Background on the National Ignition Facility (NIF) Project Discussed in the Assessment by Dr. Stephen Bodner

The Natural Resources Defense Council asked Dr. Stephen Bodner, former Director of the Laser Fusion Program at the U.S. Naval Research Laboratory in Washington, D.C., to attend the November 2010 Annual Meeting of the American Physical Society, Division of Plasma Physics, and provide a written assessment updating NRDC's Nuclear Program on the technical status and prospects of achieving inertial confinement fusion in the National Ignition Facility (NIF).

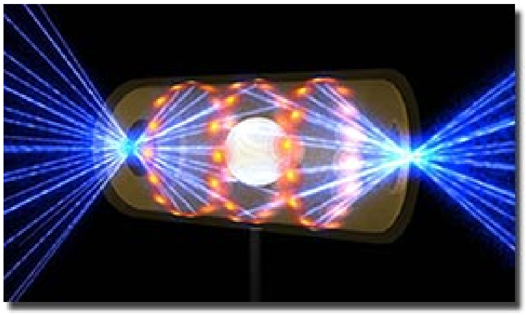
NIF is a solid-state glass laser facility the size of three football fields that has been constructed over the past 13 years, at a total project cost exceeding $ 5 billion dollars, at the Department of Energy's Lawrence Livermore National Laboratory in California for the primary purpose of achieving controlled thermonuclear fusion in the laboratory by means of "indirect drive" inertial confinement fusion, a technique intended to convert laser energy into a specially shaped pulse of x-rays that ablates the surface of a tiny spherical fusion target and propels it inward, compressing it to a very high density.

In a series of lawsuits and studies conducted during the period 1996-2000, NRDC's Nuclear Program sought to put the brakes on this now $5 billion plus project, arguing that the then cost estimate of $1.7 billion was illusory, and that the scientific understanding and technology base to support a successful attempt at inertial fusion had not yet been sufficiently demonstrated. Despite the impressive but costly advances in solid state laser and optical technology achieved by the NIF Project, Dr. Bodner's report suggests that the complex physics of using a massive laser pulse to uniformly illuminate a fusion capsule with x-rays, compressing and heating it to fusion conditions, remains a major challenge, despite the confident declarations made more than 13 years ago that the physics and technology obstacles had had been mastered sufficiently to justify construction of the most costly and complex laser facility in history.

In the case of NIF, "fusion ignition" may be defined as obtaining as much fusion energy out of the tiny millimeter-scale target capsule of frozen heavy hydrogen as the huge laser system is required to deposit in a tiny centimeter-scale gold-lined cylinder, called a "hohlraum," to get the fusion reaction going. The hohlraum surrounds the target and acts, in physical terms, as a radiating black body cavity, converting the laser light energy into a shaped pulse of x-rays. These are intended to uniformly compress and heat the spherical target capsule to levels that will spark formation of a propagating fusion "hotspot "at the center of the compressed material. While this is not the same mode of ignition used in nuclear weapons, the overall concept resembles in microcosm what occurs on a much larger scale in the secondary component of a two-stage thermonuclear device, except that the x-rays in micro-fusion are generated by lasers instead of being produced by a precursor fission explosion equivalent to several hundred to several thousand tons of TNT.

This relationship to nuclear weapons is why DOE's indirect-drive ICF program is funded and managed by the National Nuclear Security Administration (NNSA), the quasi independent unit of the Department of Energy that administers the nation's nuclear weapons laboratories and production complex. The quest for indirect drive ICF on the NIF is also said to have value as a training tool for the next generation of nuclear weapons scientists.

This substantive and pedagogical linkage to nuclear weapons raises proliferation concerns about the continued development and diffusion of special expertise in indirect-drive ICF, and indeed – because it involves mastering complex computational modeling of hydrodynamic and thermonuclear phenomena – about the spread of ICF in general.



An LLNL artist's rendering shows a NIF target capsule inside a cylindrical hohlraum with overlapping cones of laser beams entering through openings on either end. The light energy must be distributed on the walls of the hohlraum in a manner that results in uniform compression and heating of the target to the necessary conditions for nuclear fusion to occur. Graphic Courtesy of LLNL.

Obviously, a lot can and historically has gone wrong with a scheme as complex and uncertain as indirect-drive ignition in the NIF:

- The intense ultraviolet light from the lasers can damage their costly final focusing optics, forcing reductions in the amount of laser energy that is available for focusing on the inside walls the hohlraum.

- The hot plasma created by the first arriving light beams can interfere with the light arriving in the later portion of the pulse, a partially understood process called "laser-plasma instability," avoidance of which has shaped many of the basic NIF design decisions

- The 48 individual beam "quads" (groups of 4 laser beams) that share frequency conversion crystals and final focusing optics must simultaneously be very tightly focused but also nearly uniform in their distribution of the light's intensity across the beam in order to control precisely the deposition of energy within the hohlraum. Techniques used to "smooth" the beam trade off a larger focal spot size – which can be a problem in its own right -- for reduced fluctuation in the intensity of the light striking the inner walls of the hohlraum.

- Without a form of smoothing called "spectral dispersion" – i.e. deliberately dispersing the beam energy across a wider band of frequencies around the light's central frequency -- hot spots can form in the beam that push the plasma in the hohlraum out of the way, via photon pressure. The resulting lower plasma density has a higher index of refraction, thus acting like a miniature lens. These plasma lenses focus the laser hot spots, increasing their intensity, and thus aggravate the problem of "laser-plasma instability," which in turn reduces the conversion of light energy into x-rays and thus the amount and distribution of energy available to compress and heat the target.

- Multiple inner and outer “cones “of laser beams streaming in from both ends of the holhraum can interact in ways that transfer energy from one beam to another, redistributing it in unpredictable ways.

- The x-ray flux from the hot plasma produced by the laser beams striking the gold walls at designated points on the inner surface of the hohlraum may not have the specific spatial and temporal distribution of energy needed to compress the capsule uniformly (via rocket ablation of its plastic outer surface) thereby preventing the central “hotspot” from achieving the required temperature for fusion.

- The process of plasma formation can give rise to unpredictable streams of hot electrons that penetrate the target, “pre-heating” it and preventing the necessary degree of compression.

- Inertial confinement of the fleeting central “hotspot” long enough to ensure its propagation into the colder surrounding fuel may not occur at achievable levels of energy deposition in the target, or may be undermined by the growth of “hydrodynamic instabilities” in the imploding shell material that destroy the uniformity of the implosion and curtail hot spot formation.

- To prevent or compensate for all these different effects, the NIF scientists must not only be able to diagnose and quantify them-- itself a major technical challenge—but also understand their interdependence.

Dr. Bodner’s assessment suggests strongly that the problems of light-scattering laser-plasma instabilities, and unpredictable beams of high-energy electrons preheating the tiny target, remain potential showstoppers for indirect-drive ICF, 13 years after an earlier biased and conflicted NAS Review Committee had deemed them vanquished. And he notes that for decades, NIF target designers have been neglecting a fundamental physical effect – dielectronic recombination -- in their computer modeling, despite the billions of dollars the nation has expended on giving them the most advanced computational facilities in the world. (For more on the history and problems of the NIF Project, see the “Comments of Christopher Paine to the NAS Committee on Prospects for Inertial Fusion Energy,” also posted on the Nuclear Program web page)

A Troubled and Costly History

None of the potentially crippling scientific uncertainties mentioned in Dr. Bodner’s report are new, and none were definitively resolved during the brief NIF development effort from 1993 until 1997, when a weakly supported (and highly politicized) DOE decision was taken in haste to construct the facility—at the time the Clinton Administration was anxious to placate the nuclear weapons design establishment in order to ratify the Comprehensive Test Ban Treaty (CTBT). In the event, the leaders of the DOE weapons labs damned the CTBT with faint praise, testifying that NIF and the other costly new “stockpile stewardship” tools could not ensure indefinitely their ability to certify the safety and reliability of the nuclear weapons stockpile.

The story of Inertial Confinement Fusion (ICF) research at the nation's nuclear weapons laboratories stretches back to the early 1970's. Livermore physicist John Nuckolls (who later became LLNL Director in the late 1980's) first predicted fusion ignition in 1972 with just one kilojoule (kJ) of energy, sparking construction of what were then considered big lasers at both laboratories. When this prediction failed, the DOE weapons labs successively predicted ignition at 5 kJ, 10kJ, 100kJ, 200kJ, and finally 1.8 megajoules (MJ). They built a succession of lasers – Argus, Shiva, Nova, and the NIF Beamlet at Livermore, and Gemini, Helios, Antares, and Aurora at Los Alamos – with each machine's failure to perform as predicted justifying the construction of the next (more powerful) machine.

Livermore concentrated on the development of shorter wavelength glass lasers, while Los Alamos focused initially on longer wavelength CO2 lasers. However, when the advantage of short–wavelength lasers in coupling laser energy to the target was established in the early 1980's by scientists at the Ecole-Polytechnique in France, Livermore, and other laboratories, Los Alamos panicked and abruptly changed course, secretly siphoning funds from the large "multiline" Antares project in an ultimately abortive attempt to develop a short-wavelength krypton-fluoride (KrF) "target shooter" (Aurora) that could compete with Livermore's glass laser technology.

Livermore's reputed success with the Nova Laser, as well as the disarray in the LANL ICF program, influenced the critical 1990 NAS Review that led directly to NIF. Nova, which went into operation in 1984, was originally planned as a 20 beam, 200 kJ laser that Nuckolls had calculated could create the conditions for ignition. Both the short wavelength Nova and LANL's longer-wavelength multi-line Antares carbon-dioxide laser were sold to Congress as fusion "ignition" lasers. After Nuckolls detected an error in his calculations, an October 1979 review chaired by John Foster of TRW confirmed that there was no way Nova would reach ignition. A "deal" was worked out in which Livermore received the full funding -- $186 million -- that had been requested for the original 20-beam facility, but agreed to scale it back to a "science-oriented" 10-beam facility operating with frequency tripled (blue) light.

Livermore also agreed to drop its claim that Nova could ignite a target; a task that the lab was soon projecting would be within range of the next big machine – "Nova Upgrade" – which soon morphed into NIF. After Nova construction was under way, Livermore backpedaled to 50-70 kJ of laser light at the third harmonic, while LANL promised 100 kJ with multiline Antares. In actual routine operation, however, even after extensive and expensive upgrades, Nova remained in the range of 20 -- 30 kilojoules, constrained by optical coating damage and nonlinear optical effects that were never overcome. This may be contrasted with the 1.8 megajoule design requirement for NIF, not yet achieved in the ultraviolet spectrum used for ignition experiments, which represents a huge 60-fold leap from Nova's beam energy after conversion to the shorter wavelength UV light.

Then as now, the only empirical confirmation that fusion via indirect drive *might* be feasible at laboratory scale came in the 1980's, from a secret DOE weapons lab ICF project called Halite-Centurion, which used the x-rays from underground nuclear test explosions to implode fusion capsules that were small in relation to nuclear weapons, but still quite large in comparison to what might be practically pursued in a fully-contained laboratory setting. It can be deduced from the fragmentary information in the public domain about these experiments that targets designed to absorb less than about 20 MJ in the underground tests failed to achieve "ignition," (i.e. an energy gain of at least one), and that the coupling efficiency of the incident x-ray energy to the target was perhaps on the order of 20-25%, indicating a "driver" pulse as large as 100 MJ might be needed.

As shown in Dr. Bodner's report, these known benchmarks stand in sharp contrast with the 160 kilojoules that NIF scientists now say are budgeted for deposition in a scaled-down NIF capsule driven by only 1.3 MJ of UV light delivered to the hohlraum.
While significant dissenters remain, particularly at Los Alamos, then as now the prevailing wisdom in the laser micro-fusion community might be summarized by the aphorism "energy is just a matter of size," meaning that all the important parameters needed for ignition can be scaled down to the x-ray wavelength and temperature-pressure region planned for NIF.

On the one hand, one may hope, given the vast public sums expended on the National Ignition Facility, that this premise holds true in the end, and that long quest for indirect-drive fusion ignition will not end in a total debacle for taxpayers. If it does not, it seems that perseverance, copious funding and dumb luck, as much as technical brilliance will have played a major role. But at about $450 million per year, this quest is very costly, has squeezed funding for other fusion approaches and the DOE energy research budget in general, and obviously cannot go on indefinitely.

On the other hand, others might welcome the failure of indirect-drive ignition on the NIF as a contribution to nuclear nonproliferation, as it would discourage others from pursuing this thermonuclear-weapons-relevant route to fusion energy. Moreover, as a single-shot system designed to deliver a shaped high-energy pulse once or at most a few times a day, NIF was not designed to be the prototype of an IFE system, and a successful evanescent demonstration of ignition will actually prove little about the ultimate feasibility of achieving practical and economical inertial fusion energy from a high-average-power system. Indeed, the technical obstacles encountered with NIF suggest that development of commercially relevant fusion power is on a timescale that has no bearing on meeting the pressing national and global imperative to decarbonize our energy supply systems.

In the meantime, the nuclear weapons stewardship justification for NIF remains weak, as it is not directly relevant to the technical issues involved in maintaining the "safety and reliability" of the fission primary components of nuclear weapons, where such concerns are concentrated, and the U.S. nuclear weapons stockpile has long been, and can continue to be maintained without NIF. Since the end of U.S. nuclear explosive testing in 1992, NRDC has advocated shifting to a simpler, more restrictive, and less costly paradigm for maintaining the nuclear weapons stockpile, one that would better position our nation to take the lead in the global reduction and eventual elimination of these weapons.

Christopher Paine, Director
NRDC Nuclear Program
December 16, 2010