High-Power Laser Source Evaluation

C. A. Back, C. D. Decker, G. J. DiPeso, M. Gerassimenko,
R. A. Managan, F. J. D. Serduke, G. F. Simonson, L. J. Suter

July 1997

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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I-Introduction and Overview

Robust Nuclear-Weapons-Effects Testing (NWET) capability will be needed for the foreseeable future to ensure the performance and reliability of the evolving U.S. stockpile of weapons and other assets in nuclear environments. The use of high-energy lasers to generate environments of use in nuclear weapon effects simulations has been addressed in the work described in this report. Laser-driven hohlraums and a variety of other targets have been considered in an effort to develop NWET capability of the highest possible fidelity in above-ground experiments. The envelope of large-system test needs is shown as the gray region in fig. 1. It does not represent the spectrum of any device; it is just the envelope of the spectral region of outputs from a number of possible devices. It is a goal of our laser-only and ignition-capsule source development work to generate x rays that fall

Figure 1: Plot of the uniform fluence-area products of various NIF non-ignition sources against a background of the envelope of large-system test requirements suggested by Dr. Cyrus Knowles of Jaycor. We thank Dr. John Davis of Alme & Associates who provided this figure and generated the various source capabilities.

somewhere in this envelope. One of the earlier appearances of this envelope is in ref. 1.

The Defense Special Weapons Agency has supported work described herein. A total of \$200K was provided in IACRO 96-3043. The period of performance specified in the Statement of Work ran from 28 February 1996 until 30 November 1996. This period was extended, by agreement with DSWA, for two reasons: 1) despite the stated period of performance, funds were not available at LLNL to begin this work until somewhat later in

the fiscal year, and 2) we agreed to stretch the current resources until follow-on funds were in hand, to minimize effects of ramping down and up again.

The tasks enumerated in the Statement of Work for this IACRO were the following:

- 1) Non-ignition source model benchmarking and design. This involves analysis of existing and new data on laser-only sources to benchmark LASNEX predictions
- 2) Non-ignition source development experiments.
- 3) Model the debris environments of NOVA and NIF. Measure impulse environment on NOVA experiments.
- 4) Ignition capsule design to improve x-ray/neutron output ratio and total x-ray output.
- 5) Produce briefings, a published article, and a comprehensive final report.

The work that is reported in this document is actually supported by a funding triad that includes the Defense Special Weapons Agency, the NIF Project and LLNL's Weapons Program. The additional work presented here shows how the DSWA-funded work integrates with the larger effort.

There has been continued success in the development and fielding of the potentially longer-duration non-ignition beryllium-can sources. There have been significant advances in understanding of the relevant physics of these underdense radiators as well as further experimental support for the validity of the predictions. This report includes results that permit optimism for prospects of improving the hot-x-ray-to-neutron ratio and total hot x-ray yield for seeded ignition targets.

We want to be good citizens of the NIF user community. As such, we would like to field survivable samples, sometimes close to the NIF target chamber center, that impose minimal collateral damage to the chamber itself. A first mapping of results from the rad-flow hydrocode LASNEX to an Arbitrary Eulerian-Lagrangian code, CALE, has been written. This combination of codes will ultimately model the NOVA and NIF debris environments. We have completed a round of measurements of the debris environment at NOVA that will serve to benchmark modeling of late-time phenomena relevant to assessing the survivability of our exposure cassettes and the collateral damage they produce. Our ice-over-metal-foam concept for protecting close-to-target-chamber-center samples has continued to evolve. It is being used to protect the NIF target holder with B₄C replacing the ice. Analytic, 2D and 3D calculations are presented.

An important summary of the laser-only x-ray environments appears in this document. This summary serves as an audit trail for the non-ignition-sources that are projected for NIF based on experimental results and on projections of LASNEX modeling. The appendix to this report contains two documents that were published in the 1996 Laser Program Annual Report (UCRL-LR-105821-96-3): the first is a discussion of the gasbag experiments that were done on the NOVA laser in 1995, and the second is a theoretical report on underdense-plasma x-ray sources.

Reference:

1. NWET Applications for NIF Workshop (a compendium of viewgraphs) 15-17 March 1994. ed. by Gregory Simonson of LLNL

II-Experimental Results from NOVA: Tamped Xenon Underdense X-Ray Emitters

II-1. Introduction

Experiments to develop high photon energy x-ray sources were carried out on the NOVA laser in August 1996. Ten laser beams delivered approximately 42 kJ of energy in 2 ns into a Be cylinder filled with Xe gas. The conversion efficiency into x-rays > 4 keV was measured to be 5 - 20% , depending on the angle, which is the highest ever measured for laser-produced x-ray sources in this photon regime. The temporal dependence of the x-ray emission indicates that the bulk of x rays emerge in the first half of a 2 ns pulse. A large complement of diagnostics was fielded to image the volume in emission as well as provide initial data to measure the plasma temperature. Overall, these sources produce relatively little debris and a significant amount of x rays. These experiments have provided a basis for understanding the x-ray emission of a heated gas and will allow us to optimize the target design for higher conversion efficiencies.

II-2. Experimental setup

Experiments were performed in August 1996 using the NOVA laser which delivered approximately 42 kJ of $0.35\ \mu\text{m}$ laser light in a 2 ns flat-topped intensity profile. The laser beams entered the beryllium hohlraum target through the holes in the endcaps of the target and irradiated the xenon gas fill of the cylindrical Be target. The lasers heat the gas to form a highly ionized plasma which emits x-rays. The warm x-rays pass, with minimal attenuation, through the walls of the Be cylinder and are detected by both time-resolved and time-integrated diagnostics.

The targets were Be cylinders that had $100\ \mu\text{m}$ thick walls and $50\ \mu\text{m}$ thick endcaps. This material is of low Z and therefore provides little attenuation for the emission above 2 keV, but does significantly attenuate lower photon energies. The emphasis for these measurements was the photon energy region above 4 keV where the transmission is 85% or greater. The low Z wall material of the target was designed to produce a tamping effect that would prolong emission of warm x-rays for the full duration of the laser drive.

Figure 1 shows a schematic of the target where the blue regions represent the geometry of the laser beams irradiating the inside walls of the Be cylinder. An actual photograph of the target is shown in figure 2 where one can see the endcaps of the enclosure which are glued onto the ends of the cylinder. The target is 1.7 mm long and 2.0 mm in diameter. The laser entrance holes are 1 mm in diameter and are covered with $1\text{-}\mu\text{m}$ -thick polyimide windows that confine the Xe gas.

Figure 1. Schematic of the Be cylinder targets. The shaded regions represent the laser beam illumination of the inside of the target.

Figure 2. Photograph of the actual target. The cylindrical wall of the target was 100 μm thick and the endcaps were 50 μm thick. Thin CH windows covered the laser entrance holes so that the target could be filled with Xe gas.

The primary diagnostic was a time-integrated x-ray detector fielded to obtain absolute measurements on conversion efficiency. Other diagnostics included 2-dimensional x-ray imaging, spatially-resolved gated spectra and streaked spectra. The measurements were performed for two Xe gas pressures, 1 atm and 2 atm. In addition, this series of experiments also measured the backscatter to determine whether future experiments would benefit from beam smoothing techniques.

II-3. Experimental Results

Four shots were performed in this series of experiments. Two were performed on 2 atm targets and two were on 1 atm targets. Furthermore, preliminary measurements of the effects of beam smoothing using a kinoform phase plate (KPP) on Beam 7 of NOVA's ten beams were performed on one of the 2 atm shots. The phase plate did not have a significant effect on the Stimulated Brillouin Scattering (SBS), the measurements were < 1.5% SBS on all shots and seemed to increase the Stimulated Raman Scattering (SRS) from 5% to 11%. The same complement of diagnostics was fielded on all shots and will be discussed by comparing the data from the two different gas fills.

Figure 3. X-ray images of emission above 4 keV at 1.5 ns. The side view of the beryllium can is shown on the figure as a rectangular box. The emission from plasma streaming out of the target's laser entrance holes is quite pronounced at this time.

X-ray images of the heated target are important because they show the volume of plasma that is contributing to the x-ray emission. The x-rays are filtered by Be and Al to produce time-sequenced pinhole images of > 4 keV emission which are recorded on a gated microchannel plate. The 2-dimensional images are striking in that they show a non-uniform heating that was not expected from the design of the target. Figure 3 shows a side view of the target at 1.5 ns for the two different gas pressures. The left and right sides of the target are each heated by 5 beams and the images clearly show that two plasma sources are created. The central region of the target is not in emission. Subsequent calculations

found that the expansion of the Be near the laser entrance holes interfered with deposition of the laser energy. This will be discussed in more detail later in the section on hohlraum modeling. Here, we see plasma jetting out of the laser entrance holes. Exploratory calculations find that neither electron conduction nor any other mechanism was sufficient to heat the central region to emit x-rays above 4 keV. The calibrated x-ray film exposure in narrow horizontal strips passing through the centers of the images in figure 3 has been converted to x-ray intensity in the two lineouts presented in figure 4; the red line is data from the 1 atm target and the blue line is from the 2 atm target. The yellow region represents the length and position of the hohlraum. The data at 1.5 ns of intensity vs. position show that $\sim 500 \mu\text{m}$ (just about one third) of the 2 atm target length is not contributing to the emission while only $\sim 250 \mu\text{m}$ is not in emission for the 1 atm target.

Figure 4. Intensity of the x-ray emission along the length of the cylinder. The red line is data from the 1 atm target, the blue line is data from the 2 atm target.

X-ray images end on to the cylinder were also obtained and they are shown in figure 5. In this figure, we compare the results from two targets at different pressures near 500 ps. Since the images are gated, the time the snapshot of the image is obtained is not exactly the same. These images also show that the 1 atm target allows the beams to propagate further into the target. Here we see spots on the inside circumference of the target which correspond to the five-fold symmetry of the laser beam irradiation. The 2 atm target at nearly the same time also shows a five-fold symmetry, however, the clear appearance of the spots on the wall is not as evident. Later images of the 1 atm target show a clear stagnation of the plasma on axis which produces an emission spike at the center. The 2 atm case does not show as significant a spike. The ablation of the inside wall of the cylinder produces a Be plasma that is expected to compress the Xe gas. These images corroborate this effect, however, the temporal evolution was significantly affected by blow off of the Be from the laser entrance holes, so these images are difficult to compare directly to simulations.

Figure 5. End-on x-ray pinhole images of the targets from radiation made by x rays > 4 keV. The outside diameter of the cylindrical Be hohlraum is overlaid on the images.

Spectrometers were fielded on the target and these can provide the temporal history and electron temperature measurements. Spectrometers to record the temporal history were flat RAP crystals coupled to x-rays streak cameras. For electron temperature measurements, a flat PET crystal was coupled to a gated microchannel plate. Since the target creates a large extended plasma, spatial resolution is essential for differentiating between the plasma inside the target and the plasma outside of the target. These diagnostics provided useful information, however, better spatial resolution to obtain better measurements is necessary to enable a true temperature measurement.

The temporal history of the data can be obtained on x-ray streak cameras. Calculations of the temporal history are sensitive to the way the electron conduction is modeled in the plasma. These measurements quantify the duration of the x-ray emission as well as the distribution of the intensity in time. Figure 6 shows that the emission peaks at approximately 1 ns during the 2 ns heating pulse. While there are some variations the peak intensity due to changes in the filtering of the diagnostic, we see here that three of the laser experiments produced a source that lasted ~ 1 ns. There is a weak indication that the 1 atm ten-beam case, does show some evidence that the x-ray emission may increase at 2 ns near the end of the pulse when stagnation is expected to occur and enhance the hard x-ray emission. More experiments will be necessary to verify this.

Figure 6. Emission above 4 keV as a function of time. The laser pulse was 2 ns long.

Figure 7. Example of spectra from a highly ionized Xe plasma created by the laser heating the gas inside the Be cylinder. Each lineout is a spectrum taken at different times during the laser pulse.

An example of the spectrum obtained from the streak camera which views the entire source is shown in figure 7. Although these measurements are preliminary, they are encouraging because they show that measurements of plasma conditions will be possible in future experiments. The spectral features of the emission show that the Xe is ionized well into the L shell, past the neon-like ion stage and for the densities expected in these targets, this implies the electron temperature is well above 3 keV. Because of the large density gradients in the plasma jetting out of the target, the spectra shows emission from over 5 different ion stages. These large density gradients makes it crucial to have a spatially resolving spectrometer to obtain information about the plasma temperature and density.

Figure 8. Example of data used to obtain the conversion efficiency measurements.

Another gated spectrometer was fielded for this purpose; however, the emission inside the target saturated the gated spectrometer so a conclusive measurement could not be made. Nevertheless, based on these data, it is clear that there is enough signal for a spectrometer with higher spatial resolution and future experiments will be able to diagnose plasma conditions inside the cylinder.

The primary data are the absolute photon measurements of the Xe emission. An example of these data is shown in figure 8. This is recorded on a time-integrating Bragg crystal spectrometer and was obtained at two different angles on each shot. One spectrometer viewed down the cylinder axis, while the other viewed the side of the target. The spectrum for each shot is integrated over the photon energy to produce the conversion efficiency of the source. The blue line in the figure shows the running integral of this shot. The data for the 4 shots are summarized in table 1 below where the conversion efficiency (CE) is shown for the two positions for each shot. The view through the laser entrance hole (LEH) produces a conversion efficiency that is consistently higher for all the shots. Measurements are now in progress to calibrate the relative intensity of the crystals to verify this angular dependence. Calibrations show a slight angular dependence, however, it is not as pronounced as measured in our hohlraum experiments.

	CE (LEH)	CE (Side)
• 26082118 - 10 beams, 1 atm	15.4 %	5 %
• 26082120 - 10 beams, 2 atm	14.3 %	6 %
• 26082203 - <u>5 beams</u> , 1 atm, SSD	22.8 %	2.7 %
• 26082206 - 10 beams, 2 atm, SSD	24.5 %	no data

Table 1. Conversion efficiency (CE) of NOVA laser energy to x-ray energy with $h\nu > 4$ keV as measured by two time-integrating Bragg crystal spectrometers with different views of the beryllium can.

II-4. Conclusions

Experimental measurements have been performed on laser-produced plasmas which show they can produce a significant amount of warm x-rays above 4 keV. The conversion efficiency was 5% - 20%, depending on the angle of view. Calibrations are being performed to test whether the angular dependence is a real effect. It is interesting to note that the conversion efficiency, as viewed through the LEH, is no different for the 5-beam shot than it is for the full ten-beam shots. These data show a conversion efficiency significantly higher than x-ray sources produced by laser irradiation of simple disk targets and may be greater than those of gasbag targets. It is also expected that these cans will emit x rays over a longer period of time than will gasbags.

III- Modeling Multi-keV Radiation Production of Xenon-filled Beryllium cans

III-1. Introduction

Recently, it has been proposed to use laser-heated Xe-filled Be cans for multi-keV radiation production. These sources are predicted to have a high conversion efficiency and an x-ray output duration longer than those from laser-heated gas bags. These features make them attractive for several applications such as backlights and preheat sources. As a result, experiments were executed to assess the performance of these underdense radiators and to test our ability to model them. In this report we present simulations that were performed before and after the experiments. These simulations help to understand the experiments as well as to aid in designing of the next round of experiments.

III-2. Initial modeling results

Prior to the experiments, several two-dimensional LASNEX simulations were performed which modeled the anticipated experimental conditions. The simulations were of Be cans filled with 1 and 2 atm of Xe gas being irradiated with 40 TW of 0.35 mm light over a 2 ns duration. The dimensions of the Be can were 1.7 mm long by 2 mm diameter with a laser entrance hole (LEH) diameter of 1.0 mm. In summary, the simulation predicted a very good conversion efficiency of laser energy to warm x rays. In particular, 15% of the laser energy was re-radiated at photon energies above 4 keV for the 1 atm case and 14% was converted for the 2 atm case.

In order to illustrate the plasma conditions of this radiator, we plot the modeled electron temperature and density in figures 1 and 2 at a time of 1.0 ns (midway through the pulse) for the 1 atm case. The electron temperature reaches peak value of 5-to-6 keV near the laser entrance hole. The reason the electron temperature is so high here is this is the location of laser absorption. The bulk of the Xe in the hohlraum is predicted to be heated to temperatures just below 5 keV. Also plotted in figure 1 is a solid black contour that indicates the interface between the Be and Xe gas. It is clear from this plot that the Be wall has ablated inward and tamped the Xe plasma. This effect results in a compressed Xe plasma late in the pulse leading to a second peak in the emission as we will show below. We note that the electron density reaches its maximum on axis at a value of 1.2×10^{22} electrons/cm³.

Figure 1. Electron temperature at 1 ns. Also shown in black is the contour between the Be blowoff and the Xe gas fill.

Figure 2. Electron density at 1 ns.

Figure 3. Modeled stimulated emission pattern. The emission pattern is quite uniform despite the change of colors of the contour values.

We post-process the LASNEX simulations to focus on the emission patterns and their time history. Shown in Figure 3 we plot the spatial emission pattern for the 1 atm case (frequency integrated for $h\nu > 4$ keV) at 1 ns. In figure 4, we plot the predicted temporal history of the emission for both 1 and 2 atm fill.

Figure 4. Temporal history of >4 keV x-ray emission.

III-3. Discrepancy with experiments

As shown in figure 3 and 4, the predicted emission patterns are spatially uniform and the x-ray radiation extends over the duration of the laser pulse. However, these initial results are not in accord with the experiment measurements. The experimental images showed gaps in the emission patterns and the duration of the x-ray emission was only 1 ns (half the time the laser was on).

We looked at several scenarios to explain the discrepancy between the modeling and the experiment. First, we examined inhibited electron heat transport. The idea was that if the heat conduction were limited than the Xe plasma at the center of the Be can may not be getting as hot as LASNEX predicted. Since electron temperatures in excess of 2 keV are needed in order to get significant L-shell emission there would be no x-ray production in the center and the spatial images would show gaps. In addition, recent Thomson scattering experiments indeed indicated that the electron heat transport may be more inhibited than that modeled using the standard value of the flux limiter of 0.05 that is used by default in LASNEX. We therefore, performed simulations with a flux limiter more in line with the Thomson experiments of 0.01. However, even with this inhibited transport there was enough conduction to heat the center of the can and uniform emission patterns were observed.

Our studies varying the flux limiter showed that if the laser beam gets sufficiently far into the Be can, then electron heat conduction results in uniform emission patterns. Therefore, we next looked for mechanisms that would prevent or limit the amount of laser energy entering the Be can.

A possible mechanism limiting laser propagation into the Xe plasma is laser scattering from parametric instabilities such as Stimulation Brillouin Scattering (SBS) or Stimulation Raman Scattering (SRS). In SBS the incident laser light is scattered from an ion-acoustic wave whereas in SRS the incident laser light is scattered by an electron plasma wave. In both cases, the reflected light interacts (beats with) the incident light to form a ponderomotive wave that drives the scattering wave. The scattering wave grows and further scatters the incident light wave. In this way a feedback loop is formed and the instability continues to grow until nonlinear effects saturate or quench its growth. LASNEX cannot directly model either SBS or SRS. Therefore, we mock up this effect by lowering the incident power at a time when we expect SBS to occur. We assume that after 1 ns the incident laser power would decrease by 30%. Although, the reduction in laser power reduced the peak electron temperatures the plasma remain hot enough to emit L-shell radiation over a 2 ns duration.

Another mechanism that may limit laser energy into the hohlraum is "beam steering" due to transverse plasma flow in the presence of filamentation. This effect requires both filamentation of the laser beam and plasma flow at sonic velocities out of the LEH transverse to the laser beam. As the laser beam filaments it creates density depressions or wells in the flowing plasma region. These moving density depressions guide the laser beam and steers it toward the LEH. Like SBS and SRS, beam steering is not modeled in LASNEX and therefore the effect must be mocked up. We do this by changing the incident angle of the laser beam at various times. Simulations show that a 20° deflection at 1 ns would be sufficient to account for the observed features in the experiment. The laser beam would then strike the lip of the LEH and effectively turn off the heating of the Xe gas. However, an analytical estimate using the flow profiles from the LASNEX calculations indicate that beam steering would not reasonably be expected to produce such large deflection angles.

III-4. Refraction of incident laser beams

In the first set of simulations the mesh and zoning scheme was similar to that used in modeling standard ICF hohlraums. In this scheme the hydrodynamics is run in a Lagrangian mode until such time that the mesh becomes distorted. At that time, the mesh is re-mapped, or re-zoned, back to the original mesh. Any material that has exited the hohlraum through the LEH is removed from the simulation after a re-zone. This algorithm works well for modeling the high-Z Au hohlraums filled with a low density gas. However, the low-Z Be material ablates much faster than Au and must be followed. In particular, the Be from the LEH lip along with Xe gas emerging from the LEH can form a high density plasma outside the LEH.

Figure 5. Spatial emission pattern at 1 ns.

Figure 6. Temporal history of warm x-ray emission.

Suspecting that this accumulating plasma might be a problem, we re-ran the calculations using a scheme that also tracked of the material outside the LEH. We found that electron densities from the Be blowoff plasma reached critical density outside the LEH. Moreover, this blowoff plasma was producing density gradients sufficient to refract the incident laser beam. This refraction was so severe that the laser beam was deflected to hit the LEH. When this occurred only the Xe in the LEH was heated and emission in the center had stopped.

Figure 5 shows the emission when refraction occurs. Although the images are not identical to the experimental images, this does indicate that refraction may be playing a role in the x-ray emission. Refraction also

affects the duration of the output pulse. Figure 6 is a plot of the xenon L-shell x-ray power versus time for experiment along with the simulation with and without refraction effects.

III-5. Target designs for next experiments.

From the results of the last simulations, it is apparent the refraction of the incident laser beam by the ablated Be lip can greatly reduce the performance of these radiators. In order to mitigate this effect we have run simulations with larger LEH diameters of 1.5 mm. The results are that refraction is no longer important and the emission patterns are uniform and last the duration of the laser pulse. The next round of NOVA experiments will feature designs using significantly larger laser entrance holes.

IV-Mapping a Calculation from LASNEX to CALE

IV-1. Introduction

An effort is underway to develop a procedure for mapping a calculation from LASNEX to CALE. Results of the first version of this mapping are presented here. The goal is to allow us to run a hohlraum calculation as far as possible with LASNEX, then to continue it in CALE to late times in order to learn more about the debris produced and its effect on close-to-target-chamber-center objects. In this context, the laser drive and the ICF capsule (if present) merely serve to put energy into the hohlraum which is the primary source of debris. It is difficult to run LASNEX to late times when its mesh is turning itself inside out, e.g., in the modeling of jetting of hohlraum inner-wall material out through the laser entrance holes. The Arbitrary Lagrangian-Eulerian (ALE) capabilities of CALE make it much easier to run the simulation late in time. The energy and momentum of the debris produced by a hohlraum is needed by the groups designing the NIF target positioner as well as those planning experiments close to a target hohlraum.

Lagrangian problems have been mapped by means of a BASIS routine that writes a CALE input deck. The routine defines one CALE region for each region in the LASNEX problem. The EOP number is used to define a default equation of state/material model for each region. The routine then defines the location and velocity of each node. For each zone the materials present are entered by their volume fraction and the electron temperature is used as the temperature of the zone. This work is being extended to work with calculations that have mixed zones. This work provides a useful way to map LASNEX to CALE and thus to continue a simulation when the detailed radiation physics of LASNEX is no longer needed.

For future work, we propose to validate these calculations for NIF it is necessary to do similar calculations for NOVA hohlraums and compare the results with experiments. Impulse gauges for this purpose have been developed and fielded on NOVA by Gerassimenko and Serduke; see topic VI of this report. We plan is to use LASNEX to calculate the early phases of the problem where it is uniquely capable, namely, for the tasks at which it excels:

- laser deposition
- high temperature physics and opacities
- fusion burn

The calculation should be carried late enough in time so that the hohlraum is in LTE, e.g. the electron, ion, and radiation temperatures are roughly equal. Then we can map to CALE where we have these features:

- Arbitrary Lagrange-Eulerian hydro for large hohlraum deformations at late time
- diffusion radiation transfer
- material strength effects

IV-2. The Mapping Procedure

LASNEX is built around BASIS, a powerful scripting language. The LASNEX-to-CALE map was implemented by writing a BASIS routine named `caledeck` that queries the LASNEX variables and writes a CALE input file. If more detail is required a CVM (Coordinates, Velocities, and Materials) data file could be written. Caledeck does the following:

Caledeck performs the following tasks:

- converts units as needed
- sets common parameters (problem time, mesh size, temperature mode, ...)
- defines one material for each region in LASNEX
- sets the coordinates and velocity of each node
- sets the material number, density, electron and radiation temperatures of each zone
- Determines the boundaries and likely boundary conditions

IV-3. Current Limitations

Currently the map sets the proper rigid boundary conditions for edges that are on the z-axis or the equatorial plane. It sets an edge for which all the points are coincident (e.g. at the center of a polar grid) as a fixed boundary. Other edges are set to be free boundaries. These boundary conditions must be checked by the user since there are many possibilities that the map doesn't check. For example, internal voids are ignored but could be added.

Mixed zones are not properly defined for CALE. They are assigned a material number based on the region number that LASNEX assigns to that zone. LASNEX tracks the elements that are present but not the regions from which the elements originated. It should be possible to reconstruct the amount of each material in a zone. However, the solution may not be unique. This could be remedied by putting one unique isotope in each region as a tracer that would allow the routine to determine the fraction of mass that comes from each LASNEX region. A new version of caledack is under development that calculates the amount of each region's material that is present in a zone and the appropriate volume fractions for each mixed zone. The procedure has not been automated yet and must be individually set for each case.

Sources are ignored at this time. The plan for this routine was to map after most of the source action has been finished and indeed, all the sources have turned off.

IV-4. Other Considerations

When mapping from one code to another, the question arises about matching the equations of state used in the two codes. CALE allows the use of EOP equation-of-state tables used by LASNEX. This may not be the best choice and the user may want to use a different material model to include material strength for instance. There are many options but all will involve disturbing the problem to some extent at map time.

We are also looking at several BASIS rezoning functions that have been written by X-Division physicists. Some of these automate the rezoning process while others implement an ALE capability. These functions may allow us to carry a LASNEX simulation out late enough in time to complete the debris calculation entirely within LASNEX.

IV-5. Results

The map is functional as shown in the following figures from LASNEX and CALE. We start with a NOVA ignition hohlraum calculation kindly provided by Larry Suter. The calculation was stopped shortly after the capsule burned. This calculation was not zoned to accurately model the hohlraum debris. Therefore it was merely used to test the map. For the map to behave properly the calculation should be run later in time so the conditions are closer to LTE. Figure 1 shows the electron temperature before and after the map. There is good agreement since the electron temperature maps over exactly by construction.

For zones that are mixed or with different electron, ion and radiation temperatures the pressure is not calculated correctly in CALE since it has not been given that information. This shows up in the channel region. For example, at $r=0$, $z=0.08$ (on the horizontal axis) the material is highly mixed. The hydrogen, deuterium, carbon, and gold atoms are present in roughly equal numbers. Therefore the mass is dominated by the gold. Yet LASNEX still considers this zone as part of the channel region that is defined as the deuterium gas. Therefore CALE thinks the composition is nearly pure deuterium with only one part per million of hydrogen, carbon, and gold. Since it is density and temperature that are mapped, CALE has a larger number density of atoms to get the same mass in a zone. Even considering the ionization state of the gold CALE will think there are more particles than LASNEX had and thus CALE will calculate a larger pressure as seen in fig. 2. In an early test of a map that accounts for mixed zones the pressure agreement is much better. However, this map has other problems based on how CALE treats mixed zones. It appears that there are ways to resolve these problems and make the mapping more useful.

Figure 1. This figure shows the electron temperature before and after the map; the same color table was used in both plots. The upper figure is from LASNEX. Its plotting package does no interpolation on the grid resulting in the boxy appearance. The lower plot is from CALE which does interpolation. The contour labels in the upper figure are temperatures. In the lower figure the contour labels reference the table above the hohlraum within the grid box. Note that the temperatures agree as they must and the region boundaries are faithfully brought over by the map. You can see in both that the hohlraum has blown in by about 0.03 cm.

Figure 2. This figure shows the pressure before and after the map; the same color table was used in both plots. The upper figure is from LASNEX and the lower is what was mapped into CALE. Again note that the LASNEX figure is not interpolated from the grid while the lower one is. While the general features are the same the mapped calculation has pressures that are a factor of 2 higher in the channel region around $(r, z) = (0, 0.08)$. This is due to the large amount of mixing that has occurred and is not shown in these figures. At this point H, C, and Au ions are present in roughly equal numbers. Thus the mass is dominated by the gold. Yet LASNEX still labels this region as one consisting of H ions. Therefore when CALE calculates the pressure it assumes that there are only H ions present.

V-Hot X Rays from Seeded NIF Capsules

V-1. Introduction

Radiation effects testing needs warm-to-hot x rays ($h\nu > 5\text{keV}$) in copious quantities; this is evident from the envelope of system test needs shown in fig. 1 of the Introduction and Overview chapter of this document. For some test objects, it is very desirable both to increase the x-ray fluence and decrease the neutron fluence. Earlier studies by Tabak and Shaw and by Carman and Heidrich showed that this can be done by adding a high-Z dopant in roughly a part per thousand (ppt) atomic fraction to the outer third of the frozen DT shell in a NIF ignition capsule. The effect of this seeding is to dud the DT fusion reaction somewhat but to enhance greatly the fraction of greater-than-five-kilovolt x rays emitted. One figure of merit in such studies is the fraction of the fusion yield that appear in these hot x rays. For unseeded capsules, this ratio is about 0.7%. Adding 1 part per thousand gold seed has already been shown to increase this ratio to nearly 3%. In our exploratory calculations, by using a new capsule design, employing a higher-atomic-number seed, and reducing the hohlraum wall thickness to 6 μm , we are able to increase this ratio to more than 6%. This result suggests that nearly one-third of the fusion energy not in neutrons appears as these hot x rays.

We present the results of one dimensional LASNEX calculations that explore two issues: (1) the effect of changing the seed fraction, (2) the effect of seeds other than gold as well as seed mixtures. Firmer conclusions will require closer evaluation of the relevant physics modeled by LASNEX as well as two- and three-dimensional calculations. The basic idea explored here and by others, most notably Max Tabak, is that seeding, while decreasing the overall yield, boosts the hot x-ray content of the photon spectrum. Much of the previous work has already been summarized in the 1995 report to the DNA (ref. 1) (Defense Nuclear Agency) as well as in the Defense Research Review (ref. 2). We use 1-D LASNEX (ref. 3) simulations generated from input files modified from files used in the previously reported gold-seeding studies.

Experimental verification of the calculations cannot happen without capsule yield shots. Analytic verification is difficult because of the strongly coupled hydrodynamics, electron transport, and photonics. Checking the simulation results at this stage can only be done by increasing numerical resolution and/or trying different physics packages to see if the results are preserved. Here, we only do numerical tests, keeping the physics packages previously chosen. Though some testing of the physics packages has been reported, we will eventually need to explore carefully the physics behind the Non Local Thermodynamic Equilibrium (NLTE) opacities of the in-line XSN code to verify that they do not artificially prejudice our results.

Seeding materials were selected for their electronic radiative characteristics with no concern for the practical aspects of the choices. These are exploratory studies. Several different changes in the seeding or target have been explored:

- 1) The amount of seed in the outer third of the solid DT region ranged from 1 seed ion per 10^6 hydrogen ions up to 1 seed ion per 10^2 hydrogen ions. Once above 5×10^{-3} , the hot-x-ray/neutron ratio changed slowly and was roughly four times larger than it was for an unseeded capsule.
- 2) Seeding materials of different atomic number cause changes in the hot x-ray spectrum with higher Z increasing the total hot-x-ray/neutron ratio.

- 3) Changes in the capsule geometry and in the laser source can improve the hot-x-ray/neutron ratio to over 8 times that of our baseline unseeded capsule case. Indeed, the last case resulted in 6.2% of the fusion yield emerging as hot x rays. This is nearly one-third of all of the fusion energy that is not found in neutrons.

The report is divided into six more sections. In Section 2, we give an overall discussion of seeding. In Section 3, we present our base 0.001 Au seeding simulation, correlating the results with previous work. In Section 4, we show the effect of changing the gold concentration. In Section 5, we show the effect of changing the seed material. In Section 6, we present simulations with an alternate geometry and input energy which give improved results. Some concluding remarks are made in Section 7.

V-2. Seeding Overview

Seeding is the addition of a high-Z dopant in some region of a DT capsule so that during burn, the seeding material heats leading to enhanced emission of hot x rays which are defined to be x rays of energy greater than 5 keV. The 5 keV cutoff is chosen because there is a notch in the unseeded and gold-seeded output spectrum at this energy. Seeding tends to decrease the overall yield because in the time before thermonuclear burn, the presence of impurities alters the compression dynamics. Michael Shaw (X Division) has shown that taking a simulation up to burn with seeded material and then restarting with or without the seeded material leads to the same reduced total fusion yield. Seeded fuel absorbs more photons which generally leads to preheat, reduced compression, and lower fusion yield. Reduced yield may be a bonus for hot x-ray source applications if the total hot x-ray output can be maintained in a seeded capsule because reduced yield means reduced neutron output and an increased hot-x-ray-to-neutron ratio.

Earlier calculations have given a factor-of-four improvement in this hot x-ray ratio for gold seeding (refs. 1 and 2); for reasons that will be discussed in detail elsewhere, we believe that these results may be overly optimistic. Location, concentration, and seeding material are among the options to be explored to optimize the hot x-ray output. Tailored laser pulse shapes have long been used to improve fusion yield. It may also be possible further to improve the hot x-ray output by pulse tailoring. Finally, a direct drive offers the possibility of reduced absorption of hot x rays once created because of the absence of any x-ray absorption by the walls of a hohlraum.

Potential worries for seeding of capsules include Rayleigh-Taylor (RT) instabilities, x-ray preheating before compression and incorrect opacities calculated from NLTE absorption and emission routines. Based on the work reported last year, no evidence for an RT instability due to 0.001 Au seeding in the outer third of the solid fuel region seems to exist (ref. 1). Changing the location and concentration of the seed may alter this observation. As mentioned above, x-ray preheating and altered compression dynamics have been considered, but should be investigated in detail. Improved opacity calculations are a continuing effort throughout the high energy density establishment. A high-Z, NLTE emission and absorption opacity model that contains LTE results as a special case and has the quality of OPAL (ref. 4) (acknowledged by many to be the world's best low-Z LTE opacity code) is a general goal to be pursued.

In this report we make no attempt to address these worries. We confine seeding to the outer third of the fuel in the expectation that RT instabilities will not occur for our choices of seeding. A 2D simulation should be done to verify this premise for some subset of our calculations. We do not retune our capsule design for the presence of seeding although this may lead to better results. Finally, we use the default LASNEX options

(tabulated cold opacities or XSN averaged atom opacities, depending on Z and electron temperature) for our opacities.

V-3. Baseline (0.001 Gold) Seeded-Capsule Calculations

Our LASNEX calculations have been carried out in a 1-D spherical geometry. XSN opacities and charge states are used in all regions. Only the seeded region uses NLTE opacities. The laser-generated hohlraum x rays are modeled as a defined source, derived from a 2-D simulation. Figure 1 gives the baseline capsule design for the simulations presented in this section and in Sections 4 and 5.

The output hot x-ray (> 5 keV) distribution after burn is shown in figure 2. Note in figure 2 that the cold component of the x-ray output is not pictured. This was done because the simulations were stopped shortly after burn when hot x-ray output is finished but cold x-ray output has not really started. Terminating the calculation in this manner results in the saving of considerable computer time and does not affect our hot-x-ray seeding results.

The 0.001 Au-seeded capsule has a significantly boosted hot x-ray component compared to that of the unseeded capsule.

Table 1 summarizes the yield results. Note that the hot x-ray ratio, $E(> 5 \text{ keV})/E_n$, increases only by a factor of two via seeding for this particular calculation. We can approach the previously-quoted factor of four by reducing the hohlraum thickness (see fig. 1) from 12 microns to 6 microns (ref. 2) although there are some additional issues that would need to be addressed by such a reduction of the gold thickness.

Figure 1. Geometry of the 1-d seeding calculations showing the gold hohlraum containing He gas and the capsule that consists of an ablator, partly seeded solid DT and DT gas. The frozen DT contains seed in its outer one-third, from a radius of 0.1056 to 0.1090 cm, and the density is corresponding adjusted to 0.28 g/cc.

Seed	Yield (MJ)	$E(> 5 \text{ keV})/E_n$	$E(> 5 \text{ keV})$ MJ	% of Yield
none	29.4	0.00909	0.214	0.727
0.001 Au	22.1	0.0206	0.364	1.65

Table 1. Results for baseline unseeded and gold-seeded calculations.

Figure 2. Seeded and unseeded capsule emission above 5 keV for the baseline capsule shown in figure 1.

V-4. Effect of Changing the Seeding Concentration

The idea behind varying the seeding concentration is to find an optimum. Too little seed gives high yield but little hot x-ray enhancement. Too high of a concentration may

Figure 3. Calculated fusion yield vs. seeding concentration for the baseline design of fig. 1..

dud the capsule to the point of zero yield and no hot x-ray output. Somewhere between these extremes, the concentration may still dud the yield but maintain a somewhat increased production of hot x rays at lower concentrations. The point is that some dudding is acceptable to optimize the energy ratio of hot x rays to neutrons or to increase the yield of hot x rays.

We maintain the seeding location and material and vary the concentration from 10^{-6} to over 10^{-2} Au atom fraction. The density in the seeded material was kept at 0.28 g/cc. This was done to avoid retuning the x-ray drive and with the assumption that DT can be made at a density such that with seeding 0.28 g/cc is the resulting density. The results are summarized in figs. 3 and 4.

Note that the yield begins dropping at 0.0001 atom fraction and converges to a steady value at 0.005 atom fraction. The hot x-ray ratio increase with seeding fraction slows (log scale in seeding fraction) at 0.005 Au atom fraction. Clearly, we have not reached a high enough concentration to completely dud the capsule. One possible explanation of this plateau is that at higher concentrations, the emission lines are optically thicker so that less radiation can escape.

Figure 4. Hot-x-ray to neutron energy ratio vs. gold seeding concentration for the baseline design of fig. 1.

V-5. Effect of Seeding Material

There are many high-Z materials that could be used as a seed in lieu of or in addition to gold. Since we are interested only in the atomic properties (not the nuclear reaction characteristics) of the seed elements, the use of uranium in our work would be of the non-fissile isotope, ^{238}U . The elements barium (Ba, $Z=56$) and gadolinium (Gd, $Z=64$) have features that do not overlap those of gold (Au, $Z=79$) or uranium (^{238}U , $Z=92$). Furthermore, uranium has a shifted and slightly stronger emission than gold. This led us to try seeding with 0.001 ^{238}U and a mixture consisting of 0.001 atom fraction of ^{238}U , Ba, and Gd. The ^{238}U and mixed seed results are summarized in the following table and fig. 5 shows the output spectra. The Au and unseeded results of Section 3 are included for comparison.

Seed	Yield (MJ)	$E(>5 \text{ keV})/E_n$	$E(>5 \text{ keV})$ (MJ)	% of Yield
none	29.4	0.00909	0.214	0.727
0.001 Au	22.1	0.0206	0.364	1.65
0.001 ^{238}U	23.2	0.0242	0.449	1.94
mix	19.6	0.0267	0.419	2.14

Table 2. Results for uranium-238 and mixed seed hot x-ray output together with baseline results.

Figure 5. X-ray spectra for no seeding, gold seeding, uranium-238 seeding and mixture seeding, all at concentrations of 1 seed atom per thousand hydrogen atoms.

In terms of hot x-ray ratios, the mixed result does best but because of yield loss, the ^{238}U results does best in terms of total hot x-ray output. Also note that the mixture fills in the slight dent in ^{238}U output around 30 keV and boosts the 12 keV ^{238}U output from 11 MJ / keV to 16 MJ / keV. Unfortunately, we were not found a way to fill the output gap centered at 18 keV. To have stronger emission for a given photon energy, the seeded region could be made more optically thick. The emission would approach the Planckian limit and enhance overall energy output if the increased thickness does not lead to increased reabsorption. It may be true that altering the concentration level and location of each mix component could improve the results, however, given the strong coupling between hydro and seeding, it would difficult to find the optimum without a long series of trial and error LASNEX runs.

V-6. Effect of Alternate Capsule and Laser Drive

The following table shows an alternate capsule design. The alternate capsule is driven by a roughly 2 sh shaped pulse of 1.09 MJ of source radiation. The fig.-1 base-case capsule is driven by different shaped pulse that lasts about 1.5 sh and contains 1.28 MJ of source radiation. The alternate capsule ablator is brominated which contributes to a high hot x-ray ratio for the alternate capsule even if this capsule were not seeded. Calculations for the new capsule also has similar resolution in the photon energy bins.

	Fig. 1 capsule region outer radius (cm)	New capsule region outer radius (cm)	Fig. 1 capsule region density (g/cc)	New capsule region density (g/cc)
gas DT	0.1	0.0995	0.0003	0.0003
solid DT unseeded	0.1056	0.1058	0.25	0.25
solid DT seeded	0.109	0.109	0.28	0.28
ablator (CH)	0.128	0.127	1.05	1.05
source (He)	0.5	0.435	0.0005	0.001
hohlraum(Au)	0.5012	0.436	19.28	19.28

Table 3. Radii and densities of regions for the baseline (fig. 1) and "new" capsules

We use the ^{238}U seeding discussed in Section 5 since that produced good results for the Fig 1. capsule. All LASNEX packages remain in use. We also used a new capsule design with a hohlraum thickness reduced to 6 microns (hohlraum outer radius 0.4356 cm instead of 0.436 cm). The results are summarized in the following table. The fig. 1, unseeded capsule results are shown for comparison. As a numerical check, the 0.005 ^{238}U case is repeated (denoted by *) with doubled spatial resolution in the fuel, and doubled resolution in the radiation transport.

Seed	Yield (MJ)	$E(> 5 \text{ keV})/E_n$	$E(>5 \text{ keV}) \text{ MJ}$	% of Yield
none	29.4	0.00909	0.214	0.727
0.003 ^{238}U	20.8	0.0735	1.22	5.88
0.005 ^{238}U	19.9	0.0780	1.24	6.24
0.005 $^{238}\text{U}^*$	19.2	0.0770	1.18	6.16

Table 4. Output results for the new capsule design. The ^{238}U with the asterisk is one that was done with doubled resolution to check the robustness of the result.

Much of the improvement in the hot x-ray ratio when the new capsule design is used is due to the reduction of the hohlraum wall thickness. The fig. 1 capsule hohlraum wall is 12 microns and the new capsule hohlraum is 10 microns thick. Since the Au thickness is reduced, more hot x-rays escape. Further reducing the hohlraum thickness of the new capsule to 6 microns leads to even better results, suggesting the best results may be from direct drive. Also, the increased resolution results show our calculations are at least numerically robust.

V-7. Concluding Remarks

We have made some additional progress in our seeded capsule calculations and we can make four conclusions for seeding fixed in the outer third of the solid fuel region. First, 0.001 atom fraction of ^{238}U gives more hot x-rays than 0.001 atom fraction of Au and higher concentrations of any single high-Z dopant greater than 0.005 atom fraction may be of benefit unless there is complete dudding of the yield. Second, a thinner hohlraum allows more hot x rays to escape giving a higher hot x-ray ratio. Third, high-Z mixtures have, at minimum, the potential to increase the hot x-ray output spectrum for particular frequency bands that would be of special interest to NWET, and perhaps can lead to even higher overall output. It is also clear that NIF ignition capsules have the potential to address the higher-photon-energy portion of the composite envelope of system test needs that was discussed in the Introduction and Overview chapter of this report.

Short term work includes verifying the robustness of results with different opacity models, understanding the hot-x-ray versus seeding concentration results, and trying more seeding mixtures via the hydro history technique. Even with different physics packages, we suspect the trends found with capsule and seeding variations remain intact. Furthermore, Max Tabak has completed a simulation similar to that presented in Section 3 but with an opacity model that differs from XSN (averaged atom opacities). He found very similar capsule performance with no discernible change in the x-ray output. Frequency dependent optical thicknesses as a function of seeding concentration may be useful to verify and explain our hot-x-ray versus seeding concentration results. Mixtures of high-Z seeds at <0.005 atom fraction can then be investigated as a way better to tailor the output spectrum of hot x-rays.

V-8. References

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VI-Hohlraum Debris Measurements at Nova

VI-1. Introduction

The use of NIF as a nuclear weapons effects testing (NWET) facility will require specialized targets in close proximity to the radiation source(s). Planning of NWET experiments relies on the ability to calculate a test object's response to the radiation and debris environment, and to calculate its contribution to the debris loading of the target chamber. This has prompted interest in characterizing debris on NOVA, to acquire data that can be compared to code calculations. As part of this effort, this report addresses the fielding of passive impulse gauges on a series of four NOVA shots that were dedicated to the study of debris for NIF; our gauges were a significant part of this effort. This report describes the gauges, their calibration, the data obtained and their analysis. It is a follow-on to our initial report, ref. 1. Lessons learned in the execution of experiments described in that report were incorporated in several modifications to the gauge and support structure design, as described below.

VI-2. Design Considerations

The impulse level at a distance of 20 cm from a scale-1 hohlraum is in the range of ten to a few tens of taps so a very sensitive gauge is needed. We chose to adapt a design, originated by W. Comfort of LLNL, that had been used on several underground nuclear weapons effects tests. Comfort found that measurements of the passive gauge agreed with those of active momentum gauges to within better than 5%. A schematic of the gauge is shown in figure 1.

The design has several key features: the shape of the hinge section of the paddle, the paddle reinforcement and the rounded anvil. The rounded anvil keeps the hinge from breaking; it is designed to produce a maximum strain of ~4% in the hinge as it bends around the top of the anvil. The paddle is made of 0.004" thick sheet of 1100-o aluminum stock. The paddle is reinforced with 0.005" thick 1100-H14 aluminum. The purpose of the reinforcement is to confine bending to the hinge section of the paddle. Its necessity was established by modeling of the gauge with the three-dimensional structures code DYN3D. Finally, the shape of the hinge section is such that a different and wider part of the metal hinge is bent as the angle through which the gauge is bent increases. Without this feature, the measured impulse is proportional to the square root of the deflection angle, severely limiting the gauge's dynamic range. With it, the impulse is nearly proportional to the deflection angle, and the dynamic range is greater, over an order of magnitude for our gauges. The components of one of these disassembled gauges are

Figure 1. Drawing of the passive impulse gauge that was fielded on NOVA. The gauge dimensions are 3.5 cm by 1.25 cm.

shown in figure 2. The leftmost piece is the front block that faces the debris source. It now features a hinge shield to protect the rather delicate hinge section of the paddle from direct encounters with debris. One hundred paddle sections were mass produced by laser cutting from the same sheet of relatively soft aluminum; it is the middle component of figure 2. The upper reinforcement section was also laser cut from its own sheet and laser-spot-welded to the paddle section. On the right is the anvil block with its rounded top. A new reinforced paddle was used on every calibration drop and NOVA experiment.

Figure 2. Components of a Bent-Metal Impulse Gauge at a magnification of 2X. From left to right, these are the front block, the laser-cut reinforced paddle and the anvil block. Note the hinge shield that has been added to the top of the front block.

Experience gained in our piggybacked experiments led to a redesign of the gauge support assembly. In part to protect the gauges from being bumped as they are installed in the target chamber diagnostic tubes, a C-shaped support was designed. This support's principal function was to permit us to field gauges in pairs to get some sense of the repeatability of the experiment and the homogeneity of the blowoff. Each gauge was mounted in its own block and anvil.

A top view (or, the hohlraum's view) of one of the fielded assembly of two impulse gauges is shown in the upper part of figure 3. This is a full-scale image of the impulse gauge assembly and shows how the impulse is measured twice on gauges in very close proximity to each other. The lower image in figure 3 is the side view of the same gauge.

Figure 3. Top and side view of the protective C-shaped mounting bracket showing two bent-metal-impulse-gauge blocks ready to be fielded in the NOVA target chamber. This top view is also the hohlraum's view of these gauges.

Figure 4. Side view of a bent-metal-impulse-gauge assembly after exposure to a NOVA hohlraum. In this case, the two gauges responded in a very similar manner.

VI-3. Gauge Calibration

The gauge was calibrated by dropping different sized balls of rolled up glue stick onto the reinforced portion of the paddle from various heights. Only cases where the glue ball stayed stuck to the paddle near the middle of the reinforced area were considered. The impulse of the glue ball is $m_1 v = m_1 \sqrt{2gh}$ where m_1 is the mass of the ball, h the height from which it is dropped and g the gravitational acceleration. Since the mass of the ball is added to that of the paddle, it needs to be corrected out. We take $I = f(\theta) \sqrt{m_0}$ where I is the impulse measured, θ the angle of deflection of the paddle, $f(\theta)$ a function of θ and m_0 the mass of the paddle. To correct for the added projectile mass, we calculate the impulse that would have produced the same deflection of the paddle if no mass were added to it,

$$I_o = I_1 \sqrt{\frac{m_0}{m_1 + m_0}}$$

where I_o is the corrected impulse and I_1 the impulse of the glue ball. To calculate m_0 , we only consider the reinforced part of the paddle, which represents almost all of the mass set in motion by the impact. This portion of the paddle has a mass of ~ 0.082 g and an area of 1.35 cm^2 . Measured and calculated quantities for eight calibration experiments are listed in Table 1. The relationship of impulse to deflection angle is shown in figure 5. It is evident that the impulse is reasonably linear with angle with a threshold of about 4 taps.

Calibration #	m_1 g	h cm	I_1 taps	$\sqrt{\frac{m_0}{m_1 + m_0}}$	I_o taps	θ degrees
1	0.051	10	7.14	0.785	5.61	4.2
2	0.051	30	12.37	0.785	9.71	7.6
3	0.302	10	42.7	0.462	19.73	27.4
4	0.302	30	74	0.462	34.19	58.4
5	0.038	20	7.52	0.826	6.21	3.2
6	0.038	20	7.52	0.826	6.21	5.7
7	0.182	10	25.5	0.547	13.94	16
7	0.182	30	44.7	0.557	24.91	42

m_1 = mass of glue ball

m_0 = mass of paddle ≈ 0.082 g

h = height from which glue ball is dropped

I_1 = glue ball momentum/area of reinforced section of paddle

$\sqrt{\frac{m_0}{m_1 + m_0}}$ correction factor for mass of glue ball

I_o = impulse which would produce observed deflection of paddle if glue ball mass were infinitesimal

θ = observed deflection of the paddle

Table 1. Bent-Metal Impulse Gauge calibration data

Figure 5. Calibration of the impulse gauge. The line is a linear fit to the data

VI-4. NOVA Data

The impulse gauges were fielded on four NOVA shots designated RET_DEBRIS 13, 14, 15 and 16 on January 17 and February 14, 1996. The hohlraums to which the gauges were exposed were slightly larger than a standard scale-1 hohlraum. These hohlraums were 2 mm long and 2 mm in diameter; the hohlraum walls were 25 μ m thick gold. These hohlraums had no diagnostic apertures on their sides. The only apertures were the laser entrance holes on each end. As a consequence, the passive impulse gauges that were fielded in or near the waist of the NOVA target chamber (and facing the cylindrical waist of the hohlraum) were exposed only to minimal x-ray fluence, not enough to produce impulse due to x-ray blowoff (see ref. 1 for a more extensive discussion). Any impulse measured on these gauges is due to debris impact.

A pair of passive impulse gauges was fielded in a NOVA target chamber diagnostic tube (SIM tube) at a range of 20 cm from target chamber center. There were four separate shots in this final series of debris shots. Gauges were fielded in four of the seven SIM tubes. SIMs 4 and 6 are in the waist of the target chamber and in a position normal to the hohlraum's cylindrical wall. SIM 1 is 22 degrees forward of the normal to the hohlraum cylindrical wall. SIM 7 is looking directly into the laser entrance hole and is on the hohlraum's axis.

Photographs of these hohlraums from the perspective of the fielded impulse gauge are shown in figure 6. These hohlraums were built to have a gas fill. In two of these four shots, a 1 atm propane fill was used. The gas-fill tube is glued to the hohlraum as is evident in the photos. A separate experiment used the backlighter appendage visible on one side of

the hohlraum. There was also a thin 0.6 μm plastic window to confine the gas fill that is visible in the SIM-7 view.

Results of our measurements are presented in Table 2. Two numbers appear in each entry. These are the impulse measurements of the two identical gauges that were fielded millimeters apart as shown in figure 3. We believe that a significant fraction of the differences in the readings of the twin gauges can be ascribed to inhomogeneities in the blowoff.

The C-shaped bracket in which the gauges were mounted served also to protect the rather delicate gauges during mounting and dismounting in the SIM tubes and during pre- and post-shot handling. Data readout was simple; each side of the C-shaped bracket was placed on a nearby Xerox copier and the green button was pressed. The angle of the paddle deflection was measured from these Xerox copies as illustrated in figure 4.

Figure 6. Views of the NOVA hohlraum from the various diagnostic SIM tubes in which passive impulse gauges were fielded. At the time the target was photographed, we were expecting to field our gauges in SIM 2. Requirements of the experiment necessitated a change to SIM 1 which is symmetrically placed on the opposite side of the target chamber waist.

NOVA SHOT	RET_DEBRIS 13 26011715	RET_DEBRIS 14 26021409	RET_DEBRIS 15 26011717	RET_DEBRIS 16 26021412
	gas fill	gas fill	no gas	no gas
SIM 1	6 , 10 taps	7 , 15 taps	9 , 9 taps	5 , 7 taps
SIM 4	13.5 , 13.5 taps	18 , 20 taps	13 , 13 taps	5 , 9 taps
SIM 6	13 , 24.5 taps	7 , 21 taps	15 , 15 taps	16 , 19 taps
SIM 7	5 , 9.5 taps	no data	31 , 31 taps	<4,<4 taps
Averaging separately over the gas-fill and no-gas measurements				
SIM 1	gas fill: 9.5 ± 2.0 taps		no gas: 7.5 ± 1.0 taps	
SIM 4	gas fill: 16.3 ± 1.6 taps		no gas: 10.0 ± 2.2 taps	
SIM 6	gas fill: 16.4 ± 3.9 taps		no gas: 16.3 ± 1.0 taps	
SIMs 4+6	gas fill: 16.3 ± 2.0 taps		no gas: 13.1 ± 2.5 taps	
Averaging over all measurements from a given SIM				
SIM 1	8.5 ± 1.1 taps			
SIM 4	13.1 ± 1.7 taps			
SIM 6	16.3 ± 1.0 taps			
SIMs 4+6	14.7 ± 1.3 taps			

All reported uncertainties are 1-sigma standard errors of the mean.

Note: a tap is momentum per unit area in cgs units. $1 \text{ tap} = 1 \text{ gm cm/sec} / \text{cm}^2 = 1 \text{ dyne-sec} / \text{cm}^2$

Table 2. Impulse measured on passive impulse gauges fielded on four NOVA shots. All hohlraums were built for a gas fill. A 1 atm propane fill was used on two shots.

VI-5. Data Interpretation

There are probably three different populations of measurements in our data. SIMs 4 and 6 combined would be from one population. Both of these SIMs are in the waist of the target chamber and would see blowoff that emerges normal to the hohlraum cylindrical wall. SIM 1 would generate the second population; It is about 22 degrees forward of the normal to the cylindrical wall. Finally, SIM 7 is directly on the hohlraum axis and might be hit by a jet of debris emerging from the laser-entrance hole. Except for the SIM-7 measurements, the impulse produced appears to depend only weakly on the presence or absence of the gas fill. For purposes of discussion, we will combine the gas/no gas measurements as well as those from SIMs 4 and 6. The combined body of data from SIMs 4 and 6, both gas fill and no gas fill has a mean value of $14.7 \text{ taps} \pm 1.3 \text{ taps}$. The error bar is the 1-sigma standard error of the mean. This implies that if another set of data were obtained, we would expect the mean of that set to be within that standard error of the mean away from the value 14.7 taps . This is in contrast to the standard deviation of the sample which is 5.1 taps . We interpret this to mean that an additional single measurement would fall within 5.1 taps 68% of the time.

The data for the gauges in SIM 1, which is 22 degrees forward of the waist, have a significantly lower result, $8.5 \pm 1.1 \text{ taps}$. We believe that we should expect more debris impulse normal to the hohlraum wall; these data appear to support this notion.

The data from SIM 7 are not as complete and considerably more difficult to interpret. First, we are faced with the fact that under seemingly identical conditions, one shot measured significant impulse and the other measured no impulse at all. The threshold value for these gauges was 4 taps as is evident from the calibration curve, figure 5. Second, as can be seen in figure 6, gauges in SIM 7 view the interior of the hohlraum, not the interior wall where most of the emission originates. In these circumstances, the x-ray flux at the gauges depends on the plasma conditions inside the hohlraum for which we presently do not have good information. We have not attempted to calculate the effect of x-rays on gauges in SIM 7. If additional shot opportunities become available, we have considered fielding in SIM 7, pairs of gauges that have reinforcements that have very different x-ray absorption properties. Adjacent paddles with aluminum and beryllium might be plausible candidates for such a pair. It would be possible to place such a pair at a range where the x-ray fluence would not vaporize beryllium but would vaporize aluminum. The difference in gauge responses would permit us to estimate the magnitude of the x-ray fluence.

Material that flows inward from the interior walls of the hohlraum has, on many occasions, been observed to stagnate on the hohlraum axis. It has been suggested that a jet of material occurs following this stagnation. It is possible that a jet did form - in one case it hit the gauge, and in the other, it missed. The stagnation in gas filled hohlraums occurs later in time as the convergence is tamped by the gas. Our gas fill results are suggestive of a jet that is weaker in the case of the gas-fill hohlraums.

If we were to treat the entire body of SIM 1, 4 and 6 measurements as a single body of data, we would obtain a mean of 12.6 ± 1.1 taps. The median value of this body of data is 13 taps.

Rob Managan (ref. 2) has performed a one-dimensional LASNEX calculation of a scale-1 hohlraum that predicts an isotropic debris momentum of 8.4 taps. It will be interesting to see the degree of anisotropy predicted by two-dimensional calculations.

VI-6. Conclusions

We have made measurements of the debris impulse from NOVA hohlraums. This data should serve to benchmark two-dimensional LASNEX or LASNEX/CALE calculations. Our measurements show nearly a factor of two anisotropy between measurements normal to the hohlraum's cylindrical wall and those that are 22 degrees forward of that normal. There is sketchy evidence for a jet of material emerging from the laser entrance hole for hohlraums without a gas fill.

We would like to express our gratitude to Bob Turner and Andy Anderson of the laser program with whom we worked together to field these and other diagnostics in an effort to acquire data relevant to the NIF x-ray and debris environment.

VI-7. References

1. Michel Gerassimenko and Frank Serduke, *Passive Impulse Gauge Measurements on NOVA*. D-Division Report number DDV 95-0021, 1995
2. Rob Managan, private communication

VII-Foam and Structural Response Calculations for NIF Neutron Exposure Sample Case Assembly Design

VII-1. Introduction

Calculations have been done to design an aluminum foam protection layer for a stainless steel neutron exposure sample case. The layer protects the case from impulsive loads generated by a 20 MJ NIF capsule 10 cm from the sample case assembly. Impulse only from ablating x rays and hohlraum plasma debris is considered. One dimensional CALE foam response calculations and analytic estimates are used to show that 1 cm of aluminum 6101-T6 foam 10% of solid density is sufficient to attenuate the incoming peak pressure without complete melting on crush-up. Two dimensional DYNA calculations show that a 304 stainless steel spherical shell sample case with an inner radius of 1 cm and a wall thickness of 2 mm encased in 1 cm of foam does not yield to the pressure that is transmitted through the foam by a 220 Pa-sec (2.2 ktap), 2 GPa (20 kbar) load due to recoil of x-ray ablation. An unprotected spherical shell case subjected to a gentler load with peak pressure reduced to 0.2 GPa (2 kbar) not only yields but its effective plastic strain exceeds the failure point of 0.4 in 304 stainless steel after 160 μ sec. Doubling the impulse for the protected case to account approximately for debris loading results in very localized yield and an effective plastic strain that does not exceed 0.014. The simplest sample case assembly for neutron exposure is a metal case surrounded by a shock absorbing foam. The foam is metal based since polymer foams could lose their strength due to neutron and x-ray heating and ceramic foams crumble during crush-up. The foam surface is covered with 1 mm of ice or some other ablating material that is innocuous to target chamber parts and cryogenics, *i.e.* does not coat optical surfaces. This thin layer is needed so that the foam itself is not ablated. Calculations presented here will show foam shock attenuation performance and assembly structural response for a preliminary design.

The ice/foam concept proposed by Kruger (ref. 1) is a method by which NIF target chamber parts (*e.g.* target positioner, sample cases) can be protected from an impulse load due to cold (100 eV BB) x rays and plasma debris generated by a disassembling hohlraum. The ice guarantees absorption of the cold x rays but the resulting ablation contributes to recoil impulse. For a 20 MJ capsule 10 cm away from the front face of an ice/foam layer, the cold x-ray portion of the impulse has been simulated with the result that as the recoil pressure pulse progresses to 1 mm depth in the ice, the peak pressure is 1.8 GPa (18 kbar) and the impulse is 220 Pa-sec (2.2 ktap) (ref. 2). The plasma debris portion of the impulse is a subject of ongoing simulations. Managan's calculations show an additional 150 Pa-sec (1.5 ktap) impulse due to a 30 micron hohlraum (ref. 3). Also, Per Peterson (ref. 4) of the UC Berkeley Nuclear Engineering Department showed that for a combination of hohlraum cold x-rays and debris plasma impinging on a frost layer, the peak pressure stays around 2 GPa but the impulse is slightly more than doubled. We use these numbers as a starting point to calculate the foam thickness required to attenuate the pulse.

Since momentum is conserved, the sharp pressure pulse is attenuated into a much weaker but much longer pulse. The material response to the long time pulse dictates the design of the sample case that is surrounded by the foam, particularly the case wall thickness. We chose stainless steel as a material since our NIF neutron exposure tests will include liquids. Rounded corners are a simple way to reduce stress concentrations and taking this idea as far as it can go, we chose a spherical shell case shape. The final design will probably look more like a test tube with some mechanism to seal the top. The structural response of the final design as well as protection mechanisms for macroscopic debris in the target chamber, *e.g.*, cryo tube shrapnel, are not considered in this report.

The report is divided into four more sections. Section 2 is a detailed discussion of foam dynamics. Section 3 gives CALE (ref. 5) calculations of foam performance with comparisons to the analytical model of Section 2. Section 4 gives DYNA (ref. 6) structural response calculations of the sample case assembly and a bare sample case to demonstrate the necessity of the foam. Section 5 describes future work.

VII-2. Foam dynamics

A generic stress strain curve for a foam is shown in fig. 1. According to Gibson-Ashby (ref. 7), the plateau or foam yield stress for plastic failure of foam cell joints is given by

$$\sigma_p = a\sigma_{ys}\delta^{3/2} \quad (1)$$

where δ is the ratio of the initial foam density to the base material density, σ_{ys} is the base material yield strength and a is a fitting constant. A good foam to consider for our purposes is ERG's Duocel foam, based on aluminum alloy 6101-T6 (ref. 8). All subsequent appearance of aluminum in this report should be understood to mean this particular alloy. The alloy has a density of 2700 kg/m^3 and a yield strength of about 195 MPa over a range of -80 to 20°C (ref. 9). Given initial NIF cryo conditions and neutron and x-ray heating before shock attenuation (ref. 2), the range is appropriate. The fitting constant in eq. (1) is 0.5 based on Duocel data (ref. 8). If the foam is fabricated to an initial density of 270 kg/m^3 , $\delta = 0.1$. Equation (1) with $a = 0.5$ and $\sigma_{ys} = 195 \text{ MPa}$ gives $\sigma_p = 3.1 \text{ MPa}$.

Gibson and Ashby derive an estimate for the foam thickness required for impact attenuation. Their idea is that the impact loads the foam along the foam's stress strain curve until densification. Integrating the function shown on fig. 1 until densification gives an energy density absorbed on impact which can then be used to estimate the required foam thickness given the impact energy per unit area. This estimate is appropriate for shipping packaging analysis. Unfortunately this model does not account for shocking the foam which is expected in our case since the nominal incoming peak pressure is nearly three orders of magnitude greater than the plateau stress.

Figure 1. Generic stress-strain curve for a foam

In fact, the shocking of the foam occurs in three distinct phases. In the first phase, kinetic energy in the pressure pulse in ice is absorbed in the foam as kinetic and internal energy. At the same time, a precursor pulse is launched. This phase is over on the order of microseconds. In the next phase, the main pressure pulse decreases as the foam continues to crush. During this phase, the kinetic energy in the crushing converts to internal energy while the precursor continues to advance. This phase is completed on the order of tens of microseconds. In the final phase, the main pulse dissipates leaving only the precursor. If the foam were very thick, we would expect a long square pulse with height σ_p and width τ related by the momentum conserving relation $I_0 = \sigma_p \tau$, where I_0 is the impulse contained in the original pressure pulse that went through the ice. It is this precursor pulse that loads the object that the ice/foam layer protects. The long time (hundreds of microseconds) behavior of the protected object due to the loading requires a two dimensional structural response simulation. Here, we just want to estimate the amount of foam needed to sustain the transient crush. To do this estimate, we use the well known snowplow model.

The snowplow model in a foam assumes Rankine-Hugoniot jump conditions across the shock interface and that the shock irreversibly crushes the foam to its solid state. If the density in the unshocked foam is ρ_0 and the unshocked foam is under no pressure and has no material velocity, then the density, material velocity, and pressure in the shocked material is given by

$$\rho = \rho_s \quad (2)$$

$$u = \mu V_s \quad (3)$$

$$P = \rho_0 u^2 / \mu \quad (4)$$

where

$$\mu = 1 - \delta = 1 - \rho_0 / \rho_s \quad (5)$$

is the initial porosity, ρ_s is the solid material density, and V_s is the shock speed.

The shock or foam front s starts at 0 and moves as

$$\frac{ds}{dt} = V_s \quad (6)$$

s is the length of uncrushed foam consumed by the shock. The mass per unit area of shocked material is then $\rho_0 s$. Therefore, the impulse carried by the main pressure pulse in the crushing foam is

$$I = \rho_0 s u \quad (7)$$

To limit σ_p loading pressure, low density foams with $\delta < 0.2$ are of interest. Because of the low foam density, a tensile wave would be reflected at the ice-foam interface. However, ice can support a tensile wave of only a few bars, so we assume all of the impulse in the ice is delivered to the foam, or $I = I_0$ initially. As the main pressure pulse propagates, some of the impulse in the main pressure pulse is lost to the precursor so that eq. (7) becomes

$$I_0 - \sigma_p t = \rho_0 s u \quad (8)$$

Note that this equation applies only for $t < I_0 / \sigma_p$.

Eliminating V_s in eq. (3) with eq. (6) and then substituting the results into eq. (8) gives an ODE equation for s^2 which when solved with the initial condition $s = 0$ gives

$$s^2 = (2I_0^2 / \rho_0 \mu \sigma_p)(x - x^2 / 2) \quad (9)$$

where the dimensionless quantity

$$x \equiv \sigma_p t / I_0 < 1$$

We now use eq. (9) to solve eq. (8) for u^2 as a function of x and substitute the result into eq. (4) to obtain

$$P = \sigma_p \frac{(1-x)^2}{2x(1-x/2)} \quad (10)$$

P falls to σ_p when $x=1-1/\sqrt{2}$. Substituting this result into eq. (9) gives our estimate of the foam crush depth

$$D = \sqrt{I_0^2 / 2\rho_s(1-\delta)a\sigma_{ys}\delta^{5/2}} \quad (11)$$

where we have substituted Eqs. (1) and (5). We will check our estimate with CALE simulations.

VII-3. CALE simulations

CALE is an arbitrary Euler-Lagrange hydrodynamics code with various equation of state and material strength models that can be chosen by the user. Our ice/foam simulations consist of a simple 1-D geometry with 1 mm of ice covering 2 cm of aluminum foam. The left boundary condition is a pressure pulse with peak pressure of 2 GPa and an impulse of 220 Pa-sec. The right boundary condition is a rigid wall.

The ice is treated as a hydrodynamic solid with a Gruneisen equation of state with reference density 917 kg/m³, an attainable minimum pressure of zero, a sound speed of 3236 m/s and a Gruneisen parameter of 0.6 (ref. 10). The ice is not allowed to support tensile waves, forcing the entire pressure pulse into the foam.

The foam is treated as a porous solid with a Gruneisen equation of state applied to the base material aluminum. To implement this model, CALE requires a crush curve of the form

$$P_c = -P_{c0} \ln(\mu)$$

where the porosity μ varies with the crushing. Converting porosity to strain and compaction pressure P_c into stress, we get a curve similar in appearance to fig. 1 but without the elastic portion. Ignoring the elastic portion, we have $\sigma = \sigma_p$ at the initial porosity $\mu = 1 - \delta$ which, for use in CALE, yields

$$P_{c0} = -\sigma_p / \ln(1 - \delta)$$

We ran simulations with foam density ratios of 0.1, 0.15, and 0.2 for impulses of both 220 and 440 Pa-sec. The doubled impulse runs were meant to model the effect of debris impulse in addition to cold x-ray impulse. Figures 2 and 3 show the foam front and energy deposition histories for the 220 Pa-sec, 0.1 foam density ratio simulation.

Note that total deposition of about 6 J of kinetic energy from the ice into kinetic and internal energy in the foam is over in about 4 μ sec with almost half of the deposition occurring less than 1 μ sec. Over this 4 μ sec period, the pressure has already dropped from 2.0 GPa (20 kbar) to 10 MPa (100 bar). Comparing fig. 3 and 2, we see that the ice kinetic energy is

Figure 2. Foam front history for an initial foam density ratio of 0.1 and an impulse of 220 Pa-sec (2.2 ktap).

Figure 3. Foam energy deposition history for an initial foam density of 0.1 and an impulse of 220 Pa-sec (2.2 ktap)

absorbed by the time the foam has squeezed down by about a millimeter. As the kinetic energy is converting into internal energy and the main pressure pulse dissipates, the foam has squeezed down by 0.516 cm. These results are only slightly modified with better numerical resolution.

With the presence of heat in the foam, we checked if the foam can melt. We must first consider the amount of energy deposition from 14 MeV neutrons and hot (11 keV BB) x rays before the shock arrives. The fluence of these radiations due to a 20 MJ capsule 10 cm away are 12 kJ/cm^2 and 100 J/cm^2 respectively (ref. 2). Monte Carlo calculations show that the neutrons deposit 42.6 J/g nearly uniformly into the foam. Aluminum opacities integrated over an 11 keV BB show that the hot x rays deposit 500 J/g into the first tenth of a millimeter of the foam. Although this is not hot enough to melt given the initial aluminum temperature, the material properties of the foam walls will be severely weakened. At 1 mm, the hot x-ray deposition drops to 160 J/g . At this point, the aluminum temperature rises to around 76.3°C assuming a cryo startoff temperature of -150°C and using a heat capacity of 0.897 J/g-K (ref. 9). Further in, the hot x-ray deposition becomes less severe. Thus, before the shock arrives, 1 mm of foam is rendered useless because the yield strength of the foam walls has dropped significantly due to the heating. (This should be contrasted to polymer foams whose performance is degraded over its entire length due to neutron deposition (ref. 2).) It is not clear what this weak foam layer does to shock transition from ice into foam and has not been modeled in our CALE simulations. If we assume that the shock travels unmolested into the foam beyond 1 mm, then we can proceed with our estimate because beyond this point, the foam material characteristics are nominal.

The highest per gram internal energy density was found for the case of 440 Pa-sec impulse on a 0.1 density foam. For this case, a maximum of 553 J/g was deposited in a thin layer of fully crushed foam that travels with the crush front. If we add 42.6 J/g for deposition from the neutrons and a maximum additional 160 J/g from the hot x-rays, we have deposited a total of almost 760 J/g . The foam starts at -150°C . Aluminum melts at 660°C with a latent heat of melting of 397 J/g . Therefore, we need 727 J/g to melt and 397 J/g through melt. Thus we are at melting but there is not enough deposition to get over the latent heat. A foam with a higher density ratio suffers less from crush heating and as we will see, squeezes down less requiring less initial thickness.

We compare eq. (11) with the results from the CALE simulations on fig. 4. There is good agreement with our estimate and the final amount the foam has squeezed in the CALE simulation. The predicted time at which foam stops crushing is smaller than CALE predicts. With $x=1-1/\sqrt{2}$, it follows that $t=0.293 I_0/\sigma_p$, but from Figs. 2 and 3, $t=I_0/\sigma_p$ appears to be a more realistic stop time. Such inaccuracies are expected given the relative simplicity of the snowplow model.

Figure 4. Foam depth vs foam density ratio for aluminum 6106-T6-based foam. Al 6101-T6 has a density of 2700 kg/m^3 and a yield stress of 195 MPa .

We now make some comparisons to frost mitigation which is an alternative protection scheme in which the frost is both the ablator and shock absorber. We again use eq. (11), replacing σ_p terms (c.f. eq. (1)) with some minimum pressure $P_{\min}$. For ice frost, $\rho_s=917 \text{ kg/m}^3$. For frost density 10% of ice density, $\delta=0.1$. We then calculate the frost

depth required to attenuate the 220 Pa-sec impulse down to a $P_{\min} = 3.1$ MPa to be 0.973 cm which is almost twice the depth the aluminum foam for the same performance. Equation (11) can also be used for quick estimates of foam crush depths for other metal foams.

Equation (11) and the CALE simulations show less foam is needed if a higher foam density is selected. Also, foam heating is less severe. However, fig. 5, calculated from eq. (4), shows the increased precursor pressure, *i.e.*, protected object loading pressure, obtained when higher foam densities are used. Therefore, the designer must balance the space allotted for the foam with how much loading the protected object can withstand.

To demonstrate the precursor pressure loading, we consider the static stress of a simply supported circular plate, *e.g.* a can lid. The peak stress (ref. 11) due to a loading pressure is:

$$\sigma = 1.24 P_L \left(\frac{R}{d} \right)^2$$

where R is the lid radius, d is the lid thickness and P_L is the loading pressure. Assuming the shock from the foam is completely reflected at the foam/lid interface, we

have $P_L = 2 \sigma_p$. For 10%

foam, $\sigma_p = 3.1$ MPa. For a 304 stainless steel can, $\sigma_y = 240$ MPa (ref. 12). If the can cross sectional area is 1 cm^2 , $d > 1 \text{ mm}$, to keep the peak static stress below the yield stress.

Figure 5. Precursor pressure for the foam of figure 4. Since this quantity is used to load CALE's foam equation of state crush curve, the simulation precursor pressures agree identically

The reflected shock may lead to spall at the foam edge that was crushed. To check if this will indeed occur, we will need to know the tensile limit for spall of the crushed foam with the caveat the foam is simultaneously heated. If the tensile limit for spall is the yield strength of solid aluminum, then spall is a strong possibility because order 1-2 mm of foam has been heated by crushing and hot x rays and the heating greatly reduces the yield strength. On the other hand, heating makes the aluminum more ductile which increases the plastic strain to failure so that even if the tensile limit for spall, reduced by heating, is reached, the material may not fail.

VII-4. DYNA simulations

For the preliminary design phase of this work, we use DYNA. DYNA is a finite element continuum mechanics code and can deal with realistic shapes more easily than most finite difference hydrocodes. In addition, the DYNA material types and equations of state are more versatile than those of CALE.

We ran an axisymmetric DYNA calculation on the assembly shown on fig. 6. The 10% of solid density Duocel foam block is cylindrical with an embedded spherical shell 304 stainless steel sample case. We chose a shell width of 2 mm based on our lid radius estimates of Section 3. The entire assembly is free to move in any direction and is loaded uniformly at the bottom with a triangular pressure pulse in time such that the peak is 2.0 GPa (20 kbar) and the impulse is 220 Pa-sec (2.2 ktp) to model the recoil impulse from cold x-ray deposition. The basic zoning is roughly two elements per radial millimeter. The zoning in the foam over half of the bottom foam layer is finer towards the pressurized surface. This foam shock entry piece is indicated by the horizontal line between the can and the loading plane. The ratio of thickest to thinnest zone is a factor of six. This was done to avoid an immediate numerical instability at the pressurized surface.

Figure 6: Schematic of DYNA simulation geometry. The large arrows indicate the loading. The horizontal line near the bottom of the foam indicates the break in axial zoning. Below the line, in the foam shock entry piece, the zoning is finer toward the loading.

This was done to avoid an immediate numerical instability at the pressurized surface.

Beyond 10 μ sec, a slowly growing rigid body z velocity becomes noticeable. Since the transient pressure pulse is concluded at 10 μ sec, we remesh at this time to control the slower numerical instability. The meshing is similar to that used to start the problem but no ratioed zoning is required.

The steel was modeled as an elastic perfectly plastic material with density 7900 kg/m³, Young's modulus 210 GPa, Poisson ratio 0.31, and yield stress 240 MPa (ref. 12). Hardening and failure beyond yield was not specifically modeled. However, failure in 304 stainless steel occurs when the effective plastic strain reaches 0.4 (ref. 13).

The Duocel foam was modeled with a more detailed crush curve than used in Section 3. The curve stays along the plateau stress until densification starts. Then a curve fit through densification up to the fully densified regime is used. In the fully densified regime, there is a linear stress-strain behavior with the slope equal to the Young's modulus of aluminum which is 69 GPa (ref. 9).

The DYNA foam model requires the shear and bulk unloading moduli. The moduli vary depending on the crush condition of the foam, but the DYNA model accepts only one value for these quantities. Since most of the foam is exposed only to the precursor pressure and is thus not strongly crushed, we take the uncrushed value for the shear modulus. For 10% foam, the shear modulus is 345 MPa (ref. 8). Assuming unloading is most important in the strongly crushed foam edge and that the incoming pressures nearly solidify the foam, we take as the unloading modulus the bulk modulus of solid aluminum which is 74 GPa (ref. 9).

The DYNA foam model also requires a foam yield stress and a foam tensile limit. For uniaxial loading which is essentially what we have here, the foam yield stress is just the plateau stress defined in eq. (4), although a non-trivial correction for multiaxial loading is available (ref. 14). The tensile limit is taken to be the foam yield stress, negative in tension, since tension beyond this point will make the stretching foam walls touch. Further tension up to the solid aluminum yield stress would lead to spall.

The entire foam model uses nominal solid material parameters. This idea breaks down at the foam edge where crushing and hot x-ray heating lead to near-melt conditions. Since the edge is thin, we suspect that such effects do not play a large part in the global material response. However, to model spall properly, these thermal effects must be calculated self-consistently. This would require an elastic-plastic hydrodynamic foam model with strain and temperature dependent yield, yield hardening, compaction, unloading, and shear. Both CALE and DYNA have pieces of this model, but major code development would be required fully to assemble such a model.

Figure 7: Nine evenly spaced contours of Von Mises effective stress from the indicated minimum 1.2 MPa and maximum 22 MPa at 130 microseconds. The outline of the crushed foam is also shown.

The results of our simulation are shown in fig. 7. The effective stress at 130 μsec has a maximum of 22 MPa which is an order of magnitude below the stainless steel yield stress of 240 MPa. For time out to 400 μsec , the maximum effective stress drops. Given the order km/sec shock speeds and the order cm dimensions of the problem, 100 or so microseconds should be long enough to resolve wave bouncing.

Figure 8: Bare can DYNA simulation outline. The arrows at the bottom of the can indicate the load surface. Inside the small contours at the poles of the can, the effective plastic strain has exceeded the failure point.

The simulations give qualitatively similar results to the CALE simulations. Plateau pressure precursors are launched and the main pressure pulse decays away in under 10 μsec . The kinetic energy pulses up and then decays down over tens of μsec as the front of the foam crushes from 1 cm thick to about 0.4 cm thick. Finally, the DYNA rigid body z velocity is consistent with the incoming momentum

Figure 9: Doubled impulse simulation. Inside the small contours at the poles of the can, the effective plastic strain has exceeded 0.005 with the maximum value of 0.014. Also pictured is the outline of the crushed foam.

(impulse $\times$ radial surface load area) and assembly mass until the previously mentioned slow growth instability becomes noticeable.

We compare our results to the bare can simulation shown in fig. 8. This simulation is initialized with a 220 Pa-sec, 0.2 GPa pressure pulse. The gentler pulse is used here because the 2 GPa initialization is violently unstable to various zonings attempted. The simulation ran out to several 100 μ sec without changes in kinetic energy and rigid body z velocity beyond the initial pulse. The z velocity is consistent with the incoming momentum (impulse $\times$ spherical surface load area) and can mass. The zoning that achieved this required 20 elements over the 2 mm shell with a reduction in zone size by a factor of five from the inner to the outer element. Despite the gentler loading, the unprotected can reaches the failure point at 160 μ sec.

Finally, we ran a sample case assembly problem identical to fig. 7 except the impulse was doubled to 440 Pa-sec (4.4 ktap) approximately to account for the additional impulse due to plasma debris loading. The effective plastic strain at 350 μ sec is shown in fig. 9. Note the greater deformation of the foam then for the 220 Pa-sec impulse. For this load, the can does yield, but the plastic strain accumulated does not go above 0.014 which is an order of magnitude below the 0.4 effective plastic strain to failure in 304 stainless steel.

VII-5. Future work

We have demonstrated that it is possible to protect a radiation sample case from plastic failure due to cold x-ray ablation and plasma debris shocks with a reasonable amount of foam. An immediate task is to vary peak pressures and impulses in the DYNA simulation to see how far we can push the protection scheme. Future tasks also include scoping out of better materials and experimental verification of existing calculations. Eventually, the calculations will be extended by modeling ablating x rays and heating radiation coming into the sides as well as the bottom, can fasteners, and shrapnel, requiring a three dimensional model with material penetration.

A critical problem is the possible melt and/or spall of the foam. Melted foam can drop to the chamber floor and spall can make nasty projectiles. Higher aluminum foam density leads to less heat on crushing, but even without crushing, hot (11 keV BB) x-ray deposition leads to a significant reduction in yield strength on the front foam layer. This may not hurt the performance of the remainder of the foam, but can lead to spall when reflected waves impinge back onto the layer. A solution to this problem may be found by using a foam based on a metal whose radiation absorption heating, crush heating, and heat capacity lead to a temperature rise that not only keeps the metal below its melting temperature but also below a temperature where the yield strength drops significantly. An alternative foam material may also be required so that radioactive decay from neutron activation drops to a prescribed level in the shortest possible time.

It has recently been found that a B_4C ablator is easier to use than ice and additional target chamber contamination for a 3 cm diameter B_4C ablator is less than a third of the unavoidable contamination due to the 20 MJ target itself. Calculations of the cold x-ray impulse through this ablator and propagation of hot x rays on into the foam will have to be done.

The one dimensional snowplow model, eq. (11) corroborated with CALE simulations, has been used to help estimate the space required for NIF target chamber protection mechanisms. Experimental validation of the one dimensional model should therefore be done as soon as possible. This can be accomplished by shooting ice/foam

layers of varying foam densities with varying impulses. The impulse, final foam length and pressure delivered to the back of the foam may be measured to check the validity of our calculations. Two possibilities for shooting are using NOVA to ablate plastic and send a NIF comparable pressure pulse into the foam or to use the gas gun facility to accomplish essentially the same task with a flyer plate. Some more thinking in terms of ease of the experiment, usefulness of the results, and cost must be done before a final choice can be made. An added advantage of a experiment is that spall due to crush heating, reduced yield strength, and reflected waves can be detected and perhaps conclusions can be drawn on its severity.

VII-6. Acknowledgments

We wish to thank Douglas Faux of LLNL for helpful advice for using DYNA. This work was performed under the auspices of the US DOE by LLNL under contract W-7405-ENG-48.

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VIII-Non-Ignition X-ray Source Fluence-Area Products for Nuclear Weapons Effects Testing on NIF

VIII-1. Introduction

A major feature of the National Ignition Facility is that its 192 beams can drive arrays of laser-driven x-ray sources. The ability to allow beam steering up to 50 cm away from target-chamber center has not been precluded in the NIF design. Indeed, a multidisciplinary team of physicists and engineers supported by DSWA will be studying the issues surrounding facilitization of such target arrays at NIF starting in 1997. It is of interest to update projections of the capabilities of these target arrays. The fluence-area product of an array will depend on a number of factors such as the total energy available to drive the targets, the efficiency of the laser-driven production of x-rays, the attenuation of debris mitigation and the solid angle subtended with the required uniformity of fluence.

The fluence-area product for NIF can be expressed

$$F \times A = E_{\text{NIF}} \times \mu \times T \times \Delta\Omega$$

where E_{NIF} is the NIF energy that can be coupled to the sources, μ is the source efficiency per steradian (source efficiency/solid angle), T is the debris shield transmission and $\Delta\Omega$ is the solid angle that can be collected from an individual source and still have the requisite uniformity (for purposes of this discussion, we will use $\pm 10\%$).

VIII-2. Components of the Fluence x Area Product Formula

1. Usable NIF energy, E_{NIF} :

This depends on the target type and pulse length. If the targets are thick slabs, then we assume that only 1/2 of NIF will be usable since x rays produced by the other half of NIF would be seen by the test object. With underdense sources, which are more like isotropic sources, we assume that all NIF beams might be used.

The usable energy also depends on the pulse shape. In previous estimates we always assumed that NIF is a 1.8 MJ, 500-600 TW laser, producing a pulse length of ~ 3 ns. Figure 1 is a more recent, better estimate of NIF energy vs. pulse length (ref. 1). The performance ranges from 0.85 MJ in 1 ns to 2 MJ in 3 ns to over 3 MJ in 10 ns. These latest estimates of NIF fluence area products consider this performance.

Figure 1. Unofficial, 1996 estimate of NIF energy vs. pulse duration for red and blue light (ref. 1).

2. Source efficiency per steradian, μ :

In projecting NIF fluence-area products we consider three types of sources: demonstrated discs, demonstrated gas bags and predicted NIF sources. The demonstrated discs and gas bags are from NOVA experiments and are described in ref. 2 (see appendix). There are four demonstrated sources of interest:

- 1) Au disc radiating 0-1 keV photons. The total conversion efficiency is ~70%. The radiation from the disc goes into approximately 2π steradians, so μ_{disc} is ~11%/sr.
 - 2) Au disc producing M-band radiation (2-3 keV) at ~15% efficiency. This is a 2π source, so $\mu \sim 2.4\%/sr$.
 - 3) Xe-gas-bag M-shell radiation (1-2 keV). Approximately 25% efficiency into 4π . For this source $\mu \sim 2\%/sr$.
 - 4) Xe-gas bag L-shell radiation. (4-7 keV); ~8% efficiency into 4π . $\mu \sim 0.6\%/sr$.
- All these measurements were all made on targets irradiated with 1 ns pulses.

Predicted multi-keV source efficiencies for NIF come from 2-D LASNEX modelling. As described in ref. 3 (also reproduced in the appendix of this report), 2D design of NIF multi-keV sources has focused on two types of underdense sources; gas columns and tamped sources (Be cans filled with a low density mid-Z material). Because a gas column is, by definition, heated by only one of NIF's beams, it is restricted to ~10 TW maximum power. Tamped sources remove this power restriction since they allow several beams to be fired into a target. Tamped source designs exist up to 60 TW.

Xenon gas columns have been modeled with 2 and 3 ns pulses. Our 3 ns simulations indicate that about 18% of the laser energy will be converted into L-shell radiation (>4 keV) and about 45% into M-shell emission (1-2 keV) and 65% into radiation at all energies. We have also modeled gas columns of other materials (such as Fe and Ge) which produce higher photon energy radiation. This work shows that at higher photon energies, gas columns are not as efficient as tamped sources, at least for pulse lengths of 2 ns. Moreover, since tamped sources are amenable to NOVA experiments, our design work on column sources has been limited.

With the tamped source we have investigated a wide variety of source materials. We have evaluated these sources at power levels between 20 and 60 TW; well within NIF's 500-850 TW capabilities. This design work has been done only for pulse lengths of 2 ns. (Longer pulse design work has been deferred in favor of supporting NOVA proof-of-principle experiments which are 2 ns duration.)

Our predicted performance for the tamped sources is summarized in table 1 below:

element	Laser power	fraction of laser energy > hv (keV)	
Kr	60 TW	4%>13 keV	30%>2 keV
Ge	60 TW	14%>10	26%>2
Ge	50 TW	10%>10	26%>2
Ge	30 TW	7%>10	20%>2
Cu	40 TW	11%>8.5	26%>2
Cu	30 TW	10%>8.5	24%>2
Dy	60 TW	9%>8	24%>2
Xe	60 TW	30%>4	48%>1
Xe	50 TW	26%>4	48%>1
Xe	30 TW	22%>4	40%>1
Xe	20 TW	17%>4	37%>1

Table 1. Predicted performance for tamped-source targets taken from ref. 4. These targets are approximately isotropic sources. The source efficiency per steradian, μ , is found by dividing the above efficiencies by 4π .

3. Debris shield transmission, T:

For this work we assume no debris shield attenuation. For photons >4 keV, this should be a fair assumption. At lower photon energies, it is incorrect.

4. Solid angle, $\Delta\Omega$ for $\pm 10\%$ uniformity:

A constraint of $\pm 10\%$ uniformity on the experimental object limits the solid angle we can usefully collect from each source. For an isotropic point source this solid angle is 0.45 sr. For four, appropriately distributed isotropic sources, the solid angle we can utilize from each source rises to 1.6 sr. For 25 appropriately distributed, isotropic sources it is 4.5 sr. In the limit of an infinite number of isotropic point sources distributed on a plane, the solid angle would be 2π sr.

VIII-3. Estimated Fluence x Area products:

Table 2 lists fluence area products (in calories) using experimentally demonstrated efficiencies and various fielding, pulse length scenarios.

The upper part of this table is the most conservative estimate we can make, assuming 1 ns pulse length as was used on the NOVA experiments. This is a guaranteed minimum performance. Sections of this table list performance assuming targets irradiated at 2, 3 and 6 ns have the same efficiency as those irradiated at 1 ns. Assuming this to be true to 3 ns is probably reasonable; assuming it to be true at 6 ns is somewhat speculative. Thus, using demonstrated-on-NOVA efficiencies and a large number of sources, we project, with reasonable confidence, fluence area products of ~90,000-120,000 calories in the 0-1 keV range; 32,000-43,000 calories in the 1-2 keV range; 19,000-26,000 calories in the 2-3 keV range; and 10,000-13,000 calories in the 4-7 keV range. More speculative are the 6 ns estimates of ~180,000 calories, 64,000 calories, 39,000 calories and 19,000 calories in the same spectral ranges.

Table 3 lists fluence area products (in calories) using efficiencies found in 2D LASNEX design simulations of tamped targets. The single point and four point sources assumed that at least 60 TW per source would be available. The 25-point source column assumed 20-30 TW per source would be available (The NIF of ref. 1 can drive 25 sources at 30 TW/source for 2 ns; 27 TW/source for 3 ns; 20 TW/source for 6 ns).

The upper section of table 3 assumes the sources will only work for 2 ns. The central section of table 3 assumes that sources can be designed for 3 ns which have the same efficiency as the 2 ns sources. This is probably a fair assumption. The lower part of table 3 assumes that sources can be designed for 6 ns pulses which have the same efficiency as the 2 ns sources. This is speculative.

Table 3 suggests that we can reasonably hope to have sizable fluence area products in the multi-keV regime. Up to ~38,000 calories in 4-7 keV; ~12,000 calories around 10 keV; dropping to ~2400 calories at 13 keV. More speculative are the 6 ns predictions of ~44,000 calories, 18,000 calories and 3600 calories in the same spectral regions.

Table 4 shows the projected performance from arrays of Xe gas columns irradiated with ~10 TW single NIF beams. Targets such as these may lead to fluence area products of ~30,000 to 45,000 calories in the 4-7 keV range and 77,000 to 116,000 calories in the 1-2 keV range.

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FxA products using experimentally demonstrated efficiencies						
Assuming the 1ns pulse length used in the Nova experiments						
source	hv range	eff/sr	Usable NIF MJ	1pt (cal)	4pt (cal)	25pt (cal)
Au disc	0-1keV	0.11	0.425	5033	17895	50329
Xe bag M	1-2keV	0.02	0.85	1830	6507	18301
Au disc M	2-3keV	0.024	0.425	1098	3904	10981
Xe bag L	4-7keV	0.006	0.85	549	1952	5490
Assuming targets have the same efficiency at a 2ns pulse length						
source	hv range	eff/sr	Usable NIF MJ	1pt (cal)	4pt (cal)	25pt (cal)
Au disc	0-1keV	0.11	0.75	8882	31579	88816
Xe bag M	1-2keV	0.02	1.5	3230	11483	32297
Au disc M	2-3keV	0.024	0.75	1938	6890	19378
Xe bag L	4-7keV	0.006	1.5	969	3445	9689
Assuming targets have the same efficiency at a 3ns pulse length						
source	hv range	eff/sr	Usable NIF MJ	1pt (cal)	4pt (cal)	25pt (cal)
Au disc	0-1keV	0.11	1	11842	42105	118421
Xe bag M	1-2keV	0.02	2	4306	15311	43062
Au disc M	2-3keV	0.024	1	2584	9187	25837
Xe bag L	4-7keV	0.006	2	1292	4593	12919
Assuming targets have the same efficiency at a 6ns pulse length						
source	hv range	eff/sr	Usable NIF MJ	1pt (cal)	4pt (cal)	25pt (cal)
Au disc	0-1keV	0.11	1.5	17763	63158	177632
Xe bag M	1-2keV	0.02	3	6459	22967	64593
Au disc M	2-3keV	0.024	1.5	3876	13780	38756
Xe bag L	4-7keV	0.006	3	1938	6890	19378

Table 2. Predicted NIF Fluence-Area products for various pulse durations using experimentally measured efficiencies for conversion of laser light to x rays.

Projected NIF FxA products using 2D Lasnex efficiencies							
Be tamped mid Z filled targets							
Assume 2ns source and 2ns efficiencies							
source	hv range	eff per at 60TW	steradian at 30TW	Usable NIF MJ	1pt (cal)	4pt (cal)	25pt (cal)
tamped Xe	>1keV	0.038	0.0318	1.5	6136	21818	51352
tamped Xe L	4-7keV	0.024	0.0175	1.5	3876	13780	28260
tamped Dy	>2keV	0.0191		1.5	3084	10967	
tamped Dy L	~8keV	0.0071		1.5	1147	4077	
tamped Cu	>2keV	0.0207	0.0191	1.5	3343	11885	30843
tamped Cu K	~9keV	0.0088	0.008	1.5	1413	5024	12919
tamped Ge	>2keV	0.0207	0.016	1.5	3343	11885	25837
tamped Ge K	~10keV	0.0111	0.0056	1.5	1792	6373	9043
tamped Kr	>2keV	0.024		1.5	3876	13780	
tamped Kr L	~13keV	0.0032		1.5	514	1826	
Assume 3ns source with 2ns efficiencies							
source	hv range	eff per at 60TW	steradian at 30TW	Usable NIF MJ	1pt (cal)	4pt (cal)	25pt (cal)
tamped Xe	>1keV	0.038	0.0318	2	8182	29091	68469
tamped Xe L	4-7keV	0.024	0.0175	2	5167	18373	37679
tamped Dy	>2keV	0.0191		2	4112	14622	
tamped Dy L	~8eV	0.0071		2	1529	5435	
tamped Cu	>2keV	0.0207	0.0191	2	4457	15847	41124
tamped Cu K	~9keV	0.0088	0.008	2	1884	6699	17225
tamped Ge	>2keV	0.0207	0.016	2	4457	15847	34450
tamped Ge K	~10keV	0.0111	0.0056	2	2390	8498	12057
tamped Kr	>2keV	0.024		2	5167	18373	
tamped Kr L	~13keV	0.0032		2	685	2434	
Assume 6ns source with 2ns efficiencies							
source	hv range	eff per at 60TW	steradian at 30TW	Usable NIF MJ	1pt (cal)	4pt (cal)	25pt (cal)
tamped Xe	>1keV	0.038	0.0294	3	12273	43636	94952
tamped Xe L	4-7keV	0.024	0.0135	3	7751	27560	43600
tamped Dy	>2keV	0.0191		3	6169	21933	
tamped Dy L	~8eV	0.0071		3	2293	8153	
tamped Cu	>2keV	0.0207	0.0191	3	6685	23770	61687
tamped Cu K	~9keV	0.0088	0.008	3	2826	10048	25837
tamped Ge	>2keV	0.0207	0.016	3	6685	23770	51675
tamped Ge K	~10keV	0.0111	0.0056	3	3585	12746	18086
tamped Kr	>2keV	0.024		3	7751	27560	
tamped Kr L	~13keV	0.0032		3	1027	3652	

Table 3. Predicted NIF Fluence-Area products for Be-tamped sources for various pulse durations using calculated efficiencies for conversion of laser light to x rays.

Projected NIF FxA products using 2D Lasnex efficiencies						
Xe gas column source						
Assuming 3ns pulse and 3ns efficiencies						
source	hv range	eff/sr	Usable NIF MJ	1pt (cal)	4pt (cal)	25pt (cal)
Xe gas column	total rad	0.052	2	11196	39809	111962
Xe gas column	>1keV	0.036	2	7751	27560	77512
Xe gas column	4-7keV	0.014	2	3014	10718	30144
Assuming 6ns pulse with 3ns efficiencies						
source	hv range	eff/sr	Usable NIF MJ	1pt (cal)	4pt (cal)	25pt (cal)
Xe gas column	total rad	0.052	3	16794	59713	167943
Xe gas column	>1keV	0.036	3	11627	41340	116268
Xe gas column	4-7keV	0.014	3	4522	16077	45215

Table 4. Predicted NIF Fluence-Area products for xenon gas column sources for various pulse durations using calculated efficiencies for conversion of laser light to x rays.

IX-Appendix: Two Papers on the subject of Source Development

This past year, two research studies that are important to the subject of source development appeared in LLNL's Inertial Confinement Fusion Quarterly Review. These papers also provide the principal components of the audit trail for the projected NIF laser-only sources that were discussed in chapter VIII above. For completeness and convenience of the reader, we include copies of both of these papers in this appendix.

IX-1. X-Ray Production in Laser-Heated Xe Gas Targets

The first, by R. L. Kauffman, L. J. Suter, H. N. Kornblum, D. S. Montgomery, "X-Ray Production in Laser-Heated Xe Gas Targets addresses the gasbag experiments that were performed in 1995. This paper appeared in the ICF Quarterly Report, January-March 1996, LLNL, UCRL-LR-105821-96-2, page 43.

IX-2. Efficient Production and Applications of 2- to 10-keV X Rays by Laser-Heated Underdense Radiators

The second, by L. J. Suter, R. L. Kauffman, M. S. Maxon, J. F. Davis, , presents the current understanding of underdense plasma x-ray sources. This paper appeared in the ICF Quarterly Report, April-June 1996, LLNL, UCRL-LR-105821-96-3, page 96.

X-RAY PRODUCTION IN LASER-HEATED Xe GAS TARGETS

R. L. Kauffman

L. J. Suter

H. N. Kornblum

D. S. Montgomery

Introduction

High-powered lasers focused to high intensities can generate bright x-ray sources. When they directly irradiate high-Z planar targets, more than 50% of the incident laser energy can be converted to soft, or thermal, x rays.^{1,2} Enclosed targets, or hohlraums, can confine the x rays for inertial confinement fusion (ICF) and other radiation-heating experiments.³⁻⁵ Laser-heated plasmas can also be a bright source of keV x-ray emission.^{6,7} These x rays are produced by bound-bound and bound-free transitions in the hot, underdense plasmas. The spectrum is highly structured and depends on the target material.

To date, most studies of x-ray production from laser-produced plasmas have used solid or overdense targets whose initial density, when ionized, is above the critical plasma density, n_c , for absorption.^{1,8} In such targets, the laser energy is absorbed at, or near, critical densities producing a hot plasma. Electron conduction from the hot plasma efficiently heats the higher-density matter while the hot plasma expands to form a lower-density plasma, or corona. This establishes an ablation process in which the denser matter flows through the critical density region and is heated by the laser and then exhausted into the corona. X rays are produced primarily in the region around critical density that is heated by the laser, a region called the conversion layer. For high-Z targets, x rays from the conversion layer can produce a thermal wave into the dense target material, which also can contribute to the production of thermal x rays. Although this heating and x-ray production process has been shown experimentally to be efficient, a significant amount of energy is coupled to hydrodynamic motion of the expanding plasma.

We present results from a new type of target that does not rely on ablation for heating the plasma. In the new targets, the density is less than n_c when ionized. The plasma is initially cold and opaque to the laser.

The laser is absorbed efficiently by inverse bremsstrahlung heating of the plasma. As the plasma is heated, inverse bremsstrahlung becomes less efficient, making the plasma more transparent. The supersonic heat wave that is established ionizes the underdense plasma. The process has the advantage of being more efficient for radiation production, compared with overdense targets, because laser energy heats the plasma without ablation, and less energy is wasted on hydrodynamic motion. The plasma subsequently disassembles as it expands, producing hydrodynamic motion; however, this occurs after the plasma is already heated. The higher plasma temperatures can potentially produce brighter sources for both thermal and multikilovolt x rays. In addition, the higher plasma temperatures can produce higher ionization states, which may result in higher-energy x rays than those attainable using overdense targets. More efficient targets for x-ray production have several applications, including use as a bright x-ray source for backlighters and for radiation-effects experiments.

Experiment

The experiments were performed using the Nova laser⁹ to investigate underdense targets and to demonstrate their efficiency for both thermal and multi-keV x-ray production. The targets, called gasbags¹⁰, are nearly spherical thin membranes filled with gas similar to those developed for large plasma experiments. The thin membranes are made of 4000-Å polyimide ($C_{14}H_6N_2O_4$) stretched over a support washer.¹¹ Figure 1(a) is a picture of the target mounted in the Nova target chamber and viewed from the west by the polar target alignment viewer (TAV1). The striped, nearly hemispherical objects are the membranes. The stripes are caused by interference patterns of the optical illumination system in the membrane. The large black stripe in the center is a support washer for the

(a) Target viewer picture

FIGURE 1. Experimental geometry. (a) Image of the target in the target alignment viewer. (b) Schematic of focusing geometry on the target surface and view of the diagnostics. This view is from the west on Nova along the axis of symmetry of the beam cones. (08-00-0296-0438pb01)

membranes. The target is rotated 90° to the normal configuration for the large plasma experiments to allow optimal viewing by x-ray diagnostics.

The targets are filled with a gas mixture of Xe and C₃H₈ (propane) at 1 atm of pressure. We chose Xe because it is a relatively high-atomic-number gas that is easily handled. When ionized to a Ne-like configuration, Xe has x-ray line emission in the 4–6-keV range, which is of interest for x-ray radiography and x-ray exposure experiments. Xe is mixed with C₃H₈ to supply H ions to the plasma. Mixing of light ions, such as H, with heavy ions helps suppress stimulated Brillouin scattering (SBS), which could be a source of energy loss.¹² We chose C₃H₈ because it produces 32 free electrons per molecule when fully ionized. This number is similar to the 44 free electrons per molecule produced

when Xe is ionized to a Ne-like configuration. Thus, the relative concentration of the two gases could be varied without significantly changing the plasma electron density while maintaining the same initial fill pressure.

Table 1 lists the experimental parameters for a total of four Nova shots performed in this first set of scoping experiments. All targets were filled to 1 atm. The varying gas concentrations and approximate diameter of the targets for each shot are listed in the table.

TABLE 1. Summary of Xe-filled gas targets.

Shot number	Gas mixture	E_{Laser} (kJ)	Target diam (mm)	Defocus (mm)	I_{Laser} (W/cm ²)
24061417	25% Xe/ 75% C ₃ H ₈	22.1	2.75	2/5	$1.6/5.5 \times 10^{14}$
24061419	75% Xe/ 25% C ₃ H ₈	20.7	2.75	2/5	$1.5/5.3 \times 10^{14}$
24072917	75% Xe/ 25% C ₃ H ₈	22.1	2.5	1.8	6.7×10^{14}
24072919	90% Xe/ 10% C ₃ H ₈	22.1	2.5	1.8	6.3×10^{14}

The targets are irradiated with eight of Nova's ten beams. Figure 1(b) is a schematic showing the beam positions on the target membrane. The other two Nova beams were not used because they would have hit the target washer support. The beams are pointed at the center of the target. Beams 1, 2, 5, and 6 are at an angle of 43° to the washer normal; beams 7, 8, 9, and 10 are at 63°. The beams irradiate the membrane surface in converging focus. The average intensity on the membrane for each of the shots is listed in Table 1. For the first two shots, the focusing is chosen to provide the lowest intensity irradiation on the membrane and still miss the washer. The average intensity for the beams at 43° is the lower intensity value listed in Table 1; the higher intensity is for the beams incident at 63°. For the second two shots, the focusing is the same for all eight beams so that the average intensity for all beams on the membrane is the same. The laser energy is 21 to 22 kJ of 0.35-μm light in a 1-ns square laser pulse.

We measured x-ray production from the targets using several diagnostics shown in Fig. 1(b). Absolute x-ray production in the range of 0.1 to 1.8 keV is measured using Dante, a broadband, multichannel soft-x-ray spectrometer.¹³ X-ray spectra in the range of 1.8 to 7.0 keV is measured using time-integrated x-ray crystal spectrographs. Absolute yields are obtained by normalizing these spectra to a broadband, filtered x-ray diode on Dante as described below. Beam heating and propagation is measured using gated x-ray imaging.¹⁴ In addition, back-reflected light near the incident wavelength from SBS is measured on beam 7 using the Full Aperture Backscatter Station (FABS).^{15,16}

Results

We studied the heating dynamics of the gasbag using time-resolved, x-ray pinhole camera imaging. Figure 2 is an example of the images taken with the west axial x-ray imager (WAX).¹⁴ This view is the

FIGURE 2. Time-resolved x-ray images. The sequence of events is from upper right to lower left. The first image is 100 ps after the beginning of the 1-ns laser pulse. The images are of x-ray emission above 2 keV. Each image is time-resolved to about 80 ps, and time between images in a row is 40 ps. The time interval between the last image in a row and the first image in the next row is 80 ps. (08-00-0296-0439pb01)

same as that shown in Fig. 1(a), although the images are inverted in the pinhole camera. The time sequence of events run from the upper right to the lower left. The time difference between images is ~ 50 ps, and the first image is ~ 100 ps after the start of the laser pulse.

The images show the dynamics of the gasbag heating. Initially, the heating is highly localized at the surface of the gasbag. As the plasma is ionized, the beams penetrate the gasbag until all of the beams reach the center. This event appears to occur in the seventh image, or ~ 400 ps from the beginning of the laser pulse. The beams continue to propagate to the other side of the target. The plasma is still relatively cold since it is not heated by the beams. Later in time, the plasma appears to become more uniformly heated, either by electron or radiation conduction. Late time images viewed from normal to the washer indicate that the entire plasma is heated nearly uniformly by the end of the 1-ns laser pulse.

An interesting feature occurs in the region near the position that the lasers initially irradiate the membrane. This region continues to be brighter even after the laser has penetrated into the center of the gasbag. This appears to be higher-density plasma from a blast wave launched when the initial solid membrane

explodes.¹⁰ The high-density region persists long after the membrane has been ablated, but it should not significantly affect the present experiments.

We measured absolute x-ray production in the 0.1–1.8-keV range using Dante.¹³ Figure 3 shows time-integrated spectra from the three different fill mixtures. The spectra show two distinct features, one at about 270 eV, and the other between 700 eV and 1.5 keV. The highly modulated spectra suggest that the emission is generated mostly by line or band transitions from ionized Xe. High-resolution spectra were not obtained

FIGURE 3. Time-integrated x-ray spectrum from 0.1 to 1.8 keV for different concentrations of Xe. (08-00-0296-0440pb01)

below 2 keV, so positive identification of the atomic configurations producing these modulations is not possible. High-resolution spectra of Xe from Tokamak plasmas have identified two spectroscopic regions of line production.¹⁷ In the region from 21 Å (590 eV) to 12 Å (1030 eV), lines and unresolved transition arrays (UTAs) have been identified from Xe⁺²⁶ (Ni-like) to Xe⁺³⁰ (Cr-like) ions. This is approximately the spectral region for the higher-energy feature observed in the present spectrum. The present spectrum is shifted to slightly higher energy probably due to higher plasma temperatures. Reference 17 also reports observing a number of lines from 55 Å (225 eV) to 40 Å (310 eV) and identifies them as $\Delta n = 0$ (3d–3p) transitions from Xe⁺²⁷ (Co-like) and Xe⁺²⁸ (Fe-like). This is the same energy range as the lower-energy feature in the present spectrum. More work is needed to better understand the spectrum below 1.5 keV.

Time-dependent total x-ray power is derived by spectrally integrating time-resolved Dante spectra. Figure 4(a) shows results of the integrals. Time resolution is ~ 180 ps. A typical incident laser pulse summed over all eight beams is also shown. The most distinctive feature in the data is that significant x-ray power

FIGURE 4. X-ray power emitted from 0.1 to 1.8 keV. (a) X-ray and laser power as a function of time. (b) Instantaneous conversion efficiency, defined as the x-ray power divided by the laser power. Data are for 25% and 75% concentrations of Xe. (08-00-0296-0441pb01)

continues 300 to 600 ps after the end of the laser pulse. Errors in timing are estimated to be ~ 100 ps. This observation is consistent with the laser heating the gas as a supersonic heat wave and the cooling occurring later in time due to radiative cooling and hydrodynamic expansion.

Instantaneous x-ray conversion efficiency is derived by dividing the x-ray power by the laser power. Figure 4(b) shows these results. The instantaneous conversion efficiency is $\sim 25\%$ for the 25% Xe fill and varies from 40 to 60% for the 75% Xe fill over most of the laser heating pulse. The instantaneous conversion efficiency begins rising as the laser pulse turns off. Of course, this quantity does not have any significance after the laser pulse ends because the laser power in the denominator is zero. It does, however, indicate that potentially longer pulses can be used, and such pulses can still maintain efficient conversion because there does not seem to be a drop in efficiency during the heating pulse. X-ray production times will ultimately be limited by the disassembly of the target.

Figure 4(b) also shows the total conversion efficiency for x-ray power emitted below 2 keV. These values are higher than the instantaneous conversion efficiency because they include x-ray power emitted after the end of the laser pulse. These efficiencies compare quite favorably with x-ray conversion efficiencies measured from Au disks, as shown in Fig. 5. Here, the Xe data are plotted at the incident intensity on the membrane of the target. The large uncertainty for one of the intensities for the gasbag indicates the range of intensities used with the two different focusings on the membrane. The Au data points are measured conversion efficiencies using single Nova beams irradiating disk targets. The data include the thermal emission from 0.1 to 2 keV and the Au M-band emission from 2 to 5 keV. When contributions are included for the Xe L-shell emission, as discussed below, the Xe gasbags are more efficient emitters than Au disks.

Significant x-ray emission is also observed from $\Delta n = 3-2$ transitions from Xe. Figure 6 shows a typical time-integrated spectrum. The most prominent features are from Xe^{+44} (Ne-like configuration) in the wavelength (energy) range of 2.3 to 3.0 Å (4 to 5 keV). These transitions are identified in Fig. 6. Line emission is also observed between 1.8 and 2.2 Å from $\Delta n = 4-2$ transitions.

Absolute emission levels are obtained by normalizing the spectrum in Fig. 6 to a high-energy channel from Dante. In general, this normalization is within a factor of 2 of the intensity predicted using calibrations of the various spectrograph components. Results of the normalization are plotted in Fig. 7, comparing them with data from various Z disks.¹⁸ The gasbags are significantly more efficient at x-ray production in the 4-5-keV range

FIGURE 5. Time-integrated x-ray conversion efficiency as a function of intensity for x-ray production in the region of 0.1 to 1.8 keV. Xe data are shown as the closed squares (■). Also shown are data from Au disk experiments (○). Xe experiments are plotted at the average intensity on the initial gasbag surface. (08-00-0296-0442pb01)

FIGURE 6. X-ray spectrum of Xe for the 4-6-keV region. Resolution is ~ 7 mÅ. Transitions for Ne-like Xe are denoted. (08-00-0296-0443pb01)

FIGURE 7. X-ray conversion efficiency into multi-keV x rays for Xe gasbags. Data are integrated from 4 to 7 keV. The efficiency is plotted in joules of x rays (J_x) per steradian (sr) divided by the incident laser energy in joules (J_l). The efficiencies are compared with conversion efficiencies measured on solid targets. (08-00-0296-0444pb01)

than disk targets. Only M-shell x-ray production for elements emitting below 3 keV are as efficient.

We monitored backreflected SBS from the gasbags using FABS on beamline 7. As mentioned previously, Xe is mixed with propane to provide hydrogen for enhancing Landau damping of the ion wave produced by SBS.¹² This mechanism has been shown to be effective for suppressing SBS in large-scale plasma experiments.¹⁵ Low levels of SBS are observed for all targets. SBS levels of $\sim 2\%$ are observed for the 25% and 75% Xe fills

at intensities of 4 and 6×10^{14} W/cm², respectively. SBS light scattered outside of the lens was not measured for these experiments, but it has generally been comparable to the light scattered into the lens. These scattering levels are similar to levels seen from hohlraum targets using normal Nova beams.

For the 90%-Xe-filled target, the focus of beamline 7 was placed at the center of the gasbag, and the focal spot on the membrane is ~ 300 μ m in diameter. The intensity of this beam varies from $\sim 3.5 \times 10^{15}$ W/cm² on the membrane to $> 1 \times 10^{16}$ W/cm² at the center of the gasbag. SBS from this shot is $\sim 6\%$, suggesting that SBS will not necessarily be a limiting factor in optimizing the targets for irradiation intensity.

Light produced by stimulated Raman scattering (SRS) was not measured in these experiments. Fast electrons produced by SRS is monitored by measuring the x-ray bremsstrahlung. Inferred fast electron levels are low, typically less than 0.1%. Of course, this does not include fast electrons that escape the target or lose their energy to plasma expansion instead of collisional stopping in the Xe.

Summary

These experiments have demonstrated that underdense targets can be a bright source of both sub-keV and multi-keV x rays. The brightness is greater than that measured in high-Z solid target experiments. Increased x-ray production is attained by reducing the energy coupled to hydrodynamic motion and increasing the internal energy in the plasma. More efficient targets for x-ray production have several applications. One is as a brighter x-ray backlighter source. We have shown that x-ray production is enhanced by a factor of 3 or more above that from conventional solid targets. This factor of 3 directly correlates with lower laser energy requirements for backlighter beams. Spectra at different x-ray energies could be attained by changing the gas or using low-density foams doped with high-Z elements. As long as the ionized electron density of the material is below $\sim 0.25 n_c$, the foam targets should perform similarly to gas-filled targets. At higher density, laser-plasma instabilities become more significant, and at densities above n_c the targets become ablative, performing more like disk targets. Another application is as a bright x-ray source for radiation-effects experiments. In addition, such features could be incorporated into hohlraum designs for ICF to increase radiation production and heating efficiency. Significant work in calculations and experiments is still needed to optimize underdense sources for any of these applications. Nevertheless, these initial experiments demonstrate the significant advantages that underdense target have over solid disk targets as a bright laser-produced x-ray source.

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EFFICIENT PRODUCTION AND APPLICATIONS OF 2- TO 10-keV X RAYS BY LASER-HEATED "UNDERDENSE RADIATORS"

L. J. Suter

M. S. Maxon

R. L. Kauffman

J. F. Davis*

Introduction

Within the next decade, very-high-power, high-energy laser facilities may be constructed in Europe^{1,2} and the United States.³ Two-dimensional (2-D) numerical simulations with the LASNEX code⁴ at Lawrence Livermore National Laboratory (LLNL) indicate that this next generation of lasers offers the prospect of producing multi-keV x rays with unprecedented efficiency: as much as 14% above 10 keV, 30% above 4 keV. Such efficiencies, coupled with the intrinsically high energy of these facilities, should allow us to produce great quantities of multi-keV x rays—as much as several hundred kilojoules. This, in turn, may allow us to perform experiments and field diagnostics we could never consider with current facilities. Applications of high-energy, multi-keV sources with the proposed National Ignition Facility (NIF) include volume preheating of experimental targets; bright, multi-keV backlighting; pumps for fluorescent imaging of capsule dopants and Doppler velocimetry; and uniform irradiation of large test objects for Nuclear Weapons Effects Testing (NWET).

Projections of Efficiency

Conventional slab targets irradiated by current lasers produce multi-keV x rays with relatively low efficiency. At photon energies >3 keV, the typical efficiency for converting laser light into multi-keV x rays is less than 1%.⁵ Multi-keV efficiencies well in excess of those commonly obtained today are predicted to be achieved with "underdense radiators," a nontraditional source of laser-generated x rays (so called because the density of these targets is less than critical density of the laser light). Figure 1 shows two examples of such sources. Figure 1(a) is a column of gas (or foam) irradiated from one end by a single $0.35\text{-}\mu\text{m}$ (blue) laser beam. In simulations using 0.01 g/cm^3 of Xe gas irradiated by a 2-ns flattop pulse at an intensity of 10^{15} W/cm^2 , we find

FIGURE 1. Two types of "underdense radiators." (a) is a gas (or foam) column irradiated from one end with a single, large- f -number beam. (b) is a transparent container, filled with underdense gas or foam, irradiated with several beams. NIF target type (a) can be irradiated with, at most, 10 TW. Target type (b) can accept several beams, so it can be irradiated with higher total power. (20-03-0696-1296pb01)

efficiencies into photons of energy >4 keV (L-shell Xe and continuum) to be 19% with a 10-TW beam. Since a cluster of four "beamlets" of the proposed National Ignition Facility (NIF)³ will deliver 10 TW in the geometry of Fig. 1(a), good efficiency may be achievable with such gas-column sources. However, simulations indicate that higher efficiencies and higher photon energies with such a target will require more than 10 TW. This would be incompatible with the 10-TW/beam maximum of the NIF. Figure 1(b) shows a higher power source compatible with the NIF. It is a low- Z container, transparent to x rays of interest, filled with an appropriate- Z , low-density gas or foam. Since it is heated by more than one beam, it can be irradiated at much more than 10 TW. In simulations where the can is filled with Xe gas at 0.01 g/cm^3 , we find near-optimal performance for containers 2 mm diameter and 1.6 mm long with 1-mm-diam laser entrance holes. For 2-ns pulses, simulated, >4 -keV efficiencies range from 17% at 20 TW to 30% at 60 TW.

We have efficient 2-D designs of target type (b) at photon energies up to ~ 10 keV. Table 1 summarizes our LASNEX study. In all cases, the densities are 0.01 g/cm^3 , and the rest of the laser energy appears as either thermal emission (<1 to 2 keV) or plasma energy.

*Alme Associates, Alexandria, VA.

Figure 2 plots the highest source efficiencies in the third column of Table 1 vs photon energy and compares them with current disc backlighter efficiencies.⁵ The figure forcefully illustrates how much more efficient underdense radiators, heated by powerful lasers, can be compared to current backlighters.

TABLE 1. Summary of LASNEX study results.

Material	Power (TW)	Fraction of laser energy $> h\nu$ (keV)
Kr	60	4% > 13 ; 30% > 2
Ge	60	14% > 10 ; 26% > 2
Ge	50	10% > 10 ; 26% > 2
Ge	30	7% > 10 ; 20% > 2
Cu	40	11% > 8.5 ; 26% > 2
Cu	30	10% > 8.5 ; 24% > 2
Dy	60	9% > 8 ; 24% > 2
Xe	60	30% > 4 ; 48% > 1
Xe	50	26% > 4 ; 48% > 1
Xe	30	22% > 4 ; 40% > 1
Xe	20	17% > 4 ; 37% > 1

Physics of Efficient Production

Analysis of LASNEX simulations leads to a simple understanding of such high efficiencies in the multi-kilovolt regime and tells us why these are qualitatively different from standard discs. In the following discussion, we use Xe as an example, although the arguments are valid for other materials as well.

Good Multi-KeV Efficiency Is Intrinsically Possible

First, we show how high, multi-keV efficiency is possible with an underdense radiator. Figure 3 illustrates

FIGURE 2. The projected multi-keV efficiencies for sources like those of Fig. 1(b) are much higher than current disc efficiencies. K-shell refers to the Ge, Cu, and Kr sources of Table 1. L-shell refers to the Dy and Xe sources. (20-03-0696-1301pb01)

the first component of high, multi-keV efficiency. It shows theoretical estimates of Xe emission at electron temperatures of 2 keV and at 5 keV. The Xe density is 0.01 g/cm³. This plot makes a widely known but essential point: x-ray emission shifts to higher energy as plasma is made hotter. Figure 4, which plots radiation production/cm³ vs electron temperature, contains the next step in the argument. This is from an optically thin LASNEX simulation. The black line is total emission vs T_e . The gray line is the emission > 4 keV (see Fig. 3). This plot shows that the overall radiation production does not change greatly with plasma temperature. However, at higher temperatures almost all the emission will be multi-keV (see Fig. 3). Figure 4 illustrates an important point: a material that efficiently produces x rays in the softer, "thermal" region may also efficiently

FIGURE 3. Emission from 0.01 g/cm³ Xe at electron temperatures of (a) 2 keV and (b) 5 keV, simulated by XSN. Heating a material causes more of its total emission to be produced at higher photon energies. (20-03-0696-1302pb01)

produce x rays in a much more energetic region if it is made hotter.

Figure 5 is the plot needed to reach a simple, quantitative understanding of efficient multi-keV production. It shows Xe L-shell radiation production vs electron density for material at electron temperatures of 3, 4 and 5 keV. The Xe volume is that of a 1.4-mm-radius standard "gasbag"⁶ similar to ones we have shot on Nova for studies of laser-plasma instabilities.⁷ Figure 5 shows that at densities ~ 1 to 1.5×10^{21} /cm³, a 4- to 5-keV Xe-filled gasbag would produce ~ 5 to 12 TW of L-shell emission. Thus, if we can heat such a gasbag to these temperatures with a 30-TW, 1-ns Nova pulse (30 kJ energy), and if it remains together for ~ 1 ns, we might expect to produce ~ 5 to 10 kJ of L-shell emission, or 16 to 33% multi-keV efficiency.

That we can both heat the bag and that it does not disassemble too quickly follow from simple arguments. If all the material in the gasbag is at constant temperature, then its thermal energy in kJ is approximately $2.75T_e$ (in keV) $\times n_e$ (in units of 10^{21} /cm³). For the temperature and density regimes of interest (4 to 5 keV, 1 to 1.5×10^{21}), this corresponds to 10 to 20 kJ. Moreover, the sound speed of Xe gas at 4 keV is $\sim 6 \times 10^7$ cm/s, so the rarefaction takes more than 1 ns to propagate to the center of the 1.4-mm-radius bag.

The Xe emission calculations just discussed were made with a non-local-thermodynamic-equilibrium average-atom model known as XSN.⁸ Better theoretical estimates using a detailed configuration approximation model⁹ give essentially the same result. Our estimates above also assume the radiation can get out. Detailed simulations with radiation transport of the lines indicate that the radiation can escape.

Hydrodynamics for Good Efficiency

Above we reasoned that efficient multi-keV radiation production is possible. It also indicates that the achievement of good multi-keV efficiency requires a hydrodynamic system that converts most of the laser energy into hot plasma at sufficient density that it can radiate a considerable fraction of the energy before it disassembles. Underdense plasmas can provide such a hydrodynamic system. Moreover, they do this better than discs, which is the main reason underdense plasmas can be considerably more efficient multi-keV sources than discs (see Fig. 2).

We can see the hydrodynamic differences by analyzing three simulated Xe gas-column sources of different densities (0.01, 0.02 and 0.1 g/cm³) but irradiated by the same laser. Figure 6 shows the total L-shell radiation escaping 1-D simulations of these gas columns vs time. (1-D analogs of the 2-D gas column of Fig. 1[a]. The 1-D efficiency is higher than 2-D efficiency

because there is no radial hydrodynamic disassembly.) The gas column that started at 0.01 g/cm³ ($\sim 0.2n_c$ when fully ionized) has the highest efficiency. At the

FIGURE 4. Total emission per cm³ vs electron temperature and L-shell emission (Xe at 0.01g/cm³). A material that is an efficient source of thermal x rays can also be a good source of multi-keV x rays, if we can make it hot enough. (20-03-0696-1303pb01)

FIGURE 5. L-shell emission from the volume of a 1.4-mm-radius, Xe-filled gasbag, vs electron density. (20-03-0696-1304pb01)

end of the 2-ns pulse, more than half of the incident 48-TW laser power is escaping this column as L-shell emission. The column that started at 0.02 g/cm^3 behaves like the lower density one for $\sim 1 \text{ ns}$, but then its efficiency drops notably. The 0.1-g/cm^3 gas column has comparatively low efficiency the whole time. We call it disc-like since its simulated L-shell radiation production is the same as a frozen Xe slab's (not shown).

FIGURE 6. Time dependence of L-shell emission escaping 1-D LASNEX simulations of Xe gas columns of different densities. The three columns were all irradiated with 48 TW of blue laser light. (20-03-0696-1305pb01)

Now we can pass on to the next level of understanding. Figure 7 plots electron density and temperature, at 1 ns, vs length along the gas columns. The three 1-D gas columns clearly have very different hydrodynamics. In Fig. 7(a), in the 0.01-g/cm^3 gas column, the heating front moves nearly supersonically (also known as a bleaching front). However, in the poorest-efficiency, 0.1-g/cm^3 gas column, Fig. 7(b), the heating front moves subsonically (also known as an ablative front). Unlike the bleaching front, the ablative front drives a shock of dense material ahead of itself. The 0.02-g/cm^3 gas column is a transitional case; early in time it was heating in an approximately supersonic manner. However, residual hydrodynamics caused a density bump ahead of the front to accumulate, finally causing a transition, at $\sim 1 \text{ ns}$, to completely ablative heating. The transition from bleaching to ablative coincides with the efficiency drops at 1 ns seen in Fig. 6.

Further analysis shows that a bleaching front creates far hotter plasma than an ablative front, hotter plasma that is denser and therefore more efficient in producing multi-keV x rays. In particular, we find the following:

- In producing a given mass of hot plasma, more energy is lost to low-photon-energy radiation when the heating occurs in a dense ablation front than when the matter is heated in the uncompressed bleaching front. The ablative front's dense material, which is being heated by conduction from the laser-deposition region, has a very high radiation production rate. However, since it is relatively cold, the emission is not multi-keV. This emission is energy lost from the system that cannot contribute to heating plasma and, since it is low-photon energy, does not contribute to multi-keV production. From the viewpoint of multi-keV radiation production, it is a parasitic loss.

FIGURE 7. Electron temperature (keV) and electron density ($\times 10^{21}$) at 1 ns vs axial position (cm) for the three 1-D gas-column sources in Fig. 6. (20-03-0696-1306pb01)

- Because of the higher density, the material in the ablation front rises to higher pressure. This ends up as more kinetic energy per unit of mass heated.
- More kinetic energy causes the hot blowoff behind an ablative heating front to be less dense than behind a bleaching front; compare electron density profiles of Fig. 7(a) and 7(b). Consequently, the blowoff behind the bleaching front produces more coronal, multi-keV x rays per unit mass because such emission scales approximately as $(n_e)^2$ (see Fig. 5).

Experimental Validation of Modeling

Calculations similar to those above provided the first indication that we might be able to very efficiently produce multi-keV x rays with laser-heated underdense sources.¹⁰ Following these initial findings, we performed theoretical and experimental work to examine the validity of these predictions. This involved testing our ability to properly estimate the multi-keV efficiencies of published slab data,¹¹⁻¹³ as well as efficiencies from Xe-filled gasbags⁶ specifically shot at Nova to test these predictions.¹⁴ Figure 8 compares simulated and experimental absolute multi-keV efficiencies for all these experiments. Except for two low-intensity (1.4×10^{14} W/cm²) slab targets, there is general agreement between the experiment and simulations. In particular, the >4 keV, L-shell production from our Xe gasbag experiments¹⁴ agrees satisfactorily with the 2-D LASNEX estimates. They are actually slightly higher than the simulations. This favorable comparison seems to lend credibility to the predictions discussed above.

FIGURE 8. Comparison of simulated and experimental multi-keV conversion efficiencies from several databases. (20-03-0696-1307pb01)

In addition to this comparison with experiment, there is a fairly extensive and documented database indicating that LASNEX reasonably models the electron temperature in gasbags and gas-filled hohlraums.¹⁵ The capacity to properly estimate underdense plasma electron temperatures is an essential component of believable, multi-keV predictions.

Applications of Efficient Multi-KeV X-Ray Sources

Below we discuss four applications of high-energy, multi-keV sources with the NIF:

1. Volume preheating of experimental targets.
2. Bright, multi-keV backlighting.
3. Pumping for fluorescent imaging of capsule dopants and doppler velocimetry.
4. Uniform irradiation of large test objects for NWET.

Preheat Sources

Multi-keV x rays can be used to preheat experimental packages. The preheat temperature T_e produced in a package located distance d away from a multi-keV source can be found by balancing x-ray deposition with internal energy. Neglecting ionization energy, this balance is approximately

$$\frac{\eta_x E_L}{4\pi d^2 \ell} = \left(\frac{3}{2}\right) \frac{\rho(Z+1)T_e}{A} (9 \times 10^4) \quad (1)$$

Here η_x is the multi-keV efficiency; E_L is the laser power; ℓ is the scale length over which x-ray absorption occurs in the experimental package; ρ , Z , and A are the density, atomic number, and weight of the experiment we are preheating. Using $\eta_x = 30\%$, $E_L = 10^6$ J, $d = 0.5$ cm, $\rho = 1$ g/cm³, and $(Z+1)/A = 0.33$ gives $T_e = 2$ eV-cm/ ℓ . Depending on ℓ , it may be possible to preheat large $\rho = 1$ samples to ~5 eV and thinner ones up to several tens of eV, possibly approaching 100 eV. NIF applications for preheat sources like this include off-Hugoniot equation-of-state measurements and low-temperature hydrodynamics.

Backlighter Sources

Sources like these could serve as the bright, high-photon-energy, large-area backlighters needed for bigger targets. Consider, for example, the 60-TW Ge source listed in Table 1 scaled up to 100 TW (14% > 10 keV). Viewed from the end of the 2-mm-diam cylinder, the >10-keV emission/cm²/sr will be 3.5×10^{13} W/cm²/sr. This is equivalent to viewing a 10-keV hemi-isotropic

disc source of 1% efficiency irradiated by 700 TW at an intensity of $\sim 2.2 \times 10^{16} \text{ W/cm}^2$.

Pumps for Fluorescence-Based Diagnosis

Efficient multi-keV sources and high-power lasers may allow us to field fluorescence-based diagnostics—a qualitatively new way of studying hydrodynamics. The principle is simple: a multi-keV source at distance d pumps a dopant in a capsule. In imaging, the number of photons collected from a resolution element r is given by

$$\# \text{ of photons} = \frac{\eta_x P_L}{4\pi d^2} r^2 \left(\frac{r}{\ell} \right) \frac{\eta_F \delta\Omega \eta_{\text{det}} \delta\tau}{E_x} \quad (2)$$

Here, P_L is the laser power; E_x , the source's average photon energy; η_F , the dopant's fluorescent efficiency; and $\delta\Omega$, η_{det} , and $\delta\tau$, the camera's solid angle, efficiency, and time resolution. Using $r = 10 \mu\text{m}$, $P_L = 60 \text{ TW}$, $\eta_x = 10\%$, $E_x = 10 \text{ keV}$, $d = 0.5 \text{ cm}$, $\delta\tau = 100 \text{ ps}$, and $\eta_F = 0.2$ (i.e., Cu-K at 8 keV has $\eta_F = 0.2$ in Ref. 16) gives

$$\# \text{ of photons} = (3.2 \times 10^9) \left(\frac{10 \mu\text{m}}{\ell} \right) \delta\Omega \eta_{\text{det}} \quad (3)$$

For a 10- μm pinhole at 1 cm and the dopant concentration arranged so that $10 \mu\text{m}/\ell = 0.01$ to 0.1, we collect 40 to 400 photons from each 10- μm resolution element. For a curved crystal/Rowland circle system, the number of photons could be ~ 300 to 3000, at 1% crystal reflectivity.

A compelling possibility is using doppler spectroscopy of fluorescent lines to measure pusher velocity and, possibly, show the evolution of turbulence (via line broadening) at stagnation. Figure 9 indicates how the fluorescent lines may be shifted when the pusher starts to

FIGURE 9. Doppler spectroscopy of fluorescing dopants in a capsule could measure pusher velocity and, possibly, show the evolution of turbulence, via line broadening, at stagnation. Efficient multi-keV sources could pump such fluorescence. (20-03-0696-1308pb01)

move, during final acceleration, and during stagnation. A requirement for this will be an efficient spectrometer which sees only diametrically opposed parts of a doped capsule. Related to this, fluorescence might produce cut-away pictures of capsule mix, perhaps similar to those used to visualize mixing in 3-D simulations. At a velocity of 10^7 cm/s or more, narrowband Doppler imaging with a camera of spectral resolving power 1500 or greater^{17,18} could image only one side of the imploding pusher.

Large Fluence-Area Products with Good Uniformity

A requirement for NWET is that the flux over a test object be uniform to $\pm 10\%$. This allows us to describe an NWET simulator by the fluence $\times$ area product that it can produce with that uniformity. In general, the fluence $\times$ area product in a given spectral region will be

$$\text{fluence} \times \text{area} = \left(\frac{E_L \eta}{4\pi} \right) T_{\text{debris-shield}} (\delta\Omega_{10\%}) \quad (4)$$

The first term ($E_L \eta / 4\pi$) is the source output per steradian in the spectral range of interest. It is determined by multi-keV source efficiency and total laser energy. $T_{\text{debris-shield}}$ is the debris shield transmission. It will be $\sim$ unity at 5 keV and higher, but may be significantly < 1 at lower energies. The last term $\delta\Omega_{10\%}$ is the solid angle we can collect from each source and still get $\pm 10\%$ uniformity. It is a strong function of geometry. If all the emission is concentrated at a single point, as in typical pulse-power NWET simulators, we can collect only 0.45 sr with $\pm 10\%$ uniformity. However, if we produce x rays in a number of properly distributed sources, the useful solid angle increases. With four distributed sources, we can collect up to 1.6 sr from each source, and with 25 distributed sources, 4.5 sr. Thus, with proper facility capabilities, it is possible for 1 J of laser-produced multi-keV energy to be worth up to 10 J produced by a more conventional NWET simulation source. However, this improvement comes at a facilitization price. The sources need to be distributed over an area comparable to the size of the test object. For objects $\sim 1 \text{ m}$ across, this requires steering beams to irradiate sources much as 50 cm from chamber center.

On the NIF, the estimated fluence $\times$ area products with four distributed sources and 100% debris-shield transmission are as follows: 1 to 5 keV, 50,000 J-cm^2 ; 5 to 15 keV, 14,000 J-cm^2 . With 25 distributed sources: 1 to 5 keV, 140,000 J-cm^2 ; 5 to 15 keV, 40,000 J-cm^2 . This prospect for simulation capacity has led to the formation of a joint U.S. Department of Defense–Department of Energy working group (NIF Radiation Sources Users Group¹⁹) that works with the NIF Project aiming to optimize the NIF's NWET capabilities.

Acknowledgments

This work was supported by the Defense Nuclear Agency (Department of Defense) and the U.S. Department of Energy. We would like to acknowledge very useful discussions with Mike Tobin and Greg Simonsen of LLNL, C. P. Knowles of JAYCOR, and William Summa and Ralph Schneider of DNA.

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Technical Information Department • Lawrence Livermore National Laboratory
University of California • Livermore, California 94551