Development of IFE Target Systems on the NIF*

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ABSTRACT

The Target Systems session of the Workshop on NIF Experiments for IFE developed a list of critical issues for inertial fusion energy (IFE) target systems, and considered the potential of the National Ignition Facility (NIF) to help in the resolution of these issues and in the development of IFE target systems. This paper describes the IFE Target System issues, categorized into target fabrication issues and target transport issues, describes potential NIF IFE target systems experiments, considers the impact of these experiments on the NIF and discusses the development required before these experiments could be done.

Most target systems issues must be resolved by development in the laboratory, not in the NIF, and some must be resolved before the NIF can be successful. However, experiments done in the NIF could play a valuable role in developing target systems for IFE. These experiments should have modest impact on the basic design of the NIF, but could require several hundred dedicated, high yield shots.

I. INTRODUCTION

The Target Systems session of the Workshop on NIF Experiments for IFE [1] began by reviewing the target systems design results from several recent IFE power plant design studies [2–4]. We tabulated the various critical issues that will have to be resolved before these target systems could be successfully built and operated with confidence. We then reviewed a number of proposals for experiments to be done in the NIF that could address some of these issues. Target Systems was defined broadly to include (1) target fabrication (including target materials and configuration selection, capsule production, hohlraum production, target assembly, characterization, fill, and layering), and (2) target transport (transport from the target factory to the reaction chamber, and target insertion, tracking, and protection inside the reaction chamber.) We discuss below for each of these two areas, the issues that must be resolved in order to successfully develop an inertial fusion energy power plant, and the experiments that could be done in the NIF to help resolve these issues.

II. TARGET FABRICATION

IFE target fabrication includes target materials and configuration selection, capsule production, hohlraum production, target assembly, characterization, fill and layering. Although most, if not all, of these activities will be done in a separate target fabrication facility, the NIF can play an important role in their development.

A. 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 two-to-three 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. Heavy ion drivers 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 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 I 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 techniques, should be tested on the NIF. The NIF would be a unique test-bed, since the relevant test of success is ignition.

Currently, each target for ICF experiments costs thousands of dollars to fabricate. For a commercially viable IFE power plant, however, the cost per target must be around thirty cents. No doubt immense cost reductions will accompany an increase in production rate from roughly 1000/year at present to 10^9–10^{10}/year needed for an IFE-based fusion economy. This reduction will require use of cheaper mass production techniques and perhaps some changes in materials. Savings may also be realized from a relaxation of target parameters or development of new target configurations that may allow

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easier fabrication. The first three rows of Table I contain issues of low-cost production. They cannot be completely resolved for IFE targets due to limitations in the NIF output energy.

The fourth and fifth items in Table I address minimizing the tritium inventory. This requires developing a fast fill technique, such as drill, fill and seal, or a capsule material with very high permeability. Capsules would have to be filled prior to assembling into hohlraums to minimize the volume of the batch filling apparatus. Thus, since the capsule will very likely have to be kept at cryogenic temperatures to avoid rupture, a technique would have to be developed for cryogenic assembly of the capsule into the hohlraum.

The last item in Table I would investigate the range of acceptable target component qualities. Broadening this range would not only help reduce fabrication costs, but would considerably ease the inspection requirements, which may be essential for high throughput.

In Table I, we have not included issues specific to heavy-ion driven targets. However, NIF experiments relevant to these targets have been proposed [1,5] and may require additions to the table. In any case, the generic issues of low-cost, low tritium inventory, and high target quality apply to these targets as well. Finally, as mentioned above and explained more fully below, high-rep-rate injectable targets may require additional robustness, whose effects on ignition performance would have to be tested on the NIF. The issues surrounding injection of targets are summarized in Section III below.

Table I
Target Fabrication Issues

	NIF Usefulness	NIF Uniqueness
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
The 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

	Usefulness	Uniqueness
3	Complete resolution	NIF unique and required
2	Partial resolution	NIF not unique; could be used
1	Useful information	Addressed better/cheaper in new facility
0	No use	Addressed better/cheaper in existing facility

B. *Proposed Target Fabrication-Related Experiments*

Targets for NIF ignition and high gain experiments will be fabricated with the best available technology. Clearly IFE targets cannot receive the fabrication attention that ICF targets get, but equally clearly, there will be limits on the compromises that can be made in the fabrication of IFE targets without decreasing their performance to the point where their gain drops unacceptably (or they won't ignite). An experimental series exploring the affects on the target gain of the fabrication modifications dictated by the economics of IFE would be very useful to IFE.

We propose to test the affect on target performance of cheaper hohlraum fabrication techniques such as stamping, drawing, and spinning. Alternate materials that would aid in cost reduction would be tested. Similarly, the proposal would probe the performance of capsules selected that would aid in cost reduction by cheaper, automated characterization techniques for wall thickness, uniformity and fill pressure. These and other deliberate (and well-characterized) defects could be included such as imperfections in material boundaries and point defects in capsules. These effects could be tested separately and in combination by selectively including components made via proven methods. All these targets would be characterized extensively in the usual ways to provide quantitative measures of the fabrication compromises. The goal would be to define the performance costs of mass production techniques suitable for IFE, where target costs have a significant affect on plant economics. An appropriate number of shots for each variation (several hundred over 4–6 years) would be compared to the data set for high-gain targets, to provide statistically significant limits on IFE fabrication techniques.

III. TARGET TRANSPORT

IFE target transport, includes target transport from the target factory to the reaction chamber and target injection, tracking and protection inside the reaction chamber.

A. *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 II.

To proceed with development of inertial fusion for energy, we must design and develop a target handling system to transport targets from the fabrication facility to the injector on the reaction chamber. This must operate at cryogenic temperature, operate at the required rep-rate, (~1–10 Hz) and operate without damage to the target or sabot. In addition, we must design and develop a high pulse rate injector that is similarly capable of cryogenic operation at a high rep-rate, that will operate without mechanical or thermal damage to the target, and may involve use of a sabot. This injector must

Table II
Target Transport Issues

	NIF Usefulness	NIF Uniqueness
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

	Usefulness	Uniqueness
3	Complete resolution	NIF unique and required
2	Partial resolution	NIF not unique; could be used
1	Useful information	Addressed better/cheaper in new facility
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exhibit high reliability and highly repeatable accuracy. To be able to fire the driver at the right time, we must design and develop a target tracking system that will detect the target in transit in chamber and be capable of providing adequate position and timing information to driver. These tracking systems must be protected from the radiation environment of the chamber. The effect of the post-shot environment on next target is also of concern. The target must be protected from the effect of thermal radiation from chamber walls and from convective heat load from residual gases, and protected from the radiation pulse of the prior shot while waiting for injection. In addition, the effect of chamber vapor on the target trajectory must be accounted for.

Finished targets must be handled in a fashion that does not degrade the quality with which they were manufactured. The entire handling and transport to the target injector must be designed to operate at the required pulse rate and at cryogenic temperatures. This will involve conveyers and robotic handing equipment, which need to be developed and demonstrated.

Several options for injectors have been proposed [6] including gas guns and electromagnetic launchers. The key issues are to design and demonstrate a highly reliable system that is capable of operation at high rep-rate with cryogenic targets. The targets must be protected from damage during the acceleration process and during transit through the chamber. Protective sabots, which detach from the target prior to ignition, have been proposed for protection during injection. These must be demonstrated.

Conceptual solutions to target tracking and beam pointing have been developed [6]. Most rely on tracking the target before it enters the chamber so that the tracking systems can be protected from the radiation environment. Tracking systems must be developed that can provide position and timing information that will allow precise illumination of the target.

IFE chambers use either liquids or gases to protect the first wall from damage by short ranged target emissions. The vaporization and condensation of liquids or blast waves in gas protected chambers create a dynamic environment that results in heat loads to the target (radiative and convective) and that may affect the trajectory of the next target in a non-uniform manner. Radiation from the hot chamber walls could lead to excessive heating of the target prior to ignition. The thermal capacity of the target may be sufficient to keep the fuel layer from over heating (especially for hohlraum targets) or a sacrificial frozen gas layer might be added to the outer surface of the target.

B. Proposed Target Transport-Related Experiments

While most of the required development for target transport must be developed off-line and is not needed for NIF, actual integration and demonstration will require a reaction chamber environment. Further, some aspects of target transport systems may be useful to NIF.

1) *Target Alignment and Positioning:* We propose to measure the performance penalty for target positioning errors. Targets for IFE applications would be placed into the target chamber with intentional alignment and positioning errors. Targets would be illuminated in other than the optimal geometry. A series comparing the performance of deliberately misaligned targets would delineate the gain penalties of targets that were displaced from chamber center. High gain targets would be positively positioned above (or below) the ideal focal position; in the mid-plane but off-axis from the ideal illumination location, a combination of the two; and displaced angle from a axial location. The performance of these shots would be compared to the database of targets illuminated in the ideal location with the goal of determining the required beam pointing and target aiming for IFE target injection systems. A total of about 50 shots would be required. These experiments would provide performance specifications for the target injection experiments described below. Combined injection/ positioning experiments may be possible.

2) *Target Injection:* The ability to ignite targets on the fly is essential for inertial fusion energy power plants. Once components of inertial fusion energy target injection have been developed off-line, they could be demonstrated in an integral manner on NIF.

Three experiments are proposed for injecting targets on NIF which should first be developed and demonstrated off-line. The first involves dropping a cryogenic target into the NIF chamber. The target falls through a laser timing gate, which initiates the laser pulse. The target would probably be released from within the chamber to minimize target heating and more easily control target position.

The second proposed experiment is more closely related to expected IFE target injection procedures. A gas gun is used to accelerate targets into the fusion chamber. Photodiodes are used to track and time target arrival. If sufficient target position repeatability is not achieved by this method, it may be possible to electrostatically steer the targets onto the correct trajectory.

The third experiment reduces target heating. A thin frozen layer of neon (or other suitable material) is adhered to the hohlraum. During injection, this material will ablate off the surface reducing target heating. We will measure the affect of possible non-uniform ablation on target trajectory. An alternate method of minimizing the heating of a falling target is to drop the target through a cryogenic tube during the initial slow moving part of the fall.

Remote target injection methods may also be beneficial to NIF. In the baseline design, cryogenic cooling tubes lead to the target. The tubes will be destroyed and produce shrapnel debris with each shot in which they are used. Replacement cost and potential shrapnel damage could be avoided by remotely injecting targets and igniting them on the fly. This would be accomplished at the expense of reduced target position certainty.

3) *Target Chamber Environment:* NIF offers a chance to study post-shot environment under conditions that could be extrapolated to an IFE power plant. The influence of the chamber environment on the injection of subsequent targets and beam transport is critical to successful operation of an IFE power plant.

We propose an experiment to look at the repeatability and accuracy of various target injection schemes. The 5 m NIF vacuum chamber is roughly the same size as estimates of chambers needed for operational IFE power plants. Initial studies can be piggybacked on an injection shot immediately after an ignition shot. The idea is not to fire the laser at the injected target, but to determine the effects of the post-shot environment on the injected target (specifically trajectory and target temperature). The test target would be injected 0.05–0.2 s. after the laser fires. This could present the injected target with conditions that would be present in an IFE power plant operating at a 5–10 Hz rep rate. For trajectory experiments, the post-shot injected target need not be cryogenic, but should have the same size and mass as a real target. Injection schemes suitable for both direct and indirect drive should be considered. Instrumentation would include diagnostics to measure gas pressure, species, clearance time (due to vacuum pumping); chamber temperature and profile; target position, orientation and velocity; and, if possible, temperature and inner surface quality of a cryogenic target. This last measurement should first be done off-line or in a static experiment after the chamber conditions are determined and simulated.

If fluence conditions equivalent to that of an IFE power plant are desired, a dedicated series of shots would be made by inserting a one meter radius—or smaller—chamber (with holes for the laser beams) inside the NIF chamber [20 MJ $\times (5/1)^2 = 500$ MJ simulation]. This is shown schematically on Fig. 1. Non-vacuum conditions (e.g., 1 Torr of neon gas—consistent with the ability to fire the NIF lasers) could also be studied.

If it is desired to actually hit a target injected into the chamber after an initial shot, it will be necessary to provide partial power shot capability on NIF, firing 1/2 or 1/4 of the lasers at ~200 ms intervals. To avoid asymetric implosions and shrapnel, these partial power shots may need to be symmetrically distributed around the target chamber, which could require modification to the present NIF laser design.

IV. TARGET SYSTEMS R&D NEEDS

Before experiments of any kind can be done on NIF, R&D will be needed to develop ignition targets. This R&D is currently underway. To develop targets for IFE and cost-effective fabrication techniques for these energy-relevant targets, and to develop target transport systems for IFE will require further effort. Some of this effort will be needed before IFE target systems experiments can be fielded on NIF, as summarized on Table III.

A. Target Fabrication

Designs exist for ignition targets. Some development will be needed to fabricate these targets, and additional designs will surely be needed in the course of the NIF experimental program. Preliminary designs exist for IFE targets, but more detailed designs must be made and fabrication techniques must be developed before such designs could be tested in NIF.

1) *Targets for Ignition*: The present designs for NIF ignition targets are very similar to current targets shot on NOVA, just larger and cryogenic. Some development, however, will be required. Target quality capsules about 1–3 mm in diameter will be needed and are not currently available. A method is needed to fill these capsules to about 1000 atm. pressure with DT, and then cool them to cryogenic temperatures to condense the DT. The DT layer inside the capsules must meet stringent specifications for uniformity (>99%) and surface roughness (<5000Å). While R&D is underway as part of the National Cryogenic Target R&D Program to develop these capsules, it must be completed. Techniques for assembly of cryogenic capsules and hohlraums, or a method to fill capsules while they are inside ignition target hohlraums are needed. These development needs must be filled for the NIF itself, immaterial of IFE experiments. Some of the capsule and cryogenic capsule fill needs are being addressed for cryogenic targets for the OMEGA experiments at the University of Rochester. This work will directly benefit NIF, and ultimately IFE. Work on hohlraums and cryogenic assembly, however, is not yet being done and will be needed for NIF. This effort will then directly benefit IFE.

2) *Targets for IFE*: Targets for IFE will need to be developed that are inexpensive, robust for handling, transport and injection, and compatible with the chamber environment of an IFE power plant. Target materials, fabrication techniques and fill methods for IFE will surely be different than those currently envisioned for the NIF ignition targets. Prototypes of such targets must be developed and fabricated for testing on NIF.

We recommend that studies be done to design IFE targets. These studies would be analytic (paper) and would be

Fig. 1. NIF inner chamber to simulate full-scale IFE chamber.

relatively inexpensive. Designs relevant for testing on NIF would then be selected and prototype targets fabricated for NIF experiments. These prototypes would exhibit the features of IFE targets that are different from those needed for ignition alone and would examine the effect on yield of features required for IFE. Actual development of mass production capability for such targets and demonstration of target fabrication economics will require further effort and equipment, but is not needed for the experiments on NIF.

B. Target Transport

To be able to do ignition experiments on NIF will require cryogenic target transport systems to mount targets in the reaction chamber. Large scale, high throughput, highly reliable target transport, injection and tracking technologies will be needed for IFE. The experiments proposed for NIF will not require large numbers of targets, nor the automation or reliability needed for IFE. Nevertheless, some development will be needed on injection and tracking techniques to field the experiments on NIF. This development will be directly relevant to IFE, and in fact, NIF will play an important role in this development.

1) *Transport Systems*: To get cryogenic ignition or prototype IFE targets from the fill station to the center of the target chamber will require cryogenic target transport systems. These must be part of the NIF experiments, and will probably not be in any way prototypic of transport systems for IFE. Development of such systems for NIF will be able to build on the development of the cryogenic target transport system for OMEGA.

2) *Injection and Tracking*: Ignition experiments on NIF will utilize stationary mounted targets; no injection or tracking is needed. IFE will require sophisticated target injection and tracking systems to be able to inject targets into the hostile environment of the reaction chamber at the rate of 1–10 Hz. The IFE target system experiments proposed for NIF will require partial development of some of these systems. A free-fall target injector will not be adequate for IFE, but may work for NIF and is a first step toward the high speed injection system that will be needed for IFE. Development of the injection mechanisms for free-fall and high speed injection, and development of the tracking and firing systems to use these injectors will be needed for the proposed experiments to be fielded on NIF. The high rep rate, high reliability, and radiation hardening that will be required for IFE will not be required for experiments in NIF.

We recommend that studies be done to design target injection and tracking systems for IFE application. Based on these studies, appropriate tests on NIF can be planned, and the development needed to field this hardware can be carried out. By making it possible to move all hardware farther from the target ignition point, target injection systems for NIF may help facilitate other experiments and reduce the effect of blow-off from the target stalk on NIF diagnostics.

C. Development Needs Summary

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

Table III
Target Systems R&D Needs

Development Item	Needed for NIF	Needed for IFE Expts. in NIF	Needed for IFE	Current R&D Activity*
TARGET FABRICATION				
Targets for Ignition				
Ignition target design	X			A
1–3 mm capsules	X	X	X	B
High pressure DT fill and condense	X	X	X	C
Cryogenic layering	X	X	X	D
Cryogenic characterization	X	X	X	D
Cryogenic assembly	X	X	X	–
Targets for IFE				
IFE target design		X	X	–
IFE target fabrication		X	X	–
Cost-effective fabrication			X	–
TARGET TRANSPORT				
Transport Systems				
Transport to reaction chamber	X	X	X	C
High throughput transport			X	–
Injection and tracking				
Stationary mounting system	X	X		C
Free-fall injection		X		–
High speed injection		X	X	–
High rep rate, rad. hardened injection			X	–
Target tracking		X	X	–
Hardened target tracking			X	–

***:**
A: NIF Design Activity
B: Target Fabrication Development Activity
C: OMEGA Upgrade Design
D: National Cryogenic Target R&D Program

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. IFE will require sophisticated target injection and tracking systems that have yet to be seriously studied. IFE target experiments on NIF will require a portion of the development needed on these systems to be done. We recommend that IFE tracking and pointing studies be done 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.

V. SUMMARY

The Target Systems session of the Workshop on NIF Experiments for IFE reviewed the target systems design results from several recent IFE power plant design studies and developed a list of the critical issues that will have to be resolved before these designs could be successfully built and operated with confidence. These issues can be broadly categorized into two areas: target fabrication issues and target transport issues. We reviewed a number of proposed NIF experiments and found that the NIF can play an important role in development of target systems and resolution of critical target systems issues for IFE.

For the most part, the target fabrication issues must be resolved by development work done in the laboratory, not in NIF, and some must be resolved before the NIF can be successful. However, investigation of the effect on target yield of various design changes to get from ignition experiment targets to targets that can be economically mass-produced for an IFE power plant will need to be done in actual implosion experiments, and the NIF can make valuable contributions to this development. While these NIF experiments can be done with modest impact on the design of NIF, several hundred high yield shots could be needed, which could impact the NIF operating schedule and planned lifetime.

Target transport issues related to target handling, insertion and tracking must also be addressed by development work in the laboratory. However, integration of these components into a complete system, and demonstration of this system could be done most convincingly on the NIF. Use of a target injection system may, in fact, be useful to NIF in that the effect of target insertion system hardware (blow-off and debris) on NIF experiments could be reduced. The effect of inertial fusion reaction chamber conditions on the survival and performance of targets must be determined under actual reaction chamber conditions, and experiments in NIF could help in this effort. The target transport issues experiments will require insertion system hardware and an inner chamber to simulate IFE post-shot conditions be added to NIF, however, this equipment will have little impact on the basic NIF design. The total number of shots needed for these experiments should be less than 100. If multiple, partial power shots are desired, provision for firing 1/2 or 1/4 of the lasers on 200 ms intervals will be needed, probably with a symmetric distribution on the target chamber, and possibly requiring changes to the NIF laser design.

In short, much of the development work needed for IFE target systems must be done in the laboratory, not on an implosion experiment in NIF. However, experiments done in the NIF could play a valuable role in developing targets for IFE and in verifying performance of IFE target injection systems. These experiments should have modest impact on the basic design of NIF, but could require several hundred dedicated, high yield shots, probably impacting the NIF design lifetime requirement.

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