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Contributions of the National Ignition Facility to the development of inertial fusion energy

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Abstract

The US Department of Energy is proposing to construct the National Ignition Facility (NIF) to embark on a program to achieve ignition and modest gain in the laboratory early in the next century. The NIF will use a ⩾ 1.8 MJ, 0.35 μm laser with 192 independent beams, a 50-fold increase over the energy of the Nova laser. System performance analyses suggest yields as great as 20 MJ may be achievable. NIF will conduct more than 600 shots per year. The benefits of a micro-fusion capability in the laboratory include essential contributions to defence programs, resolution of important Inertial Fusion Energy (IFE) issues and unparalleled conditions of energy density for basic science and technology research. A start has been made to consider the role the NIF will fill in the development of IFE. While the achievement of ignition and gain speaks for itself in terms of its impact on developing IFE, it is believed there are areas of IFE development, such as fusion power technology, IFE target design and fabrication and understanding chamber dynamics, that would significantly benefit from NIF experiments. In the area of IFE target physics, ion targets will be designed using the NIF laser and the feasibility of high-gain targets will be confirmed. Target chamber dynamics experiments will benefit from X-ray and debris energies that mimic the spatial distribution of neutron heating, activation and tritium breeding in relevant materials. IFE target systems will benefit from evaluating low-cost target fabrication techniques by testing such targets on NIF. Additionally, it is believed that it is feasible to inject up to four targets and engage them with the NIF laser by triggering the beams in groups of ca. 50 separated in time by ca. 0.1 s. Sub-ignition neutron yields would allow an indication of symmetry achieved in such proof-of-principle rep-rate experiments. NIF will be a unique source of data to benchmark predictive capabilities to support affordable IFE technology selections. The total of NIF-IFE experiments may involve several thousands of shots. NIF may support design "certification" for the follow-on facility to NIF, dedicated to IFE, called the Engineering Test Facility.

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1. Introduction

The US Department of Energy is currently considering establishing the National Ignition Facility (NIF) as a formal project (see Fig. 1). The scientific goal of the facility is to achieve, for the first time in the laboratory, the ignition of an inertial confinement fusion target. The laser which will drive the target to ignition will deliver 1.8 MJ of 0.35 μm light, in a shaped 20 ns pulse, into a ca. 1 cm long, ·0.6 cm diameter cryogenic holhraum, creating X-rays to compress the ca. 1 mm capsule containing 0.2 mg of deuterium and tritium. While ignition is indicated by fusion yields of tens of kJ, yields of up to 20 MJ appear possible, and will be contained in a 5 m radius aluminum chamber.

The realization of ignition in the laboratory, and the capabilities of the NIF itself, will make major contributions to several areas of major national importance: science-based nuclear weapon stockpile stewardship, high-energy density science, inertial fusion energy (IFE) and complementary nuclear weapons effects testing. Here we discuss the potential use of the NIF to conduct experiments in support of the development of IFE in four specific areas: Target Physics — issues related to the design and performance of IFE targets; Chamber Dynamics — issues in IFE chambers resulting from the deposition of X-rays and debris; Inertial Fusion Power Technology — issues for energy conversion, tritium breeding and processing and radiation shielding, interactions of neutrons with materials and chamber design;

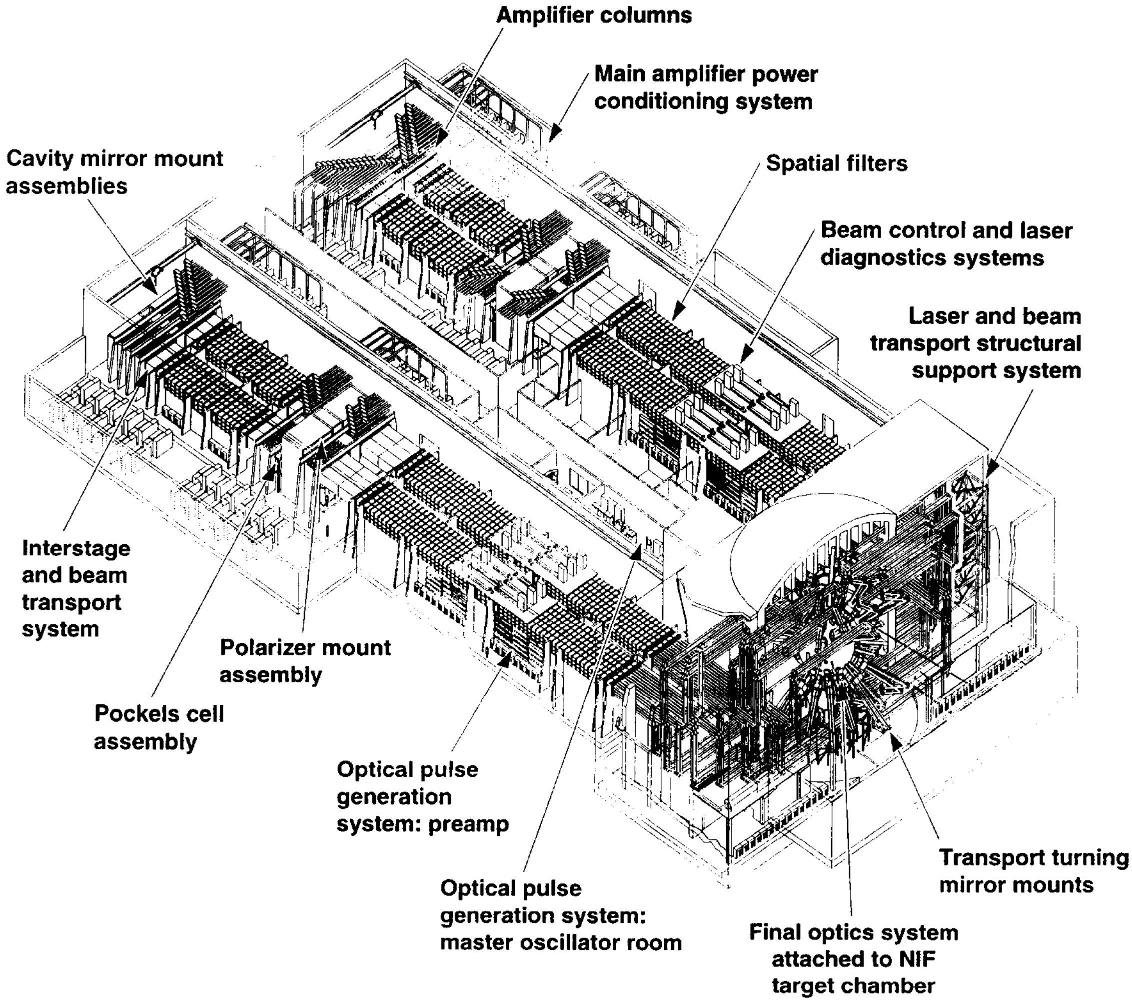

Fig. 1. View of the National Ignition Facility showing the main features. The NIF will be a low hazard, non-nuclear facility.

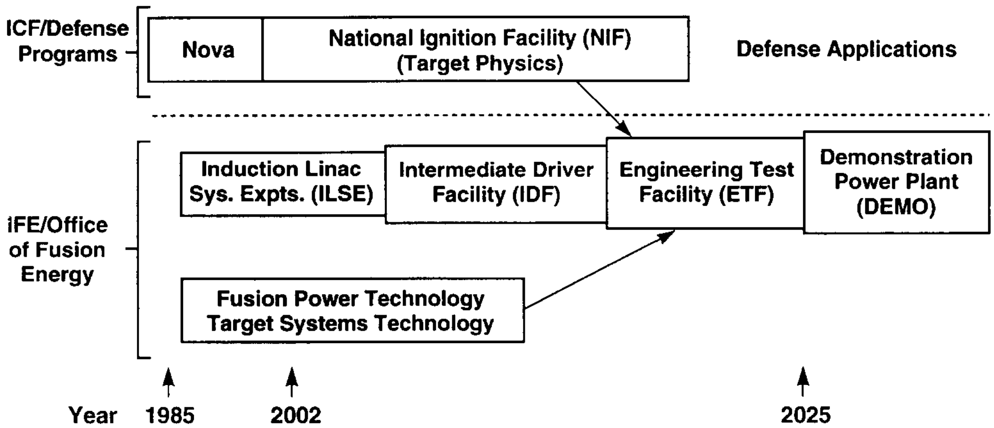

Fig. 2. The NIF is necessary, but not sufficient, to proceed to ETF. Driver development and some target and fusion power technology development in addition to NIF's contribution will also be required.

and Target Systems — issues related to automated, high-production-rate manufacture of low-cost targets for IFE, target handling and transport, target injection, tracking and beam pointing.

For key credibility and development issues in these areas, we consider what experiments could be conducted using the NIF to address or even resolve these issues. Further, we identify what developments (e.g. in diagnostics and predictive capabilities) would be needed in parallel with NIF development, construction and operations to support full utilization of the NIF for such experiments. We also suggest any improvements to the NIF design that would improve its capability to perform the proposed experiments.

We recognize, since IFE is not sufficiently developed, that it is premature to suggest the features best suited for electrical power plants based on the inertial fusion process. However, in order to discuss efficiently details of specific potential NIF experiments in this limited space, we constrain our scope of IFE. We primarily consider the issues for IFE power plants that would use a heavy ion driver and indirect drive targets, have repetition rates of 1–10 Hz and yields of 100–500 MJ and employ an inner blanket to provide first wall structural protection, breed tritium and remove heat.

The role of NIF for IFE development is considered in the context of a possible national IFE development plan (see Fig. 2 and Refs. [1–4]). The demonstration of heavy ion inertial fusion energy requires several facilities. While some important "precursor" experiments may be possible on current facilities such as Nova and soon Omega Upgrade, the NIF demonstrating target ignition and gain will be the first major IFE facility. In parallel with NIF, both the Induction Linac Systems Experiment (ILSE) facility and an Intermediate Driver Facility (IDF) are required to develop the optimum features of an IFE heavy ion driver. Fusion Power Technology and Target Systems Technology development will require smaller experimental facilities that are yet to be identified.

The Engineering Test Facility (ETF) will be the first facility to integrate all the major subsystems required for an inertial fusion power plant including the driver, target production and injection systems, blanket, chamber and tritium systems. It will demonstrate the complete technical feasibility of IFE. A Demonstration Power Plant (DPP) would follow that would actually produce electricity. The ion driver for ILSE would be successively upgraded for the IDF, ETF and DPP. The fact that a single site would experience these successive upgrades would save time and money.

Before the ETF is built, four avenues for development concerned with target physics, driver technology, fusion power technology and target systems technology will have produced positive results. A fusion power technology program (first walls and blankets, chamber dynamics, shielding, radiation confinement, chamber/driver interface, tritium recovery, etc.) and a target systems technology program (automated target production, target transport, target injection and tracking, beam steering, etc.) are needed to demonstrate certain key technologies needed to use fusion pulses to make steady power.

Detailed discussions of all relevant technical issues are, of course beyond the scope of this paper. However, Refs. [1–18] are provided for the reader to satisfy this area.

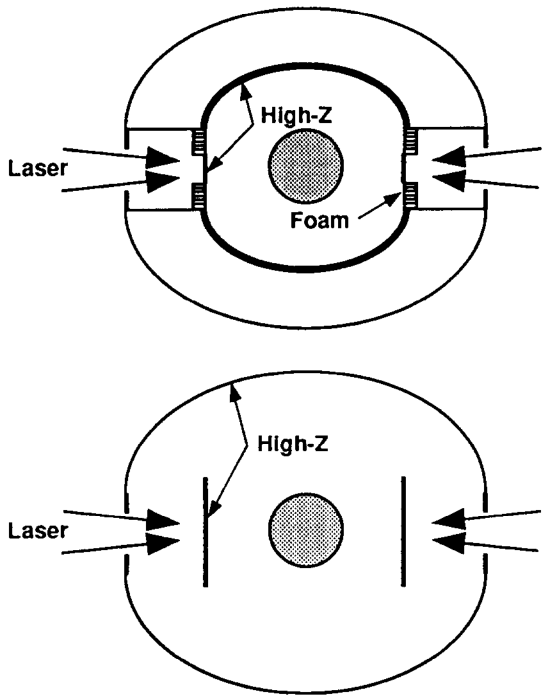

Fig. 3. Many IFE ion target issues can be addressed or resolved using ion-like laser targets.

2. Possible IFE experiments on NIF

2.1. Target physics

The baseline target designs for the NIF are indirectly driven and this is, of course, reflected in the NIF design of the illumination systems and the target chamber. (A means to convert the indirect drive scheme to an acceptable direct drive scheme, however, has been developed, that may allow up to 1.5 MJ of blue light on a direct drive target. NIF advanced conceptual design activities will consider this option.) Although we have focused on indirectly driven heavy-ion targets, there is, nevertheless, still substantial interest in direct drive targets and in laser and light-ion targets for IFE. For this reason and the possibility of a direct drive option on NIF, we shall also give some consideration to these.

A significant number of the target physics issues for IFE will be addressed by the planned experiments on the NIF for ignition and defense sciences. These include optimization of target yield and gain, studies of capsule implosion characteristics and studies of capsule ignition and burn physics. In parallel with this effort, there must be development and benchmarking of theoretical models and simulation codes needed for the understanding of target physics for IFE. In fact, the benchmarking of ICF computer codes in a regime or parameter space close to that of IFE may be one of the most significant contributions of the NIF for IFE. Thus, the already planned NIF experiments, by themselves, will greatly benefit IFE.

Beyond these, the NIF should, however, perform certain additional experiments of importance to IFE that may not necessarily be part of current planning. Completely addressing IFE ion target issues on NIF will rely on the design of and experimentation with ion-like laser targets, such as those shown in Fig. 3.

Table 1 lists the IFE issues that would be addressed by these experiments. A × indicates that the NIF can completely or almost completely resolve the issue. Table 1 shows that the NIF can resolve most issues. We believe that the NIF, along with Omega Upgrade and PBFA II, will be able to address all of these issues. The completion of these experiments will indicate the readiness, from a target physics point of view, to proceed with an IFE engineering test facility.

Indirect-drive IFE target experiments require only minor changes, if any, to the NIF conceptual design. Furthermore, the target diagnostics and codes developed for the core program are directly applicable to IFE targets. It would be useful to conduct experiments where uniform illumination of a target could be obtained using only a fraction (e.g. 1/4 or 3/4) of the beams. Since each of the 192 beamlets of the NIF is independent of the others in terms of spectral and temporal characteristics, this type of experiment would be routinely possible.

2.2. Chamber dynamics

Many of the basic issues of IFE established from past fusion power plant conceptual design studies that relate to target chamber dynamics can be addressed on the NIF. The four basic categories of issues we considered are (1) IFE target emissions, (2) materials response, (3) gas dynamics and (4) a 'miscellaneous' category.

The target emissions category covers issues related to the characteristics of IFE target emissions in radiation and debris. Materials response covers issues of radiation effects (including debris) at the first surface of the structural wall or blanket. Gas dynamics includes issues of chamber clearing, condensation and beam propagation. The miscellaneous category includes such issues as multiple-pulse radiation effects.

Table 1
List of IFE-related target physics issues that can be addressed by the NIF

	Ions[a]		Lasers[a]	
	Indirect	Direct	Indirect	Direct
Usability of a variety of pulse shapes	×	×	×	×
Radiation flow, illumination geometry and internal pulse shaping	×	NA	×	NA
Sensitivity of capsules to radiation asymmetry	×	NA	×	NA
Materials issues (capsule, hohlraum, ablator)	×	×	×	×
Fabrication surface finish and precision	×	×	×	×
Capsule mounting and injection	×		×	
Power vs. energy tradeoffs	×		×	×
Output spectra and shielding	×		×	×
Reduced tritium	×	×	×	×
Advanced targets	×	×	×	×

[a] A × indicates issues that NIF experiments can resolve.

Table 2
Materials response experiments on the NIF

Issue addressed	Experiment	Purpose	Ignition required?	Special diagnostics required	Use 2nd chamber?	NIF modifications
Ablation	Ablation issues	Benchmark ablation in codes	Desired	Pressure transducers[a] and mass spectrometer	Yes	None (extra material near target)
Erosion (ablation, melting, surface chemistry)	Response of materials to single/multiple pulses	Measure response of surface material	Desired	None	Yes	None (some impact from vaporized or spalled material)
Isochoric heating, cavitation, splash of liquids	Liquid responses	Study isochoric heating, fluid mechanics	Yes	Pressure transducers and strain gauges	No	Prepare for liquid metals, Si oils, etc. and graphite placed near target
Ablation impulse, pressure loading, stress parameters	Wall stresses	Benchmark stress codes	Yes	Pressure transducers[a]	No	None (vapor condensation)

[a] Fast response and high sensitivity.

Preparatory experiments on Nova and other facilities are key features for such aspects as assisting in developing predictive capabilities for chamber dynamics. NIF experiments (20 MJ) at 1 m stand-off (48 J cm^{-2}) can mimic IFE (350 MJ) X-ray and debris fluences (35 J cm^{-2}) at 4 m. There are also several experiments that could be performed using the laser only with energies of 100–400 kJ. A NIF operational issue may be the diagnosing and handling of liquids used in neutron isochoric heating experiments. A summary of materials response experiments needed to address these issues is shown in Table 2.

Ablation experiments considered would include the potential to use non-ignition sources (such as disks or an array of disks). In these experiments, perhaps one quarter of the NIF beams would each create a debris and X-ray source on each of four disks, separated in time enough that the time-dependent effects of the X-ray, debris and ablated material from a single, large, close-in witness plate could be measured and compared to code predictions.

The activities required for getting ready to conduct IFE experiments on NIF include the development of new diagnostics, use of Nova, use of ion-beam facilities, consideration of a second smaller NIF chamber and code development.

New diagnostics — there is a need for devices to measure the ion velocities (energies), species and flux originating from target source debris. Also, there is a need for modest extensions of existing instrumentation in experiments related to gas dynamics and condensation phenomena. Moreover, there is a need for diagnostic development to diagnose adequately the gas/plasma conditions in potential beam propagation scenarios.

In addition to specific diagnostics, there is a general need for diagnostic protection against electromagnetic interference, especially from the high yield environment arising from gamma-induced EMP. Here, the IFE community can benefit from the NWET community, which has already attempted measurements in high radiation environments.

Use of Nova — experiments should be performed on Nova to characterize further emitted X-ray and debris characteristics (including anisotropy) from target foils made of materials considered for IFE targets. Experiments on X-ray responses of first surface ablation, erosion and some other surface effects, such as cumulative X-ray and debris damage and multiple-shot debris effects, should also be performed on Nova. Additionally, preparatory experiments should be performed to examine X-ray and debris effects on ion-beam final focus magnet materials.

Use of ion-beam facilities — experiments on ion-beam facilities are needed to benchmark codes for ion-beam transport losses that depend on gas pressure and transport conditions that will be present in NIF.

Development of a second smaller NIF chamber — a smaller chamber may be cost effective for gas dynamics and condensation experiments, where only a few hundred kilojoules of laser energy are needed. The anticipated heavier laser debris-shield contamination could be tolerated and be spared the neutron activation associated with the main NIF chamber. Work could be done on X-ray responses of first surface ablation, erosion and multiple-shot surface effects such as cumulative X-ray and debris damage and cumulative heating effects. Partial simulations of a multiple-shot environment for gas dynamics could be studied having at least two debris sources

Table 3
Example IFE chamber codes

Code	Type	New developments
CONRAD [19]	1-D rad-hydro, ablation physics (no T–N burn) line transport	Laser deposition, 2-D version
HYADES [20]	1-D rad-hydro (T–N burn) laser deposition	Ion deposition, low energy density physics, 2-D version
SRIPUFF8 [21]	1-D hydro (fracture, no T–N burn)	Integrate with Hyades for radiation transport. Cumulative damage models
L2D [22]	2-D hydro (fracture, no T–N burn)	Integrate with 2-D Hyades for radiation transport
PHD-4	1-D rad-hydro (T–N burn, ion deposition)	Laser deposition
TSUNAMI [23]	2-D hydro, simple ablation boundaries	Radiation transport, boundary conditions

(hohlraum and target inserter, with other possible inserters). Further preparatory experiments could be performed on the smaller NIF chamber to investigate X-ray and debris effects on ion-beam optics materials and the mitigation of such effects by gas-fill pressure.

Code development — Although there are many useful codes for estimating NIF behavior, many of these will require additional physics or modifications to meet IFE needs. There are three classes of codes that require development: (1) multi-phase (solid, melt, vapor) hydrodynamic, (2) gas hydrodynamic, including condensation and some chemical effects, and (3) ion-beam codes. Table 3 shows examples of a few such codes and the developments needed. In addition, some ion-beam codes will need benchmarking.

2.3. Fusion power technology

Fusion power technology (FPT) in an IFE power plant includes components whose primary functions are energy conversion, tritium production and processing and radiation shielding. These components include (a) wall protection and first wall, (b) blanket, (c) vacuum vessel and (d) shield and (e) tritium processing systems. Also relevant to FPT are remote maintenance systems and those elements of targets and drivers that provide either the source term and their performance is significantly affected by the radiation environment.

The dominant issues for FPT in IFE power plants concern the nuclear and material performance of components so as to achieve economic competitiveness and to realize safety and environmental advantages [10,11, 13,15,16]. NIF will provide valuable information to IFE in two ways: (i) data from performance and operation of the basic device and (ii) data from specially designed experiments.

Particularly attractive features of NIF relevant to FPT are (a) prototypical size and configuration and (b) prototypical radiation field (neutrons, X-rays, debris) spectra and intenstiy per shot. For example, the NIF (20 MJ) neutron fluence at 1 m (5.7×10^{13}) is close to that for an IFE target (350 MJ) at 4 m (6.2×10^{13}). These features allow the possibility of conducting a range of valuable FPT-related experiments on NIF. The most important limitation of NIF for these FPT experiments is the low repetition rate. The planned repetition rate in NIF is too low to produce time-averaged relevant bulk nuclear heating and reactions.

Analysis of FPT issues and the range of possible experiments on NIF suggests that the most important contributions of NIF to FPT development for IFE are the following: (1) achieving ignition; (2) system integration — design, construction, and operation of the NIF will provide important information on the interactions among many important IFE subsystems, including FPT components; (3) demonstration of viability of first-wall protection schemes; (4) obtaining data on dose rate effects on radiation damage in materials; (5) obtaining data relevant to tritium self sufficiency in IFE power plants; data include (a) tritium burn-up fraction in target, (b) some tritium inventory and flow rate parameters and (c) data on achievable tritium breeding rate; (6) neutronics data on radioactivity, nuclear heating and radiation shielding.

Specific FPT experiments for NIF have been suggested, that appear to be both viable and useful [24]. Much future effort will be needed, of course, to address the details of such experiments and their impact on NIF design and operation. Some specific examples of NIF IFE experiments addressing a number of FPT-related issues are summarized.

Material damage

NIF (and IFE) provides a very high dose rate in each shot that can be equivalent to about 10–1000 dpa s^{-1} (dpa = displacements per atom) (an IFE power plant experiences its entire annual neutron damage during only ca. 10 s of actual irradiation time). However, the limited number of NIF yield shots restricts the dose to a maximum of about 10^{-4} dpa in one year. Therefore, NIF cannot produce a design database for IFE in metal alloys and composites (e.g. swelling, creep, embrittlement, Young's modulus and thermal conductivity). However, NIF will be useful for basic physics of radiation effects in materials. Examples include (a) cascades (morphology, size, fraction of free and clustered defects, impurities), (b) microstructural evaluation, (c) electrical properties, (d) optical properties (fiber optics, coatings) and (e) molecular cross-linking.

The incentive to produce low activation hazard structural materials for IFE also creates a dilemma: while the neutron activation characteristics may be fairly well understood, their mechanical properties under IFE conditions are generally unknown. The impact on the mechanical properties of materials of pulsed irradiation compared with continuous irradiation (such as in MFE) is not known. In addition, this short-pulse neutron effect must be understood in conjuction with other effects such as H, He and transmutation production, high-cycle fatigue and thermal cycling, all at in-reactor temperatures.

In some low-activation materials such as SiC, we predict that for IFE a large number of damage sites are produced in each pulse. Interstitials from one damage site combine with the vacancies created not only at that

Table 4
Materials damage research with NIF exploding pusher experiments[a]

Material	⟨T⟩ ($E > E_d$) (keV)	σ_{int} (barns/neutron)	Displacements per atom (dpa) ($\times 10^{-9}$)	Number of NIF neutron damage sites[b]
Si	500	1.8	4.8	180
C	689	1.2	0.8	270
SiC	600	1.5	3.0	150
Fe	228	2.5	4.6	425
Cu	190	2.85	4.7	500
Ag	72	4.1	2.5	500

[a] These NIF damage levels are easily observed with scanning electron microscope techniques.
[b] No. of damage sites = $\sigma_{int} \times \Phi \times V \times \rho$; $\Phi = 2 \times 10^{14}$ n cm^{-2}; $V = 10$ mm$^2 \times 2000$ Å $= 2 \times 10^{-11}$ cm^3.

site, but also from adjoining or nearby sites, such that there is an increased rate of recombination compared to the steady-state situation. Interstitials that do not find sinks in vacancies create clusters together, increasing clustering over the steady-state example. Increased recombination tends to reduce void swelling while increased clusters tends to increase embrittlement.

A predictive capability that calculates material responses to IFE irradiation would be a powerful IFE design tool. A candidate for part of this capability is a technique called Molecular Dynamic Simulation (MDS) [17,18,26]. This is a deterministic approach to predicting damage. It calculates responses at an atomic level by quantifying the response of a three-dimensional array of atoms to knock-on atoms that impinge on the matrix from a range of angles and with a range of energies as a result of an incident neutron flux. Potentially, MDS capabilities may include predicting for a material the number of vacancies and interstitials that will result from neutron irradiation, in addition to the cluster fraction of defects, atomic mixing and solute precipitation, and predicting phase transformations. Its accuracy is dependent on the accurate modeling of interatomic potentials.

An overall material property predictive capability would use the results of MDS predictions along with a Monte Carlo defect annealing treatment, couple this "source term" to finite element codes and then predict the changes in bulk mechanical properties such as ultimate strength, Young's modulus and fatigue limits. Data to benchmark MDS are essential if it is to be used as part of such a predictive capability. NIF can provide a source of relevant data for this purpose.

On NIF, neutrons will be produced two ways: from exploding pusher (directly driven) experiments that frequently are used to calibrate neutron diagnostics, and from indirect drive targets, with ignition (neutrons will also be produced from NIF non-ignition indirect drive shots, but the neutron yield of these, at best, will likely be about the same as the direct drive shots). With 1.8 MJ laser energy and a larger exploding pusher target, NIF will produce ca. 10^{15} neutrons. Samples to be exposed to this neutron fluence could potentially be placed within 1–2 cm of the target, provided shrapnel generation was tolerable. Such experiments would be possible as soon as the NIF laser is activated (ca. 2001). A series of experiments could be conducted to produce neutron damage in very small, thin samples. The first samples chosen for exposure would be those that have been well characterized and most computationally scrutinized by MDS, such as Ag, Cu and Fe. The damaged samples would be examined with electron microscopic techniques to determine such damage parameters as number, distribution and sizes of defect clusters. These measurements would be compared with MDS predictions. As shown in Table 4, NIF would create more than enough damage sites to allow confident validation of MDS techniques.

Another area of importance to material behavior is thermomechanical effects. NIF is unique in that it provides IFE prototypical thermal surface loads by X-rays and debris, in the range 10^1–10^3 J cm^{-2}. Therefore, a limited amount of information for design and code verification can be obtained for IFE. Examples include (a) mechanics of bonded structures (composite interphase interfaces, mirror coatings, protective coatings), (b) materials evaporation/ablation response, (c) surface damage (flaking, spalling, material loss, shrapnel) and (d) thermo-elastic wave bulk damage (fatigue, fracture).

Wall protection

A large number of wall protection concepts have been proposed for IFE power designs, covering a diverse range of concepts with different testing needs. There are many issues associated with wall protection. They can be classified in three main categories: (1) blast effects on film protectant thickness and stability; (2) film–substrate interactions due to blast impulse; and (3) damage rates at dry spots on film-protected surfaces. While many aspects of the issues above can be addressed in separate small-scale facilities, NIF will be a useful test bed for examining these issues.

Prior to performing tests in NIF, a large amount of R & D will be needed to derive the maximum benefit from testing. Several types of development are needed, including the following.

Diagnostics — numerous diagnostics are being developed for NIF to diagnose the target responses and energy yields from the blast. A large number of "engineering" diagnostics will be required in order to obtain useful information from testing. Some examples of the measurements needed include film shape, thickness and motion; surface temperature and density of vapor leaving the surface; net impulse and deflection of panels; mechanical response in structure, cavity vapor temperature, pressure and composition and aerosols. Although many of these diagnostics are well developed for conventional applications, special effort will be required to demonstrate their effectiveness in the NIF environment and/or develop new instruments which can survive the blast.

Model development — a number of very useful models currently exist; however, these tend to be simplified, often 1-D, approximations. Many of the key issues involve more complex phenomena resulting from non-uniformities or complex interactions. Further model development will be needed to interpret the results of tests and to provide validation of codes which are sophisticated enough to be useful for design purposes.

Basic properties — in some cases, measurements of basic physical and chemical properties are needed in order to provide inputs to codes and to interpret the results of tests.

Small-scale experiments — a large fraction of the remaining issues for wall protection can be addressed in existing or new facilities which are cheaper or more useful than NIF. For example, basic film flow measurements are very important as a reference point for measurements in NIF which include the effects of the blast.

Radioactivity and nuclear heating

A number of important neutronics experiments relevant to IFE appear to be viable on NIF, particularly for radioactivity/decay heat, biological dose and nuclear heating. These experiments include (a) radioactivity measurements in sample materials to measure both short and long half-life isotopic activities, (b) measurements of radioactivity from activated debris and shrapnel, (c) measurement of biological dose outside the cavity and outside the building and (d) measurements of nuclear heating rates in material samples using microcalorimeter techniques. These measurements serve the following purposes: (a) examine effects of high dose rate on double or triple neutron-induced reactions and transmutations, (b) verify calculational codes and nuclear data libraries and (c) provide experimental data for licensing future facilities such as ETF. It should be noted that the average neutron fluence obtainable in NIF, when ignited, at 20 MJ fusion energy at the first wall (ca. 5 m from target) is ca. 2×10^{12} n cm^{-2} per shot. Measurements have been conducted successfully recently at the FNS facility in Japan and in TFTR with DT shots at comparable fluences.

For nuclear heating, the state of the art of present techniques is such that a temperature rise greater than 1 mK can be measured. Such a temperature rise is obtainable in NIF at ca. 0.2 m from the target with a few MJ fusion yield. Higher yields will improve the accuracy of the nuclear heating measurements. Other experimental requirements to measure nuclear heating in NIF include (a) support 5–10 calorimeters at symmetric locations, (b) weight per probe is ca. 800 g, (c) must protect against non-neutron heating, (d) must protect against physical damage and (e) need to extract within 5–10 min after shot.

Tritium self-sufficiency

NIF can make partial but important contributions to demonstrating tritium self-sufficiency by (a) performing measurements related to the required tritium breeding ratio, including measurements of the tritium fractional burn-up in the target, and measurements on tritium flow rates and inventories wherever it is possible in the facility, and (b) measurements of the potentially achievable tritium breeding ratio in prototypical blanket modules.

Radiation shielding (bulk and for penetrations)

The leakage of neutrons out of the target chamber could cause significant activation and radiation damage in out-of-chamber components of experimental, demonstration and ICF power plants that will follow the NIF.

The two primary components to the leaking neutrons are (1) deep penetration through the chamber wall, blanket (when it exists) and shield and (2) streamlining of neutrons through the beam ports and other penetrations in the large chamber.

In certain IFE plant concepts (such as HYLIFE-II), it may be possible to reduce significantly the fraction of fusion neutrons which leak through the beam ports by use of in-vessel placed liquid jets or solid pencil-shaped objects attached to the target. This "neutron stopper" is to make use of two unique features of the IFE neutron sources: their small volume of origin ($\ll 1$ mm) and the fact that the beam aim point is separated from the small-dimension neutron source point by about 10 mm (so that the neutrons streaming towards the beam port follow a different path than the ion beam path. The NIF will provide the first opportunity to verify experimentally the feasibility of this concept.

The NIF will provide intense enough neutron pulses and representative geometries to enable one to perfom benchmark experiments which are expected to resolve most of the shielding issues of importance for the design of IFE reactors which will follow the NIF.

Thermomechanical structural response

NIF can provide important information relevant to some of the thermomechanical structural response of the vacuum vessel and the in-vessel components. For the vacuum vessel, information can be obtained to assess the effect of multiple penetrations on the integral response of the vessel to a several MJ point source of energy release under normal and off-normal conditions. Examples of information to be obtained include in-vessel strain rate, stress concentration, vibrational modes, displacements and energy damping rate. Such information can be used partially to benchmark design codes for IFE.

Reliability and remote maintenance

Remote maintenance capabilities should be designed with NIF, as they were for JET. They should be practiced during routine operation to develop efficient procedures and to uncover flaws in hardware, software, and procedures. Component failure rate data should be collected on NIF components. An extensive component failure rate database will be needed as a prerequisite for doing probability/risk assessments that are essential for estimating accident frequencies.

Safety

As we consider safety issues for an eventual IFE power source, the overriding concern is protection of the workers, public and environment, including the consequences of accidents, exposures to radioactivity or toxic materials due to routine operations and waste products. Specific issues include tritium and activation product inventories and gamma shielding to reduce doses to personnel.

NIF operation can provide useful data on routine tritium emissions, on tritium inventories in reactor components and on the effects of neutron steaming on personnel doses. We can look for the production of mixed hazardous/radioactive waste during NIF operation, and devise strategies to cope with it or to avoid its generation. We need to verify predictions of activated materials produced from target materials, structural materials or other components unique to IFE.

Performing the FPT experiments identified earlier on NIF requires three important activities: more detailed evaluation of experiments, efforts to gather and inter-

Table 5
Target fabrication issues

	NIF usefulness[a]	NIF uniqueness[b]
Low-cost mass-production techniques for capsules and their effect on quality, materials choice and gain	2	3
Low-cost mass-production techniques for laser driver hohlraums	2	3
Effect of cryogenic layer quality on gain	2	3
Automated cryogenic assembly techniques	3	3
Fast-fill techniques for low tritium inventory	2	3
High-throughput quality inspection techniques	2	3

[a] Usefulness: 3 = complete resolution; 2 = partial resolution; 1 = useful information; 0 = no use.
[b] Uniqueness: 3 = NIF unique and required; 2 = NIF not unique but could be used; 1 = issue addressed better or cheaper in new facility; 0 = issue addressed better or cheaper in existing facility.

Table 6
Target transport issues

	NIF usefulness[a]	NIF uniqueness[b]
Injection techniques for high rep-rate cryogenic operation	0	1
Time and space accuracy and sensing	0	1
Integration	2	1–2
Target survival under acceleration	2	3
Thermal protection and temperature control	2	2
Chamber environment effects on trajectory	1–2	3
Demonstration of high rep rate operation	2	3

[a] Usefulness: 3 = complete resolution; 2 = partial resolution; 1 = useful information; 0 = no use.
[b] Uniqueness: 3 = NIF unique and required; 2 = NIF not unique but could be used; 1 = issue addressed better or cheaper in new facility; 0 = issue addressed better or cheaper in existing facility.

pret relevant information generated in the magnetic fusion program and conducting R & D specific to the proposed IFE experiments.

2.4. Target systems

The term target systems was defined broadly to include targer fabrication (including capsule production, hohlraum production, target assembly, characterization, fill and layering), targer materials and configuration selection, target transport from the target factory to the reaction chamber and target insertion, tracking and protection inside the reaction chamber [9,14]. We have separated these into two broad areas: target fabrication and target transport. We discuss below, for each of these areas, the issues that must be resolved in order to develop successfully an inertial fusion energy power plant and the experiments that could be done in the NIF to help resolve these issues.

Fabrication issues with IFE targets

The targets that fuel an inertial fusion power plant based upon the indirect drive approach will be similar to the ignition and high-gain targets developed for the NIF. The IFE fuel capsules, however, will be 2–3 times larger in diameter since capsule size scales according to the cube root of the absorbed energy. For a laser driver, hohlraums will scale similarly. Ion targets will require substantially different hohlraums and X-ray converters. As with NIF high-gain targets, IFE targets will be cryogenic. The major issues associated with developing these targets, broadly stated, are (1) assuring the target component quality specifications as sizes increase and fabrication techniques change; (2) assuring a fast enough fuel fill rate to be able to maintain the plant tritium inventory at acceptable levels; and (3) developing fabrication and inspection techniques that produce high-quality, economically viable targets. A fourth issue, dealt with in the following section on target transport, is providing targets that can withstand the accelerations attending chamber injection, and can withstand the chamber environment once injected.

Table 5 lists more fine-grained issues that must ultimately be addressed to produce and use IFE targets, together with an assessment of the importance of the NIF in developing solutions. In summary, most IFE target requirements can be developed "off-line". Those that require full scaling to IFE sizes, such as capsule surface morphology, cannot be completely tested to ignition on the NIF. Those that do not require such scaling, such as changes in capsule material or target assembly techniqes, should be tested on the NIF. The NIF would be a unique test-bed, since the relevant test of success is ignition.

Target transport issues

Under the category of target transport, we include both transport from the target fabrication facility to the target injector and the injection of the target to the point of ignition. Completed targets will be stored in a cryogenic storage system prior to transport to the injector and must be kept at constant temperature throughout the entire transport and injection process. Even after the target leaves the injector and enters the chamber environment, the allowed temperature rise of the cryogenic fuel is very low, estimated to be less than 0.2 K. Targets must also survive the acceleration process. The target transport issues for IFE are listed in Table 6. As indicated the NIF will be useful for addressing many of these issues.

Table 7
Target systems R & D needs

Development Item	Needed for NIF	Needed for NIF–IFE experiments	Needed for IFE	Current R & D activity[a]
Target fabrication				
Targets for ignition				
Ignition target design	×			A
1–3 mm capsules	×	×	×	B
High-pressure DT fill and condense	×	×	×	C
Cryogenic layering	×	×	×	D
Cryogenic characterization	×	×	×	D
Cryogenic assembly	×	×	×	–
Targets for IFE				
IFE target design		×	×	–
IFE target fabrication		×	×	–
Cost-effective fabrication			×	–
Target transport				
Transport systems				
Transport to reaction chamber	×	×	×	C
High-throughput transport			×	–
Injection and tracking				
Stationary mounting system	×	×		C
Free-fall injection		×		–
High-speed injection		×	×	–
High-rep-rate, rad-hardened injection			×	–
Target tracking		×	×	–
Hardened target tracking			×	–

[a] A = NIF design activity; B = target fabrication development activity; C = OMEGA Upgrade design; D = National Cryogenic Target R & D Program.

Target system

Research and development needs for target systems are summarized in Table 7. Target fabrication and injection systems for IFE will require development. Some of the target fabrication issues must be faced in order to field ignition targets on NIF and will require continuation and expansion of current target development activities. The testing proposed in NIF of IFE-relevant targets will require that those targets first be developed. Relatively little has been done in that area to date. We recommend a program of target design and fabrication R & D to have prototypic IFE targets ready for testing on NIF. This testing will come after the NIF primary mission of ignition has been achieved, that is, about 5 years after the startup of the NIF.

Cryogenic ignition experiments on NIF will require cryogenic target transport systems. Development of these systems will benefit greatly from work on similar systems being developed for Omega Upgrade. IFE will require sophisticated target injection and tracking systems that have yet to be seriously studied. IFE target experiments on NIF will require that a portion of the development needed on these systems be done. We recommend that IFE tracking and pointing studies be done now to define the systems that could be tested on NIF, followed by development of the required hardware for these experiments. These experiments would logically follow the static tests of IFE prototype targets described above.

3. The value of NIF for IFE

The role of the NIF can uniquely cover a large and essential portion of needed IFE development in the areas of IFE target physics and design/performance optimization, IFE fusion chamber dynamics and first wall response, IFE fusion power technology, materials science and safety and for final precision/performance tests of mass-fabricated IFE targets and high repetition target injection systems.

The general focus of the proposed uses of NIF for IFE development is aimed at undertaking the basic underlying target and target chamber phenomenology, physics and materials science needed to design the ETF, an IFE development facility to follow the NIF, and to guide the selection of IFE technologies needed for future IFE power plants. Accordingly, the purpose of the NIF experiments is 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 provides target chamber environment conditions close to, but not necessarily the same as, conditions expected in specific IFE power plant concepts. The use of the NIF to establish predictive design capabilities for IFE is the key to cost-effective IFE development. The nation cannot afford to develop IFE concepts empirically, in Darwinian-evolution fashion.

Nearly all of the potential IFE-development experiments suggested for NIF can be performed within the present NIF laser system design capabilities and functional requirements, and, with a few exceptions noted below, will not require expensive modifications to the NIF target chamber. However, the scope, number and scale of identified NIF experimental campaigns for IFE implies (a) significant need for preparatory IFE developments concurrent with NIF construction and initial operation, to be ready to field some of the more important IFE experiments on NIF once ignition is achieved, and (b) a very significant additional number (2000–3000) of desired NIF shots for IFE-specific experiments with and without yield, including possible "piggy-backing", beyond those needed to produce the first ignition demonstrations in the NIF. These NIF findings need to be included in the overall national IFE development plans and in the planning for NIF operations beyond the ignition campaign. These plans need to be coordinated with the other NIF requirements for supporting weapons physics, nuclear weapons effects simulation and basic high-energy density science.

Developments are needed for NIF–IFE experiments. Diagnostics are needed for post-bang-time characterization of target emissions and distribution within the target chamber. 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, and diagnostic techniques for specific IFE experiments, would benefit from initial development tests in Nova before use in NIF.

Many IFE experiments will involve amounts of liquid and solid test samples which will condense out on the NIF chamber walls and optics windows. Compatibility tests are needed to design the NIF Vacuum Recovery System (VRS) to cope with the introduction of these condensates, and to guide the selection of compatible liquid and solid surrogates to model the dynamics of IFE material responses.

A large fraction of the NIF shots for IFE experiments do not need full NIF laser energy or fusion yield, at least for most of their test sequence up to a final full-yield NIF test. Simple foil targets can provide characteristic soft X-ray and debris spectra, at minimum relevant fluences of $> 100\ \mathrm{J\ cm^{-2}}$ over $> 1000\ \mathrm{cm^2}$ samples for relevant spatial and time scales for IFE ablation studies, requiring minimum laser energies of a few hundred kJ. Also, some IFE material samples may not be compatible with even a modified NIF VRS cleanup system for the main NIF chamber. For these reasons, a smaller, separate target chamber for non-yield IFE experiments at 100–400 kJ, 3ω laser energy, with a simple single-sided illumination geometry, is highly desirable.

To support the credibility of high-rep-rate IFE for an ETF decision in 2005, it is highly desirable for NIF to demonstrate multi-shot target precision/symmetry reproducibility in a high-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, in the main NIF target chamber. If this NIF test is feasible, then appropriate prior development of the multi-shot IFE model target fabrication, tracking and insertion systems needs to start, beginning in about 1998, to be ready to perform this test, if required, for an ETF decision shortly after first ignition is achieved (ca. 2004–2005).

4. Conclusions

Many experiments can be done on NIF to address some of the critical issues of IFE fusion power and target systems technologies. Using the output of ignited targets, NIF experiments will be able to characterize radiation, shock and debris effects on various first wall candidates and on driver/reactor interface systems providing the data necessary to design multiple pulse and high-rep-rate experiments for the ETF. NIF experiments will be essential for calibrating and improving the predictive capabilities of X-ray, debris and neutron emissions and their effects. NIF experiments can study the target manufacturing tolerances required for mass production and the positioning requirements of the injection, tracking and beam pointing systems. NIF will be not only a target physics facility, but also an important experimental facility to support a broad range of research on the IFE development path.

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