pursuit of advanced diagnostics that will enable the exploration of ICF implosions at higher levels of fidelity required to uncover and quantify important phenomena that lie beyond our present understanding. In the non-ICF HED portfolio, the immediate priority is the study of the boost process, which reaches temperatures and pressures that we are only now able to explore with recent advances at the National Ignition Facility, the Z Facility, and the Omega Laser.

While ignition remains a significant technical challenge, its pursuit and achievement remains important to the SSP into the foreseeable future. Accordingly, I have directed the Office of Inertial Confinement Fusion and the Office of Research and Development to review and implement the findings and recommendations as appropriate.

STEPHEN L. DAVIS, BRIG GENERAL, USAF
Acting Deputy Administrator for Defense Programs
National Nuclear Security Administration

1 Motivation, Objectives, and Structure for the 2015 ICF/HED Portfolio Review

At the conclusion of the National Ignition Campaign (NIC) in September 2012, the Department of Energy's (DOE) National Nuclear Security Administration (NNSA) committed to conducting a comprehensive review in three years to assess the progress toward ignition – stating in the 2012 Path Forward report that *a program assessment will occur at the end of FY 2015*. As 2015 approached, it was recognized that the Inertial Confinement Fusion / High Energy Density (ICF/HED) physics portfolio would need to be more fully assessed. The NNSA assembled a group of 20 diverse technical subject matter experts and conducted the review between May and September of 2015. The review assessed past and current efforts, but particularly emphasized future plans and opportunities to strengthen the long-term health of the Stockpile Stewardship Program (SSP). Reviewers individually submitted observations, findings, and recommendations to NNSA. This report was written by the Office of Inertial Confinement Fusion (ICF) and Office of Research and Development (R&D) and was reviewed by the Office of Advanced Simulation and Computing (ASC). These three offices are within NNSA's Office of Research, Development, Test, and Evaluation (RDT&D). This review was not a Federal Advisory Committee Act activity.

Section 1 presents the motivation, objectives, and structure for the review. *Section 2* summarizes the evolution of the program since the conclusion of the NIC, as well as achievements and challenges that emerged during the NIC. *Section 3* addresses the major observations of the individual reviewers. The report concludes with *Section 4*, Next Steps. The Appendices can be found in Volume 2. *Appendix A* includes documentation associated with the review process. *Appendix B* contains the reviewers' reports as submitted to NNSA. *Appendix C* contains additional reference documents.

1.1 Report Authorization and Recipients

The audience for this report are federal and laboratory/site leadership and management within NNSA's Defense Programs, particularly those with equities in the ICF/HED portfolio. This includes the Office of Research, Development, Test, and Evaluation (NA-11), the Office of Stockpile Management (NA-12), and the Office of Major Modernization Programs (NA-19). Consideration was given to the interest of external stakeholders in the overarching conclusions of the review and the subsequent direction of the program.

1.2 Primary Objectives of the Review

Individual aspects of the ICF/HED portfolio have been extensively reviewed since the 1980s (see Appendix C.2). These past reviews have primarily focused on the ICF Program or on the NIF. Two unique features set this review apart:

1. The major facilities that achieve high energy density conditions are multi-mission. Therefore, any observation that may impact a facility must be evaluated in its full

mission context. This necessitated simultaneous evaluation of the ICF Program and the HED aspects of the R&D portfolio[1]. This type of all-encompassing review had not been conducted in 15 years[2].

2. The majority of the previous reviews of the ICF Program focused on achieving ignition on the NIF. This review included each ICF approach. The result was a comprehensive review that included all major program elements that comprise the ICF Program.

The review was an independent technical assessment of the program of record as of May 2015. NNSA asked reviewers to provide their individual recommendations to improve current efforts, strengthen the three- to six-year program plans, and perhaps most importantly, identify areas for sound strategic investments over the next 10 to 20 years. The charge to the reviewers is provided in Appendix A.3.

1.3 Structure of the Review

The review was initiated on May 18, 2015 with reviewers attending a three-day overview of the program at which the ICF/HED leadership from the laboratories presented their respective programs. Reviewers were divided into three groups along the elements of the charge. In July 2015, the reviewers had briefings at Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), Los Alamos National Laboratory (LANL), the University of Rochester's Laboratory for Laser Energetics (LLE), the SLAC National Accelerator Laboratory (SLAC), and at DOE in Washington D.C. The laboratories which participate in the ICF Program generated fifteen white papers to prepare reviewers for their visits. Reviewers held discussions with laboratory leadership and management, attended presentations by laboratory staff scientists, and met with established laboratory scientists and early-career scientists for further discussions. Additional details of the review process can be found in Appendix A.

Group 1 – Progress Toward Ignition

Group 1 assessed the potential for achieving ignition through existing scientific capabilities and facilities. The scientific hypotheses that guide today's ICF Program were evaluated across the three established ICF approaches: Laser-driven Indirect Drive (LID), Laser-driven Direct Drive (LDD), and Magnetically-driven Direct Drive (MDD). This group assessed the effectiveness of the ICF Program's cross-platform and cross-laboratory collaborations.

Federal Lead: Lois Buitano, NNSA
Meeting locations: LLNL, LLE, SNL

---

[1] The HED aspects of the R&D portfolio are categorized into four areas: Nuclear (materials properties, hydrodynamics), Thermonuclear (mix, burn), Radiation (radiation transport and opacities), and Output and Effects (weapons effects, generating hostile/survivability environments). Over the last five years, significant progress has been made to improve NNSA's understanding of energy balance, boost initial conditions, and secondary performance.

[2] High-Energy-Density Physics Study Report, 2001, National Nuclear Security Administration

Reviewers: Jerry Chittenden, Imperial College
Siegfried Glenzer, SLAC
Jim Hammer, LLNL
Nelson Hoffman, LANL
Warren Mori, University of California, Los Angeles
Andrew Randewich, Atomic Weapons Establishment
Sean Regan, LLE
Bob Rosner, University of Chicago
Susan Seestrom, LANL, Retired
Steve Slutz, SNL

Group 2 – Non-Ignition HED Science and Long-Term Planning

Group 2 assessed current and future HED contributions to the SSP, and evaluated the long-term requirements for the ICF Program including the requirements for a "high-yield" fusion platform.

Federal Lead: Njema Frazier, NNSA
Meeting locations: LLNL, SNL, LANL, DOE-HQ

Reviewers: David Crandall, NNSA, Retired
Jill Dahlburg, Naval Research Laboratory (NRL)
John Harvey, U.S. Department of Defense (DoD), Retired
Jeffrey Quintenz, NNSA, Retired

Group 3 – Scientific Foundations

Group 3 examined the fundamental science of the ICF Program and progress made in understanding the physics relevant to ICF/HED sciences: material equations of state, hydrodynamics, thermonuclear burn, opacity, and radiation transport. Group 3 focused on the ICF Program's partnerships with external organizations in these areas. The group assessed the fundamental science experiments currently being executed and the status and contributions of university programs. Lastly, Group 3 assessed current diagnostics and computational modeling capabilities.

Federal Lead: Kirk Levedahl, NNSA
Meeting locations: LLNL, SLAC

Reviewers: Sean Finnegan, Office of Fusion Energy Sciences, DOE
Yogi Gupta, Washington State University
Stephanie Hansen, SNL
Richard (Dick) Lee, University of California, Berkeley
John Sarrao, LANL
George Zimmerman, LLNL

2 Evolution of the National ICF/HED Program since the National Ignition Campaign

The NIC was an integrated national effort consisting of partnerships between national and international labs, academia, and industrial partners to achieve ignition and robust thermonuclear burn on the NIF by the end of FY 2012. During the NIC, 84 of its 86 level one and level two milestones were completed. The two milestones not achieved were the demonstration of limited "alpha heating" and demonstration of ignition. Although the world's most powerful laser, NIF, was constructed and successfully transitioned to routine operations, ignition on the NIF was not achieved by the end of the NIC.

As the NIC was concluding, a workshop was held in May 2012, to "discuss science that had been learned during the NIC, identify new science questions that had arisen, and begin to lay the lines of experimental and theoretical inquiry that could address these over a multi-year time frame."[3] The workshop identified six Priority Research Directions (PRDs) that address key physics issues preventing the attainment of ignition on the NIF.

In December 2012, the NNSA and ICF Program scientific and technical community partners submitted to Congress the, "Path Forward to Achieving Ignition" Report. It proposed a path forward and ICF Program goals for achieving ignition on the NIF and improving understanding of relevant physics to be explored at the other major ICF/HED facilities (Z at Sandia National Laboratories, Omega at University of Rochester) over the three years following the conclusion of NIC. The report presented specific programmatic and technical goals to be pursued at each of the facilities: the LID Program predominantly conducted at the NIF; the LDD Program predominantly conducted at Omega, but with elements on the NIF; and, the MDD Program predominately conducted at Z. These goals became level two milestones for the ICF Program and were accomplished in the 2012-2015 timeframe. A summary of the milestones is provided in Appendix C.3. In addition, a summary of major accomplishments over that timeframe in the ICF/HED portfolio that were not specifically part of the "Path Forward" is provided in Appendix C.4.

---

[3] "Science of Fusion Ignition on NIF Workshop," May 22-24, 2012, LLNL-TR-570412

3 Review Topics

Each of the 20 reviewers submitted individual written reports that are available in Appendix B. While many reviewers addressed the charge given to their assigned group, NNSA encouraged reviewers to provide comments on all aspects of the program. Upon review of the individual reviewer inputs, the authors of this report sorted the reviewer's comments into the following topics:

- ICF/HED Contributions to the SSP
- The Prospects for Achieving Ignition
- Technical Challenges in Inertial Confinement Fusion
- Experimental Diagnostics and Computational Resources
- Improving Scientific Foundations in HED
- Academic Programs and External Partners
- Program Direction

The sections of the report are organized using this structure, with each topic beginning with background, followed by a segment that captures the major themes contained in the reviewer comments, and closing with a summary of the NNSA program office perspective and next steps.

3.1 ICF/HED Contributions to the Stockpile Stewardship Program

3.1.1 Summary of Reviewer Comments

With the cessation of underground testing in 1992, the U.S. nuclear weapons program could no longer directly develop and exercise the expertise of nuclear weapon scientists and the broader nuclear security enterprise (full scale manufacturing, engineering, production, etc.) through nuclear explosive tests. Established in 1994, the Stockpile Stewardship Program (SSP) was created to maintain confidence in the stockpile and sustain the nuclear deterrent in the absence of nuclear explosive testing. The SSP relies heavily on the NNSA laboratories to maintain expertise in technical areas relevant to nuclear weapons design and performance through leading-edge, science-based programs, thereby providing confidence that the United States has a safe, secure, and effective nuclear weapons stockpile. As captured in the January 20, 2015 laboratory directors' letter to the NNSA Administrator, found in Appendix C.1, "HED science remains a core technical competency for the Nation's Stockpile Stewardship Program for the foreseeable future." In particular, the "pursuit of fusion yield in the laboratory is critical for the long-term health of the Stockpile Stewardship Program." The scientific grand challenge of achieving ignition at laboratory scale attracts top scientists from around the world to the weapons laboratories. It is also recognized that the study of thermonuclear burning plasmas is important to develop and validate computational models that are used for the annual assessment of the stockpile and to resolve issues encountered during weapon surveillance.

Experimental platforms specifically developed for ICF applications have been adapted and applied to mature predictive capabilities for studying material properties, opacity and transport, hydrodynamics and burn, and outputs and effects. There is significant overlap in the skills associated with conducting complex and highly-integrated experiments in the ICF Program and those needed to conduct a nuclear explosive test. Specific skills include the ability to conduct diagnostic development and manage many different interfaces through design, fielding, and analysis. This expertise is important because one goal of the SSP is to maintain the intellectual acuity of the designers, scientists, and engineers who must remain cognizant of nuclear weapons design, development, and operation. SSP scientists, engineers, and designers rely heavily on modeling and simulation. Models and the overall simulation approach must be validated through experimentation. Predicting the results of an experiment, then conducting that work and analyzing the results and confirming or rejecting the related hypotheses and assumptions is an important learning experience: it is key to establishing experimentally validated confidence in those models and simulations, and understanding their limitations. Now, 20 years later, the ICF/HED facilities are the critical tool for providing confidence in the codes and their limitations in the high-energy regime.

NNSA and its laboratories value the ability to conduct cutting-edge research to attract and retain new employees while also advancing HED science that is critical to the nuclear weapons program. The NNSA laboratories embrace ICF/HED capabilities to test and train the next generation of stockpile stewards. LLNL and SNL are more pro-active in using the ICF/HED facilities in training their stockpile stewards. Since LANL lacks its own major HED facility, young designers at LANL should be incentivized to carry out experiments at the NIF, Omega, and Z facilities as part of their training in nuclear design.

By designing and executing experiments, scientists can experience elements of the design process from hypothesis, to experiment, through complex data interpretation and analysis. This enables development of validated understanding and design in the HED regime that is applicable to many NNSA mission areas.

Recent advances in HED science testify to the scientific and technology value that the ICF/HED portfolio is providing to the SSP. Contributions to SPP include providing equation of state (EOS) materials data and observing the lattice structure of plutonium under dynamic conditions at Z and NIF; resolving “energy balance” through experiments at the HED facilities; improving opacity models and equations of state of other materials of relevance to nuclear weapons; developing x-ray and neutron sources to test electronic components and shock reentry body/vehicle materials; and, significantly improving the understanding of radiation/hydrodynamic instabilities, an area that is very difficult to probe experimentally.

Experimental platforms have been developed for the NIF that achieve fusion yields greater than 10 kilojoules (10^4 joules). Studies of thermonuclear burn physics become possible as yields increase to the ~100 kilojoule regime. Exploring burn physics in support of the boost science effort is the primary focus for applications of yield over the next decade.[4] A multi-megajoule capability (>> 1 megajoule) would be used to extensively study burn physics and to develop an intense radiation source with an appropriate spectrum to support precise assessments of nuclear survivability and vulnerability and to validate nuclear weapons effects codes.

While the pursuit of ignition is valuable on many levels, significant challenges remain for the attainment of "high-yield" laboratory fusion. The pursuit of high yield will test the innovation of designers in ways that few other technical pursuits can. Higher yields enable experiments to test the validity of current nuclear weapon codes in temperature, pressure, and density regimes closer to nuclear weapons operating conditions, serving as a key means[5] to train the new generation of nuclear weapons scientists and engineers who have no experience preparing, fielding, or observing an actual nuclear explosive test. Although there is an inadequate technical basis today for thinking that high yield from laboratory inertial fusion can be obtained on existing facilities, the ultimate goal of high yield provides direction and shapes program decisions many years in advance of the perceived need. Assessing the need for high-yield capabilities at laboratory scale should be a long-term goal of the ICF/HED Program.

Guarding against technological surprise is another significant driver for the ICF/HED Program. Given the unique capabilities and the role of the ICF/HED Program in the SSP, continuing and broadening DOD and Congressional support for the program through improved communication is vital to the strength of the SSP and to ensuring national security.

3.1.2 NNSA Program Office Perspective and Items for Future Prioritization & Action

- NNSA will conduct a gap analysis to determine the ways the ICF/HED experimental program may be better developed to test weapon's designer skills and judgement. Additionally, reviewers commented that better intra-laboratory integration may be a welcomed step in this direction. For example, LANL should build upon recent successes to improving integration between the HED physics team and the Theoretical Design Division (XTD).
- The three laboratories must strengthen the integration of ICF/HED capabilities (particularly NIF and Z) with the weapons effects and hostile environment communities. Future Live Extension Programs for stockpiled weapons will inevitably have components that will need to be certified for evolving Stockpile-to-Target-Sequence (STS)

---

[4] Ten-year National HED Strategic Plan, January 30, 2015, COPD-2015-0003, LA-CP-15-00064

[5] In addition, for example, to sub-critical experiments executed at the Nevada National Security Site (NNSS) and hydrodynamic experiments executed at the Dual-Axis Radiographic Hydrodynamic Test (DARHT) Facility at LANL.

requirements. NNSA will pursue an effort to assess the near term and long term requirements for ICF/HED capabilities in the areas of outputs, environments, and effects.

- Working with laboratory leadership, NNSA will explore how the ICF/HED portfolio can be better balanced to avoid technological and geopolitical surprise over the long term.

3.2 The Prospects for Achieving Ignition

3.2.1 Summary of Reviewer Comments

Barring an unforeseen technical breakthrough and given today's configuration of the NIF laser, achieving ignition on the NIF in the near term (one to two years) is unlikely and uncertain in the mid-term (five years). The focus of the LID Program over the next five years should be on the efficacy of NIF for ignition. The question is *if* the NIF will be able to reach ignition in its current configuration and not *when* it will occur. The focus of integrated experiments in the LID Program should not be on high-gain capsules simply because codes and models predict they will perform well. The codes and models themselves are not capturing the necessary physics to make such predictions with confidence. A lack of appreciation for this combined with a failed approach to scientific program management, led to the failures in the NIC.

There are areas of physics that are not well understood or not properly captured in models, codes, and current simulation approaches. Therefore, it is important to probe high energy density states and the systems that create HED conditions as a function of energy density and changes in that energy density. This requires a systematic experimental program to explore factors that impact ICF implosions, and novel ways to measure the physics of the drive conditions (laser-target interactions) and the implosion characteristics throughout the time of the implosion.

Despite the failure to achieve ignition during the NIC, there are clear SSP drivers to study the properties of robust thermonuclear burning plasmas, to pursue multi-megajoule fusion yields, and to ultimately pursue high yield. This places significant onus on the NNSA, the laboratories, and the sites to take a different approach to ensure that the significant technical challenges to laboratory ICF will be met with the best possible science, within fiscal constraints.

Recent program management changes discussed in section 3.7, and sound scientific and structural groundwork, increase the odds for achieving ignition at the NIF and multi-megajoule fusion yield on a potential future laboratory driver. Nationally, a reorganization of the ICF Program has been implemented and is highly effective; providing capable leadership, greater functionality, and better alignment of the ICF Program with the broader weapons program. The new research paradigm of the ICF Program is not an open-ended scientific program or an exercise in systems engineering; but is a balance of integrated experiments, ignition science that pursues focused experiments, and physics integration.

Although buoyed by the contributions of ignition-driven and high-energy density experiments, the SSP must be prepared for the possibility that there is no existing experimental driver that will achieve ignition. Due to this uncertainty and the challenge in achieving ignition at laboratory scale, approaches to ignition in LDD and in MDD systems must be strengthened. The Z and Omega Facilities (which are not designed to achieve ignition), along with the NIF, can study the physics of the assembly and "stagnation" of thermonuclear burning plasmas, which benefits the development of all ICF approaches. The National Implosion Stagnation Physics Working Group (NISP) is in the process of identifying specific ways to do this. A summary from this Working Group's first meeting is located in Appendix C.5.

Ignition is an important step toward multi-megajoule fusion yield, not an end in itself. ICF Programs in Russia and China are pursuing platforms that may surpass current U.S. capabilities. High yield must remain a long-term goal for the ICF Program, even if ignition is not reached on the NIF. In an extended era without nuclear explosive testing, driving towards a fusion source of 500 megajoules or greater will be essential for the health of the program.

Scientific exploration the efficacy of the NIF for ignition is an important endeavor for the SSP and for broader scientific community in the United States. If the NIF achieves ignition, applications of fusion yield would be of immediate relevance to the SSP.[6] If it does not achieve ignition, the reasons for this must be understood and each major ICF facility play a could role in developing this understanding. The following sections detail the technical challenges facing each approach to ignition and the technical challenges they share.

3.3 Technical Challenges in Inertial Confinement Fusion

This section summarizes technical observations in the following areas:

- Laser-driven Indirect-Drive (LID), predominantly executed at the NIF
- Laser-driven Direct-Drive (LDD), predominantly executed at Omega
- Magnetically-driven Direct-Drive (MDD), predominantly executed at Z
- Shared Technical Challenges between LID, LDD, and MDD

3.3.1 Laser-Driven Indirect-Drive (LID)

3.3.1.1 Summary of Reviewer Comments

During the last three years on NIF, LID achieved hotspot densities and temperatures with lower convergence and higher adiabat capsule implosions, sufficient for about half of the total fusion yield to come from alpha particle plasma heating. Trends can be observed in these results, as the implosions have demonstrated better reproducibility than past implosions. Although the fusion yield is improved, it remains significantly lower than predicted by unperturbed (1-D)

---

[6] "Applications of Ignition 90-Day Study," February 29, 2012

calculations and a significant fraction of the laser energy (up to 200 kJ) remains unaccounted for in gas-filled hohlraums.

The volume of high quality published research resulting from experiments during the last three years is impressive. These articles have concentrated on the ‘high-foot’ platform, where scalar yield performance has more closely matched predictions. This platform – which uses the same capsule as the NIC point design with a larger laser prepulse (the “foot”) – has achieved close to 10^{16} DT fusion neutrons (~26 kJ). This result is important and encouraging, because significant alpha heating is a critical first step toward ignition launching a nuclear burn wave followed by a rapid 10-fold increase of temperatures and thermonuclear burning of the surrounding dense fuel. The fusion community has recognized this as a significant achievement.

New NIF diagnostic capabilities, focused experiments, and the ability to simulate the multi-dimensional effects of perturbations have improved the ability to discern which factors are making the most significant contributions to performance degradation. Principal degradation sources are thought to be time-dependent drive asymmetry due to laser-plasma interactions and shell perturbations caused by capsule mounting features (commonly known as the “tent”). In addition, high convergence implosions suffer from mix, non-uniform fuel areal densities, and shell-break up.

Despite the success of the ‘high-foot’ design, the fusion yield remains significantly lower than predicted by unperturbed (1-D) calculations. Producing adequately symmetric implosions of indirect-drive ignition capsules has proven to be much more difficult than expected on the NIF. Laser Plasma Instabilities (LPI), such as Stimulated Raman Scattering (SRS) and Cross Beam Energy Transfer (CBET), are obstacles to creating the necessary time-dependent drive symmetry. Time-dependent drive multipliers are applied in simulations to the x-ray drive to match the trajectory of the imploding shell. There appears to be a correlation between the shape of the tent’s contact with the capsule and the structure of the capsule observed in radiography images. Other contributing factors to reduced performance of the high-foot design include the fill tube, hot electron preheat, and inaccuracies in the equation of state of deuterium which impacts target design.

These are also major issues for the ‘low-foot’ design with a higher convergence ratio, wherein hydro instabilities and mix are known to be larger than in the ‘high-foot’ design. Low-adiabat implosions, known as low-foot implosions, show areal densities close to simulations and to those needed for high-fusion gain implosions. The experiments have shown low fusion yields, however, suggesting that the hot spot of the implosions is not forming adequately. Importantly, x-ray radiographs have shown evidence for shell perturbations caused by the capsule “tent” that holds the capsule in place inside the radiation cavity, i.e., the hohlraum.

The LID Program has stepped back from a singular focus on a monotonic increase of yield, but it has also become diverse. This has led to reviewers' concern that there is a slowing and dilution of progress due to pursuit of too many scientific paths at once. The number of experimental fronts pursued at the NIF grew at first but has recently decreased. This was viewed by reviewers as commendable, as focus is required for progress. Activities have been undertaken to ensure that the diversity of ideas is not lost; ingenuity and ideas are desirable even if they are ultimately discarded. Ideas that survive initial analysis may lead to short, targeted experimental campaigns on Omega or Z to determine feasibility before progressing to the NIF.

Predicting the physics of implosions through simulations is extremely challenging. While some aspects of the symmetry of imploded capsules is reproducible under small changes in initial and boundary conditions, computational capabilities for LPI are not yet fully predictive and hydrodynamics calculations have never been validated for the final stages of hot-spot assembly and fuel "stagnation."

It is unclear which path is more likely to eventually lead to ignition of the hot spot and cold fuel, and the odds of success. It is also unclear at this time whether this multi-platform approach is better than one that focuses on fewer options at a time, in greater depth. It can take five to ten experiments or shots to adequately study one concept on the NIF. Currently, there are only ~30 high-energy shots per year. Deciding which matrix of experimental campaigns to pursue is not simple and requires constant planning, technical peer-review, and some degree of flexibility.

3.3.1.1.1 Physics Issues Specific to LID

Incremental improvements in yield in LID have been achieved through an approach that circumvents problems, rather than by understanding and addressing them directly. While this has created a baseline for future design efforts, there are underlying physics issues that consistently emerge and that need to be addressed. Significant limitations to predictive capability remain. This means that the experimental exploration of parameter space is empirically-led or constrained to incremental departures from places of known performance. Investing in diagnostics and other efforts in this area could adequately constrain models, particularly hohlraum models.

Cross beam energy transfer (CBET) was one of the first problems encountered during early experiments on the NIF. There has been little attention given to assessing the time dependence of the radiation symmetry that is responsible for introducing swings in the capsule shape during implosion. It may be possible to use different pulse shaping on the inner and outer beams to provide some time-dependent control of CBET, to design a shimmed capsule with a graded ablator, or to vary dopant thickness to mitigate swings in capsule shape during the implosion. It is also possible that gas-filled hohlraums will provide the only path to ignition on the NIF and need to be understood.

The low- and high-foot campaigns experienced significant SRS from the inner beams. In fact, at least 20 percent of the energy was reflected after including the CBET. Perhaps more importantly, when comparing 15 shots with the same nominal target and laser conditions, there were variations of 15 to 20 percent in the back scatter energy. In addition, there continues to be variation in the amount of light absorbed or rescattered as it reflects back to the laser entrance hole.

The lack of control over the time dependence of the CBET within the gas-filled hohlraums has led to the development of alternative hohlraum designs with lower gas fill pressures. The reduction of the tamping effect of the gas introduces a new set of challenges and requires accurate modeling of the plasma expanding from the hohlraum wall, and modeling of the collision of plasma expansion with the blow off from the capsule. These issues can be mitigated by the use of denser ablator materials such as high density carbon or beryllium. These would require a shorter radiation drive pulse and allow the laser energy to couple to the hohlraum before it is filled by high density blow-off plasma.

A significant number of limitations remain that hinder predictive capability and inevitably mean that the experimental exploration of parameter space is constrained to incremental departures from a place of known performance. With the perturbation amplitudes apparent in current experiments, the stagnation process is intrinsically three-dimensional. In places where discrepancies lie between experimental observation and 3-D simulation, it is unclear if these are due to deficiencies in the way in which the hotspot is modeled or if the discrepancies arise before the start of the deceleration phase. Simulations of the emitted neutron spectra are an important predictor for whether or not key indicators of the hotspot temperature and velocity are observable. Anisotropy of the neutron spectrum is a clear indication of a net center of mass velocity in the hotspot. This is indicative of a low mode asymmetric implosion. Differences between the DD and DT ion temperatures inferred from neutron spectra indicate that the calculated spatial temperature distribution may be incorrect.

3.3.1.1.2 The Future LID Program

The LID research program is pursuing integrated experiments, focused experiments to understand the ignition science, and a physics integration effort with codes and models. This approach will explore many different ideas and iterate on multiple platforms such as:

- Pushing ‘high-foot’ designs toward ignition through different gas fill, ablators, hohlraum sizes and shapes, walls and drive profiles,

- Lowering convergence ratios further and pushing to higher velocities and larger hot spots so that the hot spot itself has enough mass to provide greater than 100 kJ yield, and
- Increasing the laser energy.

Within each focus area, the goal is to find an experimental platform for which there is agreement with 1-D calculations and to use this as a jumping off point and gradually push toward higher yield and ignition. The hohlraum/capsule configuration should be modified to improve symmetry without the need for CBET. This will require larger hohlraums with a reduced gas fill density. Larger hohlraums require more energy to maintain a given radiation drive temperature. Some of this energy may be obtained through reduced LPI and backscatter, but it is probable that adequate symmetry will only be achieved at lower radiation drive temperatures.

The LID Program should emphasize hypothesis-driven focused experimental campaigns that are adjudicated through the interpretation of the data. It is important that experiments test the physics models used in the radiation-hydrodynamic codes. Understanding the target physics of a few focused areas is more important than executing an exhaustive experimental campaign of many permutations of ablator, capsule mount, and hohlraum gas fill.

Ideas for reducing the effect of the capsule support structure should be pursued, with the goal of identifying an improved alternative to the current tent. Many promising concepts for less intrusive support structures have been presented and should be investigated. Since high yield can be degraded by many effects, it is necessary to conduct these experiments under stringently optimized and reproducible conditions (e.g., with good ice surfaces and well controlled laser pulses). Engineering solutions designed to reduce perturbation levels can be directly evaluated through inflight radiographic diagnostics. The relative stability of the current best performing capsules means that the perturbation induced by the capsule mount will be at the limit of diagnostic resolution when the implosion is approaching the axis.

The pursuit of reduced convergence implosions is an important new feature of the program and should be given a high priority. The so-called ‘big-foot’ design increases hot spot rho-R at the expense of the cold fuel. The results will provide an important test of the new figure of merit replacing implosion velocity with capsule convergence. If validated, this result will have important consequences for future planning and will motivate fielding designs on the NIF to deliver yields approaching 100 kilojoules. One risk with this thinner ice-layer design is that mix at the fuel-ablator interface, previously undetected in earlier experiments, could expose higher Z material to the hot spot.

Beryllium (Be) and other alternate ablators must be tested with hohlraums and laser pulses optimized for them. It will be necessary to develop beryllium target designs in hohlraums that demonstrate the expected desirable features, in order to fully evaluate and benefit from the properties of beryllium that make it a potentially appealing ablator. This will require intensive computational design and experimental efforts. Possible directions include large low-temperature hohlraums optimized for capsule absorbed energy or drive symmetry, or higher temperature hohlraums with the capsule optimized for hydrodynamic stability. It must be ensured that these designs are optimized before ranking the ablator's performance relative to other optimized target designs using other ablators.

LANL is pursuing alternate designs including double-shells, wetted foams, and Be ablators. Double-shell capsules have two advantages over the single shell designs. The required radiation drive temperature in double-shell capsules is lower and the wall motion will be easier to control due to the short pulse length requirement. It is not clear if double shells will be less susceptible to drive asymmetries due to the overall high convergence and the fabrication of double shell targets is more complex. Target fabrication issues are presently impeding progress on wetted foam designs.

LANL's innovative designs are worth exploring, but are in need of a strategy. LLNL must work more closely together to define the roadmap and decision processes for these designs.

3.3.1.2 NNSA Program Office Perspective and Items for Future Prioritization & Action

- A specific effort to better understand all aspects of LPI, including CBET and SRS independent of each other and in combination, is needed to measure, model and predict the time-dependent drive symmetry in gas-filled hohlraums. NNSA will assess ways in which this may be accomplished with a special focus on engaging the broader scientific community.
- Mitigation of the effects of the tent is one obstacle to improved performance in LID implosions. LLNL should identify a tractable number of alternate capsule support structures, and the plans to experimentally assess those should be externally peer-reviewed. For planning purposes, the program of experiments to investigate capsule support features should conclude on approximately a twelve month horizon.
- A focused campaign with precision measurement of 1-D implosions, especially with large case-to-capsule ratio experiments, is a priority. This campaign should be integrated into fiscal year 2016 planning.
- Beryllium and other ablators or concepts must be evaluated using a hohlraum and laser pulse combination optimized for the ablator under investigation. A strategy, roadmap, and decision process for alternate ablators and designs should be developed.

- More resources should be dedicated to 3-D simulations using codes that are capable of resolving the physics they are meant to simulate. This would provide insights into the residual kinetic energy in the compressed shell, hot spot assembly, and stagnation phase of the implosion.
- An evaluation should be made to determine the optimum balance between high-energy, highly-integrated ICF experimental campaigns, and lower-energy, discovery experiments on the NIF.

3.3.2 Laser-Driven Direct-Drive (LDD)

3.3.2.1 Summary of Reviewer Comments

The LDD effort has demonstrated a series of precision cryogenic implosion experiments on the Omega laser with inferred hot spot pressures of ~50 gigabar (GB), and initial NIF experiments in the polar direct-drive configuration have begun. Since direct-drive ICF target designs couple more energy to the capsule than LID target designs, the required hot-spot pressure and convergence ratio is lower for LDD target designs (~150 GB hot spot pressure for LDD versus 350-400 GB for LID, and convergence ratios of less than 25 versus ~35 for LID). However, relaxing the plasma pressure requirements in the proposed way makes it harder to meet driver and experiment fielding requirements. Requirements on the laser, such as drive uniformity, laser colors, and power balance, and requirements on fielding experiments, such as a fast shroud retractor for the cryostat, target alignment, and vibration control are more stringent than for LID implosions. In addition, the Two Plasmon Decay (TPD) instability will need to be mitigated.

The LDD Program consists of two major components. The first is a program using a partial Polar Direct Drive (PDD) configuration at the NIF to investigate LPI and other laser-target physics. The second is a scientific study of Symmetric Direct Drive (SDD) implosions at Omega, where the goal is to demonstrate high pressures in the low volume Omega targets. The demonstration of greater than 100 GB pressures on Omega DT implosions would be a significant result; calculations using LLE’s in-house codes suggest that performance may be extrapolated to NIF-scale implosions to produce ~100 kilojoule yields.

Simulations of higher convergence and lower adiabat implosions indicate that mix due to so-called target debris or capsule impurities is affecting inferred hot spot pressure. The LDD effort is actively investigating 3-D effects due to low-mode asymmetries induced by, e.g., laser power imbalance, target offsets, and beam miss-pointing effects. LLE uses an in-house code for the calculations of 3-D effects. No benchmark calculations, or comparisons with other hydrodynamic simulations or with experimental data are presently available.

3.3.2.1.1 Physics Issues Specific to LDD

A potential limitation for LDD is LPI at NIF scale-lengths. The LDD Program has made significant progress in understanding the effects of CBET and the TPD instabilities relevant to LDD. Currently, the predicted CBET for NIF-scale coronas in direct drive targets makes ignition impractical even with 1.8 MJ of laser energy using SDD without mitigation.

As the capsule implodes and becomes smaller than the laser spot sizes, there is increased overlap of the beams and an increased level of CBET. To counter this effect for SDD, LLE is developing ‘zooming’ phase plates on the five-year timescale. The present program of work using the PDD configurations on the NIF should instead concentrate on the use of an increased range of laser wavelengths as the approach to CBET mitigation. The beam zooming option is being explored on Omega and the wavelength detuning option is being explored on NIF.

TPD drives large-amplitude electron-plasma waves that cause hot electron preheat effects on the fuel, affecting compressibility and laser-target coupling. Mitigation of CBET could itself give rise to plasma conditions where the TPD instability generates significant hot electron preheat. Methods of reducing the impact of these effects will be addressed in focused experiments in the SDD configuration on Omega and in the PDD configuration on the NIF by introducing layers of intermediate Z material. It is important to adequately address the threshold and scaling for TPD with laser intensity, plasma-scale length, and for zoomed laser beams. The mid-Z layer is effective in raising the coronal plasma temperature that in turn will lead to increased Landau damping of plasma waves and consequently reduced hot electron preheat. The predicted increase in temperature has been observed with Thomson scattering. A complete assessment of mid-Z layers must analyze the effects on shock timing and possible generation of reverberating shock waves in the ablator and exacerbated hydrodynamic instabilities.

The LDD effort has benefitted from extensive experience and computational capabilities that support the modeling of CBET and TPD preheat, benchmarked against experiments on Omega. The density scale lengths are a factor of four larger in SDD on NIF compared to Omega. Predicting the behavior of LPIs in these plasmas will stretch the capabilities of these models. It is therefore important that data from PDD on NIF is obtained to validate models that may be used for extrapolation to SDD on the NIF.

Naval Research Laboratory (NRL) researchers have shown experimental results from Nike, a 2.5 kJ krypton fluoride laser located at NRL, of laser imprint reduction using thin gold overcoat layers on planar targets, as well as alternative laser beam smoothing schemes. NRL is currently extending their gold overcoat campaign to the Omega Laser System.

3.3.2.1.2 The Future LDD Program

3.3.2.1.2.1 Polar Direct Drive on the NIF

PDD experiments on NIF are an key component of the LDD Program, but are unlikely to lead to ignition. As such, this program should discontinue preparing the NIF for PDD implosions. For example, it is not clear that 48 quads of Smoothing by Spectral Dispersion (SSD) are required if PDD ignition attempts will not be pursued.

The principal aim of PDD experiments on the NIF is to provide a platform to test strategies for CBET mitigation on density scale lengths that are significantly larger than can be obtained on Omega and are within a factor of two of those that will ultimately be encountered in SDD experiments on NIF. The focus is on experiments and diagnostics leading to high fidelity tests of LPI physics (particularly CBET and TPD) at the correct scale lengths and plasma conditions relevant to ignition with SDD on NIF. The bulk of these could be planar and hemispherical experiments and include tests of high-Z overcoats or buried mid-Z layers as described in the program plan. Tests of imprint for ignition SDD conditions should be included. Smoothing on enough quads to enable high fidelity tests would be needed, but the deployment could be paced by experimental progress.

The LDD Program will need to employ and develop simulation tools that have been tested extensively against data. For example, for applications that will use the code HYDRA it will be important to further develop the code and to implement CBET ray tracing to make quantitative predictions. These tools should be tested against NIF experiments.

3.3.2.1.2.2 Symmetric Direct Drive on the NIF

The LDD strategy is based on the concept of demonstrating “hydro-equivalence” or assuming that hydrodynamics that lead to high inferred pressures on Omega at 60 kilojoules will scale to NIF implosions at 1.8 megajoules. The original papers on hydro-equivalence noted that there are many physics phenomena that will not scale. This includes CBET, LPI, and heat transport in the conduction zone, thermal conduction in the hot spot, and the mean free path to hot spot size for the equilibration of the deuterium and tritium ions.

The goal for SDD integrated DT cryogenic shots on Omega is the demonstration of an implosion that is hydrodynamically equivalent to a SDD implosion on the NIF at 1.8 MJ. Fuel pressures of about 120 GB will be needed for a direct drive ignition capsule on NIF to ignite. Similar pressures will have to be demonstrated on Omega. The plan is to increase the fuel pressure by mitigating CBET, using thicker shell capsules, and improving beam pointing (symmetry).

Proving the scientific case for investing in SDD on the NIF, and in particular, proving that the known issues such as CBET can be mitigated, represents a significant scientific challenge. This is particularly challenging in cases where not all of the physical conditions necessary for such a test can be accessed with existing facilities. It is inevitable that when scaling up a design to a larger platform, not all of the parameters ranges that will be encountered can be fully explored beforehand. It is therefore important that the data obtained in both PDD on NIF and SDD on Omega are utilized to inform and constrain theoretical and computational models that will be essential for underwriting the scientific case for SDD on the NIF.

3.3.2.2 NNSA Program Office Perspective and Items for Future Prioritization & Action

- NNSA will consider establishing a working group on hydro-equivalence with researchers from across the LDD, LID, and MDD efforts. The group should rank the areas of scientific concern with the hydro-equivalence argument, and decide what physics needs to be explored/added to the design codes.
- The LDD Program, with representatives from both LLE and LLNL, should develop a multi-year plan that describes the deliverables and milestones that would be required to technically justify a decision to convert the NIF to SDD illumination; in essence, develop a decision tree, including a time-scale for determining the cost and impact of this conversion.
- The NIF PDD experimental plan should focus on understanding the physics that does not scale hydrodynamically from Omega SDD experiments, primarily LPI.
- SDD implosions on Omega should be simulated using validated 3-D codes. Better integration is needed between LLE and LLNL in this area, which is discussed in section 3.4.2.
- Diagnostics to better quantify “mix” should be developed for Omega and experiments should be conducted to constrain simulations.
- Beam smoothing for LDD should be limited to a subset of NIF quads until/unless a decision is made to convert NIF to SDD. An assessment of the minimum quantity of beam smoothing to study LPI-related physics on the NIF is needed, to support decisions for potential future investments in SDD.

3.3.3 Magnetically-Driven Direct-Drive (MDD)

3.3.3.1 Summary of Reviewer Comments

The MDD approach provides an intriguing alternative to LID and LDD. Considerable progress has been made in the development of the Magnetized Liner Inertial Fusion (MagLIF) concept in the last few years. The achievement of fully integrated shots incorporating liner implosion, magnetization, and laser preheat represents a significant milestone. The MDD approach has lower implosion velocity, thick imploding shells, and lower required peak fuel pressure than the laser-driven approaches. There is a much smaller experimental and computational database and less is known about the potential issues. Similar to other inertial fusion concepts, the first fully integrated MagLIF experiments produced fusion yields significantly lower than those predicted by 2-D Magnetohydrodynamics (MHD) simulations.

The first MagLIF experiments at the Z Facility have reached DD fusion yields of ~4 x 10^{12} neutrons at temperatures of ~2.5 keV. It is thought that conditions suitable for 100 kilojoules of DT fusion yield with a pressure-time product ($P \cdot \tau$) of greater than 5 GB-ns and a magnetic field-radius product ($B \cdot r$) of greater than 0.5 MG-cm can be achieved on Z. DT fusion yield estimates are based on experimental demonstrations of DD equivalent yield; use of tritium on Z is not expected in the foreseeable future.

3.3.3.1.1 Physics Issues Specific to MDD

A number of mechanisms are thought to be inhibiting the fusion performance, based on experimental observations and 3-D MHD simulations. These include the non-uniformity and reduced efficiency of the laser energy absorption, hydrodynamic mix of the liner and fuel, mass loss through the Laser Entrance Hole (LEH), enhanced radial heat flow due to extended Ohm's law effects, and reduced convergence due to 3-D asymmetry at stagnation.

Much of the unpredictability of past experiments is explained by insufficient laser beam propagation in the target. In current experiments, the Z Beamlet (~2 kilojoule laser) with a target filled with D_2 fuel produce laser heating temperatures of 200 eV. Initial simulations of this process using LASNEX and HYDRA significantly over-predicted the fraction of laser energy that would penetrate the LEH foil and be deposited in the target. In addition to reducing the fraction of the beam that penetrates the LEH foil, LPI potentially causes the beam to filament and spray. Filaments that heat the electrodes or the liner could mix this material into the fuel and degrade the yield. This is supported by a recent experiment with beryllium electrodes that performed significantly better than a number of previous experiments that had used aluminum electrodes. An additional factor that complicates the modeling process is the presence of embedded magnetic fields. Collaborations have been formed between SNL, LLE, and LLNL to perform dedicated studies of the laser heating process at Omega and, soon, at the NIF.

A significant risk to the MagLIF concept is the mix of material, either liner, window, or dense DT fuel, into the hot fuel. The conventional wisdom is that at stagnation MagLIF is more prone to mix than laser-driven ICF because MagLIF designs have lower hot spot ρR than laser-driven ICF. This translates into a longer burn duration to generate enough fusion heating to ignite. Additionally, other poorly understood phenomena play crucial roles in the operation of a MagLIF target, including the implosion of a magnetized liner/plasma assembly undergoing magnetic flux loss, and magneto-hydrodynamic instabilities such as magnetic Rayleigh-Taylor and electro-thermal instability. The limited existing capability for experimental diagnostics and predictive simulations prevents sufficient understanding of target performance in these areas.

3.3.3.1.2 The Future MDD Program

The MDD Program is largely concentrated on evaluating a single computational design, primarily because experiments on Z occur at a lower repetition rate than laser experiments and the program has a limited number of shots. While many of the design aspects for MagLIF are constrained by the generator and available laser parameters, the main constraint appears to be operational as the present program has insufficient experimental opportunities and lacks availability to a sufficient number of designers and experimentalists to thoroughly evaluate more than one design. This is a cause for concern as there would be a limited selection of mature alternatives if current performance limitations ultimately prove insurmountable. Given the current constraints, it is not immediately clear how alternative designs that go beyond simple variations on a theme could grow from a nascent idea to a viable alternative.

As with the other inertial fusion approaches, it is extremely difficult to directly diagnose hotspot conditions. This is made even more difficult due to the large ρR of the liner surrounding the fuel at stagnation. Results from the NIF have shown that there is a wealth of information embedded within the neutron spectra. Progress on this has been made at SNL with measurements of primary DD spectra and secondary Triton reactions. However, the introduction of tritium handling capabilities at Sandia would mark a considerable improvement through increased yield and by introducing a range of new diagnostic options for assessing hotspot ion temperature, plasma motion, and beam-target contributions. The ability to add tritium or ^{3}He to the fusion fuel and measure the fusion gamma rays produced in DT or D^{3}He reactions would allow observation of the fusion reaction history in the implosion, placing constraints on model development.

The program could use more 3-D modeling to develop mitigations of instability features in the implosion. This would complement the fielding of improved diagnostics of axially resolved imaging, spectroscopy, and x-ray scattering to measure the conditions and allow for comparison with simulation data. Simulation tools and models (including reduced models) with magnetic fields will need to be developed and tested with focused experiments.

The MDD Program would benefit from the inclusion of LPI experts from across the complex to aid understanding of the laser plasma interactions of the preheat beam. Considering that the laser preheat is an integral part of the MagLIF research, SNL should consider hiring a post-doctoral researcher to develop in-house expertise for the laser preheat stage of the implosion.

The decades-long goal of the magnetically-driven liner fusion effort is to produce yields approaching a gigajoule. It is projected that this would require a driver with at least 130 megajoules of stored energy. The decision to turn away from the use of wire array Z-pinches for indirect drive experiments came as something of a surprise to some in the community as progress was being made using double-ended vacuum hohlraums and dynamic hohlraums. In retrospect however, this decision now seems logical as exploration of the X-ray driven indirect-drive concept is being pursued effectively at the NIF. In addition, more is known now about z-pinch-driven hohlraums than when SNL actively pursued indirect drive a decade ago.

There is an opportunity to explore alternative indirect drive designs with larger absorbed energies on a future larger-scale pulsed-power facility. As was identified in the mid-2000s, the main challenges of an MDD approach includes demonstrating enough pulse shape control to have the requisite reproducibility and drive symmetry. It is important that the scientific capability to resolve these issues be reestablished. This capability would enable a logical transition from LID to MDD in the future, should the SSP pursue "high-yield" fusion at laboratory scale.

3.3.3.2 NNSA Program Office Perspective and Items for Future Prioritization & Action

- The MDD Program's highest priority is to demonstrate laser beam propagation and heating on Z which must include collaborations with LPI and laser experts across the complex.
- A comprehensive diagnostic plan for characterizing plasma properties during MagLIF preheating and during implosion must be developed, with a focus on understanding stagnation.
- A second beam line would enable simultaneous laser preheating of the target and radiographic backlighting, providing extremely important diagnostic information from experiments. A cost and schedule estimate for the development of a second beam line on Z should be prepared for consideration.
- The ability to add tritium or ^{3}He to the fusion fuel and to measure the fusion gamma rays produced in DT and D-^{3}He reactions should be a high priority.
- Shot opportunities on Z should be increased. The MDD Program should dedicate more experiments for understanding and optimizing the power flow in the driver-target coupling, and understanding the scaling of MagLIF performance as a function of design parameters such as current, fuel preheat, magnetic field, fuel density, liner aspect ratio, and liner material over as large a range as possible at the Z Facility. There should also be more experiments that pursue alternative concepts to MagLIF.
- Additional ICF resources should be prioritized to the MDD effort to build a stronger cadre of designers, experimental physicists, and diagnosticians.

3.3.4 Shared Technical Challenges between LID, LDD, and MDD

3.3.4.1 Summary of Reviewer Comments

The ICF Program has traditionally been a 'driver–centric' research field. While the drivers themselves differ, the physical processes involved in achieving fusion through implosion are remarkably similar. It is refreshing to see the creation of working groups such as The National Diagnostic Group and the National Implosion Stagnation Physics Working Group (NISP) to advance the understanding of the physical processes common to all three ICF approaches. Measurement of and the creation of diagnostics for laser-plasma interactions, preheat, and compression and burn physics, are excellent areas for collaborations among the ICF Program elements.

All three ICF approaches must address laser plasma instabilities. LPI has been actively studied within the context of ICF for more than 40 years. The community has made some progress in its study of LPI, however, it needs improved understanding. These processes are being modeled with codes that are reduced models such as PF3D. There have been claims that these codes have been validated against experiment, but they need to be validated against codes with additional physics. While the assumptions might be reasonable at lower laser energy, they could be different at higher laser energy, and at different plasma temperatures, densities, temperatures and density scale lengths, and mixes of material. For example, none of these reduced models can include the effects of self-generated or imposed magnetic fields. Fully kinetic models such as Particle In Cell (PIC) codes have shown that the reflectivity from SRS is in short bursts, and can exceed unity for short times.

The LPI effort was a major driving force in the development of PIC codes. PIC codes are now widely used throughout the plasma physics community and are currently in limited use within the ICF effort. This recent precipitous reduction in the LPI effort is due largely to the inability of eliminating it and the hope that LPI issues could be engineered away. Unfortunately, LPI, including CBET, is arguably the biggest obstacle to high-yield designs. This philosophy has led to a significant decline in expertise on fully kinetic modeling of LPI at and outside the ICF laboratories, and has led to insufficient diagnostics for LPI on NIF.

There is the increasing realization that the stagnation phases of all three approaches are intrinsically 3-D processes. 3-D simulations could provide physical insights for many aspects of the implosion stagnation, especially in cases where there may be turbulence and where energy is flowing as a result of asymmetries. Importantly, experimental efforts focused on understanding physical processes are imperative for each approach. The NISP could help identify these specific areas.

3.3.4.2 NNSA Program Office Perspective and Items for Future Prioritization & Action

- The NISP should develop a comprehensive plan for using the NIF, Z, and Omega, and various computational capabilities, as a scientific tool set to advance fundamental understanding of the physics of the stagnation process and the state of the fuel and ablator near and at stagnation.

- A working group should be formed for LPI physics similar to the NISP in its structure and charge.

3.4 Experimental Diagnostics and Computational Resources

3.4.1 Diagnostics

3.4.1.1 Summary of Reviewer Comments

Adequate diagnostic instrumentation at NNSA's ICF facilities is needed to assess progress, develop theoretical understanding, and validate computational simulations. New diagnostics are often the driver for making new scientific discoveries and reducing uncertainty. The overall rate of scientific progress can often be directly linked to levels of diagnostic investment.

Previous experimental efforts under the NIC were frustrated by the inability to distinguish key differences between experiments. An improved diagnostic suite has enabled many of the advances since the NIC, in particular the 'high-foot' design described earlier. For example, new diagnostics have revealed structures that were not known to exist transforming the understanding of the structure of the plasma.[7]

The National Diagnostics Plan, first published in February 2015, was the result of inter-laboratory cooperation and presents a national strategy for the systematic improvement of diagnostics techniques across all ICF platforms. The plan is divided into three categories of diagnostics – transformative, broad, and local; and incorporates international scientific and engineering expertise to define the diagnostic development requirements for ICF research. The plan presents a reasonable timetable for instrument development and deployment, and identifies eight transformative diagnostics that will revolutionize the data obtained from current ICF facilities. In addition to benefitting ignition efforts, improved diagnostics will provide precision measurements for single physics experiments to improve codes and models for the broader HED portfolio. Diagnostics development is a fertile area for university collaboration, student training, and the recruitment of new staff. A technical working group established by NNSA monitors diagnostic development at every stage from concept, to analysis of alternatives, to scientific use. The scientific, engineering, and fabrication tasks of diagnostic development are divided among LLNL, LANL, SNL, LLE, NRL, and other partners, based on the efficient use of resources.

---

[7] Important diagnostic platforms now in place at the NIF include: re-emission balls, keyhole VISAR, 2DConA radiography, self-emission x-ray images, primary and down-scattered neutron images, $\Delta\rho R$ from FNADS, and outgoing shock imaging. Besides these, other diagnostic platforms under development include foam balls, 5-axis keyhole, gated SXI, late-time 2DConA, early time self-emission, higher resolution imaging at stagnation including KBO (Kirkpatrick Baez Optic) and penumbral imaging, Compton radiography at stagnation, and co-aligned neutron and x-ray imaging.

While there are common needs across all facilities, the implosion geometry at Z provides unique challenges. The MDD Program has succeeded in delivering excellent data for compression and burn. Future improvements in temperature measurements with x-ray scattering and down-scatter from beryllium or deuterium are a priority. There is a need to develop further a diagnostic plan for the MDD effort to characterize plasma properties during preheating and implosion, with a focus on understanding mix.

There is a need to improve the understanding of LPI, making optical Thomson scattering instrumentation a high priority on the NIF. At the very least, two more Near Backscatter Imagers (NBIs) should be added on NIF, one at a new azimuthal angle and another at the opposite pole. Adding another Full Aperture Backscatter (FAB) diagnostic at one of these angles would be useful.

For all ignition approaches, the time between peak velocity of the shell and stagnation is key; when inflowing kinetic energy is converted to thermal energy of the hotspot and fuel, and the whole assembly is brought to its maximum density. Imaging diagnostics to measure hot spot formation and resulting residual kinetic energy, including imaging and spatially, spectrally, and temporally resolved spectroscopy, should be a high priority.

3.4.1.2 NNSA Program Office Perspective and Items for Future Prioritization & Action

- The implementation of the National Diagnostics Plan is a high priority. NNSA is placing emphasis on improving spatial, temporal, and spectral resolution for increasingly stringent tests of theory and simulations.
- Advanced diagnostics to address the needs for fundamental physics should be among the highest priorities. This includes, for example, the observation of the Doppler broadening from x-ray emission lines to produce velocity maps and accurate measurement of residual kinetic energy; the use of particle and x-ray scattering methods to measure the physical properties of dense matter (e.g., by observing Compton and plasmon features); and spatially, spectrally, and temporally resolved focusing spectroscopy.
- Measurements that must be pursued in a sustained and meaningful manner include: accurate P-V and temperature measurements spanning a large region of density-temperature space and measurements that can directly examine the microscopic structure of the HED states.

3.4.2 Computational Resources

3.4.2.1 Summary of Reviewer Comments

Ignition will not be achieved without multi-physics design codes that have sufficient predictive capability to guide complex, integrated physics experiments. More detailed physics will need to be included in codes and models as new concepts are investigated and proven, and as new experimental data – utilizing improved, transformative diagnostics – are acquired. Across LID, LDD, and MDD, there is an incomplete knowledge of the physics being included in various models/codes, the equations being solved, and the physics packages being utilized in specific calculations. Some codes have been developed with little or no external peer review. There is duplication of code and modeling efforts and impediments to accessing codes and computational resources by sites other than the primary site where the capability was developed or resides.

Considerable funds are spent developing ICF design codes. Code and modeling efforts should be coordinated across the laboratories and external partners should be included or considered as potential leads for these efforts. To the extent possible, codes should be available to all ICF researchers with a "need to know" and the proper clearance, both for simulation purposes and for code development. At a minimum, there should be a reduction in restrictions for code-use and source-code availability (at least among the ICF laboratories). This would increase the scrutiny on the constituent models and algorithms that comprise "the code," and create opportunities for interactions from outside the originating code development team. While integrated codes are likely to remain the domain of the labs in general, it would be valuable to promote university-led microphysics code development for the validation of physics packages in integrated ICF codes, perhaps through the Stewardship Science Academic Programs. Ultimately, the codes should not be considered the property of a particular laboratory or person.

A widely-held view is that a code has been validated once it provides agreement with an experiment. However codes involve complex and nonlinear couplings among choices of reduced physics models with fitting parameters and numerical approximations. Furthermore, each reduced model should be validated against meso- and/or micro-scale physics to have confidence in the results. Additional considerations include the range of applicability for the code (is the simulation being set-up, run, and analyzed properly for the application at hand) and the 3-D nature of the features observed in LID, LDD, and MDD experiments. The ICF Program would greatly benefit from routine use of 3-D simulations. These advanced validation efforts are complementary to the fielding of spatially, temporally, and spectrally resolved imaging, spectroscopy, and x-ray scattering diagnostics to measure the conditions and allow for comparison with higher-fidelity simulations.

Many experimentalists, as well as theorists, modelers, and designers, use the HYDRA code to calculate results. Therefore, it is important to further develop the HYDRA code and to implement CBET ray tracing to make quantitative predictions. A wide range of ICF-relevant physics packages are developed and implemented in HYDRA, and the code has been tested against a large database of integrated and focused experiments. The continued development of the code, particularly the inclusion of direct drive-relevant physics, and ensuring its suitability for use with high performance computing benefits the ICF Program and its' SSP mission.

There are many areas where the physics packages need to be further developed or better integrated into the codes. LPI physics is not adequately integrated into ICF codes. Kinetic effects, which are important to properly model hohlraums and may be important in MagLIF targets, are not sufficiently characterized. Particle In Cell (PIC) codes, now widely used throughout the plasma physics community, are in limited use within the ICF Program. Vlasov-Fokker-Planck (VFP) codes now include fully parallelized architectures that expand the distribution function into an arbitrary number of spherical harmonics with implicit field solvers that can use very large cell sizes. PIC and VFP codes can be used to test physics packages or be integrated into the hydro codes. PIC codes can now model more spatial and temporal scales and can run on 1,000,000+ cores and on GPUs and Intel® Xeon Phi™ processors, allowing for the study of some hydrodynamics on relevant scales.

The ICF Program should address the following areas: the relative immaturity of LDD-related physics in some ICF codes; duplication and inefficiency in integration of the Advanced Simulation and Computing (ASC) Program and ICF Program efforts at SNL; optimization of use-time for LLNL ASC resources between capability and capacity platforms; access by LLE and SNL to codes developed at LLNL; and, reinvigoration of LPI efforts. The ICF Program relies heavily on investments made by the ASC Program, so it is worth examining the challenges emerging as a result of constraints imposed by the pursuit of exascale computing and platforms. The move at LLNL to a new computer architecture for the next generation is, in general, a challenge for the SSP.

3.4.2.2 NNSA Program Office Perspective and Items for Future Prioritization & Action

- ICF codes and models have been largely developed in a compartmentalized manner. The ICF Program Office will conduct a deeper review of: (1) the prioritization of computing resources; (2) ways to eliminate historic site boundaries that impede progress, and; (3) opportunities to engage external/academic groups to lead or participate in computational efforts where appropriate. A set of workshops, similar to the successful MHD workshop in August 2015, are needed to evaluate the best path forward for code development, particularly for fully kinetic LPI codes.
- The ICF Program Office will work with the ASC Office to conduct an assessment of the impact to the ICF/HED Program of the transition to next generation computer architectures and the pursuit of exascale.

3.5 Improving Scientific Foundations in HED

3.5.1 Summary of Reviewer Comments

New experimental capabilities are providing opportunities to improve codes and models used to support NNSA's ignition and weapons physics efforts, and to improve scientific understanding of phenomena relevant to a broad range of fields such as laboratory astrophysics and high-pressure physics. The community is now acquiring enough systematic data to discriminate between physics models in regions of interest, an improvement from the prior reliance on single measurements.

Because the interpretation of HED experiments depends on radiation-hydrodynamic simulations, the ICF Program, in close coordination with the Office of Research and Development and the Office of Advanced Simulation & Computing, will need to integrate the best possible physics models into these codes. Plasma transport models must be able to treat mixtures of elements accurately, and models must be extended to include non-Local Thermodynamic Equilibrium (non-LTE) effects through tables or algorithms that can run on future high performance computing architectures. Models for materials behavior, opacity, and transport coefficients must be self-consistent.

In most ICF/HED experiments, the laser or pulsed power driver nonuniformities imprints onto the response of the target. The nature of that interaction needs to be fully characterized before the experiment can be completely understood. The disparate temporal and spatial scales associated with characterizing and understanding interactions of radiation with matter, particularly when compared to hydrodynamic scales, make the simulation of this problem intractable. As a result, this aspect of ICF/HED physics is often oversimplified or entirely ignored.

HED experiments are deeply connected to the method of energy delivery, and each driver has its own idiosyncratic energy delivery, native efficiency, and diagnostic challenges. HED results are best validated through comparing data from different platforms or drivers. This was highlighted in the early 2000s by the controversy over the equation of state for deuterium, as determined from data obtained at Z and Nova. Recent anomalous iron opacity measurements on Z will require validation by NIF experiments. Z and NIF are natural partners for cross-platform validation.

X-ray Free Electron Lasers (XFELs), such as the Linear Collider Light Source (LCLS) at SLAC, uniquely allow for decoupling volumetric heating from the probing of the plasma. For instance, data sets were successfully obtained for Al, Si, and Mg, due to XFEL emission at wavelengths that are not emitted thermally, even though the system is hot. XFELs provide the ability to obtain data on femto-second time-scales with a probe tunable to greater than 10 keV.

A strategy of tolerance or avoidance of deleterious instabilities was used during the NIC. This is understandable given the complexity of the problem. However, laser-plasma interactions and the assembly of hot spot at "stagnation" are fundamental to ICF. Dedicated experiments, new modeling tools, and theory must be used to address this challenging problem head-on.

To establish priorities for planning integrated and focused experiments, it is important to develop a simulation database that evaluates performance degradations of DT implosions due to possible errors and uncertainties in the microphysics. Such calculations might also aid the understanding of existing experimental databases. An important area of focus is bridging between atomistic microphysics and integrated hydrodynamics. Appropriately diagnosed and focused experiments can provide insight into continuum lowering and the ionization state of dense plasmas. This would allow the validation of calculations of physical properties such as conductivity, pressure, and ionization balance used in the radiation-hydrodynamic modeling of implosions.

3.5.1.1 Equation of State physics

NIF, Z, and Omega are producing conditions within materials that only exist in nuclear weapon explosions or at the cores of astrophysical objects. Recent experimental and theoretical results have shown that Thomas-Fermi modeling provides a poor approximation to the EOS of extremely dense materials. Better approximations can improve the fidelity of future ICF designs. Resolved measurements capable of distinguishing between theoretical models will advance the field toward understanding and, ultimately, the appropriate use of simulation tools for predictive capability. Complementary facilities such as the LCLS and APS are providing the opportunity to diagnose the transition of materials through phase changes, with a level of precision capable of distinguishing between advanced theoretical models. Researchers are taking full advantage of these new capabilities to generate experimental data to constrain EOS models in ICF/HED codes.

High pressure EOS studies are relevant to the study of the formation of planetary cores, creating opportunities to engage with researchers outside of the ICF/HED Program. It is clear that the development of high quality equations of state, self-consistent with structure and strength and implemented into global models with phase transitions accurately captured, will challenge researchers for decades to come.

HED experiments and modeling should explore the time-dependent phase transitions and the effects of departures from thermal equilibrium, such as unequal electron and ion temperatures. Most modeling assumes that pressure and energy can be specified as a function of temperature, density, and composition in equilibrium. A multiphase model has the potential to include time-dependent phase information, once supplemented with the appropriate transition rate data. Strength models are usually inconsistent with the EOS and do not provide for time dependency. Unequal electron and ion temperatures exist in HED experiments, but models assume that the pressure is separable into electron and ion components without considering correlation effects, such as screening effects of ion temperature on electron pressure. Current non-LTE radiative models required to simulate hohlraums and doped fuels provide EOS quantities that do not agree with equilibrium models. Dependency on simplistic concepts, such as degree of ionization, should be reduced in favor of more fundamental modeling approaches.

The scientific field of materials modeling relevant to EOS is progressing in an efficient manner. The codes being developed provide reasonably accurate results, in agreement with experiments conducted at several NNSA facilities; and EOS models along the Hugoniot, based on shock wave experimental data, are well in hand. Remaining challenges are the lack of accurate independent temperature measurements in high pressure experiments, and the limit in phase space explored as much of the data collected is from diamond anvil cell platforms or along the Hugoniot in shock wave experiments.

3.5.1.2 Opacity and Transport

Opacity and transport studies are foundational to the field of high energy density physics, and underpin the ability to model and predict ICF system performance. The availability of facilities such as NIF, Z, and LCLS and the development of high performance computing platforms are enabling scientists to improve the understanding of microphysics and atomic processes in extreme conditions.

Opacity models that are based on the assumption of Local Thermodynamic Equilibrium (LTE) agree with one another better than they agree with experimental data. For example, codes predict that the ionization state of carbon in the dense ablator plasma of an ICF implosion is close to two. However, advanced modeling and experiments suggest that the correct ionization state is four, which has consequences for opacity and heat transport. This illustrates the need for advanced models with detailed configuration accounting, non-LTE physics, and continuum lowering physics that are validated through experiments.

Measurements of emission and absorption non-LTE opacity are difficult, as are measurements of plasma transport coefficients such as thermal conductivity, electron-ion coupling, and stopping power in a uniform plasma of known temperature. Experiments designed to measure these properties are highly integrated, and are best suited to validating theoretical models. The recent measurements at the Z Facility of the opacity of iron indicate that the opacity is approximately twice the average calculated by the best models. If the Z data are correct, the approach to modeling opacity needs to be rethought.

The research community clearly understands the significant challenges and opportunities that exist to advancing the understanding of the physics of opacity. Researchers are making excellent use of multiple NNSA experimental facilities and DOE facilities such as the LCLS, to test theoretical models and predictive capability. Data from the Z Facility are in excellent agreement with models of some materials, such as nickel, and are in striking disagreement for other materials, such as iron. The discrepancies between observations and theoretical models are clear opportunities to advance NNSA's understanding.

As with opacity research, scientists studying transport properties are making excellent use of experimental facilities in NNSA and outside NNSA, such as LCLS and the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory. There is limited experimental data in ICF-relevant regimes, but this is changing; precision measurements are now providing data that is challenging the state-of-the-art microphysics modeling in codes such as DFT-MD and Purgatorio.

Accurate modeling of non-LTE population kinetics, which likely dominates the ionization state and distribution of atomic configurations in virtually all laser-plasma experiments, is an enormous challenge for simulation codes, as the number of levels can become intractable for high-Z plasmas. Benchmarking opacity calculations with experiments has been a low priority. There have been several attempts over the last 35 years to create data to benchmark radiative properties, such as line shapes, population kinetics, and collision physics. These efforts have been thwarted by difficulties with the plasma gradient structure; creating a uniform volumetrically heated sample to diagnose is challenging.

Magnetic fields affect electron thermal conduction, which then affects plasma density gradients and hydrodynamic instability growth rates. Routinely running 3-D simulations at adequate resolution with magnetic fields is resource intensive. Incorporating the possible need for transport modeling, in place of flux-limited diffusion, is a grand challenge. The validity of using a single fluid hydrodynamic model is questionable for simulating performance in low density hohlraums and exploding pusher targets.

The diminishing numbers of scientists trained in the fields of opacity and high temperature, high energy density atomic physics, and spectroscopy is a big concern. There is a severe shortage of young talent in opacity modeling at the national labs, and if left unaddressed, will erode NNSA's strength in this core competency.

3.5.1.3 Hydrodynamics and Burn

The importance of hydrodynamic and burn physics to the ICF/HED Program cannot be overstated, and the program's portfolio is unmatched in its breadth, depth, and standing. However, a systematic approach to enhanced predictive understanding appears to be lacking.

The program lacks sufficient diagnostics for the conditions of an imploding ICF capsule, and research is dependent on numerical modeling to characterize these conditions. Because outputs from numerical simulations are routinely used to infer the properties of imploded targets (such as the hot spot temperature used as an initial condition for inferring fundamental properties), it is important to be able to accurately diagnose the hydrodynamic and kinetic behavior in converging targets, including 3-D flows and viscosity.

Experiments focused on hydrodynamic instability growth are well matched by simulation, but the community seems overly focused on hydrodynamic growth and its impact on implosion and ignition, and not on the underlying general coupled multi-physics problem. A key issue is the inability to assess accurately the full impact of the driver on initial conditions, such as CBET and hot electron pre-heat. This may be more important than the relatively well settled issue of predicting the growth of hydrodynamic instabilities, such as Rayleigh-Taylor (RT), Richtmyer–Meshkov (RM), or Kelvin–Helmholtz (KH) at low or high mode number.

Instabilities can combine in ways that are difficult to predict; but are apparent in astrophysical phenomena, ICF/HED experiments, and nuclear detonations. Much can be learned from astrophysical phenomena, however weapon scientists need more information than can be obtained from astrophysics, and this was clear during the review discussions. LANL scientists have developed a shock-shear platform that demonstrates complex plasma instability behavior in a controlled manner. Used on Omega and NIF, this platform is providing data of value to fundamental science and has value towards answering specific weapons performance questions. Other fundamental science efforts by labs and university groups explore colliding plasmas and various plasma hydrodynamic phenomena, and are of value to the weapons community. New diagnostics, coupled with more sophisticated models, create opportunities to pursue previously unresolved fundamental questions. Many of the challenges in hydrodynamics and burn are common to the ICF/HED Program and other scientific communities, presenting opportunities for generating innovative ideas through collaborations.

In layered implosion simulations, all unstable wavelengths can be resolved in the highly resolved spatial representation of the material structure in the calculation. This provides an opportunity to advance understanding of the evolution of these instabilities into turbulence with the resulting mixing of materials in the target. For example, LES and RANS models are needed to simulate turbulent mixing in deuterated carbon mix experiments. Unfortunately, these models have not been successful in correctly predicting all three DD, TT, and DT reaction yields. Most capsule simulations are done in 2-D using diffusive energy transport and without self-generated magnetic fields.

A growing body of data enabled largely by the nuclear diagnostics developed by MIT suggests the importance of kinetic processes. Developing understanding of these processes will challenge experimental platform development, diagnostics development, and development of multi-scale modeling capabilities. The integration of kinetic or microphysics effects into the modeling of integrated systems in a self-consistent way is a grand challenge and will push the frontiers of high performance computing.

Although "strength models" are used to model time-independent, inelastic deformation of solids, this may not be the correct way to represent the physics of Resistance to Deformation (RTD) under dynamic loading. But the determination of material strength or RTD needs to go beyond time-independent, phenomenological approaches. Understanding RTD or developing accurate strength models applicable to a wide variety of load paths remains a significant challenge and is important. Plane shock wave or ramp compression data are not sufficient to discriminate between different strength models.

3.5.2 NNSA Program Office Perspective and Items for Future Prioritization & Action

- Regarding fundamental science efforts, the ICF Program Office will:
    - Support individual investigators at laboratories who are pursuing fundamental physics research, through capture of specific goals into program plans and annual implementation plans to emphasize this work.
    - Pursue of theoretical quantum molecular dynamics and other approaches for development of equations of state, transport properties, radiation properties (particularly line shapes), and non-LTE physics. Emphasis will be placed on experimental observables that can be used to post-process simulations for direct and detailed comparisons with data.
    - Support university investigators working in the area of HED physics through both experimental time on HED facilities and financial support for graduate students, postdoctoral fellowships, and research costs.
- The ICF Program Office will specifically seek opportunities to validate physics models directly by utilizing all available experimental platforms, making cross-platform comparisons, and developing complementary platforms and diagnostics. This includes:
    - Validating the recent Fe opacity experiments on Z through further experiments on Z and conducting experiments on the NIF, and
    - Understanding and utilizing the unique and complementary characteristics of the LCLS for HED investigations.

3.6 Academic Programs and External Partners

3.6.1 Summary of Reviewer Comments

Partnerships with academia and private industry are instrumental to success in HED science, particularly for ICF. Scientific engagement with partners outside the NNSA laboratories lessens insularity and reduces the potential for group think. Therefore it is important to maintain a vibrant community of researchers external to the national laboratories to serve as a pool of collaborators and as a scientific system of checks and balances.

The DOE Office of Science (SC) and NNSA share an interest in nurturing partnerships and developing researchers in HED science. The interests of emerging scientists should influence program planning in SC and NNSA; the pending retirement of professors in the field makes this somewhat urgent and strengthens the importance of the ICF Program PRDs. The PRDs provide a link between basic and applied science in ICF, and help to establish more effective ties between the academic community and laboratory scientists.

The ICF/HED Program maintains a world-leading set of experimental facilities, from modest facilities such as Trident, Jupiter, and Nike, to larger facilities such as the National Ignition Facility, Z Facility, and the Omega Laser Facility. These facilities enable research at the frontier of discovery science in HED and ICF and attract many of the best and brightest researchers into the field with the opportunity to study matter in the laboratory at states that otherwise only exist in astrophysical systems.

The availability of new facilities provides an extended set of capabilities that NNSA must consider when executing its mission. For example, facilities like LCLS operate on the basis of the peer group proposal process, with the best proposals awarded beam time. ICF should support newer capabilities being built around the world, such as petawatt lasers generating relativistic electrons and other extreme conditions, high energy swift heavy ion sources, and sub-picosecond, intense hard x-ray free electron lasers (XFELs), and use these new capabilities to build new partnerships, provide relevant benchmark data, and recruit from a broader pool of high-quality students.

The Z Facility and the NIF are not considered typical user facilities. At both facilities, in order for an external (non-NNSA) user to conduct an experiment, there must be strongly engaged NNSA laboratory scientists with the understanding and requisite savvy to efficiently support the experiments as well as a genuine interest in the science being explored. They must have a strong scientific interest, the time, the experience, and the stature in the facility to help the academic partner succeed. It is important to provide some open experimental time through a competitive peer review process to capture the full potential for fundamental science on these facilities. Although only a limited amount of time is made available, every fundamental science experiment provides tremendous value to the researcher, student, or partnering agency.

Although NNSA requirements necessarily limit the amount of experimental time dedicated to user-driven discovery science, there is broad agreement among the reviewers that it is an important component of the suite of experimental activities. Another important aspect of user access is for that access to be multi-year with commensurate funding needed for graduate students to complete their work and for laboratory staff to support the experiments. Finally, access to codes by external researchers is needed for experimental design, to broaden the code user base, and to level the playing field for leading edge research.

The state-of-the-art ICF/HED research facilities and the grand challenge of ignition makes NNSA laboratories attractive to talented young researchers and helps to retain the highly-competent staff who contribute directly to the SSP. One strategy to broaden the pipeline is to engage near neighbor disciplines. Many leading professors with good track records of supplying students to NNSA laboratories are nearing retirement. At some universities there is no clear succession plan and the path to sustain the research program and the student pipeline is not apparent.

NNSA invests in university HED science through multiple programs: the Stockpile Stewardship Academic Programs, which includes the Stewardship Science Academic Alliance (SSAA) Program, the National Laser Users' Facility (NLUF) Program, and the Joint Program in High Energy Density Laboratory Plasmas (JPHEDLP); and through support of users groups such as the Omega Laser Users' Group (OLUG) and the NIF Users' Group. More could be done to support the academic programs that train the next generation of scientists and to recruit them, by creating and strengthening partnerships between the national laboratories and universities, grant programs, graduate student fellowships, and by providing more access to experimental facilities. The talent pipeline should be monitored to ensure that individuals with relevant skill sets are available in sufficient quantities; so that the program is better informed to make decisions regarding investments in academic programs.

3.6.2 NNSA Program Office Perspective and Items for Future Prioritization & Action

- A call for Centers of Excellence, which includes the current HED Centers, is scheduled for summer 2016. Academic investments for the HED portfolio will be selected, informed by the results of the 2015 ICF/HED Review, with consideration given to partnering with SC and industry. A Center structure with scientific independence is envisioned, but with exposure to the national laboratories for students, with fellowships and collaborative projects, and with critical skills developed through incentivizing key scientific areas.
- NNSA will consider a sabbatical program through which national laboratory or university scientists could spend dedicated time at another lab or university to foster scientific collaborations.
- NNSA will review ways to better use the full breadth of SC and worldwide scientific capabilities that can achieve the HED conditions for the SSP mission. This will include identifying ways to reward scientists at the laboratories for developing and fostering successful collaborations with researchers at universities and private companies.
- NNSA will explore metrics to measure the health of the staff pipeline, tracking both the number of students entering the laboratory system and the schools and faculty training them. Ideally, future funding decisions will consider this data.
- The NNSA will explore potential user models for the ICF/HED facilities that balance mission-specific requirements with the desire for access from the broader scientific community.

3.7 Program Direction

3.7.1 Summary of Reviewer Comments

3.7.1.1 Integrated Strategic Roadmaps

Since the publication of the 2012 Path Forward Report the program has considerably strengthened the impact and linkages to the SSP. SNL has shifted the majority of the use of Z Facility time from ICF to stockpile-relevant plutonium materials research, opacity studies, and radiation effects science. At the end of the NIC, facility time on the NIF shifted from 85 percent ICF to approximately 50 percent HED experiments, each of which is reviewed and approved by the HED Council – the multi-site body of technical experts and cognizant program managers that provides recommendations as to the use of experimental resources dedicated to HED experiments, in accordance with SSP priorities. The recent reorganization at LLNL has aligned the management and research for ICF with the Weapons & Complex Integration (WCI) Directorate, and this has effectively enforced the appropriate balance of priorities at the NIF. The resulting organizational structure needs time to stabilize to tackle the challenges with the tools and people that are being developed.

The HED Council has been a welcome influence on the direction of research on the ICF/HED facilities. The HED Council has expanded participation in experimental planning and prioritization, and has made a concerted effort to direct experiments to the most appropriate facilities without the past institutional biases. The HED portfolio is producing outstanding results for the SSP and it has a sound strategic plan.

The mission drivers for the ICF Program are quite clear. Pursuing thermonuclear burn in the laboratory, achieving ignition, and multi-megajoule fusion yield have important implications to national security. Achieving ignition in the laboratory is arguably one of the preeminent scientific challenges of our time and would represent an extraordinary demonstration of U.S. excellence in science and technology relevant to nuclear weapons. It would further NNSA's scientific capabilities, assure allies, and deter potential adversaries. Some of the excellent young scientists and engineers drawn to ignition research at NNSA's state-of-the-art HED facilities will move to nuclear weapons design work. The HED Council plays a key role in planning and decision-making for the non-ICF portfolio. ICF Program planning could be improved and the roles and responsibilities of the ICF Council – the multi-site body of technical experts and cognizant program managers that perform a cursory review of planned experimental activities for each ICF facility – could be revised/retooled to be more useful. Establishing improved roadmaps and decision processes would help to focus the workforce on the research priorities.

Program planning for the near term is critical, but it is also important to define the program 10 to 20 years from now. Ignition is one important step along the path and not the final end point.

Over the long term, the program is aimed toward a high-yield capability whether or not ignition is reached on the NIF, and major facility upgrades must be considered over a long time-scale. A fusion source on the order of 500 megajoules or greater will be important for the health of the program in an extended era without nuclear tests. Such a source is unlikely to be achieved in the next decade, but maintaining high yield as an ultimate goal should guide program thinking and direction in the interim.

The sophistication of approach, roadmaps, and decision processes varies widely among the three approaches to ICF ignition. The LID approach presented overarching goals to improve understanding and models of ignition target behavior to either demonstrate ignition or show what is needed in capability and understanding to ignite a target. However, there were few details on how a finding would result in a change in program direction. There was also a threat of dilution of intellectual energy as the number of sub-approaches increased. The LDD approach showed a roadmap and decision process based on goals for the hot-spot pressure and mitigation of cross beam energy transfer, but little to no peer review of that approach has taken place. The MDD approach presented a range of goals over the next five years aligned to the PRDs, but like the LID Program, a detailed roadmap and decision process still needs to be developed. Unlike the LID Program, however, the MDD Program suffers from a narrow research focus mostly due to resource constraints.

The roadmap for each approach (LID, LDD, and MDD) must be woven into an overarching roadmap driven by the vision described in the directors' letter at five-, 10- and 15-year waypoints. This roadmap should meet mission requirements, be inspirational, and be appropriately paced and balanced given the many technical challenges in ICF.

3.7.1.2 The Naval Research Laboratory

Over 50-years, the Naval Research Laboratory's (NRL) scientists, engineers, codes, diagnostics, and facilities have acted as a science and technology bridge between the DOD and DOE. It has provided expertise and "corporate memory" for ICF and weapons physics, pulsed power science, high power electron and ion beams, dense z-pinches, nuclear weapons effects testing, non-LTE physics, and related theories, codes, and diagnostics. NRL contributes in many areas to ICF and laser physics: in LDD and hybrid x-ray/direct drive approaches using coated capsules, investigating CBET and LPI at Nike, developing diagnostics including the Virgil M-band spectrometer for the DANTE at the NIF, and experiments and calculations in non-LTE atomic physics for nuclear weapons effects (K-shell) on Z. Scientific leadership by the NRL might be strengthened by focusing on a smaller number of high impact efforts, and through better integration internally between its research "branches."

3.7.1.3 Additional Opportunities for Technical Leadership

Independent of the small percent of funding that the ICF Program provides to academic programs for activities described in Section 3.6, NNSA should consider funding independent researchers focused on high-risk, high-impact *applied science with concrete deliverables* to the program. These independent researchers could lead working groups and teams of external and laboratory researchers focusing on key physics issues such as:

- Novel diagnostics to probe non-LTE plasmas,
- Advancing the kinetic theory of plasmas and computational capabilities for laser plasma interactions,
- Developing diagnostics to spatially, spectrally, and temporally resolve the physics of hot spot assembly and stagnation, and
- Physics validation of existing models in ICF codes in multiple areas, such as LPI and MHD.

Additionally, the ICF Program would benefit from increased competition in integrated experiments to encourage laboratory researchers within the ICF Program and researchers external to it, to propose novel ideas, have those ideas reviewed, and be awarded experimental time and funding to support their research.

3.7.2 NNSA Program Office Perspective and Items for Future Prioritization & Action

- The 2015 ICF/HED Review has informed and matured the National ICF Program Framework. The four-element Framework is as follows:
    - *Ten-year High Energy-Density (HED) Sciences Strategic Plan.* This classified requirements document outlines deliverables for the ICF/HED Program in three-, five-, and ten-year time frames, and is derived from the 25-year SSMP.
    - *National Transformative Diagnostics Plan.* This resource-loaded plan describes eight transformative diagnostics that benefit all ICF approaches. Local and broad diagnostics are managed within the next two elements of the Framework.
    - *Integrated Experimental Campaigns.* This element, frequently depicted as a Gantt-chart, contains the approach-specific experimental campaigns for highly integrated experiments with the primary goal of achieving thermonuclear burning plasma conditions and that push the limits of NNSA's capabilities and facilities. Typically progress is assessed by demonstrating improvements in integrated performance parameters, such as yield and shape. The five-year goal of this element is to determine the efficacy of NIF for ignition and a credible physics scaling to multi-megajoule yields for all ICF approaches.
    - *The ICF Priority Research Directions (PRDs).* This approach-specific six-part work breakdown structure enables cross-approach coordination and opportunities for external collaborations at the working level. The PRDs enable the development

of physics-based milestones that integrate compendiums of experimental research executed at each ICF/HED facility with the overall efforts to improve models, codes, and simulations. The PRDs are:

    - Driver-target Coupling
    - Target Preconditioning
    - Implosion Hydrodynamics
    - Stagnation and Burn Physics
    - Intrinsic and Transport Properties
    - Measurement, Modeling, Validation, and Approximation

  The Framework will be used to develop a roadmap in fiscal year 2016 with priorities, metrics, milestones and deliverables, as well as specific “decision trees” to support out-year investments. NNSA will periodically sponsor workshops on the progress toward ignition, covering all three ICF approaches. The next major workshop, related to the PRDs, will be held in June 2016 in Santa Fe, NM.

- The ICF Council Charter will be revisited to assess Council roles, responsibilities, accountabilities, authorities, and overall value. One additional role for the ICF Council could be to host a review process to award facility time for new ideas outside the mainline ICF Program efforts, as is done for general use time at SC facilities.
- NRL’s portfolio will be reviewed to identify the highest impact activities and to recommend new opportunities, such as strategic collaborations in atomic physics and spectroscopy or building collaborations with LLNL and LLE in the area of radiation source development, with supporting experiments at NIF and Omega.
- In addition to the SSP-driven requirement to maintain exceptional scientific capabilities in HED science, NNSA will stand up efforts in fiscal year 2016 to assess long-term requirements in five major areas:
  - Maintaining proficiency in secondary design and the ability to assess performance in the long term in the context of no new nuclear testing.
  - Evaluating the long-term experimental needs for threat-condition hostile environments and nuclear survivability of non-nuclear components.
  - Coalescing the vision for future capabilities for NNSA dynamic material properties research to enable safe, high-hazard materials science experiments.
  - Defining a clear experimental program in burn physics to support boost science.
  - Avoiding technological surprise.

4 Next Steps

The 2015 ICF/HED Review identified nearly 40 areas for future prioritization and action. In fiscal year 2016, NNSA plans to develop an “after actions” plan and a schedule for implementation. Several areas have been identified where priorities should be re-evaluated, including:

- Transformative diagnostics, including spatially, spectrally, and temporally-resolved imaging and spectroscopic diagnostics to observe “stagnation” at low, medium, and high convergence.
- Obtaining cross-platform data for fundamental physics validation of models/codes while improving access to codes/models, where appropriate.
- Reviving development efforts for codes to model Laser-Plasma Instabilities (LPI).
- Increasing the number of designers and experimentalists working on magnetically-driven implosions and laser-driven direct drive programs.
- Enhancing peer review by academia and other institutions.
- Developing applications for fusion yields produced on existing platforms.
- Assessing the long-term requirements case for “high yield”.
- Identifying methods such that all HED capabilities (domestic and international) may be considered as NNSA defines the means by which it will execute SSP-related experiments.
- Developing robust cadre of top researchers in key areas of atomic physics, spectroscopy, laser plasma instabilities, and low-energy nuclear physics.
- Shaping academic program investments to ensure resources are optimally deployed.

Reviewers were not asked to consider resource constraints when providing comments or recommendations. To affect all recommendations contained herein would exceed current budget profiles. The principal next step is for NNSA to identify specific resource requirements to prioritize these recommendations within existing budgets. This prioritization process will begin in FY 2016.

Acronyms, Abbreviations, and Terms List

A-C

Al	Aluminum
ALS	Advanced Light Source, Lawrence Berkeley National Laboratory
APS	Advanced Photon Source, Argonne National Laboratory
ASC	Advanced Simulation and Computing Program
Be	Beryllium
B·r	The product of the magnetic field, B, and the radius, r
CBET	Cross Beam Energy Transfer

D-E

DANTE	Soft X-ray spectrometer used to measure radiation drive temperature
DARHT	Dual-Axis Hydrodynamic Radiographic Test Facility, Los Alamos National Laboratory
D.C.	District of Columbia
DD, D_2	Deuterium-Deuterium
DESY	Deutsches Elektronen-Synchrotron, a national research center in Germany
DFT-MD	Density Functional Theory-Molecular Dynamics
D^3He	Deuterium - Helium-3
DOD	Department of Defense
DOE	Department of Energy
DT	Deuterium-Tritium
ELI	Extreme Light Infrastructure, Laser User Facility with facilities in the Czech Republic, Hungary, and Romania
EOS	Equation of State
eV	electron Volts

F-G

FAB	Full Aperture Backscatter
Fe	Iron
FLASH	A free-electron laser at DESY that generates soft X-rays
FNADS	Flange Nuclear Activation Diagnostic System
FY	Fiscal Year
GB	gigabar
GB-ns	Gigabar - nanosecond
GPUs	Graphic Processing Unit(s)

H-I

^3He, He-3	Non-radioactive isotope of helium with two protons and one neutron
HED	High Energy Density (Physics)
HYDRA	LLNL multi-physics simulation code
ICF	Inertial Confinement Fusion

ICF Laboratories	The NNSA Laboratories, the Laboratory for Laser Energetics, and the Naval Research Laboratory
ICF/HED	Inertial Confinement Fusion/High Energy Density
Intel® Xeon Phi™	Intel® Xeon Phi™ Coprocessor, from Intel Corporation

J-K

Jupiter	Jupiter Laser Facility at LLNL
KBO	Kirkpatrick Baez Optic
keV	kilo electron Volt
KH	Kelvin-Helmholtz Instability
kJ	kilo Joule
K-shell	The first shell of electrons surrounding the nucleus of an atom

L

LANL	Los Alamos National Laboratory
LASNEX	Computer code used in ICF that simulates interactions and effects between x-rays and a plasma.
LCLS	Linac Coherent Light Source, at SLAC National Accelerator Laboratory
LDD	Laser-Driven Direct Drive
LEH	Laser Entrance Hole
LEP(s)	Life Extension Program(s)
LES	Large Eddy Simulation, model for turbulence
LID	Laser-Driven Indirect Drive
LLE	Laboratory for Laser Energetics
LLNL	Lawrence Livermore National Laboratory
LPI	Laser-Plasma Interaction(s)
LTE	Local Thermodynamic Equilibrium

M

M	Millions
MagLIF	Magnetized Liner Inertial Fusion
M-band	refers to the spectra from M-band emissions, x-rays in the 1.5 to 6.0 keV range
MDD	Magnetically-Driven Direct Drive
Mg	Magnesium
MG-cm	Mega gauss-centimeter
MHD	Magnetohydrodynamics
MIT	Massachusetts Institute of Technology

N

NA-10	Defense Programs, within NNSA
NA-11	Office of Research, Development, Test, and Evaluation, within NA-10
NA-12	Office of Stockpile Management, within NA-10
NA-19	Office of Major Modernization Programs, within NA-10

NBI	Near Backscatter Imager
NIC	National Ignition Campaign
NIF	National Ignition Facility, located at LLNL
Nike	Krypton fluoride (KrF) Laser, located at NRL
NISP	National Implosion Stagnation Physics Working Group
NLUF	National Laser Users' Facility, at Omega Laser Facility, LLE
NNSA	National Nuclear Security Administration
NNSS	Nevada National Security Site
non-LTE	non-Local Thermodynamic Equilibrium
Nova	High-power laser located at LLNL, built in 1984 and dismantled in 1999
NRL	Naval Research Laboratory

O-P

OLUG	Omega Laser Facility at University of Rochester's LLE
Omega	Omega Laser Facility at the Laboratory for Laser Energetics, University of Rochester
PF3D	A laser-plasma interaction (LPI) code used to simulate experiments
PIC	Particle in Cell
PRD(s)	Priority Research Direction(s)
P-tau, P-τ	The product of the plasma pressure, P, in atmospheres, and the energy confinement time, τ, in seconds. This product is called the Lawson Criterion.
Purgatorio	LLNL microphysics code

Q-R

RANS	Reynolds-averaged Navier-Stokes Equations
rho-R, ρ-R	Product of the mass density and radius in the hot spot of an ICF implosion
RM	Richtmyer-Meshkov Instability
RT	Rayleigh-Taylor Instability
RTD	Resistance To Deformation

S

SC	Office of Science, U.S. Department of Energy
SDD	Symmetric Direct Drive
Si	Silicon
SLAC	SLAC National Accelerator Laboratory at Menlo Park, CA (originally named *Stanford Linear Accelerator Center*)
SNL	Sandia National Laboratories
SRS	Stimulated Raman Scattering
SSAA	Stockpile Stewardship Academic Alliances Program
SSAP	Stewardship Science Academic Programs
SSD	Smoothing by Spectral Dispersion
SSMP	Stockpile Stewardship Management Plan
SSP	Stockpile Stewardship Program

STS	Stockpile-to-Target-Sequence
SXI	Static X-ray Imager

T-U

TPD	Two Plasmon Decay Instability
TR	Technical Report
Trident	Trident Laser Facility at LANL
TT	Tritium-Tritium
U.S.	United States

V-W

VFP	Vlasov-Fokker-Planck Model
VISAR	Velocity Interferometer System for Any Reflector
WCI	Weapons and Complex Integration (WCI) Directorate at LLNL

X-Y

XFEL, XFELs	X-ray Free Electron Lasers
XTD	X Theoretical Design (XTD) Division at LANL

Z

Z	Z Pulsed Power Facility at SNL
Z	atomic number of a chemical element

1-D	One dimensional
2-D	Two dimensional
3-D	Three dimensional
2DConA	Two Dimensional Convergent Ablator, one of the Horizontal and Vertical Axis Radiography Platforms on the NIF
$\Delta\rho R$	Variation in ρR in an ICF implosion