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Use of the National Ignition Facility for Defense, Energy, and Basic Research Science

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I. Introduction

On January 15, 1993, the Department of Energy (DOE) approved the Justification for Mission Need (JMN) for the National Ignition Facility (NIF). This action (Key Decision Zero, or KD0) commenced the conceptual design for the facility, which has resulted in a recently completed Conceptual Design Report (CDR). The JMN document defined the NIF mission elements to include laboratory fusion ignition and energy gain, weapons physics, and nuclear weapons effects testing research (NWET). NIF has a dual benefit by contributing to inertial fusion energy (IFE), industrial technology development, new basic science areas applying high power lasers, and training young scientists for future stewardship activities. For consideration of the next DOE action, Key Decision One (KD1), all mission elements of the NIF as stated in the JMN are consistent with and important to the US stockpile stewardship program, and are expected to continue to be in the vital interest of the United States for the long term.

This document provides further information on the utility of NIF for stockpile stewardship, including support for a Comprehensive Test Ban Treaty (CTBT), and specific findings of four national workshops on the NIF utility for weapons physics, NWET, IFE and basic science research. The role of NIF for stockpile stewardship has been refined since a DOE meeting in Albuquerque, NM Feb. 1–2, 1994. The possible compliance of NIF research with anticipated CTBT and NPT limitations was discussed at the DOE Office of Arms Control and Nonproliferation in Washington, DC on March 8, 1994. The utility of NIF for IFE, weapons physics, NWET, and basic science research was considered by potential user groups in four workshops held Feb. 22–24, at UCB; Feb. 28–March 2 and March 15–17, at LLNL; and March 21–22, at UCB, respectively.

All of the experiments discussed in this paper are proposed independently of the current NIF Conceptual Design. This has several consequences: first, the facility requirements implied by these proposals must be formally reviewed by the project team to ensure capability with established project requirements; second the environmental envelope implied by the proposed experiment must fall within established NIF environmental impacts; finally, any facility conceptual design changes must undergo the established review process (under consideration by DOE). These activities are anticipated being addressed by advanced NIF Conceptual Design efforts.

II. Utility of NIF for Stockpile Stewardship

Effective science-based stewardship requires understanding, predictive capability, experiments and simulation, as well as a strong interdisciplinary science, engineering, and technology base. NIF will be a key new DP facility central to the success of this long-term stewardship strategy. In carrying out this mission, NIF will help retain the necessary scientific and engineering skills at the laboratories required for future stewardship as well as for US science and industrial competitiveness.

NIF is one of the few new DP capabilities recommended for an effective, science-based stewardship without underground weapon tests. The three most essential parts of a necessary stockpile stewardship program with a comprehensive test ban are the NIF, along with a hydrodynamic test facility and advanced numerical weapon design codes, to maintain confidence in the safety and reliability of our remaining strategic stockpile. ICF is useful primarily because the implosion of an ICF target mimics, on a much smaller scale, some thermonuclear processes in a nuclear weapon. Data from the NIF would be complementary with data from a hydro test facility, so that together they would form a more complete set of data relevant to many aspects of weapons. The NIF provides a very accessible and well-diagnosed experimental environment to obtain high quality weapons physics data that will contribute to improving our fundamental understanding of many key processes in our sophisticated nuclear weapons.

The NIF data would be used to benchmark and improve computer codes that are needed to certify the safety and reliability of our remaining stockpile. Relevant processes that NIF can contribute data to are in the areas of fusion ignition and propagating burn, radiation transport, opacity, equation-of-state, hydrodynamics, radiation hydrodynamics, and instability/mix. The NIF approaches most aspects of high energy density physics of weapons at useful scale lengths (greater than a Rosseland mean-free-path or a relevant hydrodynamic wavelength) more closely than any other proposed capability. Only the NIF, through ignition and fusion burn of a capsule, can produce neutrons on a sufficiently short pulse to volume heat materials isochorically in neutron coupled experiments.

The improved understanding of fundamental weapons physics and more accurate computer codes gained from NIF experiments will lead to better simulation and interpretation of data from the archives of our past underground tests. NIF data will improve understanding of processes important to weapons, which in turn will improve our predictive capabilities for

assessing various effects of aging on the performance and reliability of the stockpile. These same improved predictive capabilities would also help the US evaluate the implications of weapon tests of countries who may violate a CTBT, and to evaluate options for disarming or mitigating the threat of terrorist nuclear weapons.

For the long term, NIF will be the reason talented young scientists can be available for our national security needs in the future. Aside from benchmarking and improving physics models in nuclear weapon codes, the NIF will be vital to attracting, training, and retaining talented young scientists who will be needed to carry out our future stockpile stewardship program. The design, development and deployment of new nuclear weapons will not continue with a CTBT; however, the work of these future scientists, using NIF, will be critical in assuring the continued safety and reliability of our future stockpile with the CTBT.

III. NIF Compliance and Support for a Future CTBT and NPT

ICF has been acknowledged not to be a nuclear explosion, in the sense of a nuclear weapon, in previous arms control negotiations (1975 Nonproliferation Treaty review conference). NIF will produce maximum fusion energy releases equivalent to 22.5 pounds of TNT for defense applications. These NIF energy releases will be millions of times smaller than typical nuclear weapons, and would be contained nondestructively in a laboratory chamber.

Sensitive information generated using NIF for the U.S. Stockpile Stewardship Program can be protected because the NIF will be a secure facility. It will be conducting both classified and unclassified research at a US national laboratory, with the Environmental, Safety, and Health (ES&H) monitoring and safeguarding infrastructure pre-requisite to any national DOE lab.

All the nuclear weapon states (US, France, Britain, Russia and China) have developed ICF capabilities, and are planning major upgrades to their existing ICF facilities. For these countries and the US, ICF supports the US goal of securing a CTBT, because the existing nuclear weapon states will be more motivated to sign a CTBT if they each have ICF facilities to provide confidence in the safety and reliability of their own remaining stockpiles as well as its other dual benefits. For non-nuclear states, supporting ICF helps

induce the nuclear states to sign a CTBT, which itself provides the biggest impediment to the development of new, more powerful weapons. For nuclear-capable states traditionally allied with the US (such as Japan), supporting NIF would help maintain credibility of the US nuclear deterrent without testing. Nuclear-capable states with belligerent neighbors would be less motivated to develop their own nuclear weapons if the US continues to maintain a credible nuclear “umbrella”.

IV. Findings of National Workshops on The Utility of NIF

A. Overview of NIF Workshops

The ICF program from its inception has studied many potential applications of ICF technology and has interacted with potential user communities to understand their needs. These communities recognized that the accomplishment of fusion ignition in the laboratory would fundamentally change the usefulness of ICF, and therefore set the minimum basic requirements for the National Ignition Facility. This report looks beyond the basic ICF ignition requirements and explores the full flexibility of NIF to meet a broader range of experiments to support all of the user communities.

Scientists from many labs, universities and industries, and from many different disciplines from across the US were invited to four workshops early in 1994 to discuss the experimental opportunities that NIF may offer to advance research in weapons physics, NWET, IFE, and basic science research. The general purposes of these workshops were to acquaint these potential users with the current NIF design concepts and capabilities, to solicit their ideas and suggestions on what the most important and unique experiments in NIF would be in each area, and to identify any special requirements that NIF may need to support the suggested experiments. These workshops were a major step in continuing to identify and understand these customers' needs, and to guide future NIF design.

The NIF Functional Requirements and Primary Criteria were developed in support of achieving inertial fusion ignition. The inherent flexibility of the NIF to achieve its fusion ignition goal is expected to accommodate the experimental campaigns envisioned for the NIF in the JMN. The NIF-user workshops were commissioned, as anticipated in the NIF Conceptual Design Scope and Plan (NIF-LLNL-93-043), to understand more details of and the needs for experiments in weapons physics, NWET, IFE and basic science research.

Each of the workshop findings reported in the following sections attempts to identify many of the target area and laser systems needs to support the experiments described. These needs appear consistent with the NIF Functional Requirements and Primary Criteria. However, some of these needs may suggest changes in the established NIF System Design Requirements in order for NIF to support them.

The most common needs of the several user groups are highlighted in the following paragraphs. The main thrust of these proposed changes is to enhance the utility of NIF for stockpile stewardship, and to increase flexibility of the facility to accommodate a wider variety of experiments. Detailed explanation of the reasons behind these specifications can be found in the summary reports of the NIF workshop on Weapon Physics and the NIF Workshop on Applications of High Intensity Lasers. Ongoing evaluations and future experiments and analysis will better refine these needs.

1. **Higher Beam Irradiance Requirements.** Some weapons physics experiments will require higher beam irradiances than those demanded by ignition targets. The present laser spot diameter requirement for ignition targets, utilizing kinoform phase plates for beam conditioning, is 500 μm . This will be achieved using adaptive optics with the number of actuators consistent with this requirement. The NIF Functional Requirements and Primary Criteria specify the *maximum* spot size to be 500 μm . For higher irradiances that may lead to increased hohlraum temperatures and pressure desirable for weapons physics, smaller spot sizes are needed (e.g., 100 to 150 μm), or as small as possible and practical. Higher irradiances than for the present design may be obtained by increasing the number of actuators in the adaptive optic. Experiments planned on Beamlet will address beam quality, minimum spot size, and the effort required to achieve it. Following these experiments, planned as part of the supporting technology development activity, the minimum achievable spot size will be specified prior to the completion of Title 1 engineering. Beam pointing requirements, consistent with a tighter focus, will also be evaluated prior to completion of Title 1 engineering. To facilitate point projection x-ray backlighting, beams when focused to the minimum spot size should be able to effectively irradiate a 25 μm diam fiber, or equivalent, to achieve the needed backlighting.
2. **Variations in Lens Focusing Requirements.** The NIF should have the capability of putting cylindrical lenses on at least 20 beamlets for experiments utilizing laser driven x-ray lasers. These lenses should nominally produce a focus of $\sim 150 \mu\text{m}$ x 5 cm. These lenses should be capable of being easily inserted and removed. These

beamlets should also be able to operate at 2ω at power levels consistent with that required for x-ray lasers.

3. **Target Chamber Insertion Mechanisms.** The target chamber should have two target insertion mechanisms. The second target inserter does not have to have a cryogenic capability.
4. **Added Target Alignment Capabilities.** Weapon physics targets are in general more complicated than ICF targets so additional target alignment capabilities may be needed. This is most simply specified by requiring that there exist the capability to view all sides of the targets(s) during target alignment.
5. **Enhanced Shielding.** Many weapons physics experiments may be conducted at higher temperatures than ICF experiments. More extensive or backlighting requirements may be greater and heavier shielding may be needed for close-in surfaces such as the 12-inch manipulator tubes. Calculations need to be performed to determine if and how much additional shielding is needed prior to Title I engineering design.
6. **Reduced Time Between Shots.** To accommodate the expected large number of users, the time between shots should be reduced below the maximum specified eight hours. The NIF Functional Requirements and Primary Criteria specify the eight hours as the *maximum* allowed. Engineering modifications including active gas flow cooling of the amplifiers and operational adjustments including staged firing of the amplifiers are being considered to reduce the time between shots as much as practical. Experience on the Beamlet and the prototype amplifier development program will clarify the procedures and design prior to Title I engineering design completion. The facility should incorporate the improvements that are developed from these programs to ensure greater access to the user communities.
7. **Flexible Time Intervals Between Shots.** Finally, it is important to note that the largest possible timing and pulse duration flexibility needs to be incorporated into the design. Individual beamlet pulse length flexibility, as presently designed into the CDR, is highly desirable with range-of-pulse widths from <0.1 ns to >20 ns. NIF System Design Requirements should permit each cluster of four beams to be able to be independently timed with arbitrary time delays among the clusters. Time interval between first and last beams should be >200 ns. If possible, delays of up to 4000 ns between beam groups would be beneficial to some users.

These user needs are consistent with the present NIF Functional Requirements and Primary Criteria, and are also expected to be consistent with the NIF CDR total cost (including contingency). As detailed requirements for these other experimental needs become better

defined over the next year, the NIF Project Office will determine, on a cost-benefit basis in conjunction with the user groups, any NIF System Design Requirements which should be modified to best accommodate their additional needs before Title I design would start. This near-term activity is included in the National Ignition Facility Title I Preparedness Plan (NIF-LLNL-94-194). Resulting recommendations for any changes in System Design Requirements which would increase project costs will be subject to change control review and approval as specified in the NIF Project Management Plan.

B. Weapons Physics Experimentation on NIF

Introduction

The purpose of the weapons physics workshop was to illuminate potential opportunities for weapons physics research on the proposed National Ignition Facility, and to thereby further develop the mission need for the laser. The workshop was set up around previously organized working groups that covered various subareas of weapons physics. The working group areas were: opacity and atomic physics, radiation flow, diagnostics issues, hohlraums, code development, hydrodynamics in both planar and converging geometry, NLTE physics and x-ray lasers, equations of state, uses of ignition, x-ray outputs, issues of primaries, and advanced ICF ignition targets. Each of the working groups presented a plenary talk to the full workshop attendance and then reconvened to further develop their ideas for NIF experiments. There were also plenary talks as a group on capsule designs for ignition and on the basic configuration of the NIF laser system needed for fusion and the attendant diagnostics. There was considerable overlap in the subjects considered and significant interest expressed in the other three workshops that concentrated on fusion energy, basic science research and weapon effects research.

The fundamental conclusion of the weapons physics workshop was that the NIF would be a very powerful tool for studying many of the relevant processes in thermonuclear weapons at or near the relevant regime. Examples were opacity, radiation transfer, equation-of-state, and unstable hydrodynamics, as well as DT burn itself. The unifying reason that the proposed National Ignition Facility produces the correct physics for this seemingly disparate list of topics is that its energy density is appropriate for indirect drive fusion. To illustrate this point, the plenary speakers presented fairly conservative calculations that showed that NIF experiments could probe high Z opacities at interesting densities, radiation transfer in samples big enough to have many Rosseland mean free paths, large scale EOS experiments at several gigabars, Rayleigh-Taylor instability, and Richtmeyer-Meshkov

instability experiments at Mach numbers of over 30 and Reynolds numbers of 10^6 , NLTE ionization balance studies at fairly high Z, and LTE hohlraum temperatures of great interest. Another fundamental conclusion was that the NIF (or any laser system, like Nova for instance) has the capacity for doing systematic, well-characterized experiments because the laser beams can be divided into a set that prepares the high energy density target, and a set that prepares a well-characterized backlighter that probes the experiment and goes to the detector. Most of the experiments proposed in the areas mentioned above would be done this way. There is already considerable experience in doing such experiments very successfully on Nova and other lasers, and this experience would carry over onto the NIF.

Code Development

To a large extent, our weapons codes embody the corporate knowledge associated with weapons design. NIF data will help to improve and refine these codes to enable more accurate modeling of results from previous weapons tests and weapons physics experiments. Code development for ICF research has focused on the need to calculate many coupled physical processes in non equilibrium conditions and to simulate all resulting experimental diagnostics within a single computational model. In the future it will also involve the need for higher accuracy and increased engineering detail that will require better numerical methods, fully three-dimensional simulations and massively parallel computers. These ICF code capabilities will be important to weapons researchers who will need to explore the validity of any equilibrium approximation, and understand the results of NIF weapons physics experiments.

Role of Ignition

Ignition encompasses two distinct weapons physics issues: application of igniting capsules to the physics of weapons, and application of NIF target design to maintenance of critical skills. Two broad areas appear uniquely accessible to an ignition capsule. (1) The possible use to study onset of DT ignition in the presence of impurities, which can occur from mix of intentional contaminants placed in the gas. The NIF ignition facility will provide the only place where high density DT will occur in the critical ignition regime. (2) The generation of x-rays from the capsules. This will challenge our ability to model and understand burn, energy balance, and transport processes in a highly transient system having large gradients.

The NIF capsule output will not only compel physicists to model ignition, burn and transport, but can also prove useful for other experiments. Along with x-rays, the NIF capsules will also provide an intense source of 14-MeV neutrons. It is possible to use the

x-rays and neutrons to heat materials isochorically. Using the neutrons, one could instantaneously volumetrically heat material to temperatures more than 50 eV. This is a unique capability and may prove useful for other weapons physics studies such as equation-of-state experiments.

Designing capsules for the NIF is a real design problem and will challenge designers, computational physicists, and engineers. Designs, which tailor capsule output and explore efficient capsule operation, will require the diligence, innovation, and skills of weapons scientists and engineers. Such modeling will challenge our understanding of many fundamental processes associated with weapon design, and will help keep us at the leading edge of this technology.

Advanced ICF Targets

The NIF will allow us to examine several more advanced ICF target issues. One idea, the Fast Ignitor, would provide the functionality of a Laboratory Micro Fusion Facility at a greatly reduced cost and with much earlier availability. This would facilitate study of a number of issues associated with weapons physics. Studies of other advanced ICF target designs would lead to improved understanding of hydrodynamic flow in weapons physics. As with the challenge of ICF baseline ignition, these ideas all involve very challenging ICF and weapons physics. The scientific pursuit of solutions to these physics challenges will add in maintaining inventiveness and flexibility on the part of weapons physicists.

Non-LTE Physics and X-Ray Lasers

The NIF will allow us to address important issues in non-LTE physics and laser-driven x-ray laser physics. Non-LTE physics addresses situations when plasmas are not in thermodynamic equilibrium. Understanding non-LTE effects plays an important role in determining x-ray outputs, in developing temperature, ionization balance, and kinetics diagnostics, and is essential in the development of laser-driven x-ray lasers as a plasma imaging diagnostic. In the specific area of x-ray lasers, NIF will allow us to explore x-ray laser pumping schemes with various materials and conditions. Plasma conditions achieved with the NIF laser will allow us to explore important nonequilibrium effects in ignition and weapons physics.

An important dual benefit of the x-ray laser research is its use as an imaging system for both ICF and weapons physics experiments. The x-ray laser offers many advantages over conventional backlighters for imaging. Recently we used an yttrium x-ray laser to perform

Moiré deflectometry on laser irradiated targets and to perform high resolution imaging of thin accelerated foils. We plan experiments to do Mach-Zehnder interferometry with an x-ray laser source and eventually extend this to flash 3-D interferometry or holography. The high brightness, narrow bandwidth, small source size, and short pulse duration of x-ray lasers are the main advantages for use in these imaging systems. As a valuable spin-off, the NIF laser could provide conditions required to produce an x-ray laser at 38 Angstroms or shorter wavelength. This wavelength is at the water window for potential microscopy or holography experiments on biological samples.

In general, x-ray lasers are proving to be an important diagnostic for weapons physics plasmas. These lasers offer an unprecedented capability for measuring electron and ion densities, and therefore, equation-of-state .

Hohlraum Conditions for Weapons Physics Experiments

For hohlraums driven by the NIF laser, calculations indicate that high radiation temperatures are possible with minimal hot electron production. In addition, the NIF will provide well-balanced 300-eV radiation temperatures for 6 to 8 ns on larger scale (several mm) experiments. We may obtain a significant increase in radiation energy inside the hohlraum post ignition by using high-Z material seeding inside a capsule ablator. All these configurations have the potential to drive weapons physics experiments.

Materials Properties (EOS)

In the future, we will require detailed knowledge of opacity and EOS both of known and new materials. As our stockpile ages, we have to assess the effect of aging processes on weapon performance. This will require a more detailed knowledge of opacities and EOSs, as even subtle physical changes occur. It will also require knowledge of opacities and EOSs of new materials, required as substitutes for old materials. We will also need more detailed knowledge of opacity and EOS and their interdependence, especially at lower temperatures, to assess the viability and lethality of potential or actual proliferant designs.

The NIF laser will allow us to more closely access weapons conditions and to provide detailed measurements of opacities at these conditions. The NIF will access the strongly coupled regime in heavy elements. This is not possible on present AGEX facilities.

The NIF laser will allow us to perform measurements of EOS both on and off the Hugoniot. Along with this increased flexibility, the NIF will extend EOS measurements

into the Gbar pressure regime. Experiments near one Gbar will allow us to validate the many EOS models now available. These models produce widely disparate EOSs near a Gbar and there is presently no reliable data on any material above 100 Mbar. The NIF will provide good EOS data in this regime since hohlraums at 300 eV could provide planar shocks ($< 1\%$ over 400 mm at breakout) at pressures over 500 Mbar for several nanoseconds. In addition, we will be able to access EOS data off the Hugoniot. For example we could volume heat a tamped sample using hot x-rays from a disk target. Measurement of the shock speed produced in the stepped tamping material will provide measurement of the materials pressure and density along a release isentrope.

Radiation Flow

Radiation flow is a complex problem and is hard to separate from closely related material properties such as opacity. As the stockpile ages and without nuclear testing, questions of performance will force us to rely increasingly on our ability to calculate and understand subtle details associated with radiation flow. NIF conditions will allow exploration of the phenomena associated with radiation flow at conditions that more closely match weapons conditions than those obtained in present laboratory experiments. NIF experiments will provide radiation-dominated, LTE physics in geometric configurations containing many Rosseland mean free paths. This is not possible on present AGEX facilities. In addition, NIF will provide experiments that have a larger scale and higher precision than is presently available.

Opacity

NIF will allow the measurement of Rosseland mean-opacities in high-Z materials. The NIF provides a well-diagnosed laboratory environment where opacities at relevant temperatures and densities can be measured with unprecedented accuracy.

This will help us check improved atomic physics models, and thereby allow us to re-examine and re-interpret archives of past weapon tests.

Hydrodynamics

Hydrodynamics uncertainties can have a major effect on weapon performance. Without nuclear tests, this will compel us to dramatically improve our ability to calculate complex hydrodynamic interactions. Hohlraums driven on the NIF laser will allow radiatively driven shock waves at Mach numbers over 30 and Reynolds numbers over 10^6 . Thus, we will be able to address extremely compressible and highly turbulent conditions. With a drive duration of up to 8 ns, we will have experiments with the interface between materials

developing into the turbulent regime (sample thicknesses over instability wavelengths over 100). This capability is presently not available on Nova because of the limited energy. Also the large energy of NIF will allow us to study larger samples with perturbations having longer wavelengths and with reduced edge effects. Improved metrology will also lead to better measurements of conditions in the mixed region.

Past preliminary work has considered using ICF to implode metal shells (to understand convergent hydrodynamics in heavy metals), however, more work is required to understand the NIF capability and diagnostic requirements in this area.

With NIF, we shall be able to probe turbulent mixing processes in both planar and convergent (implosion) geometry at very high Reynolds numbers. The hydrodynamics experimental program on the Nova laser has provided the experience in backlighting, calculation, and diagnostics, for a successful campaign on NIF that would make use of the needed larger volumes of heated material.

Diagnostics and Facility Capabilities

The diagnostics presently being planned for the NIF laser generally satisfy the diagnostic requirements for weapons physics experiments. X-ray diagnostics similar to those on Nova can be developed for weapons physics experiments. A key component of these x-ray diagnostics is the flexibility allowed by the 12-inch manipulator tubes planned for NIF (devices for diagnostic insertion into the target chamber). These tubes will allow us to rapidly interchange diagnostics and to add new diagnostics. A key component of the neutron and gamma ray diagnostics planned for NIF is the design of a generic flight path for neutron and gamma rays. This will accommodate multiple diagnostics and will allow easy upgrades to neutron and gamma ray diagnostics.

There are other planned facility capabilities related to laser architecture that are very important to weapons physics experiments. The pulse shape on each beam can be independently adjusted anywhere from 100 ps to 20 ns. Independent timing of clusters of four beams could a nearly 1000 ns duration beam ns delay. We thus can produce total laser pulse lengths of up to 1000 ns by focusing all beams at a single target and staggering their arrival times. In addition, each cluster of four beams can point independently with offsets of up to 3 cm away from target chamber center. All of these capabilities are important for weapons physics experiments.

Additional specific needs to support the above suggested weapons physics experiments that were identified in the workshop are:

- A small focal spot size capability (<100 to $150\ \mu\text{m}$);
- Capability to fire up to three different targets within 3 cm of the chamber center, with independent pulse shapes, pulse length adjustment from 100 ps to 20 ns, and independent pulse timings with up to 200 ns delays;
- Line foci for 20 beamlets. These lenses should produce a focus of $150\ \mu\text{m}$ by 5 cm and should be able to operate at 2ω ;
- Two target insertion mechanisms. Only one needs to have cryogenic capability;
- Ability to view all sides of a weapons physics target during alignment;
- The 12-inch manipulators may require more shielding for higher x-ray backgrounds expected with weapons physics targets;
- Large area (5 x larger scale than Nova) backlighters (100 kJ); and
- 10 kJ scale, 1 ps short pulse laser (e.g., for driving x-ray lasers).

Conclusion

The weapons physics workshop served to expand the strong laser based weapons physics community. The workshop was attended by approximately 120 scientists representing mainly LLNL, LANL, and Sandia, with additional attendees from the DOE, universities, contracting agencies, and the AWE (UK). Though the workshop brought together quite a diverse array of physicists with many different opinions, a consensus was obvious that laser driven weapons physics experimentation and laser fusion are fast becoming one of the most exciting fields in physics. The excitement is growing because a strong NIF program could be a foundation for a science based stewardship program that would directly help in the understanding of physics questions pertinent to the stockpile in the absence of nuclear testing, and in a broader way, serve to develop the national capability in high energy density physics.

C. Utility of NIF for Weapons Effects Test Applications

Introduction

The workshop for Nuclear Weapons Effects Test (NWET) research in NIF was co-sponsored and organized by LLNL, DNA, LANL, SNLA, and JAYCOR, and was attended by about 100 participants. Three main sessions covered possible NIF radiation environments for NWET research, needs and issues for NWET beyond the year 2000, and the facilitization needs of NIF for NWET.

- In Session I—DNA reaffirmed its interest in NIF as a potential facility for future NWET research and described how NIF might fit into the DNA advanced simulator development program. Issues for further resolution include development of specific ignition target design to enhance weapons effects capabilities, targets for laser-generated x-ray for NWET, debris characterization, simulation fidelity and neutron mitigation.
- In Session II—the need for performing testing as an integral part of fielding or retrofitting systems in the future was affirmed.
- In Session III—analysis showed NIF will accommodate a significant fraction of potentially available test capabilities with apparently modest facilitization costs.

Ignition Sources

Session I presented preliminary calculations of outputs for electronics testing with ignition target sources and at 1.8 MJ NIF laser driver energy. The results indicate NIF may provide a substantial capability over current simulators in the warm x-ray regime (15-40 keV photons). Target optimizations using high-Z seeding of capsule and/or ablator lead to the possibility of providing a four-fold enhancement of the ratio of warm x-ray output to neutron production, an issue of importance to tests of electronics. Previous work showed that the x-ray pulse could be lengthened to several nanoseconds, the spectrum made to appear warmer, and the uniformity of dose across a test item increased by the use of a lithium-hydride scatterer. Two major issues remain: the neutron environment may need to be reduced by another order of magnitude, and the potential difficulties and costs of using LiH in the NIF chamber must be evaluated.

Laser-Only Sources

Very preliminary calculations suggest several different non-ignition laser-generated-x-ray targets (e.g., laser-heated discs, “gas bags,” and “hot hohlraums”), may be a useful source of x-rays for NWET, covering different parts of the threat spectrum. By irradiating a mosaic of separate targets with individual clusters of laser beams (a capability that requires beam pointing up to 10-20 cm from center, more than the present 3 cm requirement), these type of targets may be able to produce a broad Planckian spectrum of a few to several nanoseconds duration with uniformity over significant sample areas. Smaller target arrays using laser beam pulses stacked back-to-back can produce significantly longer pulses, with as much as 10^4 calories fluence x area in the cold and warm x-ray regimes.

In “hot hohlraum” targets, stimulated Raman scattering (SRS) of 1ω laser light in a gas-filled hohlraum can generate copious hot electrons which produce bremsstrahlung radiation on the high-Z hohlraum metal walls. Scaling the hot electron production and x-ray production from Shiva experiments indicates that this type of target could produce 1000–2000 calories fluence $\times$ area with a 50 keV spectrum. While not an increase in fluence $\times$ area over planned simulators, NIF’s hot spectrum may have a more correct spectral shape.

Further work on these preliminary NIF target designs are required, particularly for the underdense-plasma “gas bag” targets. In particular, resolution of line width and line absorption uncertainties could lead to lower output estimates in these types of targets. For this reason, confirming Nova experiments are essential.

Laser-generated x-ray sources are of additional interest for NWET because of their potential for reduced debris, no neutrons, reproducibility, and control of spectrum and pulse length. These characteristics are of special interest for the NWET response of optical surfaces and coatings, baffles, sensors of cold x-ray radiation, and multi-threat, thermo-mechanical responses. The larger laser energy of NIF allows the results from current lasers to be scaled up to study the effects of shocks and turbulence produced by both nuclear and conventional explosions. NIF may produce shock waves with Mach numbers up to a few hundred, pressures up to a gigabar, and temperatures up to 1 keV.

NWET Applications for NIF Neutrons

NIF will have the capability to provide short pulses of neutrons for NWET (<1 ns to >50 μ s). A 14 MeV neutron fluence of order 10^{15} neutrons/cm² at a distance of approximately 20 cm from a capsule of 20 MJ yield is possible. This capability can be enhanced by neutron multiplying assemblies (NEUMA) (driven by the direct capsule neutron output), which could be optimized for several classes of experiments including collateral effects mitigation, co-radiation tailoring, pulse-stretching and customized spatial configuration. Fast pulse neutron applications unique to NIF include cruise missile survivability against proliferated nuclear Surface-to-Air Missiles (SAMs), neutron vulnerability of focal plane arrays and star trackers on inertial guidance systems, space-based interceptor and surveillance platforms, and lethal effects of small nuclear warheads on nuclear, biological, or chemical warheads. No current or future facility could produce these environments.

NWET Needs Beyond 2000

Session II drew several preliminary conclusions about the need for NWET beyond the year 2000:

- The requirement for hardened systems will continue. Based solely on technical considerations, the sophistication of the nuclear threat could increase significantly during the next 10-15 years. Trying to solve the problem by adding margin for more robust designs does not appear to be cost effective.
- Deployment of a system based on an erroneous assessment of system hardness can have serious consequences. System effectiveness can be virtually eliminated by relatively small errors in hardness. This sensitivity will require validation of system hardness through NWET tests.
- NIF has both an advantage and disadvantage with its short pulse target x-ray temporal characteristic (< 1 ns). Very short pulses could lead to anomalous responses in certain experiments, such as causing spall and delamination of multilayer coatings that would not occur in longer pulses. On the other hand, NIF ignition targets with an appropriate scatterer, or NIF laser-generated x-ray targets with stacked beam pulses, could provide both fast rise and short pulse exposures that could be useful for electronics and multilayer coating testing.
- NIF ignition capsules may uniquely provide high level fluences for continuous spectrum warm x-rays over large areas. However, these require fusion yields of 15 MJ or more, and NIF target area activation could impose limitations on the number of allowed shots at this yield. More target area shielding may be cost-effective to increase the allowed number of high yield shots, but at present, only 10 to 20 high gain shots per year may be allowed without impacting NIF operations. With additional shielding, 50 shots per year may be feasible.

Facilitization Needs for NWET with NIF

The goal of Session III was to identify facilitization issues associated with NIF as an NWET simulator. At a minimum, DNA needs sufficient initial capabilities to allow an assessment of NIF's NWET potential. Specific DoD needs involve cleanliness of test areas, neutron and debris mitigation, and x-ray temporal and spectral fidelity. NIF must incorporate "user friendliness" for DNA access and use of the target area. Limited high-yield shot availability for NWET will need careful scheduling. Activation of the target area and of DNA test articles are of concern.

Three facilitization options were considered, whose costs would be borne by DNA, if any were implemented. All options would seek to implement:

- Longer pulse flexibility (up to 20 ns) by stacking beams back-to-back (already met by NIF baseline design);
- Multiple target source arrays wider than 3 cm, up to perhaps 20 cm (for greater uniformity on test assemblies);
- 1-m-scale diam test modules designed for rapid insertion and alignment;
- Chamber access for a 2-m diam access port at the equatorial plane of the target chamber;
- Space for assembly of test modules;
- Space for special DNA diagnostics and data acquisition systems;
- Facility modifications to support as many as 50 to 100 annual full-yield shots; and
- A CO₂ in-chamber cleanup system (VRS), or other systems, capable of cleaning up the extra debris generated from DNA tests. For example, a system to quickly bring a LiH-contaminated chamber back to pre-shot conditions.

Option (1). No special DNA test facilities, other than one large 2-m diam access port near the equatorial plane of the main chamber, with lifts, floor support, and enough diagnostics to allow DNA to assess the benefits of ICF for NWET. This lowest cost option would not be expected to have an impact on the present NIF baseline design, and would be expected to cost DNA less than \$10 M.

Option (2). A 20,000 ft² DNA support building would be added, including a transport module to move test hardware between the support building and the chamber, with at least 1000 shielded data channels between them. This would include some associated additional target area operational and maintenance costs for DNA testing. This option is estimated to cost less than \$50 M.

Option (3). A separate large test chamber for all 192 beams would be added to the first main chamber of the NIF, dedicated to DNA use. This option could allow a higher routine yield and a larger number of such shots, larger test articles, and a capability to handle small, non-critical amounts of fissionable material. This option is estimated to cost less than 150 \$M additional.

Conclusion

NIF may be able to provide very attractive radiation environments with both ignited and laser-generated x-ray targets for a variety of important NWET applications. Much more

work is required to review and validate these preliminary conclusions, to investigate methods to minimize neutron environments for electronic tests, to examine possibilities for even better, more threat-like environments, and to obtain increased fidelity environments. For any of the three optional levels of DNA use of NIF, participation by DNA and others, in partnership with the NIF project and DOE, will be required for a successful outcome.

D. Utility of NIF for Development of Inertial Fusion Energy (IFE)

Introduction

Workshop attendees represented diverse groups of experts and contributors (national stakeholders in IFE development), ICF and MFE-fusion labs, universities, and private US corporations and small businesses. Approximately 60 participants were asked to consider how the National Ignition Facility can and should be used to advance Inertial Fusion Energy development. These potential users of the NIF showed great enthusiasm for the NIF experimental opportunities for IFE development, exhibiting sparkling originality, innovation, individual initiative, and cross-disciplinary teamwork. The workshop was co-sponsored and organized by LLNL and UC Berkeley and was structured to include plenary and parallel working sessions. The first plenary session was devoted to introductory talks by the workshop organizers, and to provide an overview of the NIF design, capabilities, and baseline diagnostics. Following were four parallel workshop sessions:

- Target physics
- Chamber dynamics
- Fusion power technology
- Target systems

The second plenary on the last day provided summaries of each workshop session, discussion of the results and follow up work to provide better definitions of proposed experiments and supporting requirements for testing on NIF.

General Findings of The NIF-IFE Workshop

Relevance to IFE. *NIF can uniquely provide a large and essential portion of developments needed for the IFE Program, to more firmly establish the feasibility and technical basis for the design of an Engineering Test Facility (ETF), the major IFE facility to follow the demonstration of ignition in NIF.*

NIF was found to provide major opportunities in all the IFE areas covered: IFE target physics and design/performance optimization, IFE fusion chamber dynamics and first wall response, IFE fusion power technology, materials science and safety, and final precision-integration tests of mass-fabricated IFE targets and high-repetition target injection systems. Achievement of ignition in NIF will itself provide a major prerequisite for IFE.

Much of the ignition target physics development for ICF defense program activities will accomplish the most challenging target development requirements for IFE. Experiments that characterize materials response to target emissions (ablation, generation of shocks, chamber vacuum recovery) will be of importance to both defense and energy applications of ICF, and will aid the development of design codes for both programs. Accomplishing the defense program on NIF will automatically develop many technologies and codes relevant to IFE and ETF design, accentuating NIF's dual-benefit capability:

- Demonstration of fusion target ignition, propagating burn, and energy gain;
- System integration information provided by the design, construction, and operation of the NIF itself;
- Demonstration of first wall and optics protection schemes in the target chamber;
- Data on high-dose-rate neutron effects on materials;
- Data on neutron heating, tritium breeding reactions, activation, and shielding; and
- Development of cryogenic targets for NIF.

There will, however, also be many opportunities to use NIF for experiments and tests that are specific and important to IFE but not necessarily required for defense program needs:

- Design and optimization of capsules and hohlraums for non-laser drivers such as heavy-ions;
- Tests of advanced targets to produce higher gain, to allow simplified illumination geometry, and to reduce the required precision for lower cost target fabrication, and to develop injectable targets;
- Techniques for fast chamber vacuum recovery, and behavior of protective liquid films and jets;
- Tests of single-shot breeding and neutron multiplication performance of small sub-scale IFE blanket modules or liquid jets;
- Experiments to measure tritium burnup and recovery efficiency; and
- Tests of model IFE target-beam engagement precision and repeatability in a multi-shot chamber environment (5 Hz, 4 shot burst of injectable, thin wall hohlraum targets).

IFE Code Development and Benchmarking. *The proposed uses of NIF for IFE development are aimed primarily at understanding the basic underlying target and target chamber phenomenology, physics, and materials science for IFE.*

There are far too many IFE concepts and technology choices to all be tested by trial and error, so using the NIF to establish predictive design capabilities is the key to cost-effective IFE development. The IFE design codes are needed to design the ETF, an IFE development facility to follow the NIF, and to guide the selection of IFE technology developments needed for future IFE power plants. These same codes would also be used for design of a larger-yield ICF defense capability (e.g., on a separate ETF target chamber used as an LMF). Accordingly, the purposes of the NIF experiments are to benchmark and improve the computational tools to be used for future IFE system designs, instead of trying to pick winners and losers of IFE technology options from empirical tests. It is therefore sufficient for these purposes, as we found, that NIF provide target chamber environment conditions close to, but not necessarily the same, as would be expected in specific IFE power plant concepts.

NIF Shots Needed Specific for IFE. Besides the initial shots to demonstrate ignition on the NIF, there are many additional shots following ignition that would be very important and specific to the IFE specific tests identified above. These additional shots were estimated to be in the range of 2000 to 3000, including perhaps 1000 that would require yield, and 200 to 400 that would require high yield. These IFE specific shots would need to be coordinated with shots using other targets specific to other NIF users for weapons physics, NWET, and high energy density science. Many of the needed IFE shots other than for IFE specific target tests (e.g., for chamber dynamics, IFE fusion technology and materials tests) could probably be piggy-backed with other non-IFE experiments, but the proportion of these will need further study.

Laser-Generated X-Ray and Debris Target Sources for IFE Experiments.

Many experiments to study material responses to soft x-ray and debris, with ablation and shock formation, do not require targets that ignite. Some of the laser-generated x-ray and debris sources for these IFE experiments would be the same as those discussed in the NWET laser-generated x-ray/debris sources. Some would be designed to generate more debris than for NWET targets. The NIF laser energy is large enough to provide characteristic soft x-ray and debris loadings of $>100 \text{ J/cm}^2$ over $>1000 \text{ cm}^2$ samples, mimicking in-chamber IFE conditions. Nova experiments can achieve similar intensities,

but not with samples large enough to support IFE-relevant spatial and time scales for the ablated material evolution. Laser energies of at least 400 kJ at 3ω , with single sided illumination geometry, may suffice for some of these types of IFE experiments.

NIF Impacts and Flexibility Needs for IFE. *With a few exceptions noted below, nearly all of the potential IFE-development experiments suggested for NIF can be performed within the present NIF laser system and target area design capabilities and functional requirements, and would not require expensive modifications to the NIF laser or target chamber.*

There are some specific needs identified for IFE possibly impacting NIF flexibility and possible design modifications or additions, which could significantly enhance the utility of NIF for IFE development:

- Diagnostics for post-bang-time characterization of target emissions including angular and energy distributions within the target chamber are required. These include fast, spatially resolved pressure transducers, neutron activation and heating microcalorimeters, ion mass spectrometers, and visible/UV/x-ray backlighters positioned to view target debris and wall ablation, including droplet motion, on relevant spatial scales. Many of these new diagnostics for specific IFE experiments would benefit from initial development tests on Nova before use on NIF.
- Many IFE experiments will involve various amounts of liquid and ablated solid test samples which will condense or solidify on the NIF chamber walls and optics windows. Compatibility tests are needed to find out what condensates the NIF Vacuum Recovery System (VRS) can clean up, and to guide the selection of compatible liquid and solid surrogates to model the dynamics of IFE material responses. These debris problems turned out to be incompatible with the main NIF target chamber, or result in long chamber recovery times for cleanup. These IFE experiments can benefit from the addition of a small test chamber of ~1- to 2-m diam using laser-generated x-ray/debris targets with ~400 kJ laser energy.
- One or two larger ports of about 1- to 2-m diam for conical enclosures that can mount large IFE test assemblies and be inserted in reentrant geometry. These would be needed particularly for blanket/first wall sub-module tests, or small liquid jets assemblies to test isochoric neutron heating.

- A direct drive capability on NIF would significantly expand the range of IFE target experiments which could be tested. The present NIF design has flexibility to include direct drive capability.
- To support the credibility of high-rep-rate IFE for an ETF decision in 2005, it is *highly desirable if NIF can demonstrate multi-shot target precision/symmetry reproducibility in a hi-rep-rate target chamber environment*, by shooting a sequence of at least two or perhaps four IFE model targets injected on the fly 200 ms apart, with reproducible laser illumination symmetry. Some offline development would be needed first, but finally a few multi-shot precision/integration tests would need to be done in the main NIF target chamber. The idea is to test the accuracy of injected target emplacement and alignment at the chamber center *in the post-shot chamber environment*, for several successive shots. The model IFE targets would not need to be ignited to provide this test. For example, the reproducibility and symmetry of NIF laser illuminations could be imaged through empty, thin wall hohlraums, or by diagnosing sub-ignition neutron yields. The NIF laser system would need to be able to stagger-fire four sections of the 192 or 240 beamlets about 200 ms apart, with appropriate front-end and flashlamp delays between the separate beamlet groups. If these NIF tests are feasible, then appropriate prior development of the multi-shot IFE model target fabrication, tracking, and insertion systems need to start, beginning in about 1998, to be ready to perform this test for an ETF decision shortly after first ignition is achieved (~2004–2005).

Conclusions

NIF has the potential to address many of the critical IFE issues that would be relevant to the design of ETF and IFE power plants. These possibilities have generated great interest in the fusion energy community, and have boosted the hopes of many that IFE can indeed be developed in a timely and effective manner. Many of the proposed experiments would benefit from initial tests on Nova, with NIF providing the final integration tests. Some of the IFE experiments would need some initial development offline before they would be ready for tests on the NIF. More effort is required to better define the design of these IFE experiments, the expected responses of these experiments in the NIF chamber, the specific diagnostic information that could be obtained, and needed developments of appropriate IFE chamber dynamic and materials response codes that would be used to model the resulting IFE data. These activities will be needed prior to NIF ignition, to be ready to expand IFE experiments on the NIF once ignition is demonstrated, and to permit the timely initiation of an ETF facility.

E. Workshop on Scientific Applications for High Energy Lasers

Introduction

The participants covered a wide range of scientific areas. The areas most important to the scientific community that are relevant to high energy laser systems were emphasized. Clearly, new work will evolve from the involvement of the scientific community in the study of high energy laser experiments, which will give rise to great advances in the knowledge base to assist all the communities intent on using high energy lasers for applied programs of work.

The scientific body was divided into six subareas in an attempt to impose a coherent structure on the broad diversity of interest being represented:

- Astrophysics and Space Physics,
- Hydrodynamics,
- Material Properties,
- Plasma Physics,
- Radiation Sources, and
- Radiative Properties.

The motivations of the participants and some schematic examples of the types of work to be pursued are described below for each of these categories.

Astrophysics and Space Physics. The reason for considering experiments on high energy density plasma in connection with astrophysics and space physics is simply that such plasma is a dominant aspect of many astronomical objects, whether in our solar system, in other stars, or in other galaxies. The astrophysicist or space physicist is faced with the problem of deciphering the few clues the observations provide, and these consist largely of plasma radiation. Therefore, to comprehend the plasma radiation requirements an understanding of astronomical objects is also necessary. In other cases the theoretical astrophysicist or space physicist builds up a complete conceptual structure of the object, and then tests aspects of the structure against the observations. In this case the dynamics of plasmas forms one of the basic building blocks of the theory, but it requires observational support itself.

The goal is to create in the laboratory a sample of plasma similar to what would be found in the astronomical body, then study its properties—its radiation, or its thermodynamic state;

whatever aspect is critical in the astrophysical scenario (see appropriate category). Astrophysics does not, in general, provide *new* plasma properties that need to be studied, but rather gives a specific motivation for studying those already known.

More detailed discussions of specific astrophysical motivation for studying a particular plasma are provided elsewhere, here we offer a more generic discussion. Among the properties of importance are the radiative opacity of the outer envelopes of stars, key to our understanding of how stars evolve; the equation-of-state of stellar material, which is a major determinant of how dwarf stars behave—the white dwarfs left over at the end of stellar evolution and the brown dwarfs that are the failed almost-stars. There is a close connection between the powerful tools of plasma spectroscopy and the astronomer's inference of conditions in the violent inflowing spiral of material surrounding a neutron star or a black hole that may lie at the center of a quasar. This very hot material can be recreated in a high energy density laboratory experiment. In other experiments we can study a fundamental physical process—mixing at hydrodynamically unstable material interfaces—that is important in many places in astrophysics, such as in supernova envelopes, and in terrestrial applications as well.

Astronomy provides some of the driving interest in these and other laboratory experiments, but astronomy also provides an additional data set. Merging these data will improve our knowledge of the universe, as well as our understanding of the behavior of matter found here on earth. Importantly, many of the conditions necessary for the productions and observation of these phenomena are unique to the high energy laser systems. The study of opacity of relevant hot dense material; the reproduction of the environment for the study of supernova instabilities; the study of the spectroscopy of low temperature radiatively dominated plasmas relevant to the observation of, e.g., quasar irradiated plasmas; and the testing of thermonuclear reaction rates in regimes relevant to nucleosynthesis in stars.

Hydrodynamics. In the area of fundamental fluid dynamics a set of topics which are of interest to hydrodynamicists and that may be addressed using high energy lasers have been identified. High power, laser-based facilities such as Nova and the NIF provide excellent opportunities to conduct advanced fluid dynamics experiments. The capability of a laser to deposit large amounts of energy at high powers facilitates the generation of very high density, high temperature volumes of material, which may be used to drive strong shocks and high-velocity flows. The extensive set of diagnostics available facilitates measurements of the quantities of interest, including interfacial geometries, velocities, densities, and/or

temperatures. In particular, the NIF has special promise for fluid dynamics experiments, because the larger scales, longer times and higher energies provided by the NIF will permit the experiments to be larger—to increase relative resolution; longer—to allow the hydrodynamic features to develop more fully; and more energetic—to help to maintain drive conditions and to reduce decompression effects.

The experiments will provide data that should lead to new physical understanding in these areas, and will serve as important test problems for the new generation of fluid dynamics simulations currently under development. On the basis of Nova experience and the identified topic of interest, the development of a series of fluid dynamics experiments on the NIF is appropriate and important. The experiments envisioned will investigate a variety of topics, including hydrodynamic instabilities in both planar and convergent geometries; compressible turbulent jets, shear layers, and turbulent mixing; shock hydrodynamics, including shock-shock interactions and analogies to nonequilibrium gas dynamics; hypervelocity flyer plates; and, possibly, some magnetohydrodynamics (MHD) problems.

Material Properties. The capabilities of NIF for studies of condensed matter physics at extreme conditions of pressure and temperature make it the most important new tool in high pressure physics. While we list some vital contributions that only NIF can make to this field, it needs to be made clear that for other scientific applications of NIF, such as hydrodynamics, planetary and astrophysics, radiative properties, as well as for the ICF program, a broad and precise knowledge of condensed matter properties for pressures between 1–100 TPa (10–1000 Mbar) and temperatures up to a few hundred eV, will be essential for the design, simulation, and interpretation of experiments. For example, we have yet to understand the behavior of hydrodynamic instabilities in the pressure range for which pressure ionization becomes important. One must have a “caloric” equation-of-state to interpret the entropy fluctuations and to determine the appropriate invariants for high Mach number flows under these conditions.

Presently, no models of material behavior for pressures between 1–100 TPa have been experimentally validated. At low pressures, below a few Mbar, impact and static experiments provide a wealth of data, and at very high pressures, statistical mechanical models, such as Thomas-Fermi theories, are believed valid. The upper bound is approximate, and increases with Z . At tens of TPa, i.e., hundreds of Mbar, the models that do exist only agree within about 30% in density, and vary by as much as a factor of two in temperature along a shock adiabat, or Hugoniot. These models differ quantitatively and in

functional form; and the discrepancies between the models are functions of density, pressure, and temperature. Although a few shock wave experiments have been carried out in this pressure range in the former Soviet Union (driven by a nuclear device), none have been sufficiently accurate to test theory. Over the last decade, a few laser-driven experiments have probed this region of pressure with even less accuracy. NIF provides the combination of drive energy, uniformity of drive, and the concomitant large time and length scales for real advances. This effort will substantially improve our understanding of dense fluids, pressure ionization, phase boundaries for example, in proposed plasma phase transitions and energy partition in shocked systems.

The basic experimental methods for these studies have existed for some time, and have been used on the existing facilities—the ability to exploit them at ultra-high pressures is still awaiting a NIF-class laser. Moreover, one requires the material properties over wide ranges of density and pressure. Most previous experiments have been shock wave experiments on the principal Hugoniot. The pulse-shaping capabilities of NIF are essential to reach off-Hugoniot states, especially near the isentrope. Cold compression, the room-temperature isentrope, will be limited by the eventual insulator-metal transition in diamond, which will occur at about 1 TPa. While experiments and theory have emphasized shock properties in the past, these are merely the simplest and most fundamental measurements. There is yet to be any experimental data on transport properties at these extreme conditions such as thermal and electrical conductivity, and we note that the hydrodynamics itself will depend on radiative transport away from the shock front at the highest pressures of interest.

Plasma Physics. The study of plasma physics has been motivated over the past four decades by its direct relationship to fusion energy research. The further realization that the universe is made up of plasma as the overwhelming state of matter, makes the scientific investigation of plasma even more germane to scientific inquiry.

The large number of experiments that high energy lasers permit in the area of plasma physics indicates the close connection between many of the applications. A number of the interesting phenomena that take place in plasmas, such as parametric instabilities, rely on a large degree of homogeneity in plasmas that are both hot and dense. Most plasma physics experiments to date have been complicated by the large gradients and small scale of the plasmas produced by current lasers. The advanced capability of the NIF will allow us to produce hot, dense plasmas that are both large and homogeneous, allowing detailed characterization. Thus, for example, one will be able to determine electron and ion

temperature, charge state, electron density, and plasma flow velocities. Thus, one would have a medium in which a wide range of *quantitative* experiments can be performed.

Some of the laser plasma interaction experiments that will be possible on the NIF will be developments of those already attempted on smaller, less well-characterized plasmas. However, one will be able to go beyond such experiments, that were geared to the needs of the current ICF program, and investigate a wide range of less programmatically motivated but scientifically important interactions.

There was general agreement that the NIF should include a beamline for short pulse, high power experiments. This capability is especially important for many basic plasma physics studies. These include: relativistic, ultra-high intensity regimes of laser-matter interaction, pondermotive effects, relativistic self focusing and filamentation, laser beam channeling, intense harmonics generation, ultra-high B field generation with ancillary studies of the resultant physical processes, strongly driven instability regimes, generation and transport of high electron fluxes in a plasma, high gradient accelerator schemes, new x-ray lasers, and high temporal resolution diagnostics.

Another new area of focus will be the study of magnetic fields, as large as 100 MG, generated by temperature and density gradients present in plasmas. Faraday rotation of an optical probe beam and/or Zeeman splitting of spectral lines, should allow one to investigate and quantify these magnetic fields. The generation of large currents of fast electrons, produced by SRS and Two Plasmon decay in plasmas at 0.25 of the critical electron density will be a related area of study. Coupling these electrons into a high-Z metal converter should allow the production of short duration bursts of 50–100 kV x-rays with numerous potential radiographic applications. Further, the feasibility of performing nuclear reaction experiments in the large, hot, well-characterized plasmas that will be produced on the NIF has been demonstrated in smaller experiments on the Nova laser.

In general, the larger plasmas possible on the NIF will allow longer interaction times; greater homogeneity, meaning that spatial resolution requirements on temperature and density characterization are relaxed; higher temperatures; and the longer time scales will allow ion-electron temperature relaxation. It is, therefore, expected that the NIF laser will make strong contributions to both fundamental plasma physics and some of these more esoteric studies.

Radiation Sources. A NIF class laser facility will make possible a wide variety of x-ray and particle sources suitable for addressing numerous basic and applied research areas. NIF will be capable of producing: intense broadband thermal x-rays from high-Z radiation converter targets; coherent amplified x-rays (x-ray lasers) from high gain linear plasmas; intense neutron pulses from implosion plasmas; and, intense pulses of hard x-rays produced by fast electrons. Accurate energy spectra and absolute measurements of the conversion of laser energy into all types of radiation and particle fluxes will play an important role in benchmarking our basic understanding of laser plasma interactions and atomic physics.

Broadband x-rays generated from laser produced plasma can be used to produce and characterize large and uniform plasmas relevant to ICF and astrophysics. Previous experiments using this technique have yielded important results which can be extended to high temperatures and densities. The high temperature and densities produced during implosion and subsequent ignition will be an unmatched source of continuum x-rays extending from the XUV to MeV?? with pulse durations less than 100 ps.

X-ray lasers, besides being important coherent radiation sources, offer a critical test of our atomic modeling. NIF x-ray lasers will allow us to extrapolate existing neon-like and nickel-like collisional x-ray lasers to wavelengths of $\sim 20 \text{ \AA}$. At these wavelengths x-ray laser interferometry can be used to measure electron densities in plasmas exceeding solid densities. Short pulse capabilities on NIF ($\sim 100 \text{ fs}$) will allow us to develop inner-shell pumped x-ray lasers as a viable radiation source. This new class of x-ray laser has the potential to extend down to $1 \text{ \AA}$ in wavelength with a short pulse width. High order harmonic generation, an alternative source of coherent radiation, can be used to produce tunable coherent XUV radiation.

Neutron production will exceed 10^{18} in single 100 ps pulses making it a potentially useful source for producing uniform high density and low temperature plasmas (i.e., strongly coupled). Fast electrons with hundreds of keV in energy will be generated by parametric instabilities providing another potential source of high energy x-rays for plasma backlighting and probing.

Radiative Properties. The importance of radiative properties in high energy density plasma is derived from three separate factors. (1) The radiative property can be the best indicator of the level of scientific knowledge in a particular area. (2) The radiative property

provides the classic example of the non-interfering probe. (3) Although the radiative properties provide an important test bed for theoretical development and provide diagnostic information, they are also necessary as primary data for numerous other studies. For example, one would be seriously hampered with a spectral line finding list. Therefore, the categorization of the energies of highly ionized species becomes an end in itself as spectroscopic investigations are widely used. In this way, line shape, line widths, and line shifts must be measured for use in radiation-hydrodynamic simulations of plasmas as small as in ICF microsphere implosion and as large as a galaxy. These factors together explain the interest in radiative properties in hot dense matter. It is clear that the largest part of the community of scientists, outside the x-ray laser area, involved in high energy laser experiments is in the study of radiative properties. It is a fertile area, with much to be gained by the existing high energy lasers and even more to be gained with the advent of the NIF.

Here we summarize a few of the ideas to provide an indicator of the type of experiments being considered. The current state of knowledge of highly ionized atoms as it relates to some key isoelectronic sequences indicates the importance of the experiments on high energy lasers and in particular the extrapolation to the NIF. The current state of experimental knowledge on isoelectronic sequences which lay between those presented below are even less complete. A source as powerful as the NIF laser with special long scale length plasma targets can achieve coronal temperatures of 6 keV with eventual production of 10 keV plasmas. Such temperatures will allow one to probe most elements of the periodic table to any desired degree of ionization. Next, the production of idealized environments for the study of *in situ* radiative properties can be envisioned on three levels. (1) By the use of volumetric heating of hydrodynamically isolated tamped samples one can currently get tens of eV, but will get greater than hundreds of eV on the NIF. These allow the detailed study of line shapes, line shifts, transparency window formation, line series, etc. In hot dense matter there are no techniques or capabilities that can access the regimes of interest and produce high quality data. (2) With the capability of the facility to produce these samples one can study the dynamics, or population kinetics, of the plasma. This is critical to the regime of importance to applied programs of work, as in ICF, but also of fundamental interest in the understanding of the kinetics relevant to, e.g., astrophysical plasmas. (3) The challenge of developing a diagnostic suite of instruments and experimental techniques is important to continue studies that have only been done for the

simplest atomic systems. Because previous experiments have been limited by steep density gradients and rapid changes in the plasma state, none have the capability to characterize the plasma. The NIF will allow us this capability and the experiments on the existing high energy lasers provide a path toward stepwise progress.

Modifications Desired

To a large degree the desired modification to the original NIF CDR led to many of the same requests as the other workshops. In particular the group desired smaller spot sizes, pulse variation from 100 ps, or less, to 20 ns; the need to establish line foci to perform x-ray laser experiments as important; and, to express the need to have an expanded subpicosecond capability. However, the most important request, by far, was the many demands for increased turnaround times. This took many forms, but the message was the same—a science based university intensive effort which seeks to train students requires more than one to three experiments a day. The suggestions to improve the turnaround included: additional target areas; more rapid cooling of the amplifiers; more independence of the beams, so that part of the beams could be used flexibly; and, the introduction of a smaller, e.g., Nova sized, beam for independent backlighting.

Conclusion

There was a very strong interest in participating on experiments on high energy lasers. A large number of novel ideas was generated from modeling supernova hydrodynamics and generating matter where relativistic effects can be studied, to the generation of test beds for radiation transport studies in hot dense matter. Further, the community as a whole was very strongly in favor of immediately developing a national user group, covering all large existing national laser facilities as well as NIF. The group felt very strongly that to be a viable community when the NIF becomes operational one needs to start now, on the present day high energy lasers. The plan for the user group, as it evolved during the workshop was, to build a science based community to perform high energy density research on the high energy lasers. This would satisfy several aspects of the plan that are considered paths to the future of DOE Defense Programs. (1) This promotes, in the fullest sense of the words, a collaborative dual use facility for the future. (2) It would allow us to develop the foundation of the conceptual science based stockpile stewardship program. These scientists will form the core of the resource base by providing the training for individuals to perform experiments relevant to the other three pillars of the NIF, or current ICF facilities, i.e., the IFE community, the Weapons Physics community, and the

Weapons Effects community. These three communities, together with the a viable science based user group, form a strong supporting structure for the NIF, for DOE and for the country.

As a direct out growth of this desire to initiate a science based user group an ad hoc committee has been formed to write a charter for the user group.