RECEIVED
JUN 24 1996
OSTI

Core Science and Technology Development Plan for Indirect-Drive ICF Ignition

December 1995

Lawrence Livermore
National Laboratory

Sandia National Laboratory

Los Alamos
Los Alamos National Laboratory

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This report has been reproduced
directly from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (615) 576-8401, FTS 626-8401

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.,
Springfield, VA 22161

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

Core Science and Technology Development Plan for Indirect-Drive ICF Ignition

H. T. Powell and J. D.ilkenny
Technical Editors

December 1995

Core Science and Technology Development Plan
for Indirect-Drive ICF Ignition

December 1995

Approved by:

Howard T. Powell
Program Leader
Laser Science and Technology Program
Lawrence Livermore National Laboratory

Joseph D. Kilkenny
Program Leader
Target Physics Program
Lawrence Livermore National Laboratory

Melissa Cray
Program Director of Inertial Confinement Fusion
Los Alamos National Laboratory

Jeffrey P. Quintenz
Program Manager for Light Ion Fusion
Sandia National Laboratory

Contents

Introduction	x
Development Plan Summary	xii
1.0 Laser Technology	1-1
References	1-5
1.1 Optical Pulse Generation System	1-6
1.1.1 Master Oscillator and Fiber Amplifier	1-7
1.1.2 Electro-Optic Components	1-10
1.1.3 Regenerative Amplifiers	1-10
1.1.4 Multipass Amplifier	1-13
1.1.5 High-Speed Electronics	1-16
1.1.6 Integration and Breadboard Testing	1-18
References	1-21
1.2 Multisegment Amplifiers	1-22
1.2.1 Pump Cavity	1-24
1.2.2 Flashlamps	1-27
1.2.3 Thermal Control Systems	1-30
1.2.4 Performance Measurements	1-31
1.2.5 Assembly and Maintenance	1-35
References	1-36
1.3 Multipass Laser Components	1-37
1.3.1 Large-Aperture Plasma-Electrode Pockels Cell	1-37
1.3.2 Multiaperture Pockels Cell	1-42
1.3.3 "U-turn/L-turn" Components	1-44
1.3.4 Pinholes and Beam Dumps	1-48
References	1-52
1.4 Frequency Conversion	1-53
References	1-61
1.5 Diffractive Optics	1-62
1.5.1 Beam-Smoothing Optics	1-62
1.5.2 Beam-Sampling Gratings	1-67
1.5.3 Other Diffractive Optical Components	1-69
References	1-70
1.6 Pulsed Power Systems	1-71
1.6.1 High-Current Switches	1-72
1.6.2 High-Density Capacitors	1-76
1.6.3 Pulsed Power Components	1-78
1.6.4 Prototyping and System Integration	1-81
References	1-84

1.7	Laser Diagnostics	1-86
1.7.1	Full Aperture Beam Sampling	1-86
1.7.2	Fiber-Optic Technology Development	1-87
1.7.3	Temporal Sensor Technology Development	1-89
1.7.4	Laser Diagnostic System Integration	1-89
	References	1-93
1.8	Laser Alignment and Wavefront Control	1-94
1.8.1	Light Sources for Alignment and Wavefront Control	1-94
1.8.2	Alignment Concepts Evaluation	1-96
1.8.3	Chamber Center Reference System	1-97
1.8.4	Cavity Deformable Mirror	1-98
1.8.5	Enhanced Video Controller	1-99
1.8.6	Portable Wavefront Measurement System	1-101
	References	1-103
1.9	Optics Support and Assembly	1-104
1.9.1	Optics Mounting and Assembly	1-104
1.9.2	Structural Support Systems	1-106
1.9.3	Mounting Vacuum-Loaded Square Optics	1-109
1.10	Control Systems	1-111
1.10.1	Distributed Computer Controls	1-113
1.10.2	Timing System Component Development	1-115
1.10.3	Video-Based Automatic Alignment	1-115
1.10.4	Alignment Front End Controls	1-117
1.10.5	Laser Diagnostic Data Acquisition	1-118
1.10.6	Schedule	1-118
	References	1-119
1.11	Laser Design Optimization	1-121
1.11.1	Pump Cavity Analysis	1-121
1.11.2	Propagation Analysis	1-127
1.11.3	Frequency Conversion	1-130
1.11.4	SRS/SBS Analysis	1-131
1.11.5	Data and Code Library	1-132
1.11.6	Cost Synthesis	1-132
1.11.7	Design Optimization	1-133
	References	1-134
1.12	Basic Physics, Material Properties, and Advanced Concepts	1-135
1.12.1	Amplifier Energy Extraction	1-135
1.12.2	Frequency-Conversion Efficiency	1-136
1.12.3	Nonlinear Optical Propagation and Materials Constants	1-138

1.12.4	SRRS in Nitrogen Gas/Air	1-138
1.12.5	Advanced Concepts	1-139
References		1-140
1.13	Beamlet Test and Evaluation	1-141
1.13.1	1 ω Propagation Physics	1-143
1.13.2	Large-area Damage Tests	1-145
1.13.3	3 ω Conversion and Final Focus Geometry	1-146
1.13.4	Output Diagnostics and Beam Smoothing	1-148
1.13.5	Beamlet System Engineering Improvements and Tests	1-149
1.13.6	NIF Component Tests	1-150
1.13.7	NIF Prototype System Tests	1-151
2.0	Optics Manufacturing and Processing	2-1
2.1	Laser Glass	2-2
2.2	KDP/KD*P Crystals	2-8
2.3	Fused Silica	2-14
2.4	Optics Finishing	2-17
2.5	Optical Coatings	2-21
2.6	Laser Damage Testing and Conditioning	2-28
2.7	Large-Aperture Optic Characterization	2-32
2.8	Final Optics Protection	2-35
2.9	Optics Cleaning and Processing	2-38
3.0	Target Chamber	3-1
3.1	Characterization of Target Emissions	3-1
3.2	First Wall and Target Positioner Protective Coatings	3-5
3.3	Unconverted Laser Light Absorber	3-11
3.4	Advanced Final Optic Protective Coating	3-15
3.5	Automated Tritium and Activated Debris Decontamination System	3-17
3.6	Electrical Diagnostic Component Vulnerability and Hardening Techniques	3-21
3.7	Target Emplacement, Positioner and Injection Techniques	3-26
References		3-30
4.0	Target Diagnostics	4-1
4.1	X-ray Detectors	4-3
4.1.1	X-ray Streak Cameras	4-3
4.1.2	Gated X-ray Imaging	4-3
4.1.3	X-ray Backlighter Development	4-5
4.1.4	Photocathode Development	4-5

4.1.5	CCD Readouts	4-7
4.1.6	Electro-optic Technology	4-7
4.1.7	X-ray Diode Redesign	4-8
4.1.8	X-Ray Detector Development	4-8
4.1.9	Transmission Grating Development	4-9
4.1.10	Fast-closing Apertures for Debris Mitigation	4-9
4.2	X-ray Imaging and Spectroscopy	4-10
4.2.1	Reflective X-ray Optics	4-11
4.2.2	Multilayer Optics for 10-keV Imaging	4-14
4.2.3	Tapered High-Aspect-Ratio Pinholes	4-14
4.2.4	Ablation of Protective Layers	4-16
4.2.5	Coded-Aperture Imaging	4-17
4.2.6	Focusing Crystal Spectroscopy	4-18
4.2.7	Soft X-ray Imaging, Deflectometry, and Interferometry	4-19
4.2.8	Development of Advanced Methods for X-ray Spectroscopy ..	4-20
4.3	Gamma Ray Diagnostics	4-20
4.3.1	Reaction-Rate History Diagnostic	4-21
4.3.2	Gamma-Ray Spectroscopy for Diagnosis of Fuel Conditions	4-23
4.4	Neutron Detectors	4-25
4.4.1	Neutron Detectors with High Spatial Resolution	4-25
4.4.2	Gated and High-Speed Neutron Detectors	4-27
4.4.3	Single-Hit Detector Arrays	4-28
4.4.4	Total Neutron Yield Detectors.	4-28
4.4.5	Proton Recoil Technique	4-28
4.5	Optical Detectors	4-29
4.5.1	Gated Optical Imager	4-29
4.5.2	Active Probing for Streaked Optical Pyrometer (SOP)	4-30
4.5.3	Witness Plate Technique Development	4-31
4.5.4	Thomson Scattering Diagnostic	4-31
4.5.5	High-Speed Light-Scattering Arrays	4-32
4.5.6	Optical Streak Cameras	4-33
4.5.7	Target Backscatter Diagnostics	4-33
4.6	High-Speed Electrical Recording	4-33
4.6.1	High-Speed Transient Digitizers	4-34
4.6.2	High-Speed Electrical Transmission	4-35
4.6.3	Supporting Technologies	4-35
4.7	Calibration Facilities	4-36
4.7.1	Absolutely Calibrated X-ray Sources	4-37
4.7.2	Pulsed X-ray Source	4-38
4.7.3	X-ray Imaging Calibration Sources	4-39

4.7.4	Neutron Sources	4-39
4.7.5	Optical Calibration Facility	4-39
References		4-40
5.0	Target Design and Theory	5-1
5.1	Hohlraum Design	5-2
5.1.1	Conventional Designs	5-2
5.1.2	Advanced Designs	5-4
5.1.3	Symmetry Diagnosis Design	5-4
5.1.4	Plasma Characterization Design	5-5
5.2	Capsule Design	5-6
5.2.1	High Convergence, High Gain	5-6
5.2.2	Lower-Risk Designs	5-6
5.2.3	Noncryogenic Options	5-6
5.2.4	Internal Pulse Shape Designs	5-6
5.2.5	Mix Diagnosis Design	5-7
5.2.6	Burn Diagnosis Design	5-8
5.2.7	Hydrodynamic Instability Theory and Codes	5-8
5.3	Plasma Instability Mitigation	5-8
5.3.1	Basic Theory	5-8
5.3.2	Nonlinear Saturation Theory	5-9
5.3.3	Plasma Code Development	5-9
5.4	Hydro Code Development	5-9
5.4.1	3-D Codes	5-10
5.4.2	Advanced Physics Models	5-10
5.4.3	Additional Hydro Codes	5-12
5.4.4	Massively Parallel Processing	5-12
5.4.5	Postprocessing	5-13
5.4.6	User Interface	5-13
5.4.7	Machine Interface	5-13
5.5	Advanced Concepts	5-13
5.5.1	Fast Ignitor	5-13
5.5.2	Enhanced Gain	5-15
5.6	ICF Applications	5-15
5.6.1	Inertial Fusion Energy	5-15
5.6.2	Output	5-16
5.6.3	Other NWET Sources	5-16
5.6.4	Weapon Physics	5-17
5.7	Advanced Diagnostics Development and Design and Other Spin-Offs	5-17

5.7.1	X-Ray Laser Probing	5-17
5.7.2	Commercial Spin-Offs	5-17
5.7.3	NIF-Based Science and Technology	5-17
Reference		5-18
6.0	Target Components and Fabrication	6-1
6.1	Capsules	6-1
6.1.1	Polymer Capsules	6-2
6.1.2	Beryllium/Boron Capsules	6-6
6.1.3	Foam Shells	6-8
6.2	Cryogenic Fuel Layers	6-10
6.2.1	Solid Layers	6-11
6.2.2	Liquid Layers	6-14
6.3	Hohlraums	6-14
6.3.1	Cryogenic Environment Control	6-14
6.3.2	Experimental Compatibility Including Filling	6-15
6.3.3	Noncryo Hohlraums	6-17
6.4	Cryogenic Target Support Systems	6-17
6.4.1	Tritium Fill System	6-17
6.4.2	Transport System	6-18
6.4.3	Solid Layer Formation and Characterization	6-18
6.4.4	Insertor/Positioner	6-18
6.5	Characterization	6-18
6.5.1	Fuel Layers	6-19
6.5.2	Foam Surfaces, Density Uniformity	6-19
6.6	Targets for Existing Facilities	6-19
6.6.1	Nova	6-19
6.6.2	Trident Targets	6-20
6.7	NIF Target Production	6-21
References		6-21
7.0	Target Physics Experiments	7-1
7.1	Convergent Hydrodynamics and Mix	7-1
7.1.1	Convergence Scaling	7-2
7.1.2	Detailed Studies	7-2
7.1.3	New Techniques	7-3
7.1.4	Other Hydrodynamics	7-4
7.2	Hohlraum Experiments	7-5
7.2.1	Hohlraum Coupling Limits and Energetics	7-5

7.2.2	Symmetry in Gas-Filled Hohlraum and Advanced Control Techniques	7-6
7.2.3	Development of Time-Dependent Symmetry Techniques	7-7
7.2.4	3-D Symmetry Tests	7-7
7.2.5	Colliding and Interpenetrating Plasma Experiments	7-8
7.2.6	X-ray Spectroscopy Characterization of Hohlraum Plasmas	7-8
7.2.7	Electron Transport Experiments	7-8
7.2.8	Magnetic Field Generation in Hohlraums	7-9
7.2.9	Thomson Scattering Characterization of Hohlraum Plasmas	7-9
7.2.10	Initial NIF Pulse Experiments	7-9
7.3	Laser-Plasma Instabilities	7-10
7.3.1	Large-Scale-Length Plasma Experiments	7-11
7.3.2	Support of Laser-Plasma Instability Experiments at Trident	7-12
7.3.3	Support of Laser-Plasma Instability Experiments at Omega Upgrade	7-13
7.3.4	NIF Filamentation and SBS/SRS Development	7-13
7.4	Ignitor Experiments	7-13
7.5	Experiments at the Omega Upgrade Laser at Rochester	7-14
7.6	Facility Operations	7-15
7.6.1	Nova Facility	7-15
7.6.2	Trident Facility	7-16
7.6.3	Omega Upgrade Facility	7-17
7.6.4	Saturn and PBFA II Pulsed Power Accelerators	7-17

Introduction

Over the past 20 years, the U.S. national inertial confinement fusion (ICF) program has successfully built and operated experimental facilities of increasing size and capabilities to support the goal of achieving laser driven nuclear fusion. The next step is the proposed National Ignition Facility (NIF), which requires a system that can deliver 1.8-MJ/500-TW laser pulse at 350 nm on a routine basis, and target systems capable of handling and diagnosing targets with routine deuterium-tritium (DT) fusion yields up to 20 MJ. Also, the NIF will be capable of both direct- and indirect-drive target illumination. Not only must the NIF and other advanced ICF facilities meet high performance specifications, they must achieve these at acceptable cost.

Successful technology programs in the past have shown that relatively small investments in research and development can have high payback in reducing risk, as well as increasing capability. This R&D investment reduces risk by ensuring that the schedule, cost, and performance goals of new ICF facilities can be met. To define the development work needed to support ICF program goals, we have assembled this Core Science and Technology (CS&T) Plan that encompasses nearly all science research and technology development in the ICF program.

The objective of the CS&T Plan described here is to identify the development work needed to ensure the success of advanced ICF facilities, in particular the NIF. This plan is intended as a framework to facilitate planning and coordination of future ICF programmatic activities. The CS&T program described in this report has been developed with input from all three of the national weapons laboratories: Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), and Sandia National Laboratory (Sandia). All three Laboratories will take important roles in the execution of this crucial preparation for NIF. Although they are not formal contributors to this report, the other ICF laboratories, University of Rochester, Laboratory of Laser Energetics (LLE), General Atomics (GA), and the Naval Research Laboratory (NRL), will also contribute significantly to these developments and to NIF. These core participants will also encourage participation by other organizations in the federal research, academic and industrial communities to ensure that the ablest and most competent talents are available for developing this major new research facility.

The CS&T Plan covers all elements of the ICF program including laser technology, optic manufacturing, target chamber, target diagnostics, target design and theory, target components and fabrication, and target physics experiments. The CS&T Plan has been divided into these seven different technology development areas, and they are used as level-1 categories in a work breakdown structure (WBS) to facilitate the organization of all activities in this plan, as shown in Fig. 1. We also use this same list of seven elements as main chapter headings in this report to link task descriptions with the WBS-based planning details. The scope of the CS&T Plan includes all research and development required to support the NIF leading up to the activation and initial operation as an indirect-drive facility. Thus, R&D work that specifically supports advanced concepts such as direct drive, fast ignition, and inertial fusion energy (IFE) are not included here. A second volume of the CS&T Plan which will cover these areas will be issued later. In each of the CS&T main development areas, we describe the technology and issues that

7/7/94

70-00-0694-2687A pub

Figure 1. Core Science & Technology work breakdown structure.

need to be addressed to achieve NIF performance goals. These performance goals are driven by laser requirements that were defined in the *NIF Conceptual Design Report* (CDR). The Nova Technical Contract (NTC) and the Omega Technical Contract (OTC) constitute the principal target physics validation objectives for the national ICF Program. The target physics development described here extend the effort beyond the NTC and OTC to be better positioned to realize ignition on the NIF. The plans discussed here are consistent with the NIF CDR but are also generally applicable to any new future ICF system.

To resolve all issues and achieve objectives, an extensive assortment of tasks must be performed in a coordinated and timely manner. We describe these activities and present

planning schedules that detail the flow of work to be performed over a 10-year period corresponding to estimated time needed to demonstrate fusion ignition with the NIF. The schedules incorporate logical relationships with critical NIF dates to assure consistency and timeliness with the proposed project. Development markers and milestones are also indicated in the schedules to provide monitors of progress.

Besides the benefits to the ICF program, we also discuss how the commercial sector and the nuclear weapons science may profit from the proposed research and development program. In the past, technologies developed within the ICF program have made noteworthy contributions to private industry and to core weapons competency at the nuclear weapons laboratories. We fully expect this development to be equally fruitful. The latter areas are primarily within the target physics program including experiments, diagnostics, theory and design, and fabrication.

Development Plan Summary

A top-level summary schedule for all of the CS&T activities is shown in Fig. 2. NIF project activities are also shown to indicate the relative timing of events. Plans extend from FY95 to FY04, although the detail of the activities described is much greater for the first few years. Laser and optics development activities will be the most intense during the first three to four years to maintain pace with the needs of the NIF whose design will be largely completed by the end of FY97. At this time, many new technologies will have been demonstrated to justify the NIF baseline design and estimated cost. Similar but more detailed schedules are given in the text for each WBS level 2 milestones are indirected by diamonds and markers (lesser indicators of progress) by circles.

It is essential that laser technology development be aggressively supported over the next three years starting in FY95. Successful completion of the specified activities will reduce risk, improve performance, reduce cost, enhance reliability, and provide the technical basis that will be critical to the NIF Key Decision-3 (KD-3). Some laser component development work will extend into FY98 for components that permit shorter procurement lead times. Laser activities cover the development of components and subsystems, including the optical pulse generator, power amplifier, optical switch, frequency converter, diffractive optics, pulsed power system, laser diagnostics, laser alignment and wavefront control, optics support and assembly, and control systems. It will also provide the basic science, small-scale testing, and integrated performance of a single beamlet to confirm fundamental principles of laser design and operation. In succeeding years, efforts will be at a reduced level to provide continuing support for NIF and advanced high-power, solid-state lasers.

It is equally important that optics manufacturing development be aggressively supported over this initial three-year period. Optic development will focus on all aspects of producing large-aperture, high-quality optics in large quantities. This includes laser glass, KDP crystals, fused silica, and high-damage-threshold coatings, together with the testing and characterization to prove the optics meet the demanding specifications. Emphasis will be placed on improved manufacturing processes and quality control to achieve significant reductions in the unit cost of each large-aperture optic.

■ = CS&T

▨ = NIF project

Figure 2. Summary schedule of all CS&T activities.

The development must be completed in less than three years because of the long manufacturing time required to produce the large quantity of optics required for the NIF (3700 laser slabs, 600 KDP crystals, and 1400 mirrors, all at full aperture).

The optics manufacturing and laser component development activities are also discussed in the *Manufacturing Readiness Plan (MRP) for the National Ignition Facility* (NIF-LLNL-94-204, April 1994) together with an assessment of the risk associated with these developments. The MRP summarizes some of what is presented here and was written specifically to address a request from the Secretary of Energy following Key Decision Zero (KD-0). While the development activities discussed in this CS&T Plan are presumed to be funded solely by the operating budget of the national ICF program, the

MRP also covers manufacturing facilitization and component reliability and lifetime testing which are included as "other project costs" for the NIF.

We have identified target chamber development activities for characterizing the target debris, radiation, and electromagnetic interference threats to chamber hardware; we are also developing ways to cope with these threats. Target chamber components include the "first wall" (interior surface of the target chamber, which is exposed to target debris and radiation), target positioner, laser beam dump, the final optics protection, and in situ tritium and debris cleaning systems. Some of this work must also be supported early in the CS&T Plan to validate designs that will be finalized by KD-3 at the end of FY97. After NIF becomes operational in FY03, additional source characterization work will be performed to confirm analytical predictions, enhance the existing empirical database, and update threat projections for future ICF facilities.

Four general types of target diagnostics (x-ray, neutron, gamma-ray, and optical detectors) will be developed to meet the requirements of future ICF facilities. Since many of the diagnostics are not needed immediately and fabrication times are relatively short, the necessity to complete development early does not exist. In fact, it is advantageous to delay target diagnostic production for NIF as late as possible so that we can incorporate the latest technical advances. However, diagnostic development needs to be performed in this area up to commencement of operations in NIF and beyond.

Continued theory and design work is needed to provide reasonable confidence and further reduce the risks associated with achieving ignition on the NIF, and for exploring advanced concepts. There are planned activities in target design and theory and experiments to study hohlraum design, capsule design, plasma instability mitigation, hydrodynamic instabilities, and fundamental physics. Research into high-speed, multidimensional (1-3-D) computational capabilities will incorporate state-of-the-art physics and numerical algorithms. This development effort also covers a 10-year span and will continue after NIF becomes operational.

Target components and fabrication development activities will cover research and development in the area of capsule and hohlraum manufacture, including cryogenic fuel layer formation and cryogenic support systems. Baseline target designs will be scaled to NIF requirements; alternative approaches will be explored for enhanced performance. We will improve measurement techniques to characterize cryogenic fuel layers and alternative capsule designs.

Target experiments will continue to develop a more fundamental understanding in many important aspects related to NIF ignition target designs. Experiments in support of indirect drive are envisioned in three broad areas: convergent hydrodynamics and mix, hohlraum dynamics, and laser-plasma interactions. In addition, experiments will test the validity of advanced target design concepts such as the fast ignitor. To address these issues, Nova is expected to operate at least through FY2000. Trident and Omega Upgrade, as well as other facilities where appropriate, will also have a major role in executing the CS&T experimental plan.

1.0 Laser Technology

Introduction

Laser drivers in future inertial confinement fusion (ICF) facilities must deliver very-high-energy laser pulses at very-low cost per unit of energy compared to past ICF systems. To meet this challenge, we have formulated a development plan that addresses all elements of the laser system to provide high confidence that performance and cost goals can be achieved. To a large measure, this is a risk-reduction activity. This section discusses the development activities in each of these areas, with special emphasis on benefits to the National Ignition Facility (NIF).

Table 1.0-1 contains the top-level laser system performance requirements that drive many of the laser technology development activities. These specifications have resulted from a detailed understanding of the physics requirements for attaining fusion ignition with indirect-drive targets. Technology development activities have been formulated to assure that these requirements and their detailed specifications can be achieved.

The development activities are based on the laser system configuration (Figure 1.0-1) chosen in the *National Ignition Facility Conceptual Design Report*.¹ This laser configuration is typical of modern, cost-effective ICF laser designs. The design uses a four-pass laser architecture to achieve higher energy per unit cost ("bang per buck") compared to single-pass systems. The low-energy input pulse is amplified in four passes through

Table 1.0-1. Laser beamline performance requirements (1.8 MJ, 192-beam NIF).

Parameter	Value
3 ω energy	9.4 kJ
3 ω power	2.6 TW
3 ω pulse length	3.6 ns
1 ω energy	17.5 kJ
1 ω power	3.4 TW
1 ω pulse length	5.1 ns
1 ω wavelengths	1.0523 μm 1.0533 μm 1.0543 μm 1.0553 μm
Hard aperture	40 cm
Beam spot size on target	500 μm
Beam stability on target	50 μm

40-00-0394-0789pb01

Figure 1.0-1. Schematic diagram of four-pass main amplifier and beam transport to the target.

two amplifier modules, which are separated by a unity-magnification spatial filter to minimize the growth of nonlinear self-focusing. The laser gain medium is neodymium-doped, flashlamp-pumped, phosphate-glass slabs. The flashlamps are driven by the power conditioning system, which is capable of delivering 340 MJ of electrical energy in the NIF design. This architecture requires an optical switch that deflects the beam out of the laser cavity after the fourth pass. For this purpose, a large-aperture plasma-electrode Pockels cell is located inside the laser cavity to cause polarization rotation of the beam after four passes; this causes the beam to reflect off of the polarizer and out of the cavity. Additional gain of the laser is provided by the booster amplifier both before the beam is injected into the laser cavity and after it has exited. The booster amplifier reduces the optical fluence on the polarizer.

Spatial filtering is a key element necessary to remove high-spatial-frequency noise that can be amplified by nonlinear self-focusing and can cause laser damage to downstream optics. Two spatial filters are required for this laser architecture: (1) the cavity spatial filter located within the laser cavity and (2) the transport spatial filter located between the booster amplifier and the target area. Prior to amplification, the initial high-quality, low-energy laser pulse (about 2 J prior to spatial shaping) provided by the pulse generation system, is injected into the transport spatial filter. After two passes through the booster amplifier and the four passes in the cavity, the laser energy is increased to almost <18 kJ. At the target chamber, the laser beam is conditioned in the final optics assembly. Here, the laser frequency is tripled as efficiently as possible in the converter using a pair of KDP crystals (one of which is deuterated). The beam is focused by a lens and passed through an efficient kinoform phase plate (to control beam uniformity on target) and through a debris shield to protect the output optics against target debris.

This laser design resulted from many years of practical experience with ICF systems; it incorporates several features, which clearly increase its cost effectiveness. The multipass amplifier cavity eliminates the need for a costly high-energy driver section,

such as one employed in Nova, to provide adequate fluence for efficient energy extraction from the final amplifiers. The large-aperture optical switch is the enabling component in the multipass design. A concern in multipass laser systems is the coherent addition of aberrations, which can potentially reduce the focusability of light on target. Thus, in the NIF design and on Beamlet, we have utilized a deformable mirror to compensate for reproducible phase aberrations. Lastly, to minimize optics costs, we have chosen the clear aperture to be as large as feasible, as limited by amplified spontaneous emission in the amplifiers and transverse nonlinear parasitic processes in the output optics. Clearly defining these limits is part of the development program.

The laser technology development activities are organized according to the work breakdown structure (WBS) shown in Table 1.0-2. Thirteen areas of activity are planned to address a broad range of issues. The first ten WBS level-2 categories develop technologies specific to individual laser subsystems. This includes basic subsystems needed to generate, amplify, and transport the laser beam; this also includes supporting subsystems for control, diagnostics, and alignment. The final three WBS level-2 categories include activities with broader impact on laser design and performance evaluation. The Beamlet tests are particularly important in that they provide confirmation of the integrated performance of a single, full-aperture beamline.

Figure 1.0-2 shows the proposed development activities planned to be completed in three years commencing at the beginning of FY95. During the first year, emphasis will be placed on developing basic technologies and on constructing facilities necessary for

Table 1.0-2. Laser technology work breakdown structure.

1.1	Pulse generation
1.2	Multisegment amplifiers
1.3	Multipass laser components
1.4	Frequency converters
1.5	Diffraction optics
1.6	Pulsed power systems
1.7	Laser diagnostics
1.8	Laser alignment and wavefront control
1.9	Optics support and assembly
1.10	Integrated computers and control
1.11	Laser design optimization
1.12	Basic physics, material properties and advanced concepts
1.13	Beamlet test and evaluation

Figure 1.0-2. Laser technology development schedule.

test and evaluation. Activities in the following years will be directed toward the fabrication and test of full-scale technology prototypes similar to the components required for NIF. The timing of these activities has been coordinated with the NIF project to assure that tasks are promptly completed, consistent with the engineering needs during Title I and Title II design, and with NIF production, which is expected to commence in FY98. The schedule also shows that tasks have been integrated with qualification/reliability and lifetime testing activities that are part of NIF Other Project Costs (OPC); they are discussed in the *National Ignition Facility Manufacturing Readiness Plan*.²

References

1. *National Ignition Facility Conceptual Design Report*, Lawrence Livermore National Laboratory, Livermore, CA 94550, UCRL-PROP-117093 (1994).
2. *National Ignition Facility Manufacturing Readiness Plan*, Lawrence Livermore National Laboratory—Laser Programs Directorate, Livermore, CA 94550, NIF-LLNL-94-204, L-16825-1 (1994).

1.1 Optical Pulse Generation System

Introduction

The optical pulse generation (OPG) system proposed for the NIF is a logical evolution of traditional master oscillator/front-end designs. For current systems such as Nova, Omega Upgrade, and Trident, the master oscillator provides a pulse, which is only shaped in time to compensate for amplifier gain saturation. The need for spectral and spatial control were later demonstrated on the above mentioned systems and other lasers. All of these capabilities are required for the NIF OPG system with high accuracy and reliability. There are numerous other issues that will require development, including oscillator operation at four wavelengths centered around the LG-770 gain curve, fiber optic distribution of the laser pulses, and amplification of the oscillator pulse up to ~ 10 J at a pulse length of 20 ns.

Table 1.1-1 lists the top-level requirements of the NIF OPG system. These requirements were determined by working backwards from the x-ray drive conditions needed for ICF target ignition. To reach the specification of less than a 5%-rms beam-to-beam power imbalance during any 2-ns time interval, it is necessary to control the pulse shape, timing, and energy delivered to each beamline very precisely. In contrast to the Nova laser where one pulse is divided between the ten beamlines, the NIF OPG system controls individual beam lines to achieve temporal and spatial shaping independently for each of 192 beamlines. This feature enables the OPG system to compensate for variations in manufacture and assembly that would otherwise cause unacceptable beam-to-beam variations at the output. Temporal modulation requirements are especially stringent, since the NIF amplifiers are highly saturated and the NIF targets require a large contrast pulse. The pulse-shaping system must be able to produce a foot-to-peak ratio as large as 275:1. The development program detailed below addresses these issues for all OPG systems starting from the oscillator through amplification in the preamplifier.

Table 1.1-1. Top-level technical requirements for the optical pulse generation system.

Beamline to beamline rms power balance (over a 2-ns interval)	<5%
Pulse synchronicity	± 10 ps
Pulse contrast, peak to foot (injected into main laser cavity)	65:1
Pulse width range	100 ps to 20 ns
Spatial beam shape, peak to minimum contrast (one dimension only)	5:1
Output energy (injection into power amplifier)	<10 J @ 20 ns
Wavelength separation between oscillators	10 Å (1.0523, 1.0533 1.0543, 1.0553 μm)
Optical bandwidth at 1ω needed for SBS suppression in 3ω optics	30 GHz

Since the construction of the Nova laser system, there has been considerable progress in the base technologies for generating the required temporal, spectral, and spatially shaped optical pulses. The basic approach is to use integrated fiber-optic components to create, transport, and temporally and spectrally shape the pulse. This is followed by a preamplifier and spatial shaping module to boost these pulses to fluence levels appropriate for amplification in the main NIF power amplifier. Figure 1.1-1 is a schematic of the integrated fiber optical system, which contains the master oscillator, amplitude modulators, fiber amplifiers, and splitters. Transport by single-mode fiber brings the oscillator pulse to the preamplifier module, which contains a regenerative amplifier, spatial shaper, and multipass rod amplifier. Figure 1.1-2 shows the preamplifier, whose function is to amplify the laser pulse energy up to 0.5 J and to spatially shape the intensity distribution. Although a conceptual design for the NIF OPG system has been developed, there is no off-the-shelf commercial technology available that can be used without further development. The Beamlet pulse generation system, as described by VanWanterghem et al.,¹ demonstrates many aspects of this new approach; it is the first step in the total development effort that must be completed before NIF procurement.

1.1.1 Master Oscillator and Fiber Amplifier

The master oscillator proposed for the NIF (shown in Fig. 1.1-3) is a unidirectional fiber ring oscillator pumped by a >120 mW laser diode. The heart of the oscillator is an

70-50-0195-0098pub01

Figure 1.1-1. Fiber oscillator, amplifier, splitters, and distribution.

40-00-0394-0759 pub

Figure 1.1-2. Engineering layout of the NIF preamplifier module assembly. The module contains the regenerative amplifier, multipass rod amplifier and beam shaping optics.

ytterbium-doped silica fiber amplifier, designed with a single-pass gain greater than 60. This amplifier will be used both in the oscillator and in amplifiers in the fiber distribution system. Stability and maintenance considerations lead to the selection of a doped single-mode fiber for the amplifier gain media. The fibers are diode pumped, giving good gain stability, and will provide adequate tunability for producing the four NIF wavelengths.²⁻⁶ Although the communications industry has developed erbium-doped fiber amplifiers for use at 1.5 μm , the only commercial source of Yb-doped fiber amplifiers is a company in Russia that produces a connectorized module about the size of a small paperback book. With this device as a starting point, we will develop a unit for our particular needs. We may procure Yb-doped silica fiber and fabricate our prototype amplifiers, but the NIF quantities will require an industrial supplier.

We will develop a master oscillator, which produces a single-frequency transform-limited pulse, using commercially available components plus the fiber amplifier.

40-00-0294-0524.pub

Figure 1.1-3. Fiber oscillator based on Yb-doped gain fiber.

Devices such as directional couplers, polarizers, and Q-switches are available for use in the 1.3- and 1.5- μm communications bands, but we will need special devices made for our use at 1.053 μm . Mode selection is by tunable etalon, and wavelength control is done with a fiber version of a birefringent filter. Although we plan to build only one or two complete master oscillators in the development program, we will show that they operate satisfactorily at all four NIF wavelengths. In addition, the oscillators will be tested beyond the NIF specifications to establish the operational limits and margins. The oscillators will also be the signal source for the subsequent laser front-end systems for the duration of this development program.

Fiber-optic components. Because we are operating at a wavelength that is not used in fiber communications, we must evaluate special components such as splitters, fibers, couplers, etc., which vary from those that are normally available. The power levels are high (up to 40 W) in some sections of the fiber and integrated optic system, thus the components will be damage tested to these levels.

1.1.2 Electro-Optic Components

Phase and amplitude modulator testing. Integrated electro-optic modulators provide the means for temporally shaping the master oscillator pulse to meet the individual needs of each NIF beamline. Suppression of transverse stimulated Brillouin scattering (SBS) at 3ω in the target chamber optics is accomplished by adding frequency modulation to the optical signal using an integrated phase modulator. In Beamlet, a lithium-niobate phase modulator is used ahead of two Mach-Zehnder amplitude modulators all mounted on a single chip. Microwaves at two frequencies are applied to the phase modulator to provide a nearly uniform spectrum of sidebands. For NIF, we plan to separate the two functions of bandwidth addition and pulse shaping to simplify the distribution of microwave energy and to allow the two operations to be independently optimized. The possibility of intracavity modulation of the oscillator to achieve the bandwidth will be considered. We will study modulator performance at higher levels of peak power than what we have been using in Beamlet, and will look for long-term degradation. We will also measure loss, extinction, ringing, etc. The measurements require working oscillators and amplifiers, but we can start testing early using the Beamlet oscillator, which has sufficient power for our needs. Other than the elevated optical power levels, the NIF modulators are small variations on the Beamlet device; they are even somewhat easier to manufacture due to separation of phase- and amplitude-modulation functions

After the amplitude modulators are tested independently, they will be tested with the pulse shaper by the fast electronics discussed in Section 1.1.5. We will evaluate how well these elements work together, as part of the overall system integration program.

Fail-safe system. Failure of the phase modulator to add the required bandwidth to the master oscillator pulse could lead to costly component damage in the final optics. The fail-safe system determines whether an oscillator pulse has been properly phase modulated; the system lets the oscillator pulse pass if it satisfies the required criteria, otherwise the pulse is blocked. A version of this is being developed for Beamlet, but it is slow, and only blocks the next pulse, not the one detected. We need to develop a faster detector and a delay path to make the NIF version. This can be done without optical signals, but the final development requires the phase modulator (mentioned above) and oscillator signals. This will become part of the final oscillator system part way through oscillator system development.

Radio frequency and timing system development. To synchronize the phase and amplitude modulation applied to the master oscillator pulse, we need to assemble an electronic system of phase modulation radio frequency (RF) and modulator trigger timing, which has precise timing control and low jitter and drift. The NIF system can be assembled from commercial components, but the component and system performance must be tested and evaluated. In particular, the synchronization between the RF generators and the modulator triggers must be verified, and the jitter and drift of a fanned-out multiple-trigger system must be measured.

1.1.3 Regenerative Amplifiers

The regenerative amplifier (RA) provides the majority of the amplification in the preamplifier module. It interfaces the fiber-optic master oscillator and pulse transport

systems to larger-aperture components. Nominal gain required from this amplifier is on the order of 10^7 , delivering about 8 mJ to the next section of the preamplifier. Figure 1.1-4 shows an optical schematic of the proposed NIF regenerative amplifier.

Regenerative amplifiers use one or more amplifier heads located in an optically relayed cavity, such that a laser pulse can be injected and amplified for a specified number of round trips before it is switched out. Usually the RA is followed by a pulse slicer to block unwanted leakage from previous passes. NIF requirements necessitate new RA designs. Most RAs amplify relatively short pulses (<1 ns), and drive the amplifier into saturation. In our case, we need to amplify a long pulse (20 ns), and operate in the linear regime to preserve the pulse shape. The first requirement necessitates a long cavity. The second requirement makes the output energy very susceptible to variations in the gain of the amplifier. This is the most challenging issue to be addressed in the RA development program.

Some of the relevant issues for NIF have been addressed during the development of the Beamlet front-end RA. The Beamlet RA requires a larger overall gain than the NIF design because of lower injected energy, but has a shorter amplified-pulse duration (3 ns). The NIF regenerative amplifier will have a similar cavity configuration, but scaled from 4 m to 9 m to accommodate the NIF pulse length and the Pockels cell rise and fall times. Both Beamlet and NIF use a self-imaging optical cavity, with apertures located at the relay and focal planes, and a 10-mm-aperture KD*P Pockels cell. A major new element for NIF are the diode-pumped Nd:glass amplifiers as opposed to the Beamlet flashlamp-pumped heads. Beamlet has demonstrated that flashlamp pumping imposes undesired limits on repetition rate, output energy stability, and lamp lifetime. We also found that conditions which improve stability also shorten flashlamp lifetime. These considerations motivated our selection of diode laser pumping for the NIF RA.

Based upon extensive LLNL experience in diode-pumped amplifiers, we propose to construct two end-pumped amplifiers for each RA. Micro-lens-arrayed diode bars followed by a light-concentrating lens duct provide pumping of a 5-mm-diam, 50-mm-long Nd:glass

40-00-0294-0820C pub

Figure 1.1-4. Optical schematic of the NIF preamp regenerative amplifier. The seed pulse is fiber optically transported to and then trapped for 13 passes in a ring cavity by a combination of a Pockels cell, 90° rotator and two polarizers. Two diode-pumped Nd:glass amplifier heads provide the gain to deliver 9–10-mJ output energy in a pulse with 20-ns maximum duration.

rod to achieve a double pass gain of 0.67 Nepers per head (see Fig. 1.1-5) using 4 kW of pump light. Longitudinal pumping has the advantage of being insensitive to drift of the pump wavelength, provides uniform gain over the rod cross section (this may be useful if we want to add spatial shaping to the RA), and minimizes thermally induced stress birefringence. However, if surface distortion due to end-pumping leads to excessive wavefront distortion, alternative schemes such as side-pumping can be readily incorporated in the

40-00-0294-0511 pub

Figure 1.1-5. Layout of the diode-pumped amplifier head. The diode array is coupled through a concentrating light guide and totally-internally-reflected down a 5-mm-diam, 50-mm-long Nd:glass rod. The rod's input face is highly reflective at $1.05\ \mu\text{m}$ and used in a near normal retro-reflecting configuration. The very compact package includes the diode laser power supply.

design if needed. Using two amplifier heads allows us to extend the bandwidth by choosing two different glass types, e.g., HAP-3 and APG-2. The RA heads will be tested for gain stability (long term and short term) and heat dissipation effects, such as thermal birefringence and lensing.

A breadboard prototype of the NIF RA will be constructed in FY95 to evaluate output energy, stability and pulse shape distortion. When a multiwavelength oscillator becomes available, performance characterization will be extended to the four wavelengths required by the NIF system. Pump power, pump pulse duration, and number of round trips in the RA will be optimized to achieve the required performance with the minimum pump power.

Spatial beam profiling. The optical pulse generation (OPG) system must generate the appropriately shaped spatial-irradiance profile to account for spatial gain nonuniformity in the main amplifier and produce a spatially uniform output. The Beamlet OPG system is designed to produce a flat top-hat irradiance profile with a smooth super-Gaussian roll-off at the edge. In that design, the single Gaussian mode developed by the RA (previously discussed) is expanded and flattened into a top-hat distribution in both dimensions by means of a birefringent shaper. The final beam edge is defined by a serrated square aperture that is photolithographically deposited on a glass plate (Fig 1.1-6). A spatial filter removes the high-spatial-frequency noise imposed by the sharp edges, producing a smooth profile with a super-Gaussian roll-off.

On Beamlet, we have demonstrated that the OPG system can precompensate for amplifier gain roll-off in the long axis of the amplifier slabs caused by amplified spontaneous emission (ASE), discussed in Section 1.2. A spatially varying transmission filter is used to shape the irradiance profile. (The Beamlet filter's reflectivity varies quadratically in one dimension.) The filter was commercially fabricated and has an edge-to-center ratio of 5:1, which is the NIF specification (Fig. 1.1-7). The intent of this development effort is to develop industrial partners to produce a less costly method for manufacturing these filters and to investigate advanced spatial-shaping techniques.

The spatial shaping approach used in Beamlet is necessarily lossy. Beam energy is reflected in the process to form the desired irradiance profile. It is desirable to develop another method that does not incur this loss. Diffractive optical elements have been tried by some scientists⁷ to control the shape of laser beams outside and within laser cavities, but controlling the high-spatial-frequency noise from the edges of the beam may prove difficult. Also, several researchers have examined anamorphic optical systems for beam shaping.⁸ The two significant issues associated with such approaches is fabrication of the aspheric lens and alignment tolerances for satisfactory performance. (The systems also tend to be fairly long, e.g., at least 1 m.) We will examine alternative techniques for spatial intensity shaping, including techniques that would allow for programmable control, in the event this is needed for NIF.

1.1.4 Multipass Amplifier

The multipass rod amplifier (shown schematically in Fig. 1.1-8) amplifies the spatially and temporally shaped pulse from ~1 mJ up to ~10 J. Similar to the regenerative amplifier, the design is dictated by minimizing temporal and spatial pulse-shape distortion. The amplifier needs to operate in the small signal regime, and have spatially

70-10-1193-3899 pub

Figure 1.1-6. Serrated aperture in use on Beamlet. Photolithography was used to produce these detailed shapes. Serration spacing is 120 μm .

40-00-0394-0791 pub

Figure 1.1-7. Calculated spatial profile provided by the optical pulse generator assumed by the NIF conceptual design. Center-to-edge intensity ratio is 5:1.

40-00-0294-0820A pub

Figure 1.1-8. Schematic layout of the four-pass preamplifier. The four passes are achieved by using a permanent magnet Faraday rotator and quarter-wave plate. The cavity is fully relayed using two telescopes.

uniform gain. The output energy requirement determines the beam size, clear aperture, length, and pump energy of the amplifier.

We chose a flashlamp-pumped Nd:glass amplifier used in a passive four-pass configuration because it is cost-effective, reliable, and compact. The stored energy level was sufficiently low to avoid gain depletion problems, parasitic oscillation, and ASE. The design is similar to the Beamlet four-pass rod preamplifier, which uses a Nova 5-cm-diam, 48-cm-long Nd:glass rod amplifier and a 10-cm aperture permanent magnet Faraday rotator as switching element. The Beamlet four-pass amplifier has produced output energies up to 13 J while maintaining excellent output beam quality. It uses a spatial filter (2:1 magnification) to transform its $2.5 \times 2.5\text{-cm}^2$ beam to $5 \times 5\text{ cm}^2$ for injection into the power amplifier. The NIF design propagates $2.25 \times 2.37\text{-cm}^2$ beams throughout the amplifier, and uses unity magnification relay telescopes for injection into the cavity. Attention has been paid to packaging in the design. Two compact relaying telescopes are used to fold the cavity, while leaving enough space for the amplifier. The NIF preamp module occupies about 1/80th of the volume of the Beamlet preamplifier.

The Beamlet preamplifier characterization has proven the basic operational issues of large-aperture four-pass amplifiers, such as beam quality and parasitic oscillation control. Angular multiplexing, in combination with focal-plane filtering, isolates the four-passes and prevents feedback oscillation. Alignment has been proven to be simple and stable. All cavity mirrors are located in relay planes, so that a small pointing offset through the input relay plane is sufficient to separate the beams in the focal plane of the cavity relay telescopes.

The development plan will focus on two critical elements of the four-pass amplifier: the amplifier head itself and the permanent-magnet Faraday rotator. Both items require vendor participation during development.

A preliminary amplifier-head design study was done for the NIF CDR.⁹ This amplifier uses a 2.5-cm-high by 5-cm-wide and 30-cm-long LG-750 glass slab in an ethylene-glycol-flooded pump chamber using diffuse reflecting walls for the eight flashlamps (Fig. 1.1-9). However, this is a rather complicated design, and initial modeling indicates that it will suffer from birefringence in the rod corners. Therefore, our original studies will focus on a cylindrical rod in a diffuse reflector cavity configuration. We will investigate the gain, gain non-uniformity, pump efficiency, birefringence, and gain stability.

Large-aperture permanent-magnet Faraday rotators are commercially available and have been successfully tested at LLNL. Meeting the NIF delivery schedules will require development programs with (preferably) multiple vendors.

1.1.5 High-Speed Electronics

Obtaining precise shaping of the 0.35- μm output laser pulse is critical in meeting the NIF performance goals. To accomplish this, we plan an aggressive effort over two years to develop an electrical pulse generator. This pulse generator can effectively and inexpensively drive the electro-optic modulators and provide the desired 1.05- μm input pulse. Methods used up to now for pulse shape generation have been based on mechanical adjustments, whereas the NIF design will require a pulse shape system under computer control. The proposed technique to accomplish this utilizes GaAs metal

40-00-0394-0708.pub

Figure 1.1-9. Preliminary design concept of the rectangular rod amplifier. Eight flashlamps are used in a diffuser cavity, flooded with ethylene glycol. The assembly is cooled by a water jacket.

semiconductor field-effect transistors (MESFETS), which operate at greater than 10 GHz. Existing devices in both chip and packaged form are capable of switching speeds sufficient to build up a NIF-like pulse. The major challenge for this development is to utilize these devices in the large-signal regime, and develop circuit architectures that are tolerant of process-dependent device parasitics. A further development goal is to utilize low-voltage (and inexpensive) devices followed by large-signal linear amplification. For example, the combination of high-speed digital-to-analog converters followed by a chain of MESFETS could form the basis for a relatively inexpensive pulse shape generator. To prove the concept will require significant circuit modeling and electrical circuit prototyping.

The basic concept has MESFETS arranged as taps on a strip line, driven by a trigger line with the required propagation time to generate the shaped pulse. For NIF, we need more than 20 ns for the total pulse. However, as shown from the pulse shape at the

main cavity injector (Figure 1.1-10), it may be possible to use a flat 10-ns pulse to generate the foot combined with a 10-ns shaped pulse. The MESFET gate voltages are set by computer control to the desired levels, and a trigger pulse is propagated at the appropriate time to generate the shaped pulse. This generator must have the dynamic range to compensate for the transfer characteristics of the modulator and for gain saturation in the preamplifier package. We are working towards an optical contrast ratio at the modulator of 500:1 which exceeds the NIF system design requirements of 275:1.

Pockels cell drivers are another critical component. In Beamlet, we use an LLNL-designed hard-tube driver, which is too expensive and unreliable for NIF. We propose to use recent developments in commercial high-speed, high-voltage, field-effect-transistor switches that come as packaged units. Several models will be purchased and tested to provide a preliminary evaluation of NIF qualified units.

Finally, we anticipate developing laser diode pulsers and flashlamp drivers through the electronic equipment vendors. We will start with commercial products, if possible, and early in the testing program develop a set of detailed specifications. This will allow the laser design and testing to proceed while we have the pulsers developed. We will construct prototypes, test them on the evolving regenerative and multipass amplifiers, develop commercial sources, and test preproduction prototypes in the integrated system.

1.1.6 Integration and Breadboard Testing

We have described the plan for developing individual NIF components and the subsystems of the OPG system. We plan to assemble and evaluate these in an integrated

Figure 1.1-10. Nominal 1- μm pulse shape required at the injection mirror at the NIF output spatial filter. This shape is similar to the electrical pulse shape needed at the input to the modulator.

system. The process of integration will be done by successive iterations while the sub-systems are in development, leading to full system integration. As the various components reach maturity, they will evolve toward the NIF-mandated performance. We expect to be testing fully developed technology prototypes by the end of FY96 in support of the NIF Project design work. In FY97, we expect to be exercising the integrated testbed for reliability and lifetime. We anticipate continuing to test newer generation components.

Schedule. An intensive three-year development program (Fig. 1.1-11) is proposed to produce a fully functional technology prototype of the NIF pulse generation system. The first step is to begin the preparation of two facilities that will be designed to house the fiber optical work as well as the preamplifier prototypes. One room will have an electronics laboratory while the second will be suited for multijoule laser testing. We expect to occupy these rooms by the second quarter of FY95.

The technical activities begin with the development of a fiber master oscillator and a single channel of the complete fiber optical distribution system. By the middle of FY95, we will test a diode-pumped, fiber amplifier. This device is the heart of the fiber oscillator and is used in the distribution system to boost optical signals after they are split. By the end of the first year, we expect to complete testing the oscillator marked by a development milestone. The oscillator specifications will be delivered to the NIF Title I Design effort. This will include specifications of fiber optical components such as splitters, couplers, distribution chassis, etc.

Toward the end of FY95 we will start integrating special electro-optic components into the fiber optical systems. The most critical parts are the phase and amplitude modulators needed to add bandwidth to the optical pulse and provide temporal shaping. We expect to be able to procure many of these components from commercial sources. A milestone in the third-quarter of the second year is the delivery of the detailed performance measurements of these devices as well as design information to support the NIF project. Amplitude modulator testing will continue to the end of the second year to support integration as well as the preamplifier package work described below. In support of the modulator work will be a set of tasks focused on providing custom electronics to the master oscillator and preamplifier work. Most notable is the development of a programmable electrical pulse generator capable of driving the amplitude modulators over the required dynamic range.

In parallel, work will begin on the preamplifier package in FY95. This consists of a regenerative amplifier, spatial shaping devices, and a multipass glass amplifier. Based on the architecture of the Beamlet regenerative amplifier, we will develop an extremely stable amplifier using laser-diode pumping instead of flashlamps. For NIF costing and performance, we must develop new diode-packaging and microlensing techniques specific to this application (low rep-rate with a lensing duct). However, to proceed immediately with the regenerative amplifier gain-stability experiments, we will purchase standard microlensed diodes while pursuing the longer-term packaging efforts. Although work on this amplifier is expected to continue for two years, preliminary results are due to be delivered to the NIF Project toward the end of the first year; final performance evaluations are due at the beginning of the fourth quarter of FY96.

Figure 1.1-11. OPG development schedule.

In parallel, we will be developing the multipass amplifier, starting at the beginning of FY95. By the last quarter of FY96 we plan to provide a detailed report of the amplifier performance based on extensive prototype testing.

Finally, we will demonstrate full-scale capabilities in a series of integrated tests that demonstrate NIF performance levels and validate the physics and engineering designs of the OPG system prototype components. This will take place in FY97. Transition from a scientific testbed to an engineering testbed in direct support of the NIF Project is planned for FY98.

References

1. B. M. VanWanterghem, D. R. Speck, M. J. Norman, V. Karpenko, R. B. Wilcox, "The Beamlet Front End: Prototype of a New Pulse Generation System," *ICF Quarterly*, 3 (1), Lawrence Livermore National Laboratory, Livermore, CA 1992.
2. E. Snitzer, "Laser Emission at $1.06\ \mu$ from Nd^{3+} - Yb^{3+} Glass," *IEEE J. Quant. Elect.* 2(9), 562-566 (1966).
3. D. Hanna et al., "An Ytterbium-doped Monomode Fiber Laser," *J. Mod. Opt.* 37(4), 517-525 (1990).
4. V. Gapontsev et al., "Laser-Diode-Pumped Yb-Doped Single-Mode Tunable Fiber Laser," *Advanced Solid State Lasers 1991*, WC1-1, 214-216 (1991).
5. N. Bergano et al., "Fiber Laser Sources and Amplifiers III," *SPIE Conf. Proc.* 1581, 182-187 (1991).
6. K. Vahala et al., "Turnable Single Frequency Ytterbium Fiber Ring Lasers," *Proc. of CLEO 1993—Technical Digest Series 11*, 484-487 (1993).
7. Memo from Bruno VanWanterghem to S. Dixit, February 27, 1994.
8. W. Jiang, D. L. Shealy, K. M. Baker, "Design and testing of a laser beam profile reshaping system," Annual Meeting, Optical Society of America, paper ME5, Toronto, Canada (October 3-8, 1993).
9. *National Ignition Facility Conceptual Design Report*, Lawrence Livermore National Laboratory, Livermore, CA 94550, UCRL-PROP-117093 (1994).

1.2 Multisegment Amplifiers

Power amplifiers are the central component in the laser system in that they are the main source of optical energy that drives the target. When fully integrated with optics, flashlamps, and pulsed power, the power amplifiers are also the major cost center for the entire system. The power amplifiers envisioned for the NIF primarily differ from those used on Nova and Beamlet in their overall scale. Figure 1.2-1 compares the Beamlet 2×2 amplifiers with the larger 4×2 amplifiers used in the NIF design. The $n \times m$ designation denotes the number (height $\times$ width) of parallel amplifying channels or beams that are combined. To realize the size of the NIF devices, notice the person sketched in the drawing. The amplifiers are supported from an overhead space frame to enable bottom access for assembly and maintenance.

Amplifiers that combine beams are said to use a multisegment amplifier (MSA) architecture. MSAs were first proposed by LLNL in 1978 as a way to reduce the cost of MJ-class fusion lasers. Combining beams reduces costs in three ways: 1) by making amplifiers more compact, thereby reducing the size and cost of the building; 2) by increasing pumping efficiency, thereby reducing the size and cost of the pulsed-power system; and 3) by reducing the number of internal amplifier parts. The NIF design achieves considerable cost savings by making the NIF amplifiers larger than the Beamlet amplifiers.

Since 1988, LLNL has pursued an aggressive program to develop MSA technology. In tests performed on two 2×2 prototype amplifiers with 29-cm-square apertures, the efficiency advantages of MSAs relative to single-beam-per-box amplifiers were demonstrated, and techniques to produce uniform pump distributions were successfully developed. This technology was applied to the design of the 2×2 Beamlet amplifiers, which were installed on the Beamlet in the summer of 1993. Gain and beam-steering measurements have shown that the Beamlet amplifiers perform very well, extremely close to model predictions. Beamlet amplifiers produce high storage efficiency (3%), high-average-gain coefficients (5%/cm), and low pump-induced wavefront distortion (<1.5 waves of low-order distortion for the entire system) at the nominal operating point where the flashlamps are fired at 20% of their single-shot explosion energy.

The Beamlet amplifiers have also demonstrated significant advances in amplifier mechanical design: 1) the use of flashlamp cassettes that can be installed and removed without disturbing the laser slabs; 2) the use of hermetically-sealed blastshields to protect the laser slabs from contamination generated by the flashlamps; and 3) the use of one-slab-wide $\times$ one-slab-long $\times$ two-slab-high modules to reduce the size of components that need to be handled.

Despite the success of the Beamlet amplifiers, improved performance is needed to reduce NIF costs. Accordingly, we have formulated a development program to ensure that the NIF amplifiers will meet all performance requirements. Improved pump-cavity designs, which will produce higher storage efficiency and improved gain uniformity, will be tested in a modified Beamlet amplifier. We will design, build, and test NIF technology prototype MSAs that are four slabs high, up to three slabs wide, and three slabs long. With these technology prototype amplifiers, we will demonstrate the

Beamlet amplifier **NIF amplifier configuration**

70-39-0394-1394 pb02

Figure 1.2-1. Comparison between Beamlet and NIF power amplifiers.

required performance in optical gain and wavefront quality, thermal recovery, and mechanical assembly and maintenance. In parallel, working with vendors, we will demonstrate NIF-size flashlamps that have the required performance when used at NIF operating levels. Our amplifier development program will be completed in approximately three years, consistent with NIF project needs. Figure 1.2-2 shows the schedule for development activities.

1.2.1 Pump Cavity

Optical gain at the 1.05- μm wavelength in the NIF MSAs is provided by neodymium-doped, phosphate glass, rectangular laser slabs oriented at Brewster's angle with respect to the beam to eliminate reflection losses. The slabs have absorbing glass edge claddings to prevent internal parasitic laser oscillation. Each slab holder supports four slabs, one stacked above the other. Columns of slabs are separated by central flashlamp arrays that provide pumping in both directions. Slabs on the side of the amplifier are pumped by side flashlamp arrays that use reflectors behind the lamps to redirect the light in one direction. Glass blast shields, placed between the flashlamps and the laser slabs, serve two purposes: 1) they prevent acoustic waves generated by the flashlamps from propagating into the beam path and causing wavefront distortion; and 2) they provide a contamination barrier between the flashlamp cavity and the critical slab cavity. The blast shields also form a channel that could potentially be used for flowing cooling gas around the flashlamps. A top view of the NIF amplifier design, illustrating the arrangement of the slabs, flashlamps, and blast shields, is shown in Fig. 1.2-3.

We first summarize the amplifier parameters of the NIF design. The flashlamps are energized by an electrical pulse with a duration of 360 μs . The neodymium ions in the laser slabs are optically excited by the flashlamp light to produce a peak gain of 5.5%/cm averaged through the slab thickness. The gain corresponds to a stored energy fluence per slab of 1.8 J/cm², which is available for energy extraction by the laser beam. The transverse gain uniformity is determined both by the distribution of flashlamp pump light across the slab and the effect of ASE. In large slabs, ASE preferentially depletes the gain near the slab's ends because this region sees ASE that has the longest path length for internal amplification. The specified peak-to-average gain uniformity of the NIF gain coefficient is less than 1.05. Pump-induced wavefront distortion can occur from disk bending produced by the nonuniform deposition of heat in the slab, particularly near the edge cladding, which is heated by ASE during the pump pulse. The maximum pump-induced beam steering within the beam aperture is less than 1 μrad per slab.

A comparison of parameters for Nova, Beamlet, and NIF power amplifiers is shown in Table 1.2-1. Notice that the operating parameters of a single slab are similar for the three cases, aside from the marked improvement in storage efficiency from Nova to Beamlet to NIF. The operating point of the NIF amplifiers was determined by the ChainOp computer program. The program determined that the most cost-effective design would be one in which high efficiency was obtained at the cost of slightly reduced stored fluence per slab. Relative to the Beamlet amplifiers, the NIF amplifiers will obtain higher efficiency by using: 1) a lower flashlamp packing fraction; 2) anti-reflective coatings on the blastshields and flashlamps; and 3) a shorter flashlamp pulselength.

● = marker

◆ = milestone

Figure 1.2-2. Schedule for amplifier development activities.

The predicted performance of the NIF amplifiers is based on highly developed numerical models. These models were developed from, and validated by, quantitative measurements of the following: flashlamp spectral output and efficiency, cavity transfer of pump light from the flashlamps to the laser slabs, absorption and gain parameters of Nd-doped glass, and the depumping of excited neodymium ions by ASE. We are continuing to develop our amplifier models to be able to accurately predict features such as the detailed three-dimensional spatial dependence of pumping and ASE loss, and the wavefront distortion caused by thermal nonuniformities. Nonetheless, we need to perform additional modeling and experimental tests as described below to be fully confident of our amplifier performance predictions despite our extensive modeling capability.

Development plans. We propose to undertake an aggressive campaign consisting of both modeling and experiments to resolve tradeoff issues, and to develop a cost-effective pump-cavity design.

We will evaluate new pump-cavity designs by modeling. These designs will use various lamp-packing fractions, lamp positions, and reflector shapes consistent with

Figure 1.2-3. Top view of the laser slabs and flashlamps in the NIF power amplifier design.

Table 1.2-1. Comparison of power amplifier performance requirements for Nova, Beamlet, and NIF.

Requirement	Nova	Beamlet	NIF
Array size*	1 × 1	2 × 2	4 × 2
Assembly module*	1 × 1 × 2	1 × 2 × 1	1 × 4 × 1
Hard aperture	46-cm diam	39.5 × 39.5 cm	40.0 × 40.0 cm
Average gain coefficient	5.4%/cm	5.0%/cm	5.5%/cm
Stored fluence/slab	2.20 J/cm ²	1.95 J/cm ²	1.83 J/cm ²
Storage efficiency	1.8%	3.0%	3.4%
Gain uniformity	N/A	1.06	<1.05

* Number of slabs high × wide × long.

other aspects of amplifier mechanical design. Ray-trace and finite-difference calculations will be used to predict cavity transfer efficiency, gain uniformity, pump-induced wavefront distortions, and pump-induced depolarization. The predictions will be made for all (six) different types of slab positions that occur in MSAs with 4×2 or larger groupings. Methods of increasing pump light intensity at the edges of the slab, to compensate for the depumping in those regions by ASE, will be developed. The cost-effectiveness of the various pump-cavity designs will be evaluated with end-to-end beam propagation modeling. Predictions for amplifier gain, gain distributions, and pump-induced wavefront distortions will be used as inputs. Tradeoffs between the cost and performance of the parts affecting beam quality, including the amplifier, front end, and deformable mirror, will be taken into account. The figure-of-merit for each pump-cavity design will be energy output per unit cost.

The performance of the most cost-effective designs will be measured using our existing facilities with a one-slab-long 2×2 Beamlet amplifier, modified to have a pumping configuration equivalent to the NIF design. This amplifier will be outfitted with prototype 4.3-cm-bore flashlamps and will use the flashlamp packing fraction, pulselength, etc., assumed for the NIF. We will experimentally evaluate methods for increasing the pumping efficiency and gain uniformity, such as use of antireflective-coated blastshields and flashlamps, and specially designed reflectors. The results of these tests will be used to update and improve the models. Several iterations between modeling and experiments should be adequate for developing a cost-effective pump-cavity design that meets all performance requirements.

The major deliverable of the pump-cavity development effort will be a preliminary NIF pump-cavity design and reports on measured and predicted performance. This activity will be completed in FY96, in time to use the results to design a more cost-effective pump cavity for the $4 \times 2 \times 3$ technology prototype amplifier (see Section 1.2.4).

1.2.2 Flashlamps

LLNL has devoted extensive research toward developing a reliable flashlamp design. The flashlamp shown in Figure 1.2-4 is a diagrammatic sketch of a Nova flashlamp, which was made by EG&G (Salem, Massachusetts), ILC Technology (Sunnyvale, CA), and Xenon Corporation (Woburn, MA). It is also the kind of flashlamp used on the Beamlet and in the NIF baseline design.

Table 1.2-2 compares the number, size, and pulse energy of the Nova, Beamlet, and NIF flashlamps. Through a combination of increased pumping efficiency and the use of larger flashlamps, the NIF will use only 80% more flashlamps than Nova, even though the laser system produces some $40\times$ more output energy. Keeping the number of flashlamps low reduces costs and improves reliability. Due to its larger size, each NIF flashlamp dissipates approximately $6\times$ more electrical energy than the 2-cm diameter Nova flashlamp. The energy delivered to each flashlamp corresponds to 20% of the single-shot explosion energy for flashlamps that are operated in the open. Shiva, Nova, and Beamlet experience shows that reliable flashlamp operation can be achieved at this loading.

The flashlamp envelope is made of cerium-doped quartz to prevent ultraviolet light from escaping the flashlamp and damaging amplifier components. The envelopes

absorb strongly below 370 nm, although there is a small region of transmission centered at 250 nm. Ideally, the envelope is free of significant cracks and particle contaminants, such as carbon or metal; these contaminants could absorb flashlamp radiation, causing cracks to develop from the resulting thermal stresses. Further, the lamp envelope must be well annealed since, over time, stress can cause even relatively small cracks to grow, leading to flashlamp explosions.

Figure 1.2-4 identifies the flashlamp's insulating base, which is a hollow aluminum tube containing the electrical lead connection to the electrode. This base is potted with silicon rubber. The base relieves stress on the electrode seal transmitted through the lead and also provides for low-stress support of the quartz envelope. It is important that the potting material is well shielded from pump-cavity radiation to prevent carbonization.

The diagram also indicates the electrodes are made of tungsten and are doped with thorium, which makes them easier to machine. To reduce sputtering, the cathodes are made of sintered tungsten doped with low-work-function materials, which make the current at the cathode more uniform and reduce operating temperatures. These measures are necessary because material that is sputtered onto the inside surface of the lamp envelope scatters or absorbs flashlamp radiation, thereby reducing flashlamp output and causing additional thermal stress in the lamp envelope.

40-00-0394-1148 pub

Figure 1.2-4. Schematic diagram of flashlamp components.

Table 1.2-2. Comparison of flashlamps parameters for Nova, Beamlet, and NIF.

Requirement	Nova	Beamlet	NIF
Approximate number	5,000	500	9,120
Bore diameter (cm)	2.0	2.5	4.3
Arc length (cm)	48	91	180
Delivered energy/lamp (kJ)	.6	12	34

Another important component of the flashlamp is the seal that terminates each end of the envelope with an electrical conductor. The Nova flashlamps use either glass-to-metal seals, in which the conductor is a small tungsten rod, or solder seals, in which the conductor is a metal cap soldered to the end of the quartz envelope.

In general, the Nova flashlamps have been reliable. The most common types of failures have been glass-to-metal seal failures, and electrical arcs in the bases and leads. These noncatastrophic failures caused uneven pumping of the disks and gain imbalance from beam-to-beam until the failed flashlamps were replaced. Also, some of the flashlamps removed from Nova after defects, such as cracks or carbonized material burned into the quartz, were observed. Fewer than 30 of Nova's 5000 flashlamps have exploded over Nova's 6000-shot lifetime. In 28 of these cases, the source of the explosion was traced to a pulsed power problem that delivered many times the normal amount of electrical energy to the flashlamps. Most of these explosions resulted in minor damage to adjacent flashlamps or reflectors. On several occasions, however, these explosions caused serious damage to the laser disks when the protective blastshield between the lamps and disks failed to contain the debris from the explosion.

The Beamlet flashlamps have been more reliable than the Nova flashlamps. To date, after several hundred shots, there have been no online flashlamp failures.

Although the Nova and Beamlet flashlamps have operated reliably, there are still important technical issues regarding the new generation of very large flashlamps required for NIF. As with smaller flashlamps, the primary concerns are: cracks in the envelope that grow faster than expected; vacuum failure of end seals; electrical breakdown of the insulating bases and leads; escape and subsequent carbonization of electrically insulating polymeric material from the electrode bases; and undesired sputtering of the tungsten electrodes.

Development. To ensure flashlamp reliability, all flashlamp designs used in the NIF amplifiers must pass rigorous lifetime tests conducted under conditions that simulate anticipated operating conditions. To reduce the risk of performing tests on large numbers of faulty lamps, each lamp design will be tested in three stages, with each stage evaluating a larger number of flashlamps than the previous stage. Sufficient numbers of flashlamps must be tested to demonstrate low failure rates with the desired confidence level. Funding for the first two stages, called "preliminary" and "prequalification" tests, will be provided by the CS&T program. Funding for the final "qualification" tests will be provided by the NIF Project.

Each of the three testing stages consists of the following: 1) high-voltage breakdown tests for the insulating bases and leads; 2) a 25-shot infant mortality test at a flashlamp explosion fraction (f_x) of 0.30–0.35; and 3) 10,000-shot lifetime tests at $f_x = 0.2$, the anticipated operating point. The flashlamps will be preionized, just as they will be for NIF. To simulate pump-cavity conditions, the lifetime tests will be conducted with the flashlamps enclosed in a reflective cavity. Realistic mounting and magnetic forces will be assured by mounting the flashlamps in prototype NIF flashlamp cassettes.

In FY94 and FY95, the preliminary tests will be performed using an existing capacitor bank that has been modified to test full-size NIF flashlamps. These tests will be conducted on relatively small numbers of flashlamps (some 8–10 per design) with

different seal and base designs from several different manufacturers. The development schedule provides sufficient time to evaluate and refine designs through two or three rounds of testing. In FY95, we will also undertake a systematic search for sources of carbon particles in lamp envelopes, which we believe are the source of "brown spots" observed in the past after extensive use. The deliverables in FY95 are revised specifications for the NIF flashlamps and a list of vendors eligible to participate in the prequalification tests.

In the second quarter of FY96, we will begin flashlamp prequalification tests on larger numbers of lamps, using a new amplifier and flashlamp testing facility (see Section 1.2.4.) This facility will have the capacity to test 40 flashlamps simultaneously; approximately 40 flashlamps per design will be tested. Flashlamp designs will be eligible for prequalification tests only after passing the preliminary tests. In addition, lifetime tests will be conducted using fully loaded flashlamp cassettes assembled by the flashlamp vendors.

The major deliverables will be a list of vendors eligible to participate in the qualification tests; revised specifications and drawings for the NIF flashlamps; reports and results of the lifetime tests; and a quality assurance plan. The prequalification tests will be completed by early FY97, leaving sufficient time to conduct the qualification tests before NIF flashlamp orders are placed in FY98.

1.2.3 Thermal Control Systems

Flashlamp pumping heats the laser slabs and other pump-cavity components nonuniformly, producing small wavefront distortions during pumping (pump-induced beam steering and much larger distortion during cooling).

After cooling processes reestablish thermal equilibrium and the wavefront quality has recovered, the NIF laser beams will be realigned to prepare for the next shot. Because beam realignment will take up to 2 hours, and the system must be capable of firing every 8 hours, thermal wavefront recovery must occur in less than 6 hours. More rapid recovery is desirable. Development is required to ensure that the very large NIF amplifiers meet even the baseline specification.

We estimate that approximately 60% of the electrical energy delivered to the NIF flashlamps will remain in the flashlamp envelopes, 4% will be absorbed by the edge claddings, 4% will be absorbed by the pumped volume, with the remainder absorbed by the reflection. The principal cause of wavefront distortion will be the thermal gradients produced as heat diffuses from the edge claddings into the pumped volume. Additional distortion will be caused by convection currents arising from temperature differences inside the amplifier and at the ends of the amplifier cavities. Thermal equilibrium is reestablished through conduction, convection, and the exchange of thermal radiation. Radiative transfer is especially effective between glass components, such as the flashlamps, blastshields, and laser slabs, because glass components have high emissivities in the 5-20- μm region where most of the thermal radiation is produced.

Experiments performed at Appleton-Rutherford Laboratory in the United Kingdom and at the Laboratory of Laser Energetics in Japan show that amplifier cooling rates can be significantly increased by flowing gas over the flashlamps and by using gas jets in the slab cavities. It is important to cool the flashlamps and blastshields in the first half

hour after each shot before heat is transferred radiatively to the laser slabs. The gas jets disrupt the natural convection currents that would otherwise establish thermal gradients in the vertical direction. By using these two cooling methods on a system at Rutherford-Appleton with 10.9-cm disk amplifiers, wavefront recovery times were reduced from 1.5 hours to about 20 minutes.

In FY94, LLNL developed a model that predicts temperature gradients in laser slabs as a function of time after a shot. This model used a finite element computer program called TOPAZ3-D to simulate thermal conduction within the laser slab and thermal radiation between components. Model estimates for thermal wavefront recovery times are conservative because natural convection of gas between the laser slabs was neglected to simplify the model. Preliminary results show that shot rate requirement will be met, provided that the flashlamps are actively cooled by forced air.

Development. We will conduct experiments to test and validate the amplifier cooling model in FY95. In the preliminary experiments, temperatures will be measured at various locations inside a one-slab-long Beamlet amplifier. This amplifier will be actively cooled by forced convection over the flashlamps, and by gas jets in the slab cavity. To further upgrade the cooling model, similar experiments will be performed on the $4 \times 2 \times 3$ technology prototype amplifier in FY96. In FY96 and FY97, wavefront recovery of the actively cooled technology prototype amplifier will be measured directly, using interferometry or a Hartmann sensor. (Section 1.2.4 describes the technology prototype amplifier.) Tradeoffs between recovery rates and flow rates will be evaluated. The major deliverables of this effort are: 1) a validated thermal recovery model and 2) a report on the performance and cost of various cooling options.

1.2.4 Performance Measurements

Flashlamp and amplifier testing facility. A major activity during FY95 will be to build a flashlamp and amplifier testing facility. This facility will have four rooms: 1) one to house the pulsed power system; 2) one to test NIF-sized flashlamps; 3) one to test full-height amplifiers; and 4) a control room. Switches will enable the pulsed power to be directed to either the flashlamp test room or to the amplifier testing room. Although not identical to the NIF pulsed-power system, this facility will also test prototype bank components and pulse preionization.

The pulsed power system of this facility will be built in two stages. After the first stage is completed in early FY96, the facility will have pulsed power to drive 40 lamps sufficient to test a preliminary $4 \times 2 \times 1$ or $4 \times 2 \times 2$ technology prototype amplifier, or to perform prequalification tests on 40 NIF-sized flashlamps simultaneously. After the second stage is completed in late FY96, the facility will have sufficient pulsed power to test an expanded $4 \times 2 \times 3$ technology prototype amplifier, or to perform qualification tests on 72 NIF-sized flashlamps simultaneously. The qualification tests are part of the NIF project and are described elsewhere.

Technology Prototype Amplifier. During FY96, we will use the new flashlamp and amplifier testing facility to test the technology prototype amplifier. Initially, this amplifier will be four slabs high, two slabs wide, and one slab long, sufficient to assess the bottom-access NIF baseline amplifier design in terms of cleanliness and serviceability. Cleanliness of the laser slabs is important because particles or dirt heated by

flashlamp or laser light generally causes damage to the substrate. This prototype will also be used to evaluate amplifier cooling methods, including forced air over the flashlamps and gas jets in the pump cavity. Temperatures will be measured at various locations in the amplifier.

The technology prototype amplifier will be assembled in the same manner as the NIF amplifiers. The basic building blocks are box-kite-like aluminum structures called frame assembly units (FAUs), shown in Fig. 1.2-5. After the FAUs are cleaned and assembled in the clean room, with blastshields attached on two sides, the frame assembly units are wrapped in a protective covering and transported to the laser bay. There, the FAUs are mounted to the support structure and clamped together to form a stable assembly. The FAUs are aligned using external amplifier fiducials and references and installed sequentially in the direction of the beam, starting at one end. To provide clean gas flow through the FAUs as they are being installed, the end of the first unit is

70-15-0894-3068pb01

Figure 1.2-5. The NIF amplifier will be constructed from frame assembly units.

covered with a HEPA-filtered blower. After the last FAU in the chain has been installed, the blower is removed and replaced with a cover.

Slab cassettes, which hold four slabs stacked one above the other, will be inserted through the bottoms of the FAUs using a special cart. The cart envisioned for the NIF is automated, as can be seen in Fig. 1.2-6. However, to verify that cleanliness of the slabs can be maintained during insertion, a simpler, less-automated cart will be used to assemble the technology prototype amplifier. This cart will seal to the bottom of the FAU to protect the laser slabs from exposure to the laser bay.

A second cart will also be used to test in situ cleaning, which will be necessary in the event that a flashlamp explosion breaks a blastshield. As is currently envisioned, the first step in the clean-up process will be to remove the flashlamp cassettes and slab cassettes on either side of the failed unit, and to install temporary "dams" to seal the affected FAU from its neighbors. Next, the cart will be used to remove the contaminated or damaged cassette. After a preliminary cleaning of the FAU, a replacement blastshield will be installed. Final cleaning will be performed with the cart, which will extend a cleaning head into the FAU. The head will direct several jets of carbon dioxide "snow" against the inside surfaces of the FAU. The carbon dioxide and contamination will be exhausted through a large flexible tube that empties outside the building. Once this operation is complete, the dams will be removed and a clean slab cassette, residing in the cart, will be raised vertically into position. The cart will remain sealed to the bottom of the FAU throughout the entire cleaning operation.

The major deliverables of the preliminary technology prototype amplifier tests are: 1) a report that assesses the feasibility of the bottom-loading concept, with an emphasis on cleanliness of the laser slabs; 2) recommendations for the design and use of the amplifiers and the special maintenance cart; and 3) a report on the thermal recovery rate of the amplifier.

The $4 \times 2 \times 3$ size of the technology prototype amplifier is sufficient to rigorously evaluate all aspects of NIF amplifier design and performance: optical performance; ease of assembly and maintenance; thermal recovery rate; and cleanliness. To address assembly and maintenance issues, it is important that the technology prototype amplifier have the same four-slab height as the NIF amplifiers. Two slabs is the minimum width that allows the performance of slabs that are pumped by central flashlamp arrays on one side and side flashlamp arrays on one side and side flashlamp arrays to be evaluated. Three slabs is the minimum length that allows the performance of interior slabs to be evaluated.

Optical performance will be measured using full-aperture diagnostics that measure time-resolved gain distributions, pump-induced wavefront distortion, and pump-induced depolarization on a single shot. To determine wavefront recovery rates, the diagnostics will also measure wavefront distortion after shots. Beam tubes will be attached to the ends of the amplifier to evaluate their effect on convection currents and thermal recovery. The diagnostics will be moved from aperture to aperture using large translation stages. We anticipate using the diagnostic hardware to measure the performance of NIF amplifier during system activation. The major deliverables of this effort will be: 1) a report on the design and performance of the technology prototype amplifier and 2) final recommendations for the design of the NIF amplifiers. This activity must be

40-00-0494-1556 pub

Figure 1.2-6. A special cart inserts slab holder cassettes through the bottom of the frame assembly units.

completed early in the last quarter of FY97 so that the results can be incorporated in the final design of the NIF amplifiers.

1.2.5 Assembly and Maintenance

The large scale of the NIF amplifiers requires new mechanical designs that allow convenient assembly and maintenance. Access to the internal components of these large amplifiers, while maintaining stringent cleanliness requirements, is a major issue. Moreover, since the laser slabs, flashlamps, and blastshields are somewhat fragile, special handling and assembly techniques should be developed to minimize glass chipping and breakage. A critical aspect of the assembly and maintenance of ICF amplifiers is the cleanliness of the laser slabs and, to a somewhat lesser degree, the cleanliness of other parts. In the presence of high-fluence pump light and laser light, metal particles or other "dirt" can become hot enough to cause damage to the underlying substrate. In addition, if there were a flashlamp or slab failure, some convenient method of replacement would be required to ensure minimum system downtime.

The bottom-access system envisioned for the NIF amplifiers is a novel approach to these problems. Flashlamp cassettes as well as slab holders, containing four-high columns of slabs, are inserted from the bottom of the amplifier structure without disturbing other amplifier components. The basic amplifier structure consists of a metal frame plus the blastshields that separate laser slabs from flashlamps. Methods must be developed for stringent in situ cleaning of the basic assembly as well as for maintaining cleanliness while components are inserted.

Development. As described in Section 1.2.4, the technology prototype amplifier will allow for rigorous testing of the bottom-access concept. However, prior to testing this amplifier, some technical aspects of the amplifier and maintenance cart design will be addressed through tests conducted on a smaller scale. These tests will be performed to develop techniques for inserting slab holders without generating particles; to develop methods for cleaning parts in situ with carbon-dioxide sprays; and to develop dams for protecting clean amplifier parts from particles and sprays.

One important small-scale test will attempt to identify low-friction, very-low-particulation materials for lining the rails, which will be mounted in the frame assembly units to guide the slab cassettes into position. In this test, witness plates will be used to determine the relative number of particles generated when smooth metal surfaces are rubbed in a controlled manner against various candidate materials. The candidate materials will also be tested for their ability to withstand exposure to low levels of flashlamp light. The lining material must not emit gases that could damage the laser slabs or degrade silver reflectors.

Although we will use low-particulation materials to line the slab-holder rails, it is unrealistic to assume that no particles will be generated when the slab cassettes are slid into position. The baseline NIF design protects laser slabs from the generated particles with a labyrinth seal. We will evaluate labyrinth seals of various designs by generating particles on one side of the seals and collecting them on the opposite side using witness plates.

Tests will also be conducted to evaluate various methods of in situ cleaning. The baseline design uses a carbon dioxide spray, but water sprays are also a possibility. We

will use such sprays to clean a small box that has been contaminated with debris similar to that which would be produced by a flashlamp explosion. We will also use this box to test the ability to use dams to contain debris. Specifically, we will insert a dam in the box, contaminate one side of the dam with debris, clean the contaminated side, remove the dam, and evaluate the inside for cleanliness. Cleanliness can be evaluated by counting the particles rinsed off in a second water spray. These small-scale tests will be completed in FY95.

A cart for performing in situ insertion and cleaning tasks will be built in FY96. This cart will be used to assemble and clean the technology prototype amplifiers.

References

1. W. F. Hagen, *Laser Program Annual Report—1977*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-50021-77 (1978), pp. 2-228 to 2-231.
2. H. T. Powell, A. C. Erlandson, K. S. Jancaitis, and J. E. Murray, "Flashlamp Pumping of Nd:Glass Disk Amplifiers," in *High Power Solid State Lasers and Applications* (SPIE—The International Society for Optical Engineering, Bellingham, WA; *Proc. SPIE* 1277, pp. 103-120 (1990).
3. A. C. Erlandson, K. S. Jancaitis, R. W. McCracken, and M. D. Rotter, "Gain Uniformity and Amplified Spontaneous Emission in Multisegment Amplifiers," *ICF Quarterly Report* 92-2 (1992), Lawrence Livermore National Laboratory, Livermore, CA, UCRL-LR-105821-92-3, pp. 105-114.

1.3 Multipass Laser Components

Multipass laser architectures are preferred for the large Nd:glass lasers utilized in ICF research because they reduce the number of optical components required and they increase the energy extraction that can be obtained from the amplifier slabs at a given output fluence. Both of these features reduce the overall cost of the laser, which is a very strong motivation in large and expensive systems. There is a long history of multipass laser designs starting with the Long Path laser at LLNL, which was built and tested in the early 1970s. Single-pass laser designs were utilized for the Shiva or Nova lasers and their immediate predecessors because simple and cost-effective multipass laser designs and the required multipass components were unavailable at that time. This situation changed significantly in the 1980s with the invention of the plasma electrode Pockels cell (PEPC) by Goldhar and Henesian.¹ Unlike previous electro-optic switches, the PEPC switch was scalable to the large apertures required for an ICF system.

Starting in FY92, we began an intense program to further develop PEPC technology for the Beamlet laser. This development was successful and we were able to develop a reliable switch that met requirements on switching speed and switching uniformity across the full aperture. In January 1994, we installed a 37- × 37-cm PEPC switch in the Beamlet laser amplifier cavity and began tests. A photograph of this device is shown in Figure 1.3-1(a). Based on the Beamlet success, we utilized a PEPC switch in the conceptual design for the NIF. This design is shown in Fig. 1.3-1(b). To reduce technical risk, further development of the PEPC is planned to scale the Beamlet aperture design to the multiaperture design required for NIF. Sections 1.3.1 and 1.3.2 describe this required development program.

The PEPC approach to multipass laser design, as with any other approach, has unique advantages and disadvantages. For example, in the course of the Beamlet work, we learned the practical difficulty of making large polarizers with high damage fluence that are needed in the PEPC-based laser design. Also, we found that the optical finishing of the KDP crystal used in the PEPC switch must be very good to minimize downstream intensity modulations. Although improvements and/or solutions to these problems can be expected as discussed in Section 2.0, "Optics Manufacturing," we are still motivated to continue to investigate alternative multipass laser approaches in our development activities. The U/L-turn concept discussed in Section 1.3.3 is a promising new approach that we are evaluating on Beamlet.

Finally all multipass ICF laser designs must contend with several common problems. They must prevent parasitic laser oscillation, they should access the volume of the laser glass as efficiently as possible, and they must cope with the potential switch failure or less-than-unity switching efficiency. These issues are associated with pinholes and beam dumps, which are addressed in Section 1.3.4.

1.3.1 Large-Aperture Plasma-Electrode Pockels Cell

A Pockels cell is a device that changes the polarization state of a laser beam. This is accomplished by applying an electric field to an electro-optic crystal. This electric field induces birefringence in the crystal. If the applied voltage is equal to V_p , or the half-wave voltage for the crystal, the polarization of an incoming, linearly polarized beam is rotated by 90°. By combining a Pockels cell with a linear polarizer, we can realize an

(a)

Beamlet Pockels cell

70-39-0394-1396 pub

(b)

NIF 1 × 4 Pockels cell

Figure 1.3-1 (a). A photograph of the plasma-electrode Pockels cell constructed for the Beamlet laser. (b) Conceptual design for a 1 × 4 NIF PEPC module.

optical switch. The Pockels cell controls whether the beam is transmitted or reflected from the polarizer. A plasma-electrode Pockels cell differs from a conventional Pockels cell in the way the electric-field is applied to the crystal. In a conventional Pockels cell, the voltage is applied via metal electrodes deposited around the ends of the crystal. In this type of Pockels cell, the crystal length must scale with the aperture. A large-aperture cell would require an unacceptably thick crystal. In a PEPC, shown schematically in Figure 1.3-2, the metal electrodes are replaced with highly conductive plasmas, which are transparent to the laser beam. The plasmas are formed by high-current (>2 kA) electric discharges driven by the plasma pulsers between anode-cathode electrode sets in a 35-mTorr helium background. These plasmas cover both sides of the crystal, and allow uniform application of V_p via the switch-pulsers. In a PEPC, the crystal thickness does not need to scale with aperture because the electric field is applied directly across

40-00-0394-0616A pub

4/27/94

Figure 1.3-2. Schematic diagram of a plasma-electrode Pockels cell.

the crystal and not from the periphery. Since V_p is also independent of crystal thickness, the crystal can be as thin as is mechanically practical. However, the capacitance of the crystal increases with decreasing thickness. A thinner crystal requires a lower-impedance pulse generator to charge to V_p in a given time. The 37- $\times$ 37-cm Beamlet PEPC employs a 1-cm-thick crystal.

During the development of the Beamlet PEPC, we achieved several key milestones. On a prototype PEPC we demonstrated a switching efficiency >99% with KDP and KD*P crystals over a 32-cm aperture, and operation at high fluence ($>20 \text{ J/cm}^2$) with a small-aperture beam for use on Beamlet. We increased the aperture of the PEPC to 37 cm $\times$ 37 cm for the Beamlet PEPC. We also learned to deal with a number of challenging technology issues including: control of cathode sputtering; control of crystal heating; and generation of high-quality, switch-pulse waveforms. Although much of what we learned during the development of the Beamlet PEPC is applicable to the NIF laser, the NIF design requires significant extrapolations of the existing technology. To confidently design and construct optical switches for the NIF, we will need to continue our development program with new goals. The development program described below will maximize performance while minimizing the cost and technical risk of an NIF optical switch. This program will be divided into major development tasks which include: metal housing evaluation, extension to a 1 $\times$ 2 module, and finally, demonstration of a multiple-module device. In addition to this experimental effort, we will initiate an effort to computer-model important aspects of PEPC operation. We discuss each of these tasks below.

Metal housing evaluation. In this section, we will discuss our plan to evaluate a PEPC constructed with metal housings. The PEPC housings are key structural components that form the vacuum regions on either side of the KDP crystal. The housings also integrate other components in the PEPC, including the discharge anodes and cathodes, the outside windows, the vacuum system, and the gas-feed system. To date, these housings have been fabricated from an electrically insulating material, which guarantees electrical isolation between the discharge electrodes. The specific material choice for the Beamlet prototype and the actual Beamlet PEPC was Ultra-High-Molecular-Weight (UHMW) polyethylene. We chose UHMW because of its low material cost and its low outgassing rate under vacuum. Currently, the baseline design for the NIF switch also calls for the housing to be made out of an insulating material, because we have demonstrated excellent performance from PEPCs with insulating housings. However, insulating materials pose a number of disadvantages. For example, UHMW is inexpensive but difficult to machine to close tolerance; it also tends to creep under vacuum load. Other plastics can have large outgassing rates. Ceramics are expensive and hard to obtain in large sizes. Cast glass is a possibility but is difficult to machine.

Another possibility is to make the housings out of metal such as aluminum or stainless steel. Figure 1.3-3 shows the mechanical difference between an insulated-housing PEPC and a metal-housing PEPC. Although not shown in Fig. 1.3-3 for the insulated housing case, the switch-pulse cables must be connected to the anodes via mounting brackets.

In the metal housing approach, the entire housing acts as the anode electrode while the cathode electrode is mounted inside an insulating bucket. The main technical issue

70-15-0494-2239pub

Figure 1.3-3. A comparison of insulated and metallic housing PEPC designs. The insulated design has discrete anodes and cathodes. In the metal-housing design, the housing acts as the anode.

associated with this design is plasma uniformity. It is possible that the discharge will be localized near the cathode side, and not cover the entire crystal with sufficient uniformity. However, the discharge uniformity can be greatly improved by reducing the effective anode area with a surface magnetic field over most of the inside surface. Such a magnetic field can be readily produced with rows of permanent magnets. This technique, originally developed by McKenzie at UCLA,² has found application in a wide range of plasma devices. Assuming we can produce a uniform discharge in a metal-housing PEPC, we can expect an improvement in switching performance because the anode now surrounds the crystal. Since the switch pulse is applied to the crystal via the anodes on each side, the average path length from the crystal to the anode is much less than if the anode is only along one edge of the crystal. This is particularly true of layouts employing two or more crystals per housing. The metal housing approach also offers mechanical advantages, including: easy to machine to close tolerances; lower material cost; lower manufacturing cost and risk; and thinner housing dimensions due

to material strength. The potential cost and performance advantages of the metal housing approach make this a high priority of the NIF switch-development program. Our current plan is to evaluate the metal housing approach by the end of the first quarter of FY95, and then decide if we should focus on metal or insulated housings.

1.3.2 Multiaperture Pockels Cell

In the NIF laser, components in the main amplifier cavity will be configured in groups or bundles of beamlets where the clear aperture of each beamlet will be on the order of 40 cm. The baseline of the NIF is a 4×2 array with the beamlets stacked four high and two wide. The individual beamlets in this 4×2 bundle will need to be tightly integrated both mechanically and electrically. To achieve a tightly integrated 4×2 array, it will be necessary to combine four beamlets into 1×4 modules. Two 1×4 modules will then be combined to form a 4×2 beam line. While the mechanical module size will be 1×4 , electrically, each 1×4 module will function as two - independent 1×2 Pockels cells. Using this approach, most of the electrical connections and the vacuum system can interface to the 4×2 switch array at the top and bottom. This avoids the problem of having to route cables and vacuum plumbing in between beamlets.

If the metal housing tests are successful, we will have two viable material options for the NIF switch. We will down-select between metal and insulator, or carry both alternatives through the next step, the demonstration of a 1×2 module. A diagram of a 1×2 module is shown in Fig. 1.3-4.

In a 1×2 module, the plasma-pulsers drive discharges across two crystals compared to one in a 1×1 module. This increase in anode-cathode spacing will alter the operating

70-15-0494-2240pub

Figure 1.3-4. A 1×2 plasma-electrode Pockels cell. The discharge must uniformly cover two crystals.

pressure, peak current, and current-pulse-width requirements from the 1×1 case. These operating parameters will be determined experimentally as part of our development plan. As in the 1×1 case, the switch-pulsers will connect across the anodes as shown on the left side of Fig. 1.3-4. One switch-pulsers will be provided to charge both crystals in each 1×2 Pockels cell.

After we demonstrate the operation of a 1×2 PEPC module, we will show that several PEPC modules can operate in close proximity. During the development of the Beamlet PEPC, we observed that magnetic fields from the plasma-discharge current can interfere with uniform charging and discharging of the crystal. This situation is shown in Fig. 1.3-5.

During experiments with the Beamlet prototype PEPC, we observed that the cables carrying the plasma-discharge return current produced a significant switching

70-15-0494-2241pub

Figure 1.3-5. Magnetic field from cables carrying the plasma discharge current can cause regions of non-uniform switching. These regions appear as bright spots when the cell is viewed in a polarimeter.

nonuniformity in the corner of the crystal near the wires. If the wires were routed above the cell, the switching nonuniformity was in the upper corner. If the wires were routed under the cell, the nonuniformity moved to the bottom of the cell. We solved this problem by arranging the wires so that they carried current in opposite directions. Thus the magnetic field from one wire was canceled by the field from the other. We employed this wiring configuration with the Beamlet PEPC, but during testing we still observed magnetic nonuniformities. This time we found the nonuniformities were on the opposite side from where the wires were connected. Using magnetic field probes, we traced

Figure 1.3-7. Schematic of the U-turn.

The beam is inverted to reduce pointing errors on target. In the baseline, beam pointing and focusing errors caused by vibrations, thermal drift, and pump induced steering add coherently with the number of passes. By inverting the beam in the U-turn, the pointing errors accumulated on passes one and two are subtracted (rather than compounded) on passes three and four. This does not apply to the focusing errors, but those can be corrected with the wavefront correction system. In this sense, the cavity is self-stabilizing.

Separation of passes 2 and 3 also makes possible a change in the beam sizes of passes 2 and 3 in the main cavity. If passes 1 and 2 have a beam area about half that of passes 3 and 4, the vignetting loss is dictated by only passes 3 and 4. This essentially reduces the vignetting loss by 50%. This scheme also reduces aberrations because the first two passes use the center of the amplifiers, avoiding the more aberrated edges of the amplifier slabs.

In contrast, the French L-turn does not invert or change the size of the beam. As in the U-turn, pass 2 is picked off in the transport spatial filter, but unlike the U-turn, passes 2 and 3 are never completely separated. While the passes are pointed differently, they physically overlap. The overlap permits the two passes to share the same optics including a pick-off mirror, turning mirror, collimating lens, and cavity mirror. The

pressure, peak current, and current-pulse-width requirements from the 1×1 case. These operating parameters will be determined experimentally as part of our development plan. As in the 1×1 case, the switch-pulsers will connect across the anodes as shown on the left side of Fig. 1.3-4. One switch-pulser will be provided to charge both crystals in each 1×2 Pockels cell.

After we demonstrate the operation of a 1×2 PEPC module, we will show that several PEPC modules can operate in close proximity. During the development of the Beamlet PEPC, we observed that magnetic fields from the plasma-discharge current can interfere with uniform charging and discharging of the crystal. This situation is shown in Fig. 1.3-5.

During experiments with the Beamlet prototype PEPC, we observed that the cables carrying the plasma-discharge return current produced a significant switching

70-15-0494-2241pub

Figure 1.3-5. Magnetic field from cables carrying the plasma discharge current can cause regions of non-uniform switching. These regions appear as bright spots when the cell is viewed in a polarimeter.

nonuniformity in the corner of the crystal near the wires. If the wires were routed above the cell, the switching nonuniformity was in the upper corner. If the wires were routed under the cell, the nonuniformity moved to the bottom of the cell. We solved this problem by arranging the wires so that they carried current in opposite directions. Thus the magnetic field from one wire was canceled by the field from the other. We employed this wiring configuration with the Beamlet PEPC, but during testing we still observed magnetic nonuniformities. This time we found the nonuniformities were on the opposite side from where the wires were connected. Using magnetic field probes, we traced the source of this effect to vertical current flow in the discharge electrodes. If the wires are connected to the top end of the electrode, there is a component of the current flow down through the electrodes as the discharge current fans out through the plasma. This leads to a horizontal magnetic field, which encircles the electrodes. The plasma near the electrodes is magnetized, which can lead to increased resistivity and can also cause particle drifts, which would create plasma nonuniformities. Before we can successfully operate multiple PEPC modules in close proximity, we need a better understanding of these magnetic effects, and must develop methods to minimize magnetic field related switching nonuniformities. A demonstration of two or more PEPC modules operating in close proximity will show that the magnetic effects can be controlled to acceptable levels. According to our proposed schedule, we plan to operate two adjacent 1×2 modules in the first quarter of 1997. The final discharge current feed configuration will be determined by experiments with this dual 1×2 setup.

Computer modeling. In the preceding sections, we described our plan to experimentally develop PEPC technology for the NIF. We also plan to initiate a computer modeling effort to support the experimental plan. The primary tool in our modeling effort will be modified versions of the PDPn (Plasma Devices Planar n-dimensions)³ codes from University of California at Berkeley. The PDPn codes are electrostatic, particle-in-cell plasma simulations, which also account for atomic physics processes such as ionization and charge exchange. These atomic processes play an important role in the type of plasma discharge employed in a PEPC. The PDP1 code tracks one positional dimension and three particle velocity components; PDP2 is a two-dimensional (2-D) version. We will use these codes to model plasma formation in a PEPC from the low-current, simmer discharge to the high-current pulse required for optical switching. After calibrating the codes to our experimental results from the prototype and Beamlet PEPCs, we will use the codes to predict discharge behavior in a 1×2 cell. We also plan to modify the 2-D code, so that we can model the charging and discharging of the KDP crystal.

1.3.3 "U-turn/L-turn" Components

The U-turn design (see Fig. 1.3-6) is an alternative laser architecture for the NIF. The U-turn has different performance risks, but it also has several potential advantages including fewer large-aperture components and higher performance. The U-turn was conceived at LLNL in 1992. A similar concept, the L-turn was independently discovered by the French group at CEL-V. Both concepts are based on using small optics in the transport spatial filter to turn the beam around after two passes for another two passes through the amplifiers. In contrast to the NIF baseline, a large Plasma Electrode Pockels

TOP VIEW

Figure 1.3-6. Schematic of the U-turn architecture.

cell (PEPC) and polarizer are not needed to switch the beam out of a cavity after four passes but are used only for the purpose of isolation. Locating the PEPC and polarizer near the cavity mirror provides an option for pairing beams such that only one PEPC is needed for every two beamlines, thus reducing costs. Because all the amplifier slabs are in the cavity and four passed (the booster amplifier slabs in the baseline are only double passed), fewer slabs are needed to extract the same energy. Furthermore, the U-turn layout is straight-line, eliminating the second cavity mirror and elbow mirror needed for a switch design.

The L-turn is the current baseline for the French Megajoule laser project, which utilizes a laser system of comparable scope and size to the NIF laser. This concept is similar to the U-turn except that the incoming and outgoing laser beam are overlapped on common optics to reduce the number of optics.

Description of the U-turn and L-turn architecture. The U-turn architecture enables four passes through an amplifier using small optics in the transport spatial filter. Unlike the NIF-baseline, the large PEPC and polarizer are used only for isolation (see Fig. 1.3-7). The U-turn components consist of small optics located inside the transport spatial filter which pick-off the beam after pass 2 through the amplifier and turn it around to make pass 3 through the amplifiers. Pass 4 proceeds directly to the target chamber. The U-turn hardware consists of seven small optical components: five high-damage threshold mirrors and two lenses.

The U-turn mirrors divert the beam off-axis permitting other components to be utilized without interfering with the final pass. These mirrors are paired to invert the beam in the vertical dimension when the beam enters the U-turn and invert the beam in the horizontal dimensions when the beam exits the U-turn. The entrance mirrors also direct the beam through a lens and onto the cavity mirror. The first lens collimates the beam at about 7×7 cm and properly relays it through the U-turn. The beam reflects from the cavity mirror to pass at a slightly different angle to exit the U-turn. The exit optics are essentially the same as the entrance optics with a second lens to refocus the beam and two more mirrors to redirect the beam onto pass three and four through the amplifiers, and finally to the target chamber. Two of the five mirrors are remotely controlled to point and center the beam through pass three and four. The final mirrors are positioned to compensate beam rotation in the U-turn.

END VIEW **SIDE VIEW**

Figure 1.3-7. Schematic of the U-turn.

The beam is inverted to reduce pointing errors on target. In the baseline, beam pointing and focusing errors caused by vibrations, thermal drift, and pump induced steering add coherently with the number of passes. By inverting the beam in the U-turn, the pointing errors accumulated on passes one and two are subtracted (rather than compounded) on passes three and four. This does not apply to the focusing errors, but those can be corrected with the wavefront correction system. In this sense, the cavity is self-stabilizing.

Separation of passes 2 and 3 also makes possible a change in the beam sizes of passes 2 and 3 in the main cavity. If passes 1 and 2 have a beam area about half that of passes 3 and 4, the vignetting loss is dictated by only passes 3 and 4. This essentially reduces the vignetting loss by 50%. This scheme also reduces aberrations because the first two passes use the center of the amplifiers, avoiding the more aberrated edges of the amplifier slabs.

In contrast, the French L-turn does not invert or change the size of the beam. As in the U-turn, pass 2 is picked off in the transport spatial filter, but unlike the U-turn, passes 2 and 3 are never completely separated. While the passes are pointed differently, they physically overlap. The overlap permits the two passes to share the same optics including a pick-off mirror, turning mirror, collimating lens, and cavity mirror. The result is fewer optics and easier alignment. However, the system does not reduce system alignment errors or wavefront aberrations because the beam cannot be manipulated without separating the passes. Also, since the L-turn optics are used in the double-pass mode, the pulse can overlap itself in time, and the optics can see higher laser fluences. Thus, the L-turn optics will likely be larger than U-turn optics to reduce risk of damage.

Unlike the NIF baseline, the Pockels cell and polarizer are used only for isolation in the U and L-turn architecture and not for switching the beam from the cavity. Consequently, the isolation unit can be located anywhere in the beamline. By locating the isolation unit at the start of pass 4 (near the cavity mirror), the shot energy is lower than for its position in the baseline, and it rejects output back-reflections (from pinholes, final optics, targets, etc.) after only one pass through the laser. Since the pulses can go through the PEPC in either direction, pairing of beams is an option such that only one PEPC for two beams is needed. Space for the flashlamps and beam walk off in the optics provides room for the PEPC to be located between the two beamlines. A beam injected into beamline 1 of a beam-pair passes through the isolation unit and into beamline 2. The U/L-turn returns the beam along beamline 2, through the isolation unit again and back into beamline 1 to exit the laser. This scheme reduces the number of PEPCs by 50% and provides access to each one, thus avoiding the need for 1×2 PEPCs (although it may be more cost effective to use them anyway). Furthermore, in the case of the U-turn, the beam is inverted so the beam never sees the same part of the optics twice, eliminating any coherent addition of aberrations.

To protect against back reflections, the PEPC is tilted as a half wave plate, rotating the beam 90° (vertical) when "off" and 180° when activated. Therefore, if and only if the PEPC is activated will the beam transmit through the next polarizer and continue through the laser; otherwise, it is rotated 90° , reflects from the next polarizer, and is dumped. The small percentage of vertically polarized beam that does not reflect off the polarizer ($<1\%$) is further dissipated in the amplifiers because surface reflection loss for a vertically polarized beam is greater than the gain of the amplifiers. This technique is used to pass the pulse beam but reject undesirable back-reflections and parasitic oscillations, lowering by a factor of more than 400, the fluence of back reflections that would otherwise enter the U/L-turn. Because the PEPC sees the pulse beam at two different times, it must either be activated twice for a duration of about 50 ns long or once for a duration of about 500 ns long.

Development plan.

Analysis and testing are required to confirm these advantages, quantify their cost impact, and resolve detailed technical issues. In March 94, a team from LLNL and CEL-V established a joint project for two phases of testing the L-turn and U-turn concepts on Beamlet. The first phase, in FY 94 and early FY 95, was to design, build, and test a Hybrid device that could validate both the U-turn and L-turn. Costs and effort were shared between CEL-V and LLNL. Comparable energy output to the Beamlet baseline was achieved with the Hybrid device proving the validity of the concept. Of particular importance was confirmation that the U/L-turn's optics could routinely handle the required peak irradiance levels. However, the isolation proved inadequate to prevent damage from reflections from spatial filter lenses, prompting relocation of the isolation unit from inside the U/L-turn to the location near the cavity mirror. Since this isolation arrangement is new, testing it on Beamlet is planned during FY 96 (see Fig. 1.3-8). Ideally, beams would be paired to test that scheme, but Beamlet has only one beamline. Therefore, the cavity mirror will be arranged normal to the beam. The beam will pass a total of four times through the PEPC during a shot.

Figure 1.3-8. Moving the isolation unit near the cavity mirror is planned in Phase II of the U or L- turn tests on Beamlet.

1.3.4 Pinholes and Beam Dumps

Pinholes. We do not currently have an adequate knowledge of "pinhole physics" to scientifically design pinholes for NIF. In particular, we do not sufficiently understand pinhole blowoff, pinhole closure, or the onset of refraction and back-reflection from too much beam energy on the edge of the pinhole.

Pinhole "blowoff" refers to the material ejected or evaporated from the pinhole when high-power beams are focused through them to strip the beam of high-spatial-frequency components. There is ample evidence for this in the form of badly eroded pinholes from Nova. The eroded material deposits throughout the inside of the spatial filter, presumably more so near the eroding pinholes. The NIF multipass laser architecture introduces several optical components that must operate at high fluence levels near these pinholes. The injection mirror and the beam dumps for the PEPC leakage are examples. We currently have no experience with long-term (hundreds of shots) operation of critical optics in this environment. Further, Beamlet will not provide enough high-fluence shots to determine if blowoff is a problem for these optics.

Consequently, we propose an experimental effort to investigate this problem from mid-FY96 through FY97 with a possible completion date at the end of FY97. Initial testing would use a 10 pps, one-joule-class 1- μm laser and a small vacuum chamber to investigate short- and long-term blowoff effects.

A preliminary excursion into the available literature on laser ablation shows that pinhole blowoff consists of both vapor and ejecta (small, $\sim 1\ \mu\text{m}$,³ molten and solid droplets of the pinhole material). Although a buffer gas has been demonstrated to effectively stop the deposition of blowoff vapor,⁴ scaling to the required pressure to protect the close-in optics (at 1 to 2 m from the pinholes) gives too high a pressure for the spatial filters. Furthermore, buffer gas is not effective on ejecta,⁵ and blowoff is

mostly ejecta⁵ above $\sim 10^{11}$ W/cm². Although it is not encouraging that ejecta seems to be an ongoing problem for x-ray projection lithography, where the intensity on the target is similar to that on our pinholes, we have a wider choice of materials. Our initial plans are to investigate pinhole materials like carbon, which might be converted to CO and CO₂ by an O₂ buffer gas.

Pinhole closure occurs when enough laser intensity hits the pinhole edge to generate a plasma and deflect or reflect part of the laser pulse. An experimental investigation of pinhole closure using the Janus laser facility compared to hole-in-plate pinholes to tapered, conical pinholes of the same diameter and showed that the latter close 2× slower than the former. These results are hard to characterize in detail, because of the poor and nonreproducible temporal and spatial properties of the Janus laser. However, they are sufficiently promising to justify further tests on the Beamlet laser. Because the pinhole design will not significantly affect the spatial filter design, we can delay completion of these tests to the end of FY96.

Refraction and back-reflection can result from partial closure of a pinhole. Refraction is caused by the refractive index gradient of the plasma expanding from the pinhole edge. It can deflect part of the beam onto the edges of mounts and other hardware near the beam, causing damage to this hardware as well as possible contamination of nearby optics, reducing transmission and damage thresholds. Back-reflections can potentially be amplified to damage fluence levels, and thereby directly threaten beamline optics and beam dumps. The onset of deflection or back-reflection determines the maximum permissible intensity and fluence on the pinhole edges. This in turn determines a maximum permissible pinhole misalignment. It also determines the maximum beam aberration for a given pinhole size. We plan experiments on Beamlet in conjunction with the pinhole closure experiments mentioned above, and we also plan to test different pinhole materials.

All multipass architectures assume that the cavity is stable against parasitic oscillations, and that the cross-coupling between passes is insignificant. Although the NIF baseline does not significantly differ in gain from the Beamlet, its pinhole spacing is substantially smaller in one dimension. Further, modeling efforts to increase system performance have suggested small signal gains between spatial filters of 1000 or more, significantly larger than have been demonstrated. Consequently, we should experimentally demonstrate the minimum pinhole spacing that eliminates significant cross-coupling between passes, and we should experimentally show that the largest gain of interest between spatial filters is indeed stable against parasitics. Both of these questions depend on the amount of aberration in the intervening optics, and the minimum pinhole spacing also depends on the high-frequency noise on the pulsed beam. Although neither of these is likely to be the same for NIF and Beamlet, definitive data with quantified aberrations for conditions reasonably close to the NIF design point can insure predicted performance.

We propose a small experimental effort on Beamlet on a ride-along/fill-in basis (see Sec. 1.13) during FY96 to investigate these two questions. Beamlet could easily be configured to test gains in excess of 1000 between pinholes by completely opening the pinhole plane of the multipass spatial filter and by deactivating the PEPC switch. In that case, amplified spontaneous emission (ASE) would traverse the 11 multipass amplifiers disks and the 5 booster disks twice between two pinholes in the output spatial filter. At

an explosion fraction of 0.20, the normal Beamlet operating point, the gain/disk = $\exp(0.242)$, giving a gain between pinholes of 2300. Further, the Beamlet bank can be operated at reduced energy, allowing the gain to be increased in small steps. We would increase the gain slowly from known stable levels, while monitoring ASE and watching for parasitic lasing from pinhole plane components.

The PEPC switch in the NIF baseline architecture protects against many of the parasitic paths involving cross-coupling between pinholes. The most serious and remaining problem is cross-coupling between pinholes 3 into 2, which are about 1 cm apart for NIF compared to 3 cm for Beamlet. This could couple energy from the outgoing pulse back toward the front end. This problem is made worse by the small-angle scatter from the diamond turning marks on the PEPC KDP. For this back-reflection to be smaller than the initial injected pulse, the cross-coupling must be less than the 4-pass small-signal gain of the multipass, about 10^6 for NIF.

We propose testing the NIF pinhole spacing on Beamlet in parallel with the parasitic tests mentioned above. We would initially measure the coupling for smaller pinhole spacings at low-pulse energy and low gain to protect the injection optics, and increase gain and energy slowly toward the full-scale demonstration.

Beam dumps. The NIF baseline design requires beam dumps in several locations to safely absorb unwanted beams. Leakage through the PEPC switch on passes 2 and 4 and reflections from the harmonic generators are examples of unwanted beams. These unwanted beams travel at small angles to the main beam, and consequently are separated from the main beam only near the pinhole plane of spatial filters. They must be "dumped" in these regions to prevent damage to other pinhole-plane components, and to prevent reflections back toward the front-end of the system.

The most demanding beam-dump requirements for the actively switched multipass architecture are for those beam dumps that must routinely absorb the leakage through the PEPC switch and must also handle the entire amplified pulse in the event of a worst-case failure of the PEPC. The back-reflection from these beam dumps must be small enough so as not to jeopardize the injection optics or the front-end components. For a worst-case PEPC failure, calculations⁶ show that a reflectivity of less than 10^{-6} is required to protect the injection optics. Also, these dumps must survive indefinitely for normal operation of the PEPC (less than 2% leakage).

The current strategy for NIF is to absorb the leakage energy with two absorbing glass beam dumps, as shown in Fig. 1.3-9. Each beam dump would be well polished to minimize backscatter and have a surface curvature designed to prevent focusing inside the glass. They would intercept the beam at a large enough beam area that the fluence would be below the damage threshold of the beam-dump glass. This beam-area requirement dictates a minimum beam separation at the pinhole plane, which sets the minimum angular separation for NIF between beams. Consequently, the size of these beam dumps contributes to a reduction in fill factor for the entire laser system.

Because output energy is directly proportional to fill factor, there is a strong incentive to reduce the size of these beam dumps. Tests of scaled beam dumps on the Optical Sciences Laser (OSL) showed⁷ that they easily met the above requirements and

70-15-0494-2237pub

Figure 1.3-9. The beam dump concept uses two absorbers located on either side of the pinhole plane in the spatial filter.

suggested that they were too conservatively designed. The authors suggested that it may be possible to operate these beam dumps above their single-shot damage threshold and still meet the 10^{-6} reflectivity specifications. In that case, they would sustain some damage on routine shots, and the concern would be their useful lifetime.

We propose continuing the tests on scaled beam dumps to investigate back-reflectivity at input energies above the damage threshold. Experimental demonstration of failure mechanisms and possible dependence on beam dump geometry and absorber material would be conducted on the OSL, GDL or Trident. Lifetime testing of promising designs would be done on one of the higher-shot-rate lasers used for damage testing. We propose a small experimental effort, with completion in mid-FY97.

Figure 1.3-10 summarizes the schedules for all of the activities in Section 1.3. The work is completed in a three-year time span starting in FY95. In the first year, Phase I testing of the U/L turn optics was completed, and design on the 1×2 Pockels cell was initiated with fabrication and testing planned in FY96. Also in FY96, a Phase II U/L-turn test is scheduled along with pinhole and beam dump experiments which should continue into FY97.

● = marker

◆ = milestone

Figure 1.3-10. Multipass laser component development schedule.

References

1. J. Goldhar and M. A. Henesian, "Large Aperture Electro-optical Switches with Plasma Electrodes," *IEEE J. Quantum Electronics*, **QR22**, 1137 (1986).
2. W. F. Vivergilio, P. M. Kam, D. S. Pappas, K. R. McKenzie, *Am. J. Physics*, **42**, 169 (1974).
3. C. K. Birdsall, "Particle-in-Cell Charged Particle Simulations, Plus Monte Carlo Collisions with Neutral Atoms, PIC-MCC," *IEEE Trans. Plasma Science*, **19**, 65 (1991).
4. M. L. Ginter, T. J. McIlrath, "Debris and VUV Emission from a Laser-Produced Plasma Operated at 150 Hz Using a Krypton Fluoride Laser," *Applied Optics* **27**, 5, 1 (March 1988) pp. 885-9.
5. G. Kubiak, Sandia National Laboratory, Livermore, CA, private communication.
6. J. Woodworth, B. Boyd, D. Eimerl, D. Milam, H. Patton, and M. Webb, "Results of Preliminary Tests on the Prototype Beam Trap for Beamlet," LLNL internal memo, Jan. 28, 1992.
7. K. Estabrook, "An Improved Pinhole Spatial Filter," LLNL internal memo, 1987.

1.4 Frequency Conversion

Introduction

High-efficiency third harmonic generation is accomplished by a sequential, or cascaded, application of sum-frequency mixing via the second-order nonlinear polarizability of crystalline media. One crystal is used to generate a beam at the second harmonic, and a second crystal mixes the second harmonic with the residual fundamental beam to generate the third harmonic. The harmonic generation efficiency in each crystal is dependent upon the nonlinear polarizability of the medium, the thickness of the medium, the phase mismatch between the input and generated waves, and the intensities of the input beams. The harmonic generation efficiency is particularly sensitive to phase mismatch and to the balance between the intensities of the input waves (the mix ratio).¹⁻⁵

Phase mismatch, Δk , is the difference between the k -vector of the output wave and the sum of the k -vectors of the input waves. When the sum-frequency generation process is perfectly phase matched, i.e., $\Delta k = 0$, the input and generated waves traverse the nonlinear medium with their phases locked together allowing maximum energy transfer to the wave at the sum frequency. The most common method of achieving phase matching is the use of the birefringence of crystalline media to offset spectral dispersion. This rather naturally leads to two types of phase matching: type I, in which the two input waves have the same polarization inside the nonlinear medium, and type II, in which the two input waves are orthogonally polarized in the nonlinear medium.

Mix ratio is a critical parameter in the third harmonic generation crystal. An imbalance in the photon fluxes of the fundamental and second harmonic beams incident upon the tripling crystal leads to back-conversion of the third harmonic beam even with perfect phase matching. Craxton^{1,2} has proposed two simple methods for controlling the mix ratio incident upon the tripler: 1) adjusting the phase mismatch in the doubling crystal by angularly detuning it from perfect phase matching; 2) adjusting the polarization of the fundamental wave incident upon the doubling crystal. The second of these two mix ratio control methods is termed polarization bypass for a type I doubler, and polarization mismatch for a type II doubler. Angle detuning and polarization adjustment are attractive schemes for controlling the mix ratio because they can be implemented simply in an inline geometry.

The two most common third harmonic generation schemes, type I SHG/type II THG and type II SHG/type II THG, are shown schematically in Fig. 1.4-1. Both of these harmonic generation schemes have delivered high-efficiency third harmonic generation on Nova. However, the type II/type II scheme required repolarization to achieve high-conversion efficiency.⁶ Figure 1.4-2 shows a plot of third harmonic conversion efficiency versus input intensity, i.e., dynamic range for each of these two third harmonic generation schemes. Both schemes have nearly identical dynamic range, which is fundamentally limited by the mix ratio control methods of these two designs. In each case, the mix ratio control method causes the second harmonic generation efficiency to vary with input intensity. This limits the input intensity range over which optimum mix ratio is delivered to the tripling crystal.

Figure 1.4-1. Schematic diagram of type I / type II and type II / type II third harmonic generation schemes.

70-50-0595-1396pb01

Figure 1.4-2. Third harmonic conversion efficiency versus input intensity for type I/type II and type II/type II schemes. These curves were calculated using ideal plane waves. Perfect phase matching is assumed for all crystals except the type I doubler, which is detuned 250 μrad to provide near-optimal mix ratio to the tripling crystal.

The plot in Fig. 1.4-3 shows the sensitivity of each of these designs to angular detuning. The angular rate of change of phase mismatch for type II third harmonic generation exceeds that for either type I or type II second harmonic generation. Thus detuning of the tripler dominates the angular sensitivity of third harmonic conversion efficiency for the type II/type II design. However, the angular sensitivity of third harmonic generation efficiency for the type I/type II design is dominated by the doubler detuning because mix ratio control in the type I/type II design is achieved by purposely detuning the doubling crystal from exact phase matching. Although the type I/type II scheme is significantly more angularly sensitive than type II/type II, the focusability requirements of the NIF place more stringent tolerances on beam quality and pointing than that required for high-efficiency third harmonic generation.

The plot in Fig. 1.4-4 displays the sensitivity of each of these designs to depolarization. The type I/type II design is practically insensitive to small levels of depolarization. The input energy carried in the incorrect polarization does not participate in the harmonic generation process in the type I/type II design. Thus, the input energy has the same effect on conversion efficiency as a simple energy loss. On the other hand, the type II/type II design is much more sensitive to depolarization than is type I/type II. This is a consequence of using the polarization angle of the input beam to the type II/type II design as the mix ratio control method. Depolarization of the fundamental beam alters the second harmonic conversion efficiency, which in turn affects the mix ratio delivered

70-50-0595-1397pb01

Figure 1.4-3. Third harmonic conversion efficiency as a function of internal angle relative to exact phase matching for a 10.5 mm type I SHG crystal and a 9 mm type II THG crystal. These curves were calculated using an ideal plane wave input of 4 GW/cm².

70-50-0595-1398pb01

Figure 1.4-4. Sensitivity of third harmonic generation to depolarization of incident fundamental beam at an input intensity of 4 GW/cm². Dotted vertical lines indicate 0.2%, 0.5%, and 1.0% of the incident energy in the wrong polarization.

to the tripler. Unless the laser is extremely well-polarized, high-conversion efficiency with type II/type II requires the use of high-damage-fluence polarizers.

Converter Crystal Design

One of the primary activities of the harmonic generation development plan is a thorough study of advanced frequency conversion designs that potentially offers increased dynamic range. The dynamic range translates directly into increased energy conversion efficiency for shaped pulses, and/or reduced sensitivity to beam parameters such as depolarization, wavefront quality, and pointing stability. Using both plane-wave and more sophisticated computer models of the harmonic generation process, we will compare the conversion efficiency and sensitivities of advanced harmonic generation schemes to those of the two-crystal baseline designs.

Such advanced designs include generalized quadrature and alternating-z schemes that utilize three or more crystals to reduce the sensitive dependence of the conversion efficiency to beam parameters such as depolarization, beam quality, and beam pointing stability. These designs utilize pairs of crystals that are oriented relatively to each other in order to cancel the effects of small variations in the polarization, pointing, or wavefront quality of the input beam. More complicated designs that utilize beam-splitting techniques to achieve mix ratio control will also be investigated. Whatever improvements these designs offer will have to be weighed against the increased number of crystals and/or additional optics and hardware necessary to implement them.

Concurrently, we will undertake examinations of the beam characteristics necessary for high-conversion efficiency, and of the engineering feasibility, costs, and difficulties of implementing the most promising of these advanced designs. Using the results of these studies we will design and execute experiments that will validate the results of these studies.

Crystal Properties Study

In order to provide more accurate input to our harmonic generation computer programs, we will measure crystal parameters that are relevant to frequency conversion. We need to study the patterns and levels of stress incorporated during growth and the resulting influence on phase matching in "real" crystals. We also need to understand the impact of nonideal crystal characteristics on frequency converter performance so that meaningful specifications can be established for harmonic generation crystals. We also need to understand the impact of surface finish quality on performance and downstream modulation.

Transverse Parasitic Control

As high-intensity, high-fluence laser light propagates through large aperture optics, Raman and Brillouin scattered light can experience high gain along directions transverse to the main beam path. This scattering geometry is shown schematically in Fig. 1.4-5. Because this scattered light propagates through a much smaller cross-sectional area than that of the main beam, the intensity and fluence of the scattered light can exceed that of the main beam before significant energy is extracted from the main beam. Consequently, the transverse stimulated Raman (SRS) and Brillouin (SBS)

Figure 1.4-5. Transverse stimulated scattering geometry in the tripling crystal. The intense third harmonic light that is created in the latter half of the tripling crystal drives stimulated scattering that can experience high gain along directions transverse to the main beam path.

scattered beams pose a serious damage threat to the tripling crystal and optics downstream from it.

A sophisticated computer code has been developed to model these stimulated scattering phenomena. However, critical parameter values, such as gain coefficients and phonon decay times, used by this code are not known to sufficient accuracy for us to adequately predict safe operating limits for the NIF. In addition to attempting to determine operating limits for the laser, we have also used this code to explore the effectiveness of techniques for suppression of these stimulated scattering parasitics. Both calculations made with this code and data from Nova experiments⁷ indicate that approximately 30 GHz of phase-modulated bandwidth applied to the fundamental beam is more than sufficient for complete suppression of transverse SBS. Our subaperture harmonic generation experiments indicate that this amount of bandwidth causes only a slight decrease in third harmonic generation efficiency.

In principle, phase-modulated bandwidth could also be used to suppress transverse SRS as well as SBS. Unfortunately, the Raman spectral lines are so broad as to require a

phase modulated bandwidth that is too large to propagate through the laser or convert efficiently to the third harmonic without heroic efforts. The results of preliminary spontaneous Raman scattering measurements, shown in Fig.1.4-6, indicate that a deuterated KDP tripling crystal reduces the Raman gain coefficient in the tripler by about a factor of two. Furthermore, the use of large bevels on the edges of the tripling crystal should limit the Raman scattered light to a single pass through the high-gain region of the crystal.

Even though we have very limited data on transverse SBS and SRS from Nova experiments, the Beamlet laser will provide the first opportunity to study high-efficiency third harmonic generation in the presence of transverse SBS and SRS. The Beamlet frequency converter has been designed to provide clear access to the edges of the tripling crystal, so these phenomena may be studied in more detail. Initially, the Beamlet tripling crystal will be fitted with fiber optic probes to monitor side scattered light levels as the third harmonic milestone is approached. For phase II of the Beamlet operation, a more sophisticated side scattered light diagnostic will be designed and activated to study these phenomena in sufficient detail to benchmark our computer code. Specifically, we plan to obtain sufficient data to do the following: 1) improve the accuracy of the stimulated scattering gain coefficients and phonon decay times, 2) study the effectiveness of applied bandwidth for suppression of transverse SBS, and 3) determine the usefulness of edge bevels for reducing the transverse SRS threat.

Mounting, Processing, and Thermal Issues

We will also study the mechanical engineering issues that are critical to the construction of large-aperture, high-fluence, high-efficiency frequency converters. The high

Figure 1.4-6. Spontaneous Raman scattering spectra of KDP crystals with various levels of deuteration. All of the samples were oriented as type II triplers. Use of 60% deuteration provides approximately a factor of two reduction in SRS gain.

aspect ratio of conversion crystals for large-aperture and high-intensity fusion lasers can lead to a significant gravitational deflection (as much as 160 μrad) when the crystals are held by the corners, as they currently are on Nova. We need to measure the amount of this deflection and its effect on phase matching. To minimize this problem, we need to develop stress-free mounting designs that hold crystals along their perimeter; our preliminary calculations indicate this reduces the crystal deflection to about 30 μrad for the doubling crystal. In order to clean, coat, and install a large number of frequency converter crystals, we need to develop reliable fixturing and high-volume processing equipment. Carefully designed beam apodizers must be developed for the frequency converter mount so that aperture loss is minimized. We must also develop a way to control the temperature of the conversion crystals to a level that eliminates any significant change in phase matching angle brought about by thermal variations.

Full Scale Performance Tests

In conjunction with the NIF Title I frequency converter design, a full-scale, full-performance frequency converter will then be designed, fabricated, and tested on Beamlet to provide validation information for completion of Title II design of the NIF frequency converter.

Schedule

Tasks 1.4.1 through 1.4.4 are scheduled to be completed by the end of the first quarter of FY96 so that the results of this work can be input to the NIF Title I frequency converter design task (see Fig. 1.4-7). Physics and engineering reports on advanced crystal converter design concepts will be completed in the third quarter of FY95. The results of crystal parameter measurements will be available in the fourth quarter of FY95, and crystal specifications will be determined by the start of FY96. A plan to control transverse parasitics and a report on mounting and processing will be completed in the first quarter of FY96.

WBS	CS&T activities and milestones	1995				1996				1997			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1.4	Frequency Conversion												
	Converter Crystal Design												
	Perform design study												
	Physics design study report												
	Transverse Parasitic Control												
	Design/fab SRS diagnostics												
	Perform/analyze SRS experiments												
	Mounting, Processing & Thermal Issues												
	Crystal holding study												
	Mechanical design & process report												
	Continuing development												

● = marker

◆ = milestone

Figure 1.4-7. Schedule for development activities for frequency conversion.

References

1. R. S. Craxton, "Theory of High Efficiency Third Harmonic Generation of High Power Nd-Glass Laser Radiation," *Optics Communications*, **34**, 474 (1980).
2. R. S. Craxton, "High Efficiency Frequency Tripling Schemes for High-Power Nd:Glass Lasers," *IEEE J. Quantum Electron.*, **QE-17**, 1771 (1981).
3. R. C. Eckardt and J. Reintjes, "Phase Matching Limitations of High Efficiency Second Harmonic Generation," *IEEE J. Quantum Electron.*, **QE-20**, 1178 (1984).
4. D. Eimerl, "High Average Power Harmonic Generation," *IEEE J. Quantum Electron.*, **QE-23**, 575 (1987).
5. M. A. Henesian, P. J. Wegner, D. R. Speck, C. Bibeau, R. B. Ehrlich, C. W. Laumann, J. K. Lawson, and T. L. Weiland, "Modeling of Large Aperture Third Harmonic Frequency Conversion of High Power Nd:Glass Laser Systems," *Modeling and Simulation of Laser Systems II*, SPIE Proceedings 1415 (1991); Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-104439 (1991).
6. P. J. Wegner, M. A. Henesian, D. R. Speck, C. Bibeau, R. B. Ehrlich, C. W. Laumann, J. K. Lawson, and T. L. Weiland, "Harmonic Conversion of Large Aperture 1.05- μ m Laser Beams for Inertial Confinement Fusion Research," *Applied Optics*, **31**, 6414 (1992).
7. J. R. Murray, J. Ray Smith, R. B. Ehrlich, D. T. Kyrazis, C. E. Thompson, T. L. Weiland, and R. B. Wilcox, "Experimental observation and suppression of transverse stimulated Brillouin scattering in large optical components," *J. Opt. Soc. Am. B*, **6** (12), 2402 (1989).

1.5 Diffractive Optics

Two types of diffractive optics are proposed for use in the NIF: 1) kinoform phase plates at the output of the system to control the beam irradiance profile on target and 2) weak surface-relief gratings to provide beam samples for diagnostic purposes. Although these components are reasonably well understood theoretically, the CS&T program must develop and test diffractive optics that meet the performance specifications and have the overall size, laser damage thresholds, and fabrication costs needed for the NIF. Making these optics for NIF will be a major advance for U.S. industry because the total area of diffractive optics needed for the NIF exceeds the area of all previously produced diffractive optics. This development obviously could have spin-off value into new diffractive-optics applications requiring either very large or many small pieces.

The baseline NIF specifications are to deliver the 3ω laser energy to the target at the focus of the 7-m focal length lens in a super-Gaussian profile that contains 95% of the energy in a 500- μm diameter spot and greater than 98% of the energy in a 600- μm diameter spot (far-field irradiance distribution). This beam profile has a superimposed speckle pattern whose fine spatial scale, is determined by the f -number of the focusing

L-17588-3

Figure 1.5-2. Examples of the far-field intensity distributions generated by an RPP (left) and a KPP (right). The central spot is about 500- μm diam in each case.

References

1. R. S. Craxton, "Theory of High Efficiency Third Harmonic Generation of High Power Nd-Glass Laser Radiation," *Optics Communications*, **34**, 474 (1980).
2. R. S. Craxton, "High Efficiency Frequency Tripling Schemes for High-Power Nd:Glass Lasers," *IEEE J. Quantum Electron.*, **QE-17**, 1771 (1981).
3. R. C. Eckardt and J. Reintjes, "Phase Matching Limitations of High Efficiency Second Harmonic Generation," *IEEE J. Quantum Electron.*, **QE-20**, 1178 (1984).
4. D. Eimerl, "High Average Power Harmonic Generation," *IEEE J. Quantum Electron.*, **QE-23**, 575 (1987).
5. M. A. Henesian, P. J. Wegner, D. R. Speck, C. Bibeau, R. B. Ehrlich, C. W. Laumann, J. K. Lawson, and T. L. Weiland, "Modeling of Large Aperture Third Harmonic Frequency Conversion of High Power Nd:Glass Laser Systems," *Modeling and Simulation of Laser Systems II*, SPIE Proceedings 1415 (1991); Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-104439 (1991).
6. P. J. Wegner, M. A. Henesian, D. R. Speck, C. Bibeau, R. B. Ehrlich, C. W. Laumann, J. K. Lawson, and T. L. Weiland, "Harmonic Conversion of Large Aperture 1.05- μm Laser Beams for Inertial Confinement Fusion Research," *Applied Optics*, **31**, 6414 (1992).
7. J. R. Murray, J. Ray Smith, R. B. Ehrlich, D. T. Kyrazis, C. E. Thompson, T. L. Weiland, and R. B. Wilcox, "Experimental observation and suppression of transverse stimulated Brillouin scattering in large optical components," *J. Opt. Soc. Am. B*, **6** (12), 2402 (1989).

1.5 Diffractive Optics

Two types of diffractive optics are proposed for use in the NIF: 1) kinoform phase plates at the output of the system to control the beam irradiance profile on target and 2) weak surface-relief gratings to provide beam samples for diagnostic purposes. Although these components are reasonably well understood theoretically, the CS&T program must develop and test diffractive optics that meet the performance specifications and have the overall size, laser damage thresholds, and fabrication costs needed for the NIF. Making these optics for NIF will be a major advance for U.S. industry because the total area of diffractive optics needed for the NIF exceeds the area of all previously produced diffractive optics. This development obviously could have spin-off value into new diffractive-optics applications requiring either very large or many small pieces.

The baseline NIF specifications are to deliver the 3ω laser energy to the target at the focus of the 7-m focal length lens in a super-Gaussian profile that contains 95% of the energy in a 500- μm diameter spot and greater than 98% of the energy in a 600- μm diameter spot (far-field irradiance distribution). This beam profile has a superimposed speckle pattern whose fine spatial scale, is determined by the f -number of the focusing lens. Recently, we proposed the use of specially designed kinoform phase plates (KPPs) for this purpose, as described below. In general, phase plates provide a more spatially homogeneous profile, which reduces the large-scale intensity variations present in the input beam. Thus, we refer to the KPPs as beam-smoothing optics. Beam smoothness has particular relevance for the NIF for direct drive, where the beam uniformity is a critical parameter in maintaining the hydrodynamic stability of the imploding capsule.

The surface-relief gratings provide a convenient method of obtaining a flexible, damage-resistant, stable, and uniform sample of a high-power beam. Beam-sampling gratings provide flexibility in choosing sample fractions and diffracted-beam direction, and they have a high damage threshold when fabricated in fused silica. Finally, when the diffracted beam is scattered in the forward direction, the sampling fraction is independent of surface contamination and is thus very stable.

1.5.1 Beam-Smoothing Optics

Most ICF research facilities around the world use spatial beam smoothing provided by binary random phase plates (RPPs),¹ which are transmissive optics that are fully tiled with regular regions (typically hexagons or squares) randomly chosen to introduce a phase delay of either 0 or π on the incident beam (see Figure 1.5-1). This randomization of the phase in the near field reduces the coherence of the laser beam, increasing the far-field spot size. The overall envelope of the focal spot is determined by the far-field diffraction pattern of a single RPP element with a superimposed speckle pattern caused by the interference among the far-field contributions from the various RPP elements. The size of the intensity speckles reduces to the diffraction-limited spot size of the full aperture ($2.44f \cdot \lambda$). For an aberrated beam, the far-field pattern is modified to be the electric-field convolution of the phase-plate pattern with the beam pattern alone (Schell's theorem). Although binary RPPs are relatively simple to manufacture, they are energy inefficient, achieving less than 85% energy efficiency into the central spot, far below the requirements for the NIF. In addition, the profile of the far-field spot is

Figure 1.5-1. Illustration of the phase screens for an RPP (left) and a KPP (right). For RPP, the black and white regions introduce a phase delay of 0 and p . The phase delay introduced in a KPP varies continuously between 0 (black) and $2p$ (white).

essentially constrained to a shape similar to an Airy function (a parabolically profiled central lobe surrounded by a series of rings).

To address these deficiencies, LLNL has recently developed continuously varying phase screens for ICF applications called kinoform phase plates.² KPPs are capable of producing far-field beam patterns with an arbitrary envelope that contains most (>95%) of the incident energy inside the desired region. We also have designed KPPs that meet the NIF specifications for both the far-field envelope profile and the energy content in it. A calculated phase contour of a KPP that produces a super-Gaussian top-hat profile is shown in Figure 1.5-1 and is compared with a binary phase pattern. A general similarity exists between the RPP and KPP phase profiles, but far more texture in the KPP pattern is evident. Notice that the current KPP design algorithm produces phase patterns which are modulo 2π . This leads to 2π phase jumps, which are apparent in Figure 1.5-1 as the sharp transitions between black and white regions.

The predicted far-field patterns for conventional RPPs and KPPs are compared in Figure 1.5-2. Notice the overall top-hat envelope for the KPP and the absence of the surrounding intensity rings. This leads to the previously mentioned higher efficiency of the KPP. This efficiency improvement is further illustrated in Figure 1.5-3, which shows the integrated intensity as a function of radius. This graph shows the predicted 95% efficiency into the region of interest, compared to a value around 83% predicted for the simple binary design.

Development issues. Despite the apparent attractiveness of KPPs, several fundamental theoretical and experimental issues remain in the CS&T development program. The first question is the limit on their theoretical efficiency. Are KPPs theoretically limited to 95%. That is, is the 5% inefficiency a consequence of pixelation in the theoretical calculations or the presence of 2π phase jumps, or is it simply related to the spot size compared to the diffraction limit? A second issue is the near-field modulation that KPPs

Figure 1.5-2. Examples of the far-field intensity distributions generated by an RPP (left) and a KPP (right). The central spot is about 500- μm diam in each case.

70-15-0894-3067pb01

Figure 1.5-3. Comparison of the far-field energy content for an RPP and a KPP. The RPP and the KPP designs are chosen to produce an $\sim 500\text{-}\mu\text{m}$ -diam central spot.

impose on the beam. Such modulation, which is produced both by the 2π phase jumps and the much smaller phase jumps associated with multilevel fabrication methods, can be damaging to downstream optics. To sidestep this issue, the NIF CDR has assumed that KPPs are fabricated on the target side of the debris shield. We would much prefer to develop KPPs that exhibit minimal near-field intensity modulation and can be positioned where we can avoid concerns about their surviving target debris and the possible cost of their frequent replacement.

An alternative to the present KPP approach is to develop phase-plate designs that do not have 2π phase jumps. Such designs are also being investigated at the Laboratory for Laser Energetics at the University of Rochester (J. Kessler, private communication). Such designs potentially could produce higher efficiency and less near-field modulation. Design codes for such phase plates will be developed during the remainder of FY94 and during FY95, as shown in Figure 1.5-4. Based both on theoretical predictions and the performance of small-scale demonstration parts in terms of efficiency and damage threshold, we would make a downselection during FY95 to a preferred KPP design for the NIF.

To assess the intensity-modulation problem theoretically for all designs, we will calculate the far-field intensity profiles at best focus, before and after best focus up to ± 5 cm in order to assess the evolution of the irradiance profile around the focal plane. We also will estimate intensity modulations at the position of the beam dump (5 m past focus) in order to assess the damage threat to the beam dump caused by such modulations. The placement of KPP on the output surface of the final focusing lens will be evaluated as a proposed alternative approach to minimizing the damage threat caused by intensity modulations. This requires identification of issues related to the placement of the KPPs on a curved surface. We will continue to assess the effect of beam aberrations (including the results of Beamlet measurements of beam phase) on the predicted far-field profiles using a KPP.

KPP fabrication methods. Although substantial capability exists within U.S. industry for manufacturing large binary phase plates, fabrication of the KPPs is only in the developmental stage. LLNL is developing a method for fabricating multilevel, quasicontinuous phase plates based on multimask exposure of photoresist following by chemical etching of fused silica in buffered HF.^{3,4} The masks are binary (on/off) and are produced by a commercial photoplotter. The first mask defines 0 and π phase regions. This is followed by subsequent etching steps that define $\pi/2$ and $3\pi/2$ regions, in addition to the 0 and π levels already defined. Additional steps of photoresist coating, mask exposure, and etching produces 2^n levels for n masks. With enough masks, a truly continuous profile can be approached, although calculation predicts that 5 masks and 32 levels should be ample.

Preliminary data suggest that, although this fabrication method will achieve the desired far-field profile, the energy efficiency may be below that required for the NIF. Measurements of a 12-cm-diam, 16-level KPP made in the above manner showed an efficiency slightly less than 90%. We attribute the failure of this preliminary piece to reach the 95% NIF goal to the lack of precision in mask alignment combined with errors in the level heights. During FY95, we will assess the sensitivity of KPP performance to fabrication errors in order to establish tolerances on these parameters. We also will

● = marker

◆ = milestone

Figure 1.5-4. Phase optics development schedule.

explore whether this general fabrication method can make "deep" phase plates that do not contain 2π phase steps. As soon as the design issues are better resolved, we will make a KPP of this type.

We also will fabricate small KPPs using direct-write techniques in which the photoresist is directly exposed by a light or electron-beam source without using a mask. The direct-writing technique can make truly continuous profiles or pixelated ones with up to 256 levels and with spatial resolution as low as $1\text{ }\mu\text{m}$. Multiple-mask techniques are easier to implement but require extreme care in preparing and accurately overlaying the sequence of the binary masks. Since each approach has advantages and disadvantages, small KPPs will be fabricated by both techniques and their optical performance will be evaluated. The desired approach will be determined based on the optical performance of these KPPs.

We will evaluate wet etching vs. reactive ion etching techniques for producing KPPs in fused silica. Wet etching is easy to implement but produces edge definitions typically on the order of a few micrometers. Although reactive ion etching, on the other hand, can produce extremely sharp features, it requires expensive facilitization for scaling up to NIF-size optics. Initially, we will carry out KPP fabrication by both methods to assess the benefits and risks associated with each approach.

Finally, we will investigate fabrication and efficient replication of KPPs on polymer films having high-UV laser-damage thresholds for use on NIF. The film would be applied to an optic, and the KPP pattern pressed into it. The advantage of this approach is the reduction in fabrication time, which significantly lowers cost.

Prototype KPP fabrication. A major goal is to fabricate a full-size NIF phase plate and to test its performance on the Beamlet under full-power operation using a planned far-field diagnostics station (see Section 1.13). This currently is planned for FY95 but could be delayed, depending on progress with small-scale KPP samples. We will fabricate a $40\text{-}\times\text{40-cm}$ KPP, using the fabrication technique selected after completing the developmental research on small apertures. If the multiple-mask method is used, then facilitization requires a large mask-making facility, a mask-aligning facility, and a large etching facility (wet etch or reactive ion etching). If the direct-write technique is selected, then facilitization requires a large x - y - z translation stage and an etching facility. For writing KPPs on lenses, either approach requires process modification.

1.5.2 Beam-Sampling Gratings

Characterization of high-power laser beams on NIF is critical to assessing the laser performance in terms of deliverable energy to the target, beam quality, beam uniformity across the aperture, etc. The current NIF baseline includes placing two low-efficiency diffraction gratings to pick off a small ($\sim 0.1\%$) sample of the incident beam for diagnostic purposes. One of the gratings is to be placed on the flat surface of a gas box window or 45° high-reflectivity mirror and will sample the beam at the fundamental wavelength of $1.053\text{ }\mu\text{m}$ in a backward-going grating order. The second grating is expected to be placed on the final focus lens to sample the frequency-converted third harmonic beam at $0.351\text{ }\mu\text{m}$ in a forward-scattered order. To accurately sample the laser beam, the grating efficiency has to be uniform across the aperture, and the 3ω grating must be etched into the curved surface of the focus lens. Both linear and focusing grating

samplers are envisioned for use at 1ω also. The scope of this effort is to develop design and fabrication technology for producing diffractive beam samplers (gratings) that can meet NIF specifications.

Current state of the technology. Low-efficiency diffraction gratings have been developed for beam sampling in high-average-power laser systems by major U.S. defense contractors. The development and application of this technology to other systems have been hampered by the release rules associated with these previously classified military laser programs and the proprietary nature of the fabrication techniques. Large-scale ($>1\text{-m}$) sampling gratings with circularly symmetric grooves have been fabricated in ZnS for use in the $3\text{--}5\text{-}\mu\text{m}$ range for high-average-power chemical lasers. Essentially no work has been done in the oxide multilayer structures that will be used at $1\text{ }\mu\text{m}$ on the NIF.

For 3ω sampling, the grating is etched directly into the fused silica focusing lens or the debris shield. Shallow, low-efficiency sampling gratings are now available at small scale ($\sim 1\text{ in.}$) from several, small, diffractive-optics companies (e.g., Gentec, Rochester Photonics). No manufacturer has demonstrated an ability to produce gratings of the required size, uniformity, and damage threshold required for the NIF.

LLNL is developing the world's largest holographic exposure capability for producing the high-efficiency, linear gratings required for the petawatt laser project. We will be capable of uniform holographic exposure of gratings up to 85 cm in diameter, exceeding the size requirements of NIF optics. The grating design codes available at LLNL for high-efficiency gratings are directly applicable to low-efficiency sampling gratings in oxide multilayer structures. LLNL has also developed the meniscus coating technology required for photoresist deposition on large optics and has expertise in the development of high-damage-threshold coatings and materials.

Technology required to achieve NIF specifications. Achieving the performance specifications of the NIF gratings requires substantial development in both the design and fabrication technology for low-efficiency sampling gratings. The objective of our technology-development plan is to produce a full-scale prototype of both a 3ω grating etched into fused silica and a 1ω sampling grating produced on a 45° $\text{HfO}_2/\text{SiO}_2$ multilayer-coated turning mirror. These gratings would have the same dispersion, sampling uniformity, and efficiency as required for the NIF. Their performance would be tested on the Nova or Beamlet laser. Once a successful prototype is developed, the fabrication technology would be transferred to U.S. industry for mass production. Development at LLNL would occur over FY95 and FY96 with technology transfer to industry during FY97. The work breakdown is as follows:

- Design linear and spherical gratings in fused silica for beam sampling at 3ω , analyze the sensitivity to beam aberrations and determine the uniformity requirements. We will design linear gratings in a $\text{HfO}_2/\text{SiO}_2$ multilayer high reflector for beam sampling at 1ω Littrow at an angle of 45° . This would be an option if it becomes unfeasible to place the 1ω sampling gratings on the window surface. We will calculate the uniformity requirements such that the diffracted wavefront adds no greater than a $\lambda/8$ distortion to the beam. Optics packages will be designed for NIF to support the sampling gratings.

- Fabricate small-aperture (15-cm) fused-silica linear and circular gratings by holographic exposure and lithographic processing. Wet- and reactive-ion-etching methods will be evaluated with regard to the uniformity, damage threshold, and cost. We will also evaluate the feasibility of fabricating gratings in PMMA layers deposited on fused silica as alternatives to fused-silica etched gratings. 1ω sampling gratings will be fabricated in a $\text{HfO}_2/\text{SiO}_2$ multilayer coating using holographic exposure followed by reactive-ion etching. The diffraction efficiency, damage threshold, sampling uniformity, and the diffracted wavefront will be measured. We also will fabricate polyimide gratings on $\text{HfO}_2/\text{SiO}_2$ multilayer and measure their diffraction efficiency, damage threshold, sampling uniformity, and the diffracted wavefront. Following the initial small-scale fabrication, the appropriate fabrication technologies for NIF will be identified.
- Fabricate full-scale prototype sampling gratings for use and validation on the Beamlet laser. For this activity, we will use the technology selected following the small-scale fabrication development. The performance of these gratings will be tested with regard to their diffraction efficiency, damage threshold, sampling uniformity, and the diffracted wavefront.

1.5.3 Other Diffractive Optical Components

Diffractive optical elements may provide means for shaping the near-field profiles of NIF beams.⁵ The near-field beam profile on NIF laser arms corresponds to a square super-Gaussian with sharp edges. Current NIF designs use extracavity beam shapers to tailor the near-field spatial profile. This reduces the energy input to the power-amplifier chain and introduces additional optical components to the beam, thereby increasing their complexity. In this part of the development effort, we propose to design, fabricate, and test intracavity DOE beam-shaping elements that would produce directly the required super-Gaussian intensity profile. This would eliminate the external-cavity beam-shaping components and permit the full output energy of the regenerative amplifier to be injected into the multipass-amplifier chain.

We will design the required kinoform phase screen for producing desired output profiles on NIF, assess the mode selection from the viewpoint of cavity gain, and adapt the designs for use in regenerative amplifiers. We also will assess performance sensitivity to the number of levels and other critical design features.

Fabrication of the diffractive optical beam shapers will be carried out during FY97 using lithographic techniques similar to those developed for KPP fabrication. We will fabricate full-scale beam-shaping elements and test their performance on the Beamlet laser. At this point, we will decide whether to include these beam shapers in the NIF design. If they are included in the final NIF design, full-scale production of the beam shapers will be undertaken by a U.S. manufacturer.

References

1. S. N. Dixit, I. M. Thomas, B. W. Woods, A. J. Morgan, M. A. Henesian, P. J. Wegner, and H. T. Powell, "Random Phase Plates for Beam Smoothing on the Nova Laser," *Appl. Opt.* **32**, 2543 (1993); Y. Koto, K. Mima, N. Miyanaga, S. Arinaga, Y. Kitogaura, M. Nakatsuka, and C. Yamanaka, "Random Phasing of High Power Laser for Uniform Target and Plasma Instability Suppression," *Phys. Rev. Lett* **53**, 1057 (1984).
2. S. N. Dixit, J. K. Lawson, K. R. Manes, H. T. Powell, and K. A. Nugent, "Kinoform Phase Plates for Focal Plane Irradiance Control," *Opt. Lett.* **19**, 417 (1994).
3. S. N. Dixit, I. M. Thomas, M. Rushford, R. Merrill, M. D. Perry, and H. T. Powell, "Fused Silica Kinoform Phase Plates for the Generation of Uniform Focal Profiles," to be published.
5. J. R. Leger, D. Chen and Z. Wang, "Diffractive Optical Element for Mode Shaping of a Nd:YAG Laser," *Opt. Lett* **19**, 108 (1994).

1.6 Pulsed Power Systems

Introduction

Advances in pulsed power technology are needed to achieve the cost goals for the NIF power conditioning system. The design approach used for previous laser ICF facilities (e.g., Nova) is adequate from a technical performance perspective, but its cost exceeds the NIF allocation. A cost reduction of approximately 30% (\$20M) relative to using currently available technology (Beamlet) will result from the successful completion of this development program.

In many respects, the NIF pulsed power system represents an evolutionary step in the design of pulsed power systems for solid-state laser ICF facilities. Table 1.6-1 illustrates this by comparing NIF system parameters with those of previous facilities.

The NIF system's stored energy is several times larger than Nova's, but the total number of capacitor modules is nearly the same. Flashlamp current and capacitor energy have increased steadily as pulsed power system designs have evolved. Recent systems have included flashlamp preionization to increase laser efficiency.

A simplified schematic of the NIF module is shown in Figure 1.6-1. The LLNL module schematic is shown as a comparison. The NIF design uses fewer components and is less expensive to assemble than the Nova design. The simple NIF circuit approach relies on a single switch to discharge a large, parallel capacitor bank into a large transmission line. The transmission line transports the energy to a junction box near the laser amplifier, which distributes current to a number of flashlamps operated in parallel. Inductors in the junction box act as ballast to ensure current sharing among the lamps. A charging power supply and embedded computer controller are included within the capacitor assembly enclosure. A conceptual layout of the module is shown in Figure 1.6-2.

The increased stored energy per module, simplified circuit topology, increased flashlamp current, and larger capacitors of the NIF design drive the development goals. The pulsed power development is divided into five subelements: high-current switches, high-density capacitor arrays, pulsed-power components, system integration and prototyping, and continuing development. The following sections describe the development requirements and plans.

Table 1.6-1. Comparison of NIF system parameters with those of previous facilities.

	Bank energy stored (MJ)	Module size (MJ)	Number of modules	Module current (kA)	Flashlamp current (kA)	Capacitor energy (kJ)	Preionization
NIF	400	1.6	240	500	25	83	Yes
Omega Upgrade	42	0.4	120	120	7	24	Yes
Beamlet	13	0.4	32	100	13	52	Yes
Nova	60	0.6	125	100	6	12	No
Shiva	25	0.5	70	120	5	5	No

70-15-0794-2851pb01

Figure 1.6-1. Simplified schematic of the NIF pulsed power system.

The development of low-cost, reliable, pulsed power components benefits US Industry and the laser ICF Program in areas where similar technologies are applied. For example, high-energy flashlamp systems are now used in commercial systems to strip paint and sterilize food. Although these systems are much smaller than the NIF, the NIF design is modular, and the reliability requirements are similar to those required for a commercial system. Another commercial application requiring similar-size switches and transmission lines to the NIF is pulsed power mining and rock crushing. Finally, the development of a switch that meets NIF requirements is desirable in the design of electromagnetic launchers for defense applications.

1.6.1 High-Current Switches

Modular designs are used for large capacitor banks, such as those in laser ICF facilities, to minimize initial construction costs, assembly, and maintenance costs. The cost of the pulsed power system decreases with increased energy stored and delivered by each module. The maximum energy per module is limited by the peak current capability of

40-00-0394-0758.pub

Figure 1.6-2. Conceptual layout of the capacitor module, electrical substation, laser amplifier, and connecting transmission lines.

the switch because peak current increases in proportion to stored energy. Therefore, improved switches are a primary goal of the development program.

Ignitron switches traditionally have been chosen for laser ICF capacitor bank designs. They have the attractive characteristics of long life and high charge-transfer capacity. These characteristics result from the ignitron's self-healing liquid-mercury cathode. Existing ignitron designs have demonstrated reliable operation up to 200 kA, while the NIF module requires a 500-kA switch. In addition, voltage ratings for individual ignitron tubes typically are limited to 13 kV, so two tubes must operate in series to switch the 24-kV NIF capacitors. Vacuum or pressurized spark gaps, or solid-state

devices, represent potential alternatives to larger ignitrons as the NIF switch technology. Progress has been made recently in developing all of these technologies, but to date, no switch design has demonstrated all of the NIF requirements. The requirements and technology status are summarized in Table 1.6-2.

The goal of the switch development program is to determine the best technology from this list and to develop a switch that meets the NIF requirements based on that technology. The development program requires a combination of testing, analysis, and design. Ongoing work will determine which two or three of the five candidate technologies warrant further investigation and development. A test facility that produces current pulses that exceed the NIF requirements will be constructed to test the promising designs. Test facilities at switch vendors may be used to collect additional data on some switches once the facility and test procedures are approved by NIF personnel. A series of test cycles and design iterations will produce the NIF prototype switch. The field of

Table 1.6-2. Switch technology requirements and status.

Switch technology	Source(s)	Peak current (kA)	Operating voltage (kV)	Lifetime (shots)	Comments
NIF requirements		500	24	10,000	1.6-MJ capacitor module, 360- μ s pulse width
Size "D" ignitron	Richardson Electronics, English Electric Valve Ltd.	120	12	20,000	Switches used on Nova and Beamlet, 2 in series, at 22 kV, 50 coulombs.
Size "E"	Richardson Electronics, English Electric Valve Ltd.	230	12	1,000	Limited life test data is available. Performance at 500 kA is unknown.
Vacuum spark gaps	Maxwell/Russian design (TVS-40)	140	25	7,500	Several in parallel required for 500 kA. Possible prefire problem at 24 kV. Limited data.
Pressurized air spark gaps	Physics International (ST-300A)	600	50	700	Series-injection trigger requires isolation. Requires frequent cathode replacement.
Solid state devices	Russian reverse-switched dynistor (RSDs), Asea Brown Boveri	200	2 kV per device	Unknown	Stacks of devices needed. RSD's require injection trigger. Cost may be too high.

candidate technologies will be narrowed so that a technology decision can be made prior to the third test cycle. Two additional cycles will refine and validate the design and qualify vendors.

Ignitrons are a leading candidate because they have been used successfully in previous laser ICF systems, and because recent progress has increased their peak current capacity to near NIF levels. Recent modifications have included reducing the anode-cathode spacing, increasing the anode-wall spacing, and using an annular anode with the ignitor centered inside. These changes prevent the arc from transferring from the mercury cathode to the wall. The transfer releases impurities that coat the ignitor and inhibit triggering. A de-mountable design with these properties was designed and tested at LLNL (see Fig. 1.6-3).¹ Ignitron vendors have developed sealed ignitron designs incorporating these features, which are now commercially available. These represent a step beyond the size-E switches in Table 1.6-2. Limited test data exist on ignitrons with these new designs. Ignitrons have two major disadvantages. First, the cathode material is mercury, which is highly toxic. This represents a waste-disposal issue for failed switches and at the NIF decommissioning. This also represents a personnel safety hazard if a tube fails and leaks mercury. The second problem is the limited vendor base for ignitrons. There is only one ignitron vendor (Richardson Electronics), and the shrinking world ignitron market causes them to commit to future production only one year at a time. Thus, it is prudent to investigate alternatives to ignitrons.

Vacuum spark gaps (from Maxwell Laboratories, Inc., USA or Thomson, France) are also a candidate NIF switch. These devices are presently limited to 100 kA, so larger devices or parallel operation will be required for the 500 kA NIF application. The currently available models have high rates of prefire above 20 kV, making them unacceptable for the 24-kV NIF bank. However, small design modifications could extend the

70-10-0594-2535.pub

Figure 1.6-3. Cross-section of the de-mountable hollow-anode (DM-HA) ignitron.

reliable operating voltage range. Additional design work, test data, and detailed cost estimates are needed to determine whether vacuum spark gaps are a viable alternative for the main NIF switch. The NIF preionization system switch requirements are 100 kA at 20 kV. The vacuum gap may be ideal in this NIF application.

A high-pressure air spark gap (ST-300A) developed at Physics International (PI), Inc., meets the NIF current and voltage requirements. The primary limitation of these devices is that electrode erosion shortens their lifetime by changing the gap dimensions. The current version of these devices would require replacement of the electrode after only 700 shots, or less than one year of NIF operation. PI engineers believe that this lifetime could be extended by designing the switch with an adjustable gap so that electrode erosion could be compensated for by moving the electrodes closer to each other. This concept, however, has not been demonstrated on large switches. Another possibility is that a "quick service" version of the device could be developed in order to minimize the NIF switch maintenance time. A second problem with the PI switch is that it requires a high voltage (70-kV) pulse across the device for reliable triggering, compared with the "third electrode" triggering on the ignitrons and vacuum gaps. Additional components, such as saturable inductors, would be required to isolate this short pulse from the other NIF pulsed power components while the switch is triggered. These issues and potential solutions will be explored during the development program.

Recent developments in power semiconductor technology make solid-state switches an alternative for the NIF. Peak currents as high as 200 kA, for NIF pulse lengths, have been reported for a reverse-switched-dynistor (RSD) switch developed in Russia. Similar but smaller switches are available from Brown Boveri in Switzerland. Series-parallel arrays would be required to reach NIF voltage and current requirements. Arrays of solid-state devices would have potentially long life, and require low-trigger energy. However, the cost of these arrays may be prohibitive for the NIF application. The reliability of the Russian source of these devices is also unknown. Additional investigation is needed to determine whether solid-state arrays are a viable alternative for the NIF.

1.6.2 High-Density Capacitors

The NIF will use a new technology, first utilized on Beamlet, for the energy storage capacitors. The NIF capacitors will have a self-healing, metallized dielectric system, compared with the discrete foil-film/paper capacitors typically used in the past. Figure 1.6-4 illustrates the differences in construction and failure modes between the two capacitor designs. In a discrete foil capacitor, a single dielectric system fault results in a discharge causing a catastrophic failure that permanently shorts the capacitor. In a self-healing capacitor, a fault in the dielectric system is automatically cleared, resulting in an insignificant degradation in capacitance and performance. Thousands of fault/healing events may occur before the capacitance is reduced enough to substantially degrade capacitor performance. Typically, a 5% loss in capacitance is used to define "failure" of a self-healing capacitor.

Recently developed self-healing capacitors provide significant advantages over traditional designs in large capacitor banks such as in the NIF. The soft failure mode virtually eliminates capacitor infant mortality, thus improving system reliability. To identify "failing" capacitors before they affect system operation, the gradual capacitance

70-15-0794-2850pb01

Figure 1.6-4. Comparison of metallized-dielectric and film-foil capacitor designs.

loss can be monitored by measuring output current over time. Unplanned maintenance time is reduced since operators can wait until scheduled maintenance periods to replace weak capacitors. The volumetric energy density of metallized-dielectric capacitors is roughly twice that of discrete-foil capacitors, so less space and mounting hardware is needed. They also reduce procurement costs because the capacitors need not be overdesigned to meet system lifetime and reliability requirements. For example, the Nova capacitor bank uses capacitors with a characteristic life of over 200,000 shots to achieve a 100-shot mean time between failures (MTBF) over a 5000-shot lifetime. This overdesigning is necessary with discrete foil capacitors to reduce the rate of catastrophic infant failures to an acceptable level. Since catastrophic infant failures do not occur with self-healing capacitors, the dielectric system can be designed to last only as long as the facility.

Activation of the 13-MJ Beamlet capacitor bank was recently completed using metallized-dielectric capacitors. A statistical analysis of the qualification and acceptance test data from these capacitors, extrapolated to the NIF system, indicates that similar performance of the NIF capacitors would provide adequate reliability. The Beamlet has fired over 1000 shots to date with no measurable capacitance loss. Operation of the Beamlet over the next several years will provide valuable information about the performance of metallized-dielectric capacitors in a large bank.

Since the Beamlet capacitor design demonstrates the self-healing capacitor technology planned for the NIF, the primary development goal is to reduce the capacitor cost. The development program will achieve cost reductions in three ways: increased competition among vendors, increased energy per capacitor, and careful matching of the capacitor design to the lifetime requirements of the NIF. These goals will be achieved, in

confidence in the designs. The results will be used to develop a final specification for the cable.

Charging supplies. Each NIF capacitor module will contain a dedicated charging supply to convert the 480-V primary power to a constant current that charges the capacitors to 24 kV. A 50-kJ/s supply is required to charge the module in less than 40 s to minimize the time the capacitors are under stress, which is desirable to prolong their lifetime. Compact and efficient solid-state switching power supplies are commercially available with ratings up to 12 kJ/s, powered from 200- to 360-V lines. These can be operated in parallel to achieve increased charge rates. The challenge for the NIF is to develop supplies that operate reliably from 480 V, at 50 kJ/s, without the cost of many parallel units.

A prequalification test cycle will provide the power supply vendors with the incentive to develop a 50-kJ/s supply for the NIF. Technology prototypes from several vendors will be tested to ensure that the supplies meet all NIF requirements. The charging supply isolation circuit will also be validated during these tests. A final NIF charging supply specification will then be developed, prior to vendor qualification.

Damping resistors. Laser ICF pulsed power systems traditionally have used fuses to isolate capacitors within a module from one another during faults. Fuses are unreliable (they frequently re-strike) and expensive, and they generate high-voltage transients which may damage other components. In the NIF design, we will use damping resistors in place of fuses as the isolating component. A low-value (40-m Ω) resistor will be connected in series with each capacitor output. During normal operation, this resistor represents only a small (~6%) energy loss. However, during a capacitor fault, the damping resistor in series with the shorted capacitor limits the current in neighboring capacitors to safe levels and dissipates nearly all of the 1.6 MJ stored in the module. A small amount of inductance added to this resistor (3 to 10 μ H in series) limits capacitor currents during faults in the buswork or transmission line. The resistor would be designed for indefinite lifetime during normal operation, or bus faults. The resistor in series with a faulted capacitor presumably would be damaged permanently and replaced after a fault. Conceptually, a few pounds of stainless steel with the proper dimensions is adequate for the resistor element. The development program will address force bracing, insulation, packaging, inductance, and low-cost assembly of these devices.

Development of the damping resistors will require circuit modeling, design analysis, prototyping, and testing. The resistor will be a "build-to-print" component based on a NIF design because no commercially available devices currently meet the NIF cost and performance requirements. Several designs are under consideration, including folded sheets and coiled rods of stainless steel. Analysis is needed to determine if the configurations of either approach will result in the desired resistance, inductance, physical size and shape, and reliability. The analysis will also address force bracing. Electromagnetic forces are of particular concern during capacitor faults, when both the resistor current and dissipated energy are the highest. Full-energy prototype testing of candidate designs will be performed using the capacitor module test bed. The test results will be used to determine the exact resistance and inductance values desired and iterate the resistor design to meet the NIF requirements.

Figure 1.6-4. Comparison of metallized-dielectric and film-foil capacitor designs.

loss can be monitored by measuring output current over time. Unplanned maintenance time is reduced since operators can wait until scheduled maintenance periods to replace weak capacitors. The volumetric energy density of metallized-dielectric capacitors is roughly twice that of discrete-foil capacitors, so less space and mounting hardware is needed. They also reduce procurement costs because the capacitors need not be overdesigned to meet system lifetime and reliability requirements. For example, the Nova capacitor bank uses capacitors with a characteristic life of over 200,000 shots to achieve a 100-shot mean time between failures (MTBF) over a 5000-shot lifetime. This overdesigning is necessary with discrete foil capacitors to reduce the rate of catastrophic infant failures to an acceptable level. Since catastrophic infant failures do not occur with self-healing capacitors, the dielectric system can be designed to last only as long as the facility.

Activation of the 13-MJ Beamlet capacitor bank was recently completed using metallized-dielectric capacitors. A statistical analysis of the qualification and acceptance test data from these capacitors, extrapolated to the NIF system, indicates that similar performance of the NIF capacitors would provide adequate reliability. The Beamlet has fired over 1000 shots to date with no measurable capacitance loss. Operation of the Beamlet over the next several years will provide valuable information about the performance of metallized-dielectric capacitors in a large bank.

Since the Beamlet capacitor design demonstrates the self-healing capacitor technology planned for the NIF, the primary development goal is to reduce the capacitor cost. The development program will achieve cost reductions in three ways: increased competition among vendors, increased energy per capacitor, and careful matching of the capacitor design to the lifetime requirements of the NIF. These goals will be achieved, in

part, through a series of prequalification and qualification tests of capacitors from potential NIF vendors.

There are only two proven sources of self-healing metallized dielectric capacitors: Aerovox, Inc., and Maxwell Laboratories, Inc. The prequalification testing will encourage other vendors (such as General Electric) that are developing capacitors with this technology to focus on the NIF application, thus increasing vendor competition.

The NIF design requires a capacitor that stores 83 kJ, a 60% increase from Beamlet. This is a relatively low-risk development because the energy density will remain the same but the individual capacitor volume will be 60% higher for the NIF. This change reduces both production and assembly costs per joule of capacitor energy for the NIF. Production costs are reduced because the larger capacitor size reduces the number of capacitors that must be handled, oil-impregnated, assembled, tested, and documented. Module assembly costs are reduced because fewer capacitors must be installed and connected for each module. Handling the larger capacitors is not expected to be significantly more difficult than for the Beamlet capacitors since lifting and handling fixtures and fork-lift operations are required in either case. The capacitors produced for the prequalification tests will validate these assumptions for the 83-kJ capacitors.

Prequalification testing will allow the capacitor designs to be carefully matched to the NIF requirements. The soft-failure characteristics mean that adequate system reliability is achieved with a capacitor lifetime that is 1.5 to 2 times the bank life, rather than 10 to 20 times as with film-foil capacitors. Since the failure mode is a gradual reduction in capacitance, the capacitors that fail early can be replaced during planned maintenance times so that the NIF operating schedule is not affected. Prequalification test data will allow the vendors to validate capacitor lifetime predictions and increase confidence in their designs. This approach will reduce vendor risk and, therefore, the cost of the NIF capacitors.

1.6.3 Pulsed Power Components

In addition to the switches and capacitors, several other pulsed power components must be developed to achieve the NIF cost goals. These components include inductors, transmission lines, flashlamp cables, charging supplies, and damping resistors. Whereas designs already exist that meet the NIF performance requirements for these components, they do not meet the cost goals. Because of the large quantities required, any innovation that reduces the cost of these parts will pay off substantially for the NIF.

Ballast inductors. Ballast inductors, located in the junction box near the laser amplifier, enhance flashlamp triggering reliability, ensure current sharing, limit fault currents, and help determine the pump pulse length. With over 4000 inductors in the system, their unit cost is important. Development is needed to extend the peak current capacity of existing designs without sacrificing economy. The Nova inductors operate at 6 kA, whereas the Beamlet inductors operate at 13 kA. The NIF operating current is 25 kA, with fault currents up to 100 kA. Because electromagnetic forces scale with the square of the current, a significant increase in strength is needed compared with Beamlet. In addition, a compact design is desirable because space for junction boxes near the amplifiers is limited. Compact, rugged, low-cost force bracing and insulation systems will be investigated.

Ballast inductors will be developed in partnership with industry. A large vendor base exists with expertise in the design of custom inductors and transformers. These vendors will be given a list of technical requirements for the NIF inductors and asked to submit a design and cost estimate. The vendors will be encouraged to innovate with the goal of achieving a reliable, low-cost design. The most promising of the responsive vendors will then be asked to provide samples for prequalification testing. The tests will allow the vendors and NIF personnel to gain confidence in the inductor designs, gather data to predict reliability, and determine the most promising size and configuration for the inductors. The test data will be used to develop the final inductor specifications, from which the vendors will produce samples for qualification tests during Title II design.

Transmission lines and flashlamp cables. A transmission line delivers the 500-kA output pulse from the switch to the laser amplifier. It must have low inductance, resistance, and cost. Previous laser ICF systems have used many coaxial cables in parallel, but the installation and termination of these cables result in large costs for labor and hardware. To reduce these costs for the NIF, we plan to use a single (or a few) coaxial transmission line(s) for each bank module. If a single, large line is used, the conductors will be commercially available aluminum pipes, and the insulation will be PVC pipes. Multiple torsion spring contacts will be used to ensure a reliable, high-current connection at the joints. Alternately, a few, large, commercial coaxial cables could be used in parallel for each module. Each cable, carrying 100 to 250 kA, would be flexible enough to bend with a 1-m radius. Whereas the single, rigid line was assumed in the NIF CDR cost estimate, flexible lines simplify routing to the amplifier because of higher packing density and may be a less expensive solution overall. In either case, the insulation system, force handling, connections, and assembly time will be addressed during development.

The first step in developing the transmission line is to determine whether rigid or flexible cables will be used. This decision will be based on the anticipated total cost of each approach, including procurement of line(s), assembly, installation, termination, support, and maintenance. Samples of each approach will be designed, fabricated, and tested to accurately estimate the costs and validate the performance of each design. The rigid lines will be assembled in-house, whereas the flexible lines will be fabricated by vendors. A second design-and-testing iteration on the selected approach will result in the data necessary to complete the specification for the NIF transmission line and terminations.

Substantially smaller, high-voltage, twisted-pair cables connect the junction box output to the flashlamps in the amplifier. These cables must be flexible, have low resistance, and carry the 25-kA flashlamp current. A smaller version of this cable, developed for the Beamlet facility, represents a starting point for the development of this component. Maintaining flexibility with adequate force bracing and low cost is the primary challenge.

A preliminary flashlamp cable specification will be developed to allow vendors to design cables for prequalification testing. The voltage, current, flexibility, and force-handling requirements will be specified. Low-cost crimp termination capability will be specified. Vendors with promising designs will provide samples for testing to gain

confidence in the designs. The results will be used to develop a final specification for the cable.

Charging supplies. Each NIF capacitor module will contain a dedicated charging supply to convert the 480-V primary power to a constant current that charges the capacitors to 24 kV. A 50-kJ/s supply is required to charge the module in less than 40 s to minimize the time the capacitors are under stress, which is desirable to prolong their lifetime. Compact and efficient solid-state switching power supplies are commercially available with ratings up to 12 kJ/s, powered from 200- to 360-V lines. These can be operated in parallel to achieve increased charge rates. The challenge for the NIF is to develop supplies that operate reliably from 480 V, at 50 kJ/s, without the cost of many parallel units.

A prequalification test cycle will provide the power supply vendors with the incentive to develop a 50-kJ/s supply for the NIF. Technology prototypes from several vendors will be tested to ensure that the supplies meet all NIF requirements. The charging supply isolation circuit will also be validated during these tests. A final NIF charging supply specification will then be developed, prior to vendor qualification.

Damping resistors. Laser ICF pulsed power systems traditionally have used fuses to isolate capacitors within a module from one another during faults. Fuses are unreliable (they frequently re-strike) and expensive, and they generate high-voltage transients which may damage other components. In the NIF design, we will use damping resistors in place of fuses as the isolating component. A low-value (40-m Ω) resistor will be connected in series with each capacitor output. During normal operation, this resistor represents only a small (~6%) energy loss. However, during a capacitor fault, the damping resistor in series with the shorted capacitor limits the current in neighboring capacitors to safe levels and dissipates nearly all of the 1.6 MJ stored in the module. A small amount of inductance added to this resistor (3 to 10 μ H in series) limits capacitor currents during faults in the buswork or transmission line. The resistor would be designed for indefinite lifetime during normal operation, or bus faults. The resistor in series with a faulted capacitor presumably would be damaged permanently and replaced after a fault. Conceptually, a few pounds of stainless steel with the proper dimensions is adequate for the resistor element. The development program will address force bracing, insulation, packaging, inductance, and low-cost assembly of these devices.

Development of the damping resistors will require circuit modeling, design analysis, prototyping, and testing. The resistor will be a "build-to-print" component based on a NIF design because no commercially available devices currently meet the NIF cost and performance requirements. Several designs are under consideration, including folded sheets and coiled rods of stainless steel. Analysis is needed to determine if the configurations of either approach will result in the desired resistance, inductance, physical size and shape, and reliability. The analysis will also address force bracing. Electromagnetic forces are of particular concern during capacitor faults, when both the resistor current and dissipated energy are the highest. Full-energy prototype testing of candidate designs will be performed using the capacitor module test bed. The test results will be used to determine the exact resistance and inductance values desired and iterate the resistor design to meet the NIF requirements.

Flashlamp connectors. High-current, quick-disconnect connectors are required at the interface between the power conditioning system and the flashlamp cassette in the laser amplifier to allow quick removal of the cassette for flashlamp maintenance. These connectors must carry the 25-kA flashlamp pulse routinely and occasionally fault current roughly four times larger. We plan to use larger versions of commercially available, multiple-contact, torsion-spring connectors used in previous laser ICF facilities. These connectors are designed for continuous utility-power applications; however, their performance must be verified for NIF operating conditions. In addition, low-cost termination and mounting procedures and tools need to be developed.

Embedded controls. Each NIF capacitor assembly will have an embedded controller (EC) to perform local control and diagnostic functions and communicate with the integrated control system. The EC will control and monitor the charging supplies, safety systems, and triggering system; it will provide flashlamp-current diagnostics. The EC concept has been demonstrated on the Beamlet, but with different hardware and greater physical separation from the high current switches than in the NIF. In addition, the NIF module will create a more severe EMI environment compared to Beamlet or Nova because of its higher output current.

The NIF Conceptual Design Report describes the conceptual design for the embedded controller. The primary goals of the development program are to demonstrate adequate performance in the NIF environment (e.g., similar controls hardware, EMI levels, and inputs). A prototype embedded controller will be assembled and tested in the prototype module. The effectiveness of the controller EMI enclosure will be validated; effective shielding and filtering techniques will be developed. Prototype flashlamp current detectors and electronics will demonstrate the accuracy required for the NIF. Data-transfer rates to the central control system will be extrapolated from measurements on the prototype.

1.6.4 Prototyping and System Integration

The NIF design reduces cost by reducing the number of parts and simplifying the system assembly and installation. Charging and damping resistors required for each capacitor in the Nova design are eliminated in the NIF circuit. High-voltage fuses used on Nova are replaced by resistors in the NIF design. Single-bushing capacitors can be used in the NIF design (compared with the Nova two-bushing capacitors) because one capacitor terminal is grounded. In the Nova design, a separate safety-dump resistor is required for each capacitor because charge resistors and fuses isolate the capacitor circuits from each other. The NIF design, with parallel-connected capacitors, can be discharged with a redundant set of high-energy resistors and switches to enhance personnel safety and reduce cost.

The NIF circuit design, while less expensive than previous systems, carries additional technical risk associated with parallel flashlamp operation and circuit fault handling. Reliable triggering of flashlamps is critical for parallel flashlamp operation since the module energy will be shared evenly among those lamps that trigger. If only a few flashlamps trigger (out of 40 per capacitor module), the energy ratings of those lamps may be exceeded, resulting in a catastrophic (explosive) flashlamp failure. If the fault

energy is high enough to destroy the blast shield, damage to the laser slabs could result. Thus reliable triggering and current sharing is essential.

A simplified schematic of the flashlamp triggering circuit for the NIF design is shown in Fig. 1.6-5. The flashlamps are triggered by a pulse generated by the resonance of the ballast inductor with a peaking capacitor located in the junction box. This ring-up circuit creates a short (5- μ s) pulse with a peak amplitude nearly twice the capacitor bank voltage. A trigger pulse is generated automatically whenever either the preionization switch or main switch is closed. The ballast inductors provide isolation between flashlamp circuits so that a short circuit at one flashlamp does not affect the trigger pulse to the remaining lamps. This triggering circuit has been validated with modeling and experiments with Nova flashlamps. Figure 1.6-6 shows Nova flashlamp triggering delay as a function of capacitor charge voltage. It shows that the delay increases uniformly as charge voltage is decreased and that triggering becomes unreliable below 10 kV. Additional experiments must be performed with the NIF-sized flashlamps to verify that they have similar triggering performance to the 1.5-cm bore Nova flashlamps.

The capacitor modules must be designed to handle occasional faults in the pulse power circuitry without severe damage or prolonged repair time. Shorted capacitors or a short circuit in the transmission line are the fault modes of primary concern. Although capacitor faults are unlikely with self-healing capacitors, this possibility must be considered due to the large amount of energy stored in the parallel bank. Damping resistors in series with each capacitor are designed to limit the current in neighboring capacitors in

40-00-0394-0841.pub

Figure 1.6-5. Flashlamp triggering circuit diagram.

40-00-0394-0635.pub

Figure 1.6-6. Nova flashlamps triggering delay as a function of capacitor charge voltage. The delay increases uniformly as charge voltage is decreased, and triggering occurs down to 10 kV.

the event of a capacitor fault. Series inductance added to these resistors should limit capacitor currents to safe levels during a bus fault. Preliminary experiments at reduced voltage and energy confirm model predictions that this method of isolation is effective. Experiments at full module energy and voltage are needed to confirm the fault-tolerance of the design.

The remaining technical issues with the proposed NIF circuit topology will be addressed by a coordinated program of modeling and testing. Detailed circuit models will be used to predict normal and fault-mode operation and to optimize the circuit design. A 1.6-MJ testbed, built with Beamlet capacitors, will be used to simulate normal and fault-mode operation and to validate the circuit models. Specifically, the testbed will address the following technical issues:

- Transient circuit behavior during normal and fault operation.
- Circuit model validation.
- Flashlamp triggering reliability.
- Damping resistor testing.
- Preionization circuit validation.
- Low-cost, high-current connection techniques.

- High-current transmission-line testing.
- Control and diagnostic concept validation.

Components from other areas of the development program (e.g., switches, resistors, inductors, cables) will be incorporated into the testbed as they become available.

Once these technical issues have been addressed in the testbed and modeling, a NIF technology prototype module will be constructed using the current generation of components from the development program, including damping resistors, transmission lines, junction box, inductors, and controls. The prototype will be thoroughly tested to validate the NIF circuit design under normal and off-normal conditions. Assembly fixtures and procedures will be developed and tested during prototype assembly. The prototype NIF capacitors and switch will be installed and tested in the module when they are available. The design validation testing will verify that all system design requirements are satisfied, with prototypes of all module components. Completion of the prototype module validation testing will allow final specifications and drawings for NIF hardware to be completed. Testing will continue on the prototype module during Title II and Title III design. This additional testing will allow optimization of assembly and installation procedures; the additional testing will resolve issues that may arise during the procurement process.

Development plan. The Gantt chart in Figure 1.6-7 illustrates the major tasks and time line for the pulsed power development program. The four major development activities, organized by the WBS, occur in parallel for two years. During that period, technology prototypes are fabricated and delivered to the prototyping activity.

Component pre-qualification testing will be performed in parallel with tests on the module architecture. Design validation tests will then be performed using the prototype module. The lengthy test time and required design iterations make switch development the critical-path activity. Final validation tests for the switch will occur in parallel with the module design validation tests.

References

1. R. Kihara, D. B. Cummings, K. S. Leighton, and A. P. Shulski, "Commercial High Current Ignitron Development," Proc. 7th IEEE Pulsed Power Conf., Monterey, CA, June 1989, pp. 18-21 (also Lawrence Livermore National Laboratory, UCRL-100358, Rev. 1 (1989)).

● = marker

◆ = milestone

Figure 1.6-7. Pulsed power systems development schedule.

1.7 Laser Diagnostics

In the laser diagnostics area, we will develop advanced capabilities to precisely diagnose the 1ω and 3ω laser beam in ICF facilities. Our development is divided into four general categories, as specified in Sections 1.7.1 through 1.7.4 below. Section 1.7.1 through 1.7.3 address component development, while 1.7.4 addresses system integration.

1.7.1 Full-Aperture Beam Sampling

There are two methods of sampling beams for laser diagnostics that have been proposed at the 40×40 -cm aperture size required by the NIF. The first uses large area diffraction gratings to sample the beam. The second uses partially antireflective coatings. It will be necessary to demonstrate that gratings can be made at the required aperture size, with adequate optical damage resistance, and stability and uniformity of sampling efficiency. Sampling gratings fall under the category of diffractive optics development discussed earlier in Section 1.5. Gratings will be tested as part of the 1ω and 3ω output sensor diagnostic systems performance tests discussed in Section 1.7.4.

In this section, we focus our discussion on the development and testing of anti-reflection coatings for beam sampling (with or without gratings on the surface), and testing of full-aperture, high-damage-threshold calorimeters.

Partially antireflective (A/R) coatings for beam sampling. The NIF laser diagnostic system requires A/R coated surfaces with a controlled low-reflectivity and high stability for beam sampling. In the NIF CDR design the 1ω output sensor uses a back reflection from an optical surface with both a diffraction grating and an A/R coating, and in this case both the grating and the A/R coating must be adequately spatially uniform. In addition, the 3ω output sensor uses a back-reflection from an A/R coating on the KD*P frequency tripler. It is clear that sol-gel coatings will have sufficiently low reflectance and high-damage threshold, but to date, there have been no reports on the uniformity of their residual reflectivity, or how stable that reflectivity will be in a NIF environment. Given the porous nature of the sol-gel coating, it is possible that contamination of the surface would change its reflectivity.

Our development plan involves the construction of a large-aperture diagnostic to test the effects of and exposure to high-power laser beams. The Beamlet laser system is a convenient facility for such tests. An optical diagnostics station for spatially resolved measurement of surface reflectivity will be built in situ. As shown in the accompanying Gantt chart (Fig. 1.7-1), work on this project will be concluded by mid-FY97. The principal deliverable of this activity is a report confirming sampling uniformity and stability, and/or recommendations for further development.

It appears likely that suitable A/R coatings will be identified. If this is not the case, substantial cost could be incurred in redesigning laser diagnostic sensors to accommodate substantially higher reflectance coatings, and/or different methods of beam sampling must be utilized.

High-damage-threshold absorbing glass. High-damage-threshold absorbing glass is required for the NIF. In one CDR application, the front surface of calorimeters must absorb the full 3ω beam energy in the target plane diagnostic station. The damage

● = marker

◆ = milestone

Figure 1.7-1. Laser diagnostics development schedule.

threshold of calorimeters used in the Nova target chamber is currently about 5 J/cm^2 , and the absorbing glass needs to be replaced periodically to maintain accurate performance. The increased fluence in the NIF beams requires the damage threshold to be increased to approximately 15 J/cm^2 at 3ω .

We will acquire and test special absorbing glass samples. Glasses will be selected with varying optical density, low subsurface inclusion density, differing polishes, and with nonabsorbing or graded glass overlayers. Surfaces will be polished by techniques designed to reduce residual mechanical subsurface damage. Optical damage tests will be conducted and the process will be iterated to converge on optimized materials and polishing processes. An optimized 3ω absorbing glass will be selected for construction of a full-beam absorbing calorimeter. This calorimeter will be installed in the target plane diagnostic test station in Beamlet to further test its performance.

1.7.2 Fiber-Optic Technology Development

The proposed NIF laser diagnostics system includes a small number of streak camera temporal sensors that provide significantly higher temporal bandwidth than will be available from the fast photodiodes on each beam. Optical signals will be transported from the output sensors to the streak cameras using fiber-optics. To transmit the signals with adequate signal-to-noise (S/N) ratio (i.e., to maintain temporal fidelity), they must

be transmitted through bundles of fibers having a very large number of optical propagation modes which will minimize "speckle noise." On Nova, we use multimode graded-index fiber with low modal dispersion in the individual fibers, and custom bundles of up to 25 fibers. The individual fibers are made equal in length to better than 10 ps to obtain fast response times.¹

Multimode fiber with sufficiently low modal dispersion is currently commercially available for 1- μm light. However, there is no source of graded-index, low-dispersion multimode fiber for 0.35- μm light. At a minimum, therefore, we need to develop a new commercial source for 0.35- μm fiber, as well as vendors to produce the fiber bundles to our design specifications. Obtaining UV fiber with low modal dispersion is not easy because there is little interest in the fiber-optic communications industry for this wavelength range. An alternative approach may be to develop single-mode UV fiber (no modal dispersion), with thousands of fibers in each bundle.

Advanced fiber-optic bundle. The main thrust of this CS&T task will be to develop an advanced fiber-optic bundle with adequate temporal bandwidth using single-mode fiber. In the plan shown in Fig. 1.7-1, a prototype bundle will be designed and acquired. The principal deliverables for this task are the prototype fiber bundles and the reports evaluating their performance.

In addition to the transmission of temporal information, we will study the transmission of spatial images over fiber-optic bundles. Image-preserving fiber bundles may be an effective way to transmit near- and far-field beam spatial profiles away from the target chamber environment. This would be convenient and potentially reduce costs.

3 ω fiber vendor development. Once we have determined whether to pursue single-mode or multimode fiber for fiber-optic bundles, we will begin vendor development. A number of graded-index boules will need to be fabricated, and fiber will be drawn (or "pulled") from the boules. The fiber will be characterized and the fabrication will be iterated if necessary. The principal deliverables from this task will be the prototype 3 ω fiber boules and drawn fiber, a production run of the 3 ω fiber, and reports on the measured performance. The fiber produced will be suitable for use in the fiber bundles that will be produced in the following task. We regard this task as straightforward, since we have similar experience from the 1980s.²

1 ω and 3 ω engineering prototype fiber bundles. Once a decision has been made on whether to go with single-mode or multimode fiber bundles, engineering prototypes of the required bundles can be designed, fabricated, and tested. This effort will begin with the development of 1 ω fiber bundles in FY97; the development of 3 ω fiber bundles will be deferred until mid-FY99, when 3 ω fiber is available. The principal issues are to develop a product with adequate mechanical integrity, and with fiber path lengths all equal to within 10 ps to minimize temporal distortion. A suitable vendor is needed to handle production. Deliverables from this task are shown in Fig. 1.7-1. The task will be complete by the end of FY99; deployment of production devices in the NIF facility begins in FY00.

1.7.3 Temporal Sensor Technology Development

Laser pulse-shape and fusion target diagnostic will generate hundreds of transient signals that must be recorded for subsequent analysis. The NIF CDR design and cost estimate is predicated on the availability of low-cost single-shot transient digitizers (SSTDs) with 5-GHz temporal bandwidth. Commercial digitizers that meet this requirement currently cost about \$40K each (without front panel displays). The per channel cost must be reduced by about an order of magnitude to fall within the CDR cost envelope for obtaining the simultaneous capture of transient 1ω and 3ω signals from all of the beams as well as target diagnostics. Advanced SSTD devices have been under development for several years at LLNL, and it is thought that upgrades of recent designs will allow to achieve the desired cost goal (see Section 4.6.1). However, neither performance nor cost has yet been demonstrated, and additional effort is required. We will pursue the development of low cost SSTD's as our NIF component development budget permits.

Figure 1.7-2 identifies the two power diodes located in each chain output sensor. For cost estimating purposes, these diodes were assumed to be vacuum photodiodes. But smaller, faster, and possibly less expensive options exist. GaAs and InGaAs solid-state photodiodes are available with 60 GHz bandwidth. Although their tiny size makes reliable coupling of light to them difficult, it may be possible to trade off some of the unneeded bandwidth for increased active area. These devices in combination with appropriate means for focusing light onto them will be investigated as an alternative.

The CDR design utilizes a calorimeter on each beam to measure the pulsed 3ω energy diverted by a calibrated diffraction-grating beam-sampler as illustrated in Figure 1.7-3. However, no temporal measurements are planned at this location because of complications caused by temporal shear from the grating and the radiation pulse associated with a successful target shot. Ways to eliminate the restrictions on close-in high bandwidth detectors will be explored. We will also explore methods to collect 3ω near field and far field information from the 3ω diffraction-grating beam-sampler.

1.7.4 Laser Diagnostic System Integration

The preceding tasks focused on the development of individual components for laser diagnostics. Task 1.7.4 involves developing and testing integrated diagnostic systems for the NIF. Three major diagnostic systems will be developed.

Target-plane diagnostic station development. One of the major laser diagnostic systems proposed in the NIF CDR design is a target-plane diagnostic station. It will be designed to allow any one of the NIF beams to be diverted to an off-line laboratory, where its near-field, far-field, temporal, and spectral characteristics can be studied in much greater detail than will be possible at the NIF target chamber. The system capabilities will be similar to those of the Two Beam Laser Diagnostic Station (2BLDS) on Nova.³ This task involves the development of a prototype diagnostic station to be used on the Beamlet laser.

A vacuum chamber 3ω target-plane diagnostic is being installed in the Beamlet high bay. The main purpose of this diagnostic is to confirm that the Beamlet energy can be delivered with the required efficiency to a NIF target for conditions which mimic the

40-00-0494-1510 pub

Figure 1.7-2. Mechanical layout of the 1ω output sensor package.⁴

NIF design. The chamber will have the capability to operate at a variety of background gas pressures. This will allow us to study the feasibility of using low pressures of certain gases to provide some physical protection for the target chamber walls and optics. We will also use the system to determine the level of vacuum required to ensure efficient propagation of the beam to the target.

A square, wedged focus lens will be used to separate wavelengths at the center of the chamber. An uncoated spherical mirror will be used to reflect a sample of the beam back toward the diagnostic optical systems. A full-aperture, high-damage-threshold calorimeter (developed in Task 1.7.1) will collect light transmitted through the test chamber mirror, providing a full beam energy measurement at 1 , 2 , and/or 3ω . The main optical diagnostic systems will reside outside the test chamber, as shown in Fig. 1.7-4, with convenient access to allow rapid changes in configuration as needed.

40-00-0494-1519

Figure 1.7-3. A schematic drawing of the hardware for sampling the 3ω energy directed at the target for each beam.⁵

40-00-0494-1537A pub

Figure 1.7-4. Schematic drawing of the target plane diagnostic station.⁶

Design, construction, and partial activation of the target plane diagnostic station will take place in FY95. A full system performance report will be generated by the end of FY96.

1 ω and 3 ω output sensor prototypes. Once the target plane diagnostic station is operational, we will be able to build and test scientific prototypes of the NIF 1 ω and 3 ω output sensors. Full-aperture beam-sampling optics discussed in 1.7.1 and 1.5, will be installed on Beamlet. A set of sensors equivalent to that proposed for the NIF will be installed at the transport spatial filter location, and at the entrance to the target-plane diagnostic station.

The NIF prototype sensors will incorporate as many technical advances made in Tasks 1.7.1, 1.7.2, and 1.7.3 as possible. The installation will allow us to test the performance of the diffraction grating and A/R coating beam samplers, advanced fiber-optic bundles, advanced temporal sensors, and the prototype SSTDs. Our advanced development effort will include the design and fabrication of 3 ω spatial and temporal sensors suitable for installation near the incident beam calorimeter in Fig. 1.7-3. These installations will allow us to study the methods and stability of sensor calibration, using the full-beam calorimeter in the target-plane diagnostic station. A major objective of this effort will be: 1) to analyze output temporal pulse shapes and spatial profile data; and 2) to assess our capability to feed back corrective adjustments to input pulse shapes and spatial profiles using computer control devices and algorithms discussed in Section 1.10.5. A full report on the prototype output sensors' performance will be issued.

Amplifier chain damage inspection and control system. Once constructed and operating, the NIF amplifier chain will be subject to optical damage resulting from inherent imperfections and occasional degenerative operation of the system. Since any

optical damage in a high-power laser system like the NIF will have a tendency to create collateral damage, it is imperative that we have a system which can detect damage sites as early as possible (when the sites are still very small). Near-field images of the beams can be analyzed for this purpose, but the spatial resolution of the near-field cameras specified in the NIF CDR is insufficient to detect damage sites before major collateral damage becomes probable. This task will test the limits of our ability to detect and locate optical damage as soon as it occurs, and to initiate timely corrective action.

As our budget for sensor development permits, we will study methods available for this task and design a system for installation and test on Beamlet. The system should be capable of detecting optical defects as small as 200 μm in size and pinpoint their location anywhere in the amplifier chain. It has been recently proposed that near-field images of the beam could be treated as holograms that can be reconstructed in offline laboratories to locate defects. Hot spots produced by nonlinear effects would generate new virtual objects in the holographic reconstruction of high-intensity near-field patterns. This is one of the options that will be investigated further.

Ultimately, we will construct a prototype system and test it in Beamlet operations. A report that summarizes the performance achieved by a prototype system will be written. It will include recommendations that address the implementation of such systems in the NIF laser facility. Integration of the damage-sensor prototype into the $1\omega/3\omega$ output sensors will be done as a final upgrade to the prototype.

References

1. C. W. Laumann, J. L. Miller, C. E. Thompson, T. L. Weiland, J. A. Caird, and H. T. Powell, "Laser diagnostics development for Precision Nova," *LLNL ICF Quarterly Report*, vol. 4, No. 1, October-December 1993, UCRL-LR-105821-94-1, pp. 1-9.
2. C. E. Thompson and H. T. Powell, "Low-dispersion graded-index optical fibers for picosecond pulse transmission at 0.35 μm ," presented at the Conference on Optical Fiber Communication, Optical Society of America, Reno, NV, January 1987, paper TuQ4.
3. P. J. Wegner and M. A. Henesian, "Precision high-power solid-state laser diagnostics for target-irradiation studies and target-plane irradiation modeling," *SPIE proceedings* vol. 1414, paper 1414-9, pp. 162-174 (1991).
4. NIF CDR Section 5.2.13, Beam Control and Diagnostic Systems, Fig. 5.3.13-24.
5. *Ibid.*, Fig. 5.3.13-34(b).
6. *Ibid.*, Fig. 5.3.13-37.

1.8 Laser Alignment and Wavefront Control

Introduction

The scope of beam control for NIF is well beyond that of the corresponding tasks for Nova or any other existing ICF laser system. The biggest change is the more than an order-of-magnitude increase in the number of beams. This means that the alignment time per beam must be reduced, and the number of parallel activities must be increased to achieve a reasonable shot rate. In addition, alignment must be done very accurately, and wavefront correction is required for the first time to produce the desired spot size on target. The final challenge is significantly reducing the cost of control on a per-beam basis to meet the NIF cost goals. New approaches are required, and both the concepts and the hardware must be developed and proven before they are engineered for the NIF.

1.8.1 Light Sources for Alignment and Wavefront Control

Alignment systems for our present large laser systems use full-aperture laser alignment beams to simulate "shot-mode" beams for alignment purposes. These beams propagate from the front end of the laser through each amplifier chain to the target position. Insertable crosshairs are backlit by the alignment beams to provide beam centering images; far-field pinhole silhouettes produced by inserting a defocusing lens provide a measure of the pointing errors in the spatial filters. However, rapid image processing at the level of detail needed to recognize crosshair pattern positions and accurately determine the center of irregular pinhole perimeters is expensive. The initial cost and the maintenance overhead of the lasers and insertable components are also high.

For the NIF, we have proposed a less expensive alternative in which alignment systems use small-aperture, low-power light sources that are mostly in fixed locations outside the main beam path or inserted by positioners already required for other purposes. For example, light sources for beam centering are located behind turning mirrors on an extension of the main beam path. Each source is placed so that its image is relayed to the plane of the next centering reference by the amplifier chain's relay telescopes. The centerline references are viewed by a downstream alignment package camera; beamline mirrors between each pair of references are adjusted to superimpose the reference image centroids. Similar adjustments are made to superimpose images of light sources in the spatial filter pinhole planes (see Fig. 1.8-1). Finding the centroid of a simple spot in an image is an easy and rapid image-processing task. These local dedicated sources have the additional benefit of allowing alignment activities in different parts of the system to be accomplished in parallel before they are linked together by passing a beam along the entire path.

Wavefront correction systems can use some of the same local sources for monitoring wavefront. Multiplexed delivery with fiber-optics from a single source to a number of locations is a promising approach. The optimum diameter and collimation of the beam from such a source depends on the specific application, and coupling optics to adjust size and collimation are probably required at the output of each fiber.

70-00-0494-2258

Figure 1.8-1. Distributed light sources will be used for NIF alignment. This will reduce the power and number of alignment lasers required, support parallel alignment activities, and provide simple images for the control system to process.

In the NIF CDR design, light sources are needed at two wavelengths: $1.05\ \mu\text{m}$ for alignment and wavefront correction in the laser proper, and a wavelength intermediate between 2ω and 3ω at approximately $389\ \text{nm}$ for alignment to the target. As discussed in the NIF CDR,¹ the 389-nm source is injected in the pinhole plane of the transport spatial filter. Because of compensating dispersion effects in the 1ω spatial filter lens and in the 3ω target-focusing lens, the 389-nm source focuses on-target at the same distance as the 3ω converted beam. As alignment sources, these devices fall into two general categories: pointing designators located in spatial filter pinhole planes, and centering designators located at near-field image planes of the system. Power requirements range from $1\ \text{mW}$ to $50\ \text{mW}$, and in some cases the sources must be polarized. Multiplexing the sources so that each supplies light to a number of beams requires fiber-optic fanouts and couplers, some of which are polarization preserving.

We will obtain $1.05\text{-}\mu\text{m}$ diode lasers and diode-pumped YLF lasers from commercial sources for evaluation and comparison. Regardless of which type of laser is chosen, the output must be multiplexed to some number of light source locations and must preserve polarization. We will work with fiber vendors to explore options in laser-to-fiber coupling, polarization maintaining star couplers, and fiber output-lens assemblies.

Doubled diode or doubled Ti:sapphire lasers are currently the best candidates for tuning to a specific wavelength in the neighborhood of 389 nm. Although there are commercial sources of each, more development will be required to meet our requirements. The cost and complexity of 389-nm laser sources strongly suggests use of large fiber-optic fanouts. However, there is no commercially available scheme for fanning out to large numbers of single mode fibers at this wavelength. A custom fanout involving fiber arrays or some other coupling scheme must be developed.

Using a 3ω target alignment beam may be a viable alternative to the intermediate wavelength laser, and it will be considered during the NIF preliminary design. However, such a change would not alter the development requirements for fibers except to further shorten the wavelength.

Multimode fibers and associated fanout components are much easier to obtain for the intermediate wavelength or 3ω source than their single-mode counterparts. We will evaluate the effectiveness of the multimode approach first and will pursue development of single-mode components, including large fanout arrays subsequently if necessary.

We will test the lasers, light-distribution components, and associated alignment procedures in small-scale simulation experiments, and we will verify the results on Beamlet. The tests related to positioning beams on a target will include propagation through a phase plate in the final focusing optics.

1.8.2 Alignment Concepts Evaluation

The NIF design for alignment systems uses new approaches for alignment light sources, beam sampling, and beam-to-target alignment instrumentation. Alignment sensors share optics with main-beam spatial filters; alignment, wavefront, and laser diagnostic functions are combined in new ways. The basic assumptions behind these designs and the specific implementations proposed for NIF must be further evaluated before committing to the purchase of production quantities of hardware.

The best existing simulation of the NIF laser configuration is the Beamlet laser. It will be important to use this facility as a part of the concept evaluation process. Currently, however, that system is not fully suited for the task. For example, the input pulse is injected into the multipass amplifier in a different location than in the NIF; the alignment instrumentation is fundamentally different from the NIF design. It is not necessary to tilt the full-aperture Pockels cell to obtain good cavity transmission for an alignment beam, and there is no final optics system or target chamber. Thus, small-scale simulations will be performed in a development laboratory in addition to Beamlet tests.

We will design and implement a simulation capability on a small scale in development laboratories and/or at full scale on Beamlet in the following areas:

- Tiltable Pockels cell for allowing alignment beam transmission in the multipass amplifier cavity.
- Alignment sensor beam sampling near spatial filter pinhole planes.
- Multipass spatial filter alignment with local light sources.
- Near-field alignment and apodizer orientation with local light sources.

- Beam-to-target alignment using a NIF design target alignment sensor and an intermediate wavelength alignment beam.
- Inspection of beamline optics for damage using the imaging capabilities of the alignment system.

Analysis predicts that all of the concepts in question will work as required. Nonetheless, there is probably some risk associated with designing, building, and adjusting the hardware to the necessary accuracy. During our development activities, we will establish firm tolerances on the fabrication, adjustment, and stability of key components. Technology prototypes of key components will confirm our ability to meet these tolerances with cost-effective designs.

1.8.3 Chamber Center Reference System

The target chamber center (TCC) is defined as the average intersection point of the vectors normal to the center of each beam port in the target chamber. A computer-aided theodolite system will aid in determining the TCC during initial set-up. Once established, the TCC will be permanently maintained by a chamber center reference system (CCRS).² In one concept, the CCRS will comprise two optical viewing systems that have their fields-of-view centered on the TCC and their optical axes mutually orthogonal (see Fig. 1.8-2). They will not be rigidly attached to the target chamber, but will instead be supported by the same horizontal building structure that supports the target diagnostics. With this system, devices having suitable built-in light references such as the tip of a fiber-optic can be repeatedly and accurately inserted to target chamber center. The resolution and stability of this system must be good enough to consistently define TCC to within about 5 μm to ensure that the target alignment sensor (TAS) and, consequently each target, is adequately centered in the field-of-view of all the target diagnostics.

Another concept would use interferometric distance measurements to identify chamber center relative to external references. A system with high enough bandwidth could even be used to actively stabilize the target positioner.

The Nova chamber center locating system uses TCC viewers that are only stable for short time periods because they are mounted on target chamber ports. When the target chamber is pumped or vented, it distorts. This causes the viewers to point to different locations. Therefore, the Nova viewers are not used as the chamber center reference. Rather, a reference pylon with a small ball on the end is remotely inserted, and after the viewers are adjusted to match the pylon, the pylon is retracted, and the viewers are used to position the target. This approach has proven usable for Nova, but neither the resolution of the viewers ($\sim 10 \mu\text{m}$) nor the mechanical reproducibility of the pylon (25–50 μm) meets the accuracy required for NIF.

We will analyze and compare alternative approaches to the chamber center reference system. After choosing the best candidate system design, we will fabricate components and conduct laboratory tests to demonstrate achievement of the required accuracy. The viewer approach will require design, fabrication, and testing of a large-aperture, high-optical-quality, very-stable imaging system. It also depends on the

images, which must be digitized and analyzed to extract wavefront information. A controller compares the measured wavefronts with the desired ones and calculates commands for the array of actuators on each deformable mirror. The iteration rate for each loop as designed is 10 Hz using frame grabbers, image processors, and controllers that are multiplexed to control 16 wavefront correction loops each. Although the multiplexing reduces cost, it leads to an estimate of approximately three hours as the time required to calibrate all the wavefront loops in the system. This is probably acceptable because the calibrations are expected to be good for days, perhaps longer. However, less multiplexing would provide much more flexibility in operating the wavefront correction systems. Thus, it is highly desirable to develop an architecture to accomplish this improvement.

70-00-0494-2259 pub

Figure 1.8-3. A 40-cm aperture deformable mirror will provide correction for static aberrations in the laser chain optics and for the pump-induced aberrations in the laser amplifiers.

The current design requires a number of circuit boards for the heavily multiplexed framegrabbers, image processors, and mirror controllers. When the full multiplexing capacity is used, the NIF cost goals are achieved as described above. However, the base cost for a new system if an additional camera has to be added, for example, is approximately \$60K. Further development in concert with industry will lead to a cheaper and more flexible system.

We will pursue application of new commercial products to the video processing and digital controller tasks in wavefront correction. With a relatively small investment, new packaging options for microprocessors and related components can be tested. Some of these options have the potential for significantly reducing the amount of multiplexing, with corresponding reductions in complexity and improvements in performance, without increasing the system cost.

While investigating the new hardware, we will also incorporate new software and system control options needed for NIF. For example, present wavefront correction loops are intentionally transparent to tilt and include an additional sensor and mirror to control tilt. For the NIF, we propose to correct the shot-induced part of tilt as a component of the wavefront. An appropriate algorithm will be developed. In addition, Beamlet experience has shown that maintaining closed-loop operation of the wavefront correction system until one second before a shot is necessary to overcome the aberrating effects of gas motion in the amplifier chain. We will develop and demonstrate this capability on Beamlet.

The hardware and software produced as part of this task will be tested in the laboratory and on Beamlet in conjunction with the full-aperture cavity deformable mirror development.

1.8.6 Portable Wavefront Measurement System

During system installation and activation, it will be important to verify and adjust the collimation condition of each spatial filter. It is also desirable to monitor transmitted wavefront as new components are installed to detect, for example, mounting-induced aberrations. The built-in wavefront measurement system at the output of each beam will probably not be operating during these activities because it depends on other components being installed, e.g., the final spatial filter lens, gas window, and internal optics in the final spatial filter.

The standard device for such initial measurements is a shearing interferometer, and a full-aperture version of a shear plate with appropriate viewing aids and data reduction will be considered. However, the normal several inch diameter devices that can be purchased as catalog items do not have the required aperture or wavefront resolution. In addition, without a computer and wavefront analysis software, aberrated beams are very difficult to characterize from examining a shear pattern.

The initial step in this task is to examine proposed installation and activation sequences for the purpose of quantifying the estimated wavefront measurement requirements. Subsequently, we will consider full-aperture versions of a shearing interferometer, a video Hartmann sensor, and other options that can be identified for this purpose. A technology prototype of the chosen instrument will be built and tested. If a Hartmann

sensor is selected, the data processing and calculation of component spacing changes will be accomplished with the enhanced video controller described in 1.8.5.

A reliable wavefront measurement instrument that can be moved where it is needed during installation and activation of the laser will considerably improve our chances of discovering mounting or adjustment problems in real time when they are relatively easy to fix. This obviously reduces the risk of discovering problems later when identifying the faulty component or spacing will be much more complicated. However, relying on such an instrument without sufficient care in development and testing may have the opposite effect by providing incorrect answers.

Milestones and schedule for laser alignment and wavefront control. The schedule with milestones for the activities in this section is shown in Figure 1.8-4. All but two of the CS&T tasks for laser alignment and wavefront control was originally scheduled to start at the beginning of FY95, and all were to be completed in time to support the final design of the NIF alignment and wavefront control systems. However, funding limitations have affected both the extent of the effort and the schedule of work. Nevertheless, every attempt will be made to provide maximum benefit to the NIF Project on a timely basis.

● = milestone

◆ = marker

Figure 1.8-4. Alignment and wavefront control development schedule.

- Beam-to-target alignment using a NIF design target alignment sensor and an intermediate wavelength alignment beam.
- Inspection of beamline optics for damage using the imaging capabilities of the alignment system.

Analysis predicts that all of the concepts in question will work as required. Nonetheless, there is probably some risk associated with designing, building, and adjusting the hardware to the necessary accuracy. During our development activities, we will establish firm tolerances on the fabrication, adjustment, and stability of key components. Technology prototypes of key components will confirm our ability to meet these tolerances with cost-effective designs.

1.8.3 Chamber Center Reference System

The target chamber center (TCC) is defined as the average intersection point of the vectors normal to the center of each beam port in the target chamber. A computer-aided theodolite system will aid in determining the TCC during initial set-up. Once established, the TCC will be permanently maintained by a chamber center reference system (CCRS).² In one concept, the CCRS will comprise two optical viewing systems that have their fields-of-view centered on the TCC and their optical axes mutually orthogonal (see Fig. 1.8-2). They will not be rigidly attached to the target chamber, but will instead be supported by the same horizontal building structure that supports the target diagnostics. With this system, devices having suitable built-in light references such as the tip of a fiber-optic can be repeatedly and accurately inserted to target chamber center. The resolution and stability of this system must be good enough to consistently define TCC to within about 5 μm to ensure that the target alignment sensor (TAS) and, consequently each target, is adequately centered in the field-of-view of all the target diagnostics.

Another concept would use interferometric distance measurements to identify chamber center relative to external references. A system with high enough bandwidth could even be used to actively stabilize the target positioner.

The Nova chamber center locating system uses TCC viewers that are only stable for short time periods because they are mounted on target chamber ports. When the target chamber is pumped or vented, it distorts. This causes the viewers to point to different locations. Therefore, the Nova viewers are not used as the chamber center reference. Rather, a reference pylon with a small ball on the end is remotely inserted, and after the viewers are adjusted to match the pylon, the pylon is retracted, and the viewers are used to position the target. This approach has proven usable for Nova, but neither the resolution of the viewers ($\sim 10 \mu\text{m}$) nor the mechanical reproducibility of the pylon (25–50 μm) meets the accuracy required for NIF.

We will analyze and compare alternative approaches to the chamber center reference system. After choosing the best candidate system design, we will fabricate components and conduct laboratory tests to demonstrate achievement of the required accuracy. The viewer approach will require design, fabrication, and testing of a large-aperture, high-optical-quality, very-stable imaging system. It also depends on the

development of ways to incorporate small light sources in the target alignment sensor. It is desirable to demonstrate the ability to automatically center the TAS in a few minutes or less.

1.8.4 Cavity Deformable Mirror

Aberrations induced in the large glass slabs of the NIF amplifiers by nonuniform distribution of heat from flashlamps and ASE make some form of wavefront correction a requirement on each of NIF's 192 beams. If it can be achieved within NIF cost constraints, active closed-loop correction is strongly preferred because the amount of wavefront compensation can be continuously adjusted to match the thermal conditions that exist at the time of each shot. This flexibility is probably required to obtain the focused beam quality and shot rate specified for the laser. Pending further measurements and evolution of the amplifier design, the wavefront system requirement is to

40-00-0494-1497 pub

Figure 1.8-2. A chamber center reference system defines the position to which target diagnostics and the target alignment sensor are registered.

correct for as much as $\pm 15\lambda$ of beam astigmatism and $\pm 4\lambda$ of third-order aberration with an rms accuracy of $\lambda/4$. The NIF four-pass amplifier design provides the opportunity to use a deformable mirror as the double-passed cavity mirror and, thereby, reduce the required correction by a factor of 2. The development requirement is to increase the scale of existing LLNL deformable mirror technology to the full 40-cm NIF beam dimensions and seek vendor participation in defining a cost-optimized production mirror design. High temporal bandwidth and cooling are not required.

Active wavefront correction on a large multibeam high-average-power laser system has been accomplished over the past four years at LLNL in the atomic vapor laser isotope separation (AVLIS) program. In 1993, this technology was adapted to the Beamlet laser in the form of a 7.5-cm deformable mirror, video Hartmann wavefront sensor, video image processor, and digital controller. This system enables precorrection for amplifier aberrations and is working well in Beamlet tests. However, the mirror is too small to take advantage of the double-passed cavity-mirror position, and precorrecting for chain aberrations leads to large focused spots in the early spatial filter pinholes. This may ultimately limit the Beamlet performance.

We will scale the technology successfully used in smaller mirrors to the NIF 40×40 cm aperture. Figure 1.8-3 shows the conceptual design of a deformable mirror proposed in the NIF CDR.³ Additional NIF requirements, such as tolerance to the flashlamp light from the nearby slab amplifier and a transparent central section for a centering reference light source must also be addressed. The force capability of the mirror actuators will be increased because the larger aperture and correspondingly larger spacing between actuators leads to a thicker mirror substrate. In addition, coordinated development of the deformable mirror design and sol-gel coating techniques is required if the mirror is to take advantage of this less expensive coating option.

After documenting successful performance of a technology prototype, we will work internally and with potential vendors on cost and reliability engineering. The goal is to obtain a completed mirror that meets specifications from at least two vendors. This will provide the basis for competitive procurement of fully assembled production mirrors as an alternative to assembling purchased components with NIF personnel.

Initial testing of the deformable mirror and mirror components developed as part of this plan will occur in a wavefront correction laboratory that supports extensive, detailed study of performance details. Subsequently, we envision installation and testing on the Beamlet laser in a way that simulates NIF operation as closely as possible. Some important characteristics, such as the effect of flashlamp light on the mirror and its ability to compensate real slab aberrations, are best tested on a full-scale system.

Optimum operation of a wavefront correction loop requires that the optical channel pattern of the Hartmann wavefront sensor be designed to match the actuator pattern of the deformable mirror. Therefore, as development of the mirror proceeds, we will build a matching Hartmann sensor for use in the system tests.

1.8.5 Enhanced Video Controller

The wavefront sensors in the NIF conceptual design are video-based Hartmann sensors. The output from these sensors is in the form of standard RS170-format video

images, which must be digitized and analyzed to extract wavefront information. A controller compares the measured wavefronts with the desired ones and calculates commands for the array of actuators on each deformable mirror. The iteration rate for each loop as designed is 10 Hz using frame grabbers, image processors, and controllers that are multiplexed to control 16 wavefront correction loops each. Although the multiplexing reduces cost, it leads to an estimate of approximately three hours as the time required to calibrate all the wavefront loops in the system. This is probably acceptable because the calibrations are expected to be good for days, perhaps longer. However, less multiplexing would provide much more flexibility in operating the wavefront correction systems. Thus, it is highly desirable to develop an architecture to accomplish this improvement.

70-00-0494-2259 pub

Figure 1.8-3. A 40-cm aperture deformable mirror will provide correction for static aberrations in the laser chain optics and for the pump-induced aberrations in the laser amplifiers.

References

1. NIF CDR, Vol. 3, Section 5.3.13.3.1.7.
2. NIF CDR, Vol. 3, Section 5.3.13.3.1.6.
3. NIF CDR, Vol. 3, Section 5.3.13.3.4.10.

1.9 Optics Support and Assembly

Introduction

An important requirement and technical challenge for ICF laser facilities is to maintain the very high optical precision as the scale of the hardware increases. The optics must be installed on very stable optic support structures to assure accurate positioning of each laser beam on target. Each of the optics in the laser line-of-sight must be fabricated to precision tolerances, but just as importantly it must be carefully assembled in a manner that does not distort the optical substrate. This section describes development required to ensure that these engineering issues can be accomplished in a cost-effective manner.

1.9.1 Optics Mounting and Assembly

For the NIF, there will be approximately 1500 large-aperture reflective optics that will transport each of the laser beams through the power amplifiers and to the target chamber. Total position accuracy of the beam at the target must be maintained at less than 50- μm rms (7- μrad pointing accuracy) to satisfy target irradiance symmetry requirements. Given the large number of reflections at large aperture that a beam undergoes in the 4-pass NIF design, this translates to a total rotational stability requirement of less than 0.7- μrad rms for each reflective optic (mirrors and the polarizer). This includes motion from the support structure and from displacements of the mirror and mirror mount. It is critical that each mirror mount be carefully designed and tested to assure that this functional requirement is satisfied. The design of the polarizer and some of the turning mirrors is further challenged by the fact that the laser beams will be arrayed in closely packed bundles with minimal clearance between beams, see Fig. 1.9-1. In addition, the optics must be supported only around their edges to permit unobstructed transmission of laser light. This will necessitate a compact mirror mount design with thin structural sections to make the mount more flexible. The successful design will incorporate high-specific-stiffness, high-damping materials with optimized cross-section shapes to ensure that stability requirements are satisfied. Because of the large quantity of mounts that will be required, the design must also take advantage of low-cost production techniques to minimize overall cost. It is anticipated that a vigorous development campaign could lead to unit costs of less than \$6K/mirror mount.

The mirror mount stability requirement includes thermal effects and vibration. Thus, development efforts must also take into account thermal distortions and the selection of low-thermal-expansion coefficient materials or thermal compensation techniques. Some modern materials, such as graphite epoxy, offer a high stiffness-to-mass ratio; they can be layered to achieve small expansion coefficients, which makes these materials ideal choices for fabricating mirror mounts. Unfortunately, the cost will probably be prohibitive. More traditional materials, such as steel and aluminum, are less costly, but they do not offer optimum structural characteristics. The development effort will trade-off these performance and cost parameters prior to material selection.

In addition to maintaining the stability of the optic after installation, each mount must be designed to ensure that mirror surface distortions are not caused by the assembly of the mirror into the mount. Different mounting schemes will be evaluated,

40-00-0394-0664 pub

Figure 1.9-1. Closely packed array of large-aperture mirror mounts.

including a simple three-point kinematic mount. In such a configuration, each mirror would be held in place at three points optimally located on the back surface of the mirror. Sliding surfaces or flexures would be utilized to release appropriate degrees of freedom at the attachment points to achieve simply supported boundary conditions. This eliminates unwanted distortions other than those caused by gravity. Significant cost savings during the assembly process can be achieved if this technique is demonstrated to be successful. If the mount can be proven to introduce no distortion, then it will not be necessary to inspect each optic after installation into the mount. The objective of this development effort is to develop a mount and assembly process that will maintain mirror-mount-induced distortion to less than $1/20$.

Some optical assemblies for the NIF will involve multiple components in densely packed arrays. These assemblies will present technical challenges that must be addressed prior to the commitment of large production orders. Just before entering the target chamber, each of the $1.06\text{-}\mu\text{m}$ -wavelength laser beams must be frequency converted to a wavelength of $0.35\text{ }\mu\text{m}$ and focused onto the target. The opto-mechanical assembly that has been envisioned in the NIF CDR to accomplish these functions is shown in Fig. 1.9-2. This final optics assembly consists of the following: 1) enclosure, 2) vacuum bellows, 3) vacuum windows, which have curvature and wedge to focus the laser beams and which disperse the 1ω and 2ω light from the target, 4) KDP crystals for

70-39-0394-1405A pub

Figure 1.9-2. Final optics assembly must provide a highly stable platform for the frequency conversion crystals, focus lenses, and debris shields for an array of four laser beams.

frequency conversion, 5) debris shields to protect the windows from target debris, 6) mounting hardware, and 7) auxiliary and diagnostic equipment.

This assembly must provide 5- μ rad pointing accuracy for each KDP crystal and angular stability of better than 5 μ rad. The focus lens must have a remote axial adjustment capability and translational stability of 7 μ m. The stability requirement must be maintained during the alignment period (<2 hr) prior to each experiment. Thus, we must address both vibration input and thermal fluctuations. The focusing lens must be held in a vacuum-tight bezel, and it is desirable to maintain low stress-induced birefringence under vacuum load. The temperature of the KDP array must also be precisely controlled with an accuracy better than 0.1°C to ensure high-frequency conversion efficiency.

For the NIF, 48 final optic assemblies will be purchased and installed. It is vital that each package is low cost, can satisfy all of the technical requirements, and is easily maintained and reliable. To assure this, a technology prototype will be fabricated and tested prior to any production order to confirm that the above specifications can be met.

1.9.2 Structural Support Systems

The dynamic structural stability of the optic support structures is of paramount importance to high-performance ICF laser operations. Motion resulting from facility and ground vibration, and from temperature fluctuations must be maintained to less

than $0.7 \mu\text{rad}$ at mirror mount locations. For focusing elements, displacements must be maintained to less than $7 \mu\text{m}$. These tolerances must be achieved for a large number of optical support structures over a very large area (2.5 acres for NIF). For Nova, the stability requirements were similar but Nova is significantly smaller than the proposed NIF. To achieve the more demanding stability requirements for the NIF, development work is proposed that will enhance our knowledge of designing large-scale facilities with optimum dynamic stability properties.

Many of the NIF optic supports will be aluminum or steel truss structures. Because of cost, ventilation requirements, and mounting flexibility, these aluminum or steel truss structures are often the preferred solution. These structures typically have very low damping values (approximately 0.5%) for low-amplitude vibrations. The frame can be made very stiff to do the following: 1) decrease amplification within the structure and 2) reduce motions. However, it is also possible to develop a passive damping device for use on these structures that would increase the damping value by $10\times$ (5% range) and significantly reduce displacements. For example, nonload-bearing, high-loss, viscoelastic elements can be located at high-strain points in a structure to absorb vibration energy and reduce deflections (see Fig. 1.9-3). This concept was successfully used on the Miracle laser, a large high-power laser at White Sands, to reduce motions resulting from ambient background noise. Adaptation of similar passive techniques on NIF structures will require development.

Viscoelastic dampers can also be incorporated at the interface between the target chamber and support structure. Since the target chamber will support both the target and the final optic assemblies that focus each laser beam onto the target, this is an especially critical element. Increasing the damping at this location will help to satisfy overall stability requirements. The objective of the damping development effort will be to achieve 5–10% modal damping for alignment-critical structural resonances.

The optical support frames for the NIF will be mounted on large, stable concrete foundations. These will provide relatively stiff platforms with good damping characteristics, and they will be isolated to the maximum extent possible from all sources of vibration including vacuum pumps, air conditioning, etc. To successfully design these structures and accurately project their performance, we propose a research effort in three different areas of concern: 1) damping characteristics, 2) long-term stability, and 3) soil/structure interaction for widely spaced optical supports. Regarding the first two activities, relevant literature will be reviewed, and consultants will be hired to advise on optimum concrete compositions to achieve maximum damping, while maintaining good compressive strength, creep, and crack-resistant characteristics. These recommendations will be augmented with damping measurements of existing structures to confirm the recommended parameterization. Consultations will also be sought to determine computer modeling techniques that will address the interaction of the concrete foundations with the soil. This will include accounting for radiation damping into the deep soil and quantifying relative displacements between structures not closely coupled together. Depending on the wavelengths of the ground vibration surface waves, support structures may react coherently and cause larger laser beam perturbations than anticipated. The overall objective of these activities is to develop a consistent and

70-10-0594-2536 pub

Figure 1.9-3. Structural damping concept.

complete information database and skills base that will enable us to make the dynamic stability calculations required for ICF facilities.

The present neutron shielding concept for the NIF target chamber is to use aluminum-reinforced concrete, which will have the side benefit of increasing the chamber stiffness and potentially improving dynamic stability. There are a number of issues that must be resolved before this concept can be accepted. Aluminum embedded in concrete is known to react with the concrete and must be protected. Concrete can be mixed with a variety of aggregates that could have different neutron-activation and shielding properties. Finally, this material will be applied to a large spherical vessel that contains many ports, which will make installation difficult. The development plan includes evaluating these issues, and then building a mock-up of a small section of the target chamber to demonstrate the application technique and the integrity of the resulting structure.

1.9.3 Mounting Vacuum-Loaded Square Optics

Increasing amplifier pumping efficiency and minimizing cost have driven us to compact arrays of multiple laser beams with square apertures. As a consequence of this design, all of the optics for the NIF will be rectangular rather than circular as used in Nova and other previous glass laser systems. Square lenses that will be used as vacuum windows in the spatial filters have several technical issues that must be addressed before full-scale deployment. For such lenses we must evaluate stress-induced birefringence caused by vacuum loads on lenses with non-axisymmetric shapes, B-integral contributed by propagation through the thickness of the lens, and the type of lens that is selected (e.g., double convex and plano-convex). Development activities are necessary to select an optimum design.

Understanding stress-induced birefringence was important in Nova. Empirical scaling laws for round optics were developed. The scaling law, developed from finite-element analysis, enabled the birefringence to be estimated at any position in the lens as a function of lens material, shape, thickness, and diameter. Stress analysis of this type and Nova's relative insensitivity to depolarization led to a system that was designed with optical elements that are as thin as possible to minimize the effects of B-integral. (The elements were thick enough to provide a comfortable safety margin against rupture under vacuum load.) To design future ICF lasers, it will be important to more fully understand and quantify stress-induced birefringence in optics under a vacuum load.

The optimum shape for a lens to minimize stress-induced birefringence is equi-convex. The retardation caused by the compressive force on the atmospheric side is almost compensated by the retardation caused by the tensile force on the vacuum side. As the lens varies from an axisymmetric shape, this balance is lost. Knowing in detail how the birefringence changes as a function of lens shape and thickness will lead to a more fully optimized design, since lens shape (e.g., equi-convex, plano-convex, and meniscus) can be used as an optical design variable.

Other issues that must be folded into the evaluation of the vacuum window design are: ghost reflections, tilt sensitivity, and B-integral contributions affected by the optic thickness.

The objective of this development plan is to quantify the birefringence effect, establish a technical basis for the lens design selection, and produce a validated engineering model. Detailed finite element calculations will be performed and coordinated with empirical results obtained from experiments on Beamlet and on the final optic assembly and from measurements made off-line under controlled conditions. Design evaluations will be performed and coordinated with the NIF project team to assure that the final design selection has been optimized with respect to all design, cost, and performance requirements.

Development plan. The development plan for all of the activities in this area is summarized in Fig. 1.9-4. Efforts in FY95 will evaluate square optic issues resulting in a design evaluation report on vacuum-loaded square optics that is based on both experimental data obtained from full-scale tests on Beamlet and analytical results from computer models. A validated engineering model will also be presented based on experimental measurements of differently shaped lenses under vacuum load.

WBS	CS&T activities and milestones	1995				1996				1997				1998			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1.9	Optic support and assembly																
1.9.1	Mounting vacuum loaded square optics																
1.9.2	Optic mounting																
1.9.3	Structural support systems																

◆ = milestone

Figure 1.9-4. Development schedule for optic assembly and cleaning.

The optics-mount development effort will begin during FY96. Engineering activities will develop prototype mounts for mirrors and polarizers. Prototypes will be fabricated, tested and evaluated to confirm compliance with design requirements. Testing will include dynamic characterization of the mount/optic assembly, using standard modal analysis measurement techniques. Results will be corroborated with computer simulations. Thermal stability and pointing accuracy will also be confirmed experimentally. Distortions caused by gravity and by mounting loads will be measured interferometrically to validate mounting concepts. All results will be summarized in a prototype mirror mount evaluation report that will be completed before the end of FY96. During FY97, a final optics structural prototype will be fabricated and tested. Crystal pointing accuracy and stability (thermal and vibration) will be measured. The crystal thermal control system will be operated to NIF performance requirements. The vacuum integrity and optical quality of the window will be confirmed under vacuum conditions.

In FY96, we will commence activities on structural support systems including material damping and computer simulation of large-scale precision optical systems. A proof-of-principle test that demonstrates the capability to increase damping of metal truss structures will be performed. A simple truss structure, which already exists at LLNL, will have viscoelastic dampers attached. Using modal analysis instrumentation, damping will be measured before and after damper installation. Results will be evaluated and considered for ICF applications. If results appear promising, then an experiment more prototypical of specific NIF designs will be performed. Damping evaluations will also include: 1) testing of the damping mechanism proposed for the joint between the target chamber and the support structure and, 2) measurements of the damping characteristics of concrete and its sensitivity to composition and mix ratios. In parallel with these activities, a small-scale mock-up of the target chamber will be coated with the proposed neutron shielding material to verify the design concept. Finally, analytical methods for simulating large-scale soil/structure interactions will be researched, and the results will be incorporated into the dynamic models of the facility and laser-support structures.

1.10 Control Systems

Introduction

Computerized controls are central to the installation, operation, and maintenance of all ICF facilities. In this section, the major control system components are introduced, followed by a discussion of the development plan. The primary goal of this plan is to ensure expertise in modern and cost-effective control system design for future ICF projects, including the proposed NIF.

The typical ICF control system consists of a network of individual computers, workstations, file servers, interfaces, and graphic displays, which together provide the necessary hardware for the monitoring and control of the various machine components. The functional requirements of the software include remote controls, status monitoring, semi-automated sequencing, and configuration management. Data processing functions address retrieval, analysis, graphical display, archiving, and report generation.

Major modernization of ICF facility control systems have been recently completed at Nova and are still underway at URLLE's Omega. The CS&T program plan described in this section addresses the issues, both hardware and software, that will allow us to exploit this technology basis and to evolve it into the new capabilities for the large NIF control system. This technology is advanced in five important areas:

- Distributed hardware and software environments.
- A large timing system that will remain stable during long-term operation.
- Large-scale and reliable automatic alignment of optical elements.
- A front end processor (FEP) for optical component positioning.
- An FEP for diagnostic instrumentation.

Computer control systems are typically distributed by allocating functions in a hierarchically layered architecture (see Fig. 1.10-1), which is composed of hardware and software. Data within this architecture are generated, transferred, and processed both to achieve control and to diagnose experiments. The lower layers in the hierarchy interact directly with laser and target equipment, whereas the higher layers integrate the equipment into an operational facility. Each layer is responsible for coordinating the actions of lower layers and for reporting to higher layers. Processes (i.e., computer programs) at each layer communicate with subordinate, superordinate, and sibling processes, and they provide graphical user interface (GUI) controls for human operators.

Most distributed control functions are implemented by FEP units specifically tailored for each major subsystem. The FEP either interfaces directly to devices or it acts through intermediate embedded controllers. The FEP provides complex local control and processing capability, and it forms an efficient network connection between the upper level computers and the various specialized equipment. Different types of FEPs, derived from a common base, support optical pulse generation, beam control, laser diagnostics, target diagnostics, and power conditioning. Remote control of devices over the network by the supervisory software is accomplished by a library of input/output (I/O) subroutines, which are included as part of the generic FEP design.

70-15-0494-2242 pub

Figure 1.10-1. Distributed computer controls are applied to ICF facility systems, resulting in layered hardware and software architectures coupled to a data architecture. Only the primary upper and lower layers are shown.

Timing systems for future applications must meet stringent performance requirements for precision and stability at acceptable cost. The NIF timing system is charged with providing about 2,000 reliable and accurate triggers. The technology to achieve this has been demonstrated, but on a much smaller scale than the NIF and at a higher cost than we can afford. Economical solutions will be found to problems in timing signal distribution and in the implementation and measurement of electrical time delays. Work is also planned to develop less expensive methods for generating the optical fiducials used for precision cross-timing.

The computer controls described in this section are predominantly engineered from commercial hardware and standard software tools. The essential results expected from the development plan are threefold:

- Evaluate the equipment, tools, and components available from the commercial sector.

- Produce key prototypes, both hardware and software, of future ICF control system components.
- Secure the experience in newer technologies necessary for achieving satisfactory NIF cost and schedule goals.

Benefits to the ICF Program, NIF, and US Industry

Significant innovations have been made in software engineering technology since the Nova control system was designed, particularly in the area of distributed client-server systems and object-oriented programming techniques. The CS&T program will introduce object-oriented design techniques to the software engineering team, evaluate key concepts, and construct the first versions of several reusable software frameworks. By building simplified prototypes of our software architecture, we can lower the risk in the NIF software development. In addition, this program will be one of the nation's earliest software applications using the Ada95 version of object-oriented programming, and it is likely to produce innovative components that can be shared through the national software archive.

At least two of the FEP units planned for the NIF are useful in any of several ICF facilities, and they are also possible candidates for commercialization. The beam diagnostic FEP will apply inexpensive network components to the distribution of many intelligent instruments at low cost, and the alignment FEP has potential application to the motion control field. As the ICF program relies on commercial equipment wherever possible, much of the added value of these designs lies in the integration of the equipment and the substantial software developed at LLNL.

Components developed for timing applications will make the accurate generation and measurement of short time delays much more affordable, and may also create new markets. This improved technology will be available to US industry, and they are expected to participate in its development.

1.10.1 Distributed Computer Controls

The CS&T program will construct a testbed (see Fig. 1.10-2) that incorporates workstations and network connections that emulate the distributed controls architecture. Representative software development tools, particularly the new object-oriented Ada95 compiler,¹ an object-oriented design tool, and a configuration management tool, will be installed on the workstations. The testbed will serve as a foundation for the remaining elements of the control system tasks; several concurrent development plans can be executed, each structured to deliver an engineering prototype. A modern software engineering process suitable for large projects will be developed and exercised during the program execution.

We will investigate and apply object-oriented techniques to software frameworks using client-server techniques adapted from modern commercial software systems. The frameworks implement recurrent patterns determined to be useful in prior software for later reuse in multiple, similar, applications.

To address one of the more significant risks to the NIF software, our earliest development activity will be experimentation in the several approaches to interprocess communication as used in client-server programming. The NIF will benefit from a generic

70-15-0494-2243 pub

Figure 1.10-2. A testbed of workstations, file servers, and network hardware serves as a foundation for developing software prototypes and testing candidate FEP designs in a realistic software environment.

solution to the distribution of software components so that the supervisory layers of software can control processes in the several different FEPs using consistent methods. The candidate architectures will be prototyped in the testbed and integrated with prototypes of the laser diagnostic and alignment FEPs.

The favored approach to distributed software is the emerging common object request brokering architecture (CORBA) standard² being developed by the Object Management Group, a consortium of some 500 computer industry entities. CORBA defines connections between distributed software objects by way of an interface definition language. The object-oriented communication will be tested for adequate performance, ease of use (from Ada95), and interoperability with different computer equipment. An alternate to CORBA is to use the standardized Ada95 Distributed Annex.

With tools and techniques for data management and distribution in hand, we will construct prototypes of the several software frameworks needed for the NIF: a status server, a configuration server, and a sequence control language. The development strategy will follow the iterative development model in which the risks to overall project success are regularly reevaluated, and in which a small project is undertaken to resolve, by means of prototyping and measurement, the most threatening risk.

1.10.2 Timing System Component Development

The NIF timing system (see Fig. 1.10-3) design relies on the ability to generate, transmit, and detect electrical and optical signals with very low temporal jitter and excellent long-term stability. Two classes of trigger requirements, fast and precision, have been identified for the NIF (see Table 1.10-1). Additionally, cross-timing capabilities will be required to correlate diagnostic records from x-ray, optical, and electrical recorders. We will evaluate commercial technology and select suitable components to provide these functions. For capabilities that need further development we will seek industrial participation as much as possible.

Timing signals are distributed throughout large facilities by optical means wherever possible. This provides necessary ground and fault isolation while also increasing bandwidth over that realized by using long coaxial cables. We will identify components and design techniques that will provide the necessary bandwidth, stability, robustness, and reliability. This will include laser diodes and driver circuits, optical detectors, fiber-optic cables, and other optical distribution components, such as beam splitters and combiners. We expect to leverage the technology base provided by the optical communications industry for distributing multi-gigabit data streams. The product of this effort will be a distribution system design based on realizable component specifications available from multiple sources.

In addition to distribution, the timing system requires programmable delay generators to synthesize triggers and sequences from a master synchronizing signal. The CS&T program will ensure that suitable units are available for the NIF. We will either identify an economical commercial unit or, failing that, initiate development of such a product.

Cross-timing of diagnostic instruments to within 20 ps is achieved with a separate optical fiducial distribution system. Absolute timing to this accuracy is not required. A system that satisfies these requirements has been in operation on Nova for several years, but it requires high maintenance and uses older technology. We will investigate state-of-the-art subnanosecond 1.06- μm laser amplifiers and high-power optical distribution techniques. These components have greatly different requirements from those needed for timing signal distribution. The result of this work will be market-based specifications for the optical fiducial components.

The conventional master-clock architecture proposed in the NIF CDR may prove difficult to maintain under the expected operations scenarios. Therefore, our initial CS&T effort will be to investigate alternative distribution architectures. These alternatives are based on several distributed clocks rather than a single master-clock. One approach is analogous to the technology used in global positioning satellite equipment.³ Another, more likely, approach derives from advances in the components and systems used for high-speed communications networks. In either case, a novel application of the technology may provide improved time distribution.

1.10.3 Video-Based Automatic Alignment

A specialized FEP is being developed to perform unattended alignment of laser-beam transport systems. This FEP contains a video digitizer and processor capable of rapidly analyzing simple images for feature location and size. Although most analysis is of this type, a more powerful array processor is needed for algorithms such as correla-

70-15-0494-2269

5/23/94

Figure 1.10-3. Fast and precision timing signals are distributed from the master timing controller through fiber bundles to zone site controllers. The stability and accuracy of the time relationships are verified automatically.

Table 1.10-1. Summary requirements for the NIF timing system.

Class	Resolution	Range	Stability	Quantity
Fast	1 ns	± 100 ms	<1 ns	800 channels
Precision	50 ps	± 1 μ s	30 ps	40 channels

tion-matched filtering or beam-profile analysis. Table 1.10-2 lists the important processing algorithms. Additional preprocessing is applied to enhance desirable image features or to suppress undesirable features and noise. These additional steps include finite impulse response (FIR) filters, median filtering, gradient, and normalization.

To prepare for system shots in a reasonable amount of time, ICF laser beams must be aligned in parallel. The software architecture for the FEP supports this parallelism with a tasking mechanism that switches to process another independent beam whenever the current task is suspended, e.g., to wait for a motorized adjustment to complete. The controller logic maintains a separate processing thread through the software algorithm for each beamline. The FEP will be programmed in Ada95 to exploit the multi-threaded tasking features inherent in the language.

A prototype automatic alignment FEP, including digitizing hardware, image algorithms, and controller software, will be implemented to assess the performance, accuracy, and dependability of the candidate processing methods. This work will also support concurrent development of laser alignment techniques and sensors.

1.10.4 Alignment Front End Controls

Computerized alignment systems must center laser beams on component input apertures, point the beams to the next component, and finally focus them on target. Large systems can employ well over 10,000 motorized actuators, requiring elaborate remote control capabilities. This FEP has evolved from many years of experience at LLNL to provide highly integrated control of these devices. Repetitive alignment sequences are automated with supervisory software that commands FEP units to move the appropriate motors. The alignment FEP uses commercial stepping-motor controllers and interface modules that are configured in software to form compound devices such as mirror gimbals and sensor packages.

Table 1.10-2. Fundamental image processing algorithms used for alignment.

Sensor Image Type	Image Features	Image Processing Algorithm
Spot or disk	X, Y position, area, radius and out-of-bounds point count	Centroid (thresholded or weighted)—a very fast calculation
Multiple beams (i.e., spot images)	Array of centroid values	Blob analysis—tracks many simple objects simultaneously
Templates (e.g., crosshairs)	X, Y position, match goodness value	Correlation matched filter—very robust method
Gaussian beam profile	X, Y position, fitting error	Surface function data fitting—Gram/Schmidt procedure
Focusing	Area (other centroid values checked to ensure reliable analysis)	Scan through focus searching for minimum spot size—waits to move lens

This plan covers the reuse of previously developed Ada software for adaptation in future projects. The main areas to be addressed are: adding standardized network protocols and operating system services and applying distributed data methods.

● = marker

◆ = milestone

Figure 1.10-5. Control systems development schedule.

tion-matched filtering or beam-profile analysis. Table 1.10-2 lists the important processing algorithms. Additional preprocessing is applied to enhance desirable image features or to suppress undesirable features and noise. These additional steps include finite impulse response (FIR) filters, median filtering, gradient, and normalization.

To prepare for system shots in a reasonable amount of time, ICF laser beams must be aligned in parallel. The software architecture for the FEP supports this parallelism with a tasking mechanism that switches to process another independent beam whenever the current task is suspended, e.g., to wait for a motorized adjustment to complete. The controller logic maintains a separate processing thread through the software algorithm for each beamline. The FEP will be programmed in Ada95 to exploit the multi-threaded tasking features inherent in the language.

A prototype automatic alignment FEP, including digitizing hardware, image algorithms, and controller software, will be implemented to assess the performance, accuracy, and dependability of the candidate processing methods. This work will also support concurrent development of laser alignment techniques and sensors.

1.10.4 Alignment Front End Controls

Computerized alignment systems must center laser beams on component input apertures, point the beams to the next component, and finally focus them on target. Large systems can employ well over 10,000 motorized actuators, requiring elaborate remote control capabilities. This FEP has evolved from many years of experience at LLNL to provide highly integrated control of these devices. Repetitive alignment sequences are automated with supervisory software that commands FEP units to move the appropriate motors. The alignment FEP uses commercial stepping-motor controllers and interface modules that are configured in software to form compound devices such as mirror gimbals and sensor packages.

Table 1.10-2. Fundamental image processing algorithms used for alignment.

Sensor Image Type	Image Features	Image Processing Algorithm
Spot or disk	X, Y position, area, radius and out-of-bounds point count	Centroid (thresholded or weighted)—a very fast calculation
Multiple beams (i.e., spot images)	Array of centroid values	Blob analysis—tracks many simple objects simultaneously
Templates (e.g., crosshairs)	X, Y position, match goodness value	Correlation matched filter—very robust method
Gaussian beam profile	X, Y position, fitting error	Surface function data fitting—Gram/Schmidt procedure
Focusing	Area (other centroid values checked to ensure reliable analysis)	Scan through focus searching for minimum spot size—waits to move lens

This plan covers the reuse of previously developed Ada software for adaptation in future projects. The main areas to be addressed are: adding standardized network protocols and operating system services, and applying object-oriented design methods. A prototype providing several instances typical alignment devices will be integrated and tested with the supervisory frameworks discussed above.

In the first set of tasks aimed at software reuse, we will select replacements for the processor and operating system. A portion of the existing Ada software will be reverse engineered and migrated to the new system for testing and assessment. Additional tasks will be directed toward improving the FEP hardware by prototyping a higher-density stepping-motor driver module and adding DC motor capability.

1.10.5 Laser Diagnostic Data Acquisition

Laser beam diagnostics provide energy and power measurements. Precision laser operation requires a 1% energy error budget to meet an 8% beam-power-balance requirement; these are the baseline operational parameters for NIF. Nova energy sensors used for our Precision Nova project marginally achieve this specification through labor-intensive calibration procedures. Development of specialized sensors that locate critical data acquisition circuitry near the laser equipment can satisfy these high-precision requirements at lower operational costs. The FEP will use an embedded controller (Neuron™ node) and network technology (LONWorks™) from Echelon Corp. (see Fig. 1.10-4) to implement an economical approach to linking sensors that are distributed throughout the facility. We will access experience gained from the Omega Upgrade project in applying this technology.

Development tasks include preliminary work on electronics for the photodiode charge integrator and calorimeter. Data acquisition software will be developed for the associated Neuron™ nodes as well as the FEP. Engineering prototypes of these instruments will be used in diagnostic sensor packages to validate the energy measurement accuracy required for ignition experiments.

1.10.6 Schedule

Figure 1.10-5 shows the schedule to complete the CS&T control system tasks is driven by the overall requirement of delivering prototypes and engineering decisions to the NIF project at the appropriate points in Title I and Title II. There is an additional on-going effort past Title II that addresses the general task of keeping abreast of rapidly moving technology and incorporating the appropriate changes and performance enhancements as soon as practical.

70-15-0494-2244 pub

Figure. 1.10-4. A network of distributed Neuron™ embedded controllers provides a low-cost means to locate precision measurements near laser components.

References

1. Barnes, J. P., "Programming in Ada Plus an Overview of Ada 9X," Addison-Wesley(1994), ISBN 0-201-62407-9, pp. 397-464.
2. Object Management Group and X/Open, "The Common Object Request Broker: Architecture and Specification," John Wiley & Sons, Inc. (1992), OMG Document Number 91.12.1, ISBN 0-471-58792-3, pp. 27-44.
3. Brown, A., Allan, D. W., and Walton, R., "Precise Time Dissemination Using the Inmarsat Geostationary Overlay," IEEE International Frequency Control Symposium Proceedings (1993), IEEE Cat. No. 93CH3244-1, pp. 55-64.

● = marker

◆ = milestone

Figure 1.10-5. Control systems development schedule.

1.11 Laser Design Optimization

It is vital to the success of future ICF facilities that the laser system be carefully designed to maximize performance at minimum cost. Because of the size and complexity of the laser hardware, the optimization process is complex and will require a team of people dedicated to do the following: 1) synthesizing and evaluating performance/cost data; and 2) developing computer codes capable of accurately simulating the laser amplification and propagation processes, and executing fast, multidimensional optimization routines. The overall objective of these activities is to develop design specifications for critical laser components that will guide the development of the optical, mechanical, and electrical hardware for ICF facilities and the NIF.

1.11.1 Pump Cavity Analysis

Three-Dimensional Ray Trace Code. The NIF laser amplifiers must meet stringent requirements on the magnitude and spatial distribution of gain in the laser slabs, and on the pumping efficiency. Designing amplifiers to these specifications will require a full three-dimensional (3-D), time-dependent, ray tracing computer model of the transfer of pump radiation from the flashlamps to the laser slabs. Furthermore, because this model will be used to optimize the amplifier design it must run quickly enough so that many possible configurations may be examined in the allotted time.

Current models are insufficient for performing this task. The only full 3-D ray-tracing codes that are currently being used for Nd:glass amplifier design are variations of ZAP,¹ a Monte Carlo code originally developed by Systems, Science, and Software for the Naval Research Laboratory in 1971. This program can be used to model the instantaneous pumping of the laser slab at a given value of the flashlamp loading. Unfortunately, the Monte Carlo method of the calculation presents several problems. The random nature of the calculation introduces the possibility that significant variations in the pump profile, which depend on a small directed fraction of the flashlamp radiation, may be missed unless a very large number of rays ($\geq 10^9$) are tracked in each calculation (this may take several hours on a mainframe computer). This problem is exacerbated by the fact that the accuracy of a Monte Carlo calculation increases as the inverse square root of the number of rays that are tracked, therefore, increasing accuracy by a factor of 10 increases run time by 100.

Other models in recent years have made several advances toward predicting the gain distribution. A model for predicting the average gain coefficient using an empirically determined cavity transfer efficiency for the transfer of pump radiation to the slabs has been constructed;² its predictions are in good agreement with experiment, shown in Fig. 1.11-1. A new quasi-3-D ray tracing model with some built-in simplifying assumptions about the amplifier geometry has also been developed;³ this model was used to design the Beamlet amplifier modules to obtain uniform illumination of the slabs. This new model uses an adaptive integration routine that calculates the instantaneous pumping profile at the slab in a few minutes on a workstation. In Fig. 1.11-2, the observed uniform gain profile at low-loading ($f_x = .075$) in the Beamlet amplifier (where the gain roll-off due to ASE is minimal) appears to validate this new technique.

In the NIF CS&T program, we will incorporate the improvements we have validated in our early models into a new, 3-D, ray tracing pump model that is significantly faster

70-15-0894-3060pb01

Figure 1.11-1(a). Comparison of the observed amplifier performance (data points) vs the predictions of the average gain model: (a) & (b) - SSA amplifier, (c) MSA amplifier.

70-15-0894-3061pb01

Figure 1.11-1(b). Comparison of the observed amplifier performance (data points) vs the predictions of the average gain model: (a) & (b) - SSA amplifier, (c) MSA amplifier. (Continued)

70-15-0894-3062pb01

Figure 1.11-1(c). Comparison of the observed amplifier performance (data points) vs the predictions of the average gain model: (a) & (b) - SSA amplifier, (c) MSA amplifier. (Continued)

70-15-0894-3063pb01

Figure 1.11-2. Measured gain profiles for the Beamlet amplifier. The flat profile at low loading is indicative of the uniform pumping. At higher loadings ASE causes the gain profile to drop off at the edges of the slab.

and more accurate than current codes. Concurrently with the development of this model, we will conduct a program to gather a database of the material properties (spectrally-dependent reflectivities, transmissivities, indices of refraction, absorptions, etc.) that will be required as input to this model. We will also interact with the experimental amplifier activities discussed in Section 1.2 to verify the predictions of the models, particularly with regard to novel reflector shapes and placements that may increase the amplifier gain and/or gain uniformity. The final goal is an amplifier with high pump efficiency and uniform gain.

Fluorescence redistribution/ASE models. Both fluorescence redistribution and amplified spontaneous emission (ASE) can cause the peak gain profile to vary significantly from that of the incident pump radiation on the slab. Both of these processes must be included in our amplifier model, if we are to accurately simulate the gain profile of our multipass laser systems.

Fluorescence redistribution results from the spontaneous radiative decay of the excited Nd ions into the ground-state transition. This ground-state fluorescence is absorbed by other ground-state ions in the vicinity of the emitter, and appears as a migration of the excitation from its initial point of generation. In the NIF design, the Nd ion concentration will typically be about $3 \times 10^{20} \text{ cm}^{-3}$; and the absorption cross section at the ground-state fluorescence wavelength is about 10^{-20} cm^2 . So it will take many emissions and subsequent re-absorptions for a significant fraction of the excitation to migrate a few centimeters. The measurement of the actual effect of fluorescence redistribution in large laser slabs has been studied at the Troitsk Institute for Innovation and Fusion Research. The results of this study will be used to construct a model of this effect, which will be included in our amplifier design codes.

At the high gains that will be present in the NIF amplifiers, ASE can greatly increase the rate of the decay of the inversion when the energy storage nears its peak. In slabs with an aspect ratio typical of the NIF design, the increase in the decay is nonhomogeneous, and is larger at the edges of the slabs than at the center. This effect is clearly evident in Fig. 1.11-2, where the roll-off in the gain-coefficient toward the edges of the slab at high-average stored energy is quite apparent. We will develop computer codes to model the spatial variation of the ASE for inclusion in our amplifier simulation model. In parallel, we will conduct experiments in our prototype amplifier facility to measure the effects of ASE in various configurations, and compare these results to the predictions of our model.

Amplifier configuration analysis. During amplifier configuration analysis activities, we will combine our computer models for pumping, ASE, and fluorescence redistribution along with our database of material properties into a full 3-D, time-dependent computer model for predicting the gain and the thermal effects in the NIF amplifiers. This code will have the flexibility to look at the effects of changing any of the amplifier parameters, such as reflector shape and position; flashlamp size and position; laser glass position and Nd ion density; and size and duration of the electrical excitation pulse for the flashlamps. This code will verify that the amplifier designs, which may be considered during the cost-optimization process, will meet all of the scientific performance goals.

We have already taken the first steps toward developing this model with the construction of a new quasi-3-D time-dependent code which includes the spatial and temporal enhancement of the decay rate due to ASE, but which has some built-in simplifying assumptions about the amplifier geometry. We have used this simplified model to predict the gain profile in the Beamlet amplifiers. Figure 1.11-3 shows a comparison of the experimental results and model predictions. From this figure it is apparent that with this simple preliminary code we are able to get the magnitude and distribution of the gain "about right." With improvements in the code, including more accurate 3-D models and material properties, we are confident that we will be able to more accurately predict the gain in the NIF amplifiers.

Pump-Induced Distortion. An important parameter in the design of flashlamp-pumped Nd:glass amplifiers is the amount of wavefront distortion and depolarization induced on the beam. In Brewster-angle slab amplifiers, there are two significant types of pump-induced distortions: 1) edge distortions, caused by the thermal expansion of the edge claddings as they absorb the ASE; and 2) central distortions, caused by the preferential heating of one of the two sides of a laser slab by the flashlamp pump radiation. As a result, the wavefront quality of the beam is degraded as it propagates through the amplifiers. This degradation results in poor harmonic-conversion efficiency as well as poor focusability at the target plane.

Our simulation is based on the fact that when a laser slab is subjected to a thermal load, it undergoes mechanical deformation. The temperature rise in the laser and the

70-15-0894-3064pb01

Figure 1.11-3(a). Experimentally observed (a) and predicted (b) gain profiles for the Beamlet amplifier. The differences between the experimental result and the prediction may be the result of 3-D effects not included in the simple model.

70-15-0894-3065pb01

Figure 1.11-3(b). Experimentally observed (a) and predicted (b) gain profiles for the Beamlet amplifier. The differences between the experimental result and the prediction may be the result of 3-D effects not included in the simple model. (Continued)

stresses that build up due to the deformation combine to alter the refractive index of the laser slab. With the geometry and the refractive index of the slab altered, an incident plane wavefront will emerge distorted and depolarized. Based on this formalism, we have developed a model that predicts the central beam steering in a flashlamp-pumped, Brewster-angle-slab amplifier as a function of space and time. However, further code development is required to more accurately model the edge steering.

In the regions near the edge cladding, the spatial scale of the temperature gradient is very small—often much smaller than the spacing between nodes in the numerical grid. As a result, spatial resolution is lost and beam-steering values become unreliable. Simply increasing the number of nodes in the (uniform) mesh is not practical as the memory limits of the computer are quickly exceeded. The problem may be ameliorated by using a nonuniform mesh so that more nodes are placed in the regions near the edge cladding, to resolve the temperature gradients, than in the center of the slab, where the spatial scale of the temperature gradients is quite large. Unfortunately, the inherent numerical accuracy in a nonuniform grid is poor compared to a uniform grid. We have discovered a method, however, where the good numerical accuracy of a uniform grid is obtained with a nonuniform grid. We plan to implement this algorithm in the coming year.

The methodology given in this section is sufficiently general to calculate the wavefront distortion at any time t . However, for sufficiently long times, the radiative interaction among the amplifier components becomes important. Such a complex situa-

tion is not handled by our thermal code. Consequently, for long times, we must calculate the temperature distribution in the laser slab from a general-purpose thermal analysis computer code, such as TOPAZ3-D, and use the temperature predictions from this analysis to calculate the displacements. This will be implemented in FY95.

Experiments must be performed on laser amplifiers to validate our computer models. These experiments fall into three broad areas: 1) long-term thermal characterization, 2) thermal-source characterization, and 3) beam-steering measurements. Experiments on long-term thermal characterization are important to validate the temperature predictions produced by the TOPAZ3-D code. These temperature profiles will determine the long-term wavefront distortion in the amplifier. Thermal-source experiments are aimed at characterizing the thermal-source term used in the temperature section of our model. We will perform gain measurements under single-sided pumping conditions to determine the spatial dependence of the pump profile and validate amplifier gain profile models. Finally, beam-steering measurements on an amplifier will be performed to validate the predictions from the pump-induced wavefront distortion model.

Amplifier design optimization. It would be inappropriate to incorporate the full amplifier model code in the amplifier-cost design optimization, due to enormous overhead in running the full 3-D time-dependent model for each small change in the amplifier design. Instead, we will use the full model to develop a parameterization of the amplifier performance vs configuration changes under the required constraint for gain uniformity. These parameterizations will then be included into the cost optimization code, which optimizes the amplifier design. When the optimum design has been determined, the full amplifier model can be run to verify its performance. Such an approach has already proven effective in the design of the Beamlet amplifiers and the preliminary design of the amplifiers for NIF.

Figure 1.11-4 shows that development activities are expected to continue for about 3 years. During FY95, emphasis will be placed on developing 3-D simulation capability. This will allow the model to be used during NIF Title I activities to confirm design options under evaluation. Fluorescence and ASE models will be completed in mid- to late-FY96. All of the computer tools developed during the first two years will be exercised during the third year to validate final design details established during Title II engineering activities.

1.11.2 Propagation Analysis

Construction of the NIF will constitute a qualitative advance in the state-of-the-art high-energy, ns-pulse solid-state laser facilities. It will be the first to use high-power regenerative amplifier architecture where it will operate at unprecedented peak power, total fluence, and pulse contrast ratio. The NIF will feature the first use of large-aperture KDP plasma-electrode Pockels cell switches in a large-scale facility. Many components will be manufactured by advanced techniques for which there is a minimal experience base.

Such a laser cannot be designed using simple extrapolation from previous facilities. Precise and comprehensive numerical beam-propagation modeling is required to assure that we understand effects such as the formation of hot spots due to small-scale obscurations or phase defects (leading to component damage), growth of ripple noise

● = marker
◆ = milestone

Figure 1.11-4. Schedule for laser design optimization development activities.

due to component surface-finish error (leading to damage, pulse-shape distortion, and loss of conversion efficiency and beam focusability), and the trade-off between spatial-filter pinhole size, ripple growth, and extraction efficiency. A predictive understanding of the details of the beam evolution through the laser chain will lead to optimal sizing and placement of chain components, and to specification of manufacturing defect tolerances. This, in turn, will assure that the NIF laser will have minimum construction cost consistent with high confidence in meeting the programmatic goal of demonstrating thermonuclear ignition and burn.

Detailed analysis of beam-propagation dynamics in the NIF laser chain is carried out using the PROP92 suite of three codes. PROP2 is a state-of-the-art Fourier propagation code in two transverse dimensions. Also available are the much faster 1-D versions PROP1 (one linear transverse dimension) and HANK (2-D cylindrically symmetric). All three codes read the same user-friendly input files and share a common core logical sequencer—simplifying code maintenance and extension. These codes have been validated by simulating Novette and Nova operations. Good agreement has been achieved with measurements of overall energetics and near- and far-field images. Conjugate image formation from small-scale obscurations and phase defects, leading to intensity spikes, and hence to optical component damage, was verified and quantified by modeling with PROP92. Most recently, small-scale output-intensity modulation in Novette near-field photos were computationally reproduced using randomly oriented, ~1-cm ripples. After the simulations, cm-scale interferometric scans revealed similar structure on Beamlet amplifier slabs.

To certify that NIF will deliver the power, energy, and temporal pulse-shaping capability required for the ignition experiment, we must perform extensive end-to-end modeling of the laser. This modeling will include the effects of pump-induced and static phase aberrations, nonuniform gain and saturation, obscurations and bubbles, depolarization and resultant beam loss, frequency-conversion systematics, phase plate effects and near-focus beam evolution. We are looking into the possibility of linking our codes to plasma dynamics codes to continue the propagation analysis into the near- and intratarget environments. We will also model the behavior of the U-turn and L-turn configurations, and the evolution of grating-dispersed broad-band beams (SSD) on Nova and the NIF.

Carrying out this suite of modeling tasks will require both a number of extensions to the codes and an improved experimental database.

- Add polarization tracking to the code so that effects such as stress-induced birefringence in slabs and lenses can be studied.
- Extend aberration models to allow arbitrary spectral shapes.
- Add a Fourier description of the beam's temporal variation for simulating high-bandwidth beams.
- Improve Prop92's adaptive optic algorithm to include nonlocal feedback between separated sensors and actuators, and an accurate representation of the true mirror shape as a function of actuator positions.
- Implement adaptive and nonuniform mesh techniques to gain higher resolution and improved performance.

- Improve material-damage models to account for temporally shaped and/or multi-wavelength beams.
- Link LASNEX plasma descriptions to PROP92 to model laser beam propagation as it transits the hohlraum and approaches the x-ray conversion region.
- Modify PROP92 graphical output to improve visualization of the dynamic evolution of beam structure and defects.

Figure 1.11-4 shows that increasingly realistic propagation models of the NIF laser system will be developed over a three-year interval. Most of the specific code extensions mentioned above will be completed and tested during FY95. In FY96, experimental data provided by other development areas described in this document will allow code comparison, correction, and validation. By the end of FY96, we expect to have a completed and validated propagation model available. During FY97, we will continue to refine our models while carrying out extensive modeling of the NIF design options, leading to a final design by the end of that year.

1.11.3 Frequency Conversion

Conversion efficiency of the third harmonic is a crucial parameter in the design and cost analysis of the NIF. Because a small increase or decrease in conversion efficiency can result in a substantial increase or decrease in laser system size and cost, it is imperative that converter performance be predicted as accurately as possible. The accuracy of frequency-conversion modeling depends upon the code's capability to include "real" characteristics of optical components and laser beams incident on the converters.

In the last two years, a powerful set of frequency-conversion codes has been written that for the first time modeled the 3ω conversion of beams with spatially varying intensity and phase, and with applied phase modulation. The codes consider either time or space separately. These codes have been utilized for converter design for both Beamlet and NIF. They have also been used to develop a surface-finish specification for KDP crystals. The diamond turning marks on the KDP crystals can cause a degradation of conversion efficiency and intensity modulation on the 3ω beam.

Although the codes can handle input beams that are spatially varying in intensity and/or phase, there is no provision to handle spatially varying crystal properties. This is important because there will be spatially varying indices of refraction, and thus spatially varying phase mismatch factors. This will lead to 3ω conversion efficiencies that are lower than the ones currently calculated. New simulation capability must be added to determine the significance of this reduction. A most important application of this new capability would be to accurately determine the effects of crystal gravitational sag on conversion efficiency. In addition, existing codes do not account for depolarization of the beam in either crystal. For Type II conversion, this may or may not be an important effect in the NIF crystals. Only an enhanced frequency-conversion code that accounts for depolarization will provide a quantitative indication of the effect.

Existing codes were previously used to model two crystal converters. These converters have a high peak-conversion-efficiency, which is ideal for flat temporal input pulses. However, for shaped pulses such as those planned for the NIF, two-crystal designs produce a lower energy-conversion efficiency due to low-power conversion efficiency

in the low-intensity portions of the shaped pulse. Energy conversion efficiency can be improved by using converter designs with more than two crystals. One such design is the alternating-z concept, which consists of four crystals. A new code has been written to simulate the performance of these new converter designs and specifically show their sensitivity to applied bandwidth, spatially varying intensity, and phase distributions. As with the two-crystal designs, the "real" optical characteristics of the converter crystals (surface finish, etc.) need to be processed by the codes. The ultimate code will perform a converter optimization for specified beam conditions.

Code development will be done over the next two-three years. It must be accompanied by detailed measurements of converter crystal properties such as nonlinear susceptibility, bulk-loss coefficients, stress-optic coefficients, stress-strain relations, nonlinear coefficients, and surface losses at the fundamental, second harmonic, and third harmonic wavelengths. Without these detailed characterizations, the accuracy of the simulations will be limited. Code development will have two primary objectives: 1) to enhance existing software to process spatial and temporal data simultaneously, and to handle spatially varying crystal properties; 2) to develop new codes to evaluate new crystal-design alternatives.

1.11.4 SRS/SBS Analysis

Stimulated scattering in the direction transverse to the propagation and polarization of the laser beam is a potential failure mechanism for the NIF large-aperture, high-fluence final optics. In this direction, scattered light is confined to a cross-sectional area that is several tens of times smaller than that through which the laser travels, so material damage can occur well before overall energy loss becomes important. To assure the safety of the NIF design while optimizing its performance, we must improve our understanding and simulation capability of transverse stimulated Raman (SRS) and Brillouin scattering (SBS).

We have constructed a sophisticated computer code, capable of modeling the build-up from spontaneous scatter of either SBS or SRS Stokes waves, allowing for arbitrary time- and space-dependent phase and amplitude structure in the beam, and including reflections from both the edges and the faces of the subject optics. NIF design optimization was constrained (see Section 1.11.7) to remain below the predicted threshold for material damage by SRS scattered light. The steady-state SBS gain-length product is expected to be quite large, but because of the long acoustic phonon lifetime, we presently predict that SBS can be suppressed by imposing moderate bandwidth on the main beam.

The most pressing need for improving our confidence in these predictions, and hence in the viability of the NIF design, is for experimental data. The current levels of uncertainty in the steady-state SRS gain, and in the SBS gain and line width, all need to be reduced by about a factor of two. Although the code has been extensively checked and exercised, the only experiments against which it can be compared are a few preliminary observations that were made on Nova—none of which reached the applicable regime, and none of which was absolutely calibrated. The first-principles spontaneous scattering model, though believed to be reasonable, has not been experimentally verified.

We have begun collaborations with scientists at the Institute of Spectroscopy in Troitsk and the Institute for Experimental Physics in Arzamas to address some of these problems. Measurements of SRS and SBS steady-state gains and SBS line shape in relevant materials and geometries will be made, as well as measurements of spontaneous Raman scattering during frequency conversion to test the noise model. An independent computer code will be developed there, so that results can be compared. The High Fluence Test Station at CEL-V and Beamlet will be instrumented to make time- and space-dependent measurements of transversely scattered light, with well-diagnosed main beam near-field patterns and temporal pulse shapes. As this data becomes available, we will compare calculations with measurements and extend or correct our code as indicated. It is anticipated that these activities will continue for approximately two years, and that they will be followed by a year of refinement/optimization that will validate the proposed NIF design.

1.11.5 Data and Code Library

The accuracy of the NIF design optimization process depends on the quality of material and laser system data used in the modeling of the laser system, and on the quality of the computer codes used to process that data in the search for the optimum design. We intend to construct a central library of material properties and costs, which will act as the "reference standard" for optimization codes. Because many properties are not presently known with the accuracy needed for the NIF design optimization, we will work closely with experimentalists and manufacturers to gather data and reduce uncertainties. We expect that there will be ongoing change in the database as manufacturing techniques are improved, so continuous updating of the data will be required. In many cases, we will need to know properties (such as finish quality) as a function of cost.

We also intend to maintain a certified set of computer subroutines and complete codes. We intend to have test cases and test suite drivers, which will be used to check routines and codes after any changes are made to avoid inadvertent introduction of code errors. For important codes, we will attempt to have two different codes to calculate the same physics. This redundancy will lead to higher confidence in the code results.

1.11.6 Cost Synthesis

As ICF program laser and target facilities are designed, it is important that system design parameters be carefully selected to minimize cost. For a system as large and as complex as the NIF, the optimization process necessary to support this selection is sophisticated and requires computer models of both system cost and performance. We have already established a computer code, CHAINOP, which integrates these models and executes fast-optimization routines to determine optimum system designs, defined to be the lowest cost system that achieves performance requirements. In the future, we intend to modify this code with updated and improved performance and cost algorithms.

Cost/performance optimization already performed in support of the NIF has demonstrated that judicious selection of key design parameters can have a large impact on total system cost. Because the laser system dominates the cost of ICF facilities (68% of the NIF), its costs have been most carefully studied in the past. Aperture size, amplifier

pumping efficacy, frequency-conversion efficiency, phase-plate transmission efficiency and other key parameters have been identified as having high cost leverage. Small changes in these parameters will have high impact on total system cost. This information has been used to justify design decisions during the NIF CDR and identify development activities that have high leverage to lower facility costs. It is important that we continue to develop cost models to confirm the accuracy of these decisions, include factors that have not yet been considered, and identify other areas having cost reduction potential.

During NIF CDR activities, we progressed through two preliminary stages of cost modeling. At this time we have simple cost algorithms for many subsystems down to the third level of the NIF WBS structure. During the next three years, the NIF design will mature and change; the cost models must keep pace with these modifications, increase in the level of detail for higher cost leverage items; and be appended with additional models in areas that have not yet been simulated. The period over which these activities will be executed is three years commencing in FY95. The effort must be extended over this period of time to provide continuing support to the NIF Title I and Title II activities presently scheduled to be completed in FY97.

During the first year, cost algorithms will be added in areas that could have impact on basic laser-system architecture. This will be important to complete before the end of FY95 so that when Title I activities commence in FY96, the NIF project will have a firm basis for basic system design. Building cost is one example of a cost parameter that should be added soon; it could have impact on whether or not a laser switchyard should be included in the NIF. During FY96, cost models will be improved and adapted to meet the needs of NIF Title I activities. The objective is to have a final validated model by the end of the fiscal year. Activities in FY97 will support continued model refinement to assure that NIF final design details are optimal from a cost perspective.

1.11.7 Design Optimization

Design optimization requires the integration of verified performance models, validated cost models, and systematic variation of chain design parameters to minimize system cost. The number of parameters that we must simulate to achieve an accurate characterization of the beam on target is large, as shown in Fig. 1.11-5. Our efforts to improve different elements of the performance and cost modeling are described in the other sections of this chapter. The design optimization effort will integrate the results of this work together into a single optimization process that can efficiently evaluate numerous design alternatives. Within the next two years, we intend to develop a code that is fast enough to be embedded in an optimization loop and that maintains as much of the effects of diffraction and nonlinear propagation as possible. This will require considerable effort to speed up multidimensional-constrained optimization and to make a code that quickly calculates full propagation effects. We will probably have to increase our local computing power to the 1-2 gigaflop level to meet our goal, but even with such speed we will have to introduce numerous code improvements.

70-50-1195-2536pb01

Figure 1.11-5. Effects to be simulated in laser performance modeling.

References

1. J. H. Alexander, M. Troost, and J. E. Welch, ZAP Systems, Science and Software, for the Naval Research Lab, ARPA order number 660, Contract Number N00014-70-C-0341 (1971).
2. H. T. Powell, A. C. Erlandson, K. S. Jancaitis, and J. E. Murray, "Flashlamp Pumping of Nd:Glass Disk Amplifiers," *SPIE Proceedings, Conference on High-Power Solid State Lasers and Applications*, 1277 (1990), pp. 103-120.
3. K. S. Jancaitis and A. C. Erlandson, "Computational Model for Predicting the Energy-Storage Performance of Flashlamp-Pumped Nd:Glass Multisegment Amplifiers," *Lasers* 93 (1993).

1.12 Basic Physics, Material Properties, and Advanced Concepts

Introduction

Basic physics questions regarding the design and performance of ICF laser systems can sometimes be answered most efficiently in small-scale laboratory experiments. In some cases, such experiments naturally would precede more difficult and expensive demonstrations on larger scale systems, such as Beamlet. In other cases, small-scale experiments can provide a level of precision in measuring materials properties or a flexibility in trying advanced concepts that are usually not feasible with a large system. Thus, in terms of developing a scientific basis for designing and understanding ICF laser systems, it is clear that small-scale experiments play an important role.

We have several Nd:glass laser systems that potentially can contribute to the CS&T effort: the optical sciences laser (OSL) at LLNL, Trident at Los Alamos National Laboratory and smaller laser facilities at both LLNL and LANL. The OSL (see Figure 1.12-1) is a 100-J laser system operating from 100 ps to 10 ns, with significant pulse shaping (10:1) and bandwidth (>500 GHz) capability.¹ The output beam has an aperture of 8 cm and is 2 times diffraction-limited. The OSL uses a conservative design for reliable operation and routinely delivers more than 50 J to a large and well-instrumented experimental area. Los Alamos has several 1-J lasers that are suited to several of the CS&T tasks in this section.

Figure 1.12-2 shows the schedule for our CS&T development. This will be a collaborative effort between LLNL and Los Alamos in which Los Alamos will contribute to saturation measurements and nonlinear materials parameter measurements and LLNL will be responsible for the remainder.

1.12.1 Amplifier Energy Extraction

The NIF baseline calls for the beams to be arranged in groups of four beams, each one at a slightly different frequency. The wavelength of some of the beamlines may be 15 Å or more away from the peak of the gain curve. We expect that these beamlines will have lower small-signal gain and different extraction characteristics than will a beam operated at line center. Experiments are needed to measure the small-signal gain and saturation characteristics of flashlamp-pumped laser glass as a function of frequency offset. These experiments would precede and supplement similar work planned for Beamlet. The NIF pulses also will have 1 to 2 Å of FM bandwidth to suppress transverse SBS at 3ω in the output optics. It is important to investigate the gain saturation behavior for such FM-modulated pulses in order to understand whether these pulses will acquire temporal amplitude modulation as a consequence of gain saturation.

Since we do not have a fundamental predictive understanding of gain saturation in Nd-doped glasses, it is important that we measure the saturation characteristics of new laser glass compositions that are developed by the glass vendors. The techniques for making such saturation measurements have been well developed in past work.² The major determinants of the saturation characteristics of Nd:glass are the homogeneity of the spectral line and lower-level relaxation. Saturation data will be correlated with measurements of lower-level relaxation times recently made at LLNL using a direct measurement technique.³

70-50-1195-2535pb01

Figure 1.12-1. Schematic of the Optical Sciences Laser.

The gain-saturation studies will be carried out in FY95, as shown in Figure 1.12-2, and will conclude with a report on gain saturation for relevant laser glasses under a variety of conditions.

1.12.2 Frequency-Conversion Efficiency

Small-scale experiments on frequency conversion will be performed to validate computer codes used to simulate NIF performance and to conduct preliminary tests of alternative frequency-conversion schemes. Because the dynamics of frequency conversion are for the most part well understood, a primary unknown in predicting the performance of NIF frequency converters is the beam quality of the input 1ω beam. The key crystal parameters in baseline NIF frequency-converter design are the crystal thicknesses. Because conversion efficiency is sensitive to the input-beam characteristics, the process of selecting crystal thicknesses must be carried out using a simulated 1ω beam profile at the crystal array. The primary design tool is a suite of computer codes, ranging from elementary plane-wave models to full simulation capability of a beam with both temporal and two-dimensional spatial structure.⁴ The simple codes are fast and are

1.13 Beamlet Test and Evaluation

Description of the Beamlet Demonstration Project

The Beamlet Demonstration Project is a scientific testbed for the study of the technological issues of large, high-peak-power, multipass glass lasers. It allows full-scale study of many issues that cannot be adequately addressed using smaller facilities, and that would cause too much interference with target experiments if conducted at large target-shooting facilities such as Nova.

Figure 1.13-1 represents the Beamlet Demonstration Project facility, which is located in Building 381 at LLNL. Figure 1.13-2 is a schematic diagram of the laser hardware.

70-50-0695-1507pb01

Figure 1.13-1. Artist's conceptual drawing of the Beamlet Demonstration Project.

40-00-0294-0372A pub

Figure 1.13-2. Schematic drawing of the Beamlet Demonstration Project main laser system. A pulse from the preamplifier enters the main cavity near the focal plane of the intracavity spatial filter. It makes one round trip through the 11-slab main cavity amplifier and arrives back at the switch just as the Pockels cell rotates the polarization so that it can pass through the polarizer and reflect from the cavity mirror. It then makes a second double-pass through the main cavity amplifier, and returns when the Pockels cell is off. The pulse reflects from the polarizer and passes through the booster amplifier and transport spatial filter to the frequency converter.

The master oscillator and preamplifier system is an early prototype of the pulse-generation technology discussed in Section 1.1. It uses a diode-pumped oscillator and integrated optic modulators similar to the concepts described there. The pulse travels over a fiber-optic link to the main laser bay, where it is amplified to 1–10 mJ in a small regenerative amplifier, shaped into a square profile for injection into the main laser cavity, and amplified again in a four-pass rod amplifier to the energy necessary for injection into the main laser cavity (1–10 J). The front end contains a prototype of a deformable mirror wavefront correction system such as those discussed in Section 1.8.1, but with a smaller mirror.

The pulse from the front end is injected into a multipass cavity near the focal plane of the cavity spatial filter. In the baseline configuration, it makes one round trip (two passes) through a large cavity amplifier, which is one segment of a 2×2 amplifier array such as those discussed in Section 1.2. The pulse then reenters the spatial filter and emerges at the other end of the cavity, where it passes through a full-aperture plasma-electrode Pockels-cell (PEPC) switch such as that discussed in Section 1.3.1. On this pass, the Pockels cell rotates the beam polarization so that the pulse passes through a polarizer and reflects from a mirror to reenter the spatial filter and make another double pass through the cavity amplifiers. When the pulse returns, the Pockels cell has been switched so that the pulse reflects from the polarizer and exits the cavity. It then passes through a booster amplifier, transport spatial filter, and frequency converter. The pulsed-power system for the Beamlet uses the high-density capacitors and switching-mode charging supplies discussed in Section 1.6.

The Beamlet facility is instrumented throughout to carefully diagnose the spatial and temporal evolution of the laser pulse and the performance of the various

components for comparison to models and simulations of laser performance and optical propagation. The facility is also designed to allow amplifier slabs to be moved from one amplifier to another to test performance models. The transport spatial filter is designed to allow testing of the U- or L-turn reduced-aperture switch components discussed in Section 1.3.3 the first such test was performed in early FY95.

Important additions to the facility that will be completed in the near future (December 1995) are a beam-focusing system similar to that planned for the NIF target chamber and a complete set focal plane diagnostics. These systems will provide the capability to test a NIF-like focusing system at full 3ω fluence and to measure the irradiation patterns at and in the region surrounding the target plane at 3ω . The irradiation patterns of the residual energy at 1ω and 2ω can also be measured to assess their possible effect on the NIF target diagnostics. We plan to do experimental campaigns to measure the irradiation patterns directly from the frequency converters, after the addition of kinoform phase plates to provide focal spot smoothing, and with 2-D SSD beam smoothing. The focusing system will also provide the capability to do large-area damage testing of optics at 3ω with the residual 1ω and 2ω radiation present as in the NIF target chamber.

In the following, we review the technical issues and engineering studies to be addressed in tests using Beamlet. Many of these items are described under individual WBS numbers; however, they will not be studied in isolation but will be grouped into an integrated experimental plan in which more than one item will be addressed simultaneously. To aid in understanding the relative importance and the relationships between items, they have been grouped into seven categories. These are:

- 1.13.1 1ω Propagation Physics
- 1.13.2 Large-area Damage Tests
- 1.13.3 3ω Conversion and Final Focus Geometry
- 1.13.4 Output Diagnostics and Beam Smoothing
- 1.13.5 Beamlet System Engineering Improvements and Tests
- 1.13.6 NIF Component Tests
- 1.13.7 NIF Prototype System Tests

The WBS numbering is not meant to reflect priorities or the order in which tests will be done on Beamlet. The schedule for performing the tests follows the description of the items.

1.13.1 1ω Propagation Physics

In order to optimize the NIF laser design, we must understand in detail the physics issues that limit the 1ω performance of a NIF beamline. The items in this category are those that will validate our modeling of large lasers and will demonstrate performance equivalent to that required for the NIF.

1.13.1.1 Fill-factor in large lasers. We must demonstrate very high fill-factor (the fraction of the limiting component aperture that is filled with a uniform intensity profile) compared to existing lasers in order to reduce the cost per output Joule. This requires that we optimize the trade-off between sharp edges on the beam, alignment and distortion edge allowances, and spatial filtering. Experimental measurements on

actual large beams will be required to validate the theoretical models and assumptions we use to study these trade-offs. Diagnostics are in place to allow these measurements to be made during experimental campaigns for other purposes, but dedicated shots may be required. To optimize the fill factor of the Beamlet cavity amplifier requires a larger-aperture Pockels cell than the one currently on Beamlet.

1.13.1.2 Beam intensity modulation and focusability. Flaws and fabrication errors in optical components modulate the beam. These modulations evolve as a result of linear and nonlinear propagation in the laser and can damage beamline optics if they grow out of control. We model this evolution to determine the beam's near-field intensity modulation and focusability using fast Fourier transform propagation codes. These codes must be carefully validated by measurements on large systems. Beamlet is instrumented to make such validation measurements and additional diagnostics can be added as required. Print-through of the 1ω modulation onto the 3ω beam must be studied carefully for comparison to models. We plan several experimental campaigns to study these issues and can also take relevant data during campaigns to study other issues.

1.13.1.3 Smaller pinhole size and pinhole closure. Controlling near-field modulation on the NIF may require spatial filter pinholes with a cutoff angle as small as $100\ \mu$ radians, about one-half the size of those currently in use on Beamlet. These smaller pinholes require a small focal spot, tighter alignment tolerances, and are at greater risk of closure during the pulse. The benefit achieved from these smaller pinholes needs to be carefully evaluated in a Beamlet-sized laser operating with actual alignment tolerances. Because of the stringent alignment requirements, the start of a campaign to study these issues may require improvements in the alignment stability of Beamlet. Campaigns will study beam quality and fill factor versus pinhole size and pinhole closure with pinholes of various shapes and materials.

1.13.1.4 Operation at off-peak wavelengths. Because we propose to operate the NIF at four different wavelengths, we must show that the Beamlet performance at wavelengths shifted off the peak of the laser gain matches the computer models. This campaign requires a master oscillator operating at the appropriate wavelength. This capability will be provided by the NIF prototype oscillator system in the first quarter of FY 1997.

1.13.1.5 SRRS in N_2 and O_2 . We need to carefully evaluate the intensity path length product at which beam losses from stimulated rotational Raman scattering in N_2 and O_2 begin. Replacing the air in the beam tubes in the NIF switchyard with a gas that is less susceptible to SRRS is included in the NIF design and an experimental campaign to confirm that this design is necessary and adequate is required.

1.13.1.6 Redline performance. The maximum fluence at which we can operate Beamlet needs to be evaluated and compared with the computer models of Beamlet performance. This comparison will give further confidence in our ability to optimize and validate the NIF laser design. This campaign will require slowly increasing the output of Beamlet, perhaps at various pulse durations, as we monitor the diagnostics for an increase in near-field modulation, a decrease in focusability, and an increase in risk of optical damage.

peak-power efficiency approaching 85%. Similar measurements yielded 72% conversion efficiency from 37-cm aperture crystals with a 34-cm beam. The low-conversion efficiency of the larger crystals was attributed to poor wavefront quality of the large crystals caused by a combination of poor quality crystals and less than optimum mounting hardware. We will demonstrate the NIF design efficiency goal of 85% peak conversion with better quality crystals using a 35-cm beam. Reaching this goal may require more than one iteration on crystal quality, mounting hardware, and/or crystal thickness.

1.13.3.3 Separate lens from window. In the present NIF design, the focus lens serves as the vacuum window for the target chamber on each beam, thereby requiring thick focus lenses. This arrangement subjects them to an increased risk of damage from the high-fluence 3ω light in a location where catastrophic failure of a lens would cause extensive collateral damage to the interior of the target chamber. This increased damage threat could be alleviated by placing the conversion crystals inside the vacuum chamber and placing a 1ω transmission window on the chamber. The focus lens could be made thinner and the thickness of glass in the 3ω beam path would be minimized.

1.13.3.4 Three-crystal converter design. The low-energy conversion efficiency of the baseline two-crystal converter during the "foot" of a shaped pulse is a concern in the NIF design, and alternative designs with the potential for superior performance will be explored if tests of the two crystal design show it to be inadequate. An option to improve the energy-conversion efficiency is to employ a three-crystal design, which incorporates two type I doubling crystals followed by a type II tripling crystal. This scheme provides an optimum mix ratio of 1ω and 2ω energy to the tripling crystal over a wider range of 1ω drive intensities. If we decide to pursue this option, preliminary tests will be done on Optical Sciences Laser (OSL) but proof-testing must ultimately be done at full-scale on Beamlet.

1.13.3.5 60% conversion with the NIF pulse shape. We must demonstrate with Beamlet that we can produce the NIF pulse shape at the target. This will require producing the proper input pulse from the master oscillator, amplifying it in Beamlet, converting it to 3ω , and measuring the resulting pulse in the 3ω focus diagnostics. The goal will be to show $\sim 85\%$ peak and $>60\%$ average frequency-conversion efficiency from a large beam with a pulse shape similar to the NIF pulse and with acceptable reproducibility, intensity modulation, and beam divergence. A campaign to reach these goals will follow the completion of 1.13.3.2. A shortened NIF pulse (of up to 8-ns duration) can be produced in the present Beamlet front end. Producing the full-length NIF pulse will be done after installation of the prototype NIF preamplifier system, scheduled for December of 1996.

1.13.3.6 KDP gravitational sag. At their use angle, the large, thin, conversion crystals on NIF are expected to sag significantly from their own weight. This can largely be evaluated off-line but we may find it desirable to test the conversion efficiency of the NIF crystals at a typical use angle to confirm findings and predictions from the off-line tests.

1.13.3.7 SRS in KDP and KD*P. Losses and damage from transverse stimulated Raman scattering in KDP and KD*P are possible at the high intensities encountered on the NIF. We need accurate measurements of SRS intensity in KD*P as a function of 3ω drive intensity and pulse width in order to determine an accurate value for the gain coefficient and to validate modeling of transient noise source effects.

1.13.4 Output Diagnostics and Beam Smoothing

Activation of the 3ω focusing system and target plane diagnostics will allow us to do detailed measurements of the target plane irradiation distribution and to demonstrate that we can meet the NIF specification on the energy distribution in that plane ($> 98\%$ of the 3ω energy within a $600\text{-}\mu\text{m}$ spot). Installation and activation of the system will be followed by experimental campaigns to: 1) measure the 3ω focal spot; 2) measure the focal spot after the addition of a kinoform phase plate; and 3) measure the focal spot with 2-D SSD beam smoothing. We will also test the feasibility of using weak gratings to sample the 1ω and 3ω beams for laser diagnostics and look for prepulses that might affect the target.

1.13.4.1 Focal-plane diagnostics installation and activation. Installation of the focusing system and diagnostics, which includes two large vacuum vessels with their associated optics and hardware, will interrupt Beamlet operations for approximately 12 weeks. This will be followed by alignment of the optics and the initial activation and calibration of the beam diagnostics. Optical diagnostic systems dropped from the plan in FY 1995 because of budget constraints will be added in FY 1996.

1.13.4.2 Focused spot characterization. This experimental campaign will be an integrated demonstration of beam transport through the full system to the target plane, including phase correction with the deformable mirror to the extent possible. Near-field and far-field images of both the 1ω and the 3ω beams will be taken at low and intermediate powers and at the highest power available within the damage constraints on Beamlet. Shots may also be taken with various size obscurations in the far-field image in order to better quantify the energy scattered outside of the primary focal spot.

1.13.4.3 Kinoform phase plate focal-spot characterization. This campaign extends the previous one (1.13.4.2) to include a prototype of a kinoform phase plate designed for focal-spot smoothing, allowing us to validate the performance of the NIF baseline smoothing scheme in the target plane. This campaign also tests for damage and other propagation issues at 3ω introduced by adding the kinoform phase plates. Results from these experiments will be compared to our propagation models to show we can accurately predict the irradiation profile of the target spot under realistic operating conditions.

1.13.4.4 Gratings for beam sampling at 1ω and 3ω . The NIF laser diagnostics systems use low-efficiency gratings to sample both the large-aperture, high-power fundamental (1ω) and third harmonic (3ω) beams. These gratings are required to divert $<1\%$ of the beam into the diagnostics package, preserve the intensity and phase profiles of the beam to within a few percent, and not perturb the sampled beam. We plan to test prototypes of these gratings on Beamlet to characterize their sampling uniformity and repeatability and their durability in a high-power beam. The first grating to be tested will be one that will be used to sample the 1ω output beam. This will be followed later by tests of a grating that will be used to sample the 3ω beam in the focusing vessel.

1.13.4.5 Two-dimensional beam smoothing by spectral dispersion (2-D SSD). Smoothing by SSD is not included in the NIF baseline design. It will become important if the NIF is required to add direct-drive ICF capability. For this reason we have included an experimental campaign to test 2-D SSD on Beamlet. This experiment will require modification of the front end of Beamlet to install the SSD components and will make use of the 3ω focal-plane diagnostics to assess the focal spot. A key requirement of

this effort is to show that sufficient bandwidth can be propagated through Beamlet spatial filter pinholes without introducing undesirable amplitude modulation by clipping the optical spectrum.

1.13.4.6 Residual 2ω incident on the hohlraum. This measurement is important to the target diagnostic scientists to assess the effect of residual radiation on the target to their instrumentation. This measurement can probably be made during one of the previous campaigns but may require a few dedicated shots. Diagnostics to make this measurement are part of the baseline focal-plane diagnostic system.

1.13.4.7 Prepulse intensity. Prepulses caused by ghost reflections or by amplified spontaneous emission could affect the NIF target or the laser diagnostics on both Beamlet and NIF. We plan to install output diagnostics to measure the intensity of prepulses on Beamlet to aid in anticipating prepulse problems that might occur on the NIF.

1.13.5 Beamlet System Engineering Improvements and Tests

This category includes engineering evaluation of Beamlet and tests of improvements to Beamlet, most of which have direct application to the NIF. A few of these items require dedicated shot time but many can be done as "ride-along" experiments or done during periods when Beamlet is not doing shots for experiments. Many of the items will require some down time to modify or install hardware.

1.13.5.1 System repeatability, reliability, and damage. This activity includes both monitoring of system shots to detect optical damage and problems in performance and dedicated shots to check for long-term changes in performance or calibrations. It includes a number of standard shots taken at regular intervals to detect for abrupt or gradual changes. As a result of this monitoring, problems may be identified that require upgrades or changes in Beamlet or additional diagnostics may be required to more thoroughly understand a problem.

1.13.5.2 Control of ghost beams and back reflections. Stray reflections (ghost beams) are a major design issue in multipass systems. They propagate both forward and backward and can cause damage in both the input and output optics. They can also damage components or cause obscurations when they come to a focus in the laser. Options for their control must be studied and tested under real operating conditions. In FY 1996 we will try using tilted spatial filter lenses to eliminate ghost beams that propagate through the amplifiers and are amplified by the residual gain. These beams caused damage to the U-turn optics during their first test. Back-reflections from the spatial filter pinholes and the NIF target are also a concern, because the large-aperture optical switch in the baseline design provides the only isolation. Leakage through the switch makes four passes through the amplifier and has the potential of damaging the front end. In the Beamlet shot plan we have included a series of shots to assess isolation problems and to reconfigure the isolation system for further tests if necessary.

1.13.5.3 Amplifier thermal-recovery time. Thermal recovery of the amplifiers limits the time interval between shots on Beamlet and will also be a limiting factor on NIF. It may be possible to significantly reduce the thermal-recovery time by actively cooling the amplifier flashlamps. Assessing the benefit of this is probably best done in the amplifier-characterization laboratory. The Beamlet plan includes monitoring of the thermal recovery of the amplifier after a shot in its present configuration and perhaps

repeating the measurements again after an active gas cooling system is installed. The measurements can all be made outside of normal working hours but considerable resources would be required to install an active gas cooling system.

1.13.5.4 Alignment stability. It is critical that Beamlet precisely maintains its alignment from the time it is finalized until the shot is fired, presently 30 minutes to 1 hour. A misaligned beam that hits a spatial filter pinhole can cause a back reflection that can severely damage the laser optics. This issue becomes particularly critical for the 100 μ -radian cut-off pinholes that are one-half the size of the current Beamlet pinholes. We will first attempt to reduce alignment instabilities caused by mechanical vibrations that are normally present in the Beamlet high bay. If this does not solve the problem, an alignment system that actively maintains the alignment will be necessary to reduce the risk of hitting the pinholes before undertaking the small pinhole experiments. This system will be built with NIF prototype parts and will also test the alignment concepts proposed for the NIF. As a feasibility test, we plan to demonstrate that Beamlet can provide the pointing accuracy required for the NIF targets (7 μ rad) by maintaining alignment to this accuracy in the 3ω focusing vessel.

1.13.5.5 Adaptive optics system. The present adaptive optics system has been most effective in correcting the wavefront of the Beamlet output beam on the first shot of the day. Thermal turbulence in the N_2 in the amplifiers caused by their firing persists for several hours and cannot be corrected by the present system that must be locked onto a correction several minutes before the shot is fired. Modifying the present system to monitor and correct the wavefront up to 1 second before shot time would allow us to correct for this thermal turbulence and make the adaptive optics system more effective. Present plans are to have this upgrade in place during the summer of 1996.

1.13.5.6 Polarizer depolarization loss. Evaluation of the losses from the polarizer would aid making estimates of similar losses in the NIF, a quantity that is useful in evaluating the laser design. We plan to measure the polarizer losses on Beamlet during pulsed operation on a "ride-along" basis.

1.13.6 NIF Component Tests

A number of NIF components require system proof-tests or evaluation as a step in their design process. Component testing will be done off-line, making use of smaller facilities to the maximum extent possible; however, some tests will require the beam size and fluence that can only be reached in the full-size Beamlet or require the sophisticated diagnostics that are available only on Beamlet. The following is a list of such tests that have been identified up to May 1995.

1.13.6.1. Improved laser slabs. Many of the Beamlet laser slabs have a poor surface finish or small-scale internal inhomogeneities that must be identified and corrected before the NIF production cycle begins. Improved laser slabs (as they become available) will be used to replace those that are out of specification and the resulting improvements in beam quality will be quantified.

1.13.6.2 Sol-gel cavity mirror. Sol-gel high-reflectivity mirrors are being developed in collaboration with the Centre d'Etudes de Limeil-Valenton, as discussed in Section 2.5, and could be installed as cavity mirrors to validate that use in the NIF. These could be on replicated substrates, possibly figured to compensate for pump-induced astigma-

tism in the amplifiers. When available, a sol-gel mirror will be installed in Beamlet and tested as a cavity component during routine operation.

1.13.6.3 New laser glass composition. We shall have 5–8 Beamlet-sized slabs of a new Schott glass formulation (LG770) optimized for low-cost manufacture, and we may have slabs of a new Hoya glass formulation, as discussed in Section 2.1. It is not desirable to commit to using a new type of glass without full-scale tests that evaluate high-fluence extraction and damage performance, edge-cladding integrity on the new glass, fabrication errors, solarization from flashlamps under highly pumped conditions, and other performance issues. The slabs can be installed in the booster amplifier of Beamlet and can be tested with minimal effort. LG770 slabs will be available in the fall of 1995.

1.13.6.4 Debris shields. It is desirable to have low-cost, easily replaceable shields to protect the focusing optics from debris from the NIF target. Such shields, must have high optical quality, high damage threshold, and low losses at 350 nm. Much testing can be done off-line, but the Beamlet 3 ω focusing vessel is an ideal location to proof-test debris shield concepts.

1.13.7 NIF Prototype System Tests

In addition to NIF component tests, there are also prototype system tests that conveniently can be done on Beamlet. Some of these tests take advantage of the flexibility originally designed into Beamlet to evaluate alternative multipass configurations or alternate amplifier arrangements, others simply substitute a NIF prototype system for the currently operating Beamlet system. Most of these tests are scheduled for late in Beamlet's lifetime after the basic propagation, frequency conversion, and beam-focusing issues have been resolved.

1.13.7.1 NIF deformable mirror. As currently envisioned, the NIF deformable mirror will be a 40-cm aperture mirror that replaces one of the cavity end mirrors. Final proof-testing of such a mirror is best done on Beamlet, which has a multipass geometry and active and passive optical aberrations similar to NIF. The current schedule shows these tests beginning during the fall of 1995.

1.13.7.2 Injection into the transport spatial filter. The Beamlet input beam is presently injected into the cavity spatial filter. The NIF design has injection into the transport spatial filter, thus, reducing input energy requirements. However, transport filter injection constrains the system alignment more severely, introduces additional sources of wavefront distortion, and may present a larger risk from ghost beams propagating in the cavity. To test these issues we plan a test of injection into the transport filter on Beamlet in FY96.

1.13.7.3 NIF alignment and diagnostics systems. The Beamlet alignment system compares three alignment strategies; numerous other alignment and diagnostic concepts have also been suggested. The system in the NIF CDR contains several advanced concepts not included in the present Beamlet system, as discussed in Sections 1.7 and 1.8; these concepts must be tested on a large system before we commit to including them in the NIF design. Examples of these features are fiber-optic reference sources, beam samplers based on weak diffraction gratings, and other advanced concepts. Other alignment aids and diagnostic sampling techniques have been proposed, such as beam-edge sensors using leaky optical fibers and alignment based on laser range-finder con-

cepts. These must be tested on a large system before they are considered seriously. Beamlet is an appropriate facility for such tests.

1.13.7.4 Final optics protection. Alternate concepts other than debris shields for protecting the final focusing lenses are being considered for the NIF. One such concept is propagating the beam to focus in a low-pressure background gas. These alternate schemes are best evaluated in the Beamlet 3ω focusing vessel.

1.13.7.5 Alternative amplifier and cavity geometries. The baseline Beamlet amplifier slab distribution has 11 slabs on one side of the spatial filter in the multipass cavity, zero slabs in the cavity near the switch, and 5 slabs in a booster section. This distribution reduces the fluence on the polarizer (by placing slabs outside the cavity) and optimizes performance for ~ 3 -ns pulses.

The ignition pulse shape currently projected for NIF is somewhat longer than 3 ns, and may be as long as 5 ns in the 1ω part of the laser, if we use full-aperture, shaped-pulse frequency conversion. This longer pulse favors a more even split between the two amplifiers than the Beamlet baseline. Higher-damage-threshold polarizers would favor placing more of the slabs inside the cavity. Beamlet is configured to allow rearrangement of the amplifiers to test these alternative arrangements.

1.13.7.6 NIF preamplifier system. A prototype of the NIF preamplifier system will be completed during the fall of 1996. It will be able to provide the full-duration NIF pulse shape and is required for the final Beamlet tests of the NIF pulse shape. Plans are to install it to inject into the Beamlet transport spatial filter beginning in December of 1996. The following shot series will provide a thorough operational test of this preamplifier system.

1.13.7.7 Power balance control. Achieving power balance on the NIF will be done with a feed-back loop from the beamline output to modify the pulsed shape generated in the front end. It includes a timing system to synchronize the front end outputs. We plan to test a single beamline pulsed shape control system on Beamlet as a part of the development effort for the NIF power balance control system.

Schedule through FY97

The previous section describes the issues to be addressed in Beamlet experiments and engineering tests. These items will not be studied individually, but will be grouped into experimental campaigns where more than one item will be studied simultaneously. The extensive set of diagnostics on Beamlet allows this to be done efficiently. Many of the system engineering test and improvements and NIF component tests will be done as "ride-along" studies that are transparent to the primary activities. Some down-time for installation of hardware may be required for several of these items. Figure 1.13-3 is a schedule of the major activities, showing both primary activities and ride-along studies. In the near term, effort is concentrated on completing the 3ω focusing system and focal plane diagnostics. This will be followed by campaigns to characterize the 3ω focal spot, first without smoothing aids, followed by tests with a kinoform phase plate and with beam smoothing. During this period we will begin to address the issues of beam intensity modulation and pinhole size. Other studies will follow as shown in the schedule. The schedule shows activities through FY 1997 when the majority of the effort will be tests of NIF prototype systems.

■ Primary activities
 ■ Ride-along studies

Figure 1.13-3. Beamlet Phase II development schedule.

2.0 Optics Manufacturing and Processing

Introduction

Laser materials and manufacturing development in support of advanced solid-state lasers is a long-standing commitment by the ICF Program. Historically, this effort has produced such notable achievements as platinum-free phosphate laser glass, epoxy-bonded edge cladding of slabs, diamond-turning of KDP crystals, high-damage-threshold KDP crystals grown using continuous ultrafiltration, damage-threshold improvement of thin-film coatings and crystals by laser conditioning, and inexpensive and extremely efficient sol-gel antireflection coatings. Two of these developments, platinum-free laser glass and epoxy-bonded edge cladding received R&D 100 awards in 1987 and 1988, respectively. Many of these and other development activities were either performed in conjunction with qualified vendors or quickly transferred to industry in order to place the technology in a production environment. In this manner, the needs of the national ICF Program have been efficiently served, and the U.S. laser and optics communities have benefited. It is noteworthy that this form of "technology transfer" predated the current U.S. government emphasis on technology transfer by more than a decade.

The approach to optics manufacturing development for the National Ignition Facility (NIF), the primary beneficiary of the Core Science and Technology Development effort, is a continuation of this R&D philosophy. We will work with industry to adapt or advance its own existing proprietary processes and to incorporate our evolving capabilities into a production facility. Our goal is to work with two or more vendors in each manufacturing area, each taking its own route to improving its manufacturing capabilities to produce low-cost, high-quality NIF optics. This route minimizes the technical risk associated with committing to a single vendor early in the development effort, fosters a healthy competition to help guarantee the lowest possible price for NIF optics, and enhances confidence in the delivery schedule. This approach has been successful in past laser projects at LLNL and the University of Rochester, and is expected to continue to be successful for the NIF.

The NIF baseline design consists of 192 individual beamlets, of approximately 40-cm $\times$ 40-cm aperture. Each beamlet has 19 amplifier slabs, 5 lenses, either 7 or 8 large mirrors (depending on the beamline), 1 switch polarizer, 3 crystals, 3 windows, and a debris shield, for a total of 39 to 40 full aperture optics. This totals to 7520 large optics for the NIF. Spares required for the construction and initial operation increase this total to approximately 8500. In addition, the NIF has approximately 10,000 small (<15-cm-diameter) optics in the optical pulse generation (OPG) system and an additional 20,000 small optics for alignment and diagnostics.

In Table 2.0-1, the route to achieving the projected optics costs for the NIF is summarized. These activities are further discussed below. Significant markers and milestones for the development program are given in Fig. 2.0-1 and discussed in greater detail in conjunction with the manufacturing development details in Sections 2.1 through 2.8.

Table 2.0-1. Optics manufacturing development activities to reduce NIF costs.

Discipline	Cost reduction results
Laser glass blanks	<ul style="list-style-type: none"> • Advanced melting and forming process. • High-throughput postprocessing (coarse anneal, fine anneal, QA, fabrication). • Improved batching and raw materials.
Crystals	<ul style="list-style-type: none"> • Rapid-growth technology; high growth rate and yield. • Improved finishing, orientation, and interferometry.
Fused silica blanks	<ul style="list-style-type: none"> • Optimized boule geometry. • Improved process design and control for smaller inclusions, higher yield. • More-efficient shaping and interferometry.
Flats fabrication	<ul style="list-style-type: none"> • Deterministic figuring. • Improved grinding. • More-efficient shaping, cladding, and inspection.
Lens fabrication	<ul style="list-style-type: none"> • High-speed polishing. • Deterministic figuring.
Coatings	<ul style="list-style-type: none"> • Improved process design and control for high yield (spectral). • Reduced influence of defects to improve yield (damage). • Sol-gel high-reflectivity (HR) mirrors.
Gratings/phase plates	<ul style="list-style-type: none"> • Meniscus coating of photoresist. • Holographic exposure and wet or reactive ion etching.

2.1 Laser Glass

Introduction

Amplifier slabs, an example of which is shown in Fig. 2.1-1, are responsible for more than half of the cost of the NIF optics; the cost of the laser glass blanks, in turn, dominates the cost of the finished slabs. Hence, reducing the cost of the laser glass is of utmost importance. The laser glass cost will be reduced by focusing a development program in four areas: (1) an advanced melting and forming process; (2) high-throughput postprocessing to reduce the cost of annealing, shaping and grinding, and QA; (3) improved batching and raw material selection; and finally (4) yield enhancement of the entire process. The technical issues and development plan are discussed below.

Technology Status

Laser glass is the energy storage medium of the laser. It absorbs energy emitted by the electrical discharge of the flashlamps and stores it by a corresponding excitation of a

70-33-0394-1401

Figure 2.0-1. Timeline and deliverable schedule for optics manufacturing development.

dopant ion (in this case neodymium). During this process the neodymium ions populate a relatively long-lived metastable excited state. When a subsequent laser pulse propagates through the amplifier glass, it extracts the stored energy by stimulating the transition of these excited ions to a lower energy state. The photons emitted in this process exactly match the wavelength and phase of the propagating pulse, thereby producing a gain in the laser pulse energy.

To carry out the above function, the laser glass must meet a number of specific performance requirements that, in turn, are closely coupled to the glass manufacturing process. These requirements and their impact on the requirements of the manufacturing process are listed in Table 2.1-1.

70-50-0393-0716 pub

Figure 2.1-1. Beamlet amplifier slab.

With each successive ICF laser, we have had to develop new glasses and manufacturing methods that would meet the specific performance requirements of that particular laser system. In this respect, NIF is no different. The advantage with NIF is that much of the fundamental physics and chemistry of laser glasses has been explored. In fact, as part of this prior effort, LLNL compiled a series of laser glass catalogues that are still in worldwide use today. These catalogues detail the properties of an extensive set of both commercial and specialized laser glasses that have been developed over the 20-year period of our research in this area. This research has led to major improvements in the laser glass composition. For example, all the lasers up through Shiva used silicate laser glasses that gave suboptimum laser performance. The development of the Nova laser system led to the use of phosphate laser glasses that showed much-improved energy storage and extraction properties and lower nonlinear indices of refraction. In addition, working jointly with Hoya and Schott, we discovered how to effectively control damage-causing platinum inclusions from phosphate glasses, a problem that has plagued the solid-state laser field since its very beginning.

Table 2.1-1. General performance requirements for laser glass and the corresponding requirement for the manufacturing process.

Performance requirement	Glass-manufacturing process requirement
High transmission at laser wavelength	<ul style="list-style-type: none"> • High-purity raw materials. • Low contamination during manufacture.
Low wavefront distortion	<ul style="list-style-type: none"> • Homogeneous glass melting and forming method. • Annealing to reduce stress.
High damage threshold	<ul style="list-style-type: none"> • Corrosion-resistant melting container. • Elimination of discrete (undissolved) impurities.
High absorption of flashlamp light	<ul style="list-style-type: none"> • Select proper dopant ion. • Proper glass matrix. • Low-absorbing impurity content.
Low nonlinear refractive index	<ul style="list-style-type: none"> • Proper glass matrix composition.
Efficient energy extraction	<ul style="list-style-type: none"> • Dopant ion and glass matrix.
Low scattering	<ul style="list-style-type: none"> • Glass and glass melt/forming/annealing process stable against devitrification or phase separation.
Long energy-storage time	<ul style="list-style-type: none"> • Selection of proper dopant ion and glass matrix. • Manufacture of index-matched edge cladding.

In regard to the melting/forming process, note that the actual magnitude of the laser glass production is not so much the issue as is the fact that the rate is intermediate between typical small- and large-scale production methods now used by the laser glass companies. For previous ICF lasers, the scale of melting was similar to that associated with "specialty melts" that are carried out using batch processes. By batch process, we mean that a single batch of raw material is processed to produce a single (or perhaps a few) laser glass blanks; the identical process is then repeated. Although ideal for small glass orders, the disadvantages are that the rate is low, the process is both capital and manpower intensive, and the process never reaches "steady state," thereby requiring that each melt (glass piece) be rigorously inspected and tested. In contrast, for orders of large volumes of optical glass (such as optical glasses that are bought as a commodity), continuous glass-manufacturing processes have been developed. After a short start-up period, a continuous process reaches a steady state, producing a continuous flow of glass with minimal variations in glass properties from one piece to the next. For example, BK-7, one optical glass produced in this fashion, is commonly used in precision optical systems such as high-quality cameras and binoculars. Optical glasses for

ophthalmic use also are produced by continuous melting. Both laser glass manufacturers have proposed to develop an advanced melter that is capable of producing laser glass at the quality and rate we require for the NIF.

The second development activity is to improve the postprocessing of the laser glass. Compared to melting and forming of a laser slab, which may take on the order of a day or less, postprocessing of a slab can take months. This is largely because of the careful thermal annealing needed to produce the required optical homogeneity. In addition, current QA methods require that the glass be partially polished ("inspection polished") and damage tested through the entire volume. Nearly all of the postprocessing steps are time consuming and capital intensive.

The third development activity is improved batching and raw materials. The raw materials used in the production of phosphate glass can give rise to special handling or environmental issues. Consequently, development activities will be aimed at mitigating potential problems in this area. In addition, some of the glass raw materials are quite expensive, particularly the neodymium dopant. We intend to work with raw material manufacturers to reduce the cost of the glass raw material.

The fourth and final area for development is yield improvement. The yield of laser glass is dominated by two factors. One is the amount of waste glass associated with each casting, and the second is the number of rejected castings. Castings can be rejected for not meeting any of the performance specifications given in Table 2.1-1 and are usually associated with the specific process steps listed. Castings can also be lost by errors or problems in postprocessing steps (e.g., fracture while handling or errors in fabrication). The development plan is aimed at improving both of these yield factors.

Development Plan and Schedule

The successful manufacture of the large quantity of laser glass needed for NIF will require a sustained, three-year development effort. The goal of this effort is to develop an advanced manufacturing process that is capable of producing the required volume of laser glass over a three-year period at a quality consistent with NIF requirements and at as low a cost as possible. In the previous section, we outlined the technical issues that drive the laser glass development. In this section, we briefly describe the non-proprietary aspects of the manufacturing development plan. A top-level Gantt chart of the plan is shown in Fig. 2.1-2.

Both of the major laser glass manufacturers have devised separate plans and both plans can be executed in a three-year period, provided sufficient funding is available.

Glass Selection

Prior to the start of production development, a glass composition must be selected. The standard LHG-8 (Hoya) and LG-750 (Schott) glass compositions are used in the baseline for NIF. However, we also have developed and characterized several new glass compositions that have improved performance and manufacturing properties than those of the baseline glasses and therefore offer the potential for lower cost. These glasses are in the final stage of characterization.

● = marker

◆ = milestone

Figure 2.1-2. Schedule of activities and milestones for laser glass development.

Advanced Melter Design, Construction, and Operation

Development of an advanced melting and forming process is key to meeting the production rate required for the NIF laser glass. The development plan calls for the design, procurement, construction, and operation of scaled versions of the advanced melter and forming systems. If possible, this phase of the development will be accomplished with only one, scaled version of the melter. The developmental melters would be designed to yield high-quality laser glass but not necessarily at the size or rate of the final production version. An integral part of this activity is the forming process, where the glass is cast into blanks that are later fabricated into the laser slabs. The developmental melter will be used to supply the needed quantity of molten laser glass required to test the advanced forming methods.

Another important aspect of the melting process is to develop and test any environmental equipment needed to control the gaseous effluents from the melter. The scaled melters will be used to test the environmental control systems.

This melting and forming activity is expected to last almost the full duration of the laser glass development effort (2.5 years). Our goal is to begin initial melter tests within about one year after the start of development; these tests will continue at regularly spaced intervals of about 6 to 9 months.

The results from this effort will yield a successful melter and hot-forming design that will then be built to the full-scale required for NIF.

Improved Postprocessing Methods

Postprocessing of the laser glass refers to all the steps that follow casting of the laser glass into the final blank. These activities generally can be grouped into annealing, QA, and final fabrication. The annealing step can take many weeks, thereby requiring a large capital investment in annealing ovens to keep pace with the production rate. We intend to improve annealing ovens and annealing cycles to reduce this impact on the laser glass cost. The annealing development will begin about a year after the beginning of development and will last about 12 to 15 months.

The second major postprocessing step is slab inspection. With the advanced melter design, we feel that continuous, steady-state production of the glass will be possible, thereby leading to minimal piece-to-piece variations in the laser glass quality. Therefore, this development activity will focus on (1) verifying the steady-state properties of the laser glass produced by the advanced melter and forming system and (2) developing acceptable statistical inspection methods. In addition, we will develop more advanced, low-cost inspection techniques than are in use today. Most noticeably, we will develop improved platinum-inclusion and optical-homogeneity inspection methods. This effort will run on a schedule in parallel with the melting and hot-forming schedule discussed above.

Raw Materials and Batching

The raw materials used for laser glass are high purity (high cost) and, in some cases, can be chemically unstable if improperly mixed. Some raw materials also require more environmental controls than do others. We will work with the raw material suppliers to develop lower-cost, high-purity materials and also support development at the vendors to optimize the batching method so that it has a minimal impact on cost and the environment. This activity will start at the beginning of the laser glass development program and be completed within the first year.

Yield Improvement

Yield improvement encompasses all the steps in the glass manufacturing process. In terms of reducing the amount of waste glass, we will develop advanced forming methods that minimize the amount of glass that must be removed to get to the final slab dimensions. Previous batch-melting processes led to very large amounts of waste glass; the advanced forming schemes will dramatically reduce this.

The second major yield-improvement development will focus on reducing the platinum inclusion content in the laser glass consistently. Because inclusions so critically affect the glass yield and therefore cost, this has been an ongoing research activity at LLNL for several years and will continue throughout the entire three-year development effort.

2.2 KDP/KD*P Crystals

Introduction

The manufacture of the large crystals of KDP and deuterated KDP (KD*P) used for Q-switching and frequency conversion is a source of cost and schedule risk. The

estimated cost for the NIF crystals, before optical finishing, is dominated by the cost of the KD*P crystals used in the optical switch and the third harmonic generator (THG) plates. Significant schedule risk stems from the very long time required to grow the large crystal boules from which these plates are produced. Figure 2.2-1 shows the Beamlet KDP boule next to a Nova KDP boule for size comparison. Approximately two years is required at present to grow the $50\text{-} \times 50\text{-} \times 80\text{--}100\text{-cm}^3$ boules necessary to produce 37-cm-aperture doubler plates. Currently, the average yield of plates from one of these boules is lower than desired due to the numerous problems that can arise during this long growth cycle. These problems include cracking, spurious nucleation, low laser damage threshold, and high strain-induced birefringence. The cost of KDP/KD*P crystals is largely determined by the growth rate and yield of plates from each boule. Because these effects compound, modest improvements in both growth rate and yield are equivalent to large improvements in either individual area. The NIF cost goal for unfinished crystals is a factor of 8 below the current price. Based on past trends reflected in their learning curves for crystal costs, both Cleveland Crystals and Inrad, the two major KDP/KD*P crystal growers in the United States, have indicated that this goal can be achieved through increased growth rate and yield.

CLEVELAND CRYSTALS, INC.

70-59-1093-3487 pub

Figure 2.2-1. Beamlet KDP boule (left) displayed next to a Nova KDP boule (right).

Fabrication of the optical surfaces on KDP/KD*P crystals is currently done by single-point diamond turning. Diamond turning is generally more expensive than conventional polishing and is therefore reserved for applications in which polishing is particularly difficult or inappropriate. KDP and KD*P crystals are difficult to polish by means of conventional techniques, which usually leave streaks (fine scratches that can cause laser damage). In addition, precise crystal axis alignment with respect to the physical dimensions of the finished piece can be maintained far better with diamond turning than in conventional polishing. The diamond-turning process currently used at Cleveland Crystals can be improved substantially and possibly can be combined with an improved polishing procedure to reduce the crystal finishing cost by a factor of 2.

Technology Status

KDP crystals grow in a regime in which both the supersaturation of the growth solution and the flow rate past the growing faces influence the growth rate. Hence, the growth rate can be improved by increasing either of these parameters. Each approach has disadvantages, however. When present growth techniques are used, raising the supersaturation makes the solution more susceptible to spontaneous nucleation. Increasing the flow rate can produce unwanted turbulence, which can induce local growth-rate fluctuations, solution inclusions, and accompanying strain.

Recently, scientists in Russia demonstrated an improved solution treatment and growth process that enables very high supersaturation to be used without generating spontaneous nuclei. This method is undergoing further development at LLNL with the aid of the Russian scientist who demonstrated this breakthrough. Scale-up and transfer of this technology to the vendors would enable them to increase their growth rates by 200% to 2000%.

The crystal yield is defined as the actual number of plates obtained from each boule relative to the maximum number that could be harvested from a perfect boule of the same size and shape. Larger boules usually have higher strain and are more likely to crack, especially early in the growth run. Spontaneous nucleation can also occur early in the growth cycle for larger boules. Ultrafiltration techniques, which remove small particulates, have been shown to increase damage threshold and reduce scattering sites in the crystal and solution (where they can act as nucleation sites), thereby improving yield. The rapid-growth method noted above has demonstrated the potential for exceptionally high yield due to the reduced size of the regeneration region and reduced dislocation density. Optimizing these techniques will improve the yield and therefore reduce the number of boules that must be grown.

Bulk laser-damage thresholds in KDP crystals require conditioning to meet Beamlet and NIF requirements. While laser conditioning has proven successful for this purpose at small scale, its application to large areas is less certain and will be labor intensive. Recent experiments have shown that thermal annealing can also be used to condition KDP crystals, whereas successful KD*P thermal conditioning has not yet been demonstrated.

Surface-damage thresholds at the third harmonic wavelength must be maintained at or above the bulk values. The current diamond-turning process produces surfaces that meet this requirement. However, these surfaces induce a slight modulation to the

wavefront because of residual errors from the diamond-turning machine. This modulation can be reduced by improving the diamond-turning process, or by postpolishing.

Benefits to the ICF Program, NIF, and U.S. Industry

KDP crystals are a vital part of all fusion lasers and will remain so for the foreseeable future. Any development effort that improves the quality, reduces the risk, or reduces the cost will directly benefit the NIF and, in the long run, the ICF program. In point of fact, the NIF cost goals for KDP and KD*P crystals in the optical switch and frequency converters can be met only following significant development. Based on learning curves for vendor costs since Nova, the projected cost decrease following successful development is greater than a factor of 2.

Because the basis for rapid-growth technology is applicable to solution-grown crystals in general, the potential benefits to the U.S. crystal-growth industry are substantial. There are a wide variety of solution- or flux-based crystals whose cost is high and whose application is limited by the available crystal size. If applied to these systems, rapid-growth technology could give U.S. companies a significant edge over their competitors.

Development Plan

LLNL's development plan has four primary goals: (1) to increase growth rates, (2) to increase yields, (3) to increase damage thresholds and (4) to ensure that the vendors have the technical abilities to produce a NIF-size order. Toward this end, LLNL will act aggressively to scale up the rapid-growth technology. Our goal is to deliver 50- × 50- × 50-cm³, low-strain, high-damage-threshold crystals grown at 5 to 30 mm/day.

A crystallizer capable of growing NIF-size boules has been fabricated and assembled at LLNL. Operation began in May 1994, with the first large boules expected to be grown starting in December. As indicated in Fig. 2.2-2, a NIF-size boule from which plates can be fabricated will be grown by late-FY95. These plates will be tested for strain birefringence and transmitted wavefront. Representative witness samples will be fabricated and damage tested. The large plates will then be incorporated into the integrated testing program for performance evaluation. A report on the material quality based on these tests will be written in November 1995. A constant-temperature version of this crystallizer will be built, tested, and compared to the current crystallizer design, which uses a decreasing temperature ramp to grow the crystal. A crystallizer design capable of growing crystals for the NIF will be available in January 1997. This will support the NIF facilitization schedule, which begins at the start of FY97 with the ordering of major equipment and modification of facilities.

Concurrently, LLNL will work with the vendors to transfer this technology to the production floor. LLNL has had two small-business technology transfer initiatives approved which, starting in a few months, will fund two leading U.S. crystal-growth companies. Transfer of the technology for growing full-size boules will begin in earnest in early FY96, to support facilitization starting in FY97.

The second component to reducing the crystal cost is increased yield. Yield is limited primarily by internal strain. As discussed above, the large boules required for

● = marker

◆ = milestone

Figure 2.2-2. Schedule of activities and milestones for KDP/KD*P development.

Beamlet have exhibited high levels of strain, which have limited the yield of high-quality crystal plates. This strain is strongly influenced by the presence of dislocation bundles, which originate in the initial capping process at the beginning of growth. Crystals grown by the rapid technique have fewer dislocations and have been shown to be of high quality from the beginning of growth to the end. It is expected that this quality can be maintained in scaling up the process to NIF requirements, but it has yet to be demonstrated.

The performance of NIF is limited by the damage threshold of the tripling crystal. At present, this crystal is deuterated KDP, which is required for suppression of SRS. The bulk damage threshold of KD*P produced for Beamlet is adequate to meet the NIF requirements, but further improvement would enable operation at higher fluence, which would in turn increase the target design margin. The damage threshold of KDP and KD*P grown using conventional techniques has increased steadily during the last several years; further improvements are thought to be possible. We have very little damage data from rapidly grown crystals. The initial results place the quality of these crystals in the range measured for Beamlet. The damage threshold of KD*P at 351 nm is comparable to, but slightly below that of KDP for the Beamlet crystals. If the damage threshold of KDP is significantly higher than that of KD*P at the time of final design for the NIF, it may be advantageous to segment the tripler into a 2×2 array (thereby addressing the SRS problem) and use KDP. This option would introduce a loss by blocking the beam with the crystal mounting fixture, which could be offset by running at higher average fluence. The finishing and mounting costs of this option would be higher than the baseline, but the crystal cost could be significantly lower.

The mechanism for damage in bulk KDP and KD*P has yet to be elucidated. With the advent of ultrafiltration, we judge that the defects which dictate the damage threshold are different today than they were 10 years ago. Careful microscopy before and after damage tests show that the defects are sub-micrometer, since the material is generally free of any defects at damage sites. Thermal annealing experiments provide further evidence that damage is dominated by point defects. In thermal conditioning, the material is heated only to about 400 K for 48 hours, but significant enhancement (2-3 $\times$) of the damage threshold is observed at 1 μ m. Interestingly, very little improvement has been observed at 355 nm, although the severity of damage is generally reduced. Taken in their entirety, these experimental results indicate the presence of one or more initial defect state/structure(s) which strongly interact with light at both 1 μ m and 355 nm. Both thermal treatment and laser conditioning modify this defect at 1 μ m, but only laser conditioning has a significant effect at 355 nm. Work will be initiated in FY95 to determine the nature of this/these defect state(s) and to investigate ways of altering the growth conditions to minimize the impact of defects on damage threshold.

As a backup to the rapid-growth development, further improvement of conventional technology is being pursued. Sixty-seven NIF-size plates will be produced in three phases, beginning in June 1995. The first delivery will be made in late-FY97, with subsequent deliveries occurring in late-FY98 and late-FY99. Should rapid growth ultimately prove unsuccessful, the conventional-growth stations at Cleveland Crystals would be supplemented with additional tanks beginning in FY97 to supply the crystals for NIF.

The initial development activity in crystal finishing will be to determine the ability to produce diamond-turned surfaces that meet the NIF performance requirements. The diamond-turning machine at Cleveland Crystals (which is owned by the Department of Energy) will be modified to improve its performance. Potential improvements include remachining or redesign and fabrication of the precision lead screw, replacing the journal bearing and/or ball-nut, and replacing or modifying the ball-nut/carriage flexure connection and carriage bearing pads. The initial efforts will begin in late FY94 and continue into FY95. Experiments will be performed to determine the capability of diamond turning to meet the THG crystal roughness requirements; a report will be made in September 1995. In parallel with these activities, polishing of crystals will be pursued to determine the optimum balance between diamond turning and postpolishing if the improvements to the diamond-turning process described above are alone insufficient to meet NIF requirements. Development in both diamond turning and polishing will be sufficiently advanced to select a finishing process by August 1996.

At the present time, polishing is viewed as a backup technology for finishing KDP and KD*P crystals. Polishing has the advantage of producing surfaces without the coherent structure (e.g., 6-mm ripple) currently seen on diamond-turned crystals. Conversely, crystal surfaces polished using present state-of-the-art techniques have several disadvantages relative to diamond turning. The surface damage threshold is lower than diamond-turned surfaces, particularly at 355 nm, and is sometimes below that of the bulk. Scatter from residual streaks is significantly higher for polished crystals, which will be manifested as a higher loss. Finally, wavefront control is presently extremely difficult relative to diamond turning. Nevertheless, a light polish may be necessary to achieve the required surface roughness for the NIF crystals, particularly the KDP doubling crystal. Present analysis and preliminary Beamlet tests indicate that current diamond-turning capabilities, or slightly improved to remove the 6 mm ripple, will be adequate for the switch and tripling crystals. Results from the Beamlet through FY94 and continued propagation analysis will be used to better define the NIF requirements. Polishing development will then be pursued in FY95 as appropriate.

Although not strictly a development issue, the cost of D₂O contributes substantially to the ultimate cost of KD*P. The DOE has a substantial stockpile of low-tritium heavy water, some of which may be used for the growth of KD*P during development as well as production to reduce KD*P costs even further. DOE has loaned 12 metric tons of heavy water to LLNL for this purpose. If rapid-growth technology is used for NIF production, this quantity of D₂O should be sufficient for the entire order. Otherwise, additional D₂O may be required and efforts will be made to ensure its availability.

2.3 Fused Silica

Introduction

The process for manufacturing fused silica blanks for transmissive optics of the size and quality required for NIF is relatively mature, but can be improved to obtain better utilization and reduce the size of inclusions. The development activities involve optimizing the boule geometry to the NIF blank size to minimize raw material cost, improving process design and control (the details are proprietary) to reduce inclusion size and

produce higher yield, and improving the postprocessing of the fused silica boules to reduce the time necessary for blank fabrication and interferometry.

Technology Status

Specifications for bubbles and inclusions in ICF transmissive optics are extremely tight to minimize scattering losses and the potential for damage in downstream optics due to holographic reimaging produced by nonlinear effects at high laser power. The maximum inclusion size specification for the NIF fused silica optics is 250 μm , as compared with 500 μm for Beamlet. While challenging, it is within the capability of qualified fused silica companies. The yield of blanks with 150- to 250- μm -diameter inclusions of the size of the NIF blanks is currently fairly low from as-formed boules. This low yield, in turn, results in a relatively high price. Alternatively, blanks with large bubbles can be homogenized through suitable postprocessing to decrease the bubble size, which in turn increases the blank cost. With development, it is expected that fused silica blanks can be produced with most bubbles less than 100 μm in diameter, so the yield will be high, the cost low, and expensive postprocessing unnecessary.

Standard sizes of fused silica boules are produced to yield optical blanks for a variety of customer applications. The large volume of fused silica required for the NIF warrants a customized boule geometry to maximize the yield of blanks. The production process will then have to be optimized to accommodate the modified boule. The homogeneity of fused silica in existing boules meets NIF specification; modifications to the boule geometry and production process must maintain this good homogeneity.

An effort also will be initiated to evaluate a potential low-cost alternative to fused silica made from quartz starting material. This material is expected to be acceptable for applications at the first harmonic wavelength; the primary question is its performance at the third harmonic in the focus lens and debris shield.

Benefits to the ICF Program, NIF, and U.S. Industry

Most laser systems providing high energy rely upon fused silica as a principal material for windows and lenses. The problems associated with material homogeneity, inclusions, and bubbles in fused silica have been and will remain a critical area for development for all laser systems used in the ICF community. Any development effort that improves the quality while reducing the cost of this vital material will directly benefit the NIF and, in the long run, the ICF program.

Fused silica has excellent transmission properties throughout the UV, visible, and near-IR wavebands. Because of the versatility of this material, it is a mainstay in the optical community at large. Specifically, the advent of UV and DUV photo-lithography for the semiconductor industry has placed stringent demands on the material properties of fused silica, the material used for virtually all imaging in reticle projection steppers and inspection equipment. With the continued research intended in this development into the nature and properties of fused silica, U.S. industries will be able to maintain their position of advantage in the world marketplace as producers of high-quality, high-homogeneity, low-cost material. This will become increasingly important with the supply of fused silica from the former Soviet Union and elsewhere continuing to grow.

Development Plan

Figure 2.3-1 shows the activities and milestones of fused-silica development. Because details of the development program are extremely sensitive and proprietary, only a brief summary is provided here. Early in the development program, the fused-silica manufacturing process will be characterized to determine sources of inclusions and bubbles. This process will then be suitably modified to reduce the occurrence of bubbles and inclusions, thereby increasing the yield and reducing cost. Simultaneously, an effort to optimize the boule geometry for the NIF fused silica blank size and shape will be initiated. Full-size blanks will be delivered to LLNL approximately every three to six months in order to monitor progress in the development program. These blanks will also be used in the finishing development effort, as well as for windows and lenses required for the component development program.

A report will be written at the end of FY95 to summarize progress both in optimizing boule geometry and inclusion reduction. A preliminary evaluation of the low-cost alternative will also be complete by the end of FY95. Boules meeting NIF specifications for homogeneity and inclusions will be formed from a full-size NIF prototype furnace in mid-FY96. A furnace design and process specification will be available in August 1996, in time to support facilitization at the beginning of FY97.

Fused quartz, which has the potential for lower cost than fused silica, will be evaluated on Beamlet in late FY94 and early FY95. If this material is acceptable (for either 1 μm spatial filter lenses and windows or 355-nm-focus lenses and debris shields), then a development program would be initiated for cost-effective production for NIF quantities.

Potential problems for fused quartz at 351 nm include color center formation due to higher impurity levels, particularly of transition metals, relative to fused silica. An effort will be initiated in FY94 to begin studying both fused silica and fused quartz obtained from leading manufacturers. Efforts in FY95 will concentrate on understanding the

WBS	CS&T activities and milestones	1995				1996				1997			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
2.3.	Fused Silica												
2.3.1	Vendor development												
	Furnace and processing technology												
	Preliminary fused silica furnace design												
	Process design and Prototype												
	Preliminary furnace prototype test results												
	Process validation												
	Deliver fused silica processing report												
2.3.2	Material evaluation												
	Fused silica material evaluation												
	Fused quartz material evaluation												
	Deliver fused silica material evaluation												

● = marker

◆ = milestone

Figure 2.3-1. Schedule of activities and milestones for fused-silica development.

nature of point defects in fused silica and fused quartz, and their impact on color-center formation and laser damage. Potential problems with neutron damage in the debris shield, conversion crystals and focus lens will also be addressed beginning in FY95; details of this investigation are yet to be defined.

2.4 Optics Finishing

Introduction

Large optics, such as the amplifiers, windows, and lenses used in the NIF, require a significant effort for fabrication and finishing. For a NIF-size order of these elements, optics finishing is the second largest optics cost center after laser glass blanks. This cost is driven by the surface area of the optics required, and the high facilities costs required to generate, grind, and polish more than 6000 flat optics and 1000 lenses ranging from 40×40 cm to 40×80 cm in size. There is potential schedule risk associated with minimizing the facilities costs. This is because the machines used for figuring large surfaces, i.e., a 140- to 170-in. continuous polisher, are rare and expensive and require between 2 and 3 years to construct and make operable. As a result, any increases in the time required per step in the fabricating process which are discovered during the pilot production phase or later will result in an increase of the total production time, since adding capacity is not possible at this late date.

Mature fabrication techniques currently used in the industry can provide the flat optics to the required specifications for NIF, but these technologies must be improved to decrease the total project cost. This will be achieved by reducing the number of man and machine hours required per part. Other fabrication technologies could potentially yield even lower finishing costs, but they will require some development and process optimization over the next three years. Other processes related to optical finishing that will also be advanced are the cladding process for amplifiers, metrology, and inspection.

The NIF design assumes the availability of large-aperture, high-precision lenses with a square aperture, fabricated from square blanks. The manufacturing technology for such lenses is considerably less mature and more expensive than for round optics. A three-year program will be required to prove and optimize the processes and equipment used in the rapid spherical generation and aspheric figuring methods that will be required. Development will focus on (1) increasing the grinding and polishing speed and rate of convergence and (2) refining the aspheric figuring to achieve the wavefront specifications near the edges of a square lens.

Technology Status

With very few exceptions, all of the amplifier slabs used on ICF laser systems have been fabricated using generating, grinding, and polishing techniques developed for Nova which are relatively slow and capital-equipment intensive. Whereas alternative techniques have been applied to laser glass in the recent past, such as small tool polishing at Kodak and high-speed synthetic lapping at Los Alamos, these have met with encouraging but limited success. Synthetic lapping looks very promising, but to date, only very small pieces of laser glass have been finished successfully in times consistent

with NIF fabrication cost goals; scaling these results to full-scale production parts will be challenging. The small tool polishing technique has been shown to be capable of achieving NIF cost goals (assuming a reasonable learning curve and economy of scale), but it has also exhibited problems associated with low-amplitude periodic structure, which may be unacceptable for high-energy performance. Both of these techniques must be further developed to achieve their full potential.

In addition to those two promising technologies, modest improvements can be made to the current fabrication process. These include techniques such as electrolytic in-situ dressing (ELID), high-speed grinding, and double-sided polishing and lapping, all of which have a high probability of success but require a significant amount of development funds due to the size of the machines and the immaturity of the technologies. At the opposite end of the spectrum are pursuits such as precision loose abrasive grinding, high speed lapping, and process modifications, which, taken as a whole, are higher risk, higher payoff development efforts that are less cost intensive.

Finally, the ion beam figuring process, which is facility intensive but moderately mature, completes the gamut of possible directions that can result in substantial cost savings when applied to nonlaser-glass optics required for the NIF.

During the first year of the development program, all of these processes will be studied for merit, cost, and yield at a low level. After a down-selection at the end of the first year, the most promising technologies will be further developed up to the time when facilitization begins.

Benefits to the ICF Program, NIF, and U.S. Industry

Because the principles to be advanced as part of the development program are used to generate all optical elements, specifically those employed in precision commercial and military systems, the benefit to the optics community in general, and aerospace optics in particular, can be substantial. The availability of low-cost, precision aspheres is a primary driving factor in the cost and even the performance of reconnaissance cameras, laser systems, and precision viewing systems, as well as optical systems employed in space applications. The speed and accuracy with which flat optics can be manufactured influence optical metrology, lithography, and many commercial applications. The development and maintenance of the technological superiority of U.S. optics fabricators in areas such as fabrication speed, fabrication precision, and metrology will be a principal contributor to the success of these companies in the early 21st century.

Development Plan

Because technical details regarding the development program are proprietary, only an overview is given here. The development plan for optical finishing has four principal thrust areas, the schedules of which are shown in Fig. 2.4-1. The first is a program to develop vendor capability to provide square, precision aspheric lenses at a substantially reduced cost. Second is a program to improve vendor technologies for flat laser optics. In the third thrust area, Los Alamos and LLNL will investigate synthetic pad polishing for applicability to NIF optical fabrication and assist the vendors through internal study, analysis, and development of the mathematical basis for the technologies to be employed by the optics fabricators in order to assist the vendors to scale up and advance the technologies with the

WBS	CS&T activities and milestones	1995				1996				1997			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
2.4.	Optical finishing												
2.4.1	Deliver focus lens to Beamlet		●										
	Spatial filter lens to Beamlet			●									
	QA agreement		●										
	Deliver machine design for lenses A spherical generator and aspheric grinder and/or polisher will be completely designed so that prototype machine construction can begin. These machines will be consistent with the cost goal of \$5k/m ² for lens manufacturing.							◆					
	Deliver lens finishing process specifications The optimum process to be used for a full lens production will be selected from the technologies and processes developed. A detailed procurement plan will be written, with the optimum specifications and requirements for all of the lenses required.										◆		
2.4.2	Process status evaluation		●										
	Large scale process demonstration A campaign of full scale flat optics finish will be completed, and a production report will be written. This campaign will be conducted using the basic technology to be employed for the NIF production campaign. Full metrology will be performed on 10 amplifier slabs and 15 other optics to determine conformity to specifications.				◆								
	Optical flat finishing QA agreement.						●						
	Deliver optical flat finishing process specs The optimum process or processes to be used for a full flat optics production will be selected from the technologies and process developed. A detailed procurement plan will be written, with the optimum specification and requirements for all of the flat optics required.										◆		
	Deliver a machine design for conventional optical flat processing A detailed machine design for the 168" continuous polisher, or equivalent, will be delivered.							◆					
2.4.3	Deliver machine design for small tool/ion beam processing The complete machine designs for final figuring of flat optics using deterministic figuring will be completed. These machines will be designed based on the prior large scale campaigns which will determine the appropriate technology for each optical material.										◆		
	Deliver synthetic pad evaluation		●										
	Conventional finishing process model						●						
	Lens process model								●				
	Small tool/ion beam process model										●		
2.4.4	Thermal evaluation of substrate alternatives												
	Feasibility study of alternate materials		●										
	Downselect mirror substrate material A report summarizing the trade-offs between Silicon Carbide, BK-7 slabs, and lightweight Tempax, Pyrex, glass, and fused silica will be written. The mirror substrate which best balances the thermal, pointing, mounting, weight and cost requirements will be selected.				◆								

● = marker

◆ = milestone

Figure 2.4-1. Schedule of activities and milestones for the optics-finishing development.

greatest leverage for the ICF community. Finally, LLNL will work with mirror substrate suppliers to identify the most cost-effective mirror blank for the NIF, which can meet the rather stringent performance requirements.

Lens Finishing

The lens development thrust area will occur in three phases. Phase 1 consists of manufacturing small quantities of square lenses for the Beamlet Phase II project, which are similar to those required for the NIF. This will demonstrate the process flow that will be used for the spherical surface grind and polish as well as the aspherising. We expect this phase to result in three accomplishments: (1) a better understanding of the manufacturing issues specific to square ICF lenses, (2) a diagnosis of the effects of the large wedge and resultant aspheric departure used in the final focusing lens, and (3) the successful manufacture of square lenses that can be used in Beamlet. A series of spatial filter lenses will be made that can be tested for stress-induced birefringence (SIB) and laser-induced damage, and other lenses that can be used by other elements of the development program. Phase 2 will focus on manufacturing a larger quantity of square lenses using the same kind of equipment to be used in the NIF, in order to (1) measure and reduce the time required for convergence during production, (2) validate the time estimates (and hence, the cost estimates) used to predict the final production costs of the NIF, and (3) to reach closure on the specification trade-offs of the lenses (e.g., how close to the edge of a square optic manufactured from a near net blank can high optical quality be maintained, using the NIF fabrication process?). Phase 3 will focus on further reducing the convergence rates of the lenses by addressing the particular problem areas identified in the first two phases, in order to prepare for the pilot demonstration. Phases 1, 2, and 3 will roughly correspond to the fiscal years 1995, 1996, and 1997, as shown in Fig. 2.4-1.

Flat Finishing

The second thrust area is to advance the finishing technology at two or three flats fabricators, to minimize the total cost of the optics. This program will consist of three phases as well. Phase 1 will have three primary goals: (1) to develop an understanding of the limitations and extremes of existing processes, in order to enhance total cost estimation reliability, (2) to identify potentially high yield processes that involve either existing or new technology, and (3) to demonstrate improved processes and finishing techniques at the vendors. The combination of these three goals, in conjunction with the LLNL internal development discussed below, will allow LLNL to select the primary and secondary sources for the NIF optics. The purpose of such a choice will be to provide the lowest possible total cost, including the cost of facilitization, for the NIF flats, with an acceptable amount of risk. To this end, the vendors will fabricate full-scale NIF components using conventional, small-tool, ion-beam figuring technologies by the end of FY95. The second and third phases of this development involve optimizing the vendor specific technologies to achieve the best compromise between cost, risk, and yield. LLNL expects to fund two suppliers for the laser slab finishing development. The same will be done in funding two sources of each of the other flat optics components, such as mirrors and windows. As with the lens development, these phases will roughly correspond to the fiscal years 1995, 1996, and 1997, respectively.

Equipment Design

Although not a development thrust area, a great deal of work will be done to design the tools needed to fabricate the NIF optics. Once a process has been selected for a given

optic, the optimum equipment required for that process will need to be designed to minimize project costs. Depending on the finishing approach, this will include devices such as continuous polishers with laps greater than 150 in., edging and generating tools customized to square and rectangular optics, small-tool polishers, and ion-beam mills.

Finishing Technology Evaluation and Modeling

The third thrust area can be broken into two parts. In the first part, Los Alamos and LLNL will conduct an intense study of synthetic pad polishing technology as applied to continuous polishing machines. Synthetic pad polishing is currently used as an alternative to the slow and costly pitch polishing process in the manufacture of low-precision commodity optics. Recent work at Los Alamos has indicated the applicability of this technology on over-arm spindle tools to small, precision optics. We will continue to pursue this over-arm approach using synthetic pad polishing, and we will work, with the assistance of Los Alamos, to implement the same material approach on a continuous polisher. In mid-FY95, a report will be issued that will describe the applicability and potential value of these approaches to large-precision-optics manufacturing. If prudent, this effort will be followed by a year of transferring the over-arm and/or CP synthetic pad technology to the finishing vendors who can most benefit from it.

The second part of this thrust area will consist of the necessary engineering and experimentation at LLNL to characterize the supplier's fabrication processes. There are two basic goals of this effort: (1) to independently investigate, with an ICF optics bias, the technologies pursued by the vendors themselves, so that we may assist in their decision-making process (in essence, to ensure that the funded vendor developments proceed in pursuit of the most promising path to a lower NIF optics cost), and (2) to understand from a mathematical viewpoint the entire fabrication processes that the vendors are planning to employ (i.e., lend determinism to the generation, grinding, and figuring processes) so that we may suggest refinements of those processes, and so that we can reasonably predict the expected cost of the optics.

Failure of the development program to meet its goals would not impact optics performance but will impact cost and possibly schedule. Increased cost would result due to the highly labor-intensive nature of present conventional finishing approaches. The schedule could be impacted because more time would be needed to purchase and install additional equipment.

2.5 Optical Coatings

Introduction

Thin-film coatings for mirrors and the polarizer contribute a small, but nonetheless significant, fraction of the NIF optics cost. More important is the ability to produce coatings with high damage thresholds and good spectral performance. Two types of coating technology will be used: conventional electron-beam coatings for the elbow and transport mirrors and polarizer, and sol-gel multilayer coatings for the cavity mirrors.

High performance multilayer, dielectric optical coatings for use as mirrors and polarizers are required for the NIF. High performance is defined by high extinction

ratios for polarizers, low losses for mirrors, and high damage thresholds and low wavefront errors for both. Such performance recently has been demonstrated at large aperture for the Beamlet laser by using electron-beam deposited $\text{HfO}_2/\text{SiO}_2$ coatings. The low manufacturing yields for such coatings make the production of NIF quantities of such optics presently impractical from both cost and schedule standpoints. For example, the two most experienced coating vendors believe that their current production yields of NIF polarizers would be no more than 30%. Yields near 90% are needed to meet NIF cost and schedule goals.

Significant progress was made during the Beamlet project to improve our understanding of the optical performance, damage threshold, and wavefront issues for large-aperture polarizers and mirrors. These advancements allowed us to produce exceptional coatings in low quantities. Improving the production yields of high-performance coatings focuses primarily on developing improved monitoring and process-control techniques.

Sol-gel mirrors are significantly cheaper to manufacture than electron-beam-evaporated coatings, and (in principle) require less testing and evaluation. This is because sol-gel coatings do not stress the optic, so wavefront measurements are not necessary. The lack of coating stress also makes these coatings more suitable for use in deformable mirrors. At present, sol-gel mirrors are specified as the baseline for NIF cavity mirrors.

Technical Status

The damage thresholds that must be achieved for the NIF are shown in Section 2.6 (Table 2.6-1). Development efforts will strive to improve these values while achieving high yield and minimum cost.

The rejection ratio of the polarizer is limited by layer-thickness control during deposition. It has been estimated that layer-thickness control during HfO_2 deposition is currently about 6%; about 1.5% is required to achieve >90% yields at high rejection ratios. Poor layer-thickness control has been correlated with the transient nature of the evaporant plume. These transients are, in turn, caused by changes in the properties of the source material (shape and composition) due to interaction with the electron gun. The path to improved layer control is to first develop better plume-monitoring techniques so that the problem can be characterized and then to develop more stable sources either through changing the e-gun sweep and power parameters or by modifying the source material directly in either shape or composition.

The laser-induced damage of e-beam-deposited $\text{HfO}_2/\text{SiO}_2$ coatings is a localized phenomenon often associated with μm -scale nodular defects in the coating. These defects are formed as a result of self-shadowing effects of seed particles on the substrate or deposited during coating. Efforts to improve damage threshold will center on prevention of these seed sources. The major source of seeds is believed to be particulates of source material ejected during evaporation. Stabilization of the source material is again important here.

In order to reach the fluences required by NIF, the mirrors and polarizers must be laser conditioned, as discussed in Section 2.6. This technique results in increasing damage thresholds by factors of 2 to 3. Currently, this conditioning is done off-line by rastering the optic with a beam from a commercial laser. Based on conditioning procedures used for the Beamlet polarizer, the conditioning process would account for 24%

of the cost of mirrors and 16% of the cost of polarizers for NIF. A development effort will be directed at minimizing this cost through reductions in scan time, either by improved control and diagnostic systems or by optimizing of the illumination sequence. The effectiveness of on-line conditioning will be tested as part of the high-fluence transport higher reflectivity (HR) tests on Beamlet. Efforts also will be directed at improving the coatings to the point that laser conditioning may not be required. The laser-conditioning process reduces the effects of the nodular defects on the damage threshold. Therefore, elimination of the defects, a major thrust in the development effort, may also remove the need for laser conditioning.

The baseline NIF design calls for beam transport of 1.053- μm light to the target chamber. There may be advantages, however, to frequency converting the beam to 0.351 μm prior to beam transport. The feasibility of producing high-damage-threshold 0.351- μm mirrors should therefore be explored. While the goal of 16-J/ cm^2 damage thresholds for 3 ns pulses has not been reached for 0.351- μm mirrors, significant progress has been made which has produced some coatings with thresholds as high as 12 J/ cm^2 . A low-level effort will be maintained to further explore coatings with higher 3ω damage thresholds.

Sol-gel mirrors with $99.2 \pm 0.2\%$ reflection over 95% of a 150- $\times$ 150-mm substrate, excluding 6-mm edge effects around the perimeter, have been produced with a manual meniscus coater at LLNL. These mirrors consist of 24–28 layers of alternating porous SiO_2 and porous ZrO_2 combined with a high-index binder. These mirrors have a laser damage threshold (LDT) of about 6–8 J/ cm^2 (3-ns pulse length, 1064-nm wavelength). These specifications are adequate for cavity-mirror applications on the NIF. Research and development are continuing with the aim of significantly improving the LDT so that sol-gel mirrors can be used in beam-transport applications, where higher fluences will exist. In January 1994, LLNL took delivery of a full-scale, automated meniscus coating machine capable of producing a functioning cavity mirror for the Beamlet laser and to enable full-scale R&D. This machine, shown in Fig. 2.5-1, can process optics up to 40 $\times$ 60 $\times$ 12 cm. Although it is a prototype production machine, if the process is ultimately successful, this machine with slight modification, can be used to coat all NIF cavity mirrors. If the R&D program to increase LDTs is successful, it could also be used to apply a sol-gel HR coating to a significant fraction of turning mirrors as well.

Benefits to ICF Program, NIF, and U.S. Industry

The damage threshold of multilayer optics, particularly the polarizer, is a dominant factor in ICF laser designs. For example, if the polarizer damage threshold is increased, more laser amplification could be done in the multipass cavity, thus making the system more efficient.

The proposed technology development offers a clear cost advantage to the NIF. Based on recent estimates, the cost for all elbow HRs, turning HRs, and polarizers for a 192-beam NIF system would decrease by more than a factor of 2 (production only) as a result of the development effort.

The technology developed as a result of this program will be of considerable benefit to the commercial laser and optical coating industry, primarily through providing improvements in laser-induced damage threshold for high-power commercial laser

70-39-0394-1407 pub

Figure 2.5-1. Large-scale meniscus coater for sol-gel multilayer high-reflectivity (HR) coatings.

systems, reduced defect densities in flat-panel displays, and improved spectral control for complex optical coating designs.

The processing technologies used to deposit sol-gel coatings have generated a great deal of interest in U.S. companies in the areas of semiconductor and flat-panel display processing. For example, this type of coating technology wastes no coating fluid; in contrast, traditional spin-coating methods used in the semiconductor industry use about 1% of the expensive photoresist applied per wafer. Coating fluid costs are 50% of the amortized annual capital equipment cost for wafer processing equipment. Thus, minimizing fluid loss is vital to a cost-effective semiconductor manufacturing process. While the concept of meniscus coating, used to create sol-gel multilayers, is not new, very few of these machines were in use prior to LLNL's involvement, and a poor understanding of the process resulted in inferior coating characteristics. Technology transfer of LLNL's R&D results, both the fundamental understanding of the fluid dynamics of meniscus coating and the practical understanding of what is required to make quality

coatings, has enabled the U.S. company that built LLNL's coater to offer much improved machines to this expanding market and to obtain new business opportunities.

In addition, LLNL researchers recently developed an ultraclean drying process for cleaning optics in situ prior to meniscus coating. One coating-machine company already has requested a license of this technology for use in its processing equipment for flat-panel displays.

Development Plan

The e-beam coating development plan consists of four main parts, as shown in Fig. 2.5-2. The first two parts focus on developing two primary coatings vendors. The plan for each includes phases for particle-reduction studies, spectral yield improvement for e-beam deposition, and scale-up and throughput enhancement. These vendors may also examine energetic deposition techniques as possible paths to improved yields. Full-size prototype polarizers and mirrors will be produced at the end of each stage to check progress.

The defect-reduction work at the vendors will focus on eliminating particulate sources in the coating chamber. The first phase will address particulates formed in pre-coating operations: substrate preparation and chamber pump-down and heating. The second phase will address particulates ejected from the source material. This second phase, the majority of the effort, will be done in conjunction with defect characterization and source stability work at LLNL. Deliverables will consist of witness samples, full-size prototype parts, and written reports from the vendors.

The spectral-yield improvement work consists of first implementing new layer-thickness diagnostics, including multiple quartz-crystal monitors and broadband optical monitors. Significant work in this area has already been done as part of the optical-coatings production effort for the Omega Upgrade at the University of Rochester's Laboratory for Laser Energetics (LLE). LLNL will work with LLE to take advantage of their work in process control and high-damage-threshold coating technology. These diagnostic techniques will be used in deposition-parameter studies to identify e-gun and source-material characteristics that provide more uniform deposition rates.

The third major part of the strategy to develop e-beam coatings is to develop alternative vendors. We will examine the capabilities of several vendors to determine if there are other technologies available, including energetic deposition techniques such as ion beam sputtering, that may be applicable to the NIF. Initial evaluation of potential vendors will be done in FY94. The top two alternative vendors will then be funded for up to 18 months to develop their capabilities to reliably produce high-damage-threshold coatings. A preliminary coatings performance report milestone is scheduled for March 1996 to discuss the results of development efforts at all vendors. In mid-FY96, a final development stage will then fund the leading alternative vendor, if required. Final decisions on the NIF production vendors will occur, at the latest, in the early part of FY97, prior to the start of vendor facilitization.

Concurrently with the vendor development effort, the fourth part of the e-beam coating development plan, an effort to understand damage thresholds and laser conditioning, will continue at LLNL. A major part of this work is defect characterization using techniques such as atomic force microscopy and focused ion-beam

◆ Milestone

Figure 2.5-2. Schedule of activities and milestones for optical-coatings development.

cross-sectioning. The goal is to determine correlations between deposition conditions, defect geometry, and laser-damage susceptibility. This work will be ongoing during FY95-97. The experimental work related to defect damage susceptibility will be supplemented with electric-field modeling studies during FY95. The objective is to study the influence of non-ideal defect geometries and non-normal incidence illumination.

In addition, the influence of modified multilayer designs, particularly reduced E-field designs and overcoat layers, will be evaluated for NIF coatings. Work will also be directed at testing alternative high-index materials that could replace hafnia, the present material of choice. A report of the results of this work will be made at the end of FY95 so that developments can be integrated into the vendor development efforts. Deposition studies at LLNL will be ongoing to maintain our in-house technical competence in this area.

Presently, damage-threshold requirements for polarizers and turning mirrors can only be met by using e-beam-deposited, laser-conditioned optics. Our previous studies indicated that conditioning may be associated with defect stabilization or removal. Research closely coupled to the defect-characterization studies will continue to help us understand the laser-conditioning process and, possibly, the damage mechanisms. A complementary effort will focus on developing procedures and equipment for conditioning the full-scale NIF optics. A report on these efforts will be presented in late FY97 so that the coating vendors can be facilitated appropriately.

The development plan for 0.351- μm mirrors will consist primarily of funded development work at vendors that have shown expertise in high-damage-threshold UV coatings. One avenue of development that will be explored is the possible use of fluoride, rather than oxide, coating materials. These coatings have shown promise in the past, but there have been problems with high coating stresses in the films. Work will continue to try to reduce this effect.

The manufacture of a $\text{SiO}_2/\text{ZrO}_2$ sol-gel HR and its installation on the Beamlet laser will be the first milestone of the sol-gel mirror project. Work on this is currently under way. This mirror will be thoroughly tested for wavefront, reflection, and transmission uniformity and laser damage.

The improvement of laser damage threshold of sol-gel coatings will focus on AlO_2 as the high-index layer. AlO_2 has shown the highest LDT of all tested high-index materials, but its index (1.44) is small compared to others, and significantly more layers are required to achieve the specified reflectivity. Addition of a polymeric binder layer to the AlO_2 to increase the layer index will be investigated. The effectiveness of the UV curing of coatings to cross-link the polymer and render it insoluble to subsequent redissolution will also be investigated. Further, the possibility of a three-component multilayer using HfO_2 or ZrO_2 as the high-index material for the first several coatings, replaced by AlO_2 in the upper layers of the stack, will be evaluated so as to take advantage of the high-index contrast at low fluence levels deep in the multilayer stack and reduce the total number of layers needed. Investigations of other particle/polymer systems also will continue.

Optimization of the coating machine and coating process also will continue during the development period. In particular, an in situ cleaning system consisting of a scanning megasonic aqueous cleaner, followed by a novel Marangoni rinsing and drying system, will allow for fast, in-place cleaning of optics just prior to coating. This capability will further reduce the processing time and thus the cost of optics mass-produced by meniscus coating.

2.6 Laser Damage Testing and Conditioning

Introduction

The NIF requires routine operation at high peak fluences, which makes optics with high laser damage thresholds necessary. The ICF Program already maintains the world's largest damage database, containing more than 11,000 tests supporting many different ICF projects. In order to provide the ICF Program with damage statistics useful for material research and quality assurance for the NIF, continued development of the damage testing and conditioning facilities is required. The development will be focused on (1) standard and automated testing, (2) large-area testing and conditioning, (3) fundamental mechanisms of damage, and (4) damage detection and characterization. Damage testing and conditioning systems based on technology prototype designs will be used by the vendors to verify that the NIF optics meet the damage threshold specifications.

Technology Status

The testing performed by the Laser Materials Group supports the development of many optical components in an ICF laser system and related research into new optical materials. Besides test data, the group provides system design engineering for damage testing systems and conditioning systems that will be used by vendors or other ICF groups. In order to meet the needs of the NIF optics development and production, the damage testing facilities will have to be upgraded in the areas of damage detection and testing rate. Currently, four facilities at LLNL will allow a variety of testing and development work. The functions of these facilities are (1) standard damage testing, (2) automated damage testing, (3) materials research, and (4) laser conditioning.

Standard damage testing. The standard damage testing system uses 100× Nomarski microscopy to detect laser damage. This system currently is used to determine damage thresholds and damage morphology. Since this type of testing has been employed for more than ten years, little further development is required.

Automated damage testing (ADT) system. A second facility to be developed as an ADT system will use new diagnostic techniques to detect laser damage instead of tedious and time-consuming microscopy. The testing will be computer controlled, allowing damage threshold measurements to be conducted at a much higher rate, and over a much larger area, than standard testing allows. Because of the high testing rate of the system, the damage thresholds determined will be better supported statistically. The automated nature of the test, however, may result in less information being gained regarding damage morphology. These tests may, therefore, be supplemented by some use of standard microscopy.

Materials research (associated with damage threshold). Optical materials are becoming more damage resistant by reducing the already identified, predominant damage mechanisms (e.g., defects in coatings, platinum in laser glass). Understanding these damage mechanisms has an effect on the design, processing, and QA testing of each optic. As the influences of defects and inclusions on damage threshold can be determined, an effort can be made to further eliminate or reduce them in a production environment.

As these predominant damage mechanisms are eliminated, fundamental damage mechanisms of the optical materials will become the issue. In order to understand these fundamental mechanisms, a full-time research program will be instituted.

Since some NIF optics are subject to simultaneous exposure of multiple wavelengths, research will be performed to understand the influence on damage threshold of this type of illumination. Work also will be done to understand the dependence of laser damage threshold and morphology on pulse shape. Pulse-shape studies will be performed to relate the damage susceptibility when a Gaussian pulse shape is used to that of the various pulse shapes anticipated for the ICF program.

Laser conditioning. Laser conditioning is a process that uses controlled, subthreshold laser illumination to raise the damage threshold of optical materials. Table 2.6-1 shows that conditioning is required to meet required NIF thresholds for several coated components. The conditioned values shown are attained by illuminating a 1- to 3-mm diameter spot on the surface several hundred times with a rep-rated laser, while the fluence is slowly increased in a ramped manner. This is the best way known for conditioning many different optical materials, but it is impractical for high-production, meter-sized optics. A second method of conditioning is laser raster conditioning, where every site on an optic is illuminated only a few times by rastering the sample through a 1- to 3-mm stationary beam. The sample area is scanned several times, with fluence increasing at each scan. For KDP and KD*P, conditioning effects are seen for both laser conditioning techniques and thermal treatment techniques.

Raster conditioning has demonstrated that it is possible to raise the damage thresholds of coatings by a factor of 2 or more. LLNL has a facility dedicated to laser conditioning of meter-sized and smaller optical components. The process was successfully demonstrated for the first time on meter-sized optical coatings when the Beamlet polarizers were laser conditioned to 1.5 times their original threshold.

An understanding of thermal conditioning of KDP crystals has become important because it shows promise for raising the 351-nm damage threshold, which is a major factor in establishing laser beam aperture size. Current laser conditioning techniques show threshold improvements of 1.3–1.6 times at 1064 nm and 1.1–1.6 times at 355 nm. The use of ovens to thermally condition KD*P crystals shows promise at 1064 nm, but this technique is risky due to the difficulty in predicting the phase transition of the crystal. This technique shows threshold improvements of 2.5–3.5 times at 1064 nm, but significant improvements at 355 nm have not yet been realized.

Development of reliable and accurate damage diagnostics can increase the speed and accuracy at which damage-related material studies can be conducted and can play a significant role in our conditioning and damage system development plans. Past and present damage diagnostic development has been centered on detecting acoustic emission and scattered light. The goal is to be able to detect damage with diameters less than 10 μm with good repeatability. The current system is capable of detecting damage as small as 20 μm with marginal repeatability, and damage greater than 50 μm with good repeatability.

Table 2.6-1. Damage thresholds for coated optics that require conditioning in order to meet NIF requirements.

NIF Optics	Damage Threshold, J/cm ²		
	Recent samples 1990–present (3 ns, Gaussian)		NIF Requirement (3 ns, Gaussian)
Component	Unconditioned	Conditioned	Conditioned
Elbow Mirror	11–17	19–33	>25
Transport Mirror	11–17	19–33	>25
Polarizer	8–15	18–35	>18

Benefits to the ICF Program, NIF, and U.S. Industry

The benefits derived from the further development of damage testing and conditioning can be summarized as follows:

- More accurate and reliable damage threshold measurements.
- Automated processing allowing quicker turnaround for development activities.
- Better understanding of damage mechanisms.
- Improved damage thresholds of optical materials.

All of these advancements have application to commercial and defense-related high-performance optical systems.

Development Plan

Figure 2.6-1 shows the development for each area and its respective milestones. Since many of the areas will be part of the NIF vendor facilitization, or depend on one another for research, much of the work is done in parallel.

The standard damage test facility is currently operating. Development of the ADT system will begin in FY94 and will be completed by the third quarter of FY95. Most of the ADT system will be copied from already existing facilities, and the key for completion will be in the integration of all the concepts into one facility. There are two milestones for damage testing in the form of status reports; one at the end of FY95 and the second in late FY96. For the NIF project, a final damage evaluation report will be delivered in mid-FY97. This allows the NIF design to be updated with the most recent damage thresholds for all of the tested optical materials.

The damage mechanisms research effort will generate biannual status reports summarizing new developments. The work will begin in FY94 in support of the optical-coatings-defect research. The second task will be to determine the influence of mixed-wavelength illumination on optical materials. The third task will be to determine the dependence of damage on pulse shape. Two milestone reports will be generated from this work. The first, due at the end of FY96, is a summary of the influence of mixed wavelengths on damage thresholds, and the second is a summary of pulse-shape influence on damage thresholds, due in mid-FY97.

Conditioning development will focus on (1) determining the best process for increasing damage thresholds of coatings and KDP/KD*P crystals above NIF levels, and

● = marker

◆ = milestone

Figure 2.6-1. Schedule of activities and milestones for laser damage testing and conditioning development.

(2) designing and demonstrating of a prototype system that accomplishes conditioning and can be implemented at vendor production facilities.

The conditioning research for optical coatings is discussed in more detail in Section 2.5. The schedule for the Damage Testing and Conditioning Group considers only the operation of the current system and the design and prototype construction of the

NIF conditioning station. This work begins in FY94 and delivers a final conditioning system design and evaluation report to the NIF project in late FY97.

KDP/KD*P conditioning research and development activities begin in FY95 and establish the best technique by mid-FY96. The final specifications for the process will be delivered to the NIF project in late FY97.

Damage diagnostics play an important role in the conditioning facility as well as in all of the damage testing areas. The diagnostic development work will be performed in three steps: (1) evaluate advanced methods for detection of laser-induced damage, (2) combine multiple methods in order to increase the repeatability and detection limits of the diagnostics, and (3) integrate the damage diagnostics into the testing systems. Bi-annual reports will summarize the latest diagnostic capabilities. As appropriate, these diagnostics will be included in the NIF damage testing, conditioning, and quality assurance systems.

Damage-testing systems for the optical coating and laser glass vendors will be developed beginning in FY95, with a design completed by mid-FY95. The systems will facilitate management of the high production rates and accuracies required by the NIF.

2.7 Large-Aperture Optic Characterization

Introduction

Large-aperture optic characterization is a central aspect of the quality assurance process for NIF optics. This includes interferometry for wavefront characterization, photometry for mirror and polarizer reflectivity and transmission, polarimetry for birefringence, crystal orientation, and scatterometry. The capability, except for aperture, to perform these measurements for the NIF optics exists today, but it must be improved to reduce the cost and improve the throughput for the NIF.

Technology Status

Accurate measurement and characterization of optical materials and surfaces is a critical capability for fabricating of precision optical components. This is especially true for optical components in high-energy laser systems that have demanding performance specifications (e.g., surface figure, surface finish, transmission, reflectivity, homogeneity). The components cannot be made without measurement and characterization tools.

Existing instruments cannot meet the requirements of future ICF laser systems for characterizing of the entire clear aperture. Commercially available phase-shifting interferometers have clear circular apertures up to 45 cm, which is smaller than the 80-cm circular aperture required for the NIF. Use-angle interferometry would limit the required aperture size to 60 cm. Development activities will address five main areas:

- Phase-shift interferometry.
- Photometry and polarimetry.
- Crystal orientation measurement.
- Scatterometry.
- Optical design and analysis support.

Phase-shifting interferometry will be used for the NIF because of its improved ability, relative to static fringe interferometry, to resolve small-scale errors and to discriminate between surface fabrication errors and bulk inhomogeneity (for transmitted wavefront). This will require extending current capabilities for full-aperture phase-interferometers from 45 to 60–80 cm, or developing a raster-based algorithm for mapping a complete optic from a series of subaperture measurements. This is a central component in surface finishing, test, and acceptance of all the NIF optical components.

Photometry is required to verify the performance of high reflectors, polarizers, and all antireflective coated optics. The current approach relies on rastering the optic through a small beam to measure transmission or reflection at only a few points. An efficient, full-aperture measurement capability is required for the NIF. Similarly, polarimetry, which is used to verify birefringence specifications must also be improved in order to obtain full-aperture information quickly and accurately.

The crystals used for harmonic conversion require precise orientation to achieve the proper phase matching conditions. The system currently used for this operation must be modified slightly for the NIF, and the computer-control and data-storage system must be updated to use modern computers and software to improve the measurement rate.

Benefits to ICF Program, NIF, and U.S. Industry

The ICF program will benefit by an improved ability to characterize optical components. This is important for laser and propagation modeling to predict performance of Nova, Beamlet, and NIF. Results from such calculations will enable the optics group to better specify the optics requirements. In addition, significant advances in grinding, polishing, diamond turning, coating, and damage conditioning will not be possible without measurement improvements.

Optics development at LLNL has historically benefited the U.S. optics industry. Improvements in interferometry, photometry, and profilometry translate into advanced manufacturing capabilities for optics vendors.

Development Plan

The development plan and schedule are summarized in Fig. 2.7-1. Development of the phase-shift interferometer begins in FY95 with proposals and conceptual designs that will be solicited from several commercial vendors. A final design contract will be awarded, with instrument delivery slated for the end of FY96. Concurrently, a suitable laboratory facility will be designed, constructed, and then activated in FY96. Validation of the instrument and measurement procedures will occur in FY97.

During FY95, extensive studies and measurements of KDP machined and polished surfaces will be performed. The aim of these measurements is characterization of the surfaces to $\lambda/100$ accuracy. A report will be issued summarizing the results and recommendations.

A full-aperture photometer and polarimeter will be designed and built in FY95. The preferred development path is construction by an outside vendor to LLNL-defined specifications and functions. Operation of the instrument and validation of the measurement procedures will begin after installation and conclude in mid-FY96.

● = marker

◆ = milestone

Figure 2.7-1. Schedule of large-aperture optics characterization development.

Crystal orientation measurement requirements and needs will be evaluated and tested in FY95. It is anticipated that current measurement capabilities will be adequate (perhaps with some modification). A commercial scatterometer capable of supporting coating and damage testing needs will be purchased in FY95. Use of the instrument, verification of measurements, and tests on optical components also will be conducted.

The main activity under optical design and support is implementation of an optics drawing system appropriate for high-energy laser system requirements. Optical design software support is also included in this area.

2.8 Final Optics Protection

The final optics for each beam must be protected from a number of electromagnetic and physical debris hazards, including neutrons, gamma rays, x rays, metallic vapor and shrapnel, and other debris. This protection scheme must meet stringent requirements for optical performance. The technical objective of this task area is to identify a design that meets these technical requirements and can be implemented at relatively low cost, both construction and operating.

The threat to the optics is divided in two: as electromagnetic and physical. The fusion of the NIF target produces primarily neutrons from the neutron decay of the $^5\text{mHe}^*$ compound nucleus, which is a product of DT fusion. At the debris shield, the integrated fluence is about 2.7×10^{12} neutrons/cm² for a 20-MJ target yield. The gamma rays primarily result from secondary reactions and have an integrated fluence of 1.9×10^{12} photons/cm² for a 20-MJ yield. The prompt gamma rays are about 10^4 lower fluence, thus, they are negligible. X rays are 1.0 J/cm² for a 20-MJ yield. All of these dose estimates are based on preliminary calculations and use the current estimate for the NIF operation schedule.

Our estimates of the physical debris are presently not precise. We have estimated that based on the current shot schedule planned for NIF during operation that the optics will accumulate about 1 nm of physical debris deposited as a vapor. The vapor and small particles are mostly low-atomic mass material from the target positioner, with some metal from the hohlraum and from other near-target metals, which are vaporized by the target. There are also infrequent metal shrapnel particles as large as 4 mm diam that are generated. In the present large ICF facilities, inorganic debris accumulate (regardless of operation) from various sources on the final optics. This debris source term is being evaluated to determine our ability to largely prevent debris accumulation in the NIF by good operational practices.

The requirements for the final optic are: it should protect the final optics from these debris threats, and they should have a high transmission. The final protection must also not contribute significantly to the steering or focusing deficiencies of the beam. We are minimizing the amount of material ablated. Still, the final optics can be protected in several ways from the remaining debris. A disposable shield scheme involves a glass, plastic or other shield that sits between the optic and the target and protects the final optic. These are replaced as often as needed, perhaps by an automatic mechanism. A second scheme involves a coating to the final optic where the debris accumulate. The coating is then removed and replaced, or the optic is replaced and refurbished as often as required to keep the transmission of the final optic at the required level. A major problem is optical damage to this final optic or disposable debris shield caused by the absorption of laser light by debris. This is effectively a transmission problem.

There are seven evaluation areas with their own coupled deliverables.

- Source terms
- Neutronics
- Disposable shield evaluation
- Optical requirements
- Mechanical integration
- Antireflection coating
- Concept definition

Source term analysis

Source term analysis is critical for quantifying the performance requirements for the final optics package, since both the neutrons and gamma rays penetrate considerably into these optical materials. The x rays are absorbed in the first few microns, thus, are primarily a problem for the surface facing the target. (These source terms are described in Section xx, but are included in the schedule for this area for completeness.)

Neutronics

Neutronics is the general area of materials response to NIF-level irradiation, including both gamma rays, x rays, and neutrons. At present we know that some types of fused silica and KDP are much more resistant to a decrease in transmission after irradiation than others. For example some forms of synthetic fused silica have no measurable change in absorption of 355-nm light after one year's equivalent energy dose of 1 MeV neutrons. Other forms of silica have optical densities of >10 after this dose. Similarly, some KDP samples have $<0.5\%/cm$ absorption of 355-nm light after one year's equivalent energy dose of 1 MeV neutrons, while others have $40\times$ higher absorption.

We plan to use three principal sources for the irradiation experiments. The Co_{60} gamma-ray source at LLNL produces 1.1- and 1.3-MeV gamma rays at the rate of 0.92 Mrads(Si)/hr, equivalent to a NIF one-year nominal dose in one minute of exposure. SPR-III is an unmoderated U_{235} reactor at SNL in Albuquerque producing about 3.2×10^{14} neutrons/cm² peaked at 1 MeV in each 100 μ s shot, giving about 0.5 year of 1-MeV neutrons and 7.5 years of 1-MeV gamma rays in each shot. The RTNS-I D-T neutron source at LBL is being reactivated. It will deliver 4-MeV neutrons at 5×10^{11} n/s cm², reaching a one-year dose in 12 minutes of beam time. In combination, these sources will be able to assess total dose issues, as well as neutron and gamma-ray pulse and energy dependence effects. The deliverables for this area are: the characterization of the radiation resistance of these materials and the identification of the characteristics of these materials that make them rad-hard. This will ensure that we understand the materials issues adequately to produce materials for NIF that meet the performance requirements.

Disposable shields

Disposable shields are an attractive option because debris accumulation and the resulting optical damage are mitigated by simply replacing the shield regularly. This shield should be very inexpensive so that it could be replaced after every shot.

Alternatively, it could be made inexpensively, yet robust enough to survive one week's debris accumulation, for example. The disposable shield will absorb the entire x-ray fluence and protect the upstream optics from physical debris and vapor. Candidates for this disposable shield can be generally classified as either glass or polymer sheet. Other shield candidate materials, such as ice, are unlikely candidates because they require further study.

Glass shields have the advantage that most good quality glass tested to date have adequate optical damage threshold; they can be made (in a volumetric sense) inexpensively. An additional advantage is that they can be readily antireflection coated using the existing sol-gel process. The primary drawback to glass shields is the current unavailability of thin, inexpensive glass sheet of adequate optical quality. No current technologies have been identified that can satisfy the quality requirement, but this is an area we will actively pursue. The second drawback with glass disposable shields is that the mounting/changing schemes identified to date are neither elegant nor compact.

Polymeric disposable shields are attractive because one can envision a "saran wrap" type roll of film which is advanced after each shot to expose fresh film. Therefore the shields can be inexpensively changed for each shot. Unfortunately polymeric films tested to date have been marginal in terms of their optical damage thresholds, most are lower than 5 J/cm^2 in 3-ns pulses, about threefold lower than is needed for the NIF debris shield. These polymeric films also tend to have poor optical quality because they are manufactured by extrusion. Some deposition techniques are available that may result in better quality films, but these are speculative at present. A final issue with these films is the lack of a viable antireflection coating scheme.

An alternative to the disposable shield is a strippable coating to the final optic that accumulates the debris and damage, which is then removed and replaced periodically. This alternative is less attractive than the disposable shield discussed above because it requires removal and recoating of the final optic. The principal options, a sol gel layer and a polymeric film, both suffer from inadequate damage threshold at present. The deliverable is the evaluation of both the disposable shield and the strippable coatings materials candidates.

Optical specifications

Optical specifications are the formal statement of the performance requirements that must be established in detail before any selection of a final optics scheme can be finalized. While the preliminary specifications have already been published in the CDR, we are working to analyze the performance requirements to set the specifications as loosely as is tolerable to allow the greatest latitude in selecting materials and design options for the final optics package. Completion of the specification is the deliverable for this area.

Mechanical integration

Mechanical integration refers to the specific design used to implement the final optics package for the NIF. At present we are considering options for remote (automatic) changing of shields, including methods that can change both disposable and refurbishable shields, and schemes that minimize radiation exposure to maintenance workers during the manual changing of shields. The deliverable for this area is a viable design that accommodates the materials options discussed above.

Antireflection coating

The antireflection coating prevents the approximate 4% per surface energy loss to reflection of each beam for normal incident optics. The baseline option is that debris shields will be coated with the standard sol-gel antireflection coating. The exception is that the final surface will be exposed to x-ray fluences that have been shown to cause the high-surface-area sol particles to sinter into the optical surface. Two candidates for better x-ray resistance are traditional hard antireflection coatings and diffractive coatings that have good antireflection properties. The deliverable for this area is the evaluation of alternative antireflection coatings, which are likely to be more resistant to structural modification caused by the x-ray flux. Included in this analysis is the cost/benefit analysis to determine whether these coating schemes are cost effective relative to leaving the final surface uncoated and accepting the resulting 4% reflection loss.

Concept definition. This general task is the distillation of the above tasks into a comprehensive final optic package design that meets the NIF technical performance goals. Secondly, it meets the cost goals established in the CDR for both the construction and operating budgets. The deliverable here is a concept design.

2.9 Optics Cleaning and Processing

Optic cleaning, coating, and processing encompasses all operations from the delivery of an optic from the manufacturing vendor through the final cleaning, coating, and assembly of an optic component into its support structure. Since the large aperture optics in ICF laser systems require precision tolerances and high damage thresholds, we must design the optic cleaning and processing to be consistent with those requirements. Particulation and residue left on optic surfaces during processing must be reduced to low levels if the highest performance level of each optic is to be achieved. Our experience gained from operating Shiva, Nova, and most recently Beamlet leads us to conclude that stringent clean room procedures are necessary for the assembly areas of most of the NIF optic components. It is anticipated that on average ten optics will have to be cleaned and assembled on a daily basis for a period of three years. In addition, optic support hardware, such as mounting bezels, support frames, apodizers and reflectors (covering a wide variety of sizes and shapes) will also have to be cleaned and assembled. The facilities required to manage this cleaning and assembly process must be developed and demonstrated prior to deployment.

To achieve the cleanliness conditions for the NIF and high optic throughput rate required by NIF requires developing automated clean room facilities. The system must be environmentally safe and minimize hazardous waste generation. For most of the optics, the central processing area for optic cleaning will include cleaning units that incorporate an aqueous cleaning solution, possibly with megasonics, a rinse station, high-pressure water spray, and a drying process. For the special case of KDP crystal cleaning, an automated non-aqueous cleaning process with solvent recovery and recycling will have to be developed on a large scale. Fixturing and other process equipment will also be required for handling of the optics prior to cleaning, after cleaning, and while the optic is being assembled into the mounting frame. Similar technology is presently being incorporated into semiconductor fabrication facilities because of

government-mandated restrictions on solvents. Scale-up of technologies developed in this industry will meet the needs of the ICF laser facilities. In return, U.S. industry will benefit from the cleaning technology initiated by this development effort. Because of the government-mandated solvent policies, many optical manufacturers, aerospace companies, and other laboratories have already requested LLNL's assistance in identifying new cleaning alternatives and materials.

The goals of this development plan will be to develop cleaning and handling systems that will support Class 10 clean room operation, and to maintain surface contamination of assembled optics to less than 0.2 particles ($>5 \mu\text{m}$)/ cm^2 . Automation will be used to increase throughput capability and reduce labor costs. Presently in Nova, four hours are required to clean each optic. During the initial assembly phase of the NIF, we project that about \$1M in technician labor will be saved by this development. Additional savings, which could easily amount to several million dollars, will result because of reduced laser downtime and preventative maintenance activities.

Development plan. The development plan for optics cleaning and processing is summarized in Figure 2.9-1. Efforts in FY95 will address the scope of the optic cleaning process. The optic cleaning development will propose a preliminary processing plan for receiving, cleaning, and assembling of large-aperture optics and optic hardware. The evaluation will include an assessment of commercial industry's capability to provide the required hardware.

During FY96, the optic processing plan will continue and other activities will commence. Reduced-scale experiments will be performed to demonstrate clean component-processing technologies. This will include aqueous and non-aqueous technology.

● = marker

◆ = milestone

Figure 2.9-1. Development schedule for optics cleaning and processing.

demonstrations that are comprehensive enough to develop system specifications for full prototype equipment. On the basis of component tests and the processing plan developed in FY96, a procurement plan for a Class 10 prototype cleaning station will be developed. This plan will be initiated near the end of FY97 so that a full-scale demonstration of the entire cleaning and assembly process can be completed in FY98. Operation will be demonstrated on components produced from the NIF optic pilot production presently scheduled for that year.

3.0 Target Chamber

A quantitative understanding of the source terms for and effects of x rays, γ rays, neutrons, and debris is key to the design of the target area. These source terms and their effects on the target chamber significantly influence the target area design and ultimately the success of the facility. The maximum combined x-ray and debris yields could be as high as 5.8 MJ for the 5-m radius NIF chamber compared to 50-kJ yield for the 2.2-m radius Nova chamber. This factor of ~ 20 higher energy fluence at the first wall, suggests that x-ray ablation of the first wall, deposition of debris and ablated material on optics, and activation of entrant diagnostics can be major obstacles to the successful operation and maintenance of the NIF. The target chamber core technology development program focuses on key development issues to be resolved in the NIF design phase. The natural progression of this effort leads into issues related to Inertial Fusion Energy. By developing key technologies such as predictive capabilities, material response validation and decontamination, a solid scientific foundation is laid for NIF and all future advanced ICF facilities. Proposed development activities include:

- Characterization of target emissions.
- Development of first wall and target positioner protective coatings.
- Development of an absorber for unconverted laser light.
- Development of a final optic protection scheme.
- Development of an automated tritium and activated debris decontamination system (CO_2 cleaner).
- Development of electrical diagnostic component vulnerability and hardening techniques.
- Development of target emplacement, positioner and injection techniques.

3.1 Characterization of Target Emissions

The technical objective of the target emission characterization task is to develop the ability to predict spectra and fluence of x rays, gamma rays, neutrons, shrapnel, and debris to within $\sim 30\%$. Not only must the fluence, spectra, and pulse length be understood but the directionality and orientation to the target and chamber are critical factors as well. Results and predictions from this area drive the baseline target chamber design. Goals for the target emission characterization tasks are (for each type of emission, x ray, debris, shrapnel):

- Develop predictive capabilities.
- Develop methods for diagnosing emissions.
- Predict Nova emissions and confirm experimentally.
- Predict NIF emissions and confirm experimentally on Nova.
- Confirm NIF emissions on NIF.

- Predict LMF-ETF and IFE emissions and test predictive capability on NIF with ignition.
- Publish Periodic Target Emission Reports.

The standard NIF cryogenic target will be a small capsule (deuterium [D], mass of about 0.08 mg, and tritium [T], mass of about 0.125 mg) inside a gold hohlraum (Fig. 3.1-1). Note that as part of an IFE research plan the hohlraum material will change from gold to lead, a more benign material from an activation hazard perspective, soon after the ignition campaign is completed. The cylindrical hohlraum is roughly 9-mm long and 5.5 mm in diameter with 2.8-mm-diam laser entrance holes in the end faces. The entrance holes are covered with 0.4- μm -thick polyimide windows which maintain the 0.3-atm ($\sim 3 \text{ mg}/\text{cm}^3$) helium environment (at 4° K) in the hohlraum.

To prepare the NIF conceptual design, the capabilities of several emission prediction codes were surveyed. The capabilities and limitations of each code are:

HYADES is a radiation/hydrodynamics code in 1-D (planar, cylindrical or spherical) developed by Cascade Sciences Inc. This code is well-suited to high-intensity laser and x-ray interactions with materials, where the low-energy material properties (such as strength) are not significant. T-N burn can be modeled. Features under development include ion deposition, material strength models, and 2-D capabilities.

40-00-0394-1435 pub

Figure 3.1-1. Schematic showing the design of cryogenic hohlraum.

CONRAD is also a radiation/hydrodynamics code in 1-D (planar, cylindrical or spherical) developed by the University of Wisconsin. This code was written to model target chamber environments, so both x-ray and debris (ion) energy loadings are implemented. Additionally, thermal radiation from hot vapor/ions can deposit energy on surfaces. The ablation model includes the effects of thermal conduction. Features under development include laser deposition and 2-D capabilities.

TSUNAMI is gas dynamics code in 2-D (planar or cylindrical) developed by Lawrence Berkeley Laboratory. This code uses a simple ablation model to determine the initial conditions for the motions of ablated vapor. A target can be included by specifying an initial mass and energy of a few cells. Real gas equations of state can be included, as these are important for dissociation and ionization of species. Features under development include radiation transport and condensation boundary conditions.

PUFF2-D is a shock/hydrodynamics code in 2-D developed by SRI Inc. This code is used to model the effects of x-ray generated (and other) shocks on condensed phases of materials. It includes extensive material and fracture models to predict failure. The initial conditions (energy deposition profile) must be determined with a separate code, so integration with such a code, perhaps HYADES, is under consideration.

DYNA2-D is a shock/hydrodynamics code in 2-D developed by LLNL. A 3-D version is also available (DYNA3-D). This code is used to model the effects of shocks and other transient loads on solid materials. It includes numerous material and fracture models. The initial conditions (energy deposition profile) for chamber modeling must be determined with a separate code.

All of these codes have been successfully used in applications both within the ICF program and outside of it. However, to date, none of these codes have been validated to the energy deposition levels anticipated for ICF missions. The accuracy with which these codes can calculate target emissions and its interaction with the target chamber must be evaluated as part of this core technology task.

The key parameters that our simulation will attempt to predict to within 30% are shown in Table 3.1-1. If we can achieve this accuracy then more modest safety factors can be used to provide the necessary design margin. Further analysis will be required to validate this accuracy and demonstrate consistency with final design requirements. Another set of computer codes [or even some of these codes] will be used to predict the response of chamber materials to these emissions. It is important that the results of the material response simulation (discussed in Section 3.2) be carefully integrated with the results of this section to assure a comprehensive and consistent predictive capability overall.

Debris and shrapnel, has already surfaced as an important issue on Nova, and will present an even greater threat on NIF. The increase in mass near the NIF target due to ancillary target material such as 1ω and 2ω shields and protection around the target diagnostic holes in the hohlraum, will result in increased mass deposition on target chamber wall and debris shields. Experiments on Nova have proven that localized melt and vaporization of metal surfaces 1 m from chamber center can occur. Figure 3.1-2 shows a calculation of the dynamic response of a Nova hohlraum generated with TSUNAMI. The jetting through the holes in the side of the hohlraum is consistent with Nova

Table 3.1-1. Parameters of interest for target emissions.

Emission	Parameters
X rays	Spectra Energy Time history Anisotropy
Debris	Peak and average ion energies Time history Anisotropy Total mass Total energy
Shrapnel	Particle size distribution Particle velocities Anisotropy

observations. A second TSUNAMI calculation was done for a baseline NIF hohlraum and a 1.8-MJ no-yield NIF shot. The result, shown in Fig. 3.1-3, suggests that the mass distribution deposited on the first wall will be highly anisotropic. The simulation accounts for the axial jetting and the ablation of material off the target holder. Although the debris shields appear to be out of the path of the jets, they will have to absorb debris and shrapnel from these other sources.

Presently, predictions of the x-ray fluence deposited on the first wall shows a Lambertian (cosine) distribution of x rays with 20× more fluence than on Nova. However, this emission prediction has not yet been experimentally bench marked and must be confirmed before first wall designs can be finalized. In addition, the response of the first wall due to both x-ray and mass deposition must be coupled in time since there will be interacting effects. This will complicate the calculations but is necessary in order to achieve the accuracy required.

If possible the computer simulation capability should be developed using unclassified codes. This would allow the results to be useful to the broad range of collaborating ICF partners at Universities and outside laboratories. Also, we must invest time and resources in developing experimental techniques that can be used to confirm model predictions. Current techniques are nascent but will be improved using Nova or pulsed power facilities such as Saturn as a test vehicle.

The schedule of development activities for the target emission characterization activities is shown in Fig. 3.1-4. Preliminary predictions of Nova emissions which have been confirmed experimentally will be published in the Nova Source Book in Oct 1995. Further calculations and experiments will project these results to NIF conditions during the following year. Results will be published in January 1997. The Source Book for NIF emissions will be completed at about the time of KD3 to confirm assumptions made in the design of the debris shield and first wall. After KD3, predictions will be extended to

Figure 3.1-2. Calculation of Nova hohlraum disassembly using TSUNAMI.

missions beyond NIF: 1) LMF, 2) ETF, and 3) IFE. A Source Book for those facilities will also be published probably in the final quarter of FY98. These predictions will be confirmed during experiments in NIF shortly after the commencement of operations.

3.2 First Wall and Target Positioner Protective Coatings

The development of first wall and target positioner protective coatings is a primary part of the target chamber core technology program. The technical objective of the first wall development task is to prevent degradation of the target chamber and final optic by material ablated by x rays and shrapnel generated by the NIF target.

70-15-0694-2709pub

Figure 3.1-3. Calculation of NIF hohlraum debris using TSUNAMI for a 1.8 MJ target shot with no yield.

Table 3.2-1 characterizes x-ray emissions relevant to the positioner and first wall response, both necessary to assess the threat to the debris shield. These values assume that 50% of the laser energy is converted into x rays and, the remainder is in debris energy. Likewise, of the 20% of the fusion yield that is not neutrons, half is assumed to contribute to x rays and half to debris. The assumed spectra is an average between disk spectra and Nova hohlraum drive temperatures. The range of fluences on the first wall for any target arises from the assumption of a Lambertian-like distribution of the x rays. The pulse length, expected to be nanoseconds long, is taken to be 1 ns for conservatism.

These x-ray fluences at the NIF target chamber wall would be high enough to ablate a large amount from a bare aluminum chamber wall (hundreds of kilograms per year). Therefore the walls will be protected with a coating of low-Z, high-temperature material to minimize x-ray ablation. One candidate material, boron, could be plasma sprayed onto aluminum panels, which will be bolted to the inside of the target chamber. This

● = marker

◆ = milestone

Figure 3.1-4. Schedule of development activities for target emission characterization.

Table 3.2-1. Assumed fluences and other x-ray characteristics.

Shot (MJ)	Energy (MJ)	Spectra (BB)	Target positioner (20 cm) (J/cm ²)	Time (ns)	First wall range (5 m) (J/cm ²)	#/year
1.0	0.5	170	99.5	1	0.16-32	250-500
1.5	0.75	170	149	1	0.24-48	250-500
1.8	0.9	170	179	1	0.29-58	50-150
1.9 (100kJ)	0.901	170	179	1	0.29-58	100
2.8 (1 MJ)	1.0	200	199	1	0.32-64	0
6.8 (5 MJ)	1.4	250	278.6	1	0.45-0.9	35
21.8 (20 MJ)	2.9	350	577	1	0.92-1.8	10
46.8 (45 MJ)	5.4	350	1075	1	1.7-3.5	0

Notes: a) Target positioner at 20 cm from target with isotropic x-ray fluence.

b) First wall reflects Lambertian peak fluence to isotropic average fluence.

design allows damaged sections to be replaced without the requirement for *in situ* plasma spraying work.

Figure 3.2-1 shows predicted x-ray ablation for the boron first wall coating along with curves for bare aluminum for comparison. Points showing the maximum expected fluence at the wall from a 20-MJ shot at both 4- and 5-m chamber radius are also plotted. The maximum fluence at the 5-m radius is below or just at the minimum to ablate the boron coating. Calculated response of a boron first surface material to x-ray loadings is shown in Table 3.2-2. This calculation indicates that no material will be removed by any shots up to and including the 20-MJ yield case. Debris is not expected to damage the first wall since the deposition times are long enough to allow the coatings to conduct away the heat without reaching vaporization temperatures.

These calculations have not been experimentally bench marked. No data exists to confirm these predictions until Nova or Saturn experiments are conducted. While boron

Figure 3.2-1. Anticipated ablation depth due to x-rays for bare aluminum and for boron coating.

Table 3.2-2. Anticipated ablation due to x-rays and target debris for boron first wall.

Shot (MJ)	Energy (MJ)	X-ray spectra (BB)	Time (ns)	First wall (5-m) (Å on DS)	#/year
1.0	0.5	170	1	0	250-500
1.5	0.75	170	1	0	250-500
1.8	0.9	170	1	0	50-150
1.9 (100 kJ)	0.901	170	1	0	100
2.8 (1 MJ)	1.0	200	1	0	0
6.8 (5 MJ)	1.4	250	1	0	35
21.8 (20 MJ)	2.9	350	1	0	10
46.8 (45 MJ)	5.4	350	1	300	0

has excellent resistance to x-ray ablation, several disadvantages keep it from being the ideal first wall material. Boron requires very high plasma spray temperatures and must be plasma sprayed in an argon atmosphere. Additionally, it is very expensive and difficult to keep pure. Boron, however, is not the only suitable candidate material. Other materials that are promising include spinel, MgO, Al₂O₃, C, and Si₃N₄. This development task entails a cost-benefit study of the effects of the various target emission source terms on a number of candidate materials. Code calculation and experiments on Nova will be used to determine the various effects on the candidate wall materials. The net fluxes that will impact the debris shields will also be assessed. This work will lead to the selection of an optimum first wall material. Bench marking of code calculations with experimental results on Nova will lead to validated predictive capability for NIF and LMF/ETF first wall materials. Goals for the first wall materials task are:

- Establish bounds on target emission source terms.
- Expand the list of potential first wall materials.
- Develop coating application technology.
- Investigate the effects of source terms on each candidate first wall material, including repetitive pulses and decontamination.
- Develop and use computer codes to study these effects.
- Perform material tests on Nova and benchmark codes.
- Use benchmark codes to predict the optimum material for NIF and LMF/ETF.

The critical effects that will be evaluated are summarized in Table 3.2-3. The three columns list source terms, potential first wall materials, and effects to be quantified. Knowledge of these effects will lead to optimum choices of protective materials for the first wall and target positioner.

We envision that several computer codes will be used to study the first wall candidate materials. Codes such as CONRAD, TSUNAMI, and PUFF described in the target

Table 3.2-3. NIF first wall material matrix.

Source term	First wall material	Effect
neutron	bare Al	vaporization melt
	alumina (Al ₂ O ₃)	spall
debris	graphite	cratering
shrapnel	flame-sprayed Al	fatigue
vapor deposition	flame-sprayed Al ₂ O ₃	delamination
	BN	...
	BC	net flux to debris shields ...
-	porous Al N	net wall material removal
-	porous Mg O	...
-	plasma-sprayed B	net structural damage ...
	plasma-sprayed B/5% W	
	Each of above PLUS:	
	1) vapor deposition from previous shot	
	2) shrapnel from previous shot	
	3) debris from previous shot	
	4) degraded surface after several shots	

emissions section are candidate first wall analysis tools. Since these codes were not developed for the purpose of modeling ICF emission interactions, we anticipate that other codes and code development work will be coordinated in a national effort.

Experiments to test various candidate first wall materials will be performed on NOVA and Saturn and on NIF as it comes on line. Comparison with code predictions will lead to bench marking of the codes. The codes can then be used to make predictions for the higher yield NIF shots and eventually for LMF/ETF parameters.

Figure 3.2-2 is the schedule of development activities for the first wall and target positioner protective coatings development task. The evaluation of the response of candidate chamber materials to x rays, shrapnel and debris is completed in late FY95. Validation of the dynamic chamber response will be completed the following year; it requires the model simulation to account for multiple source terms. An intermediate deliverable in FY96 is the performance evaluation of the first wall and target positioner.

● = marker

◆ = milestone

Figure 3.2-2. Schedule of development activities.

Further calculations and experiments will project these results to NIF conditions in FY97.

3.3 Unconverted Laser Light Absorber

The technical objective for the laser beam absorber is to benignly absorb unconverted $1\omega/2\omega$ laser light in the target chamber thereby reducing ablation and possible contamination of the final optics. The beam absorber must survive an anticipated fluence of unconverted laser light that will average 10 J/cm^2 with a beam modulation of 3:1. Additionally, the laser beam absorber must survive x-ray fluences up to 1.8 J/cm^2 . To minimize operating costs, the beam absorber lifetime requirement is at least one year.

The $1\omega/2\omega$ beam absorbers absorb the energy from unconverted laser light. This light comprises 40% of the total laser energy entering the chamber. The intensity of these beams is sufficient to cause material from the first wall to vaporize. The vaporized material would subsequently redeposit throughout the chamber, including on the laser optics.

Although beam absorbers using current technology can safely absorb the anticipated average fluence, the beam modulation of 3:1 may result in some localized damage. A proposed development program will advance the technical performance of the beam absorbers to absorb these modulations with a comfortable margin. This will require approximately a doubling of the current maximum energy handling capability. There is also the need to design the beam absorbers to survive the target emissions, particularly the x-ray fluence. This will ensure reliable, long-lived beam absorbers that do not coat the final optics with material ejected from damage sites.

The baseline NIF beam absorber design shown in Fig. 3.3-1 is based on the use of absorbing glasses. Nova currently uses a similar system in which sheets of absorbing glass are mounted directly to the wall on the far side of the chamber from the beam entrance points. The Nova glass has a damage threshold of just a few J/cm^2 , which is exceeded by the modulation on some high-energy shots. Fused silica plates are used to contain any ablated or spalled material.

Improved absorbing glass, such as that employed on Beamlet, can have damage thresholds of 15-20 J/cm^2 . The laser diagnostics development program (Section 1.7) will attempt to improve the damage limits of the absorbing glass beyond this level. Using these materials will allow the NIF design to function like Nova, with an absorbing glass that can accommodate the average laser pulse energy. As on Nova, the few spots of glass that may be damaged will require the use of some type of transparent containment.

The tasks required to develop the unconverted laser beam absorber are:

- Define source terms for the incident laser energy.
- Investigate damage limits of baseline design.
- Develop sacrificial cover for the absorber.
- Investigate benign ablating material.

40-00-0394-1437 pub

Figure 3.3-1. Scheme of beam absorber.

The first part of this effort will be to characterize the laser energy that will be incident on the beam absorbers, i.e., determine the peak intensities and their distribution on the absorber. This will form the basis of further evaluation of beam absorber components. The second part of the effort will be to develop and test possible containment materials to achieve sufficient resistance to laser and x-ray damage. X-ray testing of the absorbing glass (developed by laser diagnostic group) will also be included. The final part of the development will be to search for alternate materials that may ablate in a way that does not permit recondensation on the final optics.

The magnitude of the modulation on the laser beam at the beam absorber location is the key parameter that must be quantified. Other important characteristics will be the size of the beam on the wall, the pulse shape and duration as well as the combined effect of 1ω and 2ω impinging on the beam absorber simultaneously. This effort will also consider the possibility of 3ω energy deposition. Although it will not occur routinely, it is possible under off-normal conditions for the beams of all three laser wavelengths to impinge on the beam absorber. The design of the beam absorber must safely accommodate this potential event. Both code simulations and an experimental campaign will be used to complete this work.

A development and testing program will evaluate the ability of the absorbing glass and any other candidate containment materials to withstand the laser and x-ray environment expected in NIF. The initial phase will focus on the response of material samples to x-ray and laser energy deposition over the range of NIF conditions. Note that the laser damage testing of the absorbing glass will be part of the laser diagnostics effort. The second part of the program will be development and test of a prototype beam absorber. This will include mounting for the static containment system which may be either fused silica plates or a disposable plastic film.

The third aspect of the beam absorber development will be a parallel effort to identify an alternate design, not based on absorbing glass. A solid, opaque material might be used as the beam absorber, provided that any ablated material had acceptable impact on the final optics, and that the absorber replacement rate was reasonable. This effort would experimentally investigate laser ablation of candidate solids, with particular emphasis on the ablation products.

One possible class of materials to investigate would be those that are dissociated by the laser pulse into components that could be pumped out as benign, noncondensable gas. Plastics such as Teflon, which thermally dissociate into their monomer, hold some promise. The fragments would either be pumped out by the vacuum system or they condense as a thin, transparent film. However, additional deposition of laser light and x rays may further dissociate the material generating free fluorine which may not be acceptable. Because this offers a very inexpensive solution, this technique will be explored. Note that the ablation and condensation experiments on plastics will also be relevant to the possible use of a sacrificial film for final optics protection.

Another possible material type is one that would deposit only particles on the optics that could easily be cleaned off, such as carbon. It is known that surfaces can be cleaned of organic material if exposed to ultraviolet (UV) light (about 200 nm) in the presence of

oxygen. Therefore after each shot, some oxygen could be introduced to the chamber (perhaps contained in the beam tubes by vacuum valves); UV lights could be turned on (one for each beamport) to react the carbon into carbon dioxide, which would be pumped out by the vacuum system. The experimental effort for this material type would include ablation behavior and removal techniques.

Facilities will be needed for the laser and x-ray exposure testing activities. The most likely sites are Nova and Janus for the x-ray testing and Nova or Beamlet for the experiments to confirm laser beam modulation and other characteristics. The fabrication of plastic films to be used in evaluations of containment materials can be done at LLNL in the coating lab, or by outside vendors if necessary.

All development efforts will be completed during a three-year campaign, shown in Fig. 3.3-2. Three milestones are shown. In late FY95 the source term for the unconverted

● = marker

◆ = milestone

Figure 3.3-2. Schedule of development of laser beam absorber.

light will be characterized. During the third quarter of FY96 damage limits for the proposed materials will be characterized. Confirmation of the beam absorber concept will be completed by third quarter of FY97. This will include completion of the investigation of damage mitigation and containment with sacrificial covers. The investigation of alternate absorbing materials is also completed in third quarter FY97 with the publication of a final report. The timing of these activities will allow the results to be incorporated into the design of the NIF beam absorber. Damage threshold levels will be established prior to preliminary design. Before final design begins, the basic design concept will be confirmed with laboratory tests.

3.4 Advanced Final Optic Protective Coating

The final optic of each beamlet is vulnerable to damage from debris, shrapnel and ablated material. In addition, the protection scheme chosen must maintain demanding optical performance specifications. The technical objectives of the final optics protective coating task are to protect optics upstream of debris shield from 100% of the target chamber debris and reduce final optics refurbishment costs.

The debris shield will be at near-normal incidence, and will be AR coated on both sides. We assume the final design AR coating will have an x-ray damage threshold of at least 0.5 J/cm^2 to survive shots up to 5 MJ. The main threat to the debris shields is the accumulation of solid materials from condensation of target debris and ablated target positioner mass. Combining the accumulation per shot data from these sources over a typical week of shots gives a total of between 2 and 7 Å of material (mostly low-Z material from target positioner) on the shields before the week's final high-yield shot.

There are two approaches to optimizing the protection of the final optic. The first, addressed in Sections 3.1 and 3.2 describes development activities with goals of minimizing the amount of material ablated. Another approach, described in this section, is to develop a disposable one-shot debris shield. The baseline development for the NIF final optic protector, shown in Fig. 3.4-1, is a replaceable fused silica debris shield covered with a thin layer of plastic facing the target. Since the optic is replaced before each shot, debris deposition is avoided. The plastic coating, however, must transmit and survive the NIF 1ω , 2ω , and 3ω laser fluences. It must also survive all of the hostile target chamber source terms except shrapnel. The development of a threat assessment capability is required to assess the developmental design concepts, and provide a risk benefit analysis relative to cleaning a bare debris shield.

There are five major subtasks in this area each with its own deliverable. They are:

- Concept definition.
- In-chamber mechanism design.
- Refurbishment production line design.
- Cost-benefit analysis.
- Prototyping.

70-15-0894-3071pb01

Figure 3.4-1. Schematic of advanced final optic concept.

The concept definition phase involves the delivery of a validated feasible solution. First, the threat to the final optics must be identified and quantified. Next conceptual protection schemes such as disposable plastic films on fused silica are investigated. Samples will be fabricated, and the effect of the threats from blowoff x rays and debris will be validated using models verified with experimental results. Optical performance specifications such as laser damage threshold and beam quality are evaluated for each concept, and a rough estimate of the concept cost and feasibility is generated.

The next phase is to develop a mechanical design. The in-chamber mechanism design task delivers a costed mechanical design of in-chamber components. Requirements and designs for the removable debris shield holders and mechanisms such as rolls or hoops for applying plastic films are developed, and the capital and operating costs estimated.

Refurbishment time is a significant operational cost for the facility. The deliverable for the refurbishment production line is to deliver a costed design. Requirements such as the amount of refinishing for optics and the purity and process for depositing plastics will be defined.

Since the second goal of the final optics protection task is to reduce the cost of the final optics refurbishment, cost-benefit analysis on the entire refurbishment cycle is proposed for the design. Of the designs that are cost effective, scaled prototypes will be designed, built and tested.

◆ = milestone

Figure 3.4-2. Schedule of advanced final optic concept.

The development effort for this task will be completed by the end of FY96, as shown in Fig. 3.4-2. Three deliverables are shown. In late FY95, the final optic protection performance evaluation is complete, and a protection technique is selected for prototyping. Before final design begins, the basic concept will be prototyped and confirmed with laboratory tests. This prototype will be complete in late FY96.

3.5 Automated Tritium and Activated Debris Decontamination System

The tritium throughput projected for NIF is 600 Ci/year. This is a factor of 1200 more than the 0.5 Ci/year throughput on Nova. Presently on Nova, no activated debris is generated, while on NIF, the projected amount of activated debris will exceed hundreds of grams per year. To achieve effective, rapid removal of surface-contaminate-trapped tritium and radioactive debris while minimizing the production of mixed waste, we will develop advanced decontamination technologies. The technical objective of the project is: to develop and demonstrate advanced cleaning technologies that meet the NIF design requirements for target chamber availability and contaminant removal while minimizing personnel exposures and avoiding the generation of mixed waste. Specifically the system must clean 95% of the deposited surface contaminants for the chamber walls, and better than 99% for optical components.

We envision a CO₂ cleaning system that dislodges the surface contaminants utilizing a solid, pelletized "blasting" media applied to target chamber surfaces. This system is shown in Fig. 3.5-1. Surrounding the media delivery nozzle, a close-capture vacuum recovery system locally captures the dislodged contaminants and sweeps them away to a HEPA-filtered-particulate capturing system. To provide effective and efficient surface

Figure 3.5-1. CO₂ cleaner concept.

decontamination, this recovery process is essential to keep contaminants from subsequently redepositing. While CO₂ cleaning techniques are rapidly finding application in the nuclear power industry and in certain institutions such as NASA, the close-capture vacuum requirement for effective tritiated debris removal makes this project unique.

A similar off-line process will also be developed for the debris shield surfaces in the event that they cannot be cleaned *in situ*. In addition, since the NIF diagnostic line-of-sight tubes are difficult to access, and there is a need to localize the beryllium and tritium contaminants, we will develop a separate, robotically controlled "chimney sweep" cleaning and decontamination capability using the same technology.

The project subtasks include:

- **Demonstrate first wall CO₂ cleaning feasibility.** The first wall panels, manufactured from aluminum sheet, are proposed to be coated with a material such as boron, that possesses the required shot-physics properties. The proposed method of applying this coating is via plasma spray. Proof-of-principle CO₂ cleaning experiments must be performed on representative "coated" first wall samples to establish baseline effectiveness of tritium/surface contaminate removal and coating survivability with respect to surface cooling and inherent dynamics of the pelletized "blasting" cleaning process. This technique will also be tested on the debris shield, a fused silica substrate that shield the final laser focusing lens from the target debris. If this is successful, then significant savings in debris shield replacement could be realized for NIF.
- **Develop a vacuum recovery system.** A typical nozzle exit velocity of compressed-air-propelled CO₂ pellets ranges from 6,000–15,000 ft/s. As the pellets impact the surface contaminate, their kinetic energy causes penetration through to the surface of the substrate. The resulting sublimation (from solid to gaseous CO₂) lifts, liberates, and randomly propels the surface contamination away from the

"clean" surface. Due to the high velocity potential of the liberated surface-contaminate, an effective, local collection system must be developed and implemented to minimize the redepositing of the tritiated/activated debris.

- **Develop a prototype integrated robotic-arm-controlled CO₂ cleaning system.** To achieve thorough, consistent cleaning/decontamination results, a method for remotely and accurately positioning the CO₂ delivery/recovery system is required. The present concept shown in Fig. 3.5-1 is a small, articulated, six-degree-of-freedom robotic arm. Control of the arm will be either manual with a "joy stick," or by programmable controller with "learning" capability for automatic positioning. A prototype of this system will be developed and experimental results will be used to specify requirements for the system that will be deployed in NIF.
- **Develop a diagnostic line of sight "chimney sweep" cleaning system.** The diagnostic line-of-sight cleaners pose an additional level of decontamination complexity because of their long and narrow tubular shape whose internal surfaces must be cleaned. During NIF shots, the diagnostic lines of sight are exposed to the same debris/surface-contaminates as the NIF vacuum chamber. The inside diameters/lengths of the diagnostic line-of-sight tube enclosures varies from tube to tube. The capability to periodically decontaminate this variety of enclosures needs to be developed. The chimney sweep system shown in Fig. 3.5-2 is a concept that will be explored during the development program. The unit uses similar debris removal and collection concepts as previously described. The delivery of

70-10-0594-2538.pub

Figure 3.5-2. Diagnostic line of sight cleaner concept.

the CO₂ media is accomplished via a rotating array of nozzles which are skewed to achieve optimum contaminant removal angles with respect to the tube wall. The unit is axially translated by means of a robotic actuator. The debris recovery system is located on the aft end of the unit to vacuum the liberated contaminants back toward the end of the line-of-sight tube. This design will prevent contaminants from spreading towards the NIF chamber.

- **Perform decontamination experiments on Nova components and proposed NIF materials.** Early in the development program, proof-of-principle decontamination experiments will be performed to demonstrate the feasibility of the CO₂ cleaning process. Small-scale contaminated specimens will be obtained and cleaned. The specimens will be exposed to contamination in the Nova target chamber. This will produce realistic conditions that will be scaled to represent the high energies generated in NIF. The samples would then be cleaned/decontaminated and evaluated for effectiveness of tritium removal and overall surface activation buildup. Conducted over many cleaning cycles, these experiments establish long-term decontamination effectiveness and overall component life expectancy.

Even though the CO₂ cleaning technique has been successfully deployed in a variety of applications, the NIF environment is uniquely challenging and may make implementation of the process too difficult. If the process is proven to be not viable, the default method of cleaning/decontamination of the NIF chamber and associated components would be to use the more traditional mechanical/chemical removal techniques. This includes the use of abrasives/wire brush for the removal of target-produced debris, which mechanically bonded to surfaces, and the use of suitable wipes that have been wetted with solvents for the removal of hydrocarbon-based surface films. These methods of cleaning/decontamination would increase the annual amount of hazardous and mixed wastes by about 270 kg/year (see NIF CDR Section 5.4.6, Table 5.4.6-1). Other significant drawbacks of the use of traditional cleaning techniques include the increased personnel hazards caused by human entry into the tritium/neutron-surface-activated NIF chamber and the schedule/programmatic impact caused by the time-consuming, labor-intensive work required by these methods.

The task schedule for the project is shown in Fig. 3.5-3. The first deliverable is in 4th quarter FY95. By this date the proof-of-principle evaluation of CO₂ cleaning on samples of NIF materials will be complete and an evaluation of the cleaning techniques effectiveness made. Shortly afterwards in the first quarter of FY96, an evaluation of the feasibility of the "chimney sweep" system will also be complete. Depending upon the results of these initial experiments, prototypes of the proposed concepts will be fabricated and tested in FY96. This will include an evaluation of the robotic arm to control the positioning of the cleaning system with sufficient accuracy to achieve the requirements for contaminant removal and collection.

◆ = milestone

Figure 3.5-3. Schedule for the development of an automated tritium and activated debris decontamination system.

3.6 Electrical Diagnostic Component Vulnerability and Hardening Techniques

The conceptual design of the NIF target area instrumentation system demands that the instruments must survive in a hostile x-ray, neutron, gamma-ray, EMP, and debris environment. In addition, data integrity must be maintained for high-resolution images and sub-nanosecond transient signals while maintaining a demanding operational shot schedule. The technical objective of this task is to develop hardening techniques to allow the required diagnostics instrumentation to survive target area emission and record data from the required diagnostics in each phase of the NIF experimental plan. The NIF experimental plan has four major phases: 1) start-up activities, 2) hohlraum tuning experiments, 3) cryogenic and preignition experiments, and 4) ignition shots. Each of these phases requires different diagnostics and generates different emission source terms. Table 3.6-1 shows present predictions of prompt radiation fluxes for several areas of the target area for a 21.8-MJ yield NIF shot. In some cases, these flux levels are as much as six orders of magnitude higher than the prompt radiation levels generated by the Nova system. Prompt radiation generates photocurrents in cables and semiconductor devices; it also generates electric fields in oxides and can cause permanent degradation of device characteristics by neutron, or other

Table 3.6-1. Predicted prompt radiation flux at various target area locations for a 21.8-MJ yield.

	Flux levels				
	21.8 MJ yield				
	Source	Inside TC			Outside TC Inside TR
Radiation	0 meters	2.5 meters	5.0 meters	5.5 meters	13 meters
				Attn: 26.5:1	
Neutrons (N/cm ²)	1.00E + 19	1.27E + 13	3.18E + 12	1.00E + 11	2.00E + 10
Neutrons (N/cm ²) sec.		2.00E + 22	3.18E + 21	1.00E + 20	1.33E + 19
				Attn: 13:1	
X-ray (Mev/cm ²) sec.	350 eV BB	6.00E + 22	1.50E + 22	0.00E + 00	0.00E + 00
				Attn: 4" Al only	

displacement producing radiation. The two most prominent effects of ionizing radiation on semiconductors and dielectrics are:

- Ionizing radiation creates charge carriers in insulators and reversed biased junctions where there were previously almost no carriers.
- Radiation, particularly neutron radiation produces defects in the lattice structure. These defects act as traps and recombination centers to reduce the free carrier life time and carrier density.

In addition to the transient radiation environment, there will be at least three sources of EMP in the NIF facility: 1) prompt gamma dose that ionizes air both inside and outside the chamber; 2) the electrons driven off of hohlraum and shielding material near the target supporting chamber diagnostics; 3) the charge separations that will be generated when two materials with different electron yields to gamma radiation are adjacent, and are exposed to roughly the same gamma ray dose rate.

We present a development plan with goals to assess the performance of the NIF instrumentation response to EMP, x rays, gamma rays, neutrons and debris. Major components that will be assessed include fiber optic cable transport, high bandwidth cable, streak cameras and CCD imaging systems. The goals of the electrical diagnostic component vulnerability and hardening techniques plan are:

- Determine the neutron, gamma, x-ray, EMP, and debris environments expected for the NIF diagnostics.
- Determine the susceptibility of each type of diagnostic component.
- Determine the vulnerability of each diagnostic.
- Develop hardened instrumentation to meet the requirements of the NIF environment.

The first part of the development plan is to define a range of source terms for the environment the diagnostics are likely to see. This work is synergistic with 3.1 but will require a more detailed assessment of the diagnostics locations and the experiment plan. The major activity for this part of the plan is to develop and validate a predictive capability of the Nova electric field strength that can be expanded to the NIF geometry. Presently we have no data on the EMP present in the Nova chamber. This data is a necessary starting point in predicting the NIF EMP environment. There is limited data available on Nova at one location outside the target chamber. Radiative EMP effects are geometry dependent, and will differ at various locations in the target area. Lastly, although the source terms for the gamma, neutron, x-ray, and debris environment are calculated in another part of this plan, these source terms must be applied to the diagnostic locations consistent with the NIF experimental plan. The tasks to be performed in the phase of the work are:

- Define and validate gamma, neutron, x-ray, and debris environments.
- Determine the Nova target chamber interior electromagnetic fields.
- Determine the Nova electromagnetic fields outside the chamber at various locations.
- Develop a model to predict the EMI environment inside and outside the Nova target chamber. Validate with Nova experimental data.
- Expand model to the NIF geometry.

The second part of the development plan is to assess instrument susceptibility. Data is available from testing nuclear weapons effects but because the instrumentation systems on NIF are not widely used, much of this data is not applicable. High bandwidth coaxial cable is by far the most documented component. Table 3.6-2 gives the range of susceptibilities measured for different types of high bandwidth cable.

Numerous factors can affect the cable direct-drive transient radiation response reported in Table 3.6-2. Several sources^{5,9} indicate that a cable with 5-kV bias on it will be between one and two orders of magnitude more sensitive to gamma and neutron radiation than an unbiased cable. This is independent of high voltage polarity. Also the cable response can vary by as much as a factor of ten for different pieces of nominally identical cables. Cable response may also depend on previous cable history and handling. We will analyze all available data and perform additional tests to establish a basis for the NIF cable designs.

Susceptibility data is sparse for the rest of the NIF instrumentation. In some cases only one measurement has been taken and the sensitivity quoted cannot be corroborated by any other sources. In particular, the quoted CCD neutron sensitivity is based on only one data point and the projected instrument vulnerability based on this sensitivity is very high. Table 3.6-3 shows the sensitivity data available to date.

Tasks to be performed in this phase of project include:

- Survey instruments in target chamber to determine worst-case conditions.
- Measure CCD neutron sensitivity.
- Measure sensitivity of CCD memories and Mosfets.

Table 3.6-2. High bandwidth cable sensitivity to transient radiation.

Cable	Sensitivity
Gamma ray	
Gamma sensitivity is shown for Cobalt 60, which has gamma lines near 1.15 MeV.	
7/8" foam ^{1,2}	$1 \times 10^{-20} \frac{\text{A / m}}{\gamma - \text{MeV / cm}^2 \text{ sec}}$
7/8" L.D. foam ^{3,4}	$2 \times 10^{-23} \frac{\text{A / m}}{\gamma - \text{MeV / cm}^2 \text{ sec}}$
7/8" Air heliax ⁴	$2 \times 10^{-21} \frac{\text{A / m}}{\gamma - \text{MeV / cm}^2 \text{ sec}}$
Gore P6 ^{5,6}	$1 \times 10^{-21} \frac{\text{A / m}}{\gamma - \text{MeV / cm}^2 \text{ sec}}$
IW 2251 ^{7,8}	$4 \times 10^{-22} \frac{\text{A / m}}{\gamma - \text{MeV / cm}^2 \text{ sec}}$
RG8/RG58 ^{1,2,8}	$2 \times 10^{-21} \frac{\text{A / m}}{\gamma - \text{MeV / cm}^2 \text{ sec}}$
X-ray	
100 KeV x-rays	
7/8" foam ¹	$1 \times 10^{-19} \frac{\text{A / m}}{\gamma - \text{MeV / cm}^2 \text{ sec}}$
RG8/RG58	Not measured
Neutron	
14 MeV neutrons	
RG-213 ^{7,8}	$1 \times 10^{-19} \frac{\text{A / n}}{\text{cm}^2 \text{ sec m}}$
7/8" foam	Not measured

- Measure neutron darkening of fiber.
- Measure the radiation sensitivity of streak camera imaging diagnostics.
- Evaluate the impact on the NIF diagnostics experimental plan.

Table 3.6-3. Radiation sensitivities of instrumentation components.

Component	X ray	γ ray	Neutron	Cerenkov
Cable, 7/8" foam	$\frac{10^{-19} \text{ A / m}}{\gamma - \text{MeV / cm}^2 \text{ sec}}$	$\frac{10^{-20} \text{ A / m}}{\gamma - \text{MeV / cm}^2 \text{ sec}}$	$\frac{10^{-19} \text{ A / m}}{\text{cm}^2 \text{ sec m}}$	NA
Fiber	NA	NA	NA	$\frac{10^{-26} \text{ W / cm}}{\gamma - \text{MeV / cm}^2 \text{ sec}}$
CCD cameras	NA	NA	$\frac{10^{-4} \text{ stars}}{\text{neutron}}$	NA

Based on our initial assessment, we anticipate that hardening technology development will be required. For example, if the CCD neutron sensitivity in Table 3.6-3 (10^{-4} stars/neutron) is accurate, then the sensitivity of CCD cameras is an issue for NIF. A star in this context is one neutron-silicon interaction. This interaction can cover anywhere from one to 10 pixels. At the target chamber wall, the flux is 3.18×10^{12} neutrons/cm². Therefore on a CCD chip that is 1-cm square, there would be 3.18×10^8 stars produced. Outside of the target chamber shielding, 1×10^7 stars would be produced. Since a 512×512 chip has 2.6×10^5 pixels, in each of these cases, there are more neutron upsets than pixels, and no data is returned.

A second potential problem area based on our initial cursory assessment is Cerenkov fiber sensitivity. The Cerenkov sensitivity of fibers is $1 \times 10^{-26} \text{ W / (}\gamma\text{-MeV / cm}^2\text{)}$ per cm of fiber. With an x-ray flux of $2.4 \times 10^{22} \gamma\text{-MeV / cm}^2 \text{ sec}$, this would lead to 24 mW of optical power for each centimeter of fiber in the target chamber. Since projected signal levels are less than 1 mW, this calculation allows us to begin to bound the instrument vulnerability.

These predictions assume no shielding; the instrument location is at the chamber wall. In the NIF, shielding will be required for most diagnostics in many different geometries. The tasks identified previously will enable us to account for the wide variety of conditions to make confident recommendations regarding the type and amount of shielding that will be required.

While it is not possible to predict the outcome of the assessment of diagnostic vulnerability, it is likely that hardening will be required. Imaging cameras and diagnostics entrant to the chamber are likely candidates. The major risk of this development activity is primarily in the uncertainties of the source term predictions. Another issue is that some diagnostics components are difficult to harden. As a result, alternative diagnostic designs using scattered signals or off axis imaging might be required.

We have developed a schedule shown in Fig. 3.6-1 that is consistent with NIF activation. A range of source terms for diagnostics and an assessment of the diagnostics required and their location for each phase of the NIF experimental plan will be completed in the third quarter of FY95. A vulnerability assessment of the NIF diagnostics

● = marker

◆ = milestone

Figure 3.6-1. Schedule for the development of electrical diagnostic component vulnerability and hardening techniques.

will be completed by fourth quarter of FY96. Completion of this milestone enables the start of development of hardening techniques for the NIF diagnostics that are vulnerable. This activity is projected to be completed in the second quarter of FY97, seven months before the completion of NIF final design activities.

3.7 Target Emplacement, Positioner and Injection Techniques

The target emplacement, positioning, and injection systems provide for transport of a room temperature or cryogenic target from the target preparation facility outside the NIF target chamber to the center of the chamber, and then position the target in alignment with the focal spot of the laser beams. The system must then hold the target in position until the laser is fired, maintaining the environment of the target. In future ICF systems, an injection system must be developed which can deliver a target several times a second. For a cryogenic target, systems must be developed to layer, characterize, inspect, and transport the target within the facility.

The specific development goals of this activity are:

- To determine the vibrational characteristics of the baseline target inserter.
- To determine the vibrational tolerance of the baseline target during transport.
- To develop and test an inserter concept which meets the vibrational and positioning requirements.

- To develop a cryogenic target inserter.
- To develop a preconceptual design of a rep-ratable target inserter for the IFE program.

The current state of the art in target positioning exists on the Nova laser at LLNL. This positioner inserts a target vertically into the 2.2-m-radius Nova target chamber to an initial placement within 25 μm of the desired location and then positions the target with 5- μm resolution. Targets are manually mounted to the positioner tip outside the chamber and a lead screw mechanism lowers the target into position. A set of manually controlled stepper motors then position the target to a reference point defined by the Target Alignment Viewers (TAVs).

The NIF target inserter accepts the target outside the 5-m-radius target chamber, horizontally transports the target to the center of the target chamber, and then positions the target to be in alignment with the focal spot of the laser beams. The target is initially placed at the center of the U-shaped Target Alignment Sensor (TAS) head to within 50 μm . The target is then positioned with a resolution of a few microns guided by the TAS. The inserter must then hold the target in that position until the laser is fired. The conceptual design for the NIF target inserter is shown in Fig. 3.7-1.

A system similar to the target inserter will transport and hold the TAS alignment system(s) during the laser, diagnostic and target alignment process. The TAS must be completely removed from the chamber prior to firing the laser.

40-00-0394-1189

Figure 3.7-1. Conceptual design for the NIF target inserter.

The main issues for development with the inserter are: the development of a mechanism which horizontally transports the target over the 5-7-m distance without introducing vibrations or shocks which could damage the delicate target; and the development of the inserter to reduce the vibration of the >5-m-long cantilevered stalk to a level consistent with the 50- μ m target positioning requirement. The vibration and shock tolerance of the targets are unknown at this time and must be determined. The base vibrational frequency of the inserter is estimated to be 2-3 Hz. If this is the case, that frequency is low enough that the inserter could be excited by random vibrations from the facility. This would make positioning of the target to the required 5- μ m tolerance virtually impossible. The TAS will be mounted on a similar inserter to accomplish alignment of the individual laser beams and must be stable to a 5- μ m tolerance also.

This activity must be coordinated with the Target Fabrication Activity and the National Cryogenic Target R&D Program to determine the levels of vibration acceptable to the target during transport. The stainless tubes supporting the target and the target mass itself must be included in the vibration studies. The baseline cryogenic target is shown in Fig. 3.1-1.

The activity will begin with a system vibrational analysis. The analysis will include the target, the various target mounting options, the inserter shaft assembly, the inserter mounting system, and the estimated base facility vibrational levels. The analysis will be done using finite element modeling technics. After the analysis is complete, a testbed will be designed and built to test the results of the analysis. Realistic facility vibrational signatures will be input into the testbed and the response of mock targets will be measured.

The NIF will require cryogenic targets to achieve the goal of ignition. The National Cryogenic Target Program is developing the target and the layering and characterization systems necessary to produce these targets. A cryogenic target inserter/positioner will be required to place the targets at the focal point of the laser.

The cryogenic inserter system is an upgrade to the target inserter in Fig. 3.7-1. The cryo-inserter must accept and transfer a cold target from its transport cryostat and then perform all the functions of the target inserter while maintaining the target at a temperature of approximately 18° K until the laser is fired. Positioning and stability requirements are unchanged for the cryo targets. The targets are expected to be actively cooled with liquid helium during transport, positioning, and the hold phase awaiting laser firing. This cooling system must be developed. The primary issues are: the design of a system to flow liquid helium horizontally through the inserter/target system, the vibration caused by that flow, the long telescoping distance required of the cooling lines, and thermal isolation of the target.

Maintaining the target at 18° K may require a cryogenic shroud covering the target to provide radiation shielding between the target and the target chamber. This shroud would completely surround the target and be removed before the laser can be fired. The time allowed for shroud removal is estimated to be between 10 ms and several seconds depending on the target design. The shroud design and removal mechanism must be developed. Vibration during shroud removal, especially for short removal times is a major concern.

This effort will benefit substantially from the work being done for the Omega Upgrade cryogenic target system. Additional complications for the NIF include: the horizontal insertion; longer telescoping distance; and the geometry of the indirect-drive targets.

For advanced ICF concepts with Fusion Energy as the goal, the facility must be fired several times a second. The target injector system must place targets in the target chamber, at the proper location at this rate. It is anticipated that these targets will be cryogenic and will have very stringent positioning requirements. Methods for accomplishing this from a large distance, ~10 m, must be developed for these concepts to move forward.

The major interfaces for this development activities are the Target Alignment System development, the Target Fabrication and Development Activity, and the National Cryogenic Target R&D Program. Both of the target programs are outside the NIF project, but it is absolutely necessary that a good working relationship be established with these activities.

The schedule for the development of target emplacement, positioner and injection techniques is shown in Fig. 3.7-2. Vibrational tests on the noncryogenic inserter will be complete in late FY97. A preconceptual design of the cryogenic system will be complete prior to the completion of the NIF Title I design. This will insure that the Title I design does not preclude the addition of the required cryogenic systems during the ignition

◆ = milestone

Figure 3.7-2. Schedule for the development of target emplacement, positioner and injection techniques.

experimental campaign. After the preconceptual design is complete, the testbed will be modified to include the cryogenic cooling features. This will allow for the testing of the Cryogenic concept in FY00.

References

1. D. Buchla, T. Harper, J. Wobser, "Cable Shielding from Photon Scattering for PINEX Experiments," Lawrence Livermore National Laboratory, Livermore, CA, UCRL-51045.
2. D. Redhead, Memorandum: Gamma Sensitivities of Some 50 Ohm Cables, UOPE 70-21, October 16, 1970.
3. T. Rottunda, EG&G Memorandum: Cable Sensitivity to Radiation, LLLHSDO-2584, May 21, 1979.
4. T. Rottunda, Letter to Jim Wobser, Subject: Cable Irradiation Experiments, No. 70-17, June 30, 1970.
5. P. D. Sargis, Memorandum: Radiation Sensitivity of High-Bandwidth Cables, ADG-91-05-02, May 2, 1991.
6. R. Seno, EG&G Memorandum to J. Stokes, August 5, 1991.
7. C. Anderson, Memorandum: RG-213 Neutron Sensitivity, UOPB 73-103, November 12, 1973.
8. G. Cummings, Currents Induced in Coaxial Cables by Neutron Pulses, UOPB 72-7, January 18, 1972.
9. P. D. Sargis, Memorandum: Radiation Sensitivity of High-Bandwidth Cables, ADG-91-05-02, May 2, 1991.

4.0 Target Diagnostics

The target diagnostics for the NIF will require both evolutionary improvements from present diagnostics on Nova, Trident, Saturn, Omega, PBFA II, and other ICF facilities and revolutionary development for new techniques. Many of the initial experiments planned for the NIF are similar to experiments now done on Nova for understanding target coupling and indirect-drive symmetry. The diagnostics are expected to be similar in their design and function. Evolutionary improvements will be needed to improve their reliability and to accommodate the increased power and energy of the NIF laser.

As the experimental emphasis shifts toward high-gain targets, new diagnostic techniques will be required. Many of these new techniques, as well as many techniques presently used in ICF experiments, have synergism with techniques developed by the nuclear test programs. In addition, problems in shielding and radiation hardening on high-gain experiments are similar to those routinely encountered by test program experimenters. NIF development can greatly benefit from their experience in these problems and work on at NIF can maintain expertise in these areas enhancing its role in stockpile stewardship.

Diagnostics for present lasers such as Nova have emphasized flexibility for optimizing shot rate and data flow. This has allowed for innovative experiments and testing of new techniques on the systems themselves since they had high shot rates. For the NIF, the operations costs may be higher while the shot rate may be lower. Thus, the cost per shot will be higher. This implies a shift in emphasis to increasing productivity of each shot. In planning for the NIF, the diagnostics should, wherever possible, work the first time and every time. This means that the timing, the alignment and the calibration of the instruments should be validated before a shot; unexpected damage to the diagnostics should be minimized; and failure of data retrieval should be limited to very rare occasions.

In planning for the NIF target diagnostics, the quality of the present diagnostics should be improved. Diagnostic problems should be identified and eliminated before being fielded on the NIF. The following are examples of the kinds of issues:

- New alignment methods should be developed that preferably do not rely on opposing ports and are accurate and straightforward.
- New timing/triggering methods should be developed that do not require full laser system shots.
- A thorough analysis (with respect to cost and data quality) should be made of signal recording on instruments with the goal of completely replacing film.
- An experimental requirement plan should be developed for each instrument that outlines the calibration and characterization that will be required before it can be installed on NIF. This would include, for example, the spatial resolution of x-ray optics and absolute sensitivity calibrations.
- Currently common instrument failures such as phosphor electrode wires breaking should be identified and programs outlined for their solution.

- Routine maintenance schedules should be established and followed to improve system availability.
- Each diagnostics should be capable of recording a fiducial with the signal.
- Diagnostics should not suffer unexpected target damage.
- Instruments should be absolutely calibrated, to acceptable accuracy.
- The degree of screening required for neutron detectors should be stated before any NIF experiments.
- The EMP levels from NIF should be estimated as accurately as possible and carefully measured in its early phases of operation. Adequate screening against detrimental effects must be designed in to susceptible diagnostics, such as internal streak cameras.

This chapter discusses the work on the target diagnostics: x-ray detectors, x-ray imaging and spectroscopy, gamma ray diagnostics, neutron diagnostics, optical diagnostics, high-speed electrical recording, and facilities for test and calibration. Planning schedules for all the activities are provided at the end of each subsection. Work is defined through FY04 and covers the development effort leading up to the activation and initial operation of the NIF.

◆ = milestone

Figure 4.1-1. Planning schedule for x-ray detector development activities.

4.1 X-ray Detectors

Figure 4.1-1 shows the planning schedule for x-ray detector development activities, which are discussed in the following sections.

4.1.1 X-ray Streak Cameras

Although x-ray streak cameras have been used on Nova and other laser facilities throughout the world, several of their characteristics need improvement: specifically, the quality of the data, their reliability, and the ease of use of the instruments. In addition, a number of specific and general improvements will enhance their utility. These improvements will be implemented on NIF diagnostics as appropriate. These improvements include: improved system compatibility of streak camera controllers, installation of timing fiducial capability, on-cart sweep generator to improve repeatability, reduction of shot-dependent background, and development of a second source of intensifier power supplies. These engineering improvements are essential to develop the systems needed for acceptable NIF use, and to provide the systems needed for Omega Upgrade use. The plan is to begin demonstrating these improvements on Nova experiments between 1995–1997.

In preparation for NIF operation, direct writing of electrons onto CCDs should be developed as a replacement for the present method of using image intensifiers and recording with optical film. The direct-writing technique should be evaluated for use on NIF. We should develop a larger format camera (4–6 cm), and develop the EMP screening necessary for the camera system to function in the NIF environment. The milestones for these activities are in FY97, FY98, and FY99 respectively.

The use of x-ray streak cameras for ICF experiments on the NIF, as well as continued use on Nova and on the Omega Upgrade, will require improvements in x-ray photocathode materials, and development of a continuous and a pulsed x-ray characterization facility. These capabilities are discussed below.

4.1.2 Gated X-ray Imaging

Gated x-ray detectors in use on Nova have been a major success. However, both research and engineering development activities are needed to improve the quality of the instruments to that required for the NIF. Areas of anticipated development include: improved quantum efficiency for up to 15 keV photon energy, higher-contrast gate profiles, higher spatial resolution, routine characterization at a picosecond x-ray facility, larger-format microstrips, and multiple detector modules for the instruments.

Front cathode development. The increase in imploded capsule opacity and temperature in NIF ICF experiments will dictate imaging at higher photon energies (in the range 5–15 keV) than used on Nova. For efficient detection at such photon energies, a change from the usual front surface, webbed-Au photocathode to a transmission photocathode deposited over the full area of the microchannel plate (MCP) might be necessary. Issues associated with depositing a membrane over an MCP include: membrane roughness leading to electrical breakdown, integrity of gate pulse propagation, and a need for an x-ray calibration facility. This development has potential commercial

application. This work is planned for FY95–96 leading to a decision on its use for the NIF in FY97.

Gating for the NIF. Well-characterized, high-speed (20–30 ps), high-contrast gating will be needed to avoid motion blurring and double exposures in emission imaging or long-pulse backlighting of pusher-fuel trajectories and in-flight capsules and witness balls. In addition, longer (100–300 ps) gates may be advantageous for recording slowly evolving, weak signal phenomena. These are principally electrical engineering development issues with the generation and propagation of a well-characterized electrical pulse to the gating area of the MCP. Development in this area will be delayed until resources are available. Completion of the engineering design is scheduled in FY99.

Research issues, being addressed at Nova include: EMP shielding; maximizing gate contrast, which becomes more difficult as gate pulses shorten and laser drives lengthen from 1–3 ns (Nova conditions) to 10–30 ns (NIF designs); and high-contrast x-ray characterization. In addition, if a DC image component appears when a second MCP is used in dc mode to boost camera gain, it might be necessary to synchronously gate the second MCP. A possible alternative is to replace the phosphor and film with an electron-sensitive CCD, thereby reducing the requirements on MCP gain. Gate characterization will require continued support from picosecond UV and x-ray facilities.

NIF camera format. To image larger NIF samples and capsules (>1 mm) while maintaining current object spatial resolution (5–10 μm) requires either a larger active detector area or better detector spatial resolution. Current framing cameras have a resolution of 60 μm for an acceptable signal/noise ratio of 5, and hence only 100 resolution elements across a 6-mm microstrip. Research issues will include: improving MCP resolution and/or lowering noise by improving phosphors and/or switching from noisy film to CCD readouts, hence reducing the required magnification; and/or deploying wider (1–2 cm) microstrips.

Alternatively, large-format cameras can be developed. Presently, prototype imagers have been built with 20-mm-wide striplines that have an impedance of 5.5 Ω . Pulsars are being developed to produce 100-ps gate widths in these detectors. These gate times are of interest for some hohlraum-imaging applications. Development is needed to complete prototyping and demonstrate temporal and spatial fidelity.

After the research on improving the resolution and large-format intensifiers, the formats for the gated x-ray imagers required for the NIF will be made in FY98.

Prototype NIF camera. The TIM (twelve-inch manipulator) tubes planned for NIF should be capable of housing an array of four of the usual 4-cm format cameras, each of which might be used to record one or two large images. An improvement in the resolution could result in a decision to fully utilize the increase in the area of the TIM tube. A prototype engineering device will be started in FY98 and completed in FY99 regardless of the decision.

MCP gain stability development. A technique should be developed to normalize the sensitivity of a gated image. Unfortunately, the intensifier gain cannot be accurately inferred from a measurement of the gating pulse because gain depends strongly on the driving voltage ($\approx V^{10}$). A 5% uncertainty in the gating voltage translates into a 50% uncertainty in the gain. Measuring the peak voltage of 5% is difficult because of cable

distortion of the very-fast waveforms. Research should be directed at finding a method of the relative sensitivity of individual x-ray intensifiers to enable us to make quantitative comparisons of time-separated data taken with different intensifiers.

4.1.3 X-ray Backlighter Development

X-ray backlighting will be a crucial capability on NIF experiments. Backlighters are used for radiographic measurements of planar and convergent hydrodynamic experiments and for drive symmetry measurements. They are also essential in opacity and equation-of-state experiments.

Further backlighter development experiments on Nova, Omega, and Trident are essential to provide specifications for NIF backlighter capabilities. On Nova, an empirical approach has been taken to x-ray backlighter brightness, but the database of backlighter brightness is incomplete and should be completed using these facilities so that NIF experiments can be accurately planned. These experiments include scaling of x-ray intensity as a function of laser intensity and frequency for large area and point backlighters. In particular, we should investigate $K\alpha$ production using high-intensity diffraction limited spots of a Nova beam using 1 ω light. If high conversion efficiency to x rays is attained, this would have a dramatic impact on our experimental capabilities. This Nova work should be completed by early FY98.

4.1.4 Photocathode Development

Gated and streaked x-ray diagnostics have provided critical temporal information on Nova targets and both will be important in diagnosing NIF targets. Both achieve temporal resolution by relying on a photocathode to convert x rays to photoelectrons. Currently, transmission and reflection photocathodes are used and NIF diagnostics will probably continue to rely on both types because they offer different advantages.

Reflection photocathodes are used for gated imagers, which produce two-dimensional target images. Typically the photocathode material, such as Au, is coated directly onto a microchannel plate. X rays incident on the photocathode create photoelectrons that are accelerated down the capillaries of the microchannel plate onto a phosphor. Transmission photocathodes are used in streak cameras where the photoelectrons are focused through electron-optics and swept across a phosphor.

In the NIF facility, diagnostics will probably be further from the target and will be subject to an even harsher x-ray environment. Hence, photocathode development for NIF includes improvements of existing materials, development of new materials (possibly including cryogenic photocathodes), and establishing testing facilities.

This is high-leverage development whose solution could improve the performance of many diagnostics. The effort involving testing and development can be done at several facilities and include collaboration with the academic and university communities.

Photocathode manufacturing

Experience has shown that sensitivity, quality, and durability are important characteristics for any photocathode. Sensitivity is important because higher-sensitivity photo-

cathodes allow increased flexibility in experiment and diagnostic designs. Good-quality materials are important because nonuniformities in the material are observed as distortions in the data. Durability is directly related to reduced maintenance and better data quality. Quantitative data analysis requires de-convolution of the flat-field response of imaging data from microchannel plates, which is a time-consuming process. Although photocathodes in streaked diagnostics can be more easily replaced, breakdown and poor quality leads to a loss of data; this is clearly an issue given the stated operational philosophy for NIF. The less often a photocathode needs to be replaced, the less downtime is suffered by the diagnostic.

Improved lifetimes. Based on gated imagers at Nova, the working lifetime of an Au-coated microchannel plate is approximately two years. Coatings such as CsI, which are more sensitive to x rays, have an extremely variable lifetime because it can delaminate and is hygroscopic and therefore cannot be exposed to air for long periods of time. Developments to improve photocathode lifetimes should include:

- 1) Developing other methods of mounting microchannel plates to eliminate warping and cracking.
- 2) Experimenting with overcoats that reduce the fragility of coatings and eliminate the hygroscopic nature of photocathode materials.
- 3) Developing procedures to produce more uniform coatings.
4. Developing alternative photocathode material.

Improved cathode materials. It is difficult to speculate on new materials for photocathodes because this depends on thin film and coating technology. Materials having a peaked distribution of secondary electrons are known to be desirable for improving the temporal response of the photocathode. Alternative materials that have been used or considered as photocathodes include KBr and KI, CsBr, and CuI. Coatings of these or new materials can also be optimized for thickness and, in the case of coatings on microchannel plates, for the angle at which the plate is coated. Different substrates can be developed. Areas that can be targeted for research are:

- 1) Materials with sensitivity to higher x-ray energies.
- 2) New materials having higher stability.
- 3) Multilayer or thin film photocathodes for microchannel plates.

Photocathode Spectral Response Characterization

Several applications would benefit from better understanding of the spectral response of photocathodes in various geometries. This data is needed for unfolding x-ray spectroscopic studies, determining spectral bandpass of gated images, and assessing sources of background. Several studies have been done on the wavelength dependence of quantum efficiency for popular materials (Henke et al.), on photocathode stability for x-ray diodes (Day et al.), and for transmission photocathodes (Henke et al.). Models have been developed that in general track the data. More research is needed for understanding the materials used today in the detector geometries. For example, recent results using a continuous-wave x-ray source have indicated that the response of an Au

photocathode on a microchannel plate differs from the published calibration curves. The discrepancy may be related to either the spectral response of the photocathode, or to the angle of incidence and penetration of the x-rays. This characterization should be done both in the soft x-ray regime for applications of the soft x-ray power diagnostic and in the 1–20 keV regime for spectroscopy and imaging. Stability and reproducibility studies should be done for developing fielding plans. Efficiencies should be correlated between pulsed and static operation to understand effects of the pulsed mode operation. Sources for these calibrations are discussed in Sections 4.7.1 and 4.7.2.

4.1.5 CCD Readouts

A goal for NIF operation is the elimination of photographic film for data recording, because of imaging quality, sensitivity, and cost associated with its use. CCD readouts for SIM- and TIM-based diagnostics may provide enhanced resolution and sensitivity, and will reduce data retrieval and analysis time. We require development in several areas: optical CCDs coupled to existing SIM-based diagnostics; electron sensitivity CCDs for directly reading the output of gated microchannel plate detectors (electron energy <1 keV) and streak cameras (electron energy 10–15 keV). These detectors should be field tested on Nova or other facilities to determine their reliability in a harsh EMP environment.

Prototype CCD on Nova. The implementation of several small CCD camera systems is planned for Nova in FY95 and FY96. The system is design to be fielded directly behind the existing SIM-based streak cameras and framing cameras. In addition to reducing operational expense on Nova, these prototype systems will provide operational experience of CCD systems in a environment like the NIF.

Electron sensitivity of CCDs. CCDs that are sensitive to <1 keV electrons would greatly increase the spatial resolution of our current MCP-based diagnostics. There has been limited work done on CCD response at this energy. We require a test stand that includes an electron source to investigate CCD response.

We also require CCDs that are sensitive to 10–15 keV electrons, so that they may be used to directly record the swept electron image in the streak tubes. This must be a separate effort from the above system for reading MCP devices because the high energy of the electrons changes the interaction in the CCD device. We will, however, be able to use much of the same hardware to make these measurements. A 10-keV electron gun can be used to test the CCD. This work will be completed in FY98 to decide on systems for the NIF.

4.1.6 Electro-optic Technology

Commercial source for image intensifiers. A great deal of ICF diagnostics is based on electro-optic imaging; results of the last few years indicate that there will be an even greater dependence on this technology in the future. In addition to maintaining our current capabilities (e.g., gated imagers and 40-mm Gen II intensifiers), we want to be able to make both incremental and revolutionary improvements in our diagnostics techniques. It is important that we maintain a working relationship with other programs, laboratories, and agencies to support selected technologies, to stimulate industry to sustain and improve their capabilities through providing us with required devices.

Areas where industry has played a crucial role include MCP and phosphor/fiber optic technology, and electron-optic modeling and fabrication.

In particular, commercial sources of large-format optical intensifiers have disappeared recently. A low-level effort to identify a reliable source of intensifiers for possible NIF systems is required. This effort will continue until a decision is made on the design and sources for the streak cameras and gated imagers required for the NIF in FY98.

4.1.7 X-ray Diode Redesign

One option for the soft x-ray power diagnostic on the NIF will use a vacuum x-ray diode (XRD) that has been redesigned to have higher frequency response than the x-ray diodes currently in use on the Dante diagnostic on Nova. A redesign has been made, but not tested. Starting in FY97 and continuing for 2 years, we anticipate a low level of effort in this area to test this redesign before implementing it into the NIF diagnostic.

If this option, or a similar broadband detector system, is chosen for the soft x-ray power diagnostic, improved methods for data unfold and analysis should be explored. The goal of these efforts should be to develop algorithms that better infer the spectrum and include more quantitatively error analysis.

4.1.8 X-Ray Detector Development

Photoconductor detector. Another option for the NIF power diagnostic is based upon a transmission grating and an array of diamond photoconductors. The photoconductors are formed by placing striplines on a single diamond wafer. Conductive barriers will be put between the strips to prevent cross-talk.

Diamond photoconductors have several desirable properties: they are radiation-hard, are optically blind below the 5.5-eV band gap, have high carrier drift velocities and are bulk detectors that do not rely on surface effects. Photoconductor spectral response is relatively flat above 5.5 eV. This has been demonstrated for photons in the keV regime. Additional work is needed to calibrate the detectors in the sub-keV regime. For the softer x rays, energy is absorbed closer to the surface where surface imperfections may result in variations in the electron-hole recombination time, and hence their sensitivity. Detector sensitivity and saturation should be characterized in the sub-keV range to quantify these effects.

Currently, diamond photoconductors are made using natural Type II diamond, which has a carrier lifetime of 0.1–0.6-ns (Kania et al.). Synthetic diamond films, which can be made in larger formats and in sets of arrays normally have large carrier lifetimes (~1 ns), which limit their temporal response. By adding nitrogen impurities at the 30-ppm level, the carrier lifetime can be lowered. This method needs to be investigated to demonstrate good control of the doping rate. High-quality polycrystalline diamond wafers can be grown in 4-in-diam sizes. The detector research should be completed by demonstrating good production of detectors in the required geometry and both temporal and quantitative calibration of their response.

2–3 keV detectors: For harder x-ray spectra, significant energy can be contained in the energy range above 2 keV. As much as 10% of the incident laser energy has been measured in Au M-bands in laser-irradiated Au disks experiments. XRD's are not

necessarily the best detector in this energy range because they are relatively insensitive and can have changes in the response. Development effort should be done to evaluate alternative detector technologies for potential replacements.

Total x-ray fluence detectors. A measurement of the total x-ray fluence would complement x-ray spectral measurements. The measurement would provide an independent measure of x-ray power to ensure that all of the energy was included. If the detectors are sufficiently compact, a number could be fielded around the chamber to measure the angular distribution. Several candidate detectors such as photoconductors, bolometers, x-ray calorimetry, and XUV Si diodes have been identified that could possibly fill this role. These detectors need to be evaluated and tested for spectral response, saturation, and temporal response. They should also be cross referenced to Dante on hohlraum target experiments.

Alternative detectors. Other detector technologies should be evaluated as technology is developed. For example, thin-coated filtered scintillators coupled to fiber optics could be used for detector arrays and imaging applications.

4.1.9 Transmission Grating Development

An alternative soft x-ray spectral diagnostic to mirror/filter pairs is to use a transmission grating as a dispersion element. They have been used successfully on smaller facilities to make quantitative measurements (Eidmann et al.) Effort is required to develop this diagnostic for the NIF. Diffraction efficiencies of gratings from various sources should be measured as a function of wavelength into the various orders. Diffuse scattering should also be quantified. A prototype instrument should be developed and fielded on Nova to compare with the standard Dante diagnostic for absolute power measurements. Various recording media should be assessed. These include x-ray streak cameras, gated x-ray microchannel plate detectors, photoconductor arrays, and photoconductor striplines.

4.1.10 Fast-closing Apertures for Debris Mitigation

Compared to Nova and other operating laser facilities, the increased energy on the NIF will produce significantly more debris from the target, target support, and close-in diagnostics. On Nova, debris is a concern and damage occurs on filters and other components even for diagnostics such as Dante, which is located ~3 m from target chamber center. On Nova, the damage is infrequent and causes only a slight loss of data. On NIF, the debris issue will be much more serious and could routinely compromise data integrity. Fast-closing apertures could help alleviate the damage and reduce maintenance and operations costs.

Sandia has developed pneumatically activated closures for their pulse-power machines. Closure velocities on the order of 1 cm per msec are attainable with this technology. Such apertures, when placed at the wall of the 5-m NIF chamber would be sufficient to shield diagnostics from debris with velocities as high as 5×10^5 cm/sec. Development is needed for these valves to improve their reliability and decrease the manpower required for fielding them. This requires reengineering the valves and testing them for reliability. An alternative is to develop electromagnetically driven valves. Although the closure times are comparable, electromagnetically driven valves may be

simpler and more reliable. Development is needed to design and test prototypes of these valves for precision and reliability.

Explosively driven apertures can be used to achieve faster closing times. Explosively driven apertures presently being developed for pulsed-power applications have closure velocities of 1 cm in 25 μ s. Development is needed to make this type of closure into a reliable, low-cost production device.

4.2 X-ray Imaging and Spectroscopy

Development of the science and technology of x-ray imaging and spectroscopy for NIF is motivated by the strong role they can play in determining target performance. A key issue for these diagnostics is survival in the harsher environments associated with high-performance targets. Even for low-yield experiments, NIF implosions will have higher densities and hotter temperatures than present Nova implosions. Imaging and spectroscopy of these implosions for compression and symmetry studies should optimally be done at higher photon energy because denser implosions will be opaque to lower photon energies, and higher temperatures will produce spectra at higher photon energies. Tasks are defined to extend present techniques using pinholes (Section 4.2.3) and coded apertures (Section 4.2.5) to higher photon energy. The focusing crystal imaging task (Section 4.2.6) is for developing a combination of imaging and spectroscopy at photon energies suitable for NIF implosion conditions.

A limitation for any imaging and spectroscopic technique will be the effects of target debris and radiation on diagnostics, and the subsequent collateral damage to the chamber and focusing optics. Even for shots not having fusion gain, the target will absorb nearly 2 MJ of energy, which will be partitioned among reradiation, hot vapor, and shrapnel. Some computational studies have been done primarily to assess chamber wall issues, but there is presently little experimental understanding. X-ray ablation of protective layers (task 4.2.4) is an experimental campaign on Nova to better understand target debris issues and to develop mitigation solutions. Since such issues will not be fully resolved until experiments begin on NIF, alternative technologies for imaging are proposed using reflective optics. Task 4.2.1 is to develop a reflective system for imaging in the several keV x-ray region that is compatible with high-yield shots. The goal is to provide verification of targeting with an instrument that is survivable. Task 4.2.2 extends this technology to imaging at higher photon energy using x-ray multilayer reflective coatings.

In addition to implosion and targeting issues, imaging will be used to investigate significant issues for NIF hohlraum characterization. Better understanding of hohlraum channel conditions and filling issues can allow NIF hohlraums to operate more efficiently. Several characterization initiatives have begun on hohlraums using soft x-ray imaging and probing using x-ray lasers. Task 4.2.7 continues these development efforts and extends the technology to NIF conditions.

Figure 4.2-1 shows the planning schedule for x-ray imaging and spectroscopy development activities.

WBS	CS&T activities and milestones	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
4.2	X-ray imaging and spectroscopy										
4.2.1	Reflective replica optics										
	Prototype design & characterization										
	Polishing demonstration										
	Final NIF design & characterization										
4.2.2	Multilayer optics										
	Flat coating tests										
	Curved optic coating demonstration										
	Curved optic w/uniform coating										
	10 keV microscope development & characterization										
4.2.3	Tapered pinholes										
	Demonstration tests on Nova										
	NIF vendor work										
	NIF design & fielding										
4.2.4	X-ray ablation of protective layers										
	Passive/active tests on Nova										
	Active Imaging on Nova										
	Debris suppression on Nova										
4.2.5	Coded aperture imaging										
	Annular gating demonstration										
	NIF development & fielding										
4.2.6	Focusing crystal imaging										
	Nova demonstration										
	Omega Upgrade tests										
	NIF development and characterization										
4.2.7	Soft x-ray imaging										
	Nova deflectometry & hohlraum probing										
	NIF conceptual design										
	NIF fabrication & testing										
	NIF hohlraum probing										
4.2.8	Advanced x-ray spectroscopy method										

◆ = milestone

Figure 4.2-1. Planning schedule for x-ray imaging and spectroscopy development activities.

4.2.1 Reflective X-ray Optics

High-energy target shots and, in particular, NIF target shots with gain can potentially ablate significant amounts of materials from diagnostics located near the chamber center. This material can coat or damage laser optics and debris shields and increase maintenance and operation costs. However, these high-energy laser shots will still require sophisticated diagnostics to characterize both laser and target performance. One class of diagnostics that will allow for the large stand-off distance required to minimize diagnostic destruction and optics coating are those utilizing grazing incidence x-ray optics. Examples include: Wolther microscopes using ellipsoid and hyperboloid surfaces, Kirkpatrick-Baez microscopes utilizing spherical or near spherical optics, and multilayer coated versions of these optics.

The Nova experience is probably not relevant to the NIF in this one instance. On Nova, the original plan, set in the late 1970s, was to use reflective optics, in particular, several Wolther x-ray optics and two Kirkpatrick-Baez optics. Both systems were installed and successfully used on Nova; however, their inflexibility (compared to x-ray pinhole systems) has led to most experiments now being performed with pinhole imaging systems. On the NIF, pinhole imaging systems will be far more limited by debris problems than on Nova, so a parallel reflective-optics-development strategy is needed.

Ensuring that these types of diagnostics will be available, affordable, and will perform adequately requires a modest development program. This effort includes: 1) determination of optimal grazing incidence x-ray optics for NIF; 2) design of these diagnostics; 3) development of the required fabrication techniques; and 4) development of x-ray optic characterization techniques. Engineering, construction, and installation of these diagnostics, as well as activation and operation, would be included in project costs for diagnostics.

An example of such a diagnostic is the static x-ray imager (STXI). This is a NIF Phase I diagnostic required for measuring beam placement and pointing accuracy. This diagnostic will have the following characteristics: 5-m working distance (located outside target chamber), 20- μm spatial resolution, 1-cm field of view, 2–3-keV x-ray sensitivity, and 1×10^{-5} steradian solid angle. The field of view, the working distance, and the collection solid angle are significantly larger than can be obtained with alternative diagnostics such as pinhole cameras and coded apertures.

Achieving these specifications places stringent requirements on both the STXI surface figure and finish. This optic will require a surface figure accurate to $<5 \mu\text{rad}$ and a surface finish better than 10- $\text{\AA}$ rms. These specifications are within the abilities of existing fabrication techniques. The traditional fabrication techniques involve diamond turning and fine polishing of each optic used. This process is extremely expensive and time-consuming with a low final yield. Since two STXI are proposed to be fielded on NIF and the potential for destruction exists on high-gain shots, a lower cost, higher-yield fabrication technique is extremely desirable.

Another very important example of the use of reflective x-ray optics is the proposed soft x-ray imaging camera. This device would be analogous to the SXRFC camera on Nova, which is a pinhole based soft x-ray imager. The SXRFC has had crucial roles such as in the determination of diagnostic hole closure and soft x-ray source imaging ("spot motion") experiments. Since the pinhole must sit near the target, a straightforward extrapolation of the SXRFC is not feasible. A multilayer-based reflective optics version of this device has been proposed for the NIF. This is but one important application of reflective multilayer-coated x-ray optics, which will be an important development area for the NIF.

Replica technology development. A candidate technique for fabricating the STXI optics is to use replica technology. A mandrel is diamond turned and then polished to achieve the "negative" of the desired surface. The mandrel is then coated with Ni and an epoxy or copper backing only over a sector of the mandrel. The coating is then removed using differential cooling. Surface finishes of 3- $\text{\AA}$ rms have been obtained with this technique. This method produces a sector of the desired optic. Since only a sector is

utilized in each STXI, only the required optical area is fabricated. Additional unused optical surface is not fabricated, thereby reducing costs. The process can be repeated many times to fabricate numerous sectors as required. The expensive polishing and diamond turning need only be done once.

Use of the replica technology for fabrication of the STXI Wolther optics requires the following technology development in substrate lifetime, and polishing at discontinuous surfaces. Substrate stability is also an issue if Kirkpatrick-Baez optics are used. These two issues will have to be investigated even if a traditional fabrication approach is used. All polished and figured x-ray optics are degraded over time due to creep. This slow variation of the surface figure is caused, in part, by relief of the stress produced by the polishing process. The result of creep is that over multiyear time scales, the optic loses its figure, and spatial resolution is degraded. We need to investigate creep experimentally and theoretically, and determine the best substrate material for optimum optic lifetime. The limitations of substrate material properties, optic surface figure, and polishing techniques must be included in this effort.

The second issue is caused by the nature of the Wolther optic. Wolther optics consist of a hyperboloid surface followed by an ellipsoid surface. The actual mirror surface is discontinuous at the juncture of the two surfaces. This discontinuity makes it extremely difficult to polish a high surface finish without destroying the local surface figure. Previous Wolther optics have been fabricated with a groove located at the discontinuity. We need to investigate the effects of this groove and produce an optimal design for it in the replica mandrel.

All STXI optics will require x-ray tests to validate their performance. These characterization tests include reflectivity and spatial resolution. They must be available during the optic fabrication development effort as these measurements are the ultimate criteria for success. The facility described in Section 4.7.3 will be used for this characterization.

Wolther x-ray and Kirkpatrick-Baez microscopes can also be fabricated to operate at higher x-ray energies. It should be possible to construct large field of view ($\sim$ few mm), high-resolution ($5\text{--}10\text{ }\mu\text{m}$), large stand-off ($\sim 5\text{ m}$) x-ray optics for diagnosing the implosion dynamics. These optics will require mrad surface figure accuracy and $1\text{--}2\text{-}\text{\AA}$ rms surface finishes. Fabricating to these tolerances will involve issues of substrate stability and surface discontinuity similar to the STXI optic-fabrication effort. These high tolerances will also require the development of: 1) in situ monitoring of the surface roughness during the polishing process, 2) improved polishing techniques, and 3) methods to either add or delete material at the few- $\text{\AA}$ level to correct surface figure errors. Achieving few- $\text{\AA}$ surface finish requires extensive polishing. This extensive polishing can destroy the optic's surface figure. To avoid overpolishing, one must monitor the surface roughness in situ during polishing; these techniques need to be demonstrated.

The high level of surface finish will also require the further development of new polishing techniques, such as hydro-polishing and chemically enhanced hydro-polishing. These techniques will involve fabrication and characterization of test mirrors. Finally, achieving both high reflectivity and spatial resolution will likely require the use of plasma deposition and erosion methods to locally add or delete $\text{\AA}$ thickness amounts of material on the mirror surface. This technology is currently being used in soft x-ray

multilayer mirror fabrication and needs to be extended to higher-energy x-ray optics. These techniques will be required for either Wolther- or Kirkpatrick-Baez-based x-ray optics. Currently, replica fabrication techniques do not have the required accuracy, so the traditional fabrication methods will likely be used. We should, however, attempt to use replica methods because the potential cost savings will easily offset any development costs.

4.2.2 Multilayer Optics for 10-keV Imaging

Extension of grazing incidence x-ray mirror technology to higher x-ray energy continues to put increasing demands on the technology. An alternative method to extend x-ray optics technology to higher energy is to coat the surface with multilayer interference coatings similar to optical dielectric mirror coatings. For example, an 8–10-keV Wolther microscope design needs grazing angles of 0.5° or less. It is unlikely that this will be achievable in the near future, and the grazing incidence reflective designs discussed in Section 4.2.1 only anticipate working up to 3–4 keV. Multilayer coatings can be used to increase this angle to $\sim 2^\circ$. This allows for reduced-surface figure tolerances (lower costs) and for increased-collection solid angle. Another advantage is the narrow bandpass of the coatings allows for moderate spectroscopic analysis capability.

Flat coating tests will be performed up to the end of FY96. Implementing multilayer-coated, high-energy Wolther optics requires developing the ability to cut the Wolther surface into sectors, or further developing replica techniques. This is required because near normal access is required for high-quality coatings. Kirkpatrick-Baez-based systems similar to the present Nova 8 $\times$ microscope should be straightforward. Eight-keV systems have already been fabricated for synchrotron-based experiments. Development, in addition to that needed in the previous task, will be needed to extend the coating technology. The technology should be extended to higher x-ray energy suitable for grazing incidence optics work. The first milestone would be a good coating on a curved optic demonstration. This would be completed in two phases by 2000. It will be followed by design and manufacture of a 10-keV microscope for installation as a phase II diagnostic on the NIF.

4.2.3 Tapered High-Aspect-Ratio Pinholes

For NIF experiments, the expected increases in target debris and in x-ray fluences due to increases in plasma temperature, volume, and duration will require high-aspect ratio pinholes and collimators for imaging higher photon energies, and for mitigating ultrahard x-ray fogging and instrument damage. Present pinhole-fabrication techniques only produce pinholes with a 10:1 aspect ratio. A possible fabrication idea for such pinholes used by a Cornell group has produced square 5- μm apertures with a 1000:1 aspect ratio (Fig. 4.2-2). In addition, advanced fabrication techniques have also been investigated as part of the test program. To briefly summarize the Cornell work, 5- μm deep grooves were first cut in two flat tungsten slabs. These slabs were clamped to two other flat slabs creating two 5- μm slits. The clamped slabs were then joined end-to-end but rotated 90° with respect to each other to create a 5- μm square pinhole.

Figure 4.2-2. Schematic of the tapered pinhole fabrication showing the two sets of blocks placed at right angles. Each block is constructed from two pieces with a long slot machined in one of the pieces.

This technique could be extended to create pinhole arrays by using a series of grooved, millimeter-thick slabs sandwiched back-to-back and end-to-end. High-aspect-ratio slits and ring apertures might even be easier to make this way. Clearly, angled (tapered) grooves as shown in the accompanying figure would be necessary to accommodate finite source sizes and the multiple lines-of-sight normally inherent in ICF framing cameras. However, for any reasonable NIF x-ray detector solid angle (<0.002 sr), it is easy to show that the taper angles need not exceed 20 mrad, the angles can be customized for every line-of-sight by changing groove angle. An aspect ratio of 100–300 should be feasible, a large improvement over the current aspect ratio of 10. For example, the current 50- μm -thick Ta substrates have unit absorption depth at 37 keV and again at 67 keV, while a 500–(1500) μm substrate has unit absorption depth at 170 (260) keV. Note that the technique also offers a way of combining pinhole/slit, collimator, and additional hard x-ray shielding into one robust piece; this combination might survive longer, and perhaps be cheaper in the long run. The only penalty might be a 25–100- μm uncertainty in the exact pinhole location, but this is unimportant for most cases, especially implosion imaging. High-aspect-ratio apertures might also make 0.1–0.3 MeV x-ray imaging an alternative to neutron imaging of fusion products.

Prototype pinholes will be manufactured and tested on Nova by the end of FY97. Nova experiments could be used to test the practicality of these pinholes. By tightly focusing the Nova laser onto low-Z targets to reach values of $I\lambda^2$ exceeding 10^{16} W/

cm², copious amounts of hard x rays could be produced for a comparison between the imaging efficacy and contrast achieved by current and prototype high-aspect-ratio pinholes at various photon energy bands. In addition, the viability of satisfying few-mrad alignment tolerances on high-aspect-ratio pinhole tilt could be investigated. Initially, some cost will be needed for in-house fabrication of prototype. If promising, we envisage finding a commercial supplier. This activity would start in FY98 lasting for two years, leading to a commercial source for NIF operation.

4.2.4 Ablation of Protective Layers

The motivation for this work is to understand target chamber and diagnostic damage caused by target shots. In particular, we must determine the source of the damage, how it can be mitigated, and its implications for NIF operation. The effects are primarily degradation in target debris-shield transmission. In addition, we must understand what protective coatings on the inside wall of the target chamber, or what in-situ cleaning processes will minimize debris-shield damage and transmission degradation of the final optics. Although a number of calculations currently exist to estimate damage (material removal, melt, vaporization) for assumed sources, almost no data exists to refer to or validate these calculations. The objective of this part of the CS&T Program is to develop diagnostics, and do experiments, starting on Nova but later on NIF, to quantify the source terms for target-chamber damage caused by target shots.

The source terms are x-ray fluence, target debris (plasma and vapor), shrapnel (hypervelocity pellets), scattered 3ω light, and unconverted (1ω and 2ω) light. To quantify these source terms, we plan to do two types of measurements: (1) passive measurements of both x-ray fluence damage and debris and shrapnel damage as a function of target type, damage sample material, and sample distance; and (2) dynamic measurements to determine size, velocity, and angular distributions of debris and shrapnel, and x-ray fluence as a function of target type and geometry.

For the passive measurements on Nova and Trident, we plan to modify the diagnostic manipulators and design the NIF manipulators to allow insertion, positioning, and retrieval of sample materials without venting the chamber. We will also develop a collector system for debris and shrapnel that can be inserted, positioned, and retrieved easily between shots. The collector will allow a determination of size and angular distributions, but a determination of velocity distributions will require dynamic measurements.

Calculations suggest that for hohlraum targets, plasma ablated off the inside hohlraum walls stagnates on axis and jets axially out the laser entrance holes at velocities of 10–60 cm ms⁻¹ with temperatures of order 10 eV. The radial velocity is about one-tenth the axial velocity, so in the NIF these debris jets would reach the chamber walls in less than 50 ms and cover an area on the wall with a diameter of about 1 m. Shrapnel, on the other hand, originates in target structures external to the hohlraum (for example, support stalks, x-ray shine shields, cryo tubing) that are fractured by prompt radiation (x rays or neutrons) from the target, and then are swept along by the debris “wind” (either the debris jets or the slower expansion of the vaporized target material). There may also be secondary sources of debris and shrapnel, such as close-in diagnostic snouts.

Active imaging will be used for measuring debris and shrapnel; these measurements determine size, angular, and velocity distributions. This work will start in FY96 and last at a low level of effort for two years. We will use an optical framing camera with a wide field-of-view (a few cm) and an interframe time of about 10 ns. Such a camera would enable us to obtain time-gated images of the entire target disassembly for any type of target. The existing optical gating instruments, the GOI, are too fast for these applications and a slower camera with more frames is required. In addition, dynamic x-ray fluence measurements will be made with a broadband filter x-ray spectroscopy like the one to be used for measuring radiation temperatures in hohlraums.

4.2.5 Coded-Aperture Imaging

We have used a type of coded-aperture imaging called a ring aperture microscope (RAM), on Nova with good results. In addition, other types of coded-aperture imaging have been employed successfully in other parts of the laser fusion program. Time-integrated images have been obtained at $h\nu \sim 5-6$ keV using x-ray film. Signal-to-noise ratio (SNR) is generally >50 . Time-resolved images have not yet been obtained on Nova, but partially occluded exposures suggest that a similar (or better) SNR can be obtained using gated MCP detectors. Source-aperture separations have been about 3 cm, resolution is $5 \mu\text{m}$, and ring radius is $250 \mu\text{m}$. For similarly sized x-ray sources, the scaling of SNR for RAM imaging is approximately given by:

$$\text{SNR} \propto \Delta s \Delta q (RE_s)^{1/2} / z$$

where Δs is the width of the annulus, Δq is the desired resolution, R is radius of the annulus, E_s is the source intensity, and z is the source-aperture distance.

Nova implosions have core temperatures $T_e \approx 1$ keV. We can expect similar source intensities out of NIF implosions where $T_e \approx 2$ keV at $h\nu \approx 12$ keV, while implosions that achieve 4 or 5 keV would be an order of magnitude brighter. Let us assume that we want to achieve $10\text{-}\mu\text{m}$ spatial resolution; we can then tolerate an annular width of $15 \mu\text{m}$. At 12 keV, diffraction will limit the source aperture distance to 300 cm. For these parameters

$$\text{SNR}_{\text{NIF}} / \text{SNR}_{\text{NOVA}} = 0.12 - 0.38 \times R_{\text{NIF}}^{1/2}$$

where R_{NIF} is the aperture radius in mm.

The lower bound assumes constant brightness, while the upper bound assumes an order of magnitude increase in brightness. If we choose an aperture radius of 10 mm, and assume $\text{SNR}_{\text{NOVA}} \approx 50$, then $\text{SNR}_{\text{NIF}} \approx 19-60$, an acceptable range. To obtain an overall resolution of $10 \mu\text{m}$, the detector resolution needs to be substantially better than $10 \mu\text{m}$ referred to the source plane, although some improvement can be had by including the detector blurring in the coded image reconstruction. We could probably get good results using a $50\text{-}\mu\text{m}$ resolution detector at a magnification of 8. Therefore, the projected point-spread function (PSF) will have a diameter of 180 mm, and we will require a 200-mm-diam detector.

New technology will be necessary to build this instrument. For time-resolved operation, gated microchannel plates are attractive, but they are not available in these large sizes yet. Also, the present thin-Au photocathodes are not very efficient for 12-keV photons. The feasibility of gated operation will depend on success in the areas of photocathode optimization and or gated image conversion. If these efforts are successful, we may want to develop a large MCP with an annular gating scheme.

A prototype gated annular imaging system will be built and tested on Nova and the Omega Upgrade at the end of FY96. A few dedicated Nova shots will be required.

For time-integrated operation there are more options. Most promising is the use of Tb-doped glass scintillators followed by conventional image intensification and readout. The static image-conversion work could dovetail with neutron-detector development (task 4.4.1). We should add additional staffing to extend that work into x-ray detection.

Apertures will have to be thicker to operate at these energies, but a 30- μm -thick substrate would not be difficult with a 15- μm -wide annulus. We will probably want to nest together a number of concentric annuli (e.g., 5) to maximize the detected solid angle; this would also allow a sequence of gated images to be obtained. Aperture fabrication will need development in microfabrication for prototype manufacturing and testing. This fabrication is similar to other fabrication requirements in task 4.2.7.

4.2.6 Focusing Crystal Spectroscopy

The techniques of moderate energy x-ray imaging and spectroscopy will have to be considerably altered in order to operate in the NIF environment. The large increase in laser energy, target dimensions, and hence debris energy compared to present Nova conditions will dictate a much larger stand-off between target and diagnostics (factor of 5–10) and capsule opacity issues will dictate imaging at many keV photon energies (factor of ~ 2 higher in $h\nu$). Hence, present diffraction-limited pinhole imaging of capsule x-rays may become too inefficient or be plagued by hard x-ray backgrounds, making it unusable. One alternative technique is 2-D imaging using curved Bragg diffraction crystals. This offers a potentially large increase in luminosity (up to 100) over 5- μm pinhole imaging at 10–20 cm. The reflection geometry allows for a thick shield to be placed between detector and source, mitigating hard x-ray fogging. Bragg crystal imaging can also offer a narrow bandpass and hence the possibility of isolating emission from one-source species. Bending and shaping Bragg diffraction techniques have recently been advanced in several Laboratories.^{1–3}

The first part of the project will be to develop a prototype high-resolution monochromatic x-ray imaging for the diagnosis of ICF implosions in collaboration with University researchers (as has already begun in the case of preliminary monochromatic imaging tests done by the University of Rochester at the Trident laser in collaboration with Los Alamos). One part of the effort will consist of designing and precisely fabricating toroidally curved Bragg diffraction crystals that can provide 5- μm resolution over a field-of-view of 400 μm , at a wavelength of ~ 2 Å and a bandpass $D\lambda/\lambda$ of $\sim 10^{-2}$. The second part of the project will consist of demonstrating 5- μm resolution. Issues to be addressed at Nova will include: compatibility with diagnostic fielding technology, alignment, robustness, and integration with gated detectors. If a prototype is successful,

several focusing crystals might be deployed to provide a sequence of time frames. Further improvements in the quality of focus might follow by switching to a more sophisticated nontoroidal geometry. This Nova demonstration is being carried out in collaboration with a University. It will be completed by the end of FY96.

If 1-D, spectrally resolved imaging is appropriate, a von Hamos cylindrically bent or conically bent crystal geometry should be revisited. These designs might also benefit experiments in which increased sensitivity is paramount and spatial integration is acceptable. A prototype could be designed, built, and tested at Nova.

Following the Nova tests, a prototype will be modified and constructed for use on the Omega Upgrade. If these tests are successful, then a design and fabrication effort for the NIF will start in or about 2000.

4.2.7 Soft X-ray Imaging, Deflectometry, and Interferometry

Much of ICF and related research involves laser-generated plasmas. Unlike efforts involving lower-density plasmas, ICF has suffered from the lack of a routine density diagnostic. There has been some success using UV light to form interferograms, but this technique is limited to subcritical densities and small plasma scalelengths. Other techniques, such as the examination of SRS spectra, provide only an indirect and model-dependent measurement. A routine density diagnostic for laser-produced plasma could greatly contribute to understanding ICF. A potential routine density diagnostic could use soft x-ray illumination to perform deflectometry, and interferometry can provide routine density measurements.

An x-ray-laser-based density diagnostic would have broad application in ICF research. Most immediately, we can investigate the density profile in Nova hohlraums. Issues such as plasma filling rates, mass ablation, stagnation, and laser entrance-hole hydrodynamics could all be addressed directly with a density diagnostic. Critical experiments that address laser-plasma coupling physics in long-scalelength plasmas would also be well served by a routine density diagnostic. Finally, we should look forward to the NIF, where targets with even longer scalelengths will require shorter wavelength probes to measure the underdense plasma density profiles.

Soft-x-ray-based density measurements will also find applications beyond the immediate programmatic needs of the ICF. A soft x-ray deflectometer offers the first practical method to measure the density profile close to critical density for light absorption. Such information has long been sought by basic researchers studying the laser-material interaction. Work with short-pulse laser systems has renewed interest in this regime. Also, there is a large body of experimental data regarding SRS in laser-produced plasma. Target plasmas for these studies were usually exploding foils. The evolution of the density profile produced in these experiments has not been well characterized. Soft x-ray probing would allow such measurements.

One can conceive of other applications for a soft x-ray probe; particularly intriguing are the applications to x-ray-driven hydrodynamics. The longer scalelengths, higher densities, and lower-Z materials associated with indirectly driven ablation make soft x-ray deflectometry or interferometry particularly suitable. For example, a high-resolution density measurement should be considered as a new diagnostic of time-dependent

symmetry. Straightforward extrapolation of existing techniques would permit a spatial resolution as small as 2 μm , allowing symmetry measurements better than 0.8% at early time. Fast, 20-ps time-resolved measurements appear feasible with the very bright x-ray laser source, permitting diagnosis of critical early-time asymmetry imprint problems. At later times, density fluctuations associated with hydrodynamic instabilities may become visible close to the ablation front. X-ray probing may allow similar measurements with directly driven targets, although the extreme gradients expected in such targets may limit this application. In general, the study of x-ray and laser-driven hydrodynamics could be substantially advanced through application of soft-x-ray-laser-based density measurements.

Nova deflectometry and hohlraum probing. Development has begun on Nova to demonstrate the utility of x-ray deflectometry for plasma probing using an x-ray laser. The initial work will be completed on demonstrating 1-D probing. Most of the required hardware is already available; the only required support is Nova facility time. The technique would be extended to 2-D imaging using an x-ray beam splitter. Work has already begun on a soft x-ray interferometer, but more effort is required to complete fabrication and demonstrate the technology on Nova. A small level of Nova shots will be required in the period from FY95-97 to validate this technique.

Soft x-ray imaging comes automatically with the implementation of the deflectometer and interferometer. Other applications could be developed for such imaging measurements, such as density and temperature measurements inferred from the free-free absorption or emission of the plasma. Modest scientific effort and Nova experiments will be used to investigate such schemes.

NIF conceptual design. After successful demonstration of feasibility on Nova, effort will begin to develop NIF applications. This will require extending the techniques to shorter wavelengths because the probing pathlength will increase. A strategy for fielding an x-ray laser probe must be developed for NIF and suitable x-ray optics designed, fabricated, and tested.

4.2.8 Development of Advanced Methods for X-ray Spectroscopy

In addition to pure imaging, new methods for spatial-resolved spectroscopy will be developed for NIF. These may also involved toroidally curved crystals (such as was done in a collaborative LANL/LLNL effort a number of years ago). These techniques will apply both to emission and backlighting. In the case of backlighting, the spectral probing would involve absorption spectroscopy.

4.3 Gamma-Ray Diagnostics

Improvements in gamma instrumentation offer considerable leverage for contributing to efficient NIF operation. Development of this type of instrumentation is expected to become a major activity in the next few years. The involvement of facilities at several laboratories and universities will not only provide an efficient and effective way of testing and calibrating diagnostics, but will also provide crucial national involvement in the NIF effort, which will help in fulfillment of its mission.

Figure 4.3-1 shows the planning schedule for gamma ray diagnostics development activities.

4.3.1 Reaction-Rate History Diagnostic

Background. In ICF experiments, targets filled with deuterium or a deuterium-tritium mixture are heated and compressed to conditions under which thermonuclear fusion occurs. During plasma confinement, fusion reactions produce charged particles, neutrons, and photons. We are interested in measuring the fusion rate as a function of time relative to the incident drive radiation. This burn history depends on the coupling of laser energy to the target, the hydrodynamics of the target implosion, and the plasma conditions during peak compression. Burn history is a sensitive indicator of our ability to accurately model energy transport between laser and target. NIF experiments are expected to have plasma confinement times on the order of 100 ps, similar to Nova experiments.

Of the fusion-reaction products, only the neutrons and high-energy photons escape the target without collision. Since neutrons from deuterium-tritium (DT) and deuterium-deuterium (DD) reactions are nearly monoenergetic, their temporal distribution at a point close to a target preserves burn-history information with a time-of-flight delay. A neutron detector based on the fast rise time of a plastic scintillator measures burn history at Nova.⁴ These measurements are made with 25-ps resolution for targets producing as few as 10^8 DT neutrons. Good sensitivity and time resolution are achieved by placing a thin piece of scintillator close to the target.

Burn-history measurements using fusion neutrons have a temporal-resolution limit. Thermal motion of the reacting ions causes a small energy spread in the otherwise monoenergetic spectra for fusion neutron. This causes a corresponding temporal spread in the arrival times of the neutrons at a detector that depends on distance, d , between target and detector and on plasma ion temperature T_i . The time spread is given by:

$$\Delta t = 122d \sqrt{T_i}$$

Neutron measurements of burn history will work well at NIF when the laser energy on target permits detectors within 50 cm of the target. At this distance, a Nova-type

WBS	CS&T activities and milestones	1995	1996	1997	1998	1999	2000	2001	2002	2003
4.3	Gamma ray diagnostics									
4.3.1	Reaction history									
	NTD tests on Nova									
	Gamma converter tests on Nova/lab									
	NIF design & calibration									
4.3.2	Gamma ray spectrometer									
	Nova prototype tests									
	NIF development & testing									
	NIF design & characterization									

◆ = milestone

Figure 4.3-1. Planning schedule for gamma ray diagnostics development activities.

neutron detector can easily record burn history with 60-ps resolution for a 1-keV plasma for DT yields as low as 10^{12} neutrons.

NIF reaction-rate diagnostic. When energy levels no longer permit diagnostic instruments to penetrate within 50 cm of a NIF target, high-resolution burn history by direct neutron measurements will become difficult if not impossible to make. Burn-history measurements based on fusion products will require a different approach. One method would be to record the temporal distribution of the 17-MeV γ rays produced in DT reactions. Unlike fusion neutrons, detector distance and ion temperature cause no temporal dispersion of these γ rays since they travel at the speed of light. Another method would be to convert fusion neutrons to photons with a disposable converter built into or placed near the target. Either method will require development effort to achieve 30-ps burn-history resolution.

Fusion γ -ray detector. The concept for a burn-history measurement using 17-MeV γ rays is straightforward. γ rays produced in fusion reactions travel to a transducer located near the wall of the NIF chamber. Here they interact with the transducer to produce electron-positron pairs. Slowing of the charge particles produces light signals that can be recorded with a fast (30-ps) detector.

The major obstacle to the development of such a detector is an efficient converter scheme that preserves time resolution. The branching ratio for the production of 17-MeV γ rays is $\sim 10^{-4}$. Any detector using fusion γ rays must also be immune to the later burst of penetrating neutron radiation. The γ rays interact with high-Z material primarily by pair production. The slowing down of high-energy electrons can produce both Cherenkov radiation and scintillation in materials like glass or plastic.⁵ Possible γ -to-electron converters are Pb-glass or a thin layer of high-Z material. Possible electron-to-light converters include Pb-glass and plastic scintillator material. The fast signal can be recorded with a fast optical detector like a streak camera.

Neutron converter. Another possible scheme would be to use an expendable neutron-to-light converter within 50 cm of the target. Target neutrons would interact with the converter to produce light. A collimated and filtered optical system mounted at the chamber wall would collect the optical radiation and relay it to a fast optical detector for recording.

In this system, only the expendable converter and an associated shield would be inside the target chamber. The converter would have a volume of only a few mm^3 . Light collection optics and the fast detector would be outside the NIF vacuum chamber. The axis of the collection system would not pass through the target region of the chamber.

Detector development. The development of a reaction-history diagnostic could proceed at the Nova or Omega target chambers. Experiments would be designed to find suitable materials and combinations of materials for such a detector. Direct-drive implosions of DT targets for current laser facilities can produce more than 10^{13} neutrons. This yield should be sufficient to identify possible converter schemes and their sensitivity. Of course, experimental samples would be run substantially closer to the target than the final NIF reaction-rate detector. The major equipment (telescope and streak camera) necessary for this effort exists as the NTD instrument at Nova.

Subsequent gamma converter tests would be performed mainly on the neutron source (Section 4.7.4) in the period until 1999. In 1999, a conceptual design for a NIF instrument will be started. The instrument will be required for use on the NIF as soon as implosions start on the facility.

4.3.2 Gamma-Ray Spectroscopy for Diagnosis of Fuel Conditions

A large number of diagnostic instruments used in ICF is based on the detection of x rays or neutrons. However, no suitable device for high-energy (more than a few hundred keV) photons exists. This section describes the development of a bubble chamber for measuring high-energy photon-burst spectra. Other detection methods, which derive from test experience, have also been suggested and will be investigated. Applications for the bubble and other methods include:

- The measurement of the high-energy x-ray spectrum from ICF targets.
- The measurement of the yield of neutron-less fusion reactions via the γ -ray yield of the radiative capture branch of the reaction (e.g., $D + 3\text{He}$).
- The measurement of the alpha particle energy loss in deuterium-tritium targets through the secondary photons from the $\alpha + T \rightarrow {}^7\text{Li} + \gamma$ reaction [see Dendooven et al., *J. Appl. Phys.* 74 3638 (1993)].
- The measurement of the bremsstrahlung spectrum from high-intensity pulsed electron and ion accelerators.

We are testing a freon-filled, holographic bubble chamber as a photon-burst detector. This choice is based on the following characteristics:

- 1) The use of freon gives the instrument a large intrinsic efficiency for high-energy photons (up to tens of MeV).
- 2) Holography combines good spatial resolution with large depth of field, allowing a large number of interactions in one hologram. This improves the statistical quality of the photon spectrum and the dynamic range of the instrument.
- 3) In certain applications, the photons are accompanied by a huge neutron flux, which will certainly fill the whole chamber with bubbles as it hits the chamber. The use of a nanosecond-pulsed laser allows a hologram to be taken before these neutrons hit.

A bubble chamber is a track detector for energetic particles. The sensitive medium is a superheated liquid, created by the fast expansion of a liquid so that the pressure drops below the vapor pressure. A small amount of energy is then needed to trigger the transition from liquid to gas (boiling). If an energetic particle traverses the chamber, its energy loss results in the local boiling of the liquid, bubbles are formed along its path. Photographing these bubble tracks gives an image of the path of the particle. The momentum of a charged particle can be determined from the curvature of the track in a magnetic field.

Photons cannot be seen directly. Tracks seen in the bubble chamber will come from electrons and positrons created in Compton scattering and pair production in the cham-

ber liquid. Measuring their energy from the track curvature in the magnetic field allows one to calculate the original photon energy.

The following is an overview of the development required to get the bubble chamber operational. Three main tasks can be distinguished: 1) the mechanical operation, 2) the holography, and 3) the actual high-energy photon detection.

The mechanical operation. The bubble growth rate and the number of bubbles created per unit of track length depend on the pressure and temperature of the freon. Thus, good control over the pressure cycle and temperature is necessary to accurately assess the chamber's performance. The freon pressure is controlled by a piston acting on the freon and controlled by a servoactuator/servo valve. The pressure for the latter is provided by a hydraulic power unit. A typical freon pressure drop goes from 25–30 bar to 5–10 bar in about 5 ms. The temperature is controlled to within a few hundredths of a degree Celsius by a water circuit in the chamber walls connected to a constant temperature bath. The operating temperature will be between 20° and 70°C. At present, the temperature control is operational. The servoactuator/servo valve and hydraulic power unit have been delivered and are ready to be connected.

The bubble chamber magnet will be a water-cooled split-pair solenoid with an iron return yoke. It will provide a magnetic field of about 1.5 T throughout the chamber.

The chamber itself has been manufactured. The "visible" freon volume has about 2-in. diam.

Holography. Because we need to maximize the number of bubbles visible per unit of volume, our bubble chamber holography resembles the holography of a spray of droplets, fog, aerosols, etc. We plan to cooperate with Donald Barnhart and collaborators at the University of Illinois. They have developed a holographic particle image velocimetry system that allows the image several thousand 0.5–1.0- μm oil droplets per cm^3 with very good spatial resolution. A modification of their recording, replay, and analysis set-up seems the best approach to our bubble chamber holography. For testing purposes, holograms of glass microballoons (<10- μm diam) in water will be taken.

High-energy photon detection. Once the mechanical operation of the chamber is completed and a holographic system is in place, tests using high-energy photons can be performed. As photon sources, standard gamma-ray calibration sources will be used at first. This will allow us to measure the bubble growth rate and the number of bubbles per unit track length vs the temperature and pressure of the freon. With the magnet in place, electron track curvatures can be measured and gamma-ray energies calculated. The analysis will involve two steps: First, the bubble positions will be measured; second, the measurements will be combined into curved tracks and the electron energy will be calculated. For the latter, analysis procedures from high-energy physics will be used.

It might prove worthwhile to do tests at a pulsed electron accelerator, for this allows the study of electron tracks with prior knowledge of the electron energy. High-intensity and high-energy gamma-ray bursts can be obtained at the pulsed proton accelerator at Sandia National Laboratories (Albuquerque) using resonant (p, γ) reactions. This is an experimental situation very close to shooting an ICF target, with the advantage that the

gamma-ray energy emitted is known. This is an excellent way to measure the bubble chamber's gamma-ray energy resolution.

The Nova prototype instrument will be tested in FY94, FY95, and FY96. A few dedicated target shots will be required, although most of the shots will be ride-along.

Depending on the success of the prototype, a NIF development and design project would start in FY99.

4.4 Neutron Detectors

Figure 4.4-1 shows the planning schedule for neutron detector development activities, which are described in the following section.

4.4.1 Neutron Detectors with High Spatial Resolution

There are three different deployment schemes for a neutron-imaging system on the NIF. The "phase 1" diagnostic is similar to the present Nova neutron microscope. However, to optimize this imaging scheme, we should develop new annular-aperture geometries that give better results than present penumbral schemes. All of the neutron-imaging schemes would benefit from improved aperture designs. The latter two schemes require significant research and development. A time-resolved neutron imager would require an image-conversion scheme that provides good spatial resolution

WBS	CS&T activities and milestones	1995	1996	1997	1998	1999	2000	2001	2002	2003
4.4	Neutron detectors									
4.4.1	Neutron detector with high spatial resolution									
	NPAM tests on Nova									
	NIF configuration tests on Nova									
	NIF development & testing									
	NIF design & characterization									
4.4.2	Gated and high speed neutron detectors									
	prototype tests on Nova									
	NIF development & testing									
	NIF design & characterization									
4.4.3	Single hit arrays									
4.4.4	Burn time diagnostics									
	Prototype tests on Nova									
	NIF development & testing									
	NIF design & characterization									
4.4.4	Total yield detectors									
	Develop techniques on Nova									
	NIF development & testing									
	NIF design & characterization									
4.4.5	Proton recoil technique									
	Develop conceptual design									
	NIF development & testing									
	NIF design & characterization									

◆ = milestone

Figure 4.4-1. Planning schedule for neutron detector development activities.

($\approx 200 \mu\text{m}$), satisfactory temporal resolution ($\leq 200 \text{ ps}$), and satisfactory quantum efficiency ($\geq 0.1\%$). The most challenging problem for a time-resolved neutron detector regards the image conversion from neutrons to a more detectable form of radiation. The third scheme, designed to image high-yield targets, will also require a neutron detector scheme with high spatial resolution and good quantum efficiency, but no temporal resolution will be required.

Annular-coded apertures fabrication development. Present neutron apertures have a particular z-taper that allows high-resolution coded imaging even when the source-aperture distance is smaller than the aperture thickness. However, the penumbral coding scheme SNR has a particularly unfavorable dependence on the number of resolution elements in the source. Much better results can be obtained by going to an annular aperture design. Computer simulations verify a factor of 2-5 improvement in SNR using tapered annular apertures. An annular aperture could be built using timed-draw electroplating techniques. We will start this effort in 1997.

Neutron scintillator optimization for NIF. To use the neutron microscope with ignition or near-ignition targets, we need to move the aperture back to $>2 \text{ m}$. It therefore becomes impractical to operate the detector at large magnification. We need a higher-resolution detector, although yields may be high enough that we can afford to sacrifice some quantum efficiency. The most promising option appears to be doped-glass fiber optics. Samples of this material should be tested for light-conversion efficiency, spatial resolution, and quantum efficiency. Other materials may also be investigated (gamma-ray imaging detectors have been made using cadmium-tungstate crystals, for example). The scintillator research will require the ion-beam neutron source (Section 4.7.4), but it should probably be tested on Nova if the side-lab results are positive.

Time-resolved neutron detector. Because of thermal broadening, it is difficult to obtain temporal resolution when imaging DT fusion events. The detector must be located very close ($\approx 30 \text{ cm}$) to the neutron source, which limits the magnification of the imaging system. Therefore, we once again need a high-resolution neutron detector, which is very difficult because the neutron energy must be converted into a form of radiation that can be sensed by a fast-gated detector. So far, we know of no existing technology that can accomplish this. Recent experiments^{4,5} showed the feasibility of converting coupling neutron energy to a microchannel plate detector using recoil protons. Unfortunately, the long transverse MFP of the protons (0.7 mm) limits the spatial resolution unless the conversion screen is made thin, in which case the quantum efficiency becomes unacceptably low. However, one promising line of research is lead-doped glass capillary arrays. Here, one would add a plastic to the capillary tubes to convert the x rays to protons as before, but, hopefully, the transverse range would then be limited by the surrounding lead-doped glass. The thickness of the tube array would be limited to about 1 mm by the recoil-proton range in the plastic. Overall quantum efficiency would probably be about 0.5% , and that would be sufficient for some applications. Testing this concept would require additional work on the ion-beam neutron source. If the side-lab tests are unexpectedly favorable, the scheme should be tested on Nova or Omega.

NPAM development and use on Nova. The neutron imager on Nova (NPAM) is being retrofitted to make its alignment more reliable. Once completed, the instrument

will be used for implosion diagnosis. A few instrument-characterization shots will be required.

4.4.2 Gated and High-Speed Neutron Detectors

Ion temperatures from NIF experiments will be measured using neutron time-of-flight detectors to determine the Doppler broadening of the fusion-produced neutrons from the target. To take advantage of the speed of recently developed photo-multiplier tubes and transient digitizers, new types of neutron detectors need to be developed. In addition, changes will need to be incorporated to allow the detectors to function in the increased x-ray flux expected on NIF.

We need to determine which geometry for neutron time-of-flight detectors will offer the best performance for NIF requirements. Modifications could include geometry compensation, in which the scintillator is made long and thin (to reduce the flight time of neutrons across its thickness) and the far edge is tilted toward the source of neutrons (to compensate for the time the scintillator light travels along the scintillator to the photo-multiplier tube or other light detector). Also, it may be desirable to move the photomultiplier tube out of the line of sight of x rays produced in the target to a location where it could be shielded. This would necessitate a light-transfer system utilizing lenses and mirrors to relay the scintillator light to the detector. Since the flux of hard x rays from the target could produce a much larger light pulse in the scintillator than the neutrons do on low-yield shots, it may be necessary to develop detectors that can be gated off until the x-ray pulse has passed, and then gated on to record the scintillations from the neutrons.

Many of the new detector technologies necessary for NIF can be developed and demonstrated using high-yield Nova shots and the neutron-generator facility (perhaps with some upgrade necessary). Development of high-speed detectors to the point that they could be used reliably, and implemented on NIF, would take about three years. This work will need to be completed in 2000 to impact the NIF instrument.

Two-dimensional arrays of time-integrated neutron detectors have been developed for neutron imaging use on high-yield Nova implosions. Detectors that would allow time-resolved neutron imaging are desirable for imaging the burn region of NIF targets to determine the effects of symmetry on capsule performance, and to detect the formation of a "hot spot" ignition source in non-igniting capsules. Gated neutron imaging might be possible using techniques similar to those used with gated x-ray imagers currently in use on Nova.

Development of gated neutron imaging would be a more difficult task, and the time and resources necessary are difficult to predict. Efficient converters must be developed that will create a signal which is a function of neutron flux at a given position with a time resolution equal to or less than that desired for the system as a whole. In addition, to avoid thermal smearing of the signal due to Doppler broadening of the neutron energy distribution, the converter will need to be less than a few tens of centimeters from the target. This results in lower magnification of the image, and thus high spatial resolution is necessary. To maintain good time response, the converter must also be thin.

4.4.3 Single-Hit Detector Arrays

Nova maintenance and development. The single-hit arrays on Nova require a low level of maintenance and development. Developments include the validation of first-hit analysis of the arrays for ion temperature measurements, implying a better characterization of the instrument's delays and trigger levels. Experience developed during this period will be incorporated in the design of the NIF single-hit instrument.

4.4.4 Total Neutron Yield Detectors

The total neutron yield is a fundamental measure of target performance. Total neutron yield diagnostics based on nuclear activation have been developed for use on Nova at LLNL, Saturn at Sandia, and for a variety of experiments at Los Alamos. Other detectors such as NaI scintillators can be used to measure neutron yields but these are usually calibrated against nuclear-activation diagnostics. Thus, having an accurate, absolute calibration is essential. Despite extensive use of nuclear activation to measure DT and DD neutron yields, some uncertainty still exists concerning the accuracy of these measurements. Scattering and tritium contamination of calibration sources (usually an accelerator) have been proposed as possible sources of error. Careful calibrations will be done to eliminate the uncertainties in these measurements.

Present nuclear activation diagnostics are generally based on $(n, 2n)$ reactions in copper to measure 14.1 MeV DT neutrons and (n, n') reactions in indium to measure 2.45 MeV DD neutrons. For the high yields anticipated for the NIF, the copper diagnostic is sufficiently sensitive that the detectors used to measure the induced activity could have significant dead time even for relatively low target yields. For the NIF, developing alternative materials that are less sensitive would be desirable. These materials should have suitable characteristics including appropriate half-lives and uniqueness of identification. Titanium appears to be a good candidate and will be investigated.

4.4.5 Proton Recoil Technique

The level of thermonuclear output from a NIF target opens up the possibility of several new classes of neutron diagnostics. One such class of instruments is based on the measurement of proton recoils from the interaction of 2.45 MeV and 14.1 MeV neutrons in thin CH_2 foils (of order 100 mg/cm^2 thick). The diagnostic would operate by detecting the proton recoils at near forward angles in either time-integrated detectors or time-resolved current mode detectors. The protons may be energy resolved using range filters or by magnetic analysis. An attractive feature of this type of neutron diagnostic is that the neutron energy E_n and the proton energy E_p at an angle θ relative to the original neutron direction is simply related by $E_p = E_n \cos^2(\theta)$. Also, the elastic n-p cross section is very well known at both 2.45 MeV and 14.1 MeV. For neutron yields approaching ignition on the NIF, these two advantages largely offset the insensitivity of the technique. This diagnostic technique offers a very clean measurement of neutron yield that can be almost entirely free of scattered neutron backgrounds. At higher neutron yields, measurements of time-resolved ion temperature and reaction burn time become possible.

4.5 Optical Detectors

The optical diagnostics on Nova, Omega Upgrade, and the NIF are used primarily for the diagnosis of plasma-scattering instabilities, and also for pressure measurements by the shock breakout from witness plates. Optical streak cameras are used in most of the diagnostics. The streak cameras used on Nova are homemade and will need to be replaced in the period leading up to the NIF. A low-level effort will be required to identify a commercial source and keep the streak cameras characterized.

4.5.1 Gated Optical Imager

The gated optical imager diagnoses the performance of the laser and light emission from the plasma. For example, this device can be used to record the spatial pattern of the SBS light backscattered from the target. The gating function allows us to determine how SBS varies in time as well as in space. These imagers operate in groups, sequentially gated, to produce a coarse moving picture of the image.

The current gated optical imager on Nova was developed several years ago for another application and has been adapted to its current use on Nova. It has some constraints that must be improved in order to meet the performance and operational requirements of the NIF. Both the performance and operability of the NIF gated optical imager will be improved. The current gated optical imager has a spatial resolution of 100 μm and a field diameter of 15 mm, resulting in 150 resolution elements (pixels) across the diameter. Recent proprietary advances in the spatial resolution of image intensifiers will improve the number of pixels across a diameter by a factor of two through a combination of smaller resolution elements and a larger field. Development of this tube will be performed in conjunction with commercialization for night vision viewers.

Currently, only gate widths of 150 ps, 250 ps, or 600 ps are available, and the same gate must be applied to each group of four imagers. More flexibility in gating will be provided. Specifically, a larger range of gate widths will be developed and, more significantly, different gate widths will be able to be applied to each imager in a group. This work will be carried out in conjunction with commercial sources.

Gate width and interval selection. The current imager requires physical replacement of the gate-width module in order to change the gate width. The gating interval is obtained by installing varying lengths of coaxial cable. The NIF environment will make both of these activities very inconvenient due to physical access limitations and potential activation of materials. It is very desirable to develop a more flexible means of selecting gate width and interframe time, and to make these functions remotely programmable.

The current imager is a four-frame module in a fixed physical structure. This constrains the beam-splitting optics more than if the location of the four frames was more flexible. We plan to develop, with commercial sources, more flexibility in the physical layout to ease the beam-splitter design and to allow broader applications for the gated optical imager.

It is important to know, relative to the laser, precisely when the imager gating occurred. The addition of an output pulse synchronized to the gates will allow the NIF Integrated Timing System to measure this time to within 100 ps.

The current data readout system is onto photographic film. This approach is undesirable for the NIF because of accuracy and cost considerations; a CCD readout system will be required.

4.5.2 Active Probing for Streaked Optical Pyrometer (SOP)

A standard technique for measuring the x-ray drive in a hohlraum is to monitor the optical self-emission associated with shock-heated material on the rear surface of a witness plate. The onset of optical emission is associated with the arrival of a shock wave induced by the x-ray drive on the front surface of the witness plate. The shock velocity is determined by correlating the time of shock breakout with the thickness of the witness plate. The drive temperature is then determined by comparing the measured shock velocity with that calculated for different drive temperatures. In practice, this technique becomes unusable below radiation-drive temperatures on the order of 130 eV due to the competition of the shock signal with background noise. This background signal results from plasma produced on the outside of the hohlraum from unconverted laser light as well as optical emission from plasma streaming out the laser entrance holes. Other techniques must be developed to measure lower drive temperatures.

An alternative method of measuring the velocity of the x-ray-induced shock through the witness plate is to probe the backside of the witness plate with a laser beam and monitor the extinction of the probe signal. This extinction of the probe signal is associated with the absorption of the light by the plasma generated on the back side of the witness plate on the arrival of the shock wave. This technique has been used to successfully measure pressures as low as 0.5 Mbar and will be particularly useful on NIF where the initial part of the drive pulse is about 80 eV.

As part of the NIF CS&T effort, we plan to develop this technique to measure low hohlraum temperatures. This activity will require a low power, pulsed laser operating in the visible regime. The laser illuminates the back side of the witness plate that must be polished to a mirrorlike finish. The signal is reflected off this witness plate and imaged onto the input slit of a streak camera. The system operates exactly like the existing shock breakout diagnostic, but detects the onset of absorption rather than the onset of emission.

Initial diagnostic development can be done using the vacuum hohlraum radiation source on Saturn. The time scale, spatial scales, and radiation drive of these Saturn hohlraums are comparable to the low temperature part of the NIF hohlraum. Experiments evaluating the magnitude of the shock that can be measured can be done using direct laser-induced shocks using the Trident laser. Finally proof-of-principle experiments will be done on Nova. These experiments will verify the technique on a large laser system and will test effects of preheat and rear side heating due to unconverted light.

Addition of an interferometer to the collection optics system will allow us to develop a velocity interferometer (VISAR) for measuring the expansion velocity of the rear surface of the witness plate. This measurement technique would allow us to infer preheat perturbations that are induced on the inside surface of an ICF capsule. Demonstrating this technique on any of the above experiments would be relatively straightforward.

4.5.3 Witness Plate Technique Development

Presently, the material used for the witness plate is Al, which is chosen because it has a well-characterized equation of state (EOS). It is also not a large radiator of energy at the temperatures of interest. This is significant because the shock pressure generated in the material is related to the net energy deposition; the shock pressure is higher in Al than in higher-Z material such as Au, which radiates much more of its absorbed energy. Also, since it is a low radiator, the results are not sensitive to the atomic models used to calculate the radiation losses.

A disadvantage to using Al as a witness plate material is that it is a large energy sink that changes the hohlraum energetics and radiation symmetry pattern. Therefore, it can not easily be used simultaneously with implosions. Development of high-Z witness plates would allow us to measure temperature on implosion and other experiments. This has the advantage of not requiring dedicated shots for energetics. Also, experiments could measure the effects of the capsule on laser scattering losses and absorption and the technique could be a monitor routine target performance.

To develop high-Z witness plates, experiments should be done comparing the response of Au, or other high-Z material, with Al with identical radiation drive under a variety of shock configurations. This measurement could possibly require the active SOP discussed in Section 4.5.2. These measurements could cross-calibrate Au witness plates with the standard Al witness plates. A side benefit of these experiments could be better models of Au opacity and EOS. These experiments could be done using the Saturn, Omega Upgrade, Trident, and Nova facilities.

4.5.4 Thomson Scattering Diagnostic

Thomson scattering is a diagnostic technique to obtain space- and time-resolved measurements of the level of plasma turbulence. It can be used in the underdense plasma that will fill the NIF hohlraums. On Nova so far, we have not concentrated on an accurate measurement of the level of plasma turbulence. From FY95–FY97 there will be focused effort to explore the limitations of the laser intensity that can be propagated through an underdense plasma. The principal diagnostic to understand the level of plasma turbulence will be Thomson scattering. This work will broadly involve the scientific community.

We will develop Thomson scattering as a technique for making highly localized measurements of plasma temperature and density in large-scale hohlraums. In Thomson scattering, a probe beam scatters off of thermal electron-density fluctuations in a plasma. The two types of fluctuation in unmagnetized plasmas are ion acoustic waves (low frequency) and electron plasma waves (high frequency). Scatter from the acoustic waves is typically used for diagnosing thermal plasmas because the scattered

powers are typically several orders of magnitude larger. However, in the case of stimulated Raman scatter (SRS), the electron plasma wave fluctuations are driven to levels far exceeding thermal levels and the scattered powers become detectable (indeed the observed Raman scattered light is nothing more than Thomson scattering of the light that drives the instability off stimulated electron [Raman] and stimulated ion acoustic [Brillouin] waves). The scattering geometry (i.e., angle) is chosen so that a perturbation of known wavelength through frequency and wave number matching is probed. For ion acoustic fluctuations, the scattered spectrum is numerically fit with density and temperature being the two fit parameters. For electron plasma wave fluctuations, to good approximation (for short-wavelength perturbations), the frequency shift of the scattered signal equals a constant times the square root of the electron density.

There are several scientific issues which are important in the design of a Thomson scatter diagnostic:

- 1) Selection of probe wavelength(s).
- 2) Evaluating the consequences of probe beam refraction.
- 3) Optimizing signal-to-noise.
- 4) Developing scatter models that take gradients into consideration.
- 5) Selection of scatter geometry(ies).
- 6) Minimize stray light due to parametric processes in plasma.

The technical issues are:

- 1) Design and fabrication of an optical collection system.
- 2) Target designs which minimize stray light scatter.
- 3) Development of a synchronized probe laser.
- 4) Beam delivery and scattered light transport.

The experimental program on Nova has not focused its effort on this diagnostic technique. The work on Nova is essential to develop operational experience for use on the Omega Upgrade and the NIF.

4.5.5 High-Speed Light-Scattering Arrays

The high-speed light-scattering array will be used to measure stimulated Brillouin scattered (SBS) and stimulated Raman scattered (SRS) light at angles outside of the NIF lens arrays. This diagnostic will be used in conjunction with the full-aperture backscatter stations (FABS) to obtain the laser absorption in the hohlraum, and will be important in the study of laser-plasma physics.

Each unit will consist of absolutely calibrated photodiodes that are suitably filtered for SBS (near 351 nm) or SRS (400–700 nm). The wavelength band for the photodiodes is entirely selected by the filters, and can therefore be easily configured for other wavelengths in the range of 200–1100 nm. An array of these units will be placed at various

angles on the NIF target chamber (to be determined) to sample the light scattered out of the lens cone. The placement of the arrays should correspond to locations determined for the FABS.

There are two possible routes to be examined for time resolving the signals:

- 1) Using high-speed sampling (Single Shot Transient Digitizer) with photodiodes.
- 2) Using fiber-optics coupled to streak cameras.

Some of the trade-offs to be considered will be cost-per-channel, dynamic range, and whether the technology is developed sufficiently to use.

4.5.6 Optical Streak Cameras

The optical streak cameras on Nova are manufactured at LLNL, based on an ITT-designed optical streak tube. These streak tubes are no longer commercially available, and there have been advances in the technology of the cameras that make them more reliable and accurate. A program to evaluate and test commercially available streak cameras in the period before the NIF activation is necessary. The testing of these streak cameras requires an optical test facility described in Section 4.7.5. Once a commercial source has been identified, a low-level effort will be required to continually check the characterization of the cameras, as the electro-optical tubes on which the instruments are based change unpredictably due to aging.

The efficiency of coupling of laser output energy to the target is of critical importance to implosion performance. Target backscatter diagnostics are required to measure light that is reflected from the target. The diagnostic should measure the total power near the characteristic laser line due to diffuse scattering and SBS and the total power in wavelengths produced by SRS and two-plasmon decay. In addition, the diagnostic should measure both near- and far-field intensity distribution in the lens. In the NIF baseline, the diagnostic will be fielded on two sets of four beamlines, one set of four beamlines on the inner cone of beams and one set of four on the outer cone of beams. This task will develop and test the advanced design on Nova or another facility as appropriate.

4.5.7 Target Backscatter Diagnostics

Prototype backscatter diagnostics on Nova. A new backscatter diagnostics system will be designed and installed on Nova's beamline 7 in FY95. The design and fabrication work is being led by Los Alamos National Laboratory. Evaluation of the performance of the new diagnostic will take place in FY96 and a report will be issued. This report will establish the baseline design for backscatter diagnostics to be deployed on the NIF.

4.6 High-Speed Electrical Recording

For the NIF there is a continuing need to record fast electrical transient signals. NIF diagnostics that depend on fast electrical recording include the soft x-ray spectral diagnostic (15 to 30 channels) and the neutron time-of-flight diagnostic (at least 3 channels). In addition to collecting physics data, fast transient recorders are used to monitor the performance of time-resolved imaging diagnostics such as gated imagers and x-ray and

optical streak cameras. The NIF target diagnostics will require another 10 channels for this purpose. The NIF Laser Temporal Diagnostics system (discussed in Section 1.7.3) will also be very dependent on electrical transient digitizers in order to obtain the high degree of measurement precision required by the NIF, and most of the development effort required is covered there. Some additional effort to insure that the needs of Target Diagnostics are satisfied are included here. Figure 4.6-1 shows the planning schedule for high-speed electronic-measurement development activities.

In addition to the recording of electrical transients, complementary technologies are required to complete the high-speed measurement capability required to support the NIF and other ICF activities. These include gated integrators, fast-gate generators for integrators and imagers, and the precise generation and measurement of time delays. A level of competence will be maintained to evaluate commercial equipment and, when necessary, we will develop our own.

The NIF environment is, in many respects, a benign one. Temperature, humidity and electrical power are closely controlled, the facility is relatively stable, and personnel can be expected to be knowledgeable and careful. But a full-power NIF target shot may produce over 20 MJ of neutron and x-ray yield, and EMP will be large by Nova standards, even for relatively low-power shots. Additional noise will be generated by neighboring diagnostics, which produce fast pulses as part of their operation. These characteristics will constrain the design and location of electrical recorders, and help to define the transmission system between the detectors and the recorders.

4.6.1 High-Speed Transient Digitizers

Diagnostics proposed for the NIF require measurement of signals having frequency components up to five gigahertz. We currently record this type of signal on a commercial electron beam-based instrument that costs about \$45K per signal and uses seven inches of rack space per channel. If this instrument were to be used on the NIF, its size and vulnerability to EMP and x rays would require us to locate it outside the Target Room. This would force us to use long signal cables, which would degrade the overall temporal response. Additionally, the cost of fielding an estimated 500 units on the NIF may be prohibitive.

In response to this, we have been developing a solid-state transient digitizer for use on Nova and anticipated application to the NIF. This development has been

WBS	CS&T activities and milestones	1995	1996	1997	1998	1999	2000	2001	2002	2003
4.6	High speed electronic measurements									
4.6.1	High speed electrical recording									
4.6.2	High speed electrical transmission									
4.6.3	Supporting technologies									

◆ = milestone

Figure 4.6-1. Planning schedule for high-speed electronic measurement development activities.

publicized in the instrument manufacturing community (it won a 1993 R&D 100 Award) and there is interest in commercializing it. Through licensing, we plan to encourage commercial development of this technology following the production of a prototype currently underway.

At this time, the precise development path is uncertain as it involves developing one or more industrial partnerships. We will continue to develop the technology to insure that the NIF needs are satisfied, either independently or in cooperation with industry. Effort will continue to improve characteristics such as record length, size, and cost, as well as qualitative improvement in performance. In any event, we will take a strong role in the specification (and possibly production) of this instrument to satisfy NIF requirements.

At the same time, we will continue to maintain a close relationship with current digitizer manufacturers to stay aware of their capabilities and plans. We expect to continue to serve as an evaluation site for new products, as we have in the past.

4.6.2 High-Speed Electrical Transmission

Ideally, target diagnostic transient recorders will be located close to the detectors they serve. But even so, the transmission system will be subject to the noise sources described above. In order to obtain good measurements on the NIF, we must first generate a valid EMP and neutronics specification so that an acceptable transmission system can be installed (see Section 3.6). This will involve theoretical and experimental effort on Nova and perhaps other facilities.

Independent of cable length, we must be knowledgeable about the limitations of and alternatives to coaxial cable. The primary limitation is reduced fidelity due to skin effect, which is a function of the cable length. Alternatives include equalization and deconvolution of coaxial cable and possibly alternate transmission means such as optical fibers. The Nuclear Test Program (and supporting facilities) has a great deal of experience in all of the above aspects and we expect to draw on their expertise.

4.6.3 Supporting Technologies

In order to sustain the capabilities described above, facilities and expertise must be maintained within the ICF program. A laboratory will be provided where the electronics work described throughout Section 4 of this document and similar work described in other sections will be performed. The same talents and facilities required for digitizer development and evaluation and for transmission system analysis are applicable to the supporting work on integrators, pulse generators, and time-delay generation and measurement, as well as general electronics support for the ICF program. Maintaining this laboratory will require continuing acquisition of up-to-date instrumentation, a supply of components, and development and maintenance of the engineering and technical staff's skills.

In addition other methods for high speed-signal recording developed in the Test Program involving optical interferometry will be investigated to determine their suitability for NIF applications.

High-bandwidth cables and CCD cameras are subject to debilitating neutron noise from ignited targets, therefore it is necessary to employ shielding and hardening. These mitigating techniques will have to be tested at an intense fast-neutron source. A suitable neutron source should have a spectrum close to the scattered d-t neutron spectrum in the NIF Target Room and produce NIF-relevant fluences ($>3 \times 10^{12}$ n/cm²) during a reasonably short irradiation period. The Los Alamos Spallation Radiation Effects Facility (LASREF), located at the beam stop of the LANL 800-MeV linac, has a neutron spectrum that approximates the fusion spectrum and has been used to study neutron-damage effects for the magnetic fusion program. LASREF can irradiate cm-size samples with a neutron flux of 1×10^{13} n/cm²/s, and can also irradiate larger samples with a lower flux. For neutron noise studies requiring a pure 14-MeV neutron spectrum, the Los Alamos Ion Beam Facility can be used to produce fluxes of a few times 10^9 n/cm²/s.

High-speed transient digitizers located outside the Target Room will require long signal-transmission paths. Long electrical cables are subject to noise pickup and bandwidth degradation. It may be preferable to convert the electrical signal from a detector to an optical signal, which can then be transported over a long optical fiber without susceptibility to electrical noise and without any significant loss of bandwidth. Mach-Zehnder (MZ) transmitter systems have been developed in the Nuclear Test Program with total transmitter bandwidths of 7 GHz or higher. This type of transmission system employs a CW laser, located far from the Target Room, whose light is transmitted over optical fiber to a MZ transducer located close to the detector. The electrical signal from the detector modulates the laser light, which is then transmitted on a second optical fiber back to a receiver located near the transient recorder. Some development is needed to adapt the MZ system to the NIF environment, including neutron, x-ray, and electromagnetic pulse shielding of the transducer, and to minimize the cost per channel.

4.7 Calibration Facilities

The x-ray, optical and neutron diagnostics intrinsic to the ICF facilities require extensive calibration and check-out facilities. The facilities described here have proven invaluable to the operation of Nova and other laser fusion facilities and will be required for the continued use of diagnostics on Nova and the Omega Upgrade, as well as the development of the NIF diagnostics.

Diagnostic Support Facilities. To maintain Nova and Omega Upgrade capability and to prepare for NIF diagnostics, diagnostic development, test and calibration facilities are required. The level of this support has been established from a history of supporting Nova for the last decade. The value of diagnostic support facilities go far beyond simply qualifying instruments. They are fruitful proving grounds for many aspects of measurement technique development and thus should be widely supported by the NIF community. In other words, this will be another important area for developing the national constituency for NIF.

Support Facility for Calibration, Testing, and Development. Presently, continuous x-ray sources are used to observe the uniformity of microchannel plates and transmis-

sion photocathodes. These sources have been useful for "hardening" new streak camera photocathodes so that they do not flash when taking data. Given the expected shot rate and difficulty of doing diagnostic test shots on the NIF facility, it is necessary to ensure the quality of photocathodes and diagnostics off-line.

A very fruitful collaboration on x-ray measurement techniques and calibration has developed between the national laboratories (principally LANL, LLNL, and Sandia), universities, and other federal facilities (such as NSLS at Brookhaven). We will use and expand on this collaboration to provide a first-class environment for the development of x-ray measurement methods and support facilities for the NIF.

The support facilities should include the ability to test, develop, and characterize photocathodes. In the past, support from LBL and other facilities has enabled the calibration of Bragg crystals and development of photocathodes and multilayers. Resurrection of the X-ray Calibration Facility at LBL or elsewhere will require an investment of money to attract and retain quality researchers. However, such a collaboration would be a cost-effective way to support NIF experiments and provide an avenue for state-of-the-art developments in new materials appropriate for NIF diagnostics. Another option is to utilize beam time at a synchrotron source such as Brookhaven or Stanford to calibrate crystals or detectors. Encouraging collaborations in this area would be extremely beneficial since it would reduce, if not eliminate, the need for an in-house group to maintain the experimental apparatus.

Even with external support facilities, it is necessary to have access to or maintain a smaller-pulsed laser x-ray facility. X-ray anode sources and synchrotron sources do not allow calibration or debugging of problems related to pulsed x-ray sources. Furthermore, X-ray sources created by electron bombardment are restricted to the continuum and characteristic $K\alpha$ x-ray lines of anode materials, while synchrotron sources are limited in brightness when any given wavelength is selected. Use of a smaller laser would expand the available x-ray spectrum. Support facilities will be identified by 1998 for support of the NIF.

4.7.1 Absolutely Calibrated X-ray Sources

New x-ray sources for absolute calibration of detectors and foils will need to be developed and existing sources will need to be maintained and improved for the NIF. Calibration sources in the 0.1-10 keV regime are essential for operation of the absolutely soft x-ray spectrometer. In addition, other diagnostics such as x-ray streak cameras, gated detectors, and crystal spectrometers would greatly benefit from absolute calibration. The following is a technology development plan to ensure that sufficient calibration facilities exist well into operation of the NIF.

Absolute calibration capabilities at LLNL have recently undergone significant changes. Previously, most of the absolute calibration effort for Nova have been done using the Ionac and LEX source, which had been operated by the Nuclear Test Program at LLNL. In response to decreasing budgets, the Ionac, which operated in the energy range from 0.1–1.5 keV, has been decommissioned. Although operation of the LEX, which spans the energy range from 2–8 keV, continues its future status is uncertain. Synchrotron facilities have been used to replace the functions of the Ionac. Below 0.28 keV, the Surf facility at NIST is used for detector calibration on a pay-for-services

basis. Above 0.28 keV, the synchrotron at Brookhaven National Laboratory is used on a cooperative basis with Los Alamos National Laboratory. In addition, a secondary x-ray fluorescence source is operated at LLNL mostly for foil-transmission calibrations.

Although this arrangement is adequate for the present needs for supporting Nova experiments, resources are needed to maintain these capabilities until the commissioning of the NIF and to meet the greater demands for quality control. Calibration facilities are presently using mature synchrotron facilities. A new generation of facilities are being built that will be the main facilities in the future. These include facilities at Lawrence Berkeley Laboratory, Argonne National Laboratory, and Cornell University. They are built expressly for photon production and have much higher brightness than previous machines. With minimum investment, beam lines can be developed in cooperation with other programs interested in absolute calibration that meet the needs for NIF. The development plan has initially a small level of support exploring the facilities' capabilities. If the facilities appear to be of interest, support is included for a calibration beam line at the facility.

In addition to the synchrotrons, a local source will be needed for checking detector calibrations in a short period of time. Also, the facility can perform filter calibrations, which does not require the full power of a synchrotron. Support is included to continue operating this facility and to make incremental improvements to enhance its output.

A possible alternative to synchrotrons and continuous power sources is laser-produced plasma sources. Such sources have the advantage of being cheaper and easier to use. They also offer the possibility of calibrations in the pulsed mode. Several systems have already been developed that use laser-produced plasmas coupled with monochrometers to do calibrations. More work is needed to develop them into routine sources. This includes better reference detector standards and extension to higher energy. Development effort should be included to investigate these systems for their use as a versatile and reliable system.

The filter fluorescer experiment requires absolute calibration in the 10–100 keV range. The configuration and detectors are much more stable than for the soft x-ray spectrometer and do not demand continuous recalibration. The HEX facility operated by the Nuclear Test Program at LLNL has been used for calibrations. This source is presently maintained by other programs. No support presently is included for this facility. If plans to maintain this source change, some support will be needed to maintain this capability.

4.7.2 Pulsed X-ray Source

Quality assurance for diagnostics on the NIF is essential. Detector linearity, temporal and spatial resolution, quantum efficiency, and sensitivity uniformity (flat fielding) are of fundamental importance in interpreting data. Reliability and reproducibility are equally important in order to achieve a high shot rate and to obtain high-quality data. Therefore, the ability to characterize and test instruments prior to a shot will be a necessity.

An adequate test of the integral system response of time-resolved x-ray detectors will require a laser-produced x-ray source with high brightness. For testing gated

microchannel plate detectors, we will require a source that provides short (~ 1 ps) pulses. For testing x-ray streak cameras, the source must also provide longer pulses (~ 1 – 5 ns). The laser must be capable of producing intensities $\sim 10^{14}$ W/cm² with a shot rate of $\sim 10^{-2}$ Hz. The target chamber must be compatible with TIM-based instruments, so that instruments can be easily tested prior to their fielding on the NIF chamber. Laser systems that are already part of the ICF program, such as Trident, should play an important role in providing pulsed x-ray calibration capability. Both full-system-level and 1-ps x-ray temporal tests have already been performed in several cases on Trident and Trident CPA (short pulse). The off-line test facility for diagnostics must be equipped with a TIM to handle all NIF standard diagnostics. It should also handle adapters to be back compatible with both NOVA SIM and LLE TIM instruments to provide a communitywide test facility.

Several detector issues must be examined in detail. Gated x-ray imagers with 50 ps temporal response are required for some NIF experiments. Their temporal gate profile, even in the wings of the gating pulse, must be measured accurately to determine detector rejection. Studies of gain depletion along a stripline will also be necessary. For x-ray streak cameras, an understanding of detector linearity and temporal and spatial resolution as a function of incident intensity for single-point and full-slit illumination is required.

4.7.3 X-ray Imaging Calibration Sources

A calibration facility has been constructed for use on Nova and use of this facility will need to be continued to monitor the resolution of reflective optics, the reflectivity of grazing incidence mirrors, and layered synthetic multilayer mirrors.

4.7.4 Neutron Sources

A suitable neutron-calibration facility will be needed for routine calibration of neutron detectors for NIF. This facility should have high neutron rates, quantitative neutron output, adequate shielding, and lack of tritium contamination which can give rise to unwanted and uncharacterized DT neutrons. It is desirable that the source be pulsed with a well-characterized pulse width for the development of high-speed neutron detectors. Several possible candidates exist or could potentially be available. These sources should be identified and strategies should be developed to ensure their continued operation for supporting NIF.

4.7.5 Optical Calibration Facility

The optical streak cameras, gated optical imagers, photodiodes, and optical components used for NIF target diagnostics will need to be calibrated and characterized routinely for precise experimental measurements. The wavelengths of interest in the NIF experiments range between 200–1100 nm.

The following types of measurements will be needed to characterize the instruments and components:

- a) Streak cameras—spectral response, sweep speed, flat-fielding, resolution, and linearity.

- b) Gated imagers—spectral response, flat-fielding, resolution, and linearity.
- c) Photodiodes—spectral response, time resolution, and linearity.
- d) Optical components—spectral transmission or reflection characteristics.

For the linearity and time-resolution measurements, a small pulsed-YAG laser operating at 1ω , 2ω , and 3ω could do very well. The detectors are quite sensitive and less than $1\text{ }\mu\text{J}$ of energy in a 50-ps pulse would be needed at any of these wavelengths.

Flat-fielding techniques for optical streak cameras have been demonstrated using bright LED sources and slow sweep rates, and it is fairly straightforward to develop a system that would calibrate flat-field corrections in the time direction. Flat-field variations in the spatial (i.e., photocathode slit) direction may be wavelength dependent, but could easily be calibrated out using a uniform source, such as an integrating sphere. This could also be used to flat-field the gated imagers.

The sweep-speed calibration can use standard “comb generators,” which use a pulsed laser diode operating at 810 nm, or use another pulsed laser source and an etalon.

The spectral response calibration for the streak cameras, gated imagers, photodiodes and optical components will need a stable, controlled spectro-photometer capable of measuring absolute light intensity and capable of measuring transmission of order 10^{-5} . This calibration hardware is readily available from companies such as Oriel, Perkin-Elmer, and others.

References

1. P. Glas, M. Schnürer, E. Förster, and I. Uschmann “X-ray microscopy of laser produced counterstreaming plasmas—investigation of population inversion in [He]-like Al,” *Optics Communications*, **86** 271–276 (1991)
2. E. Förster, K. Gäble, and I. Uschmann, “X-ray microscopy of laser-produced plasmas with the use of bent crystals,” *Laser and Particle Beams*, **9**, 135–148.
3. E. Förster, K. Gäble, and I. Uschmann “New crystal spectrograph designs and their application to plasma diagnostics,” *Rev. Sci. Instrum.* **63**, 5012–5016 (1992).
4. R. A. Lerche, D. W. Phillion, and G. L. Tietbohl, “Neutron Detector for Fusion Reaction-Rate Measurements,” in *Ultrahigh - and High-Speed Photography, Videography, and Photonics, FY93*, Paul W. Roehrenbeck, Ed., *Proc. SPIE* 2002, pp. 153–161 (1993).
5. R. A. Lerche, M. D. Cable, and D. W. Phillion, “Fast Pb-glass neutron-to-light converter for ICF burn history measurements,” *Rev. Sci. Instrum.* **61**(10), pp. 3187–3189 (1990).

5.0 Target Design and Theory

Introduction

The goal of the CS&T development for the Target Design and Theory effort in the ICF program is to provide increasing confidence for achieving ignition on the NIF as quickly as possible. This is attained through design and analysis of experiments, calculations of NIF targets, studies of basic physics needed for ICF, improvements in ICF calculational capabilities, and creation of innovative solutions to current ICF challenges. In addition, invention of new ways to make ICF a success for defense applications and ultimately a clean and cost-effective energy source for the future can provide alternate pathways to the goal. This section discusses these initiatives, with a focus on delineating those core science and technology skills and tools that we will require over the next ten years to confidently ensure an expedited demonstration of ignition and gain on the NIF.

Although we are confident that the present NIF target point design will lead to ignition and gain, we also believe that by continuing to develop this core science and technology over the next decade, we can expedite the actual demonstration of ignition and gain, thus saving the project several years of semi-empirical efforts at a significant cost.

The organization of this section by WBS does not adequately show the synergism between the subefforts that comprise the elements of our cross-disciplinary goals. The following goals integrate many of these subefforts and are essential if we are to expedite the actual demonstration of ignition on NIF:

- Self-consistent model of hohlraum processes—including advanced models of atomic physics, radiation transport, electron conduction, magnetic fields, interpenetration, plasma processes, laser propagation and deposition, and the complex interdependence of all of these processes.
- Verification of the predictions of radiation-hydrodynamic codes—including radiation-driven shock in capsule materials and the absorption, transport and symmetrization of radiation within the hohlraum.
- Spectroscopy as a mature and reliable method for plasma and implosion characterization—including many of the effects mentioned above, particularly the effect of non-LTE (local thermodynamic equilibrium), non-Maxwellian distributions on the transport of heat and radiation and in the interpretation of spectra.
- A self-consistent understanding of mix—including a better understanding of 3-D and weakly nonlinear effects; the interplay of these effects in convergent geometry, complicated by the simultaneous effects of asymmetry; and the power to predict, with high confidence, the effects all of this will have on neutron and spectral outputs.
- Advanced plasma and hydrodynamic simulation codes, incorporating state-of-the-art numerical approaches—including massively parallel programming and

advanced-visualization user interfaces and graphics on a variety of computing platforms.

- Spin-offs—integrating a wide variety of emerging technologies (such as ultrahigh-intensity, ultrashort-pulse lasers and x-ray lasers) that can push the frontiers of science and technology while providing valuable testbeds for core science and technology theory and design, lead to advanced ICF diagnostic techniques, and provide alternative ignition paths with potential for significantly higher target gains, such as the fast ignitor project.

The following description details the core science and technology need of the ICF Target Design and Theory for the next ten years.

The ICF Theory and Design efforts described in this chapter will make strong contributions to Science-Based Stockpile Stewardship because of the strong synergism between the two programs. Common areas of science include plasma physics, implosion, hydrodynamics, atomic physics, radiative transport, equations of state, opacity, and computational physics. Additionally, the close coupling between the nuclear weapons program and the inertial fusion program allows designers, physicist, and code developers to work in either program, helping to maintain nuclear weapons competency at the national laboratories.

5.1 Hohlraum Design

5.1.1 Conventional Designs

Conventional hohlraum designs use high-Z material in relatively simple shapes. Typically, the laser beams irradiate the hohlraum wall, producing x rays. The x rays heat the unirradiated walls producing a nearly uniform x-ray heating of the capsule. Drive asymmetries can be caused by the effects of hot spots heated directly by the laser beams and by losses through the laser entrance holes. Conventional designs control these asymmetries by controlling the laser irradiation geometry and laser pulse intensities. Several design options have been developed to control the laser deposition region and thus the hot-spot-produced asymmetries. The present NIF point design is a helium/hydrogen-filled gold cylindrical hohlraum. Other designs have been developed using liners instead of fill gas, but these designs are calculated not to ignite. In the following we discuss several design and theory issues that must be addressed before a final target can be specified with confidence.

The low-Z plasma in the gas-filled or lined hohlraum could be a source of energy loss. Energy loss can result from the laser propagating through the hohlraum window (used to enclose the gas) and from the plasma generated inside the hohlraum by plasma instabilities and light scattering. This could also affect the radiation symmetry. An in-line plasma-physics postprocessor or an electromagnetic wave code is needed to assess the impact of these effects (see 5.4.2.7). This code should be developed in concert with results from plasma physics understanding (see Section 5.3) and experiments that benchmark and test the code.

The interface between the low-Z fill plasma and the high-Z wall plasma is potentially unstable hydrodynamically when the low-Z plasma tries to prevent the high-Z plasma from filling the hohlraum. This instability could potentially cause mixing of the high-Z and low-Z material, which could affect hohlraum symmetry. Instability analysis should be done on the interface to assess the potential impact. Experiments should be designed for Nova to verify the instability analysis.

Another potential effect of the low-Z gas fill is on ablative stabilization of the Rayleigh-Taylor growth rates for the capsule. The low-Z fill plasma can change the exhaust characteristics of the capsule, which could change the ablation profile. Sandia has investigated these effects for light-ion-driven, foam-filled hohlraum targets. They have designed Nova experiments to investigate the effect. These design studies should be extended to NIF target designs to assess the effect of the fill gas on NIF capsule stability. If warranted, experiments should be designed to test the change predicted in capsule stability.

Investigations into possible hohlraum materials other than pure gold are needed. The outcome of such investigations may lead to hybrid wall materials that increase wall opacity (i.e., one element would fill gaps in the opacity of another element in an admixture of wall materials). This increase in opacity would present more resistance for the radiation heat wave to diffuse deeper into the wall and hence would reduce wall losses and increase hohlraum temperatures and drive on the capsule. Because these hybrid materials may also result in reduced conversion efficiency of laser light into x rays, we also will need to design more-complex hohlraums in which areas subject to direct laser light may be made of different materials than the residual hohlraum wall areas. Moreover, other considerations, such as minimizing residual neutron activation, also will require further investigations of wall material. This design effort must be backed up with improved, high-Z, in-line, atomic physics packages (see Section 5.4.2.1).

Other technology design efforts will involve liner materials for the hohlraum walls such as CH or higher Z, in addition to replacing the helium/hydrogen gas fill. These liners will allow the laser light to propagate in a predictable and reproducible way to the high-density gold walls, where conversion into x rays is most efficient. Here too, various liner elements need to be optimized under multidimensional constraints and considerations, such as inverse bremsstrahlung absorption lengths and plasma instability thresholds. This optimization will require electron-conduction computational packages that can reliably predict conditions in laser-heated matter (see Section 5.4.2.3). The current LASNEX code is unable to account for interpenetrating plasmas (a phenomenon known to occur to some degree). Using an interpenetration model in-line with the code would be a significant core technology development since some designs that would otherwise seem highly desirable have been abandoned because of code predictions that indicate on-axis stagnation and an ensuing hydro impulse on the capsule that disturbs the symmetry. Currently there are several interpenetration codes in existence, both at LANL and at LLNL, which will be invaluable benchmarks for future LASNEX development. These codes are currently used to study the fundamental physics of plasma interpenetration.

The ionization state of the high-Z walls depends on the accuracy of non-LTE calculations. Laser light absorption and conversion to x rays, and hence the location of the

radiation source that will affect the symmetry of the drive on the capsule, depend on the ionization state. This also may impact the actual intensity of drive radiation as well as the quantity of the plasma filling the hohlraum, which are energetics issues. In addition, the spectral shape and intensity of the source can affect the target through radiative preheat. Thus, it is essential to model these characteristics correctly in order to heighten confidence in the design. This spectral-shape issue may be further complicated by the non-Maxwellian nature of the laser-heated electron distribution; therefore, the modeling must be sophisticated enough to account for these effects.

Other approaches that use shorter drive pulses that may lower the capsule gain but have the advantage of a somewhat less-stressing plasma physics environment (coupled powerfully, perhaps, with a hohlraum larger than the point design!) also need to be explored. In particular, a 250-eV hohlraum scenario should be explored in great detail.

Many of these issues could be tested, either in part or in total, in the post-NTC era, on either Nova or Omega Upgrade.

5.1.2 Advanced Designs

By advanced designs, we mean a significant broadening of the scope of possible hohlraum designs. These include small shields within the hohlraum that can shield the capsule from seeing the cold laser entrance hole and can be used, in principle, to engineer out small variations of higher asymmetry modes such as P4 and P6. These shields can be part of an even more sophisticated design that allows the shields to burn through and go transparent in a time-dependent way that is programmed to minimize time-dependent symmetry swings.

Other variations include changing the shape of the hohlraum from the standard right circular cylinder to something more optimal from a symmetry or energetics point of view. Shapes under consideration might include ovals (which still maintain cylindrical symmetry) and shapes or illumination schemes that require 3-D codes, such as spherical hohlraums illuminated with tetrahedral symmetry. Such designs would require, as a fundamental core science and technology development, a 3-D hydro radiation code (see Section 5.4.2).

Other initiatives should explore the limits of high T_r , trying to achieve drives above 300 eV (and with those initiatives, a concomitant effort to develop a capsule design that would go in such a hohlraum). Aside from raising T_r , efforts should be made to maximize the effects of hohlraum stagnation and reconversion of hydro motion to radiation in order to raise the radiation drive. These are high-risk, but possibly high-payoff approaches to achieving ignition. We anticipate that many of these issues could be tested, either in part or in total, in the post-NTC era, on either Nova or Omega Upgrade.

5.1.3 Symmetry Diagnosis Design

Although many designs of various hohlraums will be studied, a fundamental issue will be to measure the symmetry of the drive on the capsule, in a time-dependent way, so that we can iterate hohlraum design and illumination schemes in order to ensure ultimate success and symmetric drive. Although much has been learned during the course of the NTC, these lessons must be applied and adapted to NIF targets.

Anticipated techniques include some combination of the build-a-pulse, re-emission balls, and symmetry capsule campaigns. The first technique monitors the shape of an imploded core as the drive pulse length is successively reduced. The second technique measures the variation of x-ray flux reemitted from a nonimploding spherical ball. The last technique measures the imploded capsule symmetry as the capsule ablator thickness is reduced so that its implosion characteristics are increasingly sensitive to earlier parts of the full pulse. It is reasonable to assume that some combination of these techniques may be the most efficacious.

Another technique developed during the course of the NTC is low-density foam balls. By means of multigated pinhole pictures, this technique can show the development of the symmetry of the drive throughout the pulse on a single shot. There are, almost certainly, other techniques yet to be invented that could do the job as well, or better. An improved microtechnology, perhaps some form of micro-PINDOME coupled with fiber-optics, could monitor the arrival of shocks within a capsule as a function of angle around the capsule and of depth within the ablator.

We anticipate that each of these four current techniques can be tested in the post-NTC Nova or on Omega Upgrade.

We expect that capsule symmetry will be developed iteratively on the NIF using the above tools, thus modeling exercises can be used to better prepare the ICF Laboratories to optimize symmetry on the NIF. A possible scenario for these exercises could include one laboratory specifying laser and target conditions and a second laboratory, using a set of physics assumptions, calculating simulated target output. The first laboratory would then examine the simulated diagnostics output to determine which parameters to change (pointing, beam balance, pulse shape, etc.) to achieve ignition. They also could define intermediate experiments, such as the above time-dependent symmetry experiments, to better understand some of the variables. Iterations of this type could help the National ICF Program to expedite the achievement of ignition.

5.1.4 Plasma Characterization Design

Plasma characterization remains a formidable task after nearly two decades of preliminary efforts. Chief candidate among the techniques is plasma spectroscopy. Temperature diagnostic methods via neighboring-element isoelectronic-line ratios recently have been identified as a very promising approach.¹ Much more work must be done to definitively validate this technique for indirect-drive targets. Moreover, this validation still would leave electron-density diagnosis by means of spectroscopy as an unsolved problem. More basic research and design will be needed in this area. Ion-temperature measurements also are needed, since they may indicate the degree of plasma interpenetration vs stagnation in the hohlraum plasmas, as well as indicate the presence of saturating mechanisms for stimulated Brillouin scattering (SBS). This challenge of measuring hohlraum T_i is also in its infancy in the ICF realm.

Competing techniques for plasma characterization are even less mature. Thomson scattering, which in principle can yield time-resolved and spatially localized T_e , n_e , and T_i , has shown some initial successes in open geometry but not yet in hohlraum plasmas. Similarly, soft x-ray laser Moiré probing, incoherent XUV shadowgraphy, and XUV

interferometry have shown some spectacular initial success in open geometries but are yet to be tested in hohlraum geometries. Much design effort will be required to bring these techniques to fruition. Moreover, some design effort to optimize the XRL or XUV source probe beam will be needed, as discussed in Section 5.7.

We anticipate that many of these issues could be tested, either in part or in total, in the post-NTC era, on either Nova or Omega Upgrade.

To summarize the most salient points of this section, Isoelectronic line ratios appear to be a promising method for the determination of T_e in a hohlraum environment. Such ratios preserve diagnostic properties, even in a typical hohlraum radiation field. More work needs to be done to determine a spectroscopic diagnostic for electron density.

5.2 Capsule Design

5.2.1 High Convergence, High Gain

The baseline high-convergence ratio (35–40) moderate-gain (10–20) capsule design has not changed in several years. Alternative designs may still be required, as will refined mix and stability analyses of this target. In concert with target fabrication development, a set of specifications for ablator material properties, surface quality, gas-fill density specifications, and cryogenic-layer properties must be developed. More design work is needed on cryogenic fuel supported in a foam matrix, in case beta-layering is inadequate as a fabrication technology. Similarly, other possible techniques for fabricating the fuel layer must be investigated as they are developed by target fabrication. Target design should iterate with development of the NIF laser design and its as-built capability in order to ensure that it continues to be consistent with the requirements of this main-line target approach.

5.2.2 Lower-Risk Designs

It is important to start out slowly on the NIF, with capsules that are more forgiving from a symmetry point of view, so that we may proceed smoothly up the learning curve as we gain experience with NIF beams and hohlraums. Thus, it is imperative to design low-convergence (20–25) lower-gain (0.5–5) capsules. There are many design parameters to explore, including pulse shapes and differing target materials. Capsules designed to be driven by a shorter pulse or larger hohlraums will encounter less plasma along the laser beam path and thus present a much lower risk with regard to plasma instability. An advantage of some of these approaches is that they can be tested by properly scaled post-NTC Nova or Omega Upgrade experiments.

5.2.3 Noncryogenic Options

Noncryogenic capsules will be needed for many NIF experiments prior to the cryogenic ignition experiments. Targets need to be designed for characterizing symmetry, measuring implosion characteristics at NIF scale, verifying that we can achieve the implosion velocities needed for ignition, and a variety of other physics issues that can be explored without cryogenics. We also need to explore the idea of using LiDT as a solid fuel layer.

5.2.4 Internal Pulse Shape Designs

Achieving ignition and gain requires controlling the thermodynamic adiabat on which the DT fuel is compressed. As the internal energy of the fuel is increased, more work must be done on the fuel to compress it to high densities. The baseline target design achieves this control by tailoring the hohlraum drive, and thus the ablation pressure on the pusher, through varying the laser pulse. This control puts stringent demands on the laser to precisely deliver laser power with a large dynamic range.

An alternative design is to include shell material that moderates the radiation drive reaching the ablator through varying its opacity as it is heated. For example, a layer of intermediate Z material may be placed at a given depth in the capsule ablator. Originally it will be cool and highly absorptive. After it is radiatively heated, it will become more highly ionized and, for an appropriately chosen material, the opacity can change significantly, allowing more radiation to reach the ablator layer. These designs, called internal pulse shape (IPS) designs, could potentially reduce the requirements for the dynamic range of the laser requirements. Sandia has developed IPS target designs for light-ion drivers, and these designs should also be pursued IPS designs for the NIF. If such designs can be demonstrated calculationally to produce ignition and gain, they would contribute to reducing the risk for attaining gain on the NIF. In addition, design of experiments, presently in progress, to test IPS concepts for light ions should be extended to include studies related to NIF IPS designs.

5.2.5 Mix Diagnosis Design

5.2.5.1 Neutron output diagnosis/design. In recent years, we have made tremendous progress in measuring and analyzing fusion neutron-output spectra in order to deduce mix fractions. This effort must be extended to NIF parameters so that we may properly diagnose the degree of mix occurring in the high-gain capsules and in noncryogenic test capsules made of alternative materials such as beryllium. There may be post-NTC Nova experiments or Omega Upgrade implosion experiments that could be tune-ups for the NIF. It also is not unreasonable to anticipate advancing high convergence past those levels already achieved on the HEP 1 campaign, by using state-of-the-art, good-surface-finish capsules and precision Nova pointing and beam balance, perhaps enhanced with 10-beam RPPs, and shot in an advanced hohlraum with low time-dependent symmetry swing. Experience in this, too, would enhance the confidence level of NIF capsule performance.

5.2.5.2 Spectroscopy diagnosis/design. The use of spectroscopy in implosion geometries also has matured greatly as a result of work done on Nova. This work includes deducing mix fractions from ratios of spectral lines from elements embedded in the pusher rather than those initially implanted in the fuel. As with neutron spectroscopy, these techniques must be extended to NIF parameters. A particular challenge here will be high-p-r implosions that may prevent lines from escaping the core. This may then call for higher-Z elements, which usually present some very complex atomic physics and line-shape problems.

5.2.5.3 Other methods. There are various other methods for diagnosing mix—for example, direct imaging either in self-emission or backlighting, charged-particle activation, and planar and cylindrical experiments such as those now being performed on

Nova. Some of these methods are in their infancy, while others are mature, well-proven testbeds for outstanding experiments. There are numerous possible post-NTC Nova experiments and Omega Upgrade implosion experiments that could be used as testbeds for these alternative techniques as applied to the NIF.

5.2.6 Burn Diagnosis Design

5.2.6.1 Neutron output diagnosis/design. Because of the progress in measuring and analyzing fusion neutron-output spectra, they can now be used to deduce ion temperatures and yields. This effort needs to be extended to NIF parameters to properly diagnose the degree of burn and ion-temperature bootstrapping occurring in the high-gain capsules and in capsules made of alternative materials such as beryllium. Alpha deposition diagnosis will also be a challenge. There may be post-NTC Nova experiments or Omega Upgrade implosion experiments that could affect the NIF.

5.2.6.2 Spectroscopy diagnosis/design. Plasma temperatures and densities can now be deduced from line shapes using x-ray spectroscopy. As with neutron spectroscopy, these techniques must be extended to NIF parameters. A particular challenge will be high- ρ - r implosions that may prevent lines from escaping the core. This may then call for higher- Z elements, which usually present some very complex atomic physics and line-shape problems.

5.2.6.3 Other methods. Other methods may involve direct detection of alpha particles, although that is complicated by inherent target electric fields and perhaps other plasma physics effects. Still other methods may be invented. Direct measurement of core sizes by means of neutron, alpha, or gamma imaging will be necessary to obtain a full picture of the burn dynamics. Also, tracer elements or surrogate pusher materials may be used to obtain capsule ρ - r , perhaps through activation.

5.2.7 Hydrodynamic Instability Theory and Codes

The current state of the art of hydrodynamic instabilities has progressed enormously in recent years. Ideas on mode coupling, transitions to weak nonlinearities, and saturation have developed to the point where they are being tested quite rigorously on current Nova experiments as well as other experimental testbeds. The frontiers lie in 3-D effects, in the direct hydrodynamic modeling of multimode growth in NIF capsules, and, perhaps, in the highly nonlinear turbulent regime, although it is hoped that regime can be avoided completely. The more accurate predictions of such effects on burn will help verify target surface-finish requirements. Dedicated codes, either stand-alone or in-line with hydro simulation design codes should be advanced. Dedicated experiments that can test these codes and theories must be designed and extended to convergent geometries. Such experiments in post-NTC Nova, Omega Upgrade, and elsewhere will be required.

5.3 Plasma Instability Mitigation

5.3.1 Basic Theory

The basic theory of laser-plasma interactions remains a challenge for ICF. Hohlraum plasmas irradiated by NIF beams are predicted to have large linear gains for stimulated

Brillouin scattering (SBS) and stimulated Raman scattering (SRS). In addition, the beams may be unstable for filamentation. We must seek ways to mitigate these plasma instabilities. The role of bandwidth and particular methods of beam smoothing and bandwidth must be studied further. The new regimes of strongly coupled SBS need further development. The complex interplays of SRS, SBS, and filamentation are not yet understood. Complete 3-D theories of these instabilities must be formulated and tested. A dedicated team of world-class plasma physicists must attack these problems with a variety of powerful analytic and numerical approaches. Of course, the design and analysis of experiments to test these theories also will be necessary. These experiments could be done on Nova, Omega Upgrade, Trident, or other facilities.

5.3.2 Nonlinear Saturation Theory

Basic linear instability theory is complex enough, but if plasma instabilities in the NIF grow to nonlinear saturated levels, we must accurately predict those levels and the effects of those instabilities on laser-plasma coupling and hohlraum performance. Nonlinear saturation theory is still in its infancy, therefore, a considerable effort will be required to fully develop the theories. As before, the design and analysis of experiments to test these theories also will be necessary.

5.3.3 Plasma Code Development

Extensive 3-D nonlinear fluid plasma instability codes for SRS, SBS, filamentation, etc. (namely, the fully coupled problem) will be one of many necessary tools brought to understand the mitigation of laser-plasma instability. Efforts to parallelize the current codes surely will pay off.

Intermediate between these codes and the particle-in-cell (PIC) codes to be discussed next are hybrid codes such as kinetic ions and fluid electrons. These may be the codes of choice (in 2-D at least) to properly assess nonlinear saturation mechanisms.

More fundamental work with PIC codes also will be necessary. These codes are considered to be the most fundamental and least subject to poor answers that may result from possible compromises invoked in fluid codes. The new ZOHAR code would run on workstations, be applicable to more general geometries than just rectangular slab, and may be 3-D. Similarly newer versions of ISIS and WAVE have capabilities to address these issues, including collisional effects.

A hoped-for by-product of all of these efforts would be some plasma physics package in-line with the hydro design code that would self-consistently include plasma instability scattering and hot-electron and hot-ion production. This is described in greater detail in Section 5.4.2.7.

5.4 Hydro Code Development

The current radiation-hydro simulation design code used for ICF consists of numerical hydrodynamics technology that is three decades old. Although many improvements have been made since it was first developed, significant advances have been made in physics, numerical methods, and computer hardware. The capability now exists for developing modeling tools that have more sophisticated physics, that is faster and more

comprehensive, and that is easier to use and comprehend. The following are areas where development will improve our understanding of NIF target performance.

5.4.1 3-D Codes

Currently radiation-hydro codes are limited to only two-dimensions, requiring modelers to approximate the 3-D problem by assuming an axis of symmetry in the problem. Recently, 3-D hydro codes have been developed by a number of laboratories (NRL, University of Osaka, Rutherford-Appleton Laboratory, LLNL, LANL, and Sandia) and have shown for limited sets of problems that the results could significantly change in moving from 2-D to 3-D. Most of these codes do not have radiation transport and are limited in the physics contained in them. It seems essential to extend the general simulation capabilities to 3-D. As mentioned previously, 3-D allows the study of possible breakthrough hohlraum geometries, such as one illuminated with tetrahedral symmetry, and will allow assessment of 3-D perturbations on Rayleigh-Taylor growth, mix, and capsule performance. Indeed, accurate nonlinear multimode calculations of Rayleigh-Taylor require a 3-D code. This effort also should include, as a goal, the production of an unclassified, yet still highly sophisticated, radiation-hydro code with the relevant plasma and material physics and laser transport for the use of the ICF community at large.

5.4.2 Advanced Physics Models

5.4.2.1 Atomic physics. As mentioned previously, increasingly sophisticated in-line atomic physics will be required to enhance hohlraum performance through increased conversion efficiency, reduce wall loss through the use of optimized combinations of materials, and possibly develop high-Z fuel and pusher dopants for high-p-r capsule performance diagnostics. Several approaches are under consideration, such as in-line semiclassical / split XSN, an improved SCA, DCA, and a non-LTE STA. All of these approaches will be able to analyze non-LTE situations. In addition to this high-Z, many-electron initiative, a state-of-the-art, low-Z, few-electron atomic physics package of very high quality is needed, for example, to analyze tracer elements for spectroscopic diagnostics.

5.4.2.2 Radiation transport. Radiation transport now can be done by several techniques, each with its own advantages. New algorithms are presently under development. Research to improve radiation transport will be necessary over the next 10 years.

5.4.2.3 Electron conduction. Accurate modeling of electron conduction is fundamental to reliable predictions of laser-heated matter. Electron temperature determines where the laser propagates and absorbs, and with what efficiency it converts to x rays. Thus, the emission source, a fundamental component of drive and symmetry considerations, depends on properly modeling electron conduction. Moreover, the temperature in the underdense plasma through which the NIF beams will propagate is a high-leverage component of what plasma instabilities will grow and how fast. A nonlocal approach in 2-D is being developed

At a much more fundamental level, the Fokker-Planck approximation to electron transport should be investigated and a computationally affordable in-line package developed. This will allow us to account for the very real effects of non-Maxwellian

distributions that result from both nonlinear inverse bremsstrahlung absorption and the nonlocal electron transport itself. At this level, we then can calculate the effects of such distributions on the atomic physics and spectral line formation. Such effects may seriously affect interpretation of plasma-blowoff characterization experiments. We will need to develop state-of-the-art diagnostics that would be sensitive to such non-Maxwellian electron distributions.

5.4.2.4 Magnetic fields. It is well known that, in laser-plasma interactions, magnetic fields are generated spontaneously. Their effect on electron conduction, hydrodynamic instability growth, spectral line shapes, and laser-plasma instability growth have been studied in isolated systems, but not generally applied to systematic design studies within the context of the major design tools for hydro simulation. In particular, the existence of magnetic fields in hohlraums and their possible effects on drive symmetry are of possible concern. Undoubtedly, much work remains to be done in this area, both in validating the current magnetic field effects encoded in the simulations and in implementing improvements to them. Careful experimentation and diagnostic techniques must be applied to the study of this complex problem.

5.4.2.5 Equations of state. Detailed knowledge of equations of state (EOS) are needed to accurately predict target performance. Since NIF targets will enter extremes in parameter space never before achieved in the laboratory, this remains a daunting challenge. Failure to keep the NIF capsules on a low adiabat due to inaccuracies in shock-propagation predictions would result in severe degradation of target performance. Therefore, core EOS studies are required: basic theoretical efforts; dedicated design and analysis activity to specifically test EOS predictions via planar shock ("witness plate") experiments; and more sophisticated, laser- or radiation-driven, x-ray back-lighted, flyer-plate shock-inducing experiments.

5.4.2.6 Spectroscopy and line transfer. The ability to correctly model the transport of spectral lines becomes significantly more important for line-ratio diagnostics in high-p-r implosion systems that are many optical depths thick at line center. Accurate treatment of line transport will allow us to measure fuel temperatures, density, and degree of mix with pusher materials. A variety of approaches are under study, including Cretin, DSP, and DCA. In addition, the FINE kinetics code has been modified to output atomic models calculated with the CATS, ACE and GIPPER codes in a format suitable for use in the LASNEX postprocessor TDG.

5.4.2.7 In-line plasma physics. As mentioned previously, the NIF will be operating in regimes that stress plasma physics instabilities. Of course, mitigation techniques such as bandwidth and SSD are planned. Nonetheless, the most accurate way to account self-consistently for the effects of plasma instabilities (e.g., scattering levels and hot-electron production) would be to incorporate an in-line plasma code into the hydro design code. This could allow the designer to perform precision design studies, such as the thickness or material of a hohlraum window to hold in the fill gas vs the effects such choices would have on plasma instability growth.

5.4.2.8 Dense plasmas. Large-scale quantum-mechanical molecular dynamics simulations of dense hydrogen and its isotopes are important for an accurate determination of diffusion coefficients and conductivities in fusion plasmas. These transport

coefficients in turn play a crucial role in the thermal balance of the fuel in an imploding ICF capsule. We will continue to extend our dense plasma simulations to higher densities and temperatures, in order to improve our present simplified estimates of transport coefficients via the inclusion of many-body effects. We will also begin to look at dense-plasma effects on the radiative properties of single-trace ions (such as argon) embedded in a background of hydrogen isotopes. Such studies are important for a correct interpretation of spectral line ratios in terms of plasma conditions. Including these effects into the hydro codes will be of importance to designers.

5.4.2.9 Laser deposition. Improved laser deposition modeling in the hydro codes is needed. Various possibilities exist with a wide range of complexity. This is currently being studied.

5.4.2.10 Other. Other physics packages will be implemented into the code as ideas and needs arise. Code developers and computational physicists are needed to ensure that such changes can be implemented in a timely way with quality results. Various applications—such as ion-beam deposition and propagation for ion-beam fusion, laser-light refraction and amplification for x-ray laser design, and ICF applications such as Moiré deflectometry—are examples of other packages required in the simulation code. Implementation of packages that handle the low-irradiance, low-damage, barely plasma regime would significantly expand our modeling horizons and allow us to perhaps directly address a variety of NIF laser design and damage issues, as well as to model spin-off technological possibilities such as laser drilling and medical laser processes.

5.4.3 Additional Hydro Codes.

5.4.3.1 Arbitrary connectivity mesh. For complex hydro problems, a significant issue is the computational zoning and handling of mass flow. For standard Lagrangian problems, meshes are connected at fixed nodes and can become severely distorted, which might cause errors in hydrodynamic approximations. Several methods have been developed for remapping the zones onto new zones to reduce distortion or to reduce the distortion in the computations. An alternative hydro code has been developed at Sandia that uses a arbitrary connectivity mesh and includes deterministic radiation transport. The code could be developed as a tool for investigating hohlraum hydrodynamic issues such as corner jetting, advanced hohlraum concepts such as shine shields, and laser-entrance-hole designs.

5.4.3.2 Hybrid codes. Hybrid codes that combine fluid electrons with particle ions may be just the right approach to solve the problem of plasma interpenetration in hohlraums. Much progress has been made in this approach with the ISIS code at LANL, though much effort remains to make this a useful design tool. Incorporation of some in-line interpenetration into the 3-D hydro simulation design code also should be considered.

5.4.4 Massively Parallel Processing

It is widely recognized that the next high-leverage direction for computing that will allow significant progress in complex hydrodynamic simulations in 3-D will be massively parallel computing. We must build a team of computational physicists and computer scientists to implement and improve on massively parallel algorithms that will support this revolution for 3-D.

5.4.5 Postprocessing

Postprocessing of massive hydro and plasma code simulations is the method of choice for accurately comparing code predictions with experimental observations. Moreover, more sophisticated postprocessing actually helps the physicist understand the predominant physics for a particular area of target performance, which leads to a better understanding of discrepancies between experimental observations and code predictions. Scientific visualization on powerful graphical workstations increasingly is necessary to analyze results from such massive simulations. Moreover, the ability to make quality videos from such simulations is an important skill in communicating the results to a wider audience.

5.4.6 User Interface

It is becoming increasingly clear that, as computational complexity increases, the need for friendlier user interfaces increases as well. Development of languages and user interfaces that allow the user to learn and adapt quickly empowers the user to ask increasingly sophisticated questions of the simulation, both before the run (e.g., generator decks of great complexity form a geometry or source specification), during the run (e.g., links of sources from previous simulations to this point in the current simulation—a technique crucial for finding optimal pulse shapes), and after the run (both in the postprocessor mode and in the sense of querying the simulation for specific physics effects that play a crucial role in the particular outcome of the simulation). Graphics/videos are also key ingredients in this interface project. Creating a powerful but simple-to-use interface is a continual challenge that requires the efforts of a core team of computer scientists.

5.4.7 Machine Interface

Of importance equal to that of the human interface is a simple-to-use yet powerfully versatile machine interface that will allow the physics packages of the simulation code to be placed in a more general (computationally) shell that handles input/output/interface issues with the hardware platforms on which the code will run. This allows the computational physicist to concentrate on the physics packages instead of machine-specific input/output details. Moreover, it allows that physics code to be run on a wide variety of hardware platforms with a minimum of changes and effort. For example, the BASIS shell performs this function in a remarkable fashion. As machine hardware continues to develop, a flexible next-generation interface must be developed.

5.5 Advanced Concepts

5.5.1 Fast Ignitor

The fast ignitor is a new, alternative concept for attaining gain using short-pulse lasers. In conventional target designs, the energy to heat the central core of the compressed DT fuel is supplied by conversion of the kinetic energy of the compressed fuel to thermal energy to initiate thermonuclear burn. In the fast ignitor, thermonuclear burn is initiated by heating of the DT by fast electrons produced by high-intensity, short-pulse laser-plasma interactions. This concept has the potential to produce gain with

significantly less driver energy than conventional designs. The following subsections outline design and theory activity to validate this concept.

5.5.1.1 Target design. There are many target-design issues for the fast ignitor. Optimization of the parameters of the short, fast, ignition pulse and those of the conventional, implosion, compression pulse is in its infancy. The implosion phase alone may require effort at the same level as the hydrodynamically equivalent physics (HEP) and NIF target-design efforts. Unlike conventional ICF, optimizing the fast ignitor requires choosing both the initial geometry in 3-D and the particular drive-illumination geometry and pulse shape. These additional degrees of freedom require substantially more design effort than corresponding conventional designs. The design options will vary with the choice of implosion driver, allowed illumination geometry, and choice of direct or indirect drive. Many of these issues can be delayed until the second half of the decade after results from petawatt experiments on Nova are obtained. Early on, however, we will need assessments of direct-drive implosions on 8-beam Nova with a goal of 50 to 100 g/cm³ in plastic, as well as assessments of several indirect-drive schemes.

If it is deemed advantageous for the short ignition pulse to impinge on an indirectly driven/compressed target along an axis noncollinear with the hohlraum axis, then the use of a 3-D simulation code becomes imperative. In addition, the optimum compressed systems may not be spherical. In that case, a 3-D code would be required in order to understand hydrodynamic instability growth. Experiments that test the notion of a channeling laser that will allow the ignition pulse to couple to the high-density target core must be designed and analyzed. Preliminary proof-of-principle experiments on Nova will require careful design and analysis to realistically plan what might be observed regarding the effect of the petawatt laser on fusion performance and how that might be diagnosed. Future study of channeling will require improved understanding of filamentation instabilities in regimes where ponderomotive pressure and relativistic self-focusing predominate. We will need to understand the nonlinear-saturated state of filamentation. This will require enhancing special-purpose codes such as F3D (a 3-D LASNEX with improved hot-electron transport) or modifying a PIC/hybrid code that includes stimulated scattering and filamentation instabilities and can track through hundreds of micrometers of plasma.

5.5.1.2 Basic plasma physics. The fast ignitor project stresses our incomplete knowledge of relativistic plasma physics. Issues include the effects of a channeling laser pulse that would create a path for the main ignition pulse to couple to the high-density capsule core, the physics of coupling the main ignition pulse to the core (e.g., absorption and hot-electron production), the physics of transport of hot electrons to deeper parts of the imploded core, and the effects of self-generated magnetic fields in all of these processes. Basic theory needs to be developed in these areas. In addition, experimental design and analysis support is needed to test the theoretical models. Furthermore, target designs will be needed to structure the self-generated electric and magnetic fields to optimize the hot-electron transport, which might be accomplished by proper choice of target materials and compressed configuration when the ignition laser is turned on. Also, design work could determine the electron density gradient and peak electron density that would optimize the absorption efficiency and hot-electron temperature.

5.5.1.3 Plasma code development. The foregoing nonlinear, relativistic, plasma physics issues perhaps are best addressed with a variety of codes. PIC codes certainly must be applied to the coupling-and-transport problem. A next-generation version of ZOHAR must be developed that runs on workstation platforms, includes the effects of collisions, and is applicable to overdense regions. It may be a hybrid code or a PIC code with an interface to a hybrid code. Other hybrid codes (such as ANTHEM) that allow accurate predictions of electron transport and hydrodynamics and the effects of magnetic fields must be exercised and further developed. Ultimately, we will want to understand the interaction of these new transport effects with the burn and radiation-transport physics. That is, we want to incorporate the relativistic electromagnetic field theory in a 3-D hydro code like 3-D ICF. We want to calculate electron transport in arbitrary geometries without the assumption of quasi-neutrality.

5.5.2 Enhanced Gain

In principle, other methods besides the fast ignitor have the potential to enhance gain on the NIF. One example is polarized DT fuel. Other schemes currently are classified and cannot be described in this document.

5.6 ICF Applications

5.6.1 Inertial Fusion Energy

5.6.1.1 HIF mock-ups. The heavy-ion fusion (HIF) approach to inertial fusion energy (IFE) is envisioned with either one-sided or two-sided illumination of a hohlraum with "converters" that convert beam energy to x rays. The hohlraum approach thus serves as a vital link between HIF-IFE and the indirect-drive efforts being tested at NIF. Efforts at hohlraum/target design driven by heavy-ion beams will continue and improve, in concert with all of the previously mentioned improvements in theoretical tools and technology. In addition, since the conventional NIF hohlraum uses multiple laser beams that cover a wider solid angle than does the one- or two-sided illumination geometry envisioned for the heavy-ion-beam approach, an effort should be undertaken to design post-NTC Nova and NIF experiments that employ HIF-like illumination geometries but use laser-beam illumination. Scattering cones near the laser entrance holes may be the method of choice, or perhaps high-Z doped foams in the hohlraums will be an option. This project will allow us to validate the radiation-transport algorithms and predictions in the HIF-relevant hohlraum geometries.

An endeavor that promises some leverage is to understand the range shortening of heavy ions due to changes in Z^* (effective charge state) and other atomic physics effects. We might be able to produce a small, hot, dense plasma by irradiating a foil with a table-top, ultrashort-pulse laser moved to an accelerator. The plasma then would be traversed by the heavy-ion beam.

5.6.1.2 Other IFE tests. As mentioned in the previous section, HIF IFE hohlraums will be illuminated by narrow, solid-angle beams. This has inherent advantages for IFE of protecting the first "lens" and allowing most of the solid angle to be available for fusion output, neutron stopping, and energy conversion. Thus, if we consider other IFE drivers, such as diode-pumped solid-state lasers (DPSSLs), we also must invent

hohlraums that can provide adequate symmetric drive onto the capsule yet be illuminated with only one or two narrow beams.

Another interesting IFE issue that can be studied is the set of target specifications for mass-produced injectable targets. We could do this by intentionally lowering the quality of targets and measuring their performance. The ideas generated here could be tested in post-NTC Nova or on the NIF.

5.6.2 Output

5.6.2.1 Chamber damage issues. In designing the NIF, as well as during NIF operation and maintenance, an obvious need exists to predict and assess chamber damage caused by target output. Methods to mitigate chamber damage while maintaining high target gain may have to be invented—presumably through novel hohlraum design that directs target debris and fusion output to specific points on the chamber wall specifically set up to handle the damaging flux. Improved calculations of photon transport through high-Z gases also may be necessary. This would use our developing capabilities in NLTE radiation transport.

5.6.2.2 Nuclear weapons effects testing (NWET) output. The radiation hardening communities, in particular the Defense Nuclear Agency (DNA) and Sandia National Laboratories, are interested in a laboratory facility that produces—with as high fidelity as possible, both in spectral shape and in spectral intensity—output that mimics nuclear weapon effects. The threats that need to be assessed include damage to satellite optics, damage to electronics components of weapons systems, and damage to the operation of other nuclear weapons. The NIF is a uniquely versatile source that can produce interesting levels of cold and hot x rays and neutrons. There are ways to optimize outputs in particular parts of the x-ray spectrum, for example through seeding the DT fuel with high-Z materials that will enhance the radiative output. Novel hohlraum designs and focusing elements beyond the hohlraum also could enhance the target output in a very useful way. A risk-free approach of demonstrating the utility of the NIF to the DNA and Sandia, which does not rely on igniting a capsule, is to use the NIF laser directly on a high-Z disk, thus creating a “cold” or “warm” x-ray source. Work needs to be done to invent disks with combinations of materials that would customize the x-ray output to DNA’s needs. Apart from supplying sources for DNA, Sandia, and others, we can undertake the task of experimental integration. That is, we can design real-time diagnostics for their test objects and attempt to track failure trees. This project will require innovation, considerable interaction with future customers, and move us somewhat away from our traditional areas of expertise. However, it may exploit our skills in using NLTE atomic physics to diagnose short-lived events.

5.6.3 Other NWET Sources

We should apply our plasma physics expertise and sophisticated magneto-hydrodynamics hydro design codes (enhanced as previously described with the necessary physics packages that involve magnetic fields and interpenetrating plasmas) to the modeling of proposed pulse-power radiation sources such as the proposed JUPITER facility.

5.6.4 Weapon Physics

While the Weapons Program is carrying out most of the design and analysis of weapon physics experiments, our corporate knowledge base in laser-driven hohlraums should be applied for total quality assurance. Investigating the limits of high T_r is one area in which we may play a crucial complementary role. Another is assessing experiments that specifically take advantage of the fact that a capsule is igniting and hence could propel a test material deeper into a part of parameter space most relevant to weapons.

5.7 Advanced Diagnostics Development and Design and Other Spin-Offs

5.7.1 X-Ray Laser Probing

An advanced approach to plasma diagnosis—particularly the probing of high-density plasma regimes—is the use of laboratory soft x-ray lasers (LXRL) for probing. In recent preliminary successes with Moiré deflectometry, an LXRL was used to measure a laser-driven CH disk's plasma profile at densities higher than ever before. This process needs to be developed further. Ways of producing a low-cost, easily portable x-ray laser will need to be developed. The application of XRLs to the probing problem, plus developing other probing approaches such as holography, need to be advanced, along with computational tools and postprocessors that permit accurate modeling of the data. The theoretical tools developed here could be applied to the analysis of a wider variety of coded-aperture approaches to target diagnostics.

5.7.2 Commercial Spin-Offs

By developing sophisticated computational tools, we can expand our parameter space to simulate the interactions of lower-irradiance lasers and matter. Commercial spin-offs include modeling and optimizing laser drilling, laser machining, and laser tissue interactions for surgery. Moreover, we could help solve other problems within the ICF program, such as laser damage issues. These efforts should eventually be self-supporting.

5.7.3 NIF-Based Science and Technology

The role of NIF is expanding to include multiple stakeholders including basic science studies. A small target design and theory effort can effectively be used to foster development in many areas. For example, fast ignitor tools such as high-intensity laser coupling and electron transport, EOS of materials at 1 keV at normal density (e.g., a short pulse striking a solid in the manner of the USP laser), EOS of compressed materials (e.g., compress a high-Z material in the same manner as the ignitor, bore a hole, and then hit it with a high-power beam) can have many applications in basic plasma physics and material science. Also, short-pulse lasers may be able to produce magnetic fields in the range of 100 to 1000 Mgauss. We should search for ways to apply these fields, perhaps in atomic or nuclear physics. They also may be the basis of novel microwave devices. At very high intensities, these lasers can be copious producers of electron-positron pairs. Successors to the Petawatt laser may be able to produce pair-dominated plasmas, a state of matter heretofore observed only in astrophysical contexts.

Reference

1. R. S. Marjori banks, M. C. Richardson, P. A. Jaanimagi, and R. Epstein, *Phys. Rev. A*, 46, R1747 (1992).

6.0 Target Components and Fabrication

Even though the first target shots on the National Ignition Facility will not occur before about 2002, target and target fabrication technology will have to be developed well before that. There are several reasons for this. First, many of the target developments needed for the NIF are similar to those needed for University of Rochester's Omega, such as size scaling and cryogenic handling and maintenance. The time scale for the Omega targets are much earlier than for the NIF, some needed as early as 1996. The National ICF Program is taking advantage of the natural synergism between Omega and NIF targets by using the technical resources at LLE, LLNL, LANL, and General Atomics to solve the target development problems in the order they are needed. The cryogenics-related tasks are planned and coordinated as the National Cryogenic Target Program. The broader scope of work outlined below reflects this synergistic philosophy. Second, some developments have very long lead times, or are required early so that subsequent developments can proceed, as with cryogenic capsules. For instance, the details of how cryogenic capsules will be fabricated, filled, characterized and fielded in the NIF target chamber must be determined three-to-five years before final engineering, design, construction, and testing of cryogenic target support apparatus can commence. Finally, considerable uncertainty of technical success exists for many required or desired developments. Several options exist for the technical approaches to capsule development, and the decision paths will depend upon early results. Such is the case for beryllium capsules or scaling up of polymer capsules.

A central issue for all capsule fabrication and cryogenic fuel layer is surface roughness. To assure ignition, the capsule and DT-ice surface roughness, as well as the radiation drive symmetry, must be within specifications set by each target design to achieve a spherical implosion. Modeling has set maxima for capsule and DT-ice surface roughness. A general objective is to reduce each of the three contributions to less than 0.25 and possibly as low as 0.1 to provide increased confidence in the likelihood of ignition.

6.1 Capsules

Baseline designs of NIF ignition targets include polymer and beryllium fuel capsules,¹ and new capsule materials such as boron carbide are being evaluated as well. For nearly all capsule fabrication methods, including sputtered beryllium but excluding machined beryllium hemishells, the ablator will be deposited on a mandrel. For most designs, the mandrel will be a thin polymer shell. One exception is a capsule having an internal foam shell for cryogenic fuel support, which would also serve as the mandrel for the ablator.

Polymer capsules with NIF dimensions probably cannot be fabricated by the solution drop-tower method currently used to make Nova capsules. Thus, new fabrication methods will have to be developed. New fabrication methods might also result in fabrication cost reductions, which provide an additional incentive for their development. New methods and materials may additionally provide higher strength capsules to hold the high-pressure (400–500 atm) fills at ambient temperature, which could enable remote filling without cryogenic transport (Section 6.4). Alternate materials may

prove to be better permeation barriers to hydrogen for noncryogenic targets than the currently-used poly vinyl alcohol (PVA), which gives a fuel retention time of only a few tens of hours, is difficult to coat uniformly, and damages easily upon exposure to tritium.

Beryllium capsules are calculated to ignite with a substantially rougher fuel ice layer and may offer increased ignition margin relative to polymer-based capsules, particularly at lower drive temperatures.² This increased margin could help ease hohlraum plasma-physics problems if necessary, or it could enable hohlraum designs with higher drive symmetry. Fabrication options for beryllium capsules are also diverse, and significant progress has been made towards NIF-sized capsules even though they have been relatively modest compared to efforts in polymer capsules. The NIF ignition capsules will have very exacting tolerances, which would require either improvements to previous fabrication techniques of larger capsules or new fabrication techniques. Some fabrication methods would take advantage of the strength and low permeability of Be to enable remote filling and ambient temperature transport.

Very-low-density polymer foam capsules (around 50 mg/cm³) provide one option for supporting cryogenic fuel layers. Such capsules were made a few years ago by workers at the Institute for Laser Energetics (ILE) at the University of Osaka, Japan, with diameters of several hundred microns to 1 mm. However, the foam must also be optically transparent to provide characterization access to the liquid layer inside, and the Osaka foam shells have not been able to meet this requirement. Consequently, new formulations based upon organic aerogel chemistries are being developed, and substantial progress has been made producing resorcinol-formaldehyde foam shells up to NIF dimensions.

6.1.1 Polymer Capsules

A typical Nova polymer-based capsule consists of three layers as in Fig. 6-1. An inner layer forms a mandrel for the application of the other layers. It also provides a means of diagnosing fuel conditions and mix during the implosion experiment if it contains trace amounts of spectroscopic diagnostic elements.³ The inner mandrels are made by shell blowing from polystyrene solutions in vertical heated-zone drop towers.⁴ The PVA layer is a permeation barrier to prevent rapid leaking of the hydrogen-isotope fuels. This barrier is required for room temperature capsules, but it would not be needed for cryogenic targets, since permeabilities drop by orders of magnitude at low temperatures. It is applied by wet-solution techniques, also in vertical drop towers. The ablator layer, which may contain a dopant to control opacity, is applied by plasma polymerization.⁵ Currently available dopants are bromine and germanium, which can have concentrations as high as several percent.⁶ The polymer-based capsules for NIF will be similar to those used on Nova, but of larger size.

Table 6-1 shows the various dimensions and required tolerances for NIF indirect-drive polymer capsules. Ranges are given in some cases because the target and experiment designs for the NIF are not complete and will continue to evolve over the next several years. The tolerances are comparable to those for Nova targets, but the larger NIF targets require greater fractional precision in fabrication and characterization. In reality, all the tolerances are general guidelines. The performance of a given capsule depends in detail on the surface harmonic spectra of the outer (capsule) and inner (DT

ice) surfaces. The ignition criterion is that the measured spectra will burn in a realistic computational simulation based on the LASNEX code, including drive asymmetry. Thus, the denominators of the terms in the quadrature sum in Sec. 6.0 depend on the actual spectrum, but the distribution over "l-modes" shown have been found to ignite in a set of calculations.

The best fabrication technique for capsules may depend on capsule size. The current drop tower techniques have made good quality shells only up to about 700 μm in diameter, and models of the shell -blowing process indicate that NIF-sized capsules may not be possible by this technique in realistically sized towers.⁷ Plasma-polymer ablator layers become rougher as thickness increases,⁸ and coating a 200- μm layer could take up to 800 hours at present coating rates. We will determine whether the current methods of making Nova capsules, i.e., drop-tower mandrel formation and PVA overcoating, and plasma polymerization, or modifications of them, will scale to NIF sizes. Since the current solution drop-tower technology for making the polymer shells is not expected to scale, we will also attempt to develop alternative methods of capsule formation. There are several approaches being considered: alternative drop-tower techniques, microencapsulation, decomposable mandrels, and interfacial polymerization.

Figure 6-1. A typical Nova polymer-based capsule.

Table 6-1. Polymer capsule characteristics.

Characteristic	Nova	NIF
Materials		
Shells	CH	CH, CH foam
Inner-shell dopants	Cl, Br, Ge, Ti, Cr	Cl, Ti, Ge
Fuel-space additives	Ar, Xe	Ar, Xe
Diameter	200–600 μm	1000–3000 μm
Required tolerance	$\leq 20 \mu\text{m}$	$\leq 20 \mu\text{m}$
Shell thickness	30–50 μm	100–200 μm
Required tolerance	$\leq 2 \mu\text{m}$	$\leq 2 \mu\text{m}$
Required nonconcentricity ($l=1$)	$\leq 0.5\%$	$\leq 0.5 \mu\text{m}$
Required nonconcentricity ($1 < l < 10$)	$\leq 50 \text{ nm rms}$	$\leq 119 \text{ nm rms}$
Surface finish ($l \geq 10$)	$< 10 \text{ nm rms}$	$< 28 \text{ nm rms}$
PVA barrier layer thickness	2–6 μm	$\approx 5 \mu\text{m}^*$
Required tolerance	$\leq 1 \mu\text{m}$	$\leq 1 \mu\text{m}$

*gas targets only

A first approach to NIF-sized capsules is based upon a drop-tower technique with the starting material being a solid polymer pellet infused with 5–10 wt% of a volatile fluid that acts as a blowing agent. This method is currently being explored through a contract with the Lebedev Physical Institute (LPI) in Moscow. The advantage of this method over solution techniques is that there is much less heat and mass transfer necessary to blow the shell. However, the yield of target quality shells is lower than from solution techniques, and preparation of the initial polymer granules is more difficult. Nevertheless, using these techniques the Lebedev group can produce good quality 1-mm-diam capsules.⁹ The goals of the current contract between LLNL and LPI is to modify these techniques to allow for the production of 2- to 3-mm capsules. Hydrodynamic and heat transfer problems of conventional drop towers can be reduced further with a "Ballistic Furnace."¹⁰ In this case, the polymer granules are propelled upward into the furnace hot zone by a precisely controlled injector system so that they reach the necessary temperature and inflate near the apex of the trajectory when the hydrodynamic interactions with the surrounding gaseous medium are at a minimum. There are a number of development problems to be solved, including techniques for rapid cooling.

The microencapsulation technique forms liquid shells of polymer solutions in an immiscible background fluid, and the polymer solvent is gradually removed, resulting in a solid shell. This technique has been developed at ILE, Osaka, for thin polystyrene shells with diameters as large as 3 mm.¹¹ Similar processes are now in use at GA/Soane and at CEA, Limeil. A variety of multiple-orifice droplet generators have been developed to make uniform diameter and thickness shells. A common problem is that during solvent removal from the polymer solution shell, small vacuoles form, probably as a result of phase separation of trace quantities of water in the shell wall. Scaling of the microencapsulation process to NIF capsule sizes exacerbates this process. The vacuole formation may be controllable through very careful control of solution thermodynamics and kinetics, which is being investigated.¹² A second problem is centering the inner aqueous liquid sphere in the organic phase shell during solidification. This problem will be addressed by centrifugal centering using various stirring methods in density-matched solvents and possibly by induced shell oscillation. It may also be possible to make solid shells by a non-drying microencapsulation process such as thermally or UV-activated polymerization of liquid monomers or oligomers.

A third approach to NIF scale microshells that may overcome the vacuole problem involves the use of a microencapsulated decomposable mandrel.¹³ This method makes use of the property that poly(α -methyl styrene) thermally decomposes to monomer at a relatively low temperature. If it is possible to prepare very symmetric and smooth solid microencapsulated shells of this polymer at sizes up to several microns, they can be overcoated with a thin layer of plasma polymer, and then heated to decompose the polymer mandrel to monomers, which diffuse out of the shell, leaving a symmetric shell of the desired size. Using microencapsulated shells eliminates the problem with vacuoles and concentricity because the mandrel is removed.

A fourth approach to NIF sized capsules is based upon an interfacial condensation-polymerization technique, first suggested by workers at Monsanto Research Corporation.¹⁴ For this technique, two reactants are dissolved in immiscible solvents, and spherical drops of one are immersed in the second. The polymerization reaction occurs at the interface. Spherical shells of NIF-dimensions have been formed by this technique using a droplet generator. To perfect these preliminary results, conditions must be found that will yield better sphericity and surface finish. Depending upon the wall thickness attainable, additional ablators may have to be added by a different technique, such as plasma polymerization. This might also be necessary if the shell produced by interfacial condensation-polymerization has a composition too rich in oxygen.

NIF capsules require much larger fill pressures than Nova, and higher-strength polymers would be very desirable. For example, shells made from polyimide resins may be able to hold their fuel charges at room temperature. Microencapsulation and vapor deposition of monomers may provide methods of making such high-strength shells.

Finally, a substitute for the process of applying the second-shell PVA permeation barrier of Fig. 6-1 may have to be found since the current techniques are very inefficient, and the number of NIF-scale capsule mandrels produced may be much smaller than what we get by our current drop-tower techniques. One approach is to develop precise single-shell PVA coating techniques in which a microshell is supported in an

acoustic field or gas flow while the PVA coating is applied. Preliminary proof of principle work along these lines has been conducted. An alternative to a PVA permeation barrier is to coat the outer surface with a 5- to 10-nm thick layer of aluminum or boron carbide by sputtering.

6.1.2 Beryllium/Boron Capsules

Beryllium capsules can add considerable margin to the NIF laser energy available for developing the capsule radiation drive.² Beryllium can be driven at lower hohlraum temperatures than polymer shells and attain the same fuel densities and temperatures. Beryllium capsules can also tolerate a rougher DT ice roughness because of weaker coupling to instabilities at the external surface. Initial designs of boron and boron-carbide capsules show many of the favorable characteristics of beryllium and may have the advantage of being transparent in the IR, which would allow fuel-layer characterization and fuel-layer enhancement by IR heating, if needed.

Crucial issues associated with development of beryllium capsules are: (1) the surface finishes must approach those of polymers (50 to 100 nm rms with an acceptable power spectrum), (2) the distribution and concentrations of higher-Z elements, impurities or dopants added to tailor opacity, must be controllable and very uniform, and (3) the capsules must be fillable. Capsules may be fabricated by a variety of processes. Hemishells may be machined, and bonded in a DT atmosphere or implanted with a permeation channel that would enable filling after bonding. Alternatively, Be could be vapor deposited over a thin polymer mandrel or hot isostatically pressed (HIPed) over a solid mandrel, which would be subsequently removed by leaching through a small hole.

Advances are needed in beryllium metallurgy. Beryllium produced by the traditional pressed powder technology usually contains unacceptable levels of impurities such as oxygen and particulate iron. An important attribute of beryllium that will strongly affect surface finish and dopant uniformity is crystal size. Dopant impurities tend to lie along grain boundaries, and the surface finish is ultimately determined by the morphology of exposed crystal facets. For both these reasons, crystal grains in the few micron size-range are desired. If capsules are assembled from machined hemishells, the stock material crystal size may be reducible to micron size levels by alloying. The alloying material would change the shell opacity, therefore, alloying needs to be pursued in concert with target design. The effects on morphology of acceptable alloying materials at acceptable concentrations should be determined. Forging can also reduce crystal size, and the limits of this technique should be studied.

Vapor deposition might be used in a variety of ways in capsule fabrication. First, if bulk processing techniques cannot achieve adequately small grain sizes, amorphous or extremely small-grained beryllium for subsequent machining can be produced by CVD or PVD onto cold substrates. It is also possible to sputter beryllium directly onto a polymer mandrel, and initial results indicate the resulting columnar structure of the Be allows filling by permeation along the grain boundaries. The filling and fuel retention characteristics of the capsule, including filling and retention temperatures, could be controlled by tailoring the permeability of the underlying polymer mandrel. Reducing the columnar structure by biasing or other standard techniques, which is required to meet surface finish specifications, might also lead to an appropriate permeability.

Sputtering on a spherical mandrel also provides the option of radially varying the concentration of an opacity modifier, thereby providing additional design flexibility. Finally, it may be possible to co-deposit beryllium and a polymer by sputtering or chemical vapor deposition (CVD) to form a material with desirable permeation characteristics.

It may be possible to form spherical beryllium shells by quenching molten shells generated by dual-orifice drop-tube techniques, perhaps involving alloying mixtures or eutectics. This has never been demonstrated, and would require a substantial development effort. Even if successful, the capsules would most likely have to be filled by a drill-and-plug method.

If it is not sputtered directly onto a thin permeable mandrel or formed directly into a shell from a hollow molten droplet, beryllium made by either bulk or deposition processes would still have to be shaped into spherical shells. This could be done by single-point machining, and hemishells close to those required (1 and 2 mm o.d., polished to a 6-nm rms surface finish in a 100- μ m by 100- μ m patch) have already been fabricated at LANL. Techniques for bonding the resulting hemishells with acceptably small geometric defects and high strengths still must be demonstrated. Several techniques have been successful in the past, particularly vacuum brazing using aluminum, and high-pressure bonding. It is not known whether application of these techniques in the presence of high-pressure DT fill gas will yield a bond of suitable strength. If not, other filling techniques must be developed, discussed below.

Filling of beryllium shells requires development, unless they are rendered permeable by methods mentioned earlier or by forming a porous beryllium by sintering very fine powder and infusing the void with a polymer liquid. If none of these methods work, shells have to be bonded or plugged in the presence of the fill gas. Laser welding in the presence of hydrogen is known to cause a rough, porous fillet, and minimizing defects is a real problem. Gluing is also possible but would require development. It carries the same defect problem as other bonding approaches. However, the plug would be of small diameter and the bond long, so strength might be sufficient. If nothing else works, a fill tube may provide a solution. It is anticipated that a suitable fill tube would have a diameter less than 10 μ m, and defect-free, nonleaking bonding of the tube to the capsule would have to be developed.

Designs of boron and boron-carbide capsules have also shown many of the favorable attributes of beryllium capsules. Boron and boron-carbide are also very strong, and relatively thin shells would hold NIF fill pressures. The advantage of boron and boron-carbide over beryllium is that they are transparent in the IR, thereby, allowing fuel layer characterization and fuel-layer enhancement by IR heating. Boron is sputterable, but boron-carbide is more readily sputtered, and pure boron does not appear to have any implosion advantages. A major question is the permeability of sputtered boron-carbide films. In thin layers, they may provide superior permeation barrier to PVA or Al. As thicker shells, they may be diffusion fillable and transportable like current glass shells. Efforts on boron carbide are still in their infancy.

6.1.3 Foam Shells

A low-density foam shell overcoated with a solid ablator layer can form the basis for a liquid or solid-layer cryogenic fuel capsule. The foam acts as a sponge for the fuel, holding a thick (about 100 μm) liquid layer in place against gravity. For solid layers, the shell can be overfilled and frozen; the frozen puddle in the interior will then symmetrize by the beta-layering process. The foam adds high-Z elements to the fuel, thereby requiring increased drive for ignition to overcome energy radiated by the excess electrons. A 5- to 10- μm -thick pure solid layer on the shell interior, or a 20- to 30- μm liquid layer, would mitigate this problem. Foam also decreases the surface roughness on the interior fuel later. If a thin pure liquid layer over the foam were required, it would have to be supported by thermal fields, as discussed in Sec. 6.2.2 below. However, this should be easier than supporting a full-thickness free liquid layer.

Foam shell technology was largely developed initially at ILE.¹⁵ These shells typically are less than 1 mm in diameter and have foam wall thicknesses of less than 40 μm . Briefly the process works as shown in Fig. 6-2. Small droplets of water are microencapsulated by an organic phase having a density closely matched to the aqueous phase. The droplets are formed by a triple-orifice droplet generator, with the internal water phase carried by the inner nozzle, the "oil phase" carried in a surrounding annular nozzle, and a stripping water flow in the outer annular tube. The microencapsulated droplets are suspended in another aqueous phase and are stabilized against coagulation as the foam polymerizes. The solvent impregnated foam shells are collected and the organic solvent and most of the interior water are replaced with toluene. Subsequent solution exchanges remove all the water, and the shells are finally supercritically dried in CO_2 to preserve the structure of the low-density foam shell.

The foam shells must be coated by some method with an ablator. The shells are fragile and tend to pick up surface defects during handling if they are coated by the conventional plasma polymerization process. ILE also developed an interfacial polymerization method to coat the foam shells before supercritical drying, and work is now in progress at LLNL to develop similar methods for coating the resorcinol-formaldehyde shells.

A key problem for application of this technology for NIF scale capsules is that the foam be sufficiently transparent to allow monitoring of the liquid DT layer within.¹⁶ This will require a submicron foam cell size and thus a modification of the published formulations for this foam. Recently reported work¹⁷ along these lines by the ILE group indicates that progress can be made in this area. A different approach to a small cell-sized foam is to use a resorcinol-formaldehyde aerogel based chemistry similar to that developed originally between 1986 and 1990¹⁸ at LLNL. These foam materials are known to have very small cell size and good optical transparencies. They have recently been formed into shells by the same sorts of techniques used for the ILE shells, i.e., a triple-orifice droplet generator.¹⁹ A preliminary resorcinol-formaldehyde shell is shown in Fig. 6-3 against a ruler scale. The transparency is readily apparent.

In addition to producing foam shells of the required size and transparency for use as NIF targets, we also need to develop techniques for applying the outer full-density polymer ablator coating (formed by the interfacial condensation-polymerization technique discussed in Section 6.1.1) at the required thickness and more importantly with

(a)

(b)

70-00-0896-1679pb02

Figure 6-2. Foam shells are produced by a multistep process developed at ILE, Osaka. (a) Formation of foam shell by microencapsulation and polymerization. (b) Full-density overcoats are produced by a polycondensation interfacial reaction.

70-00-0695-1680pb01

Figure 6-3. Resorcinol-formaldehyde foam shells can be produced at densities as low as 50 mg/cm^3 .

the required surface finish. Reproducible, well controlled shell generation and centering techniques will have to be developed also, as discussed in Section 6.1.1.

6.2 Cryogenic Fuel Layers

Baseline NIF targets contain cryogenic fuel layers formed on the interior of the capsules. The interior vapor density for the baseline designs requires that the layers are solid. As discussed in the introduction Section (6.0), the surface of the layer must have a small enough roughness that it satisfies the ignition criteria quadrature sum equation. Current work investigates the surface structure of solid hydrogen ices, including DT. Surface modal spectra adequate for ignition for both plastic and beryllium capsules have been demonstrated in toroidal-cylinder geometries, but we are developing methods to further refine these surfaces to increase confidence and ignition margin. Liquid layers, if they can be stably formed, would have naturally very smooth surfaces, but a yield penalty has to be paid for the necessarily higher interior vapor densities. As a trade-off, these would have smaller convergence ratios due to the larger vapor density. Therefore, they would be less susceptible to unsymmetric drive and to Rayleigh-Taylor instabilities. We have explored methods of forming and characterizing liquid layers, but will complete that work only if they are ultimately needed. The progress with solid

layers has made that less likely.

Cryogenic fuel layers will first be used for direct-drive targets on Omega. Their surface specifications are more stringent than for NIF experiments that come as close as possible to high-efficiency ignition conditions. However, calculations have shown that good experiments can be performed on Omega with solid layers formed by beta-layering (Sec. 6.2.1); they will require a higher adiabat for the implosion than desirable for ignition. These experiments will be performed four-to-five years earlier than on the NIF (1999). The schedule for cryogenic layer development is driven by the need to provide the final techniques in time to complete the detailed engineering of the Omega cryogenic target support systems. Technique and engineering solutions for the Omega cryogenic support will largely map onto the NIF, with changes made for final scaling and hohlraum targets. As mentioned in the Introduction, the National Cryogenic Target Program is planning and executing this work.

The needed cryogenic fuel layer characteristics are summarized in Table 6-2. As for the fuel capsules, the NIF specifications for the fuel layer are that it ignite in simulation calculations, and satisfy the ignition criteria quadrature sum (Sec. 6.0). The maximum allowed surface roughness is dependent on the modal spectra, which can change with substrate and layering conditions. The NIF specifications for DT ice in a polymer capsule (the "PT" design) in Table 2 are representative. They are from a spectrum that has ignited in a set of calculations and gives a DT ice surface contribution of 1/3 to the quadrature sum. The specifications for the beryllium baseline design are just 8/3 of those for the PT, since the PT design has an ignition cliff at 3 μm (the roughness that would just start to ignite if everything else were perfect), while the cliff for the beryllium design is around 8 μm . The Omega specifications are scaled from the NIF specifications.

6.2.1 Solid Layers

Targets that achieve gain and fusion yield will contain tritium. Such targets will form uniform solid layers by the naturally occurring process termed beta-layering, in which the heating from the beta decay of the tritium drives the symmetrization. This

Table 6-2. Cryogenic fuel layer characteristics.

Characteristic	Omega	NIF
Fuel thickness	50–100 μm	50–100 μm
Required accuracy	$\leq 1 \mu\text{m}$	$\leq 1 \mu\text{m}$
Surface finish rms ($l \geq 10$)	$\leq 1000\text{--}6500 \text{\AA}$	$\leq 1.5 \mu\text{m}$ for polymer $\leq 4 \mu\text{m}$ for beryllium
Nonconcentricity ($l = 1$)	$\leq 0.2 \mu\text{m}$	$\leq 0.25 \mu\text{m}$ for polymer $\leq 0.7 \mu\text{m}$ for beryllium
Inside surface sphericity rms ($l < 10$)	$\leq 600\text{--}4000 \text{\AA}$	$\leq 0.9 \mu\text{m}$ for polymer $\leq 2.4 \mu\text{m}$ for beryllium
Temperature control	$\leq 0.2 \text{ K}$	$\leq 0.2 \text{ K}$

process has been studied for several years at LANL²⁰ and at LLNL,²¹ and the "macroscopics" of the process are now well understood, including the characteristic time constant and how the He^3 that arises from the beta-decay of tritium affects it. The remaining question is ultimate surface morphology, and whether it can be controlled. In addition to measurement of surface profiles in cylinders and hemispheres,²² more fundamental studies are being made of the growth of solid hydrogen layers from the liquid and vapor phases, including effects of substrate, thermal treatment, and methods of adding heating power to the interior vapor or solid phases. Such added heat has been found to improve the solid surface in experiments on both planar samples, and in cylindrical toroids. We are presently exploring the possibility of heating the interior vapor in a capsule by "Joule heating," i.e., driving the small electron density that results from the beta-decay of the tritium by large high-frequency electric fields. Calculations and experiments show that a 2000 V/cm field will heat the vapor in baseline NIF target designs sufficiently to smooth the surface to on the order of 0.5 μm rms. Adding to the bulk heating rate of the solid itself may also smooth the layer, since it would amplify the temperature difference between a high and a low spot on the solid hydrogen surface, thus driving the evaporation-recondensation process. Infrared pumping of collision induced vibration rotation bands in the solid provides this heating in D_2 or HD, or increases the heat generation rate of DT. We have determined the heat generation from infrared absorption by measuring the redistribution time constant of HD and D_2 contained inside a sapphire sample cell during IR pumping. Figure 6-4 shows solid HD at 15 K in a sapphire sample cell during irradiation with 11 mW of 2.57- μm light. From left to right, just after freezing and before IR heating, after IR heating for 5 minutes, and after IR heating for 14 minutes. The dark vertical bands are refractive effects from the cylindrical hole and hide a large portion of the HD ice. The distance from the top to bottom of the cell including windows is 5 mm. From the time constants, τ , measured in these experiments we calculate a heat generation rate, Q , from $\tau = L\rho/Q$, where L is the latent heat and ρ is the solid density. Figure 6-5 shows measured ("B") and calculated (bold line) redistribution time constants and the average heat generation rate ("E") and thin line) versus incident flux for HD. These data show that we can produce a heat generation rate from IR heating at least 10 $\times$ the DT value. Experiments are underway to measure the effect of this increased bulk heating on the surface roughness of HD and D_2 .

If a smoothed surface degrades in a time short compared with its time in the target chamber prior to a shot, smoothing techniques may have to be implemented in the chamber. Experiments on smoothing D_2 on flat substrates using an impressed heat flux showed that the smoothed surfaces remained for times of order hours. Similar results are expected in spherical fuel capsules.

We have also seen that thin D_2 layers grown on top of 100- μm thick resorcinol-formaldehyde foam (the same type described in Section 6.1.3) that is filled with solid D_2 , have surfaces that are considerably smoother than 100- μm thick layers without the foam present. This leads us to believe that beta layers formed inside resorcinol-formaldehyde foam shells will be viable ignition targets.

Prior to experiments with DT, we anticipate experiments will be done with D_2 or HD filled targets in the early phases of NIF. We anticipate similar targets in the early phases of NIF experiments. Absence of tritium obviously precludes beta layering in

Figure 6-4. Solid HD at 15 K in a sapphire sample cell during irradiation with 11 mW at 2.57- μm light.

these cases. Formation of solid layers will depend upon finding a substitute internal heat source to symmetrize and smooth the fuels. Such a substitute could be the infrared absorption discussed earlier, but this would be limited to transparent shells.

Figure 6-5. Measured ("B") and calculated redistribution time constants and average heat generation rate ("E") versus incident flux for HD.

6.2.2 Liquid Layers

The only method for supporting symmetric liquid fuel layers on the interior of spherical shells is by impressing a thermal field on the target which drives thermo-capillary flows. This process, in the context of cryogenic ICF targets, has been termed the "thermal gradient" technique. It has been explored experimentally in small spheres²³ (several hundred micron diameters), and current work addresses scaling to Omega Upgrade and NIF sizes.²⁴ A steady-state theoretical model for stable flows has been developed, and numerical solutions to the coupled model equations are in progress. The model will be used to guide experiments and to explore limits and instabilities in the technique. However, experiments have shown that thermo-mechanical instabilities are very easy to excite with this technique, particularly at thicker layers. Success of application would depend upon controlling these instabilities.

The magnitude of the thermal gradient, or equivalently the power flowing through the capsule, is much larger for pure component liquid hydrogens than for isotopic mixtures. DT fuels naturally form ternary mixtures. HD mixtures should behave similarly to DT. Pure D₂ is presently thought to require unphysical thermal gradients. Our approach to the pure liquid problem is to support 90% of the liquid in a low-density foam shell (as discussed in Sec. 6.1.3) with a thin, free-flowing layer inside of this. The thin layer, by calculation, should be supportable by physically realizable thermal gradients.

6.3 Hohltraums

6.3.1 Cryogenic Environment Control

Hohltraums must be engineered that will provide the necessary cryogenic environments for support of the fuel layers, i.e., stable thermal gradients for liquid layers, and isothermal environments for beta layering. This is a difficult engineering problem, so we are exploring two options for cooling the hohltraums. The first involves active cooling by supercritical helium flowing through small capillaries in thermal contact with the hohltraum. Such a hohltraum is seen in Fig. 6-6. It would be optimal for the capillaries to be formed into the body of the hohltraum for ease of assembly and maximum heat transfer, but a method for doing this must be developed. A second method is by thermal conduction through the hohltraum mounting post.

Isothermal environments will require shaping of the hohltraum isotherms by heaters affixed to the hohltraum wall, as in Fig. 6-7. For such isotherm tailoring, attention will have to be given to the hohltraum material thermal conductivity. Gold, such as is used for Nova experiments and is envisioned for the NIF, may have too high a thermal conductivity. On the other hand, the material cannot be chosen without regard to neutron activation or debris generation. A segmented composite wall may eventually be required.

Nonisothermal environments are required for liquid layers supported by thermal gradients, as discussed in Sec. 6.2.2. These environments may be provided by differential gas flows in the hohltraum or differential heating of the hohltraum walls. We are also

exploring differentially heating the capsule by transporting UV to the hohlraum interior by optical fibers.

6.3.2 Experimental Compatibility Including Filling

Cryogenic hohlraum materials must be chosen to reduce debris and activation, yet must have the appropriate thermal properties for environment control. A variety of materials can be produced using either electroplating or CVD techniques. Hohlräume must be designed to contain possible gases, such as helium-hydrogen mixtures, which prevent wall blow-in during the laser pulse. These gases would also provide thermal contact between the hohlraum and the capsule. Gas containment requires low-mass, low atomic number windows, as in Fig. 6-7, so that effects on the hohlraum dynamics will be minimized. The windows may require a thin (few hundred angstroms) coating of a metal such as aluminum to reduce the infrared load on the capsule, and to act as a diffusion barrier. This would allow filling the interior of the hohlraum with the capsule-permeating high-pressure DT, while surrounding the hohlraum with an equal pressure of a different gas to maintain a small pressure differential across the fragile

70-00-0695-1681pb01

Figure 6-6. Active cooling by supercritical helium flowing through small capillaries in thermal contact with the hohlraum.

70-00-0695-1682pb01

Figure 6-7. Shaping of hohlraum isotherms by heaters affixed to the hohlraum wall.

windows. This would greatly aid the capsule filling process, described in Sec. 6.4.1. The hohlraums must also provide diagnostic access or incorporate diagnostic features, such as shock break-out witness plates for drive determination for ICF experiments. The hohlraums must additionally be compatible with the high-pressure fill system discussed in Sec. 6.4.1. The fill system must accommodate the attached coolant capillaries or interior hohlraum gas fill lines. Making these hohlraums is a challenging task, and concepts for such hohlraums and filling procedures are being developed and will be pursued to prototype stages.

As discussed in Sec. 6.4.1, NIF capsules, particularly polymer capsules, may not be able to contain their fill pressures, which can be as high as 300–350 atm at room temperature. These are precariously close to the capsule burst pressure, so insertion into the hohlraum would have to be done at cryogenic temperatures, after the fill pressure is reduced to acceptable levels by cooling. which may be complicated by the hohlraum having to be sealed. If a small leak rate can be tolerated, a “snap-together” hohlraum could be envisioned. This arrangement would also decouple the layer improvement implementation techniques (Sec. 6.2.1) from the hohlraum design.

6.3.3 Noncryo Hohltraums

The exact designs and specifications for NIF hohltraums have not been finalized, and some developments may be necessary. For instance, the hohltraum material might be lead to reduce activation, or may be an alloy or other metallic mixture to control the x-ray spectrum. Early experiments will be devoted to hohltraum drive characterization, which may require spectroscopic diagnostic additives in the hohltraum walls. These would also benefit from diagnostic packages such as shock breakout wedges fabricated directly into the hohltraum wall. Later experiments to measure drive symmetry will depend upon imaging imploding capsules. Pinhole arrays fabricated in the hohltraum walls would reduce debris and shrapnel generation from these types of experiments.

6.4 Cryogenic Target Support Systems

Preparing a cryogenic target for a shot will involve filling it and cooling it in the fill system, transporting it from the fill system to the target chamber, placing it into a cryogenic target inserter and positioner, and maintaining the cryogenic environment up to shot time. If higher strength polymer capsules can be developed, from materials like polyimides, for instance, the cryogenic fill system could be eliminated, as could the cryogenic transport step. For beryllium capsules, the strength is most likely high enough, but radically different filling procedures would most likely be needed, as discussed in Sec. 6.1.2.

6.4.1 Tritium Fill System

For the baseline polymer capsule targets, fill pressures may exceed the capsule burst pressures. Also, the fill gas may permeate out of the capsule due to radiation damage of the permeation barrier. Therefore the capsules may have to be filled by permeation after assembly into the hohltraums and cooled to cryogenic temperatures before removal from the filling system. A system very similar to this type, but for direct-drive targets, is being developed for the Omega Upgrade system by General Atomics, and the technology may readily transfer to the NIF. A major concern is the possibility of a much larger high-pressure fill volume due to the presence of the hohltraum. Assuming the room-temperature equivalent fill pressure is 500 atm (an upper limit), and that the tritium inventory is limited to 5 g, the maximum volume of all of the high-pressure parts of the system would be about 75 cm³. If the entire hohltraum volume and any volume around it have to be temporarily filled to the same density as the desired capsule fill, then this might consume a significant amount of the inventory. Targets filled after assembly in this manner will be strongly tritium contaminated and would require special handling. If the hohltraum interior is sealed from its exterior, which it would be if it had thin windows in the laser entrance holes and over any diagnostic ports (discussed in Sec. 6.3.2), then the interior might be exposed to the high-pressure DT separately. A NIF hohltraum has a volume of about 0.2 cm³, which if filled to the capsule fuel density contains less than 100 Ci of tritium. If the capsule could be filled before assembling into the cryogenic hohltraum, the problem of a large high-pressure fill vol-

ume would also be eliminated. This would require especially developed hohlraums and cryogenic assembly procedures (discussed in Sec. 6.3.2). Both of these last two options would also reduce or eliminate the tritium contamination problem. Other problems may accompany providing a filled capsule for a cryogenic hohlraum, particularly if it is actively cooled by high-pressure helium circulating through attached tubes (discussed in Secs. 6.3.1 and 6.3.2).

6.4.2 Transport System

The filling system will be located away from the NIF experimental area. This will assure that any tritium-related problem or accident will not impact operation of the entire NIF facility. Whether the distance is near or far, the filled and cryogenically cooled targets will have to be transported to the target chamber and installed in the cryogenic target inserter. The necessary technology must be designed and constructed. We anticipate that the technology for doing this will be very similar to that being developed by General Atomics for the Omega Upgrade system.

6.4.3 Solid Layer Formation and Characterization

Solid layers formed by the techniques discussed in Sec. 6.2.1 will require systems for providing the necessary environmental control, heat sources, and characterization capabilities. These may be utilized before or after the transport step, above. Again, we anticipate building on the technology being developed and engineered at General Atomics for Omega Upgrade. Differences may arise due to the presence of the hohlraums for indirect drive.

6.4.4 Inserter/Positioner

Cryogenic targets will require a cryogenic target inserter and positioner on the target chamber. Its function will be to maintain the cryogenic layer integrity while awaiting the shot. Liquid and solid layers will have different requirements, therefore, the inserter/positioner will include liquid and solid support modules that will "plug in" to a common cryogenic platform. We will extend the technology that General Atomics is developing for Omega Upgrade, but we anticipate significant differences because of the horizontal orientation of the inserter/positioner, and because of the presence of hohlraums around the fuel capsules.

6.5 Characterization

The techniques currently used to characterize target components and assemblies will be applicable to NIF scale targets, e.g., interferometry for shell uniformity, radiography for shell layer thicknesses, atomic force microscopy for shell surfaces, metrology stations for assembled targets, etc. However, developments will be needed for characterizing cryogenic fuel layers (Sec. 6.2) and for foam shells (Sec. 6.1.3).

In general, the requirements for characterization are as much as an order of magnitude tighter than the requirements for fabrication. Characterization requirements are shown in Table 6-3.

6.5.1 Fuel Layers

Liquid cryogenic fuel layers will have to be formed and maintained inside the target chamber. Presently, we believe that the sensitivity of the thermal gradient technique requires that the layer thickness and uniformity be determined right up to shot time. This will most likely involve some type of optical interferometry in real time. Such interferometric methods have been developed and applied to thin fuel layers, and modifications for thicker layers such as needed for the NIF have been prototyped. In the case of opaque shells such as beryllium, measurements to the extent they are possible, will have to be based upon x ray or other penetrating radiations or fields. The appropriate techniques must be developed and systems engineered for inclusion in the target chamber.

Solid layers will be formed and characterized outside the target chamber. As for liquids, methods for rapid determination of layer thickness, uniformity (including composition), and surface morphology must be developed. Again, we anticipate that optical phase-mapping interferometry will play a major role, although this may have to be with white light in a convergent geometry to measure the surface roughness power spectrum. Special methods for opaque shells (e.g., beryllium) must also be developed. If surface roughness changes in a time short compared with the time in the chamber prior to a shot, then real-time *in situ* characterization methods will be needed similar to liquid layers above. Methods such as Magnetic Resonance Imaging can provide some imaging and composition measurements in nonconductive shells. However, considerable enhancements over current state-of-the-art resolution would have to be developed, and measurements could take times of the order of hours.

6.5.2 Foam Surfaces, Density Uniformity

Foam shells that support liquid fuel layers will have to be characterized for density, cell size, density uniformity, and surface modes at long wavelengths. Some of these measurements will have to be made after the foam shells are overcoated (Sec. 6.1.3).

6.6 Targets for Existing Facilities

6.6.1 Nova

We anticipate that Nova experiments will continue at least through FY1998. This will include experiments on ICF, weapons physics, laser-matter interaction, and radiation and debris effects on materials. We will continue to develop, fabricate, characterize, and assemble target components for these experiments. For the past several years, the total targets shot per year has been 1100–1300. This number may decline in the next few years, but not by much. It is also possible that we would supply some targets or components for experiments on Omega Upgrade. Likewise, we may supply targets for academic experimenters wishing to do work on the Nova Laser.

Table 6-3. Characterization requirements.

Characteristic	Nova	Omega	NIF
Shell diameter	200–600 μm	700–1400 μm	1000–3000 μm
Required accuracy	1 %	<0.5 %	<0.5 %
Shell thickness	3–5 μm	5–25 μm	5–25 μm
Required accuracy	1 μm	1 μm	1 μm
PVA barrier layer thickness	2–6 μm	(1, 2)	3–5 μm (2)
Required accuracy	1 μm		1 μm
Shine-through barrier	--	(3)	?
Ablation layer thickness	15–80 μm	25–100 μm	50–200 μm
Required accuracy	2 μm	1 μm	1 μm
Required nonconcentricity	<2 %	<2 %	<2 %
Fuel layer thickness (4)	--	50–100 μm	50–100 μm
Required accuracy	--	1 μm	1 μm
Required nonconcentricity	--	<1 %	<1 %
Capsule accuracy - External			
Required nonsphericity	<1 %	<1 %	<1 %
Required surface finish	<100 Å	<100 Å	<150 Å
Capsule accuracy - Internal			
Required nonsphericity	--	<1 %	<1 %
Required surface finish	--	<100 Å	<1000 Å

(1) Gas barrier layer will probably be 50 Å of Al - sufficiently transparent for characterization.

(2) Noncryo targets only

(3) Shine-through barrier might be thin layer of Al - opaque to optical characterization, hence will require modified characterization techniques

(4) Under conditions for which the fuel layer is to be liquid, it may be supported by foam which will cause light scattering and interfere with optical characterization. Techniques must be modified to compensate.

6.6.2. Trident Targets

The Trident laser at Los Alamos represents an opportunity to test target concepts that do not involve implosions. Its fast turn-around and accessible target chamber make it an ideal driver to test diagnostic concepts, as they are integrated into the targets themselves.

6.7 NIF Target Production

Two-to-three years prior to the first shots on the NIF, we will have to begin preparing facilities for target production. This will largely be a process of implementing developed technologies into well-engineered production stations and capabilities, including clean-rooms, automated processes, new assembly stations if needed, etc.

The anticipated NIF target production rate (including targets for development, characterization, and other "non-shot" purposes) is expected to be several thousand per year. Approximately 1000 targets per year will actually be shot in NIF.

As the NIF approaches its ignition goal, a significant number of these shots will contain DT fuel. A NIF target with megajoule-range yield may contain up to 4 Ci of tritium. As discussed in Sec. 6.4.1, a fill system may have to be developed that has a cryogenic capability. If the fill system is located far from the NIF, a safe and certified method for transporting the targets will be needed.

References

1. NIF CDR Vol. 2 UCRL-PROP-117093 Vol.2/ NIF-LLNL-94-113/L-1693-1 sect. 3.1.2, p. 3-7
2. Ibid., p. 3-9.
3. R. Cook, G. E. Overturf, S. R. Buckley, and R. McEachern, *J. Vac. Sci. Technol.* **A12**, 1275 (1994); T. R. Dittrich, B. A. Hammel, C. J. Keane, R. McEachern, R. E. Turner, S. W. Haan, and L. J. Suter, *Phys. Rev. Lett.* **73**, 2324 (1994).
4. A. K. Burnham, J. Z. Grens and E. Lilley, *J. Vac. Soc. Technol.* **A5**, 3417 (1987); R. S. Upadhye and J. G. Wilder, *1991 ICF Annual Report*, LLNL UCRL-LR-105820-91 (1991).
5. S. A. Letts, D. W. Myers, L. A. Witt, *J. Vac. Sci. Technol.* **19**, 739 (1981).
6. S. A. Letts, M. D. Saculla, F. M. Kong, S. R. Buckley, C. W. Price, E. F. Lindsey, C. E. Moore, *1991 ICF Annual Report*, LLNL UCRL-LR-105820-91 (1991); R. Brusasco, M. Saculla, and R. Cook, *J. Vac. Sci. Technol.* **A13**, 948 (1995).
7. K. R. Amundson, D. W. Blousfield, and D. S. Soong, *J. Appl. Phys.* **59**, 2306 (1986).
8. G.W. Collins, S.A. Letts, E.M. Fearon, R.L. McEachern, and T.P. Bernat, *Phys. Rev. Letters* **73**, 708 (1994)

9. A. A. Akunets, V. M. Dorogotovtsev, Y. A. Merkuliev, and S. A. Startsev, and R. Cook, "Production of Hollow Microspheres from Solid Plastic Granules," to be published in *Fusion Technology*.
10. Yu. A. Merkuliev, V. M. Dorogotovtsev, S. M. Tolokonnikov, A. A. Akunets, V. S. Bushnev, A. I. Gromov, A. I. Isakov, A. I. Nikitenko, S. A. Startsev, and R. C. Cook, *Material Research Society Symposium Proceedings*, Vol. 372, p. 119.
11. T. Norimatsu, Y. Kato, S. Nakai, and U. Kubo, *J. Vac. Sci. Technol.* **A7**, 1165 (1989).
12. T. Boone, L. Cheung, D. Nelson, D. Soane, G. Wilemski, and R. Cook, *Material Research Society Symposium Proceedings*, Vol. 372, p. 193; G. Wilemski, T Boone, L. Cheung, D. Nelson, and R. Cook, "Prediction of Phase Separation during the Drying of Polymer Shells," to be published in *Fusion Technology*.
13. S. A. Letts, E. M. Fearon, S. R. Buckley, M. D. Saculla, L. M. Allison, and R. C. Cook, *Material Research Society Symposium Proceedings*, Vol. 372, p. 125.
14. R.B.Botham, G.L. Ball, and I.O. Salyer, "Investigation of a Laboratory Process for Preparing Polyethylene Hollow Shells," LLNL UCRL 13679, 1975.
15. See reference 14.
16. G. E. Overturf, R. Reibold, S. R. Buckley, and S. A. Letts, and R. Cook, *J. Vac. Soc. Technol.* **A13**, 2564 (1995).
17. M. Takagi, T. Norimatsu, Y. Izawa, and S. Nakai, *Material Research Society Symposium Proceedings*, Vol. 372, p. 199.
18. F. M. Kong, S. R. Buckley, C. L. Giles, B. L. Haendler, L. M. Hair, S. A. Letts, G. E. Overturf, C. W. Price, and R. C. Cook, "Low-Density Carbonized Resorcinol-Formaldehyde Foams," LLNL UCRL-LR-106946 (1991); R. W. Pekala, C. T. Alviso, F. M. Kong, and S. S. Hulsey, *J. Non-Cryst. Solids* **145**, 90 (1992); R. W. Pekala and D. W. Schaefer, *Macromolecules* **26**, 5487 (1993); R. W. Pekala and L. W. Hrubesh, *J. Mat. Res.* **9**, 731 (1994).
19. G. E. Overturf, R. Cook, S. A. Letts, S. R. Buckley, M. R. McClellan, D. Schroen-Carey, "Resorcinal-Formaldehyde Foam Shell Targets for ICF," to be published in *Fusion Technology*.
20. J. K. Hoffer and L. R. Foreman, *Phys. Rev. Lett.*, **60**, 1310(1989); J. K. Hoffer and L. R. Foreman, *J. Vac. Sci. Technol.* **A 7** (3), 1161 (1989).
21. T. P. Bernat, E. R. Mapoles, and J. J. Sanchez, "Temperature- and Age Dependence of Redistribution Rates of Frozen Deuterium-Tritium", *1991 ICF Annual Report*, UCRL-LR-105820-91, p. 57, (1992).
22. G. W. Collins E. R. Mapoles, J. Hoffer, J. Simpson, J. Sanchez, R. Bell, W. Unites, "Solid Hydrogen Surfaces", *1993 ICF Annual Report*, UCRL-LR-105820-93, p. 81.
23. K. Kim, L.C. Mok, M. Erlenborn, and T. P. Bernat, "Non contact thermal gradient method for fabrication of uniform cryogenic inertial fusion target," *J. Vac. Sci. Techol.* **A**, Vol.1 no. 2, p. 1196 (1985).
24. J. J. Sanchez, E. R. Mapoles, T. P. Bernat, W. Geidt, J. Pipes, J. Hoffer, J Simpson, "Formation of H₂-D₂ liquid layers in 2 mm i.d. capsules using the thermal gradient technique," *1994 ICF Annual Report*, UCRL-LR-105820-94, p 117.
25. D. C. Wilson and N. M. Hoffman, *Bull. APS* **40**, 1695 (1995).

7.0 Target Physics Experiments

Target physics experiments must continue for the foreseeable future in four broad areas: convergent hydrodynamics and mix; hohlraum dynamics; laser-plasma instability; and advanced concepts. Although there has been significant and continued progress in all these areas, on which the expectation of NIF ignition is based, there are many important aspects for which the understanding is phenomenological, not fundamental. For the NIF project, an incomplete understanding in any of these areas increases the needed margin of safety and the likelihood of delays in attaining ignition. In addition, advanced ignition concepts, if ultimately successful, could result in significantly more fusion yield from the NIF. Considering the expected relative expense and complication of NIF shots, it is wise to invest in target physics experiments at the Nova, Omega, and Trident lasers, and PBFA pulsed-power accelerators. The choice of facility for these experiments should be guided by their capabilities and appropriateness.

7.1 Convergent Hydrodynamics and Mix

A important activity after completion of the work outlined in the Nova Technical Contract (NTC) is the study of hydrodynamic mix in both planar and convergent geometries. Nova experiments, which address the details of the growth of target imperfections, are *essential* in order for us to set realistic goals for target fabrication activities in the years before NIF experiments. Furthermore, Nova experiments that address the physics of hydrodynamics and implosions are necessary to benchmark new 3-D code development. This work, which will include studies of instability growth for high in-flight aspect ratio (IFAR) implosions and the growth of inner-surface perturbations, is essential to guide us in our choice of the NIF target ablator (CH or Be) as well as the surface-finish requirements for tritium layering. These experiments may enable us to pursue more aggressive target designs on the NIF, accelerating our progress toward ignition. If the decade before NIF operation is to be productive in the areas of target fabrication and design, it is essential for the experimental program to pursue an aggressive campaign of hydrodynamic research.

The Nova hydrodynamically equivalent physics (HEP) program (HEP 1-4) has focused on detailed measurements of Rayleigh-Taylor (RT) growth in planar geometry and indirect measurements of growth in implosions at modest convergence. Work after the NTC will focus on high-growth-factor implosions in capsules with high convergence (>10), detailed studies of the growth of surface imperfections in both planar foils and implosions, and development of new techniques for measuring mix in convergent geometries. A low level of effort will continue on the stability of directly driven targets.

Figure 7.1-1 is the planning schedule for convergent hydrodynamics and mix development activities.

WBS	CS&T activities and milestones	1995	1996	1997	1998	1999	2000	2001
7.1	Mix experiments							
7.1.1	Nova HEP-5 experiments							
	Convergent single & multiple mode							
7.1.2	Inside growth							
7.1.3	Limb imagery							
	Develop spectroscopy							
	Develop x-ray backlighting							
	Cylindrical implosions							
	CD/T mix							
	Double shells & new concepts							
7.1.4	Planar hydro							
7.1.5	Direct drive							

Figure 7.1-1. Planning schedule for convergent hydrodynamics and mix development activities.

7.1.1 Convergence Scaling

To isolate the effects of mix and asymmetry, Nova implosion experiments to date have limited the studies of high-growth-factor mix to targets with moderate convergence (~ 10). In the period after the NTC, we will perform a convergence scaling experiment, where the capsule convergence is systematically increased by lowering the fill pressure. The effects of asymmetry will be reduced by using smaller capsules, and possibly hohlraum design modifications. The capsules will use a CH ablator doped with germanium or bromine as an x-ray preheat shield to achieve high pusher areal density and thus high growth factors. The resulting mix will be indirectly measured by various techniques: x-ray spectroscopic studies of relative emission intensities of dopant materials added to the fuel and pusher, neutron emission due to mix of deuterated plastic shells with the fuel, secondary neutron spectroscopy to study triton slowing in the mixed fuel, primary neutron yield, and ion temperature. The development of high-speed techniques for measuring neutron burn width and high-resolution neutron images will provide additional data, constraining our modeling and furthering our understanding.

7.1.2 Detailed Studies

With the development of laser ablation has come the ability to produce capsules with intentionally perturbed surfaces with a desired modal spectrum. This powerful technique enables us to investigate a range of important hydrodynamic issues in a convergent geometry, including growth of a single bump, growth and saturation of single modes, and mode coupling. These studies will directly impact the target specifications for the NIF and will further our understanding of capsule hydrodynamics, allowing us to push the hydrodynamic limits of implosions. They are essential to provide a testbed for new 3-D modeling of instability growth.

Controlled studies of the RT growth of perturbations on the inside of a target have not been performed, because fabrication and characterization are difficult. Implosions in cylindrical geometry, with its easier access for fabrication and diagnosis, will play an important role here. A newly developed technique for capsule fabrication, whereby shells are formed over a plastic mandrel that is later sublimed away, allow for the possibility of controlled inside-surface variation, because the mandrel could be laser ablated prior to coating. The technique might also allow fabrication of capsules with buried pusher dopants, thus increasing spectroscopic sensitivity to moderate amounts of mix. An understanding of inside growth, which is not ablatively stabilized, will have a *direct* impact on the inner-surface-finish requirements for the tritium-layered targets necessary for NIF experiments.

7.1.3 New Techniques

A critical element in CS&T activity is the continued development of techniques for studying mix in convergent geometries. These techniques, which can be developed and tested on Nova, will be invaluable for tuning the advanced implosions on the NIF to reach ignition. Some of these techniques are described below.

When the pusher is doped with a high-Z material and the fuel is not doped, Nova experiments have shown "limb brightened" x-ray images that are dominated by the region of the pusher, which is hot. Time-resolved limb images during the implosion provide a means of inferring the trajectory of pusher material that has mixed into the hot fuel. This technique has been demonstrated on Nova, and further development will make it very useful for NIF experiments. Measurements of limb trajectories for capsules with varying RT growth factors must be made and compared with modeling.

In order to investigate the compressed-fuel conditions in NIF targets, we must extend our current x-ray spectroscopic techniques for measuring fuel density and temperature to higher photon energy, due to the higher pusher optical depth for NIF targets. In Nova experiments, xenon has been used successfully as a fuel dopant to infer electron temperature. Additional experiments on Nova are necessary to cross-calibrate proposed line-broadening measurements of fuel density (Xe 4d-2p) to the currently preferred technique (Ar 1s²-1s3p). In addition, significant advances in target-fabrication techniques have provided the possibility of a range of high-Z pusher dopants for spectroscopic measurements of mix. These should be explored before they are required for NIF experiments. Spectroscopic techniques for inferring mix in imploded capsules may distinguish between atomic mix and bubble-and-spike formation. For example, the formation of bubbles and spikes leads to transparent "holes" opening up in the pusher, which can enhance emission from the fuel dopant. This effect, may be a useful indicator of mix. Second, the inward velocity of spikes may yield measurable bulk motion Doppler broadening of pusher-dopant resonance lines. To constrain our modeling of these difficult 3-D effects, we must investigate them in carefully controlled experiments.

X-ray backlighting has been exploited extensively in planar and cylindrical hydrodynamics experiments on Nova, but we have not used this powerful technique in detailed studies of spherically convergent implosions. With x-ray backlighting, we have directly observed the RT growth of a "belt" of bumps growing on the outside of a cylindrical "capsule," and on the inside after perturbations have fed through from the

outside. Extending these techniques to a spherical geometry should allow us to study mix in a regime where convergence plays an even greater role. In addition, quantitative measurements of the pusher density profile, in flight, are possible. These techniques could be extended to higher photon energy (>7 keV) so that higher-areal-density materials could be probed, once microchannel plate detectors with enhanced-sensitivity thin-film photocathodes are developed.

Direct measurements of RT growth in a spherically convergent geometry are difficult. Cylindrical implosions, which offer the possibility of diagnosing the target axially, have demonstrated that direct measurements of growth in a convergent geometry are possible. If these measurements could be extended to high convergence, they would provide an excellent opportunity for the study of unstabilized inside growth.

Recent advances in target fabrication have allowed plastic capsules to be filled with tritium. We should investigate the possibility of inferring mix from the D-T neutron yield in deuterated plastic capsules.

7.1.4 Other Hydrodynamics

Hydrodynamics experiments in a planar geometry probably will continue to be the most accurate, unambiguous, and quantitative means of testing the modeling of instability growth. Basic questions remain that are best answered in a planar geometry. The 3-D multimode RT growth and saturation at the ablation front is still a crucial question in our modeling of capsule performance. A new 3-D code has been developed to study this problem, but the code needs to be thoroughly benchmarked against experiment before being used for capsule simulations. The RT growth of short-wavelength perturbations on the outer surface of a capsule is stabilized by ablation. This is not the case, however, for perturbations at a buried interface or on the inner surface of a capsule. To complete our understanding of the ICF-related RT growth, we must investigate these issues. They can be most easily studied in planar experiments, diagnosed by x-ray radiography.

To complete the ablation-front instability work, an extended drive is being designed to enhance the overall RT growth. In this more nearly steady-state acceleration, the indirect-drive dispersion curve will be mapped out, the differences between 2-D vs 3-D growth will be established, and the 3-D multimode saturation (Haan model) will be tested.

Prior to shock breakout during the foot of the shaped drive, Richtmyer-Meshkov (RM)-like perturbation growth due to rippled-shock dynamics is important. The rippled-shock evolution can involve phase oscillations and is sensitive to the material equation of state (EOS). The result of this RM-like growth at shock breakout then exponentiates during the RT phase. Experiments to study the shock dynamics during the foot of the pulse will be conducted initially on the Helen laser at the AWE facility in Aldermaston, England, which can generate 1–10 Mbar shocks in a 2-beam indirect-drive configuration. If needed, follow-up experiments on Nova could be conducted.

Rayleigh-Taylor unstable embedded interfaces can occur in layered capsule designs. At such interfaces remote from the ablation front, the only stabilization mechanism is due to the density gradient. Short wavelength perturbations are expected to grow more

strongly, and nonlinear mode-coupling effects could be quite pronounced. Experiments in collaboration with Defense Sciences Program to measure the evolution of single-mode perturbations at this RT-unstable interface have started, with the goal of mapping out the classical but compressible RT dispersion curve. Generalizing to 2-D and 3-D multimode experiments should be straightforward.

A quantitative measurement of feedthrough from growth at the ablation front to an inner layer also should be examined. This could be achieved by imposing perturbations on a radiographically transparent ablator material, which is backed by an opaque material. When the perturbations feed through to the opaque layer, they could be diagnosed with the appropriate energy backlighter.

Finally, growth of a perturbed surface during deceleration should be considered by tamping the back side of an RT-unstable foil with foam or other lower-density material. A final x-ray-transparent stopper foil may also be needed. It is expected that nonlinear effects will be critical here as well, since the only stabilization mechanism will be the density gradient. Experiments of this type are currently being designed in collaboration with Defense Sciences Program and UC-Santa Cruz.

7.2 Hohlraum Experiments

Experiments for understanding hohlraum performance can be separated loosely into two categories related to their impact on the Target Physics Program effort. The first category is experiments that provide increased confidence for present NIF target designs. These include experiments to test coupling and symmetry in gas-filled hohlraums. They also include experiments supporting those that have been done for the technical contract, such as laser conversion efficiency in hohlraums, continued albedo experiments, and completing demonstration of time-resolved symmetry techniques. The second category of experiments investigates physical processes that occur in a hohlraum and their effects on its performance. By better understanding issues such as colliding and interpenetrating plasmas, electron transport, role of magnetic fields, and three-dimensional effects on symmetry, target designs with better coupling can be developed more confidently. Also, as simulation capabilities evolve to include more detailed physics, experiments must provide the testbed for their development. These experiments are projected to be the major emphasis in the long term until the NIF nears completion.

Figure 7.2-1 is the planning schedule for advanced hohlraum development activities.

7.2.1 Hohlraum Coupling Limits and Energetics

These experiments will complete work already begun to understand the fundamentals of energy balance in hohlraums and to stress the limits of hohlraum performance. Hohlraum energetics balance x-ray drive produced by the laser driver with energy loss to the hohlraum walls and through laser entrance holes or windows. Initial experiments to investigate x-ray production in hohlraums suggest that it can be significantly different than open-geometry targets. These experiments will continue, including the effects of longer pulse irradiation, gas-fill, liners, and laser-intensity scaling on laser

WBS	CS&T activities and milestones	1995	1996	1997	1998	1999	2000	2001
7.2	Advanced hohlraums							
7.2.1	Hohlraum coupling limits & energetics							
7.2.2	Gas hohlraum symmetry & advanced control techniques							
7.2.3	Time dependent symmetry							
7.2.4	2-D symmetry							
	3-D symmetry							
7.2.5	Colliding & interpenetrating plasmas							
7.2.6	X-ray spectroscopy of plasmas							
7.2.7	Electron transport							
7.2.8	B-field effects on electron transport							
7.2.9	Thomson scattering							
7.2.10	Initial NIF pulse experiments							

Figure 7.2-1. Planning schedule for advance hohlraum development activities.

absorption and x-ray production. The goal of these experiments is to develop confidence that x-ray production can be predicted under a wide range of conditions in hohlraum targets. Energy loss to the hohlraum walls has been studied in a limited range of hohlraum conditions; more work is necessary at the lower (< 150 eV) temperatures. Energy loss to the gas-fill must also be studied. Shock-velocity measurements in a surrogate "witness-ball" capsule will confirm changes in x-ray drive at the capsule. These experiments are planned to be extended to various drive conditions.

The maximum drive obtainable in NIF hohlraums is not well established. High drive in hohlraums can expand the suite of experiments that the NIF can accomplish. Issues such as beam coupling to the wall, plasma filling the hohlraum, or closing the laser entrance hole ultimately could be limiting factors. To understand these limits, experiments will test scaling to smaller size, alternative geometries, and higher albedo wall materials. Issues such as plasma filling and limitations on the size of laser entrance holes also will be studied.

The longer time-scales and larger contrasts in hohlraum temperature for NIF target designs will stress our abilities to measure or infer X-ray drive. Possible complications that might arise include insufficient signal levels, diagnostic hole closure, shadowing and preheating of witness plates. New witness plate materials and/or geometries for shock breakout measurements will need testing, as well as a feasibility demonstration of active shock-sensing techniques at low temperatures.

7.2.2 Symmetry in Gas-Filled Hohlraum and Advanced Control Techniques

Present NIF designs use low-Z gas to retard the gold wall from filling the hohlraum and degrading symmetry. Experiments are under way to study the plasma physics in the underdense plasma from gas-filled hohlraums. Future experiments will test our ability to calculate beam propagation, power-deposition profiles and interface motion in 3-D, and radiation transport in gas-filled hohlraums suitable for implosions. They

would be similar in scope to symmetry experiments done in lined hohlraums where spot motion and implosion symmetry are correlated and compared to calculations.

In addition to beam phasing, several techniques have been suggested for controlling symmetry on the NIF. Experiments have begun on Nova to test one technique using radiation shields to reduce symmetry effects of the laser entrance hole. Other proposals, such as using thinned walls or different materials, have not been tested. The effort in this task is to complete the Nova experiments for testing radiation shields and to demonstrate the effectiveness of other potential symmetry-control techniques, including some that have yet to be invented.

Several potential experiments can be performed on Omega Upgrade to address NIF symmetry issues. Beam phasing is possible because the Omega Upgrade can deliver two or three rings of beams per side into a hohlraum. Design of this experiment is currently under way. Additionally, because Omega Upgrade will have the ability to field cryogenic targets in the late 1990s, experiments that use the actual helium/hydrogen gas mix proposed for the NIF can be fielded. This will give us experience with targets very close in design to the NIF ignition targets.

7.2.3 Development of Time-Dependent Symmetry Techniques

A major effort on the NIF will be devoted to symmetry tuning of the driver pulse. Experiments are in progress to test the effectiveness of several techniques to measure the time-dependent symmetry of the radiation that implodes the capsule. Effort in this task is to complete these experiments in order to be better prepared for the NIF experiments. Effort is also included to test new techniques developed in the future.

Three principal techniques are under development for time-resolved symmetry measurements: 1) implosion-sampling techniques, one of which is known as "symmetry capsules"; 2) reemission from surrogate targets placed in the hohlraum environment; and 3) "witness balls" utilizing the observation of shocks created by the hohlraum field. There has been great success in the development of these techniques at Nova but a significant series of experiments on NIF itself will be required to confirm their operation in the NIF environment.

After a brief period of testing and confirming the measurement techniques; they will be applied directly to symmetry-tuning experiments. The "symmetry capsule" implosion-sampling technique is the most straightforward extension of the extensive implosion work that has been done at Nova. For this reason we would anticipate that it would be utilized first to perform the first confirmation that temporally varying symmetry conditions are being controlled as anticipated by the phased-beam system employed on NIF. The reemission method would be eventually employed to confirm symmetry in the early stages of NIF drive (the parameter regime to which it is best suited). When backlighting capability has been fully implemented, the "witness ball" shock trajectory technique could be employed to provide a very complete picture of the temporal variation of symmetry conditions.

7.2.4 3-D Symmetry Tests

A major effort in the target design group is to develop 3-D modeling efforts to better understand details of implosions. Three-dimensional effects may manifest themselves

in asymmetry due to the finite number of beams or effects of diagnostic holes on the implosion. As the computational ability is developed, experiments will test the models and define their accuracy. Only by such synergism can the tool be made into a quantitative predictive tool.

Three-dimensional effects can readily be induced on Nova by decreasing the case-to-capsule ratio. A set of implosion experiments to measure the shape of a 3-D implosion by means of 3-D x-ray imaging will confirm the predictive accuracy of the 3-D code. One key 3-D issue for indirect drive is the number of beams per ring needed for the required symmetry to achieve ignition with high-convergence targets. Experiments on Nova have shown that high convergence is limited because Nova has only 5 beams per ring. Experiments on the Omega-Upgrade, where a larger number of beams per ring are possible, could examine this 3-D issue.

7.2.5 Colliding and Interpenetrating Plasma Experiments

Plasma dynamics in hohlraums include complicated flows such as jetting from the corners of hohlraums, converging plasma on the hohlraum center, and interaction of the capsule with the hohlraum wall. The flowing plasmas can collide and, depending on plasma conditions, the flows may interpenetrate, causing mixing of the plasmas species, or they may stagnate, producing local heating. Interpenetrating plasmas can change local plasma conditions by mixing materials. This can affect such dynamics as laser energy deposition and radiation flow. Stagnating plasmas convert their kinetic energy into thermal energy. This can change the radiation uniformity in hohlraums and can alter plasma flow, producing jetting. In general, present modeling does not treat colliding plasmas correctly. The codes either include only stagnation effects or interpenetration in an ad hoc fashion. Work is under way to treat colliding flows in a more physical fashion. These initial experiments, as well as future ones in converging geometry, will provide data to calibrate modeling predictions, and to develop a better understanding of the most important features of the colliding plasmas.

7.2.6 X-ray Spectroscopy Characterization of Hohlraum Plasmas

Understanding the underdense plasma conditions in hohlraums is important for optimizing their performance. Underdense plasma conditions control laser deposition and refraction, and they influence radiation transport and symmetry. Experiments using x-ray spectroscopy have just begun to diagnose the plasma conditions. The initial experiments use spectral lines from different elements to measure plasma temperature. This effort will be continued to complete characterization in a variety of conditions. In future spectroscopy work, diagnostic techniques for electron density and ion temperature will be developed and applied to hohlraum conditions of interest.

7.2.7 Electron Transport Experiments

Electron transport plays a central role in the heating of underdense plasmas. Recent experiments with gas targets suggest that current models of electron transport may not be accurate. This effort will define experiments to test effects of electron transport and to guide improvements to the electron-transport modeling. Such experiments may be extensions to the present gas target effort where lateral heating is studied versus irradiance. Also x-ray

spectroscopy can be used to probe different parts of the electron distribution to understand details of electron transport.

7.2.8 Magnetic Field Generation in Hohlräume

Magnetic fields may also play a major role in heating the underdense plasmas. To understand their role, a diagnostic technique such as Faraday rotation must be developed, and we must perform a systematic study in NIF-relevant plasma conditions.

A further area of focus will be to study magnetic fields generated by the temperature and density gradients present in ICF plasmas. The plan is to use Faraday rotation of an optical probe beam or Zeeman splitting to investigate and quantify these magnetic fields. By inhibiting thermal conduction, magnetic fields influence temperature distributions and hence SBS, SRS, filamentation, and propagation of laser beams in hohlraums.

7.2.9 Thomson Scattering Characterization of Hohlraum Plasmas

In addition to continuing the experiments described in Section 7.3.1, we expect that part of this work will involve further development of Thomson scattering, discussed in Section 4.5.3. That section proposes developing Thomson scattering as a technique for making highly localized measurements of plasma temperature and density in large-scale hohlraums. In Thomson scattering, a probe beam scatters off of thermal-electron density fluctuations in a plasma. The two types of fluctuation in unmagnetized plasmas are ion acoustic waves (low frequency) and electron plasma waves (high frequency). Scatter from the acoustic waves is typically used to diagnose thermal plasmas because the scattered powers are typically several orders of magnitude larger. However, in the case of SRS, the electron-plasma wave fluctuations are driven to levels far exceeding thermal levels, and the Thomson-scattered powers become detectable (indeed the observed Raman-scattered light is nothing more than Thomson scattering of the light that drives the instability). The scattering geometry (i.e., angle) is chosen so that, through frequency and wave-number matching, a perturbation of known wavelength is probed. For ion acoustic fluctuations, the scattered spectrum is numerically fitted, with density and temperature being the two fit parameters.

7.2.10 Initial NIF Pulse Experiments

The NIF pulse has a long, low-intensity initial irradiation followed by a shorter high-intensity drive. The initial part of the pulse is used to heat the low-Z gas and to initiate the shaped pressure pulse on the capsule. The hohlraum and capsule physics during this time is expected to be more benign than for the high-intensity portion of the pulse because laser-plasma interactions should be less important. Also, changes in the initial part of the NIF pulse required due to uncertainties in the physics will not significantly impact the overall energetics since power levels at this time are small. Nevertheless, some experiments can be done before the NIF is completed that may help in reducing physics uncertainties and shorten the time before reaching ignition. Hohlräume approaching initial NIF temperatures can be produced in experiments on Saturn and PBFA-Z. These hohlraums can be used to study the behavior of shocks with 1–10 Mb of pressure to study responses in capsule ablators and cryogenic DT. Such experiments might be useful for verifying NIF ignition-capsule designs. Also, Saturn and PBFA-Z hohlraums can be used to study radiation-

hydrodynamics in the low-temperature, long-time-scale regime. These experiments could help guide hohlraum-design calculations.

Nova can produce similar powers to the initial NIF pulse for several nanoseconds. Nova experiments can investigate effects of windows and fill-gas heating in NIF-size hohlraums. They could be used to benchmark energetics and initial symmetry estimates using time-resolved symmetry techniques, and the levels of laser-plasma interactions are not an issue. Also, Nova experiments could be done to measure radiation hydrodynamics of high-Z materials and EOS of capsule ablators for several nanoseconds at the NIF initial radiation temperatures. These experiments could complement the pulsed-power experiments by extending the database to higher temperatures, albeit for shorter time scales, thus spanning the entire range of NIF relevant parameters.

7.3 Laser-Plasma Instabilities

Parametric laser-plasma instabilities have always been of concern for indirect-drive inertial confinement fusion. Historically, the by-products of parametric instabilities (scattered light and superthermal electrons) have been both observed and predicted to occur at sufficiently high levels as to render several versions of laser-driven ICF impractical. Our present choices of laser wavelength, beam smoothing, beam irradiance, and hohlraum gas-fill have been motivated and constrained by our knowledge of laser-plasma interactions. Hence, the continued study of laser-plasma interactions and parametric instabilities such as stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), and filamentation remains of great importance to ICF. Fundamental issues, such as sources for seeding growth, the effects of beam statistics and beam conditioning, and mechanisms for saturation of these instabilities are not presently understood in the detail that allows quantitative modeling of experiments. We will continue to make progress in studying these phenomena at Nova, the Omega Upgrade, and Trident in the years leading up to NIF. Understanding the scattering of incident laser light by parametric instabilities is crucial from the point of view of energy balance and symmetry (SBS & SRS), as well as preheat (SRS producing fast electrons, scattered light hitting the capsule). In the large-scale-length plasmas expected in the NIF targets, the potential exists for strong SBS & SRS backscatter and sidescatter exacerbated by beam filamentation. Although initial HLP5/6 experiments have shown that we should be able to control such instabilities in the NIF, continued study of this problem will have the dual benefits of indicating where design latitude exists in the laser (by eliminating more costly smoothing schemes) and in the hohlraum design (by allowing higher intensity irradiation conditions to be considered by designers). Furthermore, continued development of our theoretical understanding of these instabilities, in tandem with an aggressive experiments program, will allow us to have confidence when we vary target designs in the future.

Figure 7.3-1 is the planning schedule for filamentation and SBS/SRS development activities.

WBS	CS&T activities and milestones	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
7.3	Laser plasma instabilities										
7.3.1	Large plasma experiments										
7.3.2	Laser plasma experiments										
7.3.3	Omega Upgrade experiments										
7.3.4	NIF filamentation and SRS/SRS development										

Figure 7.3-1. Planning schedule for filamentation and SRS/SRS development activities.

7.3.1 Large-Scale-Length Plasma Experiments

Experiments will continue on large-scale-length plasmas developed for HLP-5 and HLP-6 of the NTC. Experiments will continue to quantify and understand the levels of SRS, SRS and Two-Plasmon Decay (TPD) in these plasmas. To address more directly the HLP6 goal of better understanding filamentation, we will cover a broad range of experimental parameters by varying the color and f/number of the interaction beam and by varying the plasma conditions (temperature, density, and average Z). Indirect diagnostics of filamentation include the SRS spectrum observed through the incident beam aperture, whose width indicates the range of densities in filaments, measurements of the angular distribution of the backscattered light, as well as transmitted beam-divergence measurements to investigate beam refraction and breakup. In particular, beam deflection beyond that caused by conventional refraction has been observed in both Nova and Trident targets. This deflection is theoretically predicted to be mediated by self-focusing, and is being investigated in ongoing campaigns. Also, experiments to investigate beam smoothing as a way of turning filamentation on and off in our large-scale-length plasmas will be continued. We will continue experiments with large f/number beams shooting into a preformed plasma in order to produce a single filament. In these experiments our diagnostics will be supplemented by high-spatial-resolution XUV imaging ($\sim 1 \mu\text{m}$) and high-resolution optical probing with 4ω light.

SRS from large-scale-length plasmas has been calculated to be a potential problem in NIF hohlraums. Linear gain calculations based on LASNEX density and temperature profiles indicate that gain coefficients of up to 20 are present for the inner NIF beams even at the high electron temperatures expected in the NIF hohlraum plasma. This gain is comparable to that calculated in the same manner in open geometry gasbag and hohlraum plasmas. Experiments with such plasmas on Nova have shown that a sizable amount of SRS-scattered light can be directed back towards the incident beam. Similarly for SRS, predicted linear gains are large. However, it has been found that damping of the SRS ion acoustic waves can decrease levels much beyond predictions of linear theory for reasons that are not understood. The observation of SRS and SRS directed back toward the incident beam is consistent with SRS occurring in filaments. A significant effort will be required for understanding the level, saturation mechanisms, and the interplay of SRS and SRS with filamentation and beam smoothing. The plasma constituents, electron temperature, and density and scale length in the large plasmas will be varied in order to study the sensitivity of the SRS and SRS levels. These studies will

include spatial and temporal measurements done by imaging the scattered light. We can also investigate the effect of seeding of the instability by light scattered from other beams and the role of ion acoustic waves from SBS in reducing SRS. The levels of SRS, and the possible anti-correlation of the SBS signal with the observed SRS signal may also point to possible explanations for suppression of SBS in large-scale-length plasmas. Initial observations of competition, cooperation, and correlations between SBS and SRS and TPD, including SBS sidescatter from one beam seeding SBS and SRS in another will be pursued further.

Another area of study is the transfer of energy from one beam to the other in the forward direction by beam-to-beam interactions. This process can occur where two different color beams cross within the plasma and interference between the two light waves can excite an ion acoustic wave, which then scatters light from one beam into the other. This possibly can occur in NIF hohlraums at several places and could affect power balance.

Sidescatter is a major concern in the long-scale-length plasmas present in the NIF, as an energy-loss mechanism, as a potential seed for hydrodynamic instability (through light hitting the capsule), and as an electromagnetic seed for backscatter SBS and SRS on the other beams. Sidescatter, on the other hand, is an excellent tool for both plasma characterization along the probe beam path. For example, the Spatially Discriminating Optical Streaked Spectrograph (SDOSS), which can simultaneously time-resolve SBS, SRS and TPD, has already shown a significant difference (relative to calculation) in electron density at a certain location in a gas-filled hohlraum.

The understanding of sidescatter will still need improvement by the end of the present series of experiments on Nova. Hence, emphasis on sidescatter will be continued. For these experiments, fairly comprehensive measurements are possible with the new time-resolved sidescatter arrays that were developed for the current series of high- f /number experiments but were not implemented in time before KD1. This diagnostic will be used in conjunction with the full-aperture backscatter stations (FABS). The array will consist of absolutely calibrated photodiodes that are suitably filtered for SBS (near 351 nm) or SRS (400–700 nm). The wavelength band for the photodiodes is entirely selected by the filters and can therefore be easily configured for other wavelengths in the range of 200 to 1100 nm. An array of these units will be placed at various angles on the Nova target chamber to sample the light scattered out of the lens cone. The signals will be time-resolved in order to discriminate against contributions from the heater beams that are used to preform the plasma. The time resolution will be achieved by using fiber optics coupled to streak cameras and streaked optical spectrometers. This diagnostic has been supplemented (for scattering near the beam cone) by a diagnostic that images the near-backscatter incident on a plate that extends the angular coverage of near backscatter to a cone with a half angle of 20° , around the probe-beam lens.

7.3.2 Support of Laser-Plasma Instability Experiments at Trident

Selected, fundamental laser-plasma-instability experiments can be completed at the Trident facility. A number of plasma physics experiments can be done that do not require the full energy of a Nova or Omega-Upgrade laser. For example, electromagnetic seeding of SBS in a long-scale-length plasma by externally applied electromagnetic waves was demonstrated recently at Trident. A study of beam deflection versus laser

intensity and transverse plasma velocity has demonstrated a theoretically predicted resonance in plasma velocity at the same point. Similar basic questions are likely to appear in the future, and this smaller, flexible facility is an ideal place to study them.

7.3.3 Support of Laser-Plasma Instability Experiments at Omega Upgrade

In tandem with the work described in Section 7.3.1, scientists at the National Laboratories and Rochester's Laboratory for Laser Energetics (LLE) should collaborate on laser-plasma instability experiments and the corresponding necessary diagnostic development using the Omega Upgrade. The amount of energy available in Omega Upgrade is comparable to that of Nova, so many long-scale-length plasma targets developed at Nova can be redeployed at Omega Upgrade with a minimum of redesign and characterization. The decision to deploy a particular experiment at Omega Upgrade or Nova would be dictated by the unique illumination and diagnostic capabilities of either facility, as well as by laser availability.

7.3.4 NIF Filamentation and SBS/SRS Development

It is expected that we will have a period of two years (FY01 and FY02), when personnel involved in the interaction experiments at LLNL, LANL, and LLE will be planning and developing the experiments and diagnostics for the NIF interaction experiments. This period will involve smaller scale, proof-of-principle experiments on Nova, Omega Upgrade, and smaller lasers. The number of shots required during this time would depend on the availability of large laser facilities. As NIF becomes operational, we would begin interaction experiments to characterize scattering levels in NIF targets.

7.4 Ignitor Experiments

The "Petawatt," an ultrahigh-power beamline, will be available on Nova in late FY96. With this capability, beamline 6 in the 10-beam target area will provide 500–1000 J of 1- μm wavelength light in a 1-ps-duration pulse. This beamline will be able to produce focused intensities of up to 10^{21} W/cm² at target chamber center. Its primary purpose will be to test technological and scientific aspects of the Fast Ignitor concept, in which a high-intensity beam (10^{19} W/cm² in a 100-ps pulse) is used to heat a target that has been imploded by direct or indirect drive using the remaining laser beams.

The technological issues that must be addressed are: 1) focusing and timing the Petawatt beam so that it is incident on, and coincident with the compressed core of the imploded capsule; and 2) the survivability of the focusing optic and debris shield. The scientific issues that will be addressed on Nova are 1) demonstrating that the laser can be efficiently transported through the plasma surrounding the compressed core; 2) demonstrating that a significant fraction of the energy in the laser beam is converted to fast electrons with a range that will efficiently couple to the areal density of an implosion; 3) the design and experimental demonstration of a low-temperature, high-density implosion; and 4) unequivocal demonstration, probably by an increase in the neutron yield, that the energy in the short-pulse laser can couple to the compressed core.

To begin addressing both the technological and physics issues, we have started construction of a 100-TW laser that will produce focused intensities of up to 10^{20} W/cm² in a

0.7-ps pulse in the Nova 2-beam chamber. This beamline, which is produced by the Petawatt Master Oscillator with additional amplifiers, can be used with the existing 2-beams of Nova to allow us to conduct experiments related to hot electron generation and transport in hot, dense plasmas. Integrated experiments, where a channeling beam and a high-power beam interact with a preformed compressed plasma, will also be possible. The goal of the 100-TW experiments is to demonstrate efficient coupling of laser energy by fast electrons at depth in a material. An experimental database will enable us to extrapolate the depth of energy deposition expected for the Petawatt, and therefore the compressed-fuel areal density appropriate for the Nova Petawatt experiments.

Figure 7.4-1 is the planning schedule for ignition-concepts development activities.

7.5 Experiments at the Omega Upgrade Laser at Rochester

Starting in mid-FY95, the Omega Upgrade will be operational with both direct- and indirect-drive capabilities. Many of the target physics issues are common to the physics of x-ray drive, such as: 1) laser interactions in large-scale plasma; 2) Rayleigh-Taylor instabilities in the ablation front; 3) asymmetry; and 4) the effects of mix and compressed fuel temperatures. Laser-plasma instability experiments in open long-scale-length targets presently done at Nova can benefit from the unique uniform illumination and beam smoothing that will be possible at the Omega-Upgrade laser. A laser-imprint elimination scheme demonstrated at Trident can be tested at high power in convergent geometry at the Omega-Upgrade laser. In addition, the Omega-Upgrade laser can provide unique and important contributions to indirect drive, such as: 1) testing beam-phasing schemes to tune symmetry, which will be essential for the success of NIF; and 2) laser-plasma instability experiments in hohlraums with routine SSD capability.

Many of the diagnostics on Nova are portable and are based on six-inch manipulators (SIM). Some of the Nova diagnostics could be loaned to or replicated at Omega Upgrade. Other desirable areas of collaboration include the development of NIF-relevant diagnostic techniques. These include:

- Beam-pointing validation—In the course of the Precision Nova campaign, we have developed techniques for checking the beam pointing by referencing the position of x-ray emission with respect to fiducials. These techniques will be sufficiently accurate for the NIF, but need to be automated.
- Bumpy-ball spectroscopy—Experiments with deliberately premodulated targets will test the accuracy of the hydrodynamic mix models in convergent geometry.
- Neutron imaging—The diagnostic that needs to be developed for the NIF will be refined on Omega Upgrade because of its high yield and small core size. The

WBS	CS&T activities and milestones	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
7.4	Ignitor concepts										
7.4.1	Nova Ignitor concept experiments										
7.4.2	NIF Ignitor concept development										
7.4.3	NIF Ignitor concept experiments										

Figure 7.4-1. Planning schedule for ignitor concepts development activities.

Nova diagnostic is semiportable and will be moved to the Omega-Upgrade laser. Experience gained will be used to improve the design of the NIF diagnostic.

- Large-scale-length plasma-generation—Techniques pioneered at Nova will be used at Rochester to investigate the limit on laser intensity as a function of laser smoothing techniques. The objective of this work will be to understand the mechanisms limiting the highest values of $I\lambda^2$ tolerable for the NIF.

As with indirect drive, the direct-drive concept has its own technical contract (known as the Omega technical contract). Fulfillment of this plan will set the stage for detailing the direct-drive option on NIF. With this in mind, the three weapons labs plan to participate in target physics experiments at Omega. These experiments would involve both direct and indirect drive. Some concepts crucial to NIF such as beam phasing (for indirect drive) may be best tested at Omega.

Figure 7.5-1 is the planning schedule for Rochester support and Nova operations.

7.6 Facility Operations

7.6.1 Nova Facility

Many of the experiments required to support the CS&T development for the NIF will require the use of the Nova laser facility. The CS&T development issues that can be supported by Nova include:

- Laser Technology (CS&T WBS 1.0).
- NIF Target Chamber Issues (CS&T WBS 3.0).
- Target Diagnostics (CS&T WBS 4.0).
- Target Design and Theory (CS&T WBS 5.0).
- Target Physics Experiments (CS&T WBS 7.0).

The baseline proposal is to operate Nova with a shift and a half, which could support about 900 experiments per year.

Currently, Nova is operated two full shifts for five days a week, in addition to some overtime, resulting in about 1400 experiments per year. The Nova operations staff is approximately 90 personnel. Nova has been performing an average of 1.2 experiments per shot (i.e., the ability to produce 1220 shots actually yields about 1460 experiments). The ability to do more than one experiment per shot is primarily a result of occasionally using the two-beam and ten-beam chambers simultaneously and occasionally combining laser

WBS	CS&T activities and milestones	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
7.5	Rochester support										
7.6	Nova operations										
7.7	Nova shut down										

Figure 7.5-1. Planning schedule for Rochester support and Nova operations.

science experiments with physics experiments. If use of the two-beam chamber and combining with laser science experiments are reduced, the number of experiments per shot will be reduced correspondingly. In estimating the operations schedules, the assumption is that one shot will yield one experiment.

The baseline option for Nova operations in support of the CS&T effort is 1.5-shift operation supporting 900 experiments per year. A reduction in the time dedicated to maintenance would further tend to increase the shot rate, but this option must be carefully evaluated. Much of the "maintenance" time is actually dedicated to setup and reconfiguration of upcoming experiments, system modifications, and upgrades. It is assumed that the system will become very stable in FY95, with few changes and with most of the experiments using a "routine" system configuration. If this assumption turns out to be false, then additional time (weekends and overtime) may be required to meet our goals.

Another option is to operate Nova with two shifts. This would increase the available experiments to approximately 1200 per year. By adding a second shift that overlaps the first shift by 1 hr, an additional 7 hr per day of shot time can be obtained. Assuming an average of an additional 2.5 shots per day with a second shift, the annual shot total would increase by 500 shots (with every Monday for maintenance) or 560 shots (with every other Monday for maintenance). The addition of a second shift would add about 11 people to the staffing and \$1.6M to the cost of the single-shift operation. This option will be carefully assessed with respect to other options for NIF preparation.

7.6.2 Trident Facility

Trident has been operational since FY93. In FY94, it fired 872 high-energy target shots with single-shift operation. Additional shots were fired with lower-energy ultrahigh-irradiance subpicosecond pulses. Trident's entire crew is about ten people, which includes operations, upgrades, maintenance, and experimental support. This crew also executes approximately one-fourth of all experiments at Trident. Annual cost, including those experiments executed by the Trident team itself, is \$2.5M in FY94 dollars. These resources do not include target fabrication.

As Trident matures, its annual shot rate is expected to stabilize at ~1000 high-energy shots per year in a single shift. This rate could be increased by roughly 50% with the addition of a second shift at a cost of roughly an additional \$1M/year.

Although its several hundred Joule laser energy is not ideal for implosions, Trident is a flexible, cost-effective laser, particularly suited to:

- Laser Technology (CS&T WBS 1.0).
- Target Diagnostics (CS&T WBS 4.0).
- Fundamental laser-plasma instability experiments (CS&T WBS 7.3.2).

It is also well suited to some other tasks, such as testing unconverted light absorbers (CS&T WBS 3.3), plasma instability studies (CS&T WBS 5.3 and 7.3), and advanced concept studies (CS&T WBS 5.5, 5.7, and 7.4).

7.6.3 Omega Upgrade Facility

As has been previously stated, the Omega laser can provide important capabilities for NIF preparation. Work at Omega has not yet been fully outlined but will likely include about 100 shots/year aimed at NIF diagnostic development (target Diagnostics CS&T WBS 4.0), 100 for indirect-drive experimental technique development (target Physics Experiments (CS&T WBS 7.0), and 100 for direct-drive work specifically related to NIF relevance.

7.6.4 Saturn and PBFA II Pulsed-Power Accelerators

A large volume ($\sim 6 \text{ cm}^3$), long-lived ($\sim 30 \text{ ns}$), 75 eV hohlraum has been demonstrated on Saturn. Similar configurations on PBFA II are expected to yield larger hohlraums in excess of 100 eV. These environments may be well suited to verify the predictions of the rad-hydro design in the initial NIF pulse ("foot") (Section 7.2.10), where the temperatures range from 50 to 150 eV and hohlraum coupling energetics (Section 7.2.1). In addition, the 0.5 MJ of soft x-ray output on Saturn, and the anticipated $\sim 1.5 \text{ MJ}$ of soft x-ray output on PBFA-Z, will provide excellent testbeds for NIF soft x-ray diagnostics. The details for experiments of this type are just now being developed, and can be fielded at ~ 7 shots/week on Saturn and an anticipated rate of ~ 5 shots/week on PBFA-Z.