Department of Energy
Office of Science
Washington, DC 20585

December 27, 2012

MEMORANDUM FOR DEPUTY ADMINISTRATOR OF NNSA FOR DEFENSE PROGRAMS
DON L. COOK

FROM: ADVISOR ON NATIONAL SECURITY AND INERTIAL FUSION
DAVID H. CRANDALL

SUBJECT: Final Report of the External Review of the National Ignition Campaign Final

Following your request dated September 24, 2012, we conducted the final review of the National Ignition Campaign (NIC) on November 13 and 14 at LLNL. We attach your specific request, the Summary of that review and the list of reviewers. Each of the reviewers submitted individual reports and has reviewed this summary.

David H. Crandall
Federal Convener of the Review

Dan Meiron
Chairman for the Review

Attachments

Final Review of the National Ignition Campaign

December 27, 2012

The NNSA convened the seventh and final review of the National Ignition Campaign (NIC) on November 13 and 14, 2012 chaired by Prof. Dan Meiron. This document is a summary of comments submitted by individual reviewers and is authored by the meeting chair and the federal convener. The external reviewers have served since Dr. Steven E. Koonin, then Under Secretary for Science, initiated this review series in October 2010. For this review, Dr. Don Cook, the deputy administrator for Defense Programs at NNSA tasked the reviewers to:

- Summarize the final status of the NIC,
- Assess current impediments to ignition,
- Assess the likelihood of ignition in the future using indirect drive, and
- Identify priority research directions.

Reviewers interacted with the LLNL staff during presentations on technical progress and program plans, and reviewed and discussed drafts of the Congressionally-mandated path forward report now issued by NNSA, as well as a governance plan for the future utilization of National Ignition Facility (NIF). This review covered only the indirect drive approach to laser driven ignition.

Summary:

The National Ignition Campaign[1] was completed on September 30, 2012, having achieved all project goals with the exception of the grand challenge scientific goal of demonstrating ignition. In addition to designing and executing ignition experiments, the scope of the NIC Program included extensive development of the NIF facility, laser, target and diagnostic systems. Reviewers noted, as in previous reports, the unique capabilities of the NIF facility and the remarkable performance of the laser and diagnostics systems. They applauded the continued progress in developing sophisticated diagnostics, experimental platforms and techniques. During the campaign, the laser has been routinely operated at high energy and has met or exceeded the specifications set at the initiation of the NIC. Issues associated with

[1] J. D. Lindl and E. I. Moses, Physics of Plasmas **18**, 050901 (2011) and 3 accompanying detailed articles.

manufacturing of cryogenic layered targets have been encountered and resolved, and the quality of target capsules has steadily improved; cryogenic operation has now become routine. A total of nearly 60 diagnostics are now available, compared to around 10 when the NIC began.

The NIC executed an originally-envisioned program of tuning various aspects of the laser pulse shape, fusion target, and hohlraum dimensions and materials in working toward the goals of alpha heating and ultimately ignition. This approach was predicated upon the assumption that expertise gained in the past using the NOVA and OMEGA lasers, including the development of the relevant codes and physics models, was adequate to guide the tuning plan, and that there was a significant probability of success in achieving ignition with the higher energies available on the NIF.

The important conclusion from the NIC is that the present understanding of the physics of the hohlraum and capsule implosion as embodied in modeling and computer simulation is insufficient to predict the results of the implosion experiments aimed at achieving ignition. Reviewers indicated that, while progress towards ignition had been made, a program of scientific experiments and modeling focused on understanding the various physical effects, in isolation, that impact the integrated implosion experiments provides the best approach to eventually either achieve ignition, or to understand definitively why it may not be achievable with indirect drive using the NIF laser. Executing such a program will also require enhancing the number of diagnostic measurements of both the future focused experiments and integrated implosion experiments.

Progress since the previous review:

Since the previous review, the NIC team has developed several new diagnostics and experimental platforms that have proven indispensable in providing new insights into capsule performance. Focused experiments are being designed and executed to further understand processes viewed as the chief impediments to attaining ignition such as laser-plasma interaction (LPI) and hohlraum energetics, implosion stability, and mix. Among the achievements, two new techniques providing 2-D time-gated information on the conditions of the compressed capsule core were developed: 2-D Convergent Ablator targets and

Compton radiography. These techniques provide important new information on the conditions of the compressed capsule core. In particular, for the first time, large, low-mode asymmetries have been directly observed in the dense DT fuel.

The NIC program uses a metric to measure progress towards ignition called the Integrated Threshold Factor Experimental (ITFX)[1] which is based on the Lawson criterion used to indicate the onset of ignition in fusion plasmas. At the beginning of the NIC in September of 2010, the initial attempts at ignition produced neutron outputs from fusion that were consistent with an ITFX of approximately 0.001. Using information from the existing set of diagnostics, the program has succeeded in raising the ITFX nearly 100-fold to values of about 0.1. For reference, measurable heating of the fuel from alpha particle energy deposition occurs at values of ITFX of around 0.5 and ignition occurs when the ITFX reaches and exceeds unity. The requirements on target performance (adiabat, shape, velocity and mix) have been met, or nearly met, individually. This is a significant achievement, which should not be underestimated. However, at the same time, moving from this point to one where all requirements are met simultaneously is viewed as a significant challenge which will require further insight into the relevant physical processes.

Technical impediments to ignition:

The following phenomena are identified in the individual reviews from panel members as the current impediments to ignition:

Laser-Plasma interactions (LPI) and hohlraum energetics:

It has long been known that LPI, the interaction of the laser beams with the plasma produced in the hohlraum, leads to temporally and spatially varying scattering of the laser energy as well as transfer of laser energy among beams. This can lead to reduced and non-uniform X-ray drive on the target. Measurements from the NIC, confirmed in a new series of experiments called Viewfactor, have shown that there are additional reductions in the X-ray drive beyond those accounted for by the inferred amount of reflected light. Examination of possible causes of this reduction including the possibility that it arises from inadequate descriptions of the laser-energy transport in the hohlraum have just begun. Recent theoretical and modeling work also shows that laser-energy transport effects possibly lead to a non-uniform ablation pressure driving the capsule. As LPI is the first step in the conversion of the laser energy into pressure to drive the capsule implosion, a lack of full understanding of and ability to control LPI and the transport of X-ray radiation in the hohlraum is viewed as a significant impediment to ignition.

Control of implosion symmetry:

In order to optimally convert the laser energy into mechanical pressure to compress the DT fuel, it is imperative to control the radial symmetry of the capsule as it implodes. Recent results from radiography have shown large perturbations to spherical symmetry in the dense DT fuel. These may arise as a result of issues with the X-ray drive, as discussed above, or aspects of the target such as the presence of polymer support tents, target offsets or other uncertainties associated with target configuration. The lack of a systematic understanding of the origin and control of these asymmetries is thus also viewed as a major technical impediment.

Conversion of kinetic energy into hot spot thermal energy:

The ignition threshold is critically dependent on the hot spot pressure. Computations of spherical implosions indicate that of the 10 kilojoules or more of kinetic energy deposited in the target shell, 3-4 kilojoules of energy is converted into thermal energy at the hot spot. The hot spot energy of the best performing implosions, with an ITFX metric of 0.1, is inferred experimentally to be about 1 kilojoule. Such low conversion of kinetic energy into thermal energy leads to low hot spot pressures, roughly 3 times below the minimum pressure required for ignition of the indirect drive point-design NIC target. In a spherically symmetric implosion, the pressure is a strong function of the implosion velocity. Since NIC target implosion velocities sufficient to achieve ignition have been achieved on NIF, factors other than the shell velocity are causing the degradation in pressure. The observed low-mode shell asymmetries described above are most likely playing an important role. Finding the cause of, and reducing, low-mode asymmetries should have priority as regards the path forward. However, it is also equally important to assess if there are other mechanisms of pressure degradation. To rule out other mechanisms, one needs to show that the pressure is "as predicted" when low-mode asymmetries are not the limiting factor as in low performance implosions with lower convergence than the point design for the NIC capsule.

Mix:

It has long been known that small imperfections present initially at the inner and outer ablator surfaces as well as the inner DT ice surface will lead to growth of interfacial instabilities. These instabilities can cause the mixture of the ablator material with the DT fuel leading to radiative losses, cooling of the hot spot and quenching of the ignition process. Such phenomena are known collectively as "mix". A central goal of the NIC was to develop capsules with sufficiently small interfacial perturbations and to tailor the acceleration coming from the X-ray drive when imploding these capsules to control the hydrodynamic instabilities. Using current modeling and simulation capabilities with observed imperfections in the targets, it was predicted that the ablator and DT fuel layers would survive the implosion in that shell break-up would be avoided and the mixture of ablator and fuel would be limited to acceptable levels. There are now indications from the latest experiments that mix occurs at higher levels than predicted, implying the possibility that the modeling of the physics of mix is inadequate or that the target imperfections may not be adequately represented. It is also likely that thinning of the shell by the aforementioned low-mode asymmetries enhances the penetration of the mixing front. As this issue is investigated further, it may be necessary to revisit and adjust the tolerances for the amount of initial interfacial imperfections present at the initiation of the capsule implosion and the amount of low-mode implosion asymmetry arising from the X-ray drive.

Predictive capability of simulation codes:

At present, the ICF codes are not able to accurately model and simulate the dynamics of the capsule implosion. This is not an indictment of the use of simulation or the level of sophistication associated with these codes and the associated physics models; the codes have been designed using the collective knowledge of the ICF program, which is significant, and they also fully benefit from the advances in computing power that have been developed via the Advanced Scientific Computing program. The main issue here is that some of the models describing the key phenomena as discussed above are incomplete relative to the physical regimes encountered in a NIF shot. Without a sufficiently accurate set of models for LPI, implosion, and mix, predictive simulation and ultimately control of future NIF ignition experiments is at risk.

Assessment of the likelihood for future ignition:

There is insufficient knowledge at present to make definitive statements on the prospects for indirect drive ignition at NIF. While the data obtained from the NIC do not exclude the possibility of obtaining indirect-drive ignition on NIF, they do lead to the conclusion that its achievement remains a considerable technical challenge with an uncertain outcome. Ignition on NIF capsules requires a level of implosion convergence, and hence capsule compression, beyond previous experience. Each of the impediments identified above provides a potential failure mode, but the extent to which they may be controlled or mitigated cannot be appraised without further understanding of the underlying mechanisms. As tasked, reviewers did give personal estimates of the likelihood of future success of ignition with indirect drive; these assessments varied considerably and were tempered by uncertainty over implementation of the path forward. Some reviewers were optimistic while others remain highly skeptical as regards the prospects for future ignition. Reviewers were in broad agreement that the national ICF program should be continued in a direction aimed at gaining a more complete scientific understanding of the phenomena associated with the observed capsule performance.

Priority research directions and path forward for ignition using indirect drive at NIF:

Given the issues discussed above, panel members put forth a number of research directions that should be considered and that can be consistent with the program now initiated through the "Ignition Path Forward" within the ICF community. All reviewers agree that the main goal should be to develop predictive models of the basic implosion phenomena, and to then develop simulations that are informed by these improved models. The following research directions should be considered in the future:

- A set of systematic investigations of the physics of LPI using the NIF laser should be pursued. Additional diagnostics should be fielded to improve measurements of hohlraum plasma properties, laser-energy transport, and X-ray generation particularly at multiple viewing angles. In addition, investigations of variations in hohlraum design, including significant shape variations, should be pursued to learn as much as possible about how such variations affect laser-energy-transport and X-ray generation.

- An investigation of the achievable X-ray drive, and even more importantly, its time dependence and angular distribution as it impinges on the ablator should be pursued. These experiments will provide information on the initial drive. A new effort at LLNL has initiated two types of experiments, the aforementioned Viewfactor experiments and a new set of experiments called Crystal Ball that can potentially provide the needed information.
- Shape experiments using radiography to assess implosion asymmetries in the main DT fuel should be pursued. The goal of these experiments should be to develop a capability to predict, and ultimately minimize, the low mode asymmetries of the main fuel for a given laser drive profile. The Advanced Radiographic Capability (ARC) under development will provide the necessary late-time information, possibly from multiple views on the shape of the compressed core.
- An experimental study should be initiated of implosions with lower levels of capsule convergence. This can be accomplished by comparing the predicted hot spot conditions with those measured in low convergence, thicker shell, implosions where the low mode asymmetries can be controlled. This is a very valuable activity even if those low-performance implosions do not approach the ignition conditions.
- Lower convergence implosions should also be pursued to reestablish predictive capability of the current suite of ICF simulation codes in regimes where the impediments discussed above are thought to be less severe. It is possible that improved physical models are also required to better understand the basic radial implosion process and this can be more effectively studied at lower convergence. This will certainly involve the deliberate use of focused experiments to inform future ignition attempts that require higher levels of capsule convergence.
- A variety of mix experiments to understand the effect of imposed perturbations on the ablator outer and inner surfaces should be pursued. In particular, these experiments should validate the predictions of modeling and simulation of the growth of three-dimensional perturbations.
- Support for the development of improved diagnostics such as the Advanced Radiographic Capability laser should be pursued. The diagnostics fielded by the NIC team have performed exceptionally well to date and have provided invaluable insights into the current implosion process. This type of information is essential in order to develop a predictive capability in the future.

In their comments on the path forward, reviewers expressed broad support for a balanced campaign of focused experiments, as discussed above, and experiments examining full layered capsule implosions where the models are exercised in an integrated way. There was also broad support for further consideration of the research initiatives put forth during the recent very successful conference on the Science of Ignition held in late May by LLNL.

More generally, the reviewers support the view that future efforts should be driven by a diverse community of scientists to ensure adequate scientific breadth in future investigations of ignition. In particular, technical priorities for future path forward investigations should be set through the inclusion of and discussions among a broad community of scientists, i.e. the current NIC team, ICF scientists participating in the NNSA HED program, weapons scientists, as well as academic researchers.

Finally, the reviewers expressed a diversity of views on the appropriate future allocation of NIF shots dedicated to the investigation of ignition. There is broad support, however, for the view that, if enough shots can be dedicated to ignition, three years is an appropriate length of time to carry out the highest priority identified experiments and code modifications, and to assess the prospects for ignition. Reviewers think some regular review of progress toward ignition should occur over that time with significant evaluation at the end of the 3 years.

Department of Energy
National Nuclear Security Administration
Washington, DC 20585

September 24, 2012

Dear Reviewers:

Building on your previous involvement, I am writing to request your assistance in the final independent technical review of the National Ignition Campaign (NIC) at the National Ignition Facility (NIF) on November 13 and 14, 2012, at the Lawrence Livermore National Laboratory (LLNL). The goal of inertial fusion ignition at the NIF will remain important for the Office of Defense Programs (DP) and for the Department. You understand the challenges and opportunities well. The specified NIC ends with the end of this fiscal year, and, while we all hope for a breakthrough, we expect challenges to remain with additional exploration to be done before ignition. Your views will provide an independent summary of the status of the quest for ignition summarizing the outcome of the NIC. As a part of that summary, we want to both understand technical impediments to ignition and receive any view you are comfortable giving on the ultimate prospect of indirect drive ignition at the NIF. Dan Meiron has agreed to chair the review meeting and summarize your views.

We also want to look forward. NNSA, with input from LLNL, Los Alamos National Laboratory (LANL) and Sandia National Laboratories (SNL), will be defining use of the NIF for the coming years, and we have been developing a process to do that. Your comments on the ignition portion of that use will be highly welcome and timely. Based on your review experience, and within the context of the workshop report "Science of Fusion Ignition on NIF," we invite your comments as to which specific studies to give priority to in order to enable continuing progress toward ignition at the NIF. The direct drive approaches are of course an appropriate long-term option, but we remain most interested in indirect drive in the near term.

I hope that you can provide the reviews requested thereby sustaining the independent technical quality and credibility that I hold as critical for this important endeavor.

Sincerely,

DONALD L. COOK
Deputy Administrator
for Defense Programs

Enclosure

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