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Thermal Analysis of the Large Close Packed Amplifiers in the National Ignition Facility (NIF)

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ABSTRACT

Flashlamp pumping of the large aperture multi-segment NIF amplifiers will result in large amounts of energy being deposited as heat in the amplifier components. The magnitude of the heating and the nonuniform distribution result in a delay time between shots due to wavefront distortion and steering error. A NIF requirement is that the thermal wavefront recovery must occur in less than six hours. The principal cause of long-term wavefront distortion is the thermal gradient produced in the slab as heat diffuses from the edge cladding into the pumped volume. Thermal equilibrium is established through conduction, convection, and exchange of thermal radiation. Radiative exchange between glass components, such as flashlamps, blast shields, and laser slabs is especially effective because of the large surface areas of these components and the high emissivity of the glass. Free convection within the amplifier enclosure is also important but is on the order of a 10 to 20% effect compared to radiation for the major surfaces.

To evaluate the NIF design, the amplifier was modeled to calculate the thermal response of a single laser element. The amplifier is cooled by flowing room-temperature air or nitrogen through the flashlamp cassettes. Active cooling of the flashlamps and blast shields serves two purposes; the energy deposited in these components can be removed before it is transferred to the amplifier optical components, and the cooled blast shield provides a large area heat sink for removal of the residual heat from the laser slabs. Approximately 50 to 60% of the flashlamp energy is deposited in the flashlamps and blast shields. Thus, cooling the flashlamp cassette is a very effective method for removing a substantial fraction of the energy without disturbing the optical elements of the system. Preliminary thermal analysis indicates that active cooling with flow rates of 10 CFM per flashlamp is sufficient to meet the six hour thermal equilibrium requirement. An experiment was run with a scaled down version of the NIF laser slab to measure the thermal recovery time. This experiment was also modeled and the results from the model are compared with the thermal recovery experiment data.

Keywords: National Ignition Facility, flashlamp-pumped Nd:glass amplifier, thermal analysis, thermal wavefront recovery, active cooling.

1. INTRODUCTION

When the flashlamps are fired in a flashlamp-pumped Nd:glass laser amplifier, the various components of the amplifier become heated by the absorption of the radiant energy from the flashlamps. The magnitude of the heating and the nonuniform distribution result in a delay time between shots due to wavefront distortion and steering error. The NIF design criteria specify that the thermal wave front recovery must occur in less than six hours. The principal cause of the long-term wavefront distortion is the thermal-mechanical distortion of the slabs produced by the higher energy deposition in the edge cladding that results in higher temperatures around the edges of the slabs. Temperature differences within the laser slab cavity also result in the production of gas circulation and turbulence that causes optical perturbations. All of these effects can be eliminated by cooling the system down to a uniform temperature.

The close packed arrangement of the laser beamlets in the NIF provides very little heat transfer area for passive cooling options. The analysis presented here considers a relatively simple active cooling concept that will allow the NIF system to satisfy the design criteria. The cooling system consists of flowing room temperature nitrogen or air through the flashlamp cassettes. This cooling technique was chosen for its simplicity and the effective cooling it provides. Radiative exchange between the laser slabs and the flashlamp cassette is especially effective because of the large surface areas of these components and the high emissivity of the glass at the relatively low temperatures.

The temperature distributions predicted by the model presented here were used by Rotter¹ as input to a coupled structural mechanics/optics computer program to predict the optical perturbations resulting from the residual temperature nonuniformity. The proposed cooling scheme is adequate to satisfy the design criteria.

2. AMPLIFIER PHYSICAL DESCRIPTION

The NIF amplifiers are flashlamp-pumped Nd:glass slab amplifiers designed to produce a final 1 ω energy of approximately 20 kJ. The amplifiers as presented in the Conceptual Design Report² are arranged into four arrays; each array is four slabs high by twelve slabs wide, yielding a total of 192 beams. Each amplifier chain, or beamlet, is composed of three separate amplifiers: a nine-slab-long main cavity amplifier; a five-slab-long switch amplifier; and a five-slab-long booster amplifier.

A nine-slab-long main cavity amplifier assembly is shown schematically in Figure 1. The close packing of the array is necessary to fit the 192 beams in a reasonable space. However, this close packing places additional demands on the design, one of which is the active cooling of the amplifier arrays to control the optical distortion of the wave front to acceptable levels.

The individual laser elements are arranged in an assembly that is four slabs high. An exploded view showing the main components of this assembly is presented as Figure 2. Adjacent interior modules share a common set of flashlamps contained in a cassette. Each cassette is composed of the flashlamps, the interior diamond reflectors, two panes of glass that serve as blast shields, and the associated support structure. The blast shields are designed to provide debris containment in case of a flashlamp explosion. Thus, interior slabs are separated laterally by flashlamp cassettes, while the outer longitudinal edge slabs have a flashlamp assembly designed for single side illumination. The laser slabs at the end of each amplifier assembly share the nitrogen gas volume with the adjacent beam tube(s).

3. INITIAL ENERGY DISTRIBUTION

The energy deposition distribution just after firing the flashlamps was measured by Rotter and McCracken in a recent experiment.³ The table below is taken from their work.

Component	Energy Absorbed (% of electrical input energy to one module)
Lamps	57.
Blast Shields (central+side)	12.
Laser Slab (pumped area)	6.6
Edge Cladding (top+side)	3.9
Side Reflector	3.6
End Masks	1.4
Top and Bottom Reflectors	1.1

This test was performed using components that differ in several respects from the NIF components. However, the estimated 69% of the flashlamp energy that was absorbed in the flashlamps and blast shields is indicative of the expected energy absorption in the NIF design. Quickly cooling the flashlamps and blast-shields allows for removal of the majority of the waste heat from the system before it is transferred to the optical components. This cooling technique also provides a heat sink with a large surface area for the cooling of the laser slabs by radiation and convection.

4. IMPORTANT HEAT TRANSFER MECHANISMS

The equilibration of the temperature distribution in the NIF amplifiers includes the three heat transfer mechanisms of conduction, radiation, and convection. The convective heat transfer in the amplifier enclosure is the more difficult of the three processes to predict accurately. The relative importance of the convective process was estimated to evaluate the effect of neglecting convection on the accuracy of the initial design calculations. The simple enclosure consisting of two parallel vertical plates maintained at different uniform temperatures is presented on Figure 3A. The convective heat transfer within such an enclosure has been studied numerically and experimentally.⁴ Even though the laser slabs and the blast shield are not parallel, this model is a reasonable approximation of the convective transport and will allow a quantitative estimate of the significance of this mechanism. The conditions considered here all resulted in Grashof numbers of less than 10^{10} and result in thin essentially non-interacting boundary layers on the two opposing walls (the blast shield and the stack of laser slabs). The results of this analysis are presented on Figure 3B and indicate that the free convection in the enclosure is responsible for the transport of only 10% to 20% of the total heat transfer between the laser slab and the blast shield. This small heat transfer rate justifies neglecting the convective heat transfer rate for the initial design analysis. However, the existence of the non-uniform gas temperature will result in eddies that will produce optical

perturbations and may be an important effect on that basis. At any rate, minimizing the temperature gradients within the laser enclosures will also minimize these effects.

5. NIF CDR THERMAL ANALYSIS

A sequence of thermal analyses was performed to evaluate an option of actively cooling the flashlamp cassette. To evaluate the NIF design, the amplifier was modeled to calculate the thermal response of a single, actively cooled laser element. The relaxation time for the conduction through the thickness was calculated and found to be approximately 10 minutes, insignificant compared to the slab cool-down time. Therefore, conduction in the amplifier slab was approximated by a two-dimensional model. Because of the symmetry in the laser slab, a quarter symmetry model was used to reduce the computation time. The model is shown in Figure 4 and includes the slab, edge cladding, mask, and frame. This model represents a single internal laser element, with another laser element above and below it in a slab cassette. Other assumptions in this model are listed below:

1. Average temperature rises of 14°C, 8°C, and 0.75°C for the flashlamp tubes, slab edge cladding, and the slab-pumped areas, respectively.
2. Nitrogen gas at 20°C, at a flow rate of either 5 or 10 CFM per flashlamp, was used to convectively cool the flashlamp cassette.
3. The flashlamp is modeled as being at a uniform temperature so that the lumped-heat-capacity method of analysis can be used.
4. The free convection in the amplifier slab cavity is not included. The effect of this free convection will be to reduce the relaxation time even further.

The three-dimensional implicit finite element heat transfer code, TOPAZ3D⁵ was used in this analysis. The boundary conditions include the enclosure radiation between the slab and the mask and between the mask and frame. The Monte Carlo code MONT3D⁶ is used to calculate the exchange factors for these enclosures. A radiation boundary condition between the slab and a time varying radiation sink temperature is used to represent the actively cooled flashlamps.

The cool down of the flashlamps is calculated using the lumped-heat-capacity method. Using 10 CFM/flashlamp of nitrogen at 20°C, the flow in the flashlamp cavity is turbulent with a Reynolds number of 3551. The Nusselt number for turbulent flow in a smooth tube is calculated as

$$Nu_d = 0.023 Re^{0.8} Pr^{0.4}$$

where d represents the hydraulic diameter of the flashlamp cavity. This results in a heat transfer coefficient of 12.15 W/m²K. This heat transfer coefficient is then applied to the lumped heat capacity equation

$$\frac{T(t) - T_{\infty}}{T(0) - T_{\infty}} = e^{-\left(\frac{hA}{\rho C_p V}\right)t}$$

The time constant for the cool down of the flashlamps is calculated to be approximately six minutes and the flashlamp cools down to 20°C in approximately 30 minutes as shown in Figure 4. Figure 4 also shows the cool down of the flashlamp when 5 CFM/lamp is used. The flow is laminar at 5 CFM with a Reynolds number of 1780 and a heat transfer coefficient of 3.81 W/m²K. The cool down curve for the flashlamp then becomes the time varying radiation sink temperature used for the radiation boundary condition on the amplifier slab. The initial temperature profile for the TOPAZ3D transient analysis is based on an analysis of the Beamlet edge cladding temperatures.

Preliminary thermal analysis indicates that active cooling with flow rates of 10 CFM/flashlamp is sufficient to meet the 3 shots per day firing rate. The results from the five hour transient analysis are shown in Figure 5, which is a plot of the in-

plane temperature gradient in the slab over the entire five hour transient. The gradient is calculated as the difference between the temperature at the center of the slab and the corner of the slab. As Figure 5 shows, a flow rate of 5 CFM/lamp initially results in a faster decrease in the thermal gradient since the center of the slab is hotter in this case because the flashlamp has a slower cool down to ambient. After five hours, the thermal gradient in the 5 CFM case is twice as great as the gradient with a 10 CFM flow rate. Since the cost of installing the cooling system is approximately the same for a 5 CFM or a 10 CFM system, a flow rate of 10 CFM or greater is recommended for an active cooling system. The maximum allowable thermal gradient will have to be determined, but the temperature profile shown after four hours at 10 CFM appears acceptable. This calculation can be accomplished by coupling the TOPAZ3D output with the NIF amplifier optics code. The beam steering error and optical perturbations resulting from these temperature profiles can be calculated, and the slab optical relaxation time can be determined.

With 10 CFM per flashlamp, and 9576 flashlamps, a total of 95,760 CFM of pumping capacity would be needed for NIF. Room air in an open cooling system could be used to cool the flashlamps rather than nitrogen because they are similar thermally. If air is used, a coating might have to be applied to the silver-coated surfaces to prevent corrosion, but an open-room air system would be less expensive. In summary, an actively cooled amplifier will meet the 3 shot per day firing rate and will alleviate the variable cooling of a passively cooled system from slab to slab in the densely packed amplifier array.

6. APPLICATION OF THE NIF MODEL TO THE BAU THERMAL TESTS

The thermal recovery time of an insulated 2x2 Beamlet-sized multi-segment amplifier under various configurations of active and passive cooling was measured and the results compared to the thermal model. An experiment in which active cooling with room air at 10 CFM was used for comparison to the model. There are many differences between the NIF model described above and the experimental configuration. Primarily, the NIF laser system will consist of a 4-high by 12-wide by 9-long array of laser amplifiers, and the experiment consists of only a 2x2x1 array of amplifiers. The NIF model was used to calculate the thermal recovery time of an interior amplifier in the 4x12x9 array. Insulation was added along the edge of the 2x2 array in the experiment to better simulate an interior amplifier. In an actual laser system, the recovery time of an interior module will probably be greater than that measured in the experiment due to the presence of the other amplifier modules. Another important difference between NIF and the experiment is the size of the slab. A full size slab was not available for the experiments, so a smaller slab of approximately 40% the volume of the NIF slab was used. A comparison between the NIF model and the BAU experiment model is summarized in Table 1.

Table 1. Comparison of the NIF thermal model and the BAU thermal model

Description	NIF CDR Amplifier Model	BAU Amplifier Model
Dimensions of disk	42.4 cm x 78.8 cm x 4 cm	35 cm x 66.6 cm x 2.3 cm
Disk volume	13,364 cc	5,361 cc
Peak initial temp. in cladding	52°C	45°C
Total initial energy in the disk	34.4 kJ	12.3 kJ
Per cent of initial energy in the cladding	69%	17%
Flashlamp cooling	Active cooling @ 10 CFM	Active cooling @ 10 CFM
Disk cooling	Radiative cooling only, no convection	Radiative cooling only, no convection
ΔT in disk after two hours	2.0°C	0.2°C

In the experiment, we used two one-slab-wide by two-slab-high Beamlet Basic Assembly Units (BAUs), arranged in a two-by-two configuration. One BAU on the instrumented side was made up of two slabs of Single-Segment-Amplifier-sized LG-750 laser glass. The other, non-instrumented, side contained dummy slabs of Graylite architectural glass to simulate the laser glass. A full compliment of flashlamps was used in the experiment: two side arrays and one central array containing 10 lamps and 16 lamps in each array respectively.

The temperature was measured at 16 locations on the slab and 10 locations on the cladding. The thermocouple distribution on the slab and cladding is shown in Figure 6. The temperature was also measured in the other components of the amplifier, including the blast shield. The blast shield measurement (Figure 7) was used as the sink temperature for the radiation from the amplifier slab in the BAU model. In the NIF model, this cool down curve was calculated. The BAU model, like the NIF model, is a quarter symmetry model with radiative coupling between amplifier components. Convection has not been included at this time. The finite element mesh of the BAU model is shown in Figure 8. The total initial energy and the distribution of the energy between the cladding and the glass must be known to accurately model the amplifier. At present, the initial energy in the slab is estimated based on the thermocouple measurements and a theoretical profile of the temperatures in the cladding. In the future the initial slab temperatures will be calculated using an optics model that is being developed to determine the pump-induced wavefront distortions that develop during the flashlamp pump.

Figure 9 shows the TOPAZ3D results for the temperature contours in the BAU amplifier slab two hours after the flashlamps are fired. The thermal gradient after two hours is 0.2°C , with a temperature range from 20.3°C to 20.5°C . The calculations from the BAU model are compared to the experimental data in Figures 10 through 12. Thermocouples number 1, 4, and 12 (Figure 6) are used for comparison to the model. These thermocouples measured the temperature in the corner, side and center of the glass, respectively. Figure 10 is a plot comparing the measured temperature and calculated temperature in the corner of the glass for the three hours after the flashlamp is fired. When the flashlamp is fired, the edge cladding absorbs the Amplified Spontaneous Emission and as a result the corner of the slab is the hottest region. As shown in Figure 10, the glass in the corner spikes up to a temperature 2.5°C above ambient, then cools down to 0.3°C above ambient over a three hour period. The calculation and measurement are in good agreement. The experimental data shows that the glass initially cools down more rapidly than was calculated, but the temperatures after three hours are approximately the same. As mentioned earlier, the model only includes radiative coupling between the amplifier components. In the experiment, there is conduction between the slab and the frame and natural convection in the amplifier cavity and between the amplifier and the room. These additional heat transfer mechanisms may explain the difference in the cool down rate between the model and the experimental data. Figure 11 is a plot of the calculated and measured temperatures at the side of the glass during the three hour period after the flashlamp is fired. Again, the curves are in good agreement, with the experimental data showing a slightly faster cool down rate during the first hour of the experiment. Figure 12 is a plot of the temperature at the center of the glass. The glass is initially set at a temperature 0.9°C above ambient. As Figure 12 shows, the center of the glass heats up slightly as the blast shield radiates to the glass, and then slowly cools to a temperature 0.3°C above ambient in 3 hours. The model and experimental data are in better agreement at the center of the glass. This is primarily because the temperature at the center of the glass is not significantly effected by the initial temperature distribution in the edge cladding. The initial temperature distribution in the edge cladding is only estimated at this time. The BAU model and the experimental data are in good agreement and show that the BAU amplifier cools down to an acceptable temperature distribution in approximately two hours.

7. FUTURE WORK

The next amplifier model will be a full three-dimensional model that will include a four disk assembly (Figure 2), the blast shield, and the supporting structure. With this model, the exchange factors between the various surfaces in the amplifier can be accurately calculated. Radiation is the dominant heat transfer mechanism in the amplifier, so an improvement in the exchange factors will improve the accuracy of the model. In addition, the following changes will be incorporated into the next model to more accurately model the NIF amplifier assembly.

1. Include a simple convection model in the amplifier cavity.
2. The initial slab temperatures will be calculated using an optics model rather than estimated.
3. The heat transfer from the top and bottom of the four disk assembly will be included.

8. ACKNOWLEDGEMENTS

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Figure 1. NIF main cavity amplifier assembly (one of four).

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Figure 2. The 4-slab-high amplifier-column module from which the amplifiers are assembled.

$$F_{\text{convection}} = \frac{qA)_{\text{convection}}}{qA)_{\text{radiation}} + qA)_{\text{convection}}}$$

Figure 3A. The enclosure.

Figure 3B. The heat transfer fraction by convection.

Figure 3. Natural circulation and convective heat transfer between the laser slabs and the blast shield heat sink.

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Flashlamp cooldown (10 cfm and 5 cfm)

Figure 4. Flashlamp cooldown with active cooling (5 and 10 cfm N₂/lamp).

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1.2.2.0595.1284

Figure 5. Amplifier slab thermal gradient during the five-hour cooldown.

Figure 6. BAU experiment thermocouple distribution on the slab and cladding.

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1.2.2.0595.1286

Figure 7. Temperature history of the blast shield in the BAU experiment, taken at three different vertical positions.

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Figure 8. Finite element model of the BAU amplifier.

1/4 Geom. , BAU, 12. 3KJ , 4/21/95
time = 0.72000E+04
contours of topaz3d temperature
min.= 2.031E+01 at node 792
max.= 2.051E+01 at node 1168

contour values
A= 2.03E+01
B= 2.04E+01
C= 2.04E+01
D= 2.04E+01
E= 2.04E+01
F= 2.04E+01
G= 2.05E+01
H= 2.05E+01
I= 2.05E+01

Figure 9. Calculated temperature gradient in the BAU amplifier slab two hours after firing the flashlamps.

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1.2.2.0595.1289

Figure 10. Calculated and experimental data for the cooldown of the corner of the glass (TC#1) in the BAU experiment.

Figure 11. Calculated and experimental data for the cooldown of the side of the glass (TC#4) in the BAU experiment.

Figure 12. Calculated and experimental data for the cooldown of the side of the glass (TC#12) in the BAU experiment.