

NIF IGNITION

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1 EXECUTIVE SUMMARY

JASON was asked by the National Nuclear Security Administration (NNSA) to assess the plan and prospects for achieving inertial confinement fusion (ICF) ignition at the National Ignition Facility (NIF) by 2010, including the use of beryllium targets.

JASON was introduced to plans for ignition experiments on the NIF in a meeting on January 13, 2005, in La Jolla CA. Our detailed review of the present ignition plan took place at the Lawrence Livermore National Laboratory (LLNL) on March 24-26, 2005. We were very impressed during that visit by the accomplishments made by the NIF project and the planning efforts described by members of the National Ignition Campaign team. Before and after that visit, we corresponded extensively with NIF managers and scientists, and then held a further meeting of the JASON study group in McLean VA on April 17-19, 2005.

The NIF ignition program includes a series of experiments at OMEGA (University of Rochester) and Z/ZR (Sandia National Laboratories), as well as analysis, modeling and diagnostic development prior to 2010. However, in the current plan, further laser target experiments at the NIF await project completion. Following completion of the NIF construction project in FY 2009, the plan calls for a series of NIF laser-target shots in 2010 and beyond, aimed at commissioning target and diagnostic systems and achieving ignition.

We believe that the present choice of beryllium for the fuel capsule shell in the primary point design target is reasonable on technical grounds and appears to be technologically feasible given anticipated advances in relevant technologies. This target design is predicted to produce ignition with 1 MJ of input laser energy, but with a small (and highly uncertain) performance margin at this laser energy. Therefore, the current ignition plan, which calls for a maximum laser energy of 1 MJ in FY 2010, eventually ramping up to a maximum laser energy of 1.8 MJ, carries substantial technical risk for achieving ignition in 2010.

1.1 Response to the Questions in the Charter from NNSA

1. Will the key technologies (target fabrication, cryogenic system, etc.) be in place when needed to achieve ignition in 2010?

In our judgment the technologies necessary to support the ignition campaign are likely to be ready by 2010. The technologies that we investigated included target fabrication, target preparation, and the associated cryogenic systems. (Our analysis assumes that the NIF's plan for the laser technology will succeed.)

2. Will the key diagnostics be in place when needed, and will they be adequate for the task of guiding the experimental program through a successful ignition test program by 2010?

We believe that the full set of diagnostics, as specified by the NIF Program in its March 24-25 presentation to the JASONS, with the possible exception of shock timing, are adequate to provide the critical information needed to diagnose successful ignition campaign experiments. Unexpected results in the course of the Ignition Campaign may require certain additional diagnostics for which preliminary designs exist.

3. Does the risk mitigation plan address the highest risk issues, and are the risks at an acceptable level?

Risk mitigation elements currently being pursued by the NIF Program include: 1) a primary fuel capsule design with backup designs; 2) options for reducing the impact of laser plasma instabilities; 3) experimental campaigns on OMEGA, LIL (in France), and Z/ZR; 4) the NIF shot sequence, starting in 2009, determined on the basis of risk mitigation, with 30% of the shots held for contingency. In addition, the laser project is developing procedures to identify and mitigate incipient flaws that develop more rapidly in the final optical elements when the laser is operated above 1 MJ.

The important remaining risk factors include scientific questions, issues of complex technology development, and system integration. We believe that the highest risk issues are the restriction of the laser energy to 1 MJ in the initial stages of the ignition campaign, deleterious laser-plasma interactions, and implosion asymmetry. These are considered in the ignition program plan, but we believe that the physics issues need to be more aggressively addressed via computer simulations, experiments and theoretical studies between now and 2010. Adoption of rigorous procedures for quantifying technical uncertainties and associated risks is also needed. However, some issues and uncertainties cannot be addressed fully until the NIF is commissioned.

4. Does the program plan make reasonable use of all ICF program resources and capabilities, especially OMEGA and Z?

In the case of the OMEGA facility, there is a reasonable plan of laser shots that is integrated into the NIF program. We found that the plans to use LIL and Z/ZR are not yet adequately developed.

The NIF Ignition Program has scientific and technical risks that demand involvement by experienced personnel to the greatest extent possible. We are concerned by indications of trends to the contrary. We would like to see greater inclusion of the expertise that exists in ICF and related fields at other institutions. We also believe that training new experts in this area will be essential to the long-term success of the NIF.

5. What is the prospect for achieving ignition in 2010?

First attempts to achieve ignition on NIF are likely to take place in 2010 — this is an important and valuable goal that has strongly focused the efforts of the NIF Program. The scientific and technical challenges in such a complex activity suggest that success in the early attempts at ignition in 2010, while possible, is unlikely. The Program has identified a series of tests of the key physical processes and diagnostic instruments that provides a reasonable roadmap for progress toward ignition after the initial attempts.

1.2 Critical Findings

The NIF laser commissioning schedule and Ignition Campaign plans call for ignition experiments at 1 MJ or less through FY2010. This laser energy is adequate for system integration and some of the preliminary experiments that will address physics issues. However, at this incident laser energy, the margins on ignition are thin because unfavorable small changes in a few calculated parameters would prevent ignition.

Though raising some new technical challenges, we find that LLNL's development of a target with a doped beryllium (Be) fuel capsule ablator is sensible. In order to mitigate risk, the program will carry two fuel capsule point designs, the second one with a CH (plastic) ablator. Experiments on Be as an ablator material that are planned for the near future should address remaining technical issues.

Two physics areas in which uncertainties threaten the achievement of ignition are laser-plasma interaction and hydrodynamic instabilities such as the Rayleigh-Taylor mode. Both place large demands on computation, and 3D calculations are needed to analyze point designs to the fullest extent possible before the point designs are locked into a manufacturing cycle.

Risk mitigation would be enhanced through a significant increase in the computational resources (both capacity and capability) available to the NIF program. Examples of issues that can be addressed by these resources are the effects of laser-plasma interaction, hydrodynamic instabilities, and quantification of margins and uncertainties in fuel capsule yield arising from, for example, uncertainties in material properties and imperfect reproducibility. We view these computational resources as all the more critical in light of the inability to perform experiments on the NIF during the construction phase.

Any large technical project performing ground-breaking science and technology is subject to risks. While NIF has several risk-mitigation program elements in place, we believe that these can be considerably strengthened by instituting a program of quantification of margins and uncertainties similar to that being developed on the weapon side of the national laboratories

Standing external oversight machinery for the NIF Program appears to us to be lacking. There have been many ad hoc review committees that have evaluated aspects of the NIF program over the last decade. Such committees can be useful, but they lack the impact of a reviewing process that endures, develops a relationship of trust and candor with the program and can, therefore, help establish priorities and evaluate knowledgeably over a period of years the progress that NIF makes toward its goals.

1.3 Critical Recommendations

We **recommend** that a senior review committee (or committees) be appointed by the Laboratory Director to advise top NIF leadership on allocation of scientific resources and to provide peer review of critical scientific components, such as target and diagnostic design. The committee(s) would have technical experts and other individuals drawn from inside and outside LLNL and the NIF program; they should be standing committees and conduct regularly scheduled meetings and reviews that are open to the NIF scientific community where proposals, component designs and the ignition shot plan are discussed, debated and reviewed. The committee(s) could also have technical sub-panels of experts on specific issues (such as target design, laser-plasma interactions, diagnostics, etc).

We **recommend** that NIF Program scientists be allocated substantially increased computer resources on world-class computing facilities at LLNL, such as BlueGene/L. This is especially important for those carrying out computer simulations of laser-plasma interactions, hydrodynamic instabilities and integrated target design for risk mitigation and assessment of margins and uncertainties.

We **recommend** that the non-nuclear (X-ray and optical) diagnostics should be a focus of the early diagnostic development program in order to be able to understand which physical processes are responsible for unsuccessful experiments.

We **recommend** that the NIF program continue its aggressive program to identify and mitigate defects in final optics with a goal of routine operation above 1 MJ for ignition experiments as soon as possible in the initial ignition campaign.

We **recommend** that the NIF Program increase its efforts to resolve the remaining technical challenges related to Be fuel capsules, including microstructural and equation of state issues, utilizing the best available expertise both inside and outside of LLNL.

We **recommend** an aggressive program of experiments on high energy density laser and Z-pinch facilities, both national and international (to supplement those already planned for OMEGA), to improve our understanding of laser-plasma interaction, hydrodynamic instabilities, and other critical issues, as well as to benchmark computer simulations.

2 INTRODUCTION AND SUMMARY

2.1 Background

This JASON review of the inertial confinement fusion (ICF) ignition campaign planned for the National Ignition Facility (NIF) in 2010 and beyond was requested by the National Nuclear Security Administration (NNSA) in response to a mandate from Congress in the FY 2005 Senate and House Energy and Water Appropriations Conference Report. The complementary NNSA-sponsored review of the NIF laser construction project that was also mandated in that Conference Report is being carried out by a different panel.

In order to carry out this review, the JASON study group received briefings on the National Ignition Campaign from Lawrence Livermore National Laboratory (LLNL) scientists, engineers and program managers, as well as from other participants in the NIF Ignition Program from Los Alamos National Laboratory (LANL), from the Laboratory for Laser Energetics (LLE) of the University of Rochester, and from Sandia National Laboratories (SNL). We had introductory briefings on January 13, 2005, in La Jolla CA, and detailed briefings at LLNL on March 24-25 that were followed by an executive session on March 26. Both before and after the March meeting, we corresponded extensively with NIF managers and scientists, who were very accommodating, and we collected many publications on the key physics, computational and diagnostic issues. The study group held its final meeting in McLean VA on April 17-19, 2005.

In general, we were very impressed by the remarkable accomplishments of the NIF program and by the planning efforts described by members of the National Ignition Campaign team.

The NIF campaign to achieve inertial confinement fusion ignition and propagating burn will be a very complex and challenging scientific and technical undertaking. At the present time, the anticipated performance of the NIF target is based on computer simulation. While it is true that "experiments conducted at NTS have demonstrated excellent performance, putting to rest the fundamental feasibility of achieving high gain," fusion burn in the laboratory has never been achieved. This is the reason for the NIF and its experimental ignition campaign.

In our study, we assume that the laser beams meet the requirements set by the target designers for energy balance, spatial smoothness, temporal and spatial power profile and total energy. Our main points of focus were: (1) the coupling of the laser power to the target, which consists of a hohlraum (a gold or gold alloy cylinder used to convert the incident laser power into x-rays), within which a fuel capsule is contained; (2) the conversion of laser power to x-rays in the hohlraum; and (3) the symmetric implosion of the fuel capsule by the x-rays at the appropriate rate and to the required density and

temperature to achieve fusion ignition and propagating burn in the fuel capsule. Our working definition of “ignition and propagating burn” (often written simply as “achieving ignition” in this report) is a fusion energy yield at least equal to the laser energy absorbed in the target.

Even if the laser meets all specifications, there remain many scientific and technological issues to address and resolve in the ignition campaign. In addition, effective integration of the laser, support technologies, diagnostic systems and data analysis with each other and with the computer-simulation-based experimental design program will be necessary for success. Achieving ignition also requires building a capability beyond hardware and software. A large group of highly skilled scientists and engineers who are committed to, and engaged in, the ignition program is also essential for success of the NIF ignition program. Many of those people are in the program now, of course, but many more, both experienced scientists and fresh Ph.D’s, will be needed in future years. This implies that the NNSA must maintain a broad and strong high energy density physics program in laboratories and universities other than LLNL and LLE.

Because the NIF ignition program involves a large step forward in laser power, target fabrication requirements, etc., it is expected that areas where there are known scientific uncertainties, such as instabilities associated with laser-plasma-interaction in the hohlraum, will present challenges. Computer simulations suggest that many parameters may have to be tuned quite precisely to achieve ignition. In addition, there will be issues not at present anticipated — the notorious “unknown-unknowns” — that are usually encountered when a new experimental regime is entered. Only by doing the experiments can these be discovered and managed. The large physical scale and high complexity of the ignition experimental campaign places it firmly at the forefront of experimental physics.

All of these factors make predicting the number of experiments or the length of time required to achieve ignition extremely difficult. Although we have not uncovered anything that precludes the achievement of ignition by the end of the first campaign, we believe it is unlikely that ignition will be achieved that quickly, especially with the laser energy limited to 1 MJ through 2010, as is the case in the present plan. It is much more likely that continued experiments with laser energies growing to the design value of 1.8 MJ, diagnostic development, and 3D computer simulations benchmarked to experimental results will be needed to definitively answer the critically important scientific question for the NIF from our perspective: “Can a propagating burn be established with a 1.8 MJ laser in the laboratory?”

The Charter to which we have responded, including its introductory paragraph as well as the questions to which we responded in the Executive Summary, is as follows:

JASON Charter (Dated 1/26/05)

NNSA has formulated an aggressive program to achieve fusion ignition in the National Ignition Facility in 2010. The key technological advances that enable this schedule are the development of advanced target designs and the ability to field ignition targets that may be filled with deuterium-tritium “in situ.” In the FY2005 Energy and Water Appropriations Conference Report, Congress mandated that NNSA conduct a review of the NIF project baseline and the outlook for ignition with beryllium fill-tube targets. NNSA will accomplish the review of the NIF project through a construction project review led by an expert in project management outside of NNSA. JASON is being asked to review the plan to achieve fusion ignition in 2010, including use of beryllium targets. The NIF Project and JASON ignition reviews will be used by the NNSA laboratory and LLE directors to write a position paper assessing the prospects for achieving ignition in 2010. This position paper is due to Congress by the end of June. The preliminary JASON report is requested by June 1, 2005.

JASON is asked to assess the plan and prospects for achieving ignition at NIF by 2010. Specific questions include:

- 1. Will the key technologies (target fabrication, cryogenic system, etc.) be in place when needed to achieve ignition in 2010?*
- 2. Will the key diagnostics be in place when needed, and will they be adequate for the task of guiding the experimental program through a successful ignition test program by 2010?*
- 3. Does the risk mitigation plan address the highest risk issues, and are the risks at an acceptable level?*
- 4. Does the program plan make reasonable use of all ICF Program resources and capabilities, especially OMEGA and Z?*
- 5. What is the prospect for achieving ignition in 2010?*

Responses to these questions were presented in the Executive Summary, as were our top-level findings and recommendations. The remainder of this report provides our assessment of the NIF Ignition Plan as presented to JASON. Our summary assessment in Section 2.2 is followed immediately by a collection of the higher-level recommendations that are to be found (and justified) in Section 3.

Section 3 contains a description of the scientific and technical issues, our assessment of the status and prospects for the NIF Ignition Program to deal with those issues, and a substantial number of recommendations. The findings are not called out as such because

such a large fraction of Section 3 consists of findings, but the recommendations are separately indicated in the text. The specific issues that we discuss are hohlraum physics, laser-plasma interaction (LPI) and fuel capsule implosion. We also discuss computational needs for the program, the diagnostics needed to assure that the experimental program can move forward effectively, and the technologies needed to manufacture targets and deliver them to the center of the target chamber. Because we believe that risk mitigation must be an important element of the program between now and 2010, we discuss it from a technical perspective in each of the issues sections. In addition, we have included a separate section with recommendations on peer-review teams and to broaden the community involved in the NIF Ignition Program.

2.2 Summary Assessment and High Level Recommendations

Following their assessment of the impact of FY2005 Energy and Water appropriations, the NIF management team announced their revised plan to pursue ignition with the NIF. This plan is the subject of this JASON study. Among the new features of this plan are (1) cessation of laser-target experiments of any kind at the NIF until the laser is complete in FY09; and (2) use of fuel capsule shells that will be filled with DT fuel through a very tiny fill tube so that cryogenic handling will be required only within the target chamber.

A very important feature of the present plan is that laser operation will be limited to 0.5-1 MJ in the first phase of the ignition experimental campaign in FY2010 because of laser commissioning and other system integration activities. Laser commissioning up to the full 1.8 MJ is to be completed during FY2011. The lower laser energy is adequate for several important elements of the early experimental ignition program, such as system integration, commissioning of diagnostics and many of the preliminary experiments that will address physics issues. However, with 1 MJ incident laser energy, the margins on achieving ignition with present point design targets are thin because unfavorable small changes in a few calculated parameters would prevent ignition.

The present target point-design uses beryllium (Be) with a graded-density copper (Cu) dopant for the fuel capsule shell, with a tiny tube enabling it to be filled with deuterium and tritium (DT) fusion fuel. This choice is based in part upon recent successes in manufacturing the Be shell and attaching the fill tube. It is also based, in part, on the computer-simulation-based prediction that the Be target design will achieve ignition with 1 MJ of input laser energy, while the back-up point design based upon a CH (plastic) ablator will require perhaps 20% more laser energy to have the same (~10%) performance margin. Therefore, the current ignition plan, which calls for limiting the laser energy to 1 MJ in FY2010 (compared to the anticipated maximum laser energy of 1.8 MJ), carries substantial technical risk especially in its early phases. Extensive experimental and computational risk-mitigation efforts carried out before the start of the ignition campaign

are needed to enable the NIF ignition experiments to address the major issues most effectively starting in 2010.

The physics issues that concern us the most in the context of risk-mitigation are laser-plasma interaction in the hohlraum and hydrodynamics issues in the imploding fuel capsule, such as the Rayleigh-Taylor instability. Both of them place large demands on computational capability and capacity, as many 3D calculations are needed to analyze a point design to the fullest extent possible. Although some risk reduction can be accomplished by extensive use of 3D computer simulations in conjunction with experiments on OMEGA (LLE), Z/ZR (SNL), and perhaps elsewhere, some physics issues cannot be addressed until the full NIF is available.

Therefore, the current ignition plan, which calls for a maximum laser energy of 1 MJ in FY 2010, eventually ramping up to a maximum laser energy of 1.8 MJ in 2011, carries substantial technical risk for achieving ignition in 2010. However, the program has identified a series of tests of key physical processes involving experiments and computer simulations that, together with appropriate diagnostic instruments, provide a roadmap for progress toward ignition on the NIF after the initial attempts.

2.2.1 Recommendations

The main body of this report (Section 3) contains a discussion of the critical physics, computing, diagnostics and management issues. Embedded therein are recommendations, some of which we highlight here. Each recommendation refers to the sub-section in Section 3 from which it was drawn and in which the detailed findings that underlie it also reside.

Much remains to be done between now and the start of the NIF ignition campaign. Tradeoffs will have to be made and hard decisions reached. In addition, the broader ICF community needs to become more actively engaged in the ignition campaign. We have three recommendations in this regard:

We **recommend** that one or more technical/scientific advisory committees (TSACs) be appointed by the LLNL Director to advise top NIF leadership on allocation of scientific resources and to provide or oversee peer review of critical program elements. (Section 3.9)

We **recommend** that the NIF Ignition Program participants organize risk mitigation using a plan similar to the Quantification of Margins and Uncertainties (QMU) methodology that is being developed in the Stockpile Stewardship Program. This should involve evaluating the magnitude of both computational and experimental uncertainties and working to reduce them where possible, and should assess the performance margin in the ignition point design capsule at laser energies in the range of 1 to 1.8 MJ. (Section 3.9)

We **recommend** that LLNL create mechanisms (such as the TSACs just mentioned) that enable scientists from outside of the ignition program to contribute to the ignition campaign and to fully engage them as part of the team that works toward its potential success. (Section 3.9)

Part of the modeling and experimental effort must focus on improving the basic understanding of the laser plasma interactions (LPI) that occur when the laser light enters the hohlraum. Improvements in this regard impact hohlraum design, optimization of the laser beam parameters and configuration, diagnostics and the shot plan.

We **recommend** allocation of additional computational resources, such as on the 360 Tflop Blue Gene/L computer or comparable machines, to enable significant LPI studies. A vigorous theoretical program should be a part of this effort. (Sections 3.3 and 3.7)

We **recommend** that, in addition to the OMEGA experiments, an aggressive campaign to improve the level of understanding of LPI in NIF-like plasma and hohlraum conditions be carried out together with French scientists using the LIL laser. (Sections 3.2 and 3.3)

We **recommend** that the community invest time and effort on calculating and measuring self-generated magnetic fields in a hohlraum geometry to see if the predictions of negligible effect are borne out (Section 3.2)

We **recommend** that a "parts bin" of different hohlraum variations that are predicted in computer simulations to be promising for reducing the deleterious effects of LPI be manufactured for use at the NIF. (Section 3.2)

We **recommend** that, as part of a larger, standing risk-mitigation TSAC, a sub-committee of experts on laser-plasma interactions be formed to provide continuing peer review and advice on the LPI research effort and on LPI issues that are highest-risk to the Ignition Campaign. (Section 3.3)

Delicate control of hydrodynamic instabilities and timing within the imploding fuel capsule is needed to achieve ignition and a propagating burn. Exercising such control requires an assessment of the role of Rayleigh-Taylor and other instabilities and tight control over any initial imperfections in the ablator shell and DT fuel layer.

We **recommend** that high-resolution 3D simulations be carried out of the behavior of the ablator, DT/Be and hot spot interfaces to ascertain the risk of failure to ignite due to hydrodynamic instabilities. Such simulations should eliminate the "hot spot penetration factor" as a parameter and enable a more thorough assessment of performance margins and associated uncertainties. (Sections 3.4 and 3.7)

We **recommend** that experiments be performed on OMEGA that would enable important aspects of 3D simulation codes to be validated, such as studies of the fuel capsule interfaces, the effects of hohlraum asymmetries, etc. The resulting experimental database would be used extensively to compare with simulations. (Sections 3.7 and 3.8)

We **recommend** that remaining issues regarding the EOS of DT near 1 Mbar be resolved expeditiously, including undertaking additional experiments, if necessary. Residual issues regarding the EOS and opacity of Be and Cu-doped Be should be the subject of an experimental campaign. (Section 3.4)

We **recommend** that an active standing subcommittee of experts be established to carry out in-depth peer review of the state of modeling and theoretical understanding of ignition fuel capsules in 1, 2 and 3D. (Section 3.4)

Beyond the physics issues, there remain tough technical challenges.

We **recommend** improved characterization of the microstructures in the finished (polished) sputtered Be capsules and experiments that address the shock-melt of Be (and Cu-doped Be alloys) and directly measure the magnitude of the velocity perturbations arising from microstructural imperfections and anisotropies. (Section 3.4)

We **recommend** that the development of both the sputtered Be ablator shells with a graded dopant profile and the uniformly doped, machined Be shells be continued until a small stockpile of acceptable fuel capsule shells can be prepared from one or the other (or both) methods. (Section 3.5)

We **recommend** continued consideration of 2- ω operation in the long-term NIF Ignition Plan just as the program is considering Direct Drive in its long-term plan. (Section 3.9)

We **recommend** that the NIF program continue its aggressive program to identify and mitigate defects in final optics with a goal of routine operation above 1 MJ for ignition experiments as soon as possible in the initial ignition campaign. (Section 3.9)

Given the challenges inherent in such a large scientific undertaking, we felt it would be better to have a larger diagnostic package than was presented to us. Indeed, our sense was that the overall effort on diagnostics was largely focused on success and needs to be substantially boosted to properly diagnose failure modes.

We **recommend** that the non-nuclear (X-ray and optical) diagnostics should be a focus of the early diagnostic development program in order to understand what physical processes are responsible for tests with low neutron yields. Plans should be developed for a high energy X-ray source for X-ray backlighter imaging, for example using an ultra-high

intensity, short pulse laser, so that it can be made available as soon as possible after the start of the ignition campaign. (Section 3.6)

We **recommend** that the program plan include diagnostics early in the ignition campaign that will illuminate hohlraum plasma conditions and important details of the radiation spectrum. (Section 3.6)

We **recommend** that diagnostics be developed that will enable a direct measurement of the sequencing of the four shocks, perhaps through advanced radiographic techniques. (Section 3.4 and 3.6)

We **recommend** that a hard x-ray emission line-based diagnostic for ablation front position based upon dopants in the ablator be evaluated and perhaps tested at Z, where the radiation environment is probably at least as difficult as it will be the NIF. (Section 3.6)

3 SCIENTIFIC REPORT

Planning for the ignition phase of the NIF Program is a work-in-progress for several reasons: 1) construction activities will pace the program for the next several years; 2) actual congressional appropriations will determine what is possible; and 3) significant technical uncertainties exist in ignition components, designs and underlying physics. The NIF laser has clearly been a major engineering achievement so far, for which LLNL and its staff can be proud.

The NIF Ignition Plan formally includes three experimental campaigns, the first of which is to be carried out in 2010. The goal of that first campaign is to build up the necessary facility capability over about 100 tests, beginning with target hohlraums containing diagnostic capsules and culminating in an ignition experiment with a DT-filled Be fuel capsule before the end of 2010. While it is not impossible that everything will work “just so” in the very first ignition attempts, it is unrealistic to expect that to happen. However, that first campaign will be followed by two others in 2011, and each experiment will move the program toward the goal of achieving fusion ignition.

In this report, we assume that the laser will meet the schedule in the present NIF Ignition Program Plan and that the number of target experiments per year in 2010 and beyond will be as specified in that plan. Our focus is on the series of events after the laser reaches the entrance to the hohlraum, the uncertain scientific issues and what can be done now to both mitigate risk and prepare the ICF community for a very challenging scientific experiment.

We begin this Scientific Report section with a listing of the open scientific issues as we understand them at the present time, placing them in the context of the time line of an experiment that is attempting to achieve ignition. Because of the limited time available for this review, we cannot claim that our list of issues is exhaustive. However, with the considerable help of the participants in the program who briefed us and provided follow-up material, we hope we have included the most important ones.

We have **recommendations** of a technical nature throughout Section 3, some of which we have also presented in abbreviated form in Sections 1 and 2.

3.1 Time Line of an Ignition Experiment

We now present the time line of events in an ignition experiment starting from the arrival of the laser pulse at the laser entrance holes of a hohlraum. We assume that the 192 laser beams meet the NIF Project specifications, namely up to 1 MJ in the early NIF ignition

campaign, and up to 1.8 MJ later in the campaign, of 3- ω light with the specified beam energy balance, spatial smoothing, focal spot size and power profile. We are concerned about reproducibility at each step in the time line because it is not yet clear how good that must be for a successful ignition campaign. However, we are reassured by the apparent reproducibility of the laser power profile in the NIF Early Light experiments.

The time line is presented here in outline form, with issues listed as questions below each time line entry. The principal issues are discussed further in subsections addressing hohlraum physics, LPI, and capsule physics. In addition, we discuss technology issues, diagnostics, the importance of computer simulations and the utility of other ICF facilities to the NIF Ignition Campaign in following subsections. Finally, although we include a risk-mitigation discussion in each of these subsections, we complete Section 3 with a broader-based discussion of risk mitigation.

1. Laser beams propagate through plasma generated by their interaction with various materials present in the hohlraum, including any gas fill and foam as well as blow-off plasmas from the laser entrance hole (LEH), shine shield, the hohlraum wall or capsule ablator, and hit the walls in the hohlraum.
 - a. What is an acceptable backscatter percentage?
 - b. What are acceptable levels of hot electron production?
 - c. How much filamentation, beam bending, etc., can occur in the hohlraum before some poor performance thresholds are reached?
 - d. Will the effects of a-c be reproducible from shot to shot? If not, is the non-reproducibility directly related to laser performance or target variations or is it a result of random variations in laser plasma interaction?
 - e. Will we be able to predict a-d with computer simulations?
2. Hohlraum heats up and produces a symmetric ~ 300 eV black body at peak laser power.
 - a. Are time dependent asymmetries due to LPI and beam balance acceptable or well enough understood to control or mitigate them?
 - b. Does the wall blow off symmetrically and reproducibly?
 - c. Will shine shields achieve their goal without interfering with laser propagation?
3. Fuel capsule is irradiated by the hohlraum x-ray field.
 - a. Is fuel capsule preheat prevented by the dopant in the ablator?
 - b. Is the energy absorbed by the ablator the same as is predicted in computer simulations? If not, why?
 - c. Are the ablator and fuel surfaces adequately spherical and smooth?
 - d. Does the ablator have uniform density throughout its volume, without significant voids?
 - e. Does the first shock melt the doped Be ablator?
 - f. Do we know the doped Be Equation of State (EOS) well enough?

- g. Is the D-T EOS known and understood well enough?
4. Implosion with a radial convergence ratio of 30:1
 - a. Do we understand hydrodynamic instabilities well enough to control them?
 - b. Does the implosion velocity reach the required $3-5 \times 10^7$ cm/s?
 - c. Can we reproducibly time the 4 shocks to arrive and coalesce at the right time and place? (Can we measure the 4th shock timing accurately if required?)
 - d. How reproducible is the implosion process? Is there a suitable metric for this?
 - e. Will the appropriate amount of D-T be blown off the inner surface of the ice layer to facilitate central hot-spot ignition and propagating burn?
 - f. What fraction of the hot spot cavity will be mixed with cold fuel because of hydrodynamic instabilities? (Can we measure the extent to which hydrodynamic instabilities spoil the hot spot cavity?)
 5. Ignition of the central hot spot fuel followed by propagating burn in the surrounding fuel shell
 - a. Will measurements of the evolution of hydrodynamic instabilities be adequate to validate computer simulations?
 - b. If the fuel capsule fails to ignite, will the diagnostic suite provide adequate information to understand why?

Outside of the time-line, there are other questions that we would like to raise. These are listed here and discussed extensively in the following sections:

- Do we need some "non-success-oriented" diagnostics that are not yet in the plan?
- Has the effect of random parameter changes, within reasonable uncertainty limits, on design calculations been done in multidimensional calculations? Is there enough computer time available to the ICF program to do this?
- Is it possible that lower performance fuel capsule designs that are less subject to instabilities should be studied in the early experiments to help validate computer simulation tools?

3.2 Hohlräum Physics

In the simplest picture, an ICF ignition hohlraum is a cylindrical metal can with entrance holes for laser beams in each endcap, and a fusion fuel capsule at its center, as illustrated in Figure 1. At the NIF, ninety-six laser beams are focused through each of the two entrance holes, illuminating and heating the metal wall in four rings around the inside

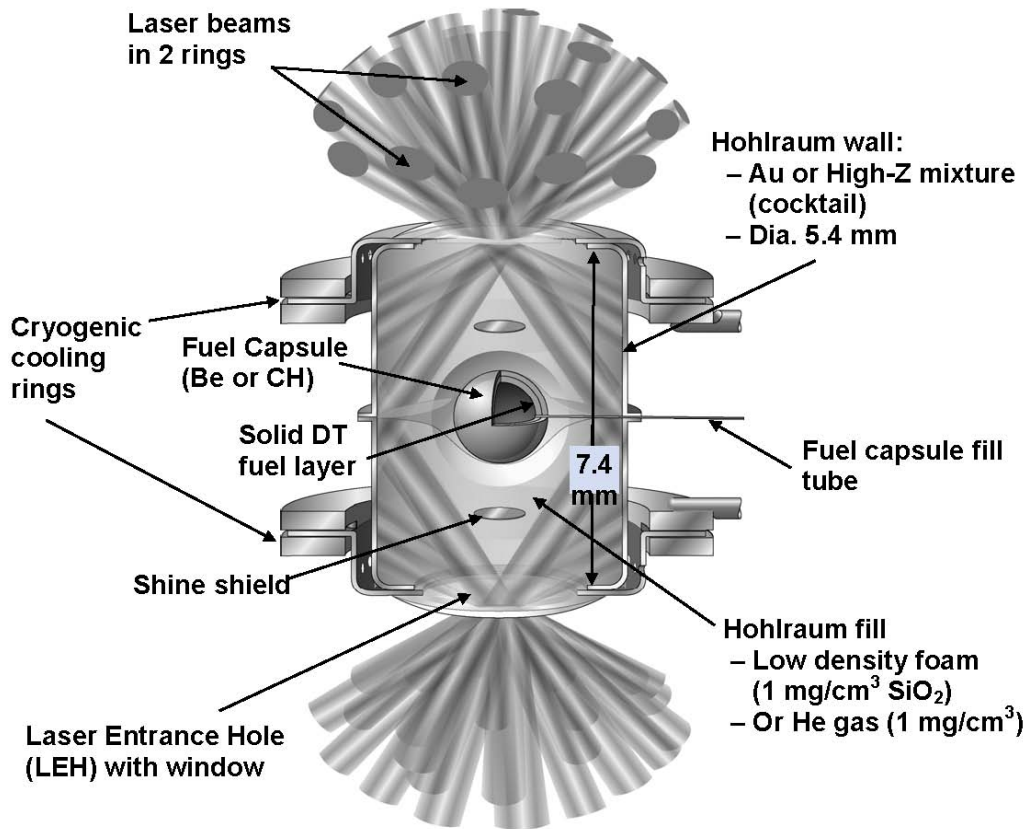


Figure 1. Typical ignition target design for 1.0 MJ delivered laser energy. (Modified from a figure provided by J. Lindl, LLNL.)

of the hohlraum, as shown schematically in Figure 1. The resulting hot metal plasma re-radiates the absorbed laser energy as x-rays that quickly thermalize as a result of multiple absorptions and re-emissions from the hohlraum wall. The thermal x-rays are the driving energy source that ablatively implodes the fuel capsule. This drive must be very symmetric to cause an effective fuel capsule implosion and ignition. These ingredients define the indirect-drive ICF target concept.

If the hot metal plasma moves a significant distance inward from the wall, then the x-ray source would change configuration, and the illumination of the fuel capsule could become unacceptably asymmetric. To minimize this wall motion, the hohlraum is filled with a low-density plasma that limits the motion of the metal plasma. The material for this plasma fill must be nearly transparent to the laser propagation, so that the laser beams can illuminate the metal wall. The presence of this plasma introduces the possibility of laser plasma instabilities (LPI), which will be discussed in detail in the next subsection (3.3). Here we discuss hohlraum issues in detail other than LPI, including LPI here only as needed to explain its effects on hohlraum design.

3.2.1 Hohlräum design and development issues

The basic task of a hohlraum is to convert incoming laser energy efficiently to a uniform thermal x-ray bath for the fuel capsule. To do this efficiently, leakage of x-ray energy into the wall and escape of x-rays through the laser entrance holes must be minimized. The competing demand on the laser entrance hole is to allow the laser light to enter efficiently and with intensity low enough to avoid deleterious laser-plasma interaction effects.

Until recently, the metal wall of the hohlraum was planned to be pure gold, and the low-density plasma fill was to be generated by the incident laser beams from a mixture of helium and hydrogen gases. Several design modifications that will enhance the overall efficiency of the hohlraum are being studied at present, largely because of the limitation of the laser energy available in the first ignition campaign to 1 MJ instead of 1.8 MJ:

1. Mixtures of materials (known as “cocktails”) are being considered for the hohlraum to reduce energy loss through the walls, i.e., to increase the opacity of the walls. This is not a new idea, but it is now more imperative to achieve the 20% energy efficiency gain that might be available, and to face the technological issues that arise from doing it;
2. The hohlraum length can be decreased to reduce the area through which wall losses can occur, and this can be done together with laser-entrance hole shields (“shine shields”) to reduce direct x-ray energy loss through the laser entrance holes, as illustrated in Figure 1;
3. To reduce the risk that LPI will result in an unacceptable amount of laser energy scattered back out of the hohlraum, larger laser entrance holes (again possibly together with shine shields) are being introduced to enable an increase in the laser focal spot size;
4. Another approach to reducing the risk of LPI is to change the material that will form the hot plasma within the hohlraum, for example, by starting from a foam instead of a gas fill.

To improve energy efficiency, the cocktail under consideration at present for the hohlraum wall consists of three different metals: gold, uranium, and dysprosium. The opacity of this mixture is predicted to be higher in the relevant part of the spectrum, and the re-emission of thermal x-rays is predicted to be enhanced. It is important to have detailed absorption and emission spectra for the hohlraum material as manufactured and delivered to the NIF experiment chamber, including oxygenation. It seems likely that this particular

"cocktail" will be feasible to manufacture; if it is not, other effective mixtures of materials are available.

Several variations in hohlraum design are under evaluation, including the following four that were presented in our briefings:

1. "Shine shields" just inside the laser entrance holes (as shown in Figure 1), and a low-density silica-glass foam for low-density plasma generation in place of the hydrogen/helium fill gas in earlier designs;
2. No "shine shields," but a pure helium fill gas (to change the damping expected in one of the stimulated scattering processes discussed in subsection 3.3 relative to the hydrogen/helium mix used in earlier designs);
3. Very low-density helium gas fill plus a thin silica-glass foam liner on the wall that will quickly become plasma after the laser pulse begins;
4. Same very low-density helium gas fill, plus a very thin solid silica-glass liner.

Each of the hohlraum variants has some scientific and technical risk. For example, the glass foam may not homogenize quickly, the shine shields may have to be too small diameter to provide a significant efficiency improvement, and motion of the plasma from the liners in options 3 and 4 may have unacceptable effects on fuel capsule implosion symmetry.

Further design work should allow the NIF Ignition Program to adopt a single point hohlraum design in 2-3 years (in FY2008 according to the present plan). With the important exceptions of laser beam propagation through, and interaction with, the plasma in the hohlraum, (to be discussed in Section II.C), the radiation-hydrodynamics codes LASNEX and HYDRA are capable of effectively simulating the hohlraum environment, even though mass motions are substantial in current designs.

We **recommend** that this design process should include peer review by scientists from the broadest possible community to evaluate the remaining physics uncertainties.

We **recommend** very strongly that a "parts bin" of different hohlraum variations that appear to be promising in the design process be manufactured to facilitate rapid deployment in experiments intended to determine the optimal hohlraum configuration on the NIF. While LLNL scientists have suggested this idea, we are concerned that the success-orientation of the program will leave the parts bin short of possibly useful hohlraum variations unless this is made a priority.

3.2.2. Discussion of risks and uncertainties

If the 1 MJ ignition target designs continue to have positive performance margins in computer simulations, then the major risks of failure in the hohlraum lie in two questions: 1) Will a sufficient fraction of the laser energy propagate to the hohlraum wall through the evolving plasma environment; and 2) Will the location of that laser deposition be predictable and reproducible? There are three physical elements that pose risk of failure of the hohlraum but which cannot be included in integrated target design computer modeling at present: (1) the quality of the incoming laser beam, (2) laser-plasma interaction, and (3) self-generated magnetic fields. The laser may in fact meet the performance requirements to drive the hohlraum effectively to the required radiation temperature. However not all of the laser requirements have been met simultaneously, and thus some uncertainty remains.

We **recommend** that consideration be given to using one quad of the laser to demonstrate, as soon as it is practical to do so, the full energy at $3\text{-}\omega$ delivered to the designer-specified focal spot with all smoothing methods used simultaneously, including full aperture continuous phase plates. This could enable adjustments in beam smoothing methods to be made in a timely and cost-effective manner.

At present, there is little predictive capability for LPI, including the effects that are important to energy efficiency and radiation field symmetry. The relevant physical processes are stimulated scattering, and laser filamentation and bending, respectively. Much more will be said about LPI in the next section. Current hohlraum designs are intended to operate below or near the filamentation threshold and in a regime where stimulated scattering is minimized (less than 10% reflection). However, one cannot be confident of the actual threshold for serious problems until physics understanding improves, and possibly not until the NIF experiments begin in FY2010.

The asymmetric density and temperature gradients in a hohlraum cause currents to flow, potentially leading to large (mega-Gauss) magnetic fields. LLNL scientists noted that they have done only limited calculations of these magnetic fields because of the computational difficulty. However, they believe that the few calculations they have done indicate that the fields will not change the x-ray generation efficiency or the hohlraum energy flows by more than a few percent. Such magnetic fields, however, could affect the dynamics of lower-density plasma within the hohlraum, possibly leading to unexpected laser beam bending, absorption or scattering of laser light. Because so few calculations have been performed, and there have been very few measurements of these magnetic fields within a hohlraum geometry, it is difficult to draw the conclusion with any confidence that they will have negligible effect.

We **recommend**, therefore, that the community invest time and effort on both calculating and measuring self-generated magnetic fields in a hohlraum geometry to see if

the predictions of negligible effect are borne out. Because of the difficulty of such calculations and measurements, we recommend that initial experiments and modeling be carried out in simpler geometries that could be used to calibrate the modeling codes.

In summary, significant risks to the NIF ignition campaign remain in hohlraum design, but these risks can and should be mitigated by coordinated effort involving theory, simulation and experiments, including work at other research centers.

3.3 Laser Plasma Interaction

The propagation of laser light through low-density plasma to the hohlraum walls can be affected by laser-plasma interaction (LPI) in the form of several physical processes. If not controlled, these mechanisms can result in significant scatter of the laser light back out of the hohlraum's laser entrance hole, thus reducing the amount of energy that is available to compress the fuel capsule. Laser-plasma instabilities also produce high-energy ("suprathermal") electrons that can preheat the fusion fuel and reduce its compression. Other possible deleterious processes include laser beam filamentation, cross-beam energy exchange, and the deflection of the laser beams from their intended paths.

If the level of light scattered out of the hohlraum's laser entrance hole is reproducible from one laser shot to another, in principle one can increase the input energy of the laser to make up for the loss. This is a plausible approach because experimental experience shows that once the reflectivity due to plasma instabilities gets above 20-30%, the fractional reflectivity does not rise further when the incident laser power is increased. The original NIF ignition target assumed 1.8 MJ of incident laser light, up to 20% reflection, and an absorbed laser energy of about 1.45 MJ. The new baseline NIF ignition target that was presented to JASON assumed 1.0 MJ of incident laser light, 10% reflection due to laser plasma instabilities, and thus 0.9 MJ of absorbed light. If instead the reflection turns out to be a reproducible 25% (or 35%), then the incident laser light would have to be increased to about 1.2 MJ (or 1.4 MJ) to yield the same 0.9 MJ of absorbed light. In principle, up to 1.8 MJ of laser energy will be available to compensate for higher levels of scatter, but not in the initial ignition campaign as presented. If the backscatter fraction is not reproducible from shot-to-shot, then increasing the incident laser power will not yield reproducible hohlraum conditions, and the predictability of ignition will depend upon the sensitivity of a given fuel capsule design to hohlraum conditions. Therefore, laser backscattering represents a serious potential risk to the goal of achieving ignition in 2010.

Similarly, if the light is reproducibly scattered or deflected to unexpected locations within the hohlraum, with sufficient experimental information, one could retune the laser's temporal and spatial pulse shapes to compensate for asymmetries in x-ray illumination of the fuel capsule. However, once again, it would not be possible to compensate for non-

reproducible movement of the energy deposition spatial and temporal profiles. While there is experimental evidence that the level of laser scatter is reproducible under some conditions, the best approach is to design the ignition target to minimize the amount of light scattered as a result of LPI, and to avoid beam deflection as much as possible.

3.3.1 Experimental results to date

Stimulated Scattering

The two laser-plasma interaction processes that backscatter laser light are called Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS). The first converts some of the incident light wave into an acoustic wave and a backscattered light wave. The second converts incident light into an electron plasma wave and backscattered light, plus some suprathermal electrons. Experiments were carried out on the NOVA laser at LLNL in the early to mid 1990's to determine if the backscattering would be adequately low in a NIF-type hohlraum to give the go-ahead to the NIF Program. The specific requirements were that SBS and SRS would separately be less than 5-10% of the incident laser energy. One could roughly combine these requirements into the simpler rule that the total scattered light energy should be less than 20%. In addition, the energy in suprathermal electrons due to LPI was required to be small enough that it would not affect fuel capsule implosions if suitable design features are included (see subsection 3.4). Some NOVA results showed high levels of backscatter. However, with full beam smoothing to decrease hot spots in the incident beam, some results from NOVA experiments met these requirements.

NIF Early Light experiments in Fall 2004, which used half the laser energy but a significantly larger plasma size than had been used on NOVA, found backscattered light levels as high as about 25%. While high backscattering was expected for some of these experiments, the level could not be predicted quantitatively. The good news is that the level of scatter was reproducible from shot-to-shot and that these results have now been explained by sophisticated computer simulations of SBS and SRS. However, the high level of scattered light is cause for concern since there was not time to fully explore these issues before the series of NIF Early Light target experiments ended.

The possibility that an instability could transfer energy from one ring of laser beams to another where the rings cross near the laser entrance hole was not investigated in the NIF Early Light experiments.

Filamentation

Another laser-plasma instability is called "filamentation." In this process, power non-uniformities initially present in the laser beam cause it to undergo self-focusing, in which

the laser first becomes locally more intense and then the beam spreads significantly. Possible results are that the development of more intense filaments could enhance the backscattering instabilities, and that the beam might not propagate to the intended area on the hohlraum wall, thereby interfering with control of hohlraum symmetry.

The NIF Early Light experiments demonstrated that use of beam smoothing (Smoothing by Spectral Dispersion, or SSD) successfully suppressed filamentation and allowed the laser beam to propagate the required distance to a hohlraum wall. This was an important positive result from the NIF Early Light experiments.

3.3.2 LPI mitigation strategies

It has been proposed that sufficient beam smoothing will reduce the level of backscatter as it did filamentation. However, the quantitative impact of beam smoothing on plasma instabilities under the conditions of a NIF hohlraum has not been resolved by the scientific community; there were not enough NIF Early Light experiments that addressed the backscattering instabilities over the appropriate plasma parameter and length scale range. Under the NIF Ignition Plan, relevant experiments will have high priority on the OMEGA laser using improved SSD smoothing. However, they will not be in the NIF laser beam performance parameter range.

We **recommend** that, in addition to the OMEGA experiments, an aggressive campaign to help improve the level of understand of LPI in NIF-like plasma and hohlraum conditions be carried out in collaboration with French scientists using the LIL laser. (This laser is expected to have similar in parameters to the NIF Early Light beams.)

Proposals to re-design the NIF hohlraum for less linear growth of the backscatter instabilities were listed in subsection 3.2. The hypothesis is that less linear growth will lead to less backscatter as long as the instability is not too strongly driven. Possible techniques to reduce the linear growth include decreasing the electron density or increasing the electron temperature in the plasma generated in the hohlraum, and decreasing the laser intensity inside the hohlraum. NIF hohlraum designs that are currently being explored by the ignition program are aimed at taking advantage of this scaling. Testing these concepts should and does have high priority in the NIF Ignition Plan, including on OMEGA prior to 2010.

Comparison of experimental results with the results from a vibrant theoretical effort and from detailed computer simulations is critical to full understanding of the impact of laser-plasma instabilities on NIF targets. A major component of risk mitigation for all deleterious forms of LPI must be increased emphasis on computational modeling together with a vigorous analytic theory program in order to understand the experiments that have been carried out in the past and to predict the results of future experiments.

We **recommend** that a strong analytic theory capability be included in the program to investigate innovative methods to control the effects of LPI as well as other deleterious processes to be discussed in other sections.

The SRS, SBS and filamentation instabilities were originally modeled using particle-in-cell computer simulation codes that follow detailed motions of both ions and electrons in order to determine plasma behavior in detail. However, such codes are computationally intensive and are not able to model large plasma regions or long enough time intervals to predict behavior in NIF-hohlraum-size plasmas. To accomplish that, modern hybrid codes such as pF3D couple the propagation of the laser beam to nonlinear hydrodynamics of the plasma, with models for the SBS and SRS and at least three types of beam smoothing included. A full cross section of the laser entrance hole region with a modest propagation distance can be modeled in this way. Alternatively, one can simulate the propagation of a laser beam cross section the full distance from the laser entrance hole to the hohlraum walls. In order to obtain the necessary level of understanding of LPI through comparison of such computer simulations with experimental results, major investment of computer resources will be required, as will be discussed in subsection 3.7.

We must expect that some uncertainties in the effects of LPI on the NIF Ignition Campaign will not be fully resolved until tests on the completed laser system can be undertaken. These tests are an important component in the planned NIF Ignition Campaign. However, a vigorous computer simulation program, together with the experiments that we have already discussed, could help determine the range of hohlraum plasma conditions that are likely to minimize the consequences of LPI on the NIF.

There have been very significant advances in theoretical and computational modeling of laser-plasma instabilities over the past several years, as well as in the ability to model laser-plasma interaction experiments. However these models are not yet fully predictive of laser scattering and filamentation: it is not yet possible to predict quantitatively the effects of filamentation, SBS, or SRS on a target design that is qualitatively different from previously tested designs. Likewise it is difficult to predict the quantitative impact of laser plasma instability mitigation ideas, such as different fill gases, foams, liner materials, or laser entrance hole shield materials.

We **recommend** continuing aggressive effort to improve the physics packages for laser-plasma interaction codes such as pF3D.

We **recommend** that, as part of a larger standing risk-mitigation advisory committee for the Associate Director for NIF, a sub-committee of experts on laser-plasma interactions be formed to provide continuing in-depth peer review and advice on the LPI research effort and on LPI issues that are highest-risk to the Ignition Campaign. Sorting out purely

hypothetical risks from those needing serious attention will be an important function of this independent panel. Members of this panel will also provide the external connections crucial to being able to staff up the NIF laser-plasma team when NIF experiments are imminent.

3.4 Capsule Physics and Shock Timing

All ICF fuel capsules under consideration for the NIF share three major components, the ablator shell, which absorbs the x-rays from the hohlraum and compresses the inner capsule as it blows off radially outward, a layer of deuterium and tritium (DT) ice that provides the fuel for the thermonuclear burn, and an inner DT vapor core, which is the result of the DT vapor equilibrium and depends on the capsule temperature just before a test. The ablator must not only drive the fuel implosion by its vaporization (ablation) and the familiar "rocket" effect, but it must also shield the DT fuel shell from preheating due to x-rays or hot electrons from the hohlraum. The DT ice layer provides both the cold fuel, which must be kept on a nearly Fermi-degenerate isentrope to provide high yield, and most (estimated to exceed 80%) of the mass for the core "hot spot," where the thermonuclear burn wave initiates. Careful temporal shaping of the x-ray flux onto the capsule is needed to time the shocks that are launched into the capsule so that the dense DT remains on a cool isentrope during compression. A series of four shocks are used that must be timed so that they coalesce a few μm inside the inner ice surface, strongly constraining the laser power profile.

There are several factors that control the fuel capsule performance, most of which are fairly well understood. First, ignition will occur only when the hot spot column density, ρr , where r is the radius of the hot spot and, ρ , is its mass density, exceeds 0.2-0.4 grams per square centimeter (adequate to thermalize the fast alpha particles created by the DT fusion reaction) at an ion temperature of about 10 keV. Reaching these conditions is primarily controlled by the implosion velocity, which needs to be at least $3\text{-}5 \times 10^7$ cm/sec. It is this implosion velocity requirement that sets the fuel capsule aspect ratio (radius divided by the shell thickness) and determines the level of hydrodynamic instability that can be tolerated. Second, in order for the compressed DT fuel to support a propagating burn that will yield an energy gain of the order of 10 relative to the laser energy incident on the hohlraum, the cold fuel must reach a column density of 1.5-3 grams per square centimeter. This can happen only if the cold DT fuel has remained at a pressure within a small factor of the Fermi-degenerate pressure during compression. This is achieved by compressing the fuel by a first shock that sets the initial adiabat and then by a series of shocks with pressure ratios generally less than four that do not significantly raise the entropy. Ignition occurs when the radius of the DT shell is about 30 times smaller than its initial size.

LLNL scientists have an excellent understanding of the relative importance of the various design parameters and have spent considerable effort optimizing the fuel capsule performance using 1D calculations. The main variables are the capsule radius (which determines the amount of energy absorbed by the capsule in a fixed hohlraum) and the capsule thickness (which determines the velocity that the capsule can reach). A critical constraint is that the capsule must survive a number of intrinsic hydrodynamic instabilities and any asymmetry in the x-ray drive. Indirect drive achieves much of its symmetry by averaging the radiation flux over the hohlraum wall, as noted in subsection 3.2. An important ratio in this regard is the hohlraum radius to the capsule radius, the larger the better for more uniformity. On the other hand the efficiency of conversion of laser energy to energy delivered to the ablator decreases as the ratio of the hohlraum wall area to capsule surface area increases. This leads to fairly straightforward tradeoffs that have led to the current NIF point design. Buried in these tradeoffs are assumptions that have not been proven, primarily the level of asymmetry and hydrodynamic instability that these capsules can tolerate.

LLNL is carrying two point design capsules that are similar in overall size and yield, but differ in the ablator material. One uses a CH (plastic) ablator doped with germanium (Ge) and the other is a beryllium (Be) ablator with a graded-density doping of copper (Cu). The CH ablator capsule has the advantage that there is a great deal more experience in its manufacture and characterization, including controlling the surface and material roughness, and in the preparation and characterization of the DT ice layer. It has the disadvantage that it is predicted to be more susceptible to shorter wavelength hydrodynamic instabilities than the graded-density Cu-doped Be target in detailed computer simulations of capsule implosions. At the present time, the graded-density Cu-doped Be ablator fuel capsule is the preferred one.

3.4.1 One dimensional uncertainties

Despite the excellent theoretical understanding at the conceptual level, NIF's success (i.e., achievement of hot spot ignition followed by a propagating burn) is not assured. An identified uncertainty in the 1D "clean" performance is the timing of the shocks. They must arrive near the inner edge of the ice layer in a tight sequence in order to control the entropy of the DT fuel. By careful timing of the shocks, all but a small fraction of the DT fuel can be kept on a constant low adiabat. If the timing is close to being ideal, heat conduction at the inner edge of the DT fuel determines its entropy profile as well as the mass that will be in the hot spot. If the shock timing is not close, the entropy profile of the inner edge of the DT fuel is determined by the temporal sequence of the shocks. The density and ρr that are achievable depend in detail on the entropy profile in this material. Demonstration that these processes take place as described is possible experimentally only by an ignition test. One possible way to determine the precise shock timing experimentally is to use a target of slightly greater DT thickness than the designed target and have all shocks coalesce at a

location a few microns beyond the designed target thickness. This technique has been proposed and used by some of the target designers at LLNL.

The material blown off of a surface also leads to density interfaces that can have a highly perturbed density structure. Passage of a shock through such a perturbed layer may deposit vorticity and could mix cold fuel into the hot spot to an extent beyond that assumed at present.

Shock timing as an issue involves control of both the shock propagation and coalescence through timing of the x-ray drive intensity variation with time, which depends, in turn, on the laser power pulse shape. We were told that the relative timing of the shocks must be accurate to 50 ps for the first three shocks. Their proposed experimental plan uses a Velocity Interferometer for Surfaces of Any Reflectivity (VISAR, see subsection 3.6) to measure the shock velocities and shock coalescence time in planar geometry. There remain uncertainties in the VISAR measurements, such as whether pre-heat will have an effect, either from fast electrons or x-rays from the point of laser deposition.

The timing of the fourth shock, which we were told needs to be known to better than 100 ps, is especially important and difficult to determine. The ignition plan presented to us calls for the correct fourth shock timing to be determined empirically by varying the timing of the peak x-ray power over a range of timings in 100 ps steps and using the resulting yield as a figure of merit. The primary difficulty with such an approach is that it assumes that this is a one dimensional optimization problem and that all other variables are already optimized. For example, if the failure to achieve ignition is related to hydrodynamic instabilities, then the correct parameter to vary may be the ablator thickness rather than the laser power pulse timing in 50 ps increments. Thus, we suspect that getting the final tuning of the shocks will be a much more difficult problem than the current ignition plan acknowledges.

The shock timing also leads to rather severe constraints on the time dependent symmetry. This effect is included in the integrated simulation and should be rolled into the early time constraints on beam power balance and reproducibility.

Uncertainties in the fuel capsule ablator opacity and in the modeling of radiation transport affect the amount and rate of ablation, which in turn affect the implosion velocity, shock velocities and the hot spot performance. Thus, the required shock timing and capsule yield depend strongly on the x-ray spectrum, especially the “hard spectrum” that can preheat the ablator material before the first shock arrives. Therefore, obtaining emission and absorption characteristics for the hohlraum and capsule ablator materials, including the harder part of the x-ray spectrum, is very important. The ablation rate and implosion velocity also depend critically on the fuel capsule materials equations-of-state (EOS), which have significant remaining uncertainties.

We **recommend** that the community of 1D fuel capsule modelers, including people at LANL, LLNL, LLE and NRL, make comparisons of multiple point designs to assess the level of code-to-code uncertainty. We also recommend carrying out computer simulations to determine the sensitivity of the point designs to EOS and opacity uncertainties, which can then be used to specify needed improvements to these parameters.

We **recommend** that a diagnostic be developed that will enable a direct measurement of the coalescence of the four shocks.

3.4.2 Multi-dimensional issues

The largest uncertainties in capsule performance are related to its response to drive asymmetries (low-order Legendre modes) and hydrodynamic instabilities during compression (high spatial frequency modes). The primary source of low mode asymmetry is the geometry of the hohlraum. Shine shields have been proposed to reduce the effect of the laser entrance holes, and careful relative timing of intensity changes of the four rings of beams is proposed to control the P2 and P4 modes (second and fourth Legendre modes). Higher modes in the drive asymmetry are reduced by the case-to-capsule ratio. Simulations show that these asymmetries can be controlled to the required degree, likely providing some design robustness. A major uncertainty lies in the modeling fidelity and whether the numerical resolution in the LPI code has been adequate to quantify the physical uncertainties introduced by filamentation and beam spray. Provided that LPI effects are reproducible and measurable, and that they do not directly impact the capsule, it may be possible to compensate for them.

Even if the hohlraum delivers a symmetric illumination of the ablating fuel capsule surface with perfect shock timing, hydrodynamic instabilities during the implosion remain a serious challenge to reaching ignition. The Rayleigh-Taylor (RT) instability acts at several stages and plays a critical role in capsule design. At early stages, the RT occurs at the outer ablation interface, as the less-dense ablating material is accelerating the more-dense shell of cool ablator material and DT ice. It also occurs at the ablator-DT interface during the acceleration, where single mode calculations for the Be capsule point design show modes as high as 300 are unstable. This is a potentially serious problem for mixing at the DT-Be interface and needs to be further investigated. At later times, deceleration occurs at the inner DT shell surface as dense DT fuel piles up on the hot, high-pressure, but low-density hot spot. At the inner and outer surfaces it is expected that ablation of material away from the boundary together with decreasing density gradients will stabilize the shortest wavelength modes. This avoidance of an arbitrarily rapid runaway (since the shortest wavelength modes grow the most rapidly with sharp density gradients) allows for the designer to attempt to control the growth of the instabilities.

At the present time, simulations of the RT instability involve calculations of the linear growth factors during an implosion. LLNL "rolls up" all of the RT growth factors into one quantity, which they call the hot spot penetration factor. This is a measure of the extent to which cold fuel is intermixing with the hot spot material. These growth factors yield constraints on the acceptable roughness of the ablator's surface, as well as the DT ice layer. Given an energy absorbed by the capsule (about 140 kJ for a 1 MJ laser input), one can calculate how large of a hot spot penetration can be tolerated without seriously impinging upon the yield. These calculations are still underway.

We **recommend** that detailed 3D simulations be carried out of the behavior of the ablator, DT/Be and hot spot interfaces to ascertain the level of risk involved. Such simulations would supplant the "hot spot penetration factor" as a parameter. We recommend that experiments be performed on OMEGA that can benchmark the 3D simulations.

We **recommend** that reliable central 'hot-spot' imaging diagnostics be implemented early in the ignition campaigns because instabilities may lead to a very non-uniform hot spot and failure to achieve ignition.

For the 2010 ignition campaign both Be and CH ablator shell fuel capsules will use a fill tube to load the DT in place at the NIF chamber center. Numerical simulations indicate that the target should survive the perturbations introduced by the fill tube and glue joint. The simulations included no other nonuniformities that might couple to this highly nonlinear perturbation. However the modes generated by this perturbation are in a range that has relatively low growth factors, and so the impact of the fill tube on the evolution of hydrodynamic instabilities during capsule implosion is considered to be a moderate risk.

3.4.3 Capsule materials issues

To achieve ignition, it is very important that the implosion of the fuel occurs with spherical symmetry, which will certainly be affected to some degree by how the ablator shell was fabricated, and by whether it contains a fill tube. For the Be ablator shells, the leading approach at present is to sputter Be onto a mandrel. However, this process leaves voids within the Be that are potential sources for RT instability. The sputtered Be capsules will include graded-density Cu doping that may provide improvements in hydrodynamic stability. An alternative is a machined capsule, constructed as two separate hemispheres. Each Be hemisphere is very uniform, but a non-uniformity is introduced when the two halves are joined. In machined capsule shells, the Cu dopant must be uniform.

The first shock is designed to melt the Be on the Hugoniot at ~ 2.5 Mbar. However, as the pressure increases there are velocity nonuniformities induced in the Be ablator due to any voids that may be present. The specifications on the size of tolerable velocity perturbations are severe and constrain the number and size of the voids in the sputtered Be.

Target characterization techniques are being developed to measure the microstructure. Smaller grain structures and minimization of voids in the Be structure should reduce these velocity nonuniformities.

Studies of the sputtered Be that is used for the fuel capsules show that elastic wave velocities can vary by 10 percent or more depending on crystal orientation and the presence of voids. This anisotropy implies a significant asymmetry in the shock velocity. The porosity and texture have the effect of imposing a ripple on the shock front, and can even result in the formation of micro-jets on the ~ 0.1 - $10\ \mu\text{m}$ range of the spatial scales of voids and crystals.

We **recommend** improved characterization of the microstructures in the finished (polished) sputtered doped Be capsules. We further recommend experiments that address the shock-melt of Be and that will directly measure the magnitude of the velocity perturbations arising from microstructural imperfections in shock-melted Be. For example, we encourage the experiments using planned high sensitivity interferometric measurements of the induced velocity perturbations in planar Be targets.

We **recommend** that 3D modeling including polycrystalline effects and other materials properties should be carried out together with the experiments in order to improve the ability of the models to simulate conditions in ignition experiments.

We **recommend** that the Ignition Program retain the machined Be alternative for the Be ablator fuel capsules until the sputtered Be is demonstrated to meet the design requirements for that shell material. More broadly, on-going projects that examine other, potentially even better ablator materials (e.g., diamond) should be continued.

The response of polycrystalline Be to the x-ray preheat felt near the outer surface of the ablator is another issue. The differential expansions during x-ray preheat due to the different grain orientations could cause small velocity perturbations that reverberate until they damp out. These velocity perturbations could lead to subsequent RT instability growth at the ablation front and at the Be-DT interface.

Rayleigh-Taylor growth on the inner surface of the DT will depend on both the inner surface roughness and on feedthrough from the DT/Be surface. The presentations were unclear as to whether the temperature dependence of the roughness of the DT layer below the triple point is actually well understood. An empirical relation between the temperature and the roughness was shown, which, since the vapor pressure is also changing along this curve, ties the residual roughness to the density of the gas in the hot spot (one of the critical design parameters).

The ability to measure the interior surface roughness of the DT ice through Be has been solved by the use of x-ray phase contrast imaging, which will be used for CH ablators as well. The DT ice roughness is evidently within the required specifications, but we saw no results showing that the specifications had been met on the need for a very uniform thickness.

3.4.4 Equations of state issues

A fundamental issue is the accuracy with which the equations of state of the critical target materials are known. The EOS of DT figures prominently in the problem of ignition, and warrants examination in view of recent controversies regarding the EOS of hydrogen isotopes. The first shock in the DT sets the initial adiabat, and the subsequent implosion closely follows an isentrope, during which the material compresses from its initial density of ~ 0.2 g/cc to ~ 1000 g/cc, to reach ignition conditions.

EOS information for DT is typically obtained from tables such as Sesame or the Quotidian-Equation-of State (QEOS) that were compiled at the national laboratories; these involve fits to experimental (both static and shock compression) data and theoretical calculations at the highest densities, with regions of interpolation where information is missing. In recent years, the Sesame tables have been revised to take into account the improved accuracy in the density range near 5g/cc made possible by advances in static-compression measurements. At pressures of about 1 Mbar, there have been major disagreements about the pressure-density relations for hydrogen and deuterium, such as the extent to which there is an anomalous volume of collapse (i.e., 30-50% increase in density). Different types of dynamic experiments (gas-gun, laser-shock, isentropic compression, and shock-loading of pre-compressed samples) appear to be in partial disagreement with each other, and there is as yet no reliable understanding of how the static and dynamic high-pressure experiments can be related to each other. The possible problems with the DT EOS at ~ 1 Mbar should have second-order effects on the behavior of the system at the more extreme conditions relevant to ignition; the differences in the Hugoniot at these pressures will affect the subsequent adiabat followed during further compression. The differences in both the DT and the Be EOS will likely affect the detailed timing between the staged shocks.

We **recommend** that the high-energy-density research community resolve remaining issues regarding the EOS of DT near 1 MB, including undertaking additional experiments, if necessary. We also recommend that residual issues regarding the EOS of graded-density Cu-doped Be be the subject of an experimental campaign.

3.4.5 Supporting data and experiments

Computer simulations depend crucially on accurate measurements of the properties of various materials, as discussed above, and on validation by comparison with

measurements. For example, there has been a large long-term national commitment to studying the coupling between radiation and matter under conditions relevant to fusion. For high Z materials, existing codes do not consider every individual absorption and emission line, but combine transitions into frequency blocks that provide effective opacity information that is then incorporated into simulations. Measurements of the emission and absorption properties of hohlraums excited by lasers are being made on OMEGA and are available and can be used to improve the opacity and radiation transport models in the simulations. The emission and absorption properties of the fuel capsule, including the ablator shell and the fuel, may be less well known. As the target becomes compressed, there is a regime in pressure and temperature where even less opacity information is available. At extremely high densities, everything becomes a metal and there are reliable theories and simulations for that regime; however, in regimes with compressions of a few to ~ 10 , there is not much available information. Molecular Dynamics - Density Functional Theory (MD-DFT) simulations using codes such as VASP represent the best current approach. (They are used at LANL, Sandia and CEA, and undoubtedly at other places as well.) This *ab initio* method has had some good success but also suffers from serious limitations.

We **recommend** measuring the opacities of compressed and heated graded-density Cu-doped Be and hydrogen under conditions similar present in the fuel capsule during the first parts of the NIF ignition pulse. Where possible, the measurements should be closely coupled to simulations.

3.4.6 Risk mitigation

The plan to carry forward two point designs (one involving a CH ablator and the other a Be ablator) is a good one. We believe that 3D simulations with both designs should be carried out with the goal of better understanding the impact of Rayleigh-Taylor instabilities on the yield. While such simulations are clearly part of the ignition campaign, including many iterations that probe the parameter space limits allowed by the uncertainties will contribute to risk reduction.

Risk mitigation should also include investigation of alternative ablator designs that reduce the risk due to instability of the DT/Be interface or that increase the robustness of the designs to uncertainties. Optimum performance capsules do not necessarily minimize risks. It is important to identify the most serious risks and perhaps consider designs and experiments that minimize those risks.

The ignition campaign has provided a focus to the NIF Ignition Programs that exercises all aspects of the effort (the laser, targets, modeling, and diagnostics) and is moving everyone forward toward a common goal. The specifications on capsule designs are now set internally by LLNL scientists and are taken as hard limits that the NIF program target fabricators must meet.

We **recommend** that, as part of a larger standing risk-mitigation advisory committee for the Associate Director for the NIF, an active standing subcommittee of experts be established to carry out in-depth peer review of the state of modeling and theoretical understanding of ignition fuel capsules. We believe that such regular review of the point designs by the national community will advance the state-of-the-art of fuel capsule modeling most rapidly and will provide the best input to the experiments once the NIF Ignition campaign begins in 2010.

3.5 Target Fabrication and Cryogenics

The design of targets for the NIF ignition experiments involves extensive use of computational tools such as LASNEX to determine potentially optimal combinations of hohlraum materials, size and shape, fuel capsule materials and shell radii, fabrication tolerances, etc. The full integration of the hohlraum size, shape and materials with the fuel capsule shell radii and materials, as well as, for example, the DT fuel solid layer thickness, and inner gas density (determined by the ice temperature) are required in the simulations. The net result of a whole series of design calculations is to set limiting specifications on many parameters, such as the fuel capsule ablator shell diameter and thickness, the roughness of the outer and inner ablator surfaces, the precise DT ice shell geometry, required thickness uniformity and surface roughness (at the solid-vapor boundary), etc. We were told that there are about sixty “top level” specifications for the hohlraum/target assembly that result from this process.

Cryogenics enters the NIF Ignition Program in three interrelated ways: 1) a cryogenic system to cool and field the target assembly in the target chamber; 2) precision transfer of the DT charge from the on-board reservoir to the interior of the fuel capsule; and 3) cryogenic layering using the concept known as “Beta-layering” to produce the symmetric DT ice layer within the fuel capsule ablator shell.

3.5.1 Target fabrication

Target fabricators have gained considerable experience in previous ICF campaigns, including NOVA and OMEGA laser experiments. The NIF ignition hohlraums are larger than those used in NOVA experiments and should be easier to fabricate. However, the inclusion of such features as low-density foam or glass liners, internal laser entrance hole shields and the use of special “cocktails” for the hohlraum wall material have not yet been demonstrated. We believe that there are no critical breakthroughs needed here, and so we expect rapid progress. The final fully integrated hohlraum-fuel capsule assembly, complete with the fill-tube, thermal shimming, DT gas reservoir, and attachments to the cryogenic

target positioner also has not been demonstrated. However, prototypes of the assembly are being tested and we can identify no insurmountable problems.

The ablator shell material closest to meeting all the required specifications of the point design is the CH ablator. (CH implies a homogeneous polymeric material made from only carbon and hydrogen atoms – no oxygen or nitrogen.) Even with the complication of four contiguous CH layers having differing compositions of Ge dopant, shells have been fabricated that meet the stringent outer and inner surface finish specifications. Minor issues remain, such as isolated material defects and the difficulty in drilling a 5- μm fill hole through the wall, but these should require only slight further development.

There are two difficulties associated with the choice of a CH ablator: 1) it requires a smoother DT ice-vapor interface (the so-called ‘ice roughness’) than a beryllium-ablator fuel capsule to achieve satisfactory robustness against hydrodynamic instabilities, 2) the poor thermal conductivity of the CH requires that the hohlraum wall be thermally shimmed to eliminate imprint of hohlraum thermal non-uniformity on the DT ice layer. Without the thermal shimming, the DT ice would not be a uniform spherical shell, thus seeding the hydrodynamic instabilities at long wavelengths.

The current point design target, dubbed “D1.1,” uses a fuel capsule shell with a Be ablator. The 160- μm -thick shell wall is composed of five contiguous layers, each having a differing amount of Cu dopant. Recent improvements in polishing have achieved an outside surface finish that is close to meeting the NIF requirements.

The manufacturing technique presently preferred for the D1.1 Be shells is sputtering onto a plastic mandrel shell that is later removed. Sputtering permits the addition of graded concentrations of Cu dopant as the shell builds up on the mandrel. Be crystal grains grow in a columnar mode, resulting in radially-oriented grains and, unfortunately, many interstitial, radially-oriented voids. The voids are particularly problematic because they represent density defects that could seed instabilities during the implosion. We consider the presence of voids in the Be ablator shell a significant risk to the ignition campaign at present.

Fabricating the Be shells by direct machining of hemispherical cavities, bonded with an 1- μm -thin Al braze, is an alternate method that has been developed at LANL. The starting material is polycrystalline Be, uniformly doped with a small concentration of Cu. Graded-density dopants are impossible with this technique, but if the same surface finish can be achieved as with the sputtered material, then the two Be shell approaches are presently predicted to have equivalent ignition margin. Finally, the subsequent fabrication steps, fill-hole drilling and fill-tube attachment, are expected to be equivalent for both approaches.

We **recommend** that the development of both the sputtered Be ablator shells with a graded-density dopant profile and the uniformly doped, machined Be shells be continued until a small stockpile of acceptable fuel capsule shells can be prepared from one or the other (or both) methods.

3.5.2 Cryogenics

The cryogenics that must be developed to field the target assemblies has been drastically simplified by the incorporation of a small fill-tube in the ablator shell. In fact, one of the drivers for the use of a fill-tube is the nearly 2-fold lower cost of the cryogenic target handling system that is required. Without a fill-tube, a CH-ablator target must be filled with DT by room temperature permeation at high pressure and then cooled inside the pressure cell to below about 30 K before removal. Cold handling and cold ‘hand-offs’ of the target assembly were unavoidable. Be-ablator capsules likewise must be filled at high pressures, either during their fabrication from machined hemispheres or by a drill and plug technique. Cold handling could be avoided only if it could be shown that the filled capsule was strong enough to be transported at room temperature. All of these technical difficulties are now avoided. By using a fill-tube, cryogenic target handling is not significantly more difficult than handling (non-ignition) room-temperature target assemblies. The residual technical challenge is the transfer of DT from the target handler to the fuel capsule through a fill tube that must be less than 10 μm in diameter.

The use of a fill-tube permits DT storage in a small volume reservoir in the target handler. This reduces the tritium inventory and hence the radiological risks involved with tritium usage. Because fill-tubes must be very small, there are some potential operational problems. The first is the length of time required to fill the fuel capsule with DT, especially in the presence of ^3He formed as a product of tritium beta-decay. The ^3He does not liquefy at temperatures of interest here and hence can act to block the flow as the DT liquefies in the fill-tube at or near the hohlraum wall. Sizeable back-pressures could occur which could be compensated by a higher starting pressure and/or inventory in the on-board D-T reservoir.

The use of beryllium as the ablator material offers substantially more margin in the required DT ice roughness than does plastic. While this has been known for nearly a decade, the choice of Be in the NIF point design target could not be made until a method was found to characterize the quality of the solid DT ice layer inside a shell of this opaque material. A successful collaboration between LLNL and LANL has now led to the development of phase-contrast X-ray imaging of the ice layer. This method is capable of resolving the surface roughness of the DT ice layers from modes 1 to about 100, i.e., nearly as sensitively as the “bright-band” optical method used in transparent spherical capsules. The x-rays are only slightly refracted in passing through the target. Hence, the method is less sensitive to optical irregularities in the ice layers such as refraction due to adjacent grain boundaries. This latter effect causes the bright-band optical method to overestimate

the ice surface roughness, especially at lower temperatures. In fact, recognizing the superiority of the new x-ray method, LLNL states it will implement it even for with transparent (CH ablator) shells.

The new characterization method confirms that the inherent roughness spectrum of beta-layered DT ice meets the NIF requirement specifications at temperatures above 19.4 K for modes above about 10. Moreover, the method confirms that the roughness spectrum does not degrade substantially at 18.3 K, the temperature that yields the point design DT vapor density of 0.3 mg/cm³. However, further research must still be done with the smaller fill tubes to eliminate the large low-mode perturbations blamed on the presence of a 50- μ m-diameter fill-tube and “large glue joint” used in that study. If this is accomplished, it will mean that no enhanced layering methods (such as IR irradiation) need be employed because native beta-layering will produce the required smoothness. However, the LLNL layering technique is very time-consuming. Added to the slow filling time, it remains to be seen whether the particular specification of “no more than 36 hours worth of ³He in the vapor space” can be met.

As noted above, for the proposed CH-ablator shells, thermal shimming of the hohlraum is required. For the direct-drive cryogenic OMEGA fuel capsules, this is accomplished by employing a spherical “layering sphere” around the capsule that is pulled away just prior to the shot. The NIF hohlraums are cylinders, not spheres, and could imprint cylindrical isotherms on the target. By slightly heating the waist of the hohlraum and slightly overcooling the ends, the interior isotherms may be made sufficiently spherical to adequately reduce the lower modes of the ice layer perturbations to meet the requirements placed by designers on the ignition fuel capsules.

With the Be ablator, thermal shimming could be unnecessary since pure Be is as good a thermal conductor as pure copper. The outer pure Be layer in a graded doped capsule shell is rather thick and might establish a good spherical isotherm in the absence of hohlraum shimming. The entire layer of a uniformly doped Be shell may likewise conduct well enough to reduce substantially the need for hohlraum shimming.

3.5.3 Risk mitigation

We have already recommended carrying forward both sputtered and machined manufacturing methods for Be ablator shells until one or the other can meet all necessary requirements set by the target designers. We find that the simplification of the necessary cryogenics afforded by the incorporation of a fill-tube adds risk because of 1) the unavoidable perturbations to capsule symmetry produced by the presence of a fill-hole through the ablator and a fill-tube inserted partially into the ablator, and 2) the disadvantages noted above of the very small fill tube. It may be possible to produce Be shells that are strong enough to reliably hold the DT charge at room temperature. Such a

capsule, filled either by a drill and plug technique or by filling during the joining of hemispheres, would require no cold handling. Of course, it would be necessary to insure that the steps of high pressure “fill and plug,” transport, installation, cool down and layering all can be carried out within the 36-hour deadline that follows from build up of ^3He to the point that it would inhibit ignition.

We **recommend** that the feasibility of high-pressure fill and plug Be ablaters be determined so that it can serve as a back-up to the use of a fill tube if necessary.

Based upon the presentations, we are concerned that LLNL is not taking maximum advantage of the experience and expertise of the national laboratories and other organizations in the critical area of Be shell production.

We **recommend** that additional expertise be brought to bear to help solve outstanding Be capsule shell materials science and fabrication issues, including especially the experts at LLNL and LANL.

3.6 Diagnostics

The diagnostics that will be required in the early stages of the NIF ignition campaign depend upon how difficult achieving ignition proves to be. If easy, it will be unnecessary to probe the physical state of the target in multiple ways, and success-oriented diagnostics should be the focus. However, if the initial ignition shots are expected to have a low probability of success without extensive tuning of target and laser parameters, then more effort should be devoted to diagnostics that illuminate the reason(s) for failure. “Non-success”-oriented vs. success-oriented diagnostics is just one of many coincident dichotomies into which NIF diagnostics can be divided, the others being 1) neutron output $< 10^{14}$ vs. neutron output $> 10^{16}$, 2) optical and X-ray vs. nuclear, and 3) implosion phase vs. burn phase.

The operational reason for the dichotomy is that if the neutron production is high, X-ray and optical instruments and electronics are not expected to work within or near the NIF target chamber. In contrast, nuclear methods require significant neutron production to work.

At the lower laser energies planned for initial NIF operation (0.5-1 MJ), the margins for success are narrow and tuning of target parameters and laser power profile must be precise. We believe that ignition will be difficult, requiring extensive empirical tuning of parameters as well as large numbers of computer simulation studies of LPI, fuel capsule and hohlraum hydrodynamics and radiation transport. As such, we believe that a non-success-oriented approach to diagnostic system planning will accelerate progress towards

achieving ignition. This means a focus on optical and x-ray diagnostics that enable a detailed study of implosion phase issues, with no neutron yields to cause problems. Measures that might be obtainable from nuclear diagnostics, such as yield, hot spot and fuel ρr and temperature, will not be sufficient to enable tuning if these quantities are greatly different from their expected values.

The practical question is the division of resources (human, materiel, and financial) between these two categories of diagnostics. If the initial ignition shots come close to ignition, then nuclear diagnostics may provide sufficient information to tune parameters to achieve ignition and successful fuel burn. However, if problems arise, very detailed LPI, hohlraum and fuel capsule implosion (non-nuclear) diagnostics will be required to resolve the problem(s).

Table 3.1 lists the diagnostics presently planned for the NIF Ignition Campaign, and indicates the intended purpose(s) of each. Details and definitions are contained in the Table caption. We are concerned that the diagnostic suite in the Table may not have enough capability to understand the reasons for a failure to achieve ignition, thereby making rapid recovery more difficult.

Table 3.1 Diagnostic systems in the present plan for the NIF Ignition Campaign

	Energetics	Symmetry	Ablator	Shocking Timing	Implosions
Optical	<ul style="list-style-type: none"> • Full Aperture Backscatter (2) • Near Backscatter Image (2) 			VISAR Interferometer	
X-ray	<ul style="list-style-type: none"> • Soft x-ray Power (DANTE) • Gated soft x-ray imager • Hard x-ray spectrometer (Filter Fluorescer) 	<ul style="list-style-type: none"> • Gated x-ray streaked imaging • Gated x-ray imaging 	<ul style="list-style-type: none"> • Soft x-ray streaked imaging • Gated x-ray imaging 	<ul style="list-style-type: none"> • Streak x-ray imaging • Streaked x-ray bangtime 	<ul style="list-style-type: none"> • Core x-ray imaging
Nuclear		<ul style="list-style-type: none"> • DD yield 		<ul style="list-style-type: none"> • DT yield 	<ul style="list-style-type: none"> • DT yield • Neutron time of flight spectroscopy • γ-ray detector (bangtime) • Magnetic Recoil spectrometer • Neutron imaging • C 12 Activation

3.6.1 Possible problems and low-yield diagnostics

Here we present an incomplete list of possible difficulties (excluding any failure of the laser or the manufactured target to meet specifications) that could cause low neutron yield. These difficulties may result from an incomplete understanding of the fundamental physics or from limitations of computational models or resources that might give the target designer confidence of success that is not warranted, examples of which are given for each difficulty in parentheses.

1. Reflected energy (LPI-induced SRS, SBS instabilities)
2. Preheat of fuel and ablator (LPI-induced fast electrons or hard x-rays)
3. An unfavorable distribution of energy in the hohlraum (refraction, scattering, cross beam coupling, beam filamentation)
4. Hohlraum inefficiency (opacity errors, plasma conditions for laser absorption)
5. Hohlraum non-black body spectrum (non-LTE effects)
6. Hohlraum hydrodynamics (pressure pulse on capsule, wall motion, partial closure of the laser entrance holes)
7. Ablator performance (opacity and/or equation-of-state errors, Be inhomogeneities)
8. Instability at the ablator blowoff surface (Rayleigh-Taylor [RT] instabilities)
9. Instability at the ablator-fuel interface (RT and Richtmeyer-Meshkov (RM) instabilities)
10. Instability at the fuel-hot spot interface (RT and RM instabilities)
11. Shock timing (equation of state errors, uncertainties in various parameters)

Notice that issues we have discussed in previous sections enter in many of the items above. For example, inadequate understanding of LPI contributes to 1-3,11, inadequate understanding of equations of state (including opacity) to 4, 5, 6, 7 and 11, inadequacy of radiation-hydrodynamic calculations to 4-7,11 and inadequate understanding of hydrodynamic instabilities and limitations of computational resources to 8-11.

Many of the issues listed above have been successfully diagnosed on laser facilities in the U.S. and abroad, the necessary diagnostics are mature and it should be straightforward to adapt them to the NIF. (Backscatter diagnostics, for example, were included in NIF Early Light Experiments.) However, some diagnostics will have to be new, and a few of the quantities listed will be a challenge to measure, such as the timing of the fourth shock, to which we will return.

Here we list some of the diagnostic systems followed by the number(s) from the preceding list of the phenomena and issues they can help illuminate:

- A. Full aperture backscatter (1, 2, 11, with spectral diagnostics for SRS)
- B. Near backscatter imager (1, 11)

- C. DANTE soft X-ray power and spectrum (4,5,11)
- D. Time-gated soft X-ray imager (3, 6-11)
- E. Filter fluorescer hard X-ray spectrometer FFLEX (2, 8-11 with line-emitting tracers)
- F. Soft X-ray streaked imager (3, 6-11)
- G. VISAR interferometer (11, but not in spherical geometry)

There are no nuclear diagnostics on this list because any of these physical processes can manifest themselves as low yield, off-specification bang time (i.e., the moment of peak fusion yield), low fuel temperature and inadequate hot spot and fuel pr, which are the quantities for which the nuclear diagnostics are appropriate. Shock timing (11) appears in all because variations that show up on any diagnostic could be related to a change in shock timing.

If LPI proves to be a major problem, it will be clear on several of the diagnostics listed here, but mitigating it will require an understanding of the plasma conditions in the hohlraum. Previously successful diagnostics, such as Thomson scattering and a more detailed, time dependent x-ray spectrometer than DANTE would be valuable for this purpose, and there could be others as well.

We **recommend** that the program plan includes diagnostics that reveal hohlraum plasma conditions and important details of the radiation spectrum in the suite to be available early in the ignition campaign.

Because of the inability of these instruments to function (or even survive) in a high radiation environment, it will generally be necessary to employ them in experiments with no neutron yield, as might be expected with laser pulses truncated to include only the first three shocks, or possibly with dudded fuel (or no fuel at all because the neutron output of even the DD and TT reactions could harm the X-ray or optical instruments). Targets without fuel are not good hydrodynamic proxies of complete targets. However, three-shock experiments will have full verisimilitude through the shell compression phase. Thus, full implosion phase and hot spot formation tests, which require the fourth and final shock, may not benefit from X-ray and optical diagnostics. Nevertheless, it is possible that experiments can be designed to answer specific questions with specific x-ray or optical diagnostics. For example, if ice smoothness is not critical to some other aspect or aspects of the implosion sequence that is to be studied, H₂ dudding can be used; if ice smoothness is critical but a significant neutron fluence can be tolerated, T₂ dudding can be used (possibly with a trace of DT to enable use of 14 MeV neutron diagnostics).

The NIF ignition plan calls for a determination of the proper timing of the fourth shock by changing the laser pulse timing in small steps in full ignition tests and optimizing the yield. This would be done after the timing of the first three shocks has been determined

and optimized in planar geometry. Unfortunately, there are several physical processes that could reduce yield and prevent ignition, including the possibility of small variations from one shot to the next in all of the processes 1-10 at the beginning of this section. Thus, varying the laser pulse in small steps with the intention of moving the timing of the fourth shock in small steps may not work.

We **recommend** that the program seek a more direct measure of the fourth shock timing, perhaps through advanced radiography, to be discussed shortly.

Among the most critical fuel capsule parameters to know to evaluate an implosion are the inner and outer radii of each shell (ablator and fuel), their thicknesses, the spread or smearing of each radius produced by hydrodynamic instability (high spatial frequency modes) at the surfaces, and deviation from spherical symmetry (low spatial frequency modes produced by phenomena 3 and 6 plus intrinsic asymmetries such as the fuel capsule fill tube and possible down-coupling of higher mode instabilities). The diagnostics that could directly address these issues are X-ray imagers, both streaked and time-gated. These are complementary; streaked imagers produce the continuous time-dependence of a one-dimensional slice of image, while time-gated imagers produce a small number (one or a few) of two-dimensional snapshots. X-ray imagers could permit direct determination of the progress of the implosion (radii vs. time, critical to shock timing), shell thickness (and hence shell adiabats), degree of mixing at interfaces (and hence effects of hydrodynamic instabilities) and asymmetry. Time-gated images may be the easiest to interpret, and are particularly suited to studying asymmetry. X-ray backlit images (which naturally provide time-gating if the backlighting pulse is short) of fuel capsules are potentially effective in disclosing and measuring asymmetry. However, we suggest that careful re-analysis of the foam-ball technique for the NIF parameters needs to be undertaken. Likewise, careful analysis of the thin-shell capsules as a measure of asymmetry for NIF parameters should be carried out.

An important issue is the progress of the ablation front in the fuel capsule. Calculations indicate that ablator burn-through must be controlled to 1% accuracy. At present, the accuracy of determining ablator burn-through is estimated to be 10% using the streaked X-ray imager in slab geometry. Much improvement will be required here, both in accuracy and in extending the measurement to converging geometry. A possible solution is the use of hard X-ray line spectroscopy of dopants embedded in the ablator in a very sharp-edged layer, the emission from which will signal the arrival of the ablation front. The emission lines require a time-resolved detector (unlike the FFLEX) and a narrow bandwidth detection scheme to discriminate against both the thermal radiation and the harder radiation produced by energetic electrons in the hohlraum. The Cu included in Be ablators and Ge in CH ablators (each required to reduce preheat) are potential x-ray line sources, or special dopants with emission lines at felicitous energies could be added. (Note

that there are significant fabrication issues here because to give a useful time-stamp the dopants must be sharply delimited.)

We **recommend** that a hard x-ray emission line-based diagnostic for ablation front position based upon dopants in the ablator be evaluated and perhaps tested at Z, where the radiation environment is probably at least as difficult as at the NIF.

The Advanced Radiographic Capability, a proposed picosecond time scale, ultra-high intensity laser-based x-ray backlighter imager, could offer a great deal of leverage in attacking many of these implosion issues (especially 7-11). An X-ray energy of 17 keV has been proposed, an energy where the cold material optical depth of a 25 μ m gold hohlraum wall is 4-5. Therefore, the backlighter imager would require the use of Be windows covered with about 5 μ m of gold, at the price of some potential asymmetry after the thinner layer of gold burns through.

We **recommend** that plans be developed for a high energy X ray source for backlighter imaging using an ultra-high intensity laser pulse so that it can be made available as soon as possible after the start of the ignition campaign.

3.6.2. Nuclear diagnostics for shots with significant fusion yield

There are a number of nuclear-based diagnostics that can be used to determine the fuel conditions in which nuclear yield is produced. The burning region is characterized by several quantities:

13. ρr (hot spot and fuel shell)
14. T_{ion} (ion temperature, both in the hot spot and in the fuel shell)
15. Total yield
16. "bang time"
17. Symmetry (both of the hot spot and the fuel shell)
18. T_e (electron temperature, both in the hot spot and the fuel shell)

Here we list some of the diagnostics, followed by (in parentheses) the parameters from the preceding list that they best diagnose:

- H. Neutron Reaction History (nRHS) (15, 16)
- I. Gamma-ray Reaction History (γ RHS) using gas Cerenkov detector (15, 16)
- J. (n,p) scattering in plastic, followed by diode detection (Protex) (15)
- K. Radiochemical activation (Cu or $^{12}\text{C}(n,2n)^{11}\text{C}$) (13, 15)
- L. Neutron imaging (unscattered and scattered) (17)
- M. Magnetic recoil spectrometry (MRS) of protons from (n,p) reactions (14)

- N. Neutron time-of-flight (nTOF) using CVD diamond detectors (13-16)
- O. High energy X-ray imager (HEXI) (13,17,18)

Most, but not all, of these diagnostics are mature. Even though not all are likely to be deployed in 2010, they will provide a powerful suite of diagnostics for assessing burn conditions when they are needed.

However, if ignition does not occur it will probably not be possible to determine how and why a shot failed from nuclear diagnostics alone because, as noted above, many failure modes may produce similar nuclear characteristics. These are really *late-time* diagnostics, and are not specific in diagnosing the early-time behavior of the target, the diagnosis of which will probably be critical to understanding a failure to ignite.

We **recommend** that, on balance, the non-nuclear (X ray and optical) diagnostics should be the focus of the diagnostic development program for early ignition campaign experiments in order to understand what physical processes are responsible for low neutron yields.

3.7 Computing and Software

Computation plays an essential role in the NIF program. The simulation of the complex processes that ensue during a NIF shot requires state-of-the-art capability. In this section we review the role of computation in modeling the radiation hydrodynamics that drive the capsule implosion as well as the complex laser-plasma interactions that take place in the hohlraum to generate the indirect x-ray drive. We also discuss briefly the role of computation in the analysis of the data that will be generated by the many experiments that will be carried out in support of the NIF Ignition Campaign.

3.7.1 Radiation hydrodynamics

The NIF program makes primary use of two radiation hydrodynamics codes to design and analyze the performance of hohlraums and capsules for ICF implosions. The first, LASNEX, is a two-dimensional legacy code based on a Lagrangian framework with a mesh remapping capability. The second, HYDRA, developed partly under the aegis of the ASC program is a fully three dimensional radiation hydrodynamics code based on an Arbitrary Lagrangian-Eulerian (ALE) framework. It includes second order differencing and monotone shock capturing algorithms. It represents a state-of-the-art capability in radiation hydrodynamics simulation. Both codes have been extensively compared with experiments relevant to the ICF problem. Both codes also include most of the relevant physics phenomena needed to model the NIF target. An important exception is that neither code currently has the capability to model laser plasma interaction (LPI) instabilities in a hohlraum. This is treated in the rad-hydro codes by decrementing the laser energy

available to the hohlraum. LPI is modeled in detail using other codes, to be discussed in subsection 3.7.4.

Numerous physics packages and post processing diagnostics packages are available in both LASNEX and HYDRA with modules that provide a variety of models for the most uncertain physics such as radiation transport, EOS, and opacity. This multiplicity of models can be used to assess the uncertainties introduced by the approximations. In addition, HYDRA is a parallel code and is capable of running on the massively parallel computers available on Livermore's ASC class computing facilities, which can provide tens of Teraflops of computational capability.

Integrated calculations including the hohlraum and capsule, plus the possibility of shine shields in front of the laser entrance windows, provide the most self-consistent simulations of all the phenomena. An important aspect of the target performance is the control of asymmetries arising from the refraction of the laser beams by density gradients in the complex plasma that results from the laser-hohlraum interaction. It is important, therefore, that adequate resolution of these phenomena be used and that a careful assessment of the consequences of numerical modeling errors be made. As discussed below, there are indications that it would be of benefit to the program to carry out more simulations in both a capability and capacity mode. The amount of computational resources dedicated to the NIF project, therefore, particularly in support of the three dimensional simulations with HYDRA, may have to be substantially increased.

3.7.2 Hydrodynamic instabilities

A critical issue affecting the ignition of the ICF capsule is the control of hydrodynamic instabilities. Because computer limitations restrict the number of modes that can be simulated in the capsule in fully integrated (that is capsule plus hohlraum) 3D simulations, the assessment of the impact of Rayleigh-Taylor and Richtmyer-Meshkov instabilities in the capsule is done in a different way. Instability growth is taken from the results of single mode simulations performed at initial amplitudes sufficiently low that they remain linear throughout the simulation. Growth factors for each mode introduced by each source (outer surface perturbations, inner surface ice roughness, internal layer nonuniformities, etc.) are then determined. The amplitude of each mode is then found by applying the growth factor to an expected initial amplitude of each mode. The modal amplitudes in this multi-mode setting are summed in quadrature. This is a valid procedure should these modes remain in the linear regime, and significant effort has gone into designing capsules that are optimized in this regard. Corrections for possible evolution of the modes into a weakly nonlinear regime are accounted for by using a weakly nonlinear saturation model developed at LLNL. The result is used to determine the penetration distance of the cold surrounding fuel into the hot spot. This, in turn, serves as a figure of merit for gain reduction. The basis of this approach is that the growth of the (fastest

growing) short wavelength modes are strongly affected and stabilized by the ablation process.

The validity of the application of linear theory is assessed by using a more limited number of multimode simulations of capsule performance where the full nonlinear interactions and yield degradation are simulated; such consistency checks were not shown during this review and, in some cases, have yet to be performed for the exact fuel capsule designs under consideration for the NIF Ignition Campaign. We view such multimode calculations using the current target designs as essential to verification of the model used in the integrated ignition calculations.

We **recommend** that experiments be performed on OMEGA to assess how the Be/DT interface behaves in drive conditions that are relevant to NIF ignition experiments and that the resulting experimental database be used extensively to compare with simulations.

A related issue is the modeling of fluid mixing during the implosion process arising, for example, from local Kelvin-Helmholtz instabilities. These are important in the context of capsule implosions because they can result in mode mixing, i.e., low spatial frequency modes produced by mixing of high spatial frequency modes. The result would be faster-moving, larger scale bubbles and spikes that can penetrate deeper into the hot spot in the late stages of the implosion. NIF capsules are optimized to minimize such mixing but it is well known that present day codes can artificially damp such instabilities if the simulations are not adequately resolved. Some very preliminary results along this line were presented by LANL scientists, who have also used LASNEX to model NIF implosions. The LANL work examined the effects on capsule implosion when subgrid scales were modeled. In view of the limited ability of most simulation codes to adequately model such mixing processes, it would be important in future work to understand the role of this mixing and whether it has any impact on the location of the fuel capsule ignition “cliff.”

3.7.3 Quantification of uncertainties in fuel capsule design

Scientists at LLNL have carried out many studies of the effects of various asymmetries and capsule nonuniformities on capsule gain and have developed an understanding of the relative importance of the various factors. They have not developed an equivalent understanding of the effects of modeling uncertainties (both numerical and physical). Extensive comparisons to experiment have provided considerable confidence in the simulation capabilities, but quantitative estimates of the uncertainties are lacking. As a result, there remains uncertainty in the gain achieved in purely 1D (radial) calculations. It is the pure radial flow that provides the base state that is then perturbed in order to assess uncertainties arising from instability growth.

We are also concerned that a quantitative understanding of the errors associated with the binning of the opacities to treat radiation transport is lacking. Uncertainties in the

radiation modeling, EOS, and opacities can also affect the growth of Rayleigh-Taylor instabilities. A quantitative assessment of the uncertainties from these effects is currently lacking but work in this direction is in progress.

Finally, a more quantitative assessment is needed of the effect of using the weakly nonlinear quadrature roll-up of single modes discussed above as a means of determining yield degradation. This will require the use of highly resolved 3D simulations with realistic initial perturbations near the ignition cliff since the location of the ignition cliff will be sensitive to these uncertainties and this, in turn, can be a critical source of risk for the project. In addition, more highly resolved 3D multimode simulations may be required to assess the behavior of the DT/Be interface for the Be fuel capsules where large growth factors at the higher mode numbers are expected. The LLNL scientists recognize these difficulties.

We **recommend** substantially increased computational resources to address the above issues. In particular, such capacity-mode calculations can help provide a thorough assessment of performance margins and uncertainties.

While very highly resolved simulations have been carried out in two dimensions (by LLNL, NRL and other groups), simulations of equivalent resolution in three dimensions will require considerable ASC-class resources (in addition to appropriate staffing). We see the need for both capacity-mode calculations (large numbers of lower resolution runs to assess uncertainties and margins) as well as capability mode calculations (to provide confidence in the lower resolution assessments).

3.7.4 Hohlräum modeling and laser-plasma interactions

In addition to the target design and analysis codes, considerable effort has gone into the development of separate codes to investigate laser plasma interaction (LPI) issues in the hohlraum. In subsection 3.3.2, we discussed the computational methods used for simulating LPI. To summarize, the present state-of-the-art code, pF3D, can study larger spatial scales and timescales approaching those in an actual NIF hohlraum. This code uses a model that couples the propagation of the laser beam to nonlinear hydrodynamics of the plasma, including models for SBS and SRS backscatter that come from hybrid simulation codes and experimental data, and also including beam smoothing. Calculations of LPI in a NIF-scale hohlraum with pF3D require substantial computational resources (typically tens of hours of runtime on several hundred processors of an ASC level computer).

From the briefings received, it is our view that it has been difficult for the laser-plasma interaction groups at LLNL and LANL to gain access to this scale of computational resources on a routine basis. Yet computations such as these serve as a very significant risk-mitigation strategy for the NIF Ignition Campaign. In particular, full pF3D runs will

be needed more frequently than they have in the past, and these runs will have to cover larger volumes and longer times than they have in the past.

We **recommend** allocation of additional computational resources, such as the 360 Tflop Blue Gene/L computer or comparable machines, to risk-mitigation studies of uncertainties related to laser-plasma instabilities. We view this as a very important risk mitigation strategy for the NIF Program.

An additional need for large-scale simulations could potentially come from studies of magnetic field generation in the hohlraum, which was introduced in subsection 3.2.2. LASNEX simulations in 2D showed that magnetic fields generated near the laser entrance holes could have significant effects on the plasma thermal conductivity, which, in turn, affects the temperature, velocity and density profiles. The 3D code, HYDRA, has a more limited magnetic field capability than LASNEX. However, temperature and density gradients in the vicinity of the laser spots and possibly near the fill tube are a potential source of magnetic fields, which are inherently 3D. The major issue in simulating this phenomenon is providing sufficient resolution to resolve the density and temperature gradients and the magnetic field generating source terms as well as the field itself. These simulations will undoubtedly also require considerable computational resources.

3.7.5. Software for the comparison of experimental results with simulations

Each NIF diagnostic instrument is to be delivered with a complete data-analysis software suite. We were told that for the NIF Early Light experiments, this data analysis software worked well and produced results soon after the target shot was complete. However when ignition-campaign experiments begin at NIF, target designers and experimenters will need other software tools to understand quickly whether the outputs of the diagnostic instrument software agree with the predictions of hydrodynamics models and of laser-plasma interaction codes. This requires a class of “interface” software that uses the output of hydro codes or laser-plasma interaction codes to compute what the expected diagnostics signatures should be for a specific target design.

It is our understanding that much of this interface software exists today and is used by target designers and laser-plasma interaction physicists to compare experiments with predictions. However, to assimilate numerous NIF target shot results rapidly and to plan for modifications in future shots, the existing interface software should be standardized, and optimized both for computational efficiency and ease of use by many potential users.

We **recommend** that standardized and optimized interface software development begin very soon.

3.8 Use of Other Facilities

The OMEGA laser system was designed and optimized for direct-drive illumination, not for the study of NIF indirect-drive targets. However, because of the significant laser energy available, up to 30 kJ, and the flexibility inherent in this laser system, OMEGA has played an important role in support of the NIF program. That role will necessarily increase now that NIF laser-target experiments are halted until the NIF Project completion in mid-FY2009. In each of the major elements of the ignition campaign, OMEGA experiments will help LLNL scientists make key decisions.

OMEGA experiments on critical issues include campaigns to evaluate hohlraum cocktails, decide between the use of gas or foams or liners in the hohlraum, evaluate Be as an ablator material, and evaluate ways of reducing laser-plasma instabilities via beam smoothing in hohlraum geometry. OMEGA will also be used to evaluate the cross-beam interactions between laser beams near the entrance holes, and their interaction with plasma blowoff from the edge of the entrance holes.

An important role for OMEGA will be used to activate and validate a variety of new diagnostics that could be used for ablator burn-through, shock timing, and fill tube perturbations. This laser could also be used for exploratory studies of self-generated magnetic fields and related diagnostics.

Some of these physics topics will require a new set of phase plates that are optimized for x-ray drive. The final design of these phase plates will be completed soon, and they will be installed on OMEGA in 2007. Future x-ray drive experiments on OMEGA will have the option of using the same beam smoothing as will be available on the NIF, or significantly more smoothing for comparison studies.

We **recommend** that experiments be designed for OMEGA that would enable important aspects of 3D simulation codes to be validated, such as studies of the fuel capsule interfaces, the effects of hohlraum asymmetries, etc.

The LIL laser facility in France is expected to begin laser-target experiments in 2006. This facility will produce laser energy and have a beam geometry similar to what was used in the NIF Early Light experiments. In other words, the laser beams will all be incident on the target from one direction, as compared to OMEGA where the laser beams are incident from all directions. LLNL is planning to take part in these French experiments on LIL.

We **recommend** that LLNL scientists propose detailed experiments to address issues related to LPI physics and other relevant physics issues on this facility because of the unique and important contributions that are possible with the LIL laser configuration.

Plans by the NIF Ignition Program to make use of U.S. high energy density facilities other than OMEGA do not appear to be well developed. The Z facility can produce 1-2 MJ of x-rays over 4-10 ns. Several types of experiments are possible with this source that might provide important contributions to the understanding of the NIF targets. These include EOS, melt morphology and radiation opacity information, on Be and high Z cocktails, at both high and low densities. The Nike KrF laser has the unique capability of producing ultra-uniform laser illumination over a spot size of nearly a millimeter. With this capability for uniform pressure generation in a simple geometry, Nike has been used to measure the DT EOS up to 1.5 Mbar. Nike could also be used to make similar measurements on Be, and also to make x-ray opacity measurements on compressed Be.

We **recommend** that LLNL scientists work with their counterparts at Sandia and NRL to determine which of the two facilities, Z/ZR or Nike, can best be used for the accurate determination of fundamental information on materials, and then appropriate experiments should be carried out.

3.9 Risk Mitigation

Any large technical project carrying forward ground-breaking science and technology, as is certainly the case with the NIF Ignition Program, is subject to scientific and technical risks. We have discussed many of them in the preceding sections, and offered specific recommendations to address some of them. Here we would like to make some suggestions as to how the program might deal with risk in a more systematic way. Because of a general orientation toward success in the NIF Ignition Program the strategies for identifying and mitigating risks are not articulated at the level of detail that we feel is appropriate.

In the limited time available for our study, we cannot expect to have identified the important physics issues more effectively than can the scientists within the program. As such, we believe that a detailed and prudent risk mitigation plan must be their product, not ours. Therefore, while we suggest a particular strategy for doing this here, our point is that a systematic approach to risk mitigation should be put in place. The purpose of such a strategy between now and the start of the NIF Ignition Campaign is to maximize the likelihood that the scientific issues associated with achieving ignition will be answered within a reasonable length of time (1-3 years) after the start of ignition experiments.

We **recommend** that the NIF Ignition Program participants organize risk mitigation using a plan similar to the Quantification of Margins and Uncertainties (QMU) methodology that is being developed on the weapon side of the Stockpile Stewardship plan. This tool should involve evaluating the risks associated with both computational and

experimental uncertainties, and should particularly assess uncertainties and performance margins associated with laser energies in the range of 1 to 1.8 MJ.

The risk mitigation strategy should both identify and quantify risks and enable agile program response when the risks associated with particular uncertainties are found to be particularly important and are amenable to mitigation, for example by experiments on OMEGA, Z/ZR, Nike or LIL, or by an aggressive and detailed computational study.

JASON was asked to focus on the early phases of the ignition campaign. Our recommendations, however, are intended to address risk mitigation up to the initial ignition campaign in 2010 as well as beyond. Long-term risk mitigation strategies should include planning for such options as direct drive and using the laser light in the green (2ω) instead of in the blue (3ω), where considerably more laser energy could be available at the hohlraum. We briefly discuss the latter possibility at the end of this section.

Probably the single most important risk mitigation activity in the current program plan is to bring the laser energy delivered to the target up to the ultimate 1.8 MJ at 3ω as early as possible in the ignition campaign. Therefore, although the laser was specified as “a given” for our study, we conclude this section with some information on the 3ω optics development effort.

3.9.1 Management structure/community involvement

NIF management is quite properly focused on completing major construction items in preparation for the ignition studies to follow. The management team is strong and they appear to be guiding the construction phase toward a successful completion within the complex set of constraints under which they must perform.

Management issues will change as NIF transitions from the construction project phase to executing the ignition program. Success in the NIF ignition program requires management of critical scientific resources such as computer time, access to special technical facilities and allocation of laser shots, in addition to the traditional project resources of time, money and scope. The very high value of individual laser shots demands extraordinary care with component designs, simulations and system-integration of laser control, hohlraums, fuel capsules and diagnostics.

We **recommend** that one or more technical/scientific advisory committees (TSACs) should be appointed by the LLNL Director to advise top NIF leadership on allocation of scientific resources and to provide peer review of critical program elements, such as target design and development of diagnostic systems. The TSAC(s) should be standing committees comprising technical experts and other individuals drawn broadly from inside and outside LLNL and the NIF Ignition Program. TSAC(s) should conduct regularly

scheduled meetings and reviews that are open to the NIF scientific community where proposals, component designs and the ignition shot plan are discussed, debated and reviewed.

We also believe that risk mitigation should include efforts to enlarge the community that is committed to the success of the NIF ignition campaign.

We **recommend** that LLNL create mechanisms (such as the advisory committees just mentioned) that enable the broadest possible community to contribute to the ignition campaign and be part of the team that works toward its potential success. If LLNL succeeds at getting participation from universities and other laboratories, it will be better positioned to address the new physics questions that are bound to arise during the ignition campaign.

3.9.2 Operation at 2- ω : Mitigating the risk of final optics damage

The baseline NIF Ignition Program calls for tripling the fundamental laser frequency in the infrared to the ultraviolet using non-linear materials, and delivering that so-called “3- ω ” light to the target. In favor of the 3- ω operation (vs 2- ω) is that higher hohlraum temperatures are predicted to be reached before LPI will cause unacceptable laser backscatter and hot electron generation; this, in turn, means that less laser energy is needed for ignition. However, this strategy introduces risks associated with a lower damage threshold for the final optics, the existence of which has long been known and which the NIF project is addressing (see next sub-section). One possible risk-mitigation strategy is to switch laser operation from the baseline 3- ω mode to operation at 2- ω (visible green light). Changing from tripling to doubling, in itself, carries little or no risk, since the technology and equipment is very nearly the same. Roughly speaking, the threshold fluence for damage of optical components by 2- ω laser light is two or three times larger than that for 3- ω light, meaning that the total laser energy output could be increased by this factor for the same level of optics damage. Target designs for 2- ω light that are comparable in performance margin to the point design for 3- ω light at 1.8 MJ, but with a hohlraum temperature reduced from 300 eV to 275 eV to account for the reduced LPI threshold, are predicted to require over 3 MJ of 2- ω light. However, that energy at 2- ω (over 3 MJ, instead of 1.8 MJ at 3- ω) can be achieved by the NIF laser.

We **recommend** continued consideration of 2- ω operation in the long-term NIF Ignition Plan just as the program is considering Direct Drive in its long-term operational plan.

3.9.3 Final Optics

We were told that damage of laser optical elements is not an issue in the NIF laser except for optical elements that are subject to a high fluence of frequency-tripled ($3-\omega$) light, i.e., the light that is to be delivered to the target. Frequency-tripling occurs just before the light is delivered to the target chamber and so only the final optics are of concern. The optics exposed to $3-\omega$ in each beam line consist of the tripling crystal and polarization smoother, both DKDP, and the wedged focus lens and the main debris shield, both made of fused silica. In addition, there is a disposable debris shield made of optical quality glass that is intended to be sacrificial and is of no consequence here. The rate of damage initiation and growth in the consequential $3-\omega$ optics increases with laser fluence, which directly impacts the operation cost of the NIF. To the extent that this increased operational cost limits the energy available to drive targets in ignition experiments, the issue of final optics damage adds risk to the Ignition Program.

A review of the characterization of prototype final optics elements confirms that they have been tested to fluences of 13 J/cm^2 on full-scale components ($400 \times 400 \text{ mm} = 1.6 \times 10^3 \text{ cm}^2$). The average fluence required for 1.8 MJ operation of the NIF is 8.2 J/cm^2 ($8.2 \text{ J/cm}^2 \times 192 \text{ beams} \times 1150 \text{ cm}^2 \text{ per beam}$). Therefore, testing to 13 J/cm^2 is certainly relevant to the most stressful experiments currently envisaged for the ignition campaigns.

The initiation and growth (with multiple pulses) of laser-induced damage has been found to be proportional to the density of surface defects and contamination observed in the final optics. In particular, there is no observation of bulk damage (that is, damage intrinsically associated with the interior of the glass or crystalline material itself). The detailed mechanisms of surface damage initiation and growth are not fully understood at present, but the damage can be found and mitigated so that the damaged optical element can be reused. The empirical conclusion is that the NIF can be operated at the peak design energy of 1.8 MJ, but the operational cost will be increased if this is the regular operational level because of the need for replacement optics and major facilities for damage mitigation.

It is significant that there have been several examples of optics that suffered no damage, even at the peak fluences tested. As might be expected, these optics were free of observed surface defects and contamination. Although damage-free conditions have not been reproducibly achieved, there is nevertheless reason to expect that increasingly stringent inspection and preparation of optics could make a difference. We were told that there is an effort underway to identify and mitigate potential damage sites in advance of their use at high fluence on the NIF. If such a program could enable experiments in the initial ignition campaign at 1.8 MJ of laser energy, this would be very important for increasing the available performance margin for the point design targets.

We **recommend** that the NIF Program continue its aggressive program to identify and mitigate defects in final optics so that routine operation above 1 MJ for ignition experiments will be possible as needed in the initial ignition campaign.