U.S. DEPARTMENT OF
ENERGY

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

Report to Congress
December 2012

United States Department of Energy
Washington, DC 20585

Message from the Administrator of the National Nuclear Security Administration

I am forwarding the enclosed report on the path forward for ignition and the impact of not achieving ignition on the Stockpile Stewardship Program as requested in the Senate Energy and Water Development Appropriations Report for FY 2012 (112-164) and in Section 3119 of the House Armed Services Committee Report for the FY 2013 National Defense Authorization Act (112-479).

At present, it is too early to assess whether or not ignition can be achieved at the National Ignition Facility (NIF). However, a key goal of NIF to discover discrepancies between codes and experiments has been demonstrated clearly. The disagreement between NIF experimental data and codes and models reflects an inadequate understanding of key physics issues required to make this determination. The emphasis going forward will be to illuminate the physics and to improve models and codes used in the Inertial Confinement Fusion (ICF) Program until agreement with experimental data is achieved. Once the codes and models are improved to the point at which agreement is reached, National Nuclear Security Administration (NNSA) will be able to determine whether and by what approach ignition can be achieved at the NIF.

This report is being provided to the following Members of Congress:

- **The Honorable Daniel K. Inouye**
  Chairman, Senate Committee on Appropriations

- **The Honorable Thad Cochran**
  Ranking Member, Senate Committee on Appropriations

- **The Honorable Carl Levin**
  Chairman, Senate Committee on Armed Services

- **The Honorable John McCain**
  Ranking Member, Senate Committee on Armed Services

- **The Honorable Dianne Feinstein**
  Chairman, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations

- **The Honorable Lamar Alexander**
  Ranking Member, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations

- **The Honorable Ben Nelson**
  Chairman, Subcommittee on Strategic Forces
  Senate Committee on Armed Services

- **The Honorable Jeff Session**
  Ranking Member, Subcommittee on Strategic Forces
  Senate Committee on Armed Services

- **The Honorable Harold Rogers**
  Chairman, House Committee on Appropriations

- **The Honorable Norman D. Dicks**
  Ranking Member, House Committee on Appropriations

- **The Honorable Howard P. McKeon**
  Chairman, House Committee on Armed Services

- **The Honorable Adam Smith**
  Ranking Member, House Committee on Armed Services

- **The Honorable Rodney P. Frelinghuysen**
  Chairman, Subcommittee on Energy and Water Development, and Related Agencies
  House Committee on Appropriations

- **The Honorable Peter J. Visclosky**
  Ranking Member, Subcommittee on Energy and Water Development, and Related Agencies
  House Committee on Appropriations

- **The Honorable Michael Turner**
  Chairman, Subcommittee on Strategic Forces
  House Committee on Armed Services

- **The Honorable Loretta Sanchez**
  Ranking Member, Subcommittee on Strategic Forces
  House Committee on Armed Services

We appreciate your continued support of this important national effort. If you have any questions, please contact me or Mr. Clarence Bishop, Associate Administrator for External Affairs, at (202) 586-8343.

Sincerely,

Thomas P. D'Agostino
Administrator

NNSA Overview and Executive Summary

The NNSA is submitting this report as requested in the Senate Energy and Water Development (SEWD) Appropriations Report for fiscal year (FY) 2012 (112-164) and in Section 3119 of the House Armed Services Committee (HASC) Report for the FY 2013 National Defense Authorization Act (NDAA) (112-479), because NNSA's National Ignition Campaign (NIC), though making significant progress and bringing NNSA closer than ever before to ignition in the laboratory, did not meet its principal program goals to achieve ignition or to achieve significant alpha heating prior to its conclusion at the close of FY 2012.

This report reflects the views of the NNSA. At the same time, engaging the views of the scientific community that has been pursuing inertial confinement fusion (ICF) ignition was a deliberate part of developing this report. The report that follows this summary was prepared principally by program representatives from the ICF laboratories and other principal contractors through participation in Working Groups (see Appendix B). The views of the Working Group participants were influenced substantially by the *Science of Fusion Ignition on NIF* report (May 2012) resulting from the workshop on this subject chaired by Dr. William Goldstein and Prof. Robert Rosner. That report was provided to the ICF Working Groups. This workshop had broad international participation from the leading scientists in this field of research.

Construction of the National Ignition Facility (NIF) was completed in March 2009. After a period of commissioning, initial experimentation, and diagnostics development, the first layered cryogenic target implosions were executed in September 2010. Over the subsequent two years of experimentation, the NIF laser performed reliably and with great precision and executed thirty-seven cryogenic implosion experiments. Power and energy have exceeded initial design specifications. Target quality is superb, and diagnostics have been developed that are returning experimental data of unprecedented quality. The quality of implosions improved substantially since the initial experiments, but the neutron yield remains a factor of three to ten less than required to initiate alpha heating and a propagating burn. The fuel is compressing to one-half the pressure that predictions would require for ignition.

NNSA's path forward is based on several key points:

- The NNSA ICF Program now has commissioned and is getting beneficial use of the NIF (at Lawrence Livermore National Laboratory (LLNL)), the refurbished Z-machine (Z) (at Sandia National Laboratories (SNL)), and Omega (including both the OMEGA and the OMEGA Extended Performance (OMEGA EP) lasers at the Laboratory for Laser Energetics (LLE) at the University of Rochester) to further the needs of NNSA's Stockpile Stewardship Program (SSP). In particular, ongoing experiments on these facilities are testing codes and models that underpin stockpile confidence, are providing fundamental scientific knowledge relevant to nuclear weapons, and are attracting and retaining the scientific talent required for NNSA's broad national security missions. Maintaining excellence in high energy density (HED) science, including the pursuit of ignition, is a critical element of stockpile stewardship.

- To date there is no compelling scientific information suggesting that the indirect drive approach cannot achieve ignition. Because the indirect drive approach has the closest relevance to nuclear weapons physics, this will remain the mainline approach for ignition either until it achieves ignition or until there is sufficient scientific understanding supporting a conclusion that priorities should be reset to favor an alternative approach. Alternate ignition concepts such as Polar Direct Drive (PDD) and Magnetically-Driven Implosions (MDIs) (pulsed-power-driven fusion) have shown promise at Omega and on Z. PDD is feasible on NIF with some modifications to the optical beamlines and is being tested at Omega. This alternative will be pursued and evaluated. However, as alternative approaches are advanced, they could face the same challenges that the indirect drive approach is facing; and, thus, a better understanding of the underlying physics issues is required before any decision to invest significant resources in the pursuit of alternatives can be made.

- This strategy is balanced to provide multiple paths to success. PDD and MDI show promise as ignition alternatives based on current understanding. PDD ignition can be implemented and tested on NIF subsequent to concept validation at Omega. Both PDD and MDI offer an alternative path to ignition if lower convergence ratios or higher energies are required. NNSA will continue to support research and technology development for both PDD and MDI fusion in parallel with developing an understanding of indirect drive ignition.

NNSA has established governance plans for the operation of each of its HED facilities to optimize the operation of its facilities across their missions. While NNSA remains committed to the pursuit of ignition, with the end of the NIC, NNSA has rebalanced its direction for the use of its HED facilities to emphasize the importance of research and development for stockpile stewardship. Shot allocations for CY 2013 are expected to be the following:

For NIF ~50 percent HED/SSP and 40 percent for ignition, and ~10 percent for fundamental science and other national security missions; for Z[1] ~65 percent HED/SSP, ~25 percent ignition, and ~10 percent fundamental science and other national security missions; and, for Omega, 30 percent HED/SSP; ~35 percent ignition; and ~35 percent fundamental science, other national security, and contingency.

In September 2012, the NNSA and LLNL delivered a path forward that transitioned NIF to a national user facility, signing out the National Ignition Facility Governance Plan. The plan put into effect the transition from NIC to a NIF national user facility model, drawing broadly from the community for both the best scientific ideas and for peer review.

The report's response to the specific topics the Congressional Committees requested the NNSA to address is summarized as follows:

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[1] LLNL planning numbers presented to NNSA Oct 16-18, 2012.

Scientific and technical barriers to achieving ignition

NIF has not yet achieved ignition. Experimental data demonstrate that the physics underlying ignition implosions are not predicted accurately by the simulation codes that were used to design ignition targets and to predict their performance. Substantial departures include opacities and equations-of-state (EOS) disagreeing with models; low mode asymmetry being larger than expected; capsule drive being lower than expected as a result of inadequate models of hohlraum and laser plasma interactions; and a hydrodynamic mix cliff occurring at lower in-flight aspect ratios than predicted by present models.

The plan and schedule for reevaluating the ignition program and for incorporating experimental data into computer models.

The path forward described in this report includes a three-year plan to:

1) Continue a modified effort to pursue the present indirect drive approach to ignition.
    i) Continuing to explore the physics revealed in experiments designed to evaluate integrated performance of the system.
    ii) Adding a significant experimental effort to explore single physics effects and improved models.
    iii) Exploring alternative indirect drive approaches.
2) Explore the underlying physics and develop a path forward for PDD or symmetric direct drive approaches, principally using the capabilities of Omega while also performing higher energy PDD experiments on NIF.
3) Explore MDI fusion on Z.

Whereas the NIC was focused necessarily on commissioning NIF and exploring a specific approach to achieving ignition, with the end of the NIC, NNSA is moving to a nationally-based program with the ability to use its broad range of facilities for a broad-based experimental program addressing a more diverse range of scientific issues and opportunities.

The best judgment of the Administrator with respect to whether ignition can be achieved at the NIF.

At present, it is too early to assess whether or not ignition can be achieved at the NIF. However, a key goal of NIF to discover discrepancies between codes and experiments has been demonstrated clearly. The disagreement between NIF experimental data and codes and models reflects an inadequate understanding of key physics issues required to make this determination. The emphasis going forward will be to illuminate the physics and to improve models and codes used in the ICF Program until agreement with experimental data is achieved. Once the codes and models are improved to the point at which agreement is reached, NNSA will be able to determine whether and by what approach ignition can be achieved at the NIF.

The impact on the Stockpile Stewardship Program including shifting resources to advance life extension programs.

Execution of the life extension programs is impacted by the substantial gap between design requirements for those programs endorsed by the Nuclear Weapons Council and resources available to the NNSA to implement those requirements. Any source of funds could help to close that gap, but decreasing funding for the ignition program, or more broadly, NIF experiments in support of the NNSA weapons science program, would run counter to the longstanding judgment of the nuclear weapons policy community on the importance of maintaining scientific expertise in support of U.S. national security goals.

Of the ICF Program funds, about 20 percent directly funds ignition efforts. The actual costs of NIF and, more broadly, the ICF Program, are dominated by facility operations costs needed for all experiments. SSP experiments provide key mission support for science, code validation and verification, maintaining HED capabilities, and attracting, recruiting, and training scientific and technical personnel. These ICF Program goals align with the Nuclear Posture Review (NPR) of April 2010 that called for strengthening the science, technology, and engineering (ST&E) base needed for conducting weapons system assessments including developing and sustaining high quality scientific staff and supporting computational and experimental capabilities. This priority is reflected in NNSA's Stockpile Stewardship and Management Plan for FY 2012. This Plan takes a balanced approach to the use of experimental and computational facilities required by the Predictive Capability Framework (PCF) to assess and to certify the stockpile in the absence of underground testing. The ICF Program is a key element supporting the development of the PCF capabilities especially in the areas of ignition and HED science.

The Department of Energy's (DOE's) mission objective for NIF was based upon the need for an experimental platform to test the advanced codes and models developed under the Advanced Simulation and Computing (ASC) Program to support weapons assessments and certification in the absence of underground testing. Present ICF codes had predicted that NIF would attain ignition at the present scale. Since ignition was not achieved, this indicates significant gaps between experimental results, present models, and scientific understanding in the ICF codes. Confidence in the present stockpile, on the other hand, is dependent upon the pedigree from a successful underground test program and a continued Stockpile Stewardship Program to understand the impact of any changes from the as tested configuration. The gaps in understanding demonstrated by the ignition campaign are not at a level that would impact confidence in the stockpile. Rather the question is the extent to which NNSA will be able to rely upon codes and models as the basis for confidence in modifications and alterations, as NNSA extrapolates from as-tested configurations. Therefore, a program to resolve these gaps in the codes and models is vital.

Consensus and future reporting

In developing this report, NNSA has followed the consensus process that engaged managers and key scientific staff from the ICF Program laboratories and that was briefed to Congressional Committees. The remainder of this report is the consensus document developed by the ICF Program laboratories.

With the end of the NIC, NNSA is submitting separately the concluding quarterly NIC report requested in the FY 2005 House Energy and Water Development (HEWD) Appropriations Report (108-554). NNSA also commits to continue to report to the Committees semi-annually on progress towards ignition and HED science in support of stockpile stewardship.

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I. Legislative Language

SEWD Appropriations Report for FY 2012 (112-164):

"If the National Ignition Facility does not achieve ignition by the end of fiscal year 2012 using a cryogenically layered deuterium and tritium target that produces a neutron yield with a gain greater than 1, the Committee directs NNSA to submit a report by November 30, 2012 that (1) explains the scientific and technical barriers to achieving ignition, (2) the steps NNSA will take to achieve ignition with a revised schedule, and (3) the impact on the stockpile stewardship program."

HASC Report for the FY 2013 NDAA (112-479):

"This section would limit the obligation and expenditure of funds for fusion ignition research and experiments to not more than 50 percent until the Administrator for Nuclear Security certifies to the congressional defense committees that fusion ignition has been achieved at the National Ignition Facility (NIF) or the Administrator submits a report on fusion ignition. The report should include a thorough description of the remaining technical challenges and gaps in understanding with respect to ignition; a plan and schedule for reevaluating the ignition program and incorporating experimental data into computer models; the best judgment of the Administrator with respect to whether ignition can be achieved at the NIF; and a description of how, if funding being spent on ignition research were applied to life extension programs, such programs could be accelerated or otherwise improved, and how this funding change would impact the stockpile stewardship program."

II. High Level Overview

Whereas NNSA is accountable for this report and its contents, this report reflects broad input from the scientific community involved in ICF, HED Physics (HEDP), and the SSP. It was developed through a collaborative inter-laboratory process supervised by the ICF Executives listed in Appendix B.

The Inertial Confinement Fusion and High Yield Campaign (called the ICF Program below) along with NNSA's Science and ASC Campaigns provide the essential capabilities and knowledge required for ongoing assessment and certification of the nuclear weapons stockpile. The ICF Program, in particular, provides scientific, facility, and other capabilities needed to examine HED science issues underlying stockpile assessment and to test and validate simulation codes in specific areas of nuclear performance. The ICF Program is the world's leading program in HED science and also serves as an important attractor of new talent to NNSA's programs.

The pursuit of ignition and high fusion yields in the laboratory is a major objective of the SSP and the ICF Program and is a 'grand challenge' scientific problem that tests our codes, our people, our facilities, and our integrated capabilities. Demonstrating ignition in the laboratory provides an understanding of some processes that cannot be addressed in any other way. The ICF Program also executes non-ignition and other experiments in support of the SSP in collaboration with the Science Campaigns and with other NNSA subprograms and supports other national security work including the Department of Defense (DoD) and other sponsors.

The ICF Program has pursued ignition via the NIC. The NIC was an integrated, national, multi-institutional effort through the end of FY 2012 with partners including LLNL, Los Alamos National Laboratory (LANL), SNL, LLE, and General Atomics (GA). Other key contributors included Massachusetts Institute of Technology (MIT), Lawrence Berkeley National Laboratory, Atomic Weapons Establishment (AWE) in England, and Commissariat à l'Energie Atomique (CEA) in France.

The NIC had two major objectives: 1) to achieve ignition and to develop this as a platform for HED applications; and 2) to transition NIF to routine operations as a user facility.

The efforts as defined in the NIC Execution Plan Rev 4.0 as necessary to meet the NIC objectives included developing or demonstrating:

- Ignition
- Significant alpha heating as a step towards ignition
- An integrated ignition point design
- Targets consistent with the point design
- Cryogenic target positioning system
- Diagnostics for hohlraum, capsule, and fusion performance
- Laser/user optics operating to 1.8 MJ and 500 TW, demonstrating NIF and NIC Primary Criteria and Functional Requirements
- Personnel and environmental protection systems
- Experiments on OMEGA in support of the NIC experimental program
- Support of ignition, non-ignition SSP, fundamental science, and other national security missions
- Transitioning NIF to routine facility operations as a national user facility

With the exception of ignition and alpha heating, the NIC completed all of the objectives described which included developing all of the facility and technological capability prescribed; conducting HED science experiments in support of weapons science, other national security, fundamental science and ICF; and reaching conditions on the NIF that have never been reached in any other laboratory. Although the grand challenge of fusion ignition and burn via ICF on NIF was not achieved, a large body of knowledge and major new capabilities were developed.

Thirty-seven implosion experiments with cryogenic hydrogen fusion fuel (tritium-deuterium-hydrogen (THD) or deuterium-tritium (DT)) ice layers were performed. Initial technical problems with the target and fuel layers were resolved quickly, and the majority of the implosion experiments were performed with targets that met specifications set by simulations. The neutron yield and the areal density of the compressed fuel are the most relevant measurements of the quality of the implosions. The highest observed yields (in terms of fusion energy) and areal densities were 2.5 kJ and 1.3 g/cm^2, respectively. This yield is approximately a factor of three to ten less than required for initiating a propagating burn, which simulations suggest would rapidly heat the fusion fuel and lead to ignition with yields greater than 1,000 kJ. Because, for the first time, the hot spot areal density is large enough to trap alpha particles, we estimate that about 10-15 percent of the current yield comes as a result of alpha heating. The compression pressure is approximately half that predicted by simulation. The reason for the deficit is not clear but is due most likely to low-mode fuel asymmetries and to the hot spot experiencing more mix than expected. Identifying the reason for the reduced peak pressure and developing mitigation strategies is a key element of the path forward experimental plan.

A number of workshops and reviews to examine NIC results have been held. Although a set of likely candidate causes of the inability to achieve and calculate ignition capsule performance has been identified, the specific causes have not been confirmed. This report summarizes these "scientific and technical barriers" as required by SEWD appropriations language. Input from these workshops and reviews has been incorporated in the path forward plan that includes activities to understand the challenges to ignition and to identify alternate paths for success. This plan has been constructed to improve understanding and predictability of simulations necessary to develop and to test mitigation strategies to overcome the barriers to ignition. It is important for the SSP to understand the physics underlying the difficulty of achieving ignition as well as to assess the important fundamental issues relevant to both ignition and weapons physics. The three-year plan culminates in a comprehensive review at the end of FY 2015. At that time, NNSA will have an assessment of the likelihood and schedule for achieving ignition.

The high level FY 2013–FY 2015 ICF Program deliverables are provided in Table 1. The FY 2015 review will include assessments of the main-line and alternative approaches to support decision-making regarding the future of the ICF Program. If the indirect drive approach has not achieved ignition, NNSA will assess whether any further progress is likely or whether priorities should be shifted to the pursuit of an alternative approach.

This plan will continue to pursue the baseline indirect drive ignition approach, but will shift the emphasis to developing an understanding of why ignition has not been achieved. This is important both to guide the experimental program and because of implications for the physics models and codes used in stockpile stewardship.

Alternatives to the mainline NIF laser-based, indirect drive effort include PDD, an alternative approach using NIF's laser beams to implode a capsule directly and MDIs using pulsed power drive. A potential advantage of direct drive, in general, is that more energy is coupled to the core, and concomitantly design flexibility is increased. Direct drive illumination could be conducted symmetrically or by illuminating the target asymmetrically. The asymmetric drive at NIF is PDD owing to the asymmetric grouping of the laser beams near the poles of the NIF chamber. The NIC was successful in advancing this alternate strategy on OMEGA. Experiments on NIF are required to validate predictive capability of this approach at the NIF scale. MDIs with pulsed power may reduce the risk for inertial confinement fusion to achieve relevant fusion conditions by increasing the energy delivered to the target and the size of the target and by magnetizing and pre-heating the fuel to possibly reduce target performance requirements.

These alternatives will require research and resources to determine whether or not they are viable alternative paths to ignition. The three-year plan for each approach is being conducted at current facilities with existing capabilities. The FY 2015 review will include an assessment of each of these alternative approaches. Information from this review will be used by NNSA to make decisions regarding the future of the fusion element of the ICF Program. The high level FY 2013–FY 2015 ICF Program deliverables are provided in Table 1.

The technical scope of this plan will be conducted on a schedule consistent with appropriated budgets. As such, milestone dates are provisional and may change in accordance with available funding.

Understanding why ignition has not been achieved is important, both to guide the experimental program, and because it could have implications to the physics models and codes used in the SSP. This may be the most important contribution of the ICF Program to the SSP. It is important to note that if ignition is not achieved eventually, then SSP's ability to investigate issues with or requiring a burning plasma in the laboratory will be limited severely. Weapon scientists will be unable to experimentally explore the potential impacts of some warhead life extension design or component options related to thermonuclear ignition and burn. Therefore, the resulting weapon analyses may have associated uncertainties that would be larger than they would be otherwise.

The status and development required for three enabling capabilities: codes and data bases, target diagnostics, and target fabrication are described in summary fashion in this report.

The capabilities and facilities provided by the ICF Program enable non-ignition HED research that supports the requirements of the SSP. These experiments will have increased priority on NIF in FY 2013 and beyond compared to the FY 2008–FY 2012 period during which the ICF Program's focus was dominated by the pursuit of demonstrating ignition in the laboratory. This increased emphasis going forward on stockpile stewardship science activities will be in support of the Primary Assessment Technology (PAT), Dynamic Materials Properties (DMP), Secondary Assessment Technology (SAT), and Advanced Certification Campaign (ACC) subprograms of the Science Campaign; the Nuclear Survivability (NS) and Enhanced Surveillance (ES) subprograms of the Engineering Campaigns; and the ASC Campaign.

The U.S. ICF Program has made major progress towards ignition and is exploring for the first time the "near-ignition" physics regime. Whereas ignition has not been achieved, the ICF Program has benefited the SSP significantly via improved physics understanding of weapons science and testing as well as validation of simulation tools used in warhead performance assessment. It also has continued to attract first-rate talent to the national laboratories and the SSP. NNSA believes it is imperative for the SSP to continue an ignition effort focused on improving the understanding of the science underlying ignition.

Table 1: Highest Level Milestones

Fiscal Year	Ignition Platform	Suggested milestone	Completion Criteria
FY 2013	All	For all fusion approaches, define the plan and specific goals for scientific and technological activities to be performed in preparation for the FY 2015 review.	For all approaches, identify and document the detailed experimental, computational, technology development, and other activities required to be performed in preparation for the FY 2015 review. For PD, this will include an assessment in FY 2013 from both the target physics and technology perspective. Based on this assessment, NNSA, LLE and LLNL will define an agreed upon set of PD tasks consistent with planned budgets and program priorities.
FY 2015	All	Review results of all three ignition approaches (IDI, PDD, MDI)	Review progress of all fusion approaches with respect to the program plan defined at end of FY 2013 and out-year plans for ICF and high yield platforms
FY 2013	IDI	Conduct experiments designed to examine scientific and implosion performance issues identified during the NIC campaign	This milestone will include a campaign of experiments to look at symmetry and mix issues and will include high-adiabat, cryogenic implosions to compare code predictions and performance.
FY 2013	IDI	Review alternate x-ray drive implosion concepts including technology feasibility.	Review alternate x-ray drive implosion concepts from both a scientific and technology perspective.
FY 2014	IDI	Conduct physics and integrated DT implosion experiments to examine experimental and computational understanding of capsule drive.	Assess experiments conducted to determine the level of experimental and computational understanding of capsule drive and hydrodynamic performance.
FY 2015	IDI	Conduct an experimental campaign and assess agreement between models and simulation of implosion compression and pressure	Develop and execute cryogenic gas-filled and layered DT implosions with convergence ratio > 20 as an integrated test of experiment and code performance. Measure fraction of yield due to alpha heating and report other performance parameters including DSR, Ti, velocity, and fuel shape
FY 2013	PD	Complete an assessment of the predicted implosion performance using the measured imprint efficiency with multi-FM smoothing by spectral dispersion	Assess the predicted implosion performance on the NIF using the measured imprint efficiency with 1D multi-FM SSD on OMEGA EP and compare with measured and simulated implosion performance using the current laser smoothing levels on OMEGA
FY 2014	PD	Perform integrated PDD implosions on the NIF to investigate symmetry control and LPI mitigation	Using current NIF capabilities, conduct PDD implosions on the NIF and compare predicted symmetry and laser energy coupling performance against simulations and OMEGA experimental results
FY 2014	PD	Conduct integrated cryogenic DT implosions on OMEGA to establish the predictive basis for NIF-equivalent hydro performance	Compare computational predictions of cryogenic DT implosion performance on OMEGA against a broad spectrum of design parameters and investigate discrepancies in the computational models
FY 2015	PD	Conduct in-depth external review of PDD point design to assess go-forward program and readiness for CD-1	Includes completion of CD-0. Reference definitions of CD-0 and CD-1. Scope and commitments need to be clear and consistent with budgets.
FY 2013	MDI	Demonstrate initial capability for magnetized and pre-heated fusion experiments.	Commission initial capability at Z to simultaneously magnetize and preheat cylindrical fusion targets on Z with requirements of initial B = 7-10 Tesla and initial laser pre-heat energy = 1.5–2 kJ. Determine the impact of the magnetic field on current coupling to the target. Conduct experiments with magnetization and pre-heat separately and together.
FY 2014	MDI	Conduct initial integrated fusion target experiments and compare results to simulations	Determine fusion plasma parameters at initial levels of pre-heat, magnetic fields, and drive currents. Apply initial methods to measure the efficacy of flux compressions by the imploding liner. Compare results to simulations.
FY 2015	MDI	Evaluate fusion performance and stagnation plasma parameters at enhanced drive conditions and compare results with simulations	Increase magnetic field, laser pre-heat, and drive current capability. Requirements are B > 20 T, laser pre-heat > 4 kJ, drive current > 22 MA. Conduct experiments to measure the stagnation plasma parameters and fusion target performance for all platforms. Compare results to simulations and quantify agreement.
FY 2015	Diagnostics	Demonstrate operation of Advanced Radiographic Capability (ARC) at NIF using one NIF beam	Complete installation of ARC equipment for one NIF beam and demonstrate ARC is operational.

III. Detailed Program Highlights

A. Current State of the Program

The primary mission of the NNSA is to maintain and enhance the safety, security, and effectiveness of the U.S. nuclear weapons stockpile. To this end, DOE's Defense Programs (later NNSA) created the SSP in the mid-1990s to simulate aspects of nuclear explosive package (NEP) physics, both computationally and experimentally, and to elucidate the required physics in laboratory experiments to provide confidence that the weapons remain safe, secure, and effective.

The ICF Program along with other NNSA activities such as the Science and the ASC Campaigns provide the essential capabilities and supporting knowledge required for ongoing assessment and certification of the nuclear weapons stockpile. The ICF Program, in particular, provides scientific, facility, and other capabilities needed to examine HED science issues underlying stockpile assessment and to test and validate simulation codes in specific areas of nuclear performance. The ICF Program is the world's leading program in HED science and also serves as an important attractor of new talent to the NNSA. The pursuit of ignition and high fusion yields in the laboratory is a major objective of the SSP and the ICF Program and is a 'grand challenge' scientific problem that tests our codes, our people, our facilities, and our integrated capabilities. Demonstrating ignition in the laboratory provides understanding of some processes that cannot be addressed in any other way. The ICF Program also executes non-ignition and other experiments in support of the SSP in collaboration with the Science and ASC Campaigns and other NNSA subprograms and supports other national security work including DoD and other sponsors.

The May 2011, NNSA Strategic Plan sets forth the policies for carrying out its responsibilities under the President's nuclear security agenda as described in the DOE Strategic Plan. The DOE Strategic Plan supports the NPR objectives and highlights the need to enhance proliferation resistance. The NNSA Strategic Plan outlines the steps required to "transform the NNSA from a nuclear weapons complex to a 21st-century Nuclear Security Enterprise, addressing the nuclear and national security challenges of the 21st century." NNSA's Plan notes that "the science, technology, engineering, and manufacturing competencies of the Enterprise and the complementary suite of facilities and supercomputing capabilities underpin the ability to assess the safety, security, and reliability of each nuclear weapons system and to address broader national security requirements." The plan further requires that the U.S. maintain second-to-none nuclear science and technology and attract and retain the best and brightest scientists, engineers, and technicians.

The principal role of the ICF Program is to achieve ignition and to perform HED research (in cooperation with the Science and ASC Campaigns) that supports the requirements of the weapons program. In terms of above ground experimental capabilities (AGEX) in the NNSA Enterprise, a facility capable of producing thermonuclear burn on a reliable platform is a major missing element to support the science-based Stockpile Stewardship Program. The ICF Program operates a state-of-the-art suite of HED experimental research facilities and has a proven record of scientific achievement and effective leadership in developing HED capabilities. It has provided expertise in support of the assessment and certification of the nuclear stockpile without underground testing. ICF experiments have played an important role in uncertainty reduction within the Quantification of Margins and Uncertainties (QMU) framework established for the SSP.[2] In addition, the ICF Program provides HED capabilities for fundamental HED science and other national security applications.

It has long been recognized by NNSA, Congress, and the laboratories that multiple platforms and methods are needed to pursue advancements in ignition and HED research to guard against systemic errors and common failure modes. Three approaches are being pursued, and each offers benefits and risks. Two use lasers to create thermonuclear conditions, and one uses MDI. The primary approach uses high-powered and high-energy lasers to create x-rays that then implode (drive) a capsule of fuel. This approach is called indirect drive. A second laser approach, called direct drive, shines the laser directly onto the capsule to implode it. The third approach uses pulsed electrical power to create a magnetic field that implodes a container holding the fuel.

Three world-class experimental HED facilities, NIF, Omega, and Z, allow the U.S. to be pre-eminent in ICF. Intermediate scale facilities, for example, TRIDENT at LANL, JUPITER at LLNL, and NIKE at the Naval Research Laboratory (NRL), are important for advancing ICF science, for training new generations of staff and scientists, and for the development of experimental techniques and diagnostics used at the larger facilities. To fully utilize the facilities the national program has a coordinated effort in target fabrication and diagnostic development. The combination of these facilities and capabilities provide the broad HED test bed required to create HEDP conditions and to obtain quantitative data in support of a number of other Campaigns:

- PAT subprogram of the Science Campaign
- DMP subprogram of the Science Campaign
- SAT subprogram of the Science Campaign
- ACC subprogram of the Science Campaign
- NS subprogram of the Engineering Campaign
- ES subprogram of the Engineering Campaign
- ASC Campaign

The definition of ignition in this context is the same used in the 1997 National Academy of Sciences review of the ICF Program: "The definition of 'ignition' adopted here is fusion energy output greater than laser energy incident on the target assembly (for indirect drive, the target assembly consists of the hohlraum and capsule; for direct drive, it consists of the capsule.)"[3] This same general definition of ignition can be applied to pulsed power systems with the following additional provisos. In the case of MDIs, the energy that is delivered to the target assembly is electromagnetic energy not laser energy. The target assembly in pulsed power

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[2] "Applications of Ignition 90-day Study," Feb. 29, 2012

[3] Review of the Department of Energy's Inertial Confinement Fusion Program: The National Ignition Facility, 1997 by Committee for the Review of the Department of Energy's Inertial Confinement Fusion Program, National Research Council ISBN: 0-309-59046-9

systems consists of the z-pinch target and the vacuum region immediately around the z-pinch. Generically then, ignition occurs when the fusion energy output equals the driver energy delivered to the fusion target, where the driver energies and fusion targets are defined as above.

Achieving ignition is a scientific discovery process in which physics unknowns and technical complexities are revealed and resolved. The principal risks to meeting the ICF Program's goals always have been target physics uncertainties associated with ignition; however, NIC was organized as a project with a beginning and an end defined as a specific point in time - the end of FY 2012.

Status of the National Ignition Campaign

The NIC was an integrated national, multi-institutional effort with partners including LLNL, LANL, SNL, LLE, and GA. Other key contributors included MIT, Lawrence Berkeley National Laboratory, AWE in England, and CEA in France.

The NIC had two major objectives: 1) to develop a platform for ignition and HED applications; and 2) to transition NIF to routine operations as a user facility.

The efforts as defined in the NIC Execution Plan Rev 4.0 as necessary to meet the NIC objectives included developing or demonstrating:

- Ignition
- Significant alpha heating as a step towards ignition
- An integrated ignition point design
- Targets consistent with the point design
- Cryogenic target positioning system
- Diagnostics for hohlraum, capsule, and fusion performance
- Laser/user optics operating to 1.8 MJ and 500 TW, demonstrating NIF and NIC Primary Criteria and Functional Requirements
- Personnel and environmental protection systems
- Experiments on OMEGA in support of the NIC experimental program
- Support of ignition, non-ignition SSP, fundamental science, and other national security missions
- Transitioning NIF to routine facility operations as a national user facility

With the exception of ignition and alpha heating, the NIC Program completed all of the objectives just described which included developing all of the facility and technological capability prescribed, performing HED science experiments in support of weapons science, other national security, fundamental science and ICF, and reaching conditions on the NIF that never have been reached in any other laboratory. Although the grand challenge of fusion ignition and burn via ICF on NIF was not achieved, a large body of knowledge and major new capabilities were developed.

This was accomplished through the execution of a series of experiments using the NIF. The experimental series brought up the facility's capabilities in a phased manner, carefully staged to systematically reduce physics uncertainties in the computational models used to predict the conditions needed for ignition. The hohlraum temperature was brought up to the point design requirements; the implosion velocity was measured at about 95 percent of requirements; the complicated time history of the laser power was adjusted to keep the incoming shell and fuel at the required low temperature; and the sphericity of the implosion was kept within the specification required by design codes. These demanding technical requirements were achieved rapidly in surrogate targets and layered targets, in part because of many years of preparation on OMEGA.

Thirty-seven implosion experiments with cryogenic hydrogen fusion fuel (THD or DT) ice layers were performed. Initial technical problems with the target and fuel layers were resolved quickly, and most of the implosion experiments were performed with targets meeting specifications set by simulations. The neutron yield and the areal density of the compressed fuel are the most relevant measurements of the quality of the implosions. The highest observed yields (in terms of fusion energy) and areal densities were 2.5 kJ and 1.3 g/cm^2, respectively. This yield is approximately a factor of three to ten less than required for initiating a propagating burn, which simulations suggest would rapidly heat the fusion fuel and lead to ignition with yields greater than 1,000 kJ. Because, for the first time, the hot spot areal density is large enough to trap alpha particles, we estimate that about 10-15 percent of the current yield comes as a result of alpha heating. The compression pressure is approximately half that predicted by simulation. The reason for the deficit is not clear but is due, most likely, to low-mode fuel asymmetries and to the hot spot experiencing more mix than expected. Identifying the reason for the reduced peak pressure and developing mitigation strategies is a key element of the path forward experimental plan.

B. ICF Management

Management tools that are in place within the ICF Program include:

- Utilization of the ICF Execs and its Working Groups for Ignition and High Yield planning efforts;
- Implementation of a national HED Planning Council (HED Council) to review and to prioritize HED research that supports the requirements of the weapons program; and the
- Implementation of a User Facility Governance model at each of the ICF research facilities to effectively manage the facilities.

ICF Executives/Working Groups

In early 2012, NNSA asked the ICF Execs (defined in Appendix B) to take a more active role in planning the program. The ICF Execs is a body of appointed institutional representatives from LLNL, LANL, LLE, NRL, and SNL with GA as an ex-officio member. Such a cross-cutting body would be able to provide robust and effective planning recommendations to NNSA. The ICF Execs represent the different institutions but have a variety of opinions and ideas to move the program forward. It was recognized that consensus recommendations are the strongest and are ideal. However, at times consensus may not be achievable. Therefore, consensus is strived for; however, if there is not a consensus, both majority and minority opinions are documented in writing and forwarded to NNSA.

It was recognized that there was a need to task working groups to provide the ICF Execs with detailed information, plans, and recommendations to be integrated across the program elements at the ICF Execs' level. Five working groups were identified initially. The working groups of Indirect Drive, Direct Drive, and Magnetic Drive Implosions with pulsed power were constituted around specific approaches to obtain ignition and high yield. Diagnostics and Target Fabrication were essential capabilities that all three approaches relied on for success. The chairperson of the working group was appointed from the corresponding lead institution of the effort. The one exception was that of Diagnostics for which it was determined that the NIF Diagnostic Working Group had been so successful that its leadership would be kept in place and its charter would be expanded to include the other large HED facilities. A minimum of one member from each of the ICF Execs' institutions was required in the working group. Consensus also is strived for in the working groups; however, minority opinions are allowed. Both majority and minority opinions are forwarded to the ICF Execs. Working groups have been meeting regularly, have developed long-term plans, and have submitted their consensus recommendations to the ICF Execs. It is expected that these working groups will be on-going and critical to the planning efforts within the ICF Program.

The ICF Execs' plans and recommendations are described below.

HED Council

In February 2010, NNSA initiated the formation of the HED Council. Members were nominated by the Principal Associate Directors for weapons programs at SNL, LANL, and LLNL. The HED Council reviews and prioritizes experimental plans developed by the different labs. The HED Council reviews proposed experiments and issues recommendations regarding experimental prioritization for non-ignition SSP experiments that produce data or results with a direct impact to either a specific stockpile tail number, radiation effects, or to the Nuclear Explosive Package (NEP) strand of the PCF. These prioritized recommendations are provided by facility (OMEGA, NIF, and Z) to the local facility program committees and laboratory SSP leadership. The Council is responsible for developing an annual three-year classified implementation plan for the HED weapons science experimental program and recommendations for long term HED diagnostic investments.[4]

C. ICF Three-Year Plan

This section summarizes the plan for the ICF Program and the milestones to measure performance for the next three years. In FY 2013 and beyond, the ICF Program will broaden its exploration of the ignition and burning plasma regime. It is important for the SSP to understand the physics underlying the difficulty of achieving ignition, as well as to assess the important

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[4] *HED 3-Year Plan and Progress Update*, FY 2012 (SRD) LA-CP-12-01144, COPJ-2012-0658, SAND-2012-8174P, September 26, 2012; Batha et al.

fundamental issues relevant to both ignition and weapons physics. The ignition program has been modified to investigate these underlying issues through code and model advances underpinned by focused experiments that separate out key contributing physics.

This plan has been constructed to improve understanding and predictability of simulations necessary to develop and to test mitigation strategies to overcome the barriers to ignition. The three-year plan culminates in a comprehensive review at the end of FY 2015. At that time, NNSA will have an assessment of the likelihood and schedule for achieving ignition.

The technical scope of this plan will be conducted on a schedule consistent with appropriated budgets. As such, milestone dates are provisional and may change in accordance with available funding.

Program elements include the pursuit of ignition with the main-line indirect drive approach and the alternative PDD and MDI approaches. The progress of each of these program elements will be assessed during the review at the end of FY 2015. ICF support of ignition and HED experiments for the broader SSP are described. Critical enabling capabilities of Codes and Databases, Diagnostics, and Target Fabrication also are important elements of the plan. The major FY 2013–FY 2015 ICF Program deliverables are provided in the Table 1 in the High Level Overview.

Non-ignition HED research that supports the requirements of the Science Campaign will have increased priority on NIF in FY 2013 and beyond compared to the FY 2008–FY 2012 period when the Program's focus was dominated by the pursuit of demonstrating ignition in the laboratory. This increased emphasis going forward on stockpile stewardship science activities will be in support of the PAT, DMP, SAT, and ACC subprograms of the Science Campaign, the NS and ES subprograms of the Engineering Campaigns, and the ASC Campaign.

Indirect Drive Ignition on NIF

The goal of the program is to achieve ignition on the NIF, while developing enhanced understanding of the physics of ignition-relevant, x-ray driven implosions to improve predictive capability in support of SSP missions. If ignition cannot be achieved on the NIF, the program will identify the major obstacles and the implications for the SSP.

The path forward plan appropriately balances the following three interrelated program elements to achieve this goal:

- Understanding of integrated implosion experiments including less demanding, lower convergence, and lower velocity implosions as a stepping stone to the higher convergence, higher velocity implosions necessary for ignition. This will test the theories and models with increasingly difficult-to-predict implosions.

- Focused experiments, as appropriate, to further isolate and understand the key physics issues of x-ray drive, many of which were identified in the workshop on the *Science of Fusion Ignition on NIF*.[5]
- Alternate x-ray driven implosions to lay the groundwork for alternate ignition designs with x-ray drive.

Element 1: Integrated Implosion Experiments

Implosion experiments combine complicated interacting physics in a demanding, but necessary, integrated test of our understanding and modeling capability. These experiments can identify where discrepancies exist between theory and experiment but, typically, cannot readily isolate either the causes or show how to improve the models.

The NIC integrated implosions produced results that were different from simulations. In particular, the performance appears to have been dominated by a pronounced level of three-dimensional (3D) long wavelength distortions in the DT fuel surrounding the hot spot and by hydrodynamic mix. These 3D effects must be understood and reduced so that implosion physics can be studied and tested in a more controlled, less stressing environment.

The integrated ignition experiments on NIF concentrated on high convergence, low adiabat implosions which are stressing on the diagnostics, targets, and modeling of the implosions. In order to more readily separate key issues of mix and asymmetry, a lower convergence implosion with less hydrodynamic instability will be developed. This is expected to result in an implosion that is more likely to achieve near one dimensional (1D) performance. This element of the program performed in parallel with Element 2 below should demonstrate that improved physical models lead to more accurate predictive capability of performance. It is envisaged that this implosion platform will be a stepping stone to more accurate predictive performance for an ignition implosion.

Element 2: Focused Experiments

The standard set of diagnostic observables from integrated implosion experiments in the NIC encoded the results of multiple interacting physics phenomena making it difficult to understand why model predictions differ from experiment. For this reason focused experiments that target specific physics issues now are part of the experimental plan.

Motivated by the results of the NIC, additional focused experiments are planned that look deeper into the behavior and physics of ignition targets. These include experiments to directly measure specific phenomena such as the ablation front Rayleigh-Taylor instability in the capsule and experiments to test and improve the underlying physics data models such as DT EOS and code algorithms.

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

Continual improvement in predictive capability will allow us to converge more rapidly on a successful ignition design and will facilitate more efficient design of experiments for SSP missions.

Element 3: Alternate Concepts

X-ray driven implosion ignition systems, that operate in different physics regimes and that emphasize different physics while achieving significant thermonuclear performance (burn), can lead to increased understanding and improved predictive capability. What we learn from the development of such platforms may not only help our understanding of ignition but also may lead to additional applications for stewardship. [6]

This research program element will use computational and theoretical studies and, potentially, experimental campaigns to test the key physics issues for each concept. Results will be beneficial both for a broader understanding of the physics of x-ray driven ignition and for the quantitative understanding of the physics underpinning of the SSP. It is anticipated that proposals for such alternative ignition designs may not be as mature as the hot spot design. Support for developing such alternatives will be required to bring them to a state at which they can undergo technical review to arrive at appropriate decisions on applying resources.

Indirect Drive as a Platform for Stockpile Stewardship Applications

Today, NIF allows access to energy densities much greater than can be achieved with other facilities. The power, precision, and reproducibility of the NIF laser, coupled with precision target fabrication and diagnostic capabilities, enables NIF to explore important regimes of HED physics directly related to the nuclear phase of operation of modern nuclear weapons in the U.S. stockpile. Developing and utilizing NIF's unique capabilities for weapons physics applications remain important objectives for the weapons programs regardless of whether ignition is achieved in the near future.

Non-ignition HED research that supports the requirements of the Science Campaign will have increased priority on NIF in FY 2013 and beyond compared to the FY 2008–FY 2012 period when the Program's focus was dominated by the pursuit of demonstrating ignition in the laboratory.

If ignition is not achieved eventually, then SSP's ability to investigate these issues in the laboratory will be limited severely. Weapons scientists will be unable to explore experimentally the potential impacts of aging on thermonuclear ignition and burn for some warhead life extension design or component options.[5] Therefore, the resulting weapon analyses may have associated uncertainties that would be larger than they would be otherwise.

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[6] "Applications of Ignition 90-day Study," Feb. 29, 2012

Polar Direct Drive

Symmetric direct drive illumination for which the laser beams directly illuminate the surface of the DT capsule has been an alternative to hohlraum-generated x-ray drive for decades. In the design phase of the NIF in the 1990's additional equatorial beam ports for symmetric illumination were incorporated into the NIF target chamber. Direct drive illumination can be performed symmetrically (e.g., the 60-beam OMEGA laser was designed for symmetric drive) or asymmetrically (on OMEGA, this is done using only the 20 most polar beams in each of the upper and lower hemispheres). The asymmetric drive configuration is PDD. Although PDD uses only 40 of the 60 beams on OMEGA, all 192 beams on the NIF can be used for PDD due to the inherent arrangement of the beams needed to drive a hohlraum. Although PDD presents additional design challenges relative to symmetric drive, it has the advantage that it can be implemented on the NIF more quickly and at a much lower cost than reconfiguring for the originally planned symmetric illumination. The laser and optical system is more complicated than indirect drive, and a PDD target manipulation and insertion system needs to be developed. The scientific basis for PDD ignition on the NIF has been developed over many years of direct-drive research including over 250 ignition hydro-scaled cryogenic implosions on OMEGA.

The efficiency of coupling laser energy into fuel kinetic energy is higher with direct drive than with a hohlraum. Simulations indicate that seven to nine times more fuel can be accelerated to the same implosion velocity with a given laser energy. This additional fuel kinetic energy increases the target design space margin.

The near-term goal for symmetric and PDD research is to demonstrate ignition hydro-equivalence using cryogenic DT implosions on the 26 kJ OMEGA laser scaled to full NIF energy. There are several non-hydrodynamic physics issues in scaling from 0.9 mm diameter capsules on OMEGA to 3.3 mm capsules on NIF including energy loss due to cross beam energy transfer (CBET) and hot electron production due to laser plasma instabilities (LPI). These physics issues minimally impact present cryogenic implosions on OMEGA but could have a significant impact on PDD implosions on the NIF.

The intermediate-term goal for PDD research (FY 2014 - FY 2015) is to address these physics issues using experiments on OMEGA and on the NIF to test and to validate models and to improve designs. The predicted mitigation of drive asymmetry induced by CBET using wavelength tuning on the NIF will be tested. The initial series of NIF PDD experiments will begin in FY 2013 with additional experiments planned in FY 2014 and FY 2015. Laser spot "zooming" as a means to minimize CBET will be developed and tested on OMEGA before the end of FY 2015. These plans are outlined in a Polar Drive Conceptual Design document[7] and require only a single additional diagnostic on the NIF.

The smoothing requirements for optics and for imprint mitigation will be validated experimentally in the near term on OMEGA and on OMEGA EP. In parallel, a multi-laboratory

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[7] Polar Drive Conceptual Design document, LLNL-TR-553311, completed by LLNL and further documentation submitted by LLE on 28 Sep 2012 to satisfy Milestone 4491.

effort will develop conceptual designs for the dedicated optics, the implementation of beam smoothing, and the PDD cryogenic target positioner on the NIF. These conceptual designs are necessary to inform the decision on investment for PDD ignition on the NIF at the ICF Program review at the end of FY 2015.

Polar Drive as a Platform for Stockpile Stewardship Applications

PDD can be used for non-ignition HEDP applications requiring high neutron yield, large high-temperature plasmas, and very bright continuum x-ray sources. The simplicity of the platform is attractive from the standpoint of diagnostic and physics package access in that there are few target structures to block lines-of-sight to key diagnostics.

LANL and LLNL are developing PDD platforms for non-ignition HEDP experiments. Aspects of these platforms are being developed at Omega. Details of these classes of experiments can be found in the *Applications of Ignition 90-day Study*.

Non-ignition HED Research on OMEGA/EP

In FY 2012, 25 percent of the shot time on OMEGA and OMEGA EP was allocated for non-ignition HED research. The goals and scope of this research were established by the national laboratories. Over the past decade, LLNL and LANL scientists have collaborated with a number of LLE scientists on aspects of HED research that include the development of x-ray absorption spectroscopy techniques (e.g., Extended X-ray Absorption Fine Structure (EXAFS)) to probe compressed matter at low temperatures and precision techniques for inferring the EOS in materials shocked to high pressures and off-Hugoniot states. This focused research is often ideal for graduate students, and several LLE-trained PhD students from the University of Rochester and MIT have joined the scientific staffs at LLNL and LANL over the past decade. With backgrounds in HED-related science, these students are particularly well-suited for careers at the national laboratories.

Magnetically-Driven Implosions (MDIs) with Pulsed Power

The Z Pulsed Power Facility efficiently stores and delivers magnetic energy to a variety of HEDP experimental platforms. These platforms produce unique environments for both the near-term and long-term needs of the stockpile stewardship programs. Planar magnetically driven experiments currently provide accurate and precise measurements of the constitutive and dynamic properties of a wide variety of materials across a broad range of pressures, temperatures, and densities for the DMP subprogram. In many cases of interest, these platforms presently are the sole means of obtaining the relevant data. Cylindrical MDIs provide bright and energetic x-ray sources, enabling the stewardship program to simulate the environments in nuclear weapons (radiation flow and opacity) for the SAT subprogram. Other cylindrical MDIs have provided the most energetic x-ray sources used for radiation effects science to simulate environments that are exposed to nuclear weapons for the NS engineering campaign. Approximately 65 percent of the experiments on Z today are performed in direct support of near-term, non-ignition experiments for SSP.

MDI platforms that directly assemble and compress fusion fuel with magnetic pressure also are being evaluated for the long-term needs of the SSP. Approximately 25 percent of Z experiments are devoted to magnetically driven implosions for fusion. Experiments on Z today are able to couple ~30 to 240 kJ to fusion fuel using large targets with sizes of 5 to 10 mm. The large current pulses produce magnetic drive pressures approaching 100 million atmospheres (MBar). Stagnation pressures of these cylindrically imploded systems are predicted to exceed 1 GBar in simulations. Magnetically driven implosion target designs have different risks than other concepts and, therefore, serve as risk mitigation for ignition in the laboratory. For example, the coupling of electromagnetic energy to targets in the form of magnetic fields operates on a different set of fundamental physical principles than the coupling of electromagnetic energy (either as visible or x-ray photons) to targets. The goal of the research between now and FY 2015 is to obtain detailed experimental data enabling high fidelity comparisons with numerical simulations.

The research program on Z is focused on understanding the science of MDIs and on validating simulations for this approach to ICF. This requires a combination of both integrated experiments to obtain needed data to compare with simulations and to determine which physics issues are most important and focused experiments to increase understanding on specific physics issues. A number of unclassified and classified target design elements are being evaluated. Much of the progress to date is classified.

In addition to large absorbed energies and large target sizes, MDI fusion targets can incorporate several other target design elements including fuel magnetization, fuel pre-heat, and cryogenic fuel. Simulations and theory show that the use of these elements together may relax the target performance requirements for ignition and high yield and, therefore, may reduce the risk. For example, simulations indicate that these elements could reduce the fuel stagnation pressure required to achieve relevant fusion conditions.

Present simulations indicate that drive currents of 27 MA, laser pre-heat energy of 6 kJ, and magnetic fields of 30 T are required for the point design.[8] Experiments are needed to test these predictions. The goals for FY 2015 are to increase the magnetic fields, laser pre-heat, and load drive current to the maximum possible permitted by the time and budget available. The target design elements discussed above and those of a classified approach studied on Z (details available on request) will be evaluated. Scientific understanding and predictive capabilities will be the key metrics by which we will judge the future prospects of MDIs. The remaining issues for MDIs will be identified, and the potential for further progress of MDIs to meet the long-term objectives of the SSP will be evaluated.

Magnetically-driven Implosions as a Platform for Stockpile Stewardship Applications

MDIs have demonstrated significant contributions to NNSA stewardship missions much of which is classified (details available on request). Platforms developed for MDI fusion have long-term SSP applications and have also allowed breakthroughs in applications to near-term

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[8] S. A. Slutz et al., Phys. Plasmas, 17, 056303 (2010)

SSP missions.[9] Over the last three years, new platforms have been developed for radiation flow, radiation effects, and materials science that arise from work done in the fusion program. Z presently is the only HED facility that can perform dynamic materials science experiments on plutonium, a topic of great interest. Cylindrical MDI platforms for dynamic materials are being developed to increase the pressures for EOS experiments and are a recent outgrowth of the MDI ICF Program. Innovative new platforms that can be applied to all subprograms of SSP and other important national security issues will continue to be developed.

D. Codes and Databases

All three of the ICF approaches - indirect drive, direct drive, and magnetic drive - rely on integrated codes to design, execute, and analyze their fusion experiments on NIF, OMEGA, and Z. The degree to which the simulations match the experimental observables is a measure of their predictive capability and the confidence that can be placed on their use to assess the probability of achieving fusion goals relevant to each approach and driver. The integrated codes are comprised of a sophisticated set of coupled physics models that simulate the delivery and coupling of the driver energy to the target; the energy transport within the target; the implosion, compression, and heating of the fuel; and the fusion burn. The models describing driver energy and transport to the implosion are largely approach-specific. The models describing the implosion through fusion burn processes are independent of approach.

The degree to which the integrated ICF codes are predictive is related directly to the degree to which they have been validated by experimental data. Decades of laser-driven integrated and fundamental experiments on NOVA and OMEGA for non-ignition targets have led to a set of reasonably predictive design models that include a wide variety of physical effects related to laser coupling, radiation drive and symmetry in hohlraums, symmetry in direct drive, as well as implosion physics and hydrodynamic instabilities. The laser ICF codes and databases need to be extended to and validated at the NIF-relevant energies and the larger spatial and temperature scales, higher convergence ratios, and rather different plasma conditions. As all of these models are extended to new regimes, comparison with integrated experiments places new stresses on their predictive capability. Tracking down the sources of error, identifying missing physics, and improving the fidelity of the codes is critically important to enabling them to guide the assessment of approaches to ignition and burn.

All weapons codes depend upon databases for EOS, opacities, conductivities, and nuclear cross sections. The larger driver energies of NIF, OMEGA EP, and Z are creating plasma conditions in new, untested regimes. We need to extend our databases and to benchmark the physical models in the regimes important for ignition physics.

The ASC Campaign and other campaigns, including ICF, are integrated through the PCF (a tool for improving and validating NNSA's fundamental understanding of nuclear weapon physics and engineering) and coordinate the development of predictive capability into modeling and

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[9] HED 3-Year Plan and Progress Update, FY 2012 (SRD) LA-CP-12-01144, COPJ-2012-0658, SAND-2012-8174P, September 26, 2012; Batha et al.

simulation tools. To date, ASC has not supported directly the development of ICF codes, though the ICF Program has benefited directly from ASC Program development of advanced computing platforms and supporting infrastructure. It is planned that a closer collaboration between these two programs will occur going forward.

E. Diagnostics

The value of experiments for stockpile stewardship is related directly to the quality of the diagnostics used to measure and compare observables against the predictions of the design codes. The three major facilities each have scores of routine target diagnostics with much commonality as well as shared calibration sources. Starting with the underground test diagnostics at the former Nevada Test Site (now the Nevada National Security Site), there has been a major collaboration between the program elements on target diagnostic development. Moreover there is diagnostic commonality with DOE's Office of Fusion Energy Science (OFES) demonstrated by a major conference, the bi-annual "High Temperature Plasma Diagnostics Conference" published in the *Review of Scientific Instruments*.

Building on past collaborations, the community recently has run seven major NIF diagnostic workshops. These have led to an exemplary sharing of scientific responsibility for the NIF diagnostics and have engendered new users. Engaging the community has led to NIF benefitting from prior experience and present development on OMEGA and Z and other expertise.

To date, facility needs for diagnostics have been driven primarily by ICF mission requirements. For the future, the mission need is broader than ICF. Recognizing the multi-year development timescale and the enabling capability but high cost of new diagnostics, a mission responsive, out-year diagnostic plan is being developed with appropriate facility commonality.

Status of NIF Diagnostics

NIF now is equipped with approximately sixty nuclear, optical, and x-ray diagnostics that together provide 300 channels for experimental data. The diagnostics have been implemented in response to the existing missions on NIF. More than half of the diagnostics are run on most shots.

Scientific responsibility for the diagnostics is shared among eleven institutions. Operation of the set of diagnostics requires set-up and control of 13,000 parameters and 1,000 control points as well as configuration control of thousands of diagnostic parameters. There are about sixty major data analysis algorithms. Most data is archived and is available to and searchable by qualified users.

The movable diagnostics on NIF are positioned by three large Diagnostic Insertion Manipulators (DIMs) which have a common interface with the corresponding manipulators for movable diagnostics on OMEGA and other smaller facilities. This allows OMEGA to be used to develop and to test diagnostics for the NIF.

Status of OMEGA Diagnostics

OMEGA and OMEGA EP have about 200 target diagnostics with up to thirty diagnostics used per shot supporting a broad range of users including the national weapons laboratories (LLNL, LANL and SNL), academia (through the National Laser Users' Facility (NLUF) Program) and international users (CEA, AWE and Japan's Institute of Laser Engineering). The extent of joint development is shown by the fact that about eighty of these 200 are the scientific responsibility of outside users.

Data from the OMEGA diagnostics are all logged to the OMEGA database, which is accessible to all facility users. The goal of the facility is to have all shot data available to the Principal Investigator within a shot cycle (typically 45 minutes).

Status of Z Diagnostics

There are about twenty classes of diagnostics on Z totaling well over 100 unique measurement capabilities. This diagnostic set was developed largely to study indirect drive ICF using z-pinch x-rays to implode gas-filled capsules. Recent shifts in the ICF Program on Z to study MDIs dictate a somewhat different set of requirements but have, so far, been able to utilize the diagnostics developed for indirect drive ICF. Recent emphasis in the DMP area has driven development of a different set of diagnostic capabilities to measure Mbar-level shock properties including velocity interferometry and streaked visible spectroscopy. The needs of non-ICF applications will continue to be a major factor in diagnostic development for the future.

Diagnostic Calibration Facilities

Diagnostic characterization and calibration are an integral part in the development and fielding of any HEDP diagnostic system. There are currently sixteen key calibration facilities that provide these sources for the entire national HEDP community.

Diagnostics Planning on the NIF, OMEGA, and Z

Diagnostic development underpins the quality of the science that can be done on any major facility. The current suite of diagnostics on the NIF largely was developed and tested at other facilities over the past decade, and all three facilities will continue to benefit from each other's innovations. Indeed, the NIF diagnostic workshops ensure coordination of these efforts. The technology and techniques that will be needed a decade from now are under development today.

Long term planning is required for the development of a new diagnostic capability. The requirements of the ICF program so far have driven the design of many diagnostics at all three facilities which have been leveraged effectively to impact the broader needs of the Science Campaigns.

The selection of future diagnostics is driven by a broader base:

- The x-ray drive, direct drive, and MDI ICF program requirements
- Science Campaign requirements
- Fundamental science requirements from the NIF, OMEGA, and Z user communities

Some of the instrumentation will be driven by mission need, whereas in some instances adapting new technology will develop new mission requirements.

Out year plans for each facility have been developed that balance the needs of the user communities against expected steady-state resource levels and estimates of schedule. These plans are based on joint diagnostic conferences (i.e., the seventh NIF Diagnostic Conference) that review the requirements for new diagnostics against mission need, anticipated resources, and development time. Several foundational diagnostics are outlined in the plans for each facility, but timelines for development are tied to experiment planning. On NIF, for example, the first phase of the Advanced Radiographic Capability (ARC) should be available in the next three years. However, some future foundational diagnostics, such as optical Thomson scattering, optical interferometry, and gamma ray spectroscopy will be delayed with a concomitant delay in certain ICF and HED experiments.

F. Target Fabrication

Targets are a critical and enabling component of ICF experiments, and their development, fabrication, and availability are paramount for success of the program. Since the target sets the initial conditions for the experiments, precision built and characterized targets are of great value to stockpile stewardship. Fabricating targets requires a mixture of precision equipment for shaping and depositing materials, which may involve nearly any element in the periodic table, and metrology equipment to provide the required characterization. More importantly, it requires having a robust, agile, highly trained scientific staff dedicated to target fabrication who are trained with an in-depth knowledge of the experiment's physics goals to produce targets that, in some cases, are yet to be designed. Such infrastructure has been established to address the needs of all three major facilities. Since target designs evolve continually, maintaining such an infrastructure with minimal duplication of effort is essential for ensuring the proper supply of targets for the program in a cost-effective manner.

Future Target Development

Gaps in target capabilities for indirect drive include developing variants for dopants and alternative ablator materials for capsules for achieving more efficient implosions. Capsule sphericity specifications likely are to be tightened, and, hence, development will be needed to produce more spherical capsules. Development also is needed in making liner-less depleted uranium and rugby hohlraums to tailor and to increase x-ray drive on capsule. Control and precise placement of a trace isotope dopant (radioactive and stable) in the shell wall of capsules needs to be developed to enable a better measurement of capsule compression through radiochemical means. Future developments for direct drive targets involve optimizing capsules to meet surface finish requirements, improving the robustness of capsule fill-tube assembly, and demonstrating DT ice layers that meet requirements in such assemblies. For MDI targets, continued development to improve liner target quality is needed. SSP target needs will encompass a variety of different and new platforms. An additional complication in fabrication of some SSP targets will arise with hazardous and toxic materials (such as plutonium) where infrastructure will need to be added to enable their safe handling. Commensurate development in characterizing materials will continue to be a crucial component of target fabrication.

G. Impact on Stockpile Stewardship on Failure to Obtain or Pursue Ignition

Achieving ignition remains the highest priority of the national ICF Program and an important goal of the broader SSP. It is important that the SSP understands the physics underlying the difficulty of achieving indirect drive ignition and assesses the important fundamental issues relevant to both ignition and weapons physics.

The ignition program has been modified to investigate these underlying issues (see the ICF Three-Year Plan section above) through code and model advances underpinned by focused experiments that separate out key physics. In addition, alternative designs that explore different regions of the physics phase-space also have been added.

Aspects of our stewardship computational capabilities could be called into question by some due to our inability to achieve ignition. The degree of concern would depend strongly on the exact underlying mechanism and the particular computational models involved. On July 10, 2012, NNSA hosted a day-long workshop of which one of the purposes was to evaluate the limits of validity and specific gaps in capabilities for simulating ignition capsules with respect to the current stockpile. Though today's simulations do not match the experimental observables on NIF, it was concluded that none of the results from the ignition effort to date raise doubts about the current U.S. stockpile. This, in part, is because confidence in the stockpile benefits from a broad science base, rigorous certification, and an extensive campaign of successful nuclear tests.

A several-year delay in achieving ignition will result in the slippage of some burn-related pegposts in the PCF and in delays of some key predictive capability advancements. These advancements are aimed at resolving a key set of physics issues related to thermonuclear ignition and burn in warheads, as well as validation of certain physics models currently employed in the numerical simulation codes used to assess and certify U.S. nuclear stockpile warheads. The *Applications of Ignition 90-day Study* summarized ignition experiments and the general topical areas that they would address. These topical areas are summarized in Table 2.

Table 2 Ignition application experiments[10]

Application	Day 1	Expanded Capabilities	Robust	High Yield
Assessment and certifications	Code V&V	Code V&V	Code V&V	Code V&V
	Nuclear Cross section	Nuclear Cross section	Material properties	
		NBI	NBI	NBI
		Initial Condition, NEP performance	NEP performance	NEP performance
Output, environment, effects			Output V&V	Effects
Other national security		Forensics	V&H	V&H
			FNWA	FNWA

Day 1: Assume a 1-MJ indirectly driven ignited capsule with currently available diagnostics and facility capabilities
Expanded Capabilities: Day 1 plus additional facility/diagnostics capabilities, such as Advanced Radiography Capability (ARC) and determining performance margins
Robust: Reproducible and higher-gain capsule (gain of 5-20)
High-yield: Different regime with yield >100 MJ
Acronyms:
V&V = Validation and Verification
NBI = National Boost Initiative
NEP = Nuclear Explosive Package
V&H = Vulnerability and Hardness
FNWA = Foreign Nuclear Weapons Assessment

If ignition is not achieved eventually then SSP's ability to investigate these issues with or requiring a burning plasma in the laboratory will be limited severely. Weapons scientists will be unable to explore experimentally the potential impacts of thermonuclear ignition and burn on some warhead life extension design or component options. Therefore, the resulting weapons analyses may have associated uncertainties that would be larger than they would be otherwise.

H. Non-ignition High Energy Density Experiments

As described above, an important class of experiments performed on all three major ICF facilities is non-ignition HED Experiments. These experiments are summarized by application in Table 3.

Non-ignition HED research that supports the requirements of the Science Campaign will have increased priority on NIF in FY 2013 and beyond to specifically take advantage of NIF's ability to access energy densities much greater than can be achieved with other facilities. The unprecedented power, precision, and reproducibility of the NIF laser, coupled with precision target fabrication and diagnostic capabilities, enables NIF to explore important regimes of HEDP directly related to the nuclear phase of operation of modern nuclear weapons in the U.S. stockpile. Developing and utilizing NIF's unsurpassed capabilities for weapons physics

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[10] "Applications of Ignition 90-day Study," Feb. 29, 2012

applications remain important objectives for the weapons programs regardless of whether ignition is achieved in the near future.

Table 3 Non-ignition SSP physics experiments[11]

Application	Non-Ignition
Assessment and certifications	Materials properties - EOS, strength, phase Complex hydrodynamics Burn physics Radiation transport Plasma properties and opacity
Output, environment, effects	Source validation Effects validation
Other national security	SGEMP V&H

Acronyms: SGEMP = System Generated Electromagnetic Pulse
EOS = equations-of-state

These SSP experiments are reviewed annually by the HED Council for experiments planned for NIF, OMEGA, and Z, and a three-year plan is updated annually.[12]

IV. Conclusions

The U.S. ICF Program has made major progress towards ignition and is exploring for the first time the near-ignition physics regime. Whereas ignition has not been achieved, the ICF Program has benefited the SSP via improved physics understanding of weapons science and testing and validation of simulation tools used in performance assessment. It also has continued to attract first-rate talent to the national laboratories and the SSP. NNSA believes it is necessary for the SSP to continue an ignition effort focused on improving our understanding of the science underlying ignition. A program assessment will occur at the end of FY 2015.

This report is responsive to both the SEWD and HASC in that:

- We have explained the scientific and technical barriers to achieving ignition.
- We have provided a path forward for the next 3 years.
- We have detailed the impacts to stockpile stewardship.
- The specific question with respect to life extension programs is beyond the scope of the report from the ICF Execs but is addressed in the NNSA Overview and Executive Summary.

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[11] "Applications of Ignition 90-day Study," Feb. 29, 2012

[12] *HED 3-Year Plan and Progress Update*, FY 2012 (SRD) LA-CP-12-01144, COPJ-2012-0658, SAND-2012-8174P, September 26, 2012;Batha et al.

NNSA believes it is imperative for the SSP to continue an ignition effort focused on improving our understanding of the science underlying ignition. This judgment is based on the plan that has been constructed that leads to a quantitative understanding of why ignition has not been achieved and that allows for the development and testing of mitigation strategies. Achievement of ignition in the laboratory remains a critical component of the SSP Plan.

Appendix A
List of Acronyms

ACC	Advanced Certification Campaign
AGEX	Above Ground Experimental
ARC	Advanced Radiographic Capability
ASC	Advanced Simulation and Computing
AWE	Atomic Weapons Establishment
CBET	Cross Beam Energy Transfer
CD	Critical Decision
CEA	Commissariat a l'Energie Atomique
DIMs	Diagnostic Insertion Manipulators
DMP	Dynamic Materials Properties
DOD	Department of Defense
DOE	Department of Energy
DSR	down scatter ratio
DT	deuterium-tritium
EOS	Equations-of-State
ES	Enhanced Surveillance
FM	frequency modulation
EXAFS	Extended X-ray Absorption Fine Structure
GA	General Atomics
HASC	House Armed Services Committee
HED	high energy density
HEDP	High Energy Density Physics
ICF	Inertial Confinement Fusion and High Yield Campaign
IDI	Indirect Drive Ignition
LANL	Los Alamos National Laboratory
LLE	Laboratory for Laser Energetics, University of Rochester
LLNL	Lawrence Livermore National Laboratory
LPI	laser plasma instabilities
MDI	Magnetically Driven Implosion
MIT	Massachusetts Institute of Technology
NBI	National Boost Initiative
NEP	Nuclear Explosive Package
NIC	National Ignition Campaign
NIF	National Ignition Facility
NLUF	National Laser Users' Facility
NNSA	National Nuclear Security Administration
NPR	Nuclear Posture Review
NRL	Naval Research Laboratory
NS	Nuclear Survivability

NTS	Nevada Test Site
OFES	Office of Fusion Energy
PAT	Primary Assessment Technology
PCF	Predictive Capability Framework
PDD	Polar Direct Drive
QMU	Quantification of Margins and Uncertainties
SAT	Secondary Assessment Technology
SEWD	Senate Energy and Water Development
SGEMP	System Generated Electromagnetic Pulse
SNL	Sandia National Laboratories
SSD	Smoothing by Spectral Dispersion
SSP	Stockpile Stewardship Program
ST&E	Science, Technology, and Engineering
T_i	ion temperature
THD	tritium-deuterium-hydrogen
V&H	Vulnerability and Hardness
V&V	Validation and Verification

Appendix B
Report Participants

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