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SUBJECT: Fourth Review of the National Ignition Campaign

I convened a fourth one-day review of the National Ignition Campaign (NIC) on October 28, 2011 at the Lawrence Livermore National Laboratory. This review is meant to provide an independent technical perspective on NIC progress and plans. It followed the format of prior reviews in which I, and a continuing group of knowledgeable individual reviewers, participated in a set of interactive presentations by the NIC leadership team.

Ignition is an overriding goal for the Department and the focus of activities at the National Ignition Facility. Thirty five experimental shots, including nine with a layered cryogenic capsule (tritium-hydrogen-deuterium, THD, or deuterium-tritium, DT) have been conducted toward that goal since my previous review five months ago.

During the summer the NIC team hosted a 2-week workshop with 17 selected inertial fusion experts to focus on a few of the most important issues that the team is addressing. The exercise enhanced the technical thinking about the ignition campaign and the NIC team has been responsive to the workshop's recommendations.

The NIC presents a mixed picture as it enters its second and final year. Well-diagnosed experiments with a well-functioning laser driving well-characterized, high-quality targets are behaving consistently and are revealing some of the challenges in achieving ignition. Some of these challenges are being addressed successfully, while others are so far proving more recalcitrant. There are also large gaps in our ability to simulate experimental results and to do extrapolative predictions.

The team has laid out an aggressive schedule culminating in ignition by end of FY12. The semi-empirical "tuning" strategy is crucial to meeting that schedule. The superb control of laser power and experiment parameters enables subtle iterations that require a number of experimental shots. While there have been technical difficulties with layered targets and optics, shot rate has increased somewhat and higher shot rate will be needed for the coming experiments. Progress during the next six months to the alpha-heating milestone will be an important indicator of whether such an approach will be successful or a more fundamentals-driven program will be necessary.

Experimental progress since the last review

An important measure of progress toward ignition, the experimental Ignition Threshold Factor (ITFX) has increased by a factor of 5 since June and currently stands at about 10% of what is required. This progress is roughly in accord with the campaign plan, but is less than what had been anticipated with the excellent experiment control and laser parameters achieved.

Specific improvements to target and laser pulse since the last review include:

- The baseline target has been adjusted to improve the x-ray drive to the capsule; the hohlraum diameter has been increased from 5.44 mm to 5.75 mm and the capsule's dopant layer is now dominantly silicon, rather than germanium. This has resulted in better implosion velocity and more flexibility in the control of crossbeam laser power coupling.
- The laser power delivered has been adjusted in specific timing, wavelength separation between beams, and power balance. These changes gave most, but not all, of the expected improvements in coupling power into the capsule. For example, the 4^{th} power rise at the capsule did not steepen.
- Laser pulse tuning has also demonstrated good control of the lowest shape mode (P2 - round rather than flat). However, the higher modes (4-sided and others) are not smooth; these can be further tuned by relatively small laser changes.
- Gold-coated, depleted uranium hohlraums, tested at the Omega laser, are being implemented now at the NIF with the initial experiment showing some increase in late time x-ray drive over gold hohlraums equivalent to a 20-30 TW increase in laser power.
- The timing in laser power steps was changed to match the tuning experiments, and laser energy and power were increased to 1.6 MJ and 420 TW from previous highs of 1.3 MJ and 380 TW, primarily in the 4^{th} pulse. The power can be increased further and 500TW is expected during this fiscal year
- Higher areal densities in the fuel (for stopping fusion alphas) were obtained and the implosion velocity was increased from 310 km/s to 350 km/s, although it is still 5% lower than desired and 10% lower than expected for the power applied.
- The ion temperature is now consistent with simulations and the adiabat obtained is only a little higher than desired. However, for example in the 1.6 MJ DT shot, the density in the hot spot is 3 times lower and the yield of neutrons is an order of magnitude lower than expected and needed.

A key issue is how four step-increases in laser power drive the x-ray field in the hohlraum. The steps generate four shocks in the capsule that must be timed to coalesce at the inside layer of the converging DT ice in order to ensure the low fuel adiabat, high velocity, and smooth shape needed for ignition. A shock tuning campaign produced useful adjustments to the timing of the first 3 shocks and revealed that the fourth shock (main pulse) rises more slowly than expected.

Experimental capabilities now exceed those most observers had expected and surprises have emerged with increasing and improved experimental data. For example, a new mirrored VISAR system can "see" the shock timing, including the crucial 4th shock, in two directions in "keyhole" targets. Unexpectedly, it showed asymmetric shock velocity. A shot on the day of the review demonstrated an interpolative laser drive modification that produced much more symmetric shocks, although the consequences of that improvement are not yet known.

Gaps in understanding

Important aspects of the target performance are not understood. Current shortfalls in simulations include the following:

- When the convergent-ablator experiments are turned to early-time phenomena, the in-flight ablator thicknesses exceeds predictions by a factor of 2 or so.
- The simulations require large *ad hoc* adjustments to the laser drive (e.g., a multiplier of 0.4 on the rise of the 4th shock, together with various time-dependent multipliers of at least 0.8 or so). This shows an inadequate understanding of the energy deposition by the laser in the hohlraum and/or the coupling of the x-ray field in the hohlraum to the capsule.
- Even with an "adjusted" drive, the experimental yields are only about 5 to 20% of that predicted by simulations and this discrepancy remains unattributed. Either inputs to the simulation (e.g., drives, geometry, etc.) are still not representative, or the resolution is inadequate, or the material models within the code are inadequate, or the physics embodied in the code is inadequate, or some combination of the above.
- There is clear indication based on Springer's isobaric model that the experimental hotspot masses and the experimental hotspot pressures are factors of 3 or more lower than expected. An intact, controlled hotspot with pressures of several hundred Gbar (instead of the 80 to 120inferred) and a sufficient hotspot areal density (not just overall system areal density), are essential for ignition.

No doubt other shortfalls will arise as experiments progress and all might be resolved with sufficient effort. Unfortunately, the schedule-driven NIC will not readily accommodate such activities. The ability to work around such shortfalls is therefore crucial to the NIC's tuning strategy.

Expectations

It has long been recognized that achieving thermonuclear ignition in the laboratory is a difficult technical undertaking. It is, first and foremost a research project not obviously compatible with the schedule-driven NIC formulation.

The next 6 months should see many experimental/simulation iterations. If ITFX can be further raised by a factor of 3 or more, alpha deposition will begin to dominate the yield of neutrons, marking a heretofore unobtainable plasma regime.

Surprises encountered on the path to ignition make it impossible to predict confidently the rate of progress on those issues of greatest concern to the NIC and so ignition by the end of FY-12 is not assured. It would therefore be prudent to devote some effort to understanding what might be the criteria for, and nature of, a "Plan B" post-FY12. Clearly what we continue to learn in the NIC will inform that effort.

The issues currently degrading ignition performance have no direct relationship to nuclear weapon performance so that progress in the NIC has no direct implications for Stockpile Stewardship. Other non-ignition NIF experiments directed at specific stockpile issues have already been very successful. The already high value of the NIF for Stockpile Stewardship would be greatly enhanced by the experiments ignition would enable.