*Experimental Investigation of the Thermal
Upset and Recovery of the National
Ignition Facility's Optics Module*

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J. D. Bernardin

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Experimental Investigation of the Thermal Upset and Recovery of the National Ignition Facility's Optics Module

by

J. D. Bernardin

Abstract

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory is being constructed as the latest in a series of high-power laser facilities to study inertial confinement fusion. In particular, the NIF will generate and amplify 192 laser beams and focus them onto a fusion fuel capsule the size of a BB. The energy deposited by the laser beams will raise the core temperature of the target to 100,000,000°C, which will ignite the fusion fuel and produce a fusion energy output that is several times greater than the energy input. The ability to generate, condition, and focus 192 laser beams onto a target the size of a BB, requires precision optical hardware and instrumentation. One of the most critical pieces of optical hardware within the NIF is the Optics Module (OM), a mechanical apparatus which is responsible for optical focusing and frequency conversion of the laser beam to optimize the energy deposition at the fusion target. The OM contains two potassium dihydrogen phosphate (KDP), frequency conversion crystals and a focusing lens. The functionality of the KDP crystals is extremely temperature sensitive. Small temperature changes on the order of 0.1°C can significantly alter the performance of these components. Consequently, to maximize NIF system availability and minimize beam conditioning problems, accurate temperature control of the OM optical components was deemed a necessity.

In this study, an experimental OM prototype, containing mock frequency conversion crystals and a focusing lens, was used determine the thermal stability provided by a prototype water temperature control system. More importantly, the OM prototype was used to identify and characterize potential thermal upsets and corresponding recovery times of the KDP crystals.

The results of this study indicate that the water temperature control system is adequate in maintaining uniform steady-state temperatures within the OM. Vacuum pump-down and venting of the OM generated significant temperature changes in the optical components. However, the corresponding recovery times of the optical components were found to be less than three hours, well within the seven hour limit posed by NIF operations. Simulated laser shots also were found to create thermal upsets within the OM's optical components over a range of heat deposition rates. However, the recovery times of these thermal upsets were found to be less than one hour. Finally, the use of non-contact infrared thermocouples was demonstrated as an effective means to track the temperature of the OM's optics.

NOMENCLATURE

<u>Symbol</u>	<u>Description</u>
A	Area
c_p	Specific heat at constant pressure
E	Energy
h	Heat transfer coefficient
k	Ratio of specific heats, thermal conductivity
P	Pressure
R	Electrical resistance
s	Thickness of a surface layer
T	Temperature
t	Thickness, time
V	Voltage
x	Distance
<u>Greek Symbol</u>	<u>Description</u>
α	Thermal diffusivity
ΔT	Temperature difference
κ	Absorption coefficient
ρ	Density
τ	Transmissivity
<u>Subscript</u>	<u>Description</u>
cal	Calibrated
f	Final
i	Initial
$meas$	Measured
RTD	Resistance temperature device
TC	Thermocouple
∞	Mean property value of the gas or environment

1. INTRODUCTION

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory is being constructed as the latest in a series of high-powered laser facilities to study inertial confinement fusion. In particular, the NIF will generate and amplify 192 laser beams and focus them onto a fusion fuel capsule the size of a BB. The energy deposited by the laser beams will raise the core temperature of the target to 100,000,000°C, which will ignite the fusion fuel and produce a fusion energy output several times greater than the energy input. The NIF will supply key empirical data needed in fusion energy and basic science research, and also serve as a research tool for safety and reliability in the U. S. Nuclear Weapons Stockpile Stewardship and Management Program.

The NIF, displayed in Figure 1, is comparable in size to a large sports arena. Its massive laser bays contain laser beam amplification, conditioning, and diagnostic equipment, large laser beam transport tubes, and a variety of optical shaping and alignment devices. At the far end of the NIF lies the target bay, which houses a 30 m diameter spherical target chamber. Within the target chamber is the BB-sized fusion fuel capsule containing hydrogen isotopes. The ability to generate, condition, and focus 192 laser beams onto a target the size of a BB, requires precision optical hardware and instrumentation. The most critical piece of optical hardware is the Final Optics Assembly (FOA), shown in Figure 1, which is the final mechanical apparatus before the target chamber. There are a total of 48 FOAs attached to the spherical target chamber, each one corresponding to a cluster of four laser beams. The FOA is responsible for optical focusing and frequency conversion of the laser beam to optimize the energy deposition at the fusion target. Each FOA contains four integrated optics modules (one per laser beam). The integrated optics module (see Figure 2) in turn, is composed of an optics module (OM) containing two potassium dihydrogen phosphate (KDP), frequency conversion crystals and a focusing lens as well as a debris shield module which protects the optics from target expulsions.

The functionality of the KDP crystals is extremely temperature sensitive. Small temperature changes on the order of 0.1°C can significantly alter the performance of these components. Consequently, to maximize the NIF system availability and minimize beam

Figure 1. Schematic of the National Ignition Facility and Final Optics Assembly.

Figure 2. Cross-section of a Final Optics Assembly and its sub-components.

conditioning problems, accurate temperature control of the OM optical components was deemed a necessity. Potential thermal upsets of the KDP crystals were identified and form the basis of this present study, which characterizes the identified thermal upsets and determines design parameters or operating conditions which will minimize their impact on the KDP crystals and the NIF performance.

Four different thermal upsets of the KDP crystals were considered in this study. They are as follows:

1. Fluctuations in the optics' temperatures due to the oscillating laboratory HVAC air temperature,
2. Heating of the optics by adiabatic compression of the venting gas during a maintenance procedure (OM is under vacuum during operation),
3. Cooling of the optics by adiabatic expansion of the fill gas while pumping down the system to operating vacuum, and
4. Heating of the optics during a laser shot (absorption of laser light).

To aid in determining the impact and extent of the thermal upsets, a thermal recovery criterion was defined for the KDP crystals. *The KDP crystals are thermally recovered and in operational condition when their mean temperature is between 19.70 °C and 20.30 °C and does not vary by more than ± 0.10 °C within one hour of a laser shot [1].*

1.1 Temperature Stability of the Optics Module

The NIF's laser focusing and alignment criteria demand extreme environmental control measures. For example, small spatial and temporal excursions in the NIF environmental air temperature may cause minute distortions in beam alignment hardware as well as index of refraction gradients in the beam transport tubes [2], which could significantly degrade the net energy yield of the NIF. To minimize the impact of thermal gradients, the NIF HVAC system has been designed to maintain a mean air temperature field of 20.00 ± 0.28 °C throughout the facility. Unfortunately, heat sources within the facility will create local hot spots in which air temperatures will exceed the upper limit of this range [3]. In addition, undesired fluctuations in the HVAC system could combine

with building heat sources to subject the OM's optical components to temperature swings outside of their operational range (as defined above).

As a result of these uncertainties, the first portion of this study was devoted to investigating the temperature stability of the OM. This included observing the temperature uniformity within the OM under the following conditions:

1. OM subjected to an oscillating lab air temperature with an amplitude of approximately 2°C and a period of 15 minutes. The OM water cooling system is shut off, and all thermal insulation is removed from the OM walls (with the exception of the insulation on the non-water cooled walls, which represented adiabatic boundaries with other OMs).
2. OM subjected to the same oscillating lab air temperature with the water cooling system turned on and no thermal insulation mounted to the OM.
3. OM subjected to the same oscillating lab air temperature with the water cooling system turned and the OM fully insulated.
4. OM fully insulated and subjected to a 1°C temperature rise of the cooling water.

1.2 Pump-Down and Venting of the Optics Module

Under normal operation, the OM will be evacuated to 1 mTorr. However, during the course of NIF's lifetime, various maintenance procedures on the FOA, such as replacing the debris shield, will require venting the OM to atmospheric pressure with dry nitrogen gas. Following the maintenance procedure, the OM will be evacuated down to its operating vacuum.

As a gas is vented into an evacuated vessel, it undergoes compression heating and its temperature rises with its pressure. Conversely, as a gas is pumped or evacuated from a vessel, it undergoes expansive cooling, and its temperature drops along with its pressure. The theoretical limit to the heating or cooling of a gas due to compression or expansion, respectively, is predicted under reversible and adiabatic (isentropic) conditions. If a perfect gas with constant specific heats, initially at a temperature and pressure of T_i and P_i , respectively, is expanded or compressed isentropically to new pressure, P_f , its new temperature, T_f , is given as [4]

$$T_f = T_i \left(\frac{P_f}{P_i} \right)^{\frac{k-1}{k}}, \quad (1)$$

where k is the ratio of specific heats for the particular gas ($k = 1.4$ for air). Obviously, the pump-down and venting of the gas within the OM will be far from isentropic. Rapid and random motion of the gas molecules and conduction/convection heat transfer with the OM components will create irreversible and non-adiabatic conditions. In addition, compressibility effects of the gas over the pressure range involved with the OM will introduce errors not accounted for in the perfect gas equation. Consequently, Equation (1) is not expected to accurately predict the OM's gas temperature change during venting or pump down. However, Equation (1) is useful in predicting the direction and upper limit of the temperature excursions under different compression or expansion processes.

1.3 Laser Shot Simulations

During a NIF laser shot, a portion of the 20,000 J incident laser beam will be absorbed by the OM's optics, resulting in an undesired temperature rise in the frequency conversion crystals and final focusing lens. A previous study used a numerical model to investigate the thermal recovery of the optics following a laser shot [5]. In that investigation, it was assumed that the Single Harmonic Generator (SHG) absorbed 6% (1,200 J) of the incident beam and the Triple Harmonic Generator (THG) absorbed 2% (400 J) of the 20,000 J, while the focus lens did not absorb any appreciable amount of the laser beam. The instantaneous temperature rise, ΔT , of the optical components, assuming uniform heat absorption of energy, E , is given as

$$\Delta T = \frac{E}{\rho A t c_p}, \quad (2)$$

where ρ , A , t , and c_p are the optical component's density, cross-sectional area, thickness, and specific heat, respectively.

At the time that the present study was conducted, the exact amount of laser energy absorption by the SHG and THG was unknown, although it was speculated to be less than the value used in the numerical study mentioned above [5]. Consequently, a range of heat absorption levels for the SHG ($1200 \text{ J} \geq E \geq 240 \text{ J}$) and THG ($400 \text{ J} \geq E \geq 80 \text{ J}$) were investigated in this study. The laser heat deposition was simulated in this study by heating the SHG and THG with thin kapton foil electrical resistance heaters attached to the outer surfaces of the optical elements.

1.4 Objectives of the Present Study

This study was initiated to observe and characterize the temperature stability of the OM, as well as the magnitude and extent of various thermal upsets to the OM's optical components. The parameter of greatest interest was the recovery time (defined above) of the optical components due to the various thermal upsets. To accommodate these endeavors, a full-scale prototype of the OM (including the vacuum window assembly, a fully populated final optics cell, the water jacket cooling system, and a vacuum pumping station) was assembled/instrumented and run through a variety of thermal tests. The results of these tests were used to identify design and operational criteria that could be used to minimize the thermal upset and corresponding recovery times of the optical components and, thus, enhance the availability and performance of the NIF. The details, procedures, and results of these various thermal tests are discussed in the following sections.

2. EXPERIMENTAL METHODS

2.1 Experimental Apparatus

A full-scale OM prototype, shown in Figure 3 with the upper vacuum window assembly and a fully populated final optics cell (FOC), was used for all of the thermal tests discussed in this report. The OM was cast from aluminum and machined for water jacket and vacuum window assembly mounts, as well as vacuum ports and instrumentation feed-throughs. Two large water jackets, with serpentine flow passages, were placed on the North and West walls of the OM, while four smaller water jackets were placed on the four walls surrounding the vacuum window. The vacuum window forms the interface between the vacuum environment in the OM and the atmospheric pressure within the laser beam transport tube. To represent the bottom interface with the debris shield module, a 25.4 mm thick aluminum plate was mounted to the bottom of the OM and painted black (to maintain approximately the same radiation surface characteristics). An aluminum FOC was positioned inside the OM with three movable alignment jacks, which gave the FOC six degrees of freedom. For the tests conducted in this study, the single position of the FOC depicted in Figure 3 was used exclusively. This manual alignment system replaced the much more complex motorized device, which was not available at the time these tests were conducted. The FOC contained three pieces of glass to represent the two potassium dihydrogen phosphate frequency conversion crystals (Single Harmonic Generator; SHG, and the Triple Harmonic Generator; THG) and the final focus lens. All walls of the OM and vacuum window assembly (including the air gap above the vacuum window) were covered with 50.8 mm of polystyrene insulation. An additional 101.6 mm of polystyrene insulation was added to the non-water jacketed walls of the OM.

Figure 4 displays the entire experimental apparatus, including the OM prototype and associated subsystems. Water temperature ($\pm 0.01^\circ\text{C}$) and flow rate (1 GPM for all tests) for the OM water jackets was supplied and controlled with a Mydax 1MP6A water chiller. The water path was designed such that the coolant water flowed into the OM West wall water jacket, followed by the vacuum window water jacket, and finally through the North wall water jacket. An Alcatel M2012A roughing vane vacuum

Note: All Dimensions are in mm and are approximated.

Figure 3. Cross-section schematic of the optics module prototype and sub-components.

Figure 4. Schematic diagram of the optics module prototype experimental apparatus.

pump was used to evacuate the OM. A convection gauge was used to monitor the vacuum within the OM prototype with an accuracy of 2% of the reading. High-precision vacuum valves were used to manipulate the pump-down and venting rates of the OM. An FTS RS33LT water chiller and air/water heat exchanger were used to control the venting air temperature.

To simulate heat deposition/thermal upset from a laser shot, the SHG and THG optical components were electrically heated. To achieve this, four Kapton foil electrical resistance heaters (381.0 mm by 76.2 mm by 0.3 mm) were attached with an adhesive to the bottom and top surfaces of the SHG and THG, respectively. The thin foil heating elements had a hemispherical emissivity of 0.86, which was nearly identical to that of the glass optical components (0.90). Consequently, their presence was not anticipated to effect the thermal response of the optics.

Each set of four heaters was wired in parallel (equivalent electrical resistance of $14\ \Omega$) and connected to a variable AC power supply. The amount of electrical energy E deposited by the electrical heaters over a time period, t , is given by Ohms law:

$$E = \frac{V^2}{R} t, \quad (3)$$

where V is the RMS voltage and R is the effective electrical resistance.

The voltage on the AC power supplies for the SHG and THG heaters were adjusted to deliver the desired amount of electrical energy over a period of seconds. For example, the two power supplies were set at 58.0 V and 33.5 V to deposit 1,200 J and 400 J into the SHG and THG, respectively, over a period of 5 seconds. Power depositions of 600 J and 240 J into the SHG, and corresponding values of 200 J and 80 J into the THG, were also investigated. The thermal resistance of convection from the back surface of the heaters to the air was calculated to be 40 times greater than the thermal conduction from the heaters to the glass. Consequently, nearly 98% of the electrical energy was deposited directly into optical components. A one-dimensional transient heat conduction analysis indicated that the SHG and THG each required roughly 10 seconds,

following the 5 second heat deposition period, to achieve the uniform temperature rise predicted by Equation (2).

Special-limit-of-error Type T thermocouples (wire diameter = 0.255 mm and bead diameter $\approx$ 0.51 mm) were used to monitor temperatures throughout the OM. The nature of the experiments and the high sensitivity of the optical components to small temperature changes required precision calibration and mounting schemes for the thermocouples. A Omega DP251 precision resistance temperature detector (RTD), with an accuracy of $\pm 0.025^\circ\text{C}$, was used to calibrate the thermocouple instrumentation packages, which included the thermocouple, vacuum feed-through, shielded extension wire, and junction connections to the data acquisition system. It was necessary to calibrate the thermocouples with all of the components in place to eliminate introducing any temperature errors with the addition/intervention of additional thermocouple wire and junctions. Heavily insulated, constant temperature water baths of 18.00°C , 20.00°C , and 22.00°C (measured to an accuracy of $\pm 0.025^\circ\text{C}$ with the precision RTD) were used to calibrate the thermocouples. The calibration procedure began by simultaneously measuring the water bath temperature with the RTD, T_{RTD} , and the thermocouples, T_{TC} . To remove precision or wandering error from the 6 digit voltmeter reading the thermocouples, 10 temperature readings were sampled and averaged for each thermocouple in each of the 3 water baths. Next, linear curve fits of the following form were established for each of the thermocouples:

$$T_{TC, meas} = m \times T_{RTD} + b, \quad (4)$$

where m and b were obtained from a least squares fit of the thermocouple temperatures to the RTD temperature over the range of 18.00°C to 22.00°C . The calibrated thermocouple temperature, $T_{TC, cal}$, was then determined by rearranging Equation (2) to give,

$$T_{TC, cal} = T_{RTD} = m^{-1} \times T_{TC, meas} - b/m, \quad (5)$$

The 0.025°C resolution of the RTD combined with the maximum error of 0.020°C introduced by the curve fit resulted in a calibrated accuracy of $\pm 0.05^\circ\text{C}$ for the thermocouples. As a final accuracy check following calibration, the thermocouples were placed in a water bath at 20.01°C (as measured with the precision RTD) and found to all lie within a 0.03°C temperature band.

The final OM design will not allow direct contact temperature measurements to be made on the frequency conversion crystals. Consequently, a non-contact temperature measurement technique was sought to monitor the optical component temperatures during operation in the NIF. The accuracy and response characteristics of non-contact infrared thermocouples were assessed in this study. An Omega OS36 type T infrared thermocouple was calibrated against the standard type T thermocouple that was surface mounted on the SHG. The infrared thermocouple was mounted on a positioning arm facing the SHG's upward facing surface at a separation distance of 5 mm. More information concerning the operation and performance of infrared thermocouples can be found in [6].

To ensure continuous and reliable thermal contact between the thermocouples and the surfaces that they were to monitor, several thermocouple surface mounting schemes were investigated. Six type T calibrated thermocouples (accuracy = $\pm 0.05^\circ\text{C}$) were mounted to the narrow end of a copper block (152.4 mm by 152.4 mm by 12.7 mm) in various fashions. The copper block was submerged in an insulated box containing a constant temperature water bath, with the narrow end of the block on which the thermocouples were attached, exposed to the laboratory air. The first thermocouple was mounted in a 1.6 mm diameter, 5 mm deep hole with an epoxy mixture consisting of 50% volume copper powder (Fisher Scientific, particle diameter $< 1.0\ \mu\text{m}$) and 50% volume high thermal conductivity epoxy (Omega, Omegathermal 201/Omegabond 101). Thermocouples two and three were pressed to the copper surface and covered with the thermal epoxy mixture. Thermocouple four was mounted inside a bead of the thermal epoxy mixture, which was resting on the copper surface. Thermocouple 5 was rigidly mounted to the copper surface with a small piece of aluminum tape, while thermocouple 6 was lightly surface mounted with the same type of tape. All thermocouples, with the

exception of number 6, read the same surface temperature within 0.03°C. Consequently, it was decided that continuous thermal contact could be made with either the thermal epoxy or aluminum tape mounting schemes. To maintain continuity in the surface radiation characteristics around the surface mounted thermocouples, the thermal epoxy mixture (high emissivity in the infrared) was used to mount thermocouples on the glass surfaces, while the aluminum tape (low emissivity in the infrared) was used to mount thermocouples to the aluminum components.

Three major types of experiments associated with the OM, including temperature stability, pump-down and venting, and laser shot simulations, were conducted in this study. The instrumentation feed-throughs connected to the OM were limited to 10 thermocouple channels. Each of the major types of experiments required a slightly different thermocouple layout to acquire temperature data specific to that particular experiment. Consequently, different thermocouple layouts, which made efficient use of the 10 thermocouple channels internal to the OM, were used for each of the major types of experiments. These thermocouple layouts are displayed in Figure 5.

The temperature and vacuum pressure data was collected with a Hewlett Packard 34970A data acquisition system, run with Labview 5.0 software mounted on an IBM PC. To minimize electrical noise and interference, the entire data acquisition/computer system was electrically insulated from other electronic equipment.

2.2 Experimental Procedures

Three different types of experiments were conducted in this study, including thermal stability of the OM, thermal response of the OM to pump-down and venting, and thermal response of the OM to a simulated laser shot. The particular experimental procedure for each type of experiment is discussed below.

2.2.1 Procedure: Thermal Stability of the Optics Module

Four different types of thermal stability tests were conducted on the OM. The major operating conditions for each test are summarized in Table 1. Each of these four tests investigated the temperature spatial uniformity and temporal stability of the OM and its

Note: • corresponds to thermocouple position.

W ↔ E

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Additional Thermocouples:

- Laboratory Air
- Water Inlet
- Water Outlet
- Center of North Wall
- Center of South Wall

(a)

Additional Thermocouples:

- Laboratory Air
- Venting/Vacuum Port

(b)

Additional Thermocouples:

- Laboratory Air

(c)

Figure 5. Thermocouple positioning layouts for the (a) water cooling system, (b) venting and pump-down, and (c) laser shot simulation tests.

components, with the oscillating laboratory air temperature supplied by a forced air HVAC system. The effects of the water cooling system and polystyrene insulation on the thermal stability of the OM were also characterized. The laboratory air temperature oscillated in a near sinusoidal fashion with a mean value of approximately 20.0°C to 21.0°C, an amplitude of 1.5°C to 2.0°C, and a period of roughly 15 to 20 minutes.

Each experiment was initiated by evacuating the OM with the roughing vacuum pump to an operating pressure of 0.1 Torr. Following the pump-down process, the OM was pre-cooled over a period of 24 hours to approximately 20.0°C with the water cooling system. During the pre-cooling period and the remainder of the experiment (3 to 7 hours), the HVAC system was programmed to deliver the oscillating laboratory air temperature discussed above. Following the pre-cooling period, the data acquisition system was turned on and programmed to read the various OM temperatures every minute. For the first of the tests listed in Table 1, the water cooling system was shut off and the uninsulated OM was allowed to reach quasi-steady equilibrium with the laboratory air. The second test was a repeat of Test #1; except this time, the water cooling system was allowed to run for the entire duration of the experiment. The third test was a repeat of Test #2; except that 5.08 mm of polystyrene insulation was added to all external surfaces of the OM. Using a fully insulated OM in Test #4, the water cooling system delivery temperature was raised from 19.80°C to 20.80°C and allowed to run for the duration of the test. Several of these tests were repeated to ensure reproducibility.

Table 1. Summary of Operating Conditions for the Thermal Stability Tests of the OM

Thermal Stability Test # and Brief Description	OM Insulation (In all tests, 12.7 cm of polystyrene insulation were placed on South and East walls of OM to represent symmetry boundaries with other Oms)	Water Cooling System Conditions	HVAC Conditions
Test #1 Response of OM to HVAC without water cooling or insulation	No extra insulation	Water chiller run for 24 hrs (water tank set to 19.80°C) to pre-cool the OM and then shut off for test	Mean temperature $\approx$ 21.0°C Amplitude of oscillation $\approx$ 2.0°C
Test #2 Response of OM to HVAC with water cooling and no insulation	No extra insulation	Water chiller run for 24 hrs (water tank set to 19.80°C) to pre-cool the OM and left on for remainder of test	Mean temperature $\approx$ 20.5°C Amplitude of oscillation $\approx$ 1.8°C
Test #3 Response of OM to HVAC with water cooling and insulation	5.08 cm polystyrene added to all walls of OM	Water chiller run for 24 hrs (water tank set to 19.80°C) to pre-cool the OM and left on for remainder of test	Mean temperature $\approx$ 20.0°C Amplitude of oscillation $\approx$ 2.0°C
Test #4 Response of OM to 1°C rise in water temperature with insulation	5.08 cm polystyrene added to all walls of OM	Water chiller run for 24 hrs (water tank set to 19.80°C) to pre-cool the OM and then water tank temp. raised to 20.80°C for remainder of test	Mean temperature $\approx$ 20.0°C Amplitude of oscillation $\approx$ 1.5°C

2.2.2 Procedure: Thermal Response of the Optics Module to Pump-Down and Venting

Five different types of thermal response tests were conducted on the OM for various pump-down and venting scenarios. Prior to each test, the OM was pre-cooled for a period of 24 hours using a water jacket coolant inlet temperature of 19.90°C. In all but one of these tests, the water jackets were held at this temperature during the thermal upset and recovery periods.

The first two pump-down tests investigated the effect of vacuum pump-down rate on the thermal disturbance and recovery time of the OM's optics. The tests were initiated by starting the roughing vacuum pump and opening the OM vacuum valve to evacuate the

OM from atmospheric pressure (≈ 600 Torr at Los Alamos, NM) down to approximately 0.1 Torr. The first test used a rapid pump-down rate (approximately 3 minutes to reach 10 Torr), while the second test used a much slower pump-down rate (approximately 12 minutes to reach 10 Torr). In both cases, the temperature and pressure data was read every 15 seconds, starting several minutes before the pump-down was initiated and continuing for the next several hours.

The third test in this section investigated the use of the water cooling system to speed up the recovery time of the OM's optics following a slow pump-down scenario. At the instant the pump-down was initiated, the water temperature in the chiller's reservoir was raised from 19.80°C to 20.80°C and held at this value. The temperature and pressure data was read in the same fashion as in the previous two tests.

The fourth test in this section was performed to observe the net recovery time of the OM's optics after a 5 minute venting from 0.1 Torr to atmospheric pressure, followed by a 1 hour lag and a slow vacuum pump-down to 0.1 Torr. Prior to this test, the OM was evacuated to 0.1 Torr. The temperature and pressure data was read in the same fashion as in the previous three tests.

A fifth and final test was conducted to observe the performance of an infrared thermocouple in tracking the SHG's temperature during a rapid pump-down scenario. In this test, the temperature in the center of the SHG was recorded every 15 seconds with both a standard surface mounted thermocouple and a non-contact infrared thermocouple.

2.2.3 Procedure: Thermal Response of the Optics Module to a Simulated Laser Shot

The laser shot simulation tests were conducted in an evacuated OM (Pressure = 0.1 Torr) that had been pre-cooled to approximately 20.00°C over a period of 24 hours. For the first of three tests, the AC power supplies and electrical resistance heaters deposited 1,200 J into the SHG and 400 J into the THG over a period of 5 seconds. The subsequent temperature rise and decay of the optics was recorded with a 15 second time delay between data points. The second test used heat deposition rates of

600 J and 200 J into the SHG and the THG, respectively, while the third test used lesser heat rates of 240 J and 80 J. For all three tests, the water jacket coolant inlet temperature was held at 19.90°C (to give corresponding wall temperatures of approximately 20.00°C) during the thermal upset and recovery periods.

3. RESULTS

The results of this study are divided into the three sections described in the introduction. First, the thermal stability of the OM to the laboratory environment is assessed for various cooling and insulation conditions. Next, the thermal upset and recovery of the OM and its optical components during various pump-down and venting scenarios is reported. Finally, the thermal response of the OM's optics during simulated laser shots is presented and discussed.

3.1 Results: Thermal Stability of the Optics Module

Prior to conducting the thermal response tests, it was necessary to characterize the response of the OM to the oscillating HVAC air temperature within the laboratory where the experiments were conducted. The HVAC system for the NIF is being designed to deliver a mean air temperature of 20.00°C with a maximum deviation of $\pm 0.28^\circ\text{C}$. The HVAC control system in the laboratory where these tests were conducted did not have near this type of sensitivity. The laboratory mean air temperature could be controlled to within 1°C of the set point with an amplitude of oscillation of 1.5°C to 2.0°C.

The first thermal stability test involved pre-cooling the uninsulated OM for 24 hours with the water cooling system. This pre-cooling resulted in quasi-steady OM component temperatures between approximately 20.00°C and 20.40°C. At this point, the water cooling system was shut off, and the OM was allowed to respond thermally to the sinusoidal oscillating lab air temperature (mean temperature $\approx 21.0^\circ\text{C}$, amplitude $\approx 1.5^\circ\text{C}$ to 2.0°C). The lab air temperature and associated OM component temperatures for this scenario are displayed in Figures 6(a) and 6(b). As expected, the temperature of the OM and its components, gradually rise to the mean air temperature value over a period of 8.5 hours. The external walls of the OM are the quickest to respond, while the internal

(a)

(b)

(c)

(d)

Figure 6. Temperature histories of the OM and its components for (a)-(b) an uninsulated, non-water cooled OM, and (c)-(d) an uninsulated, water cooled OM, exposed to an oscillating HVAC system.

optical components have the slowest response time. As expected, the thermal mass of the OM is so large that it does not display a rapid thermal response to the relatively fast oscillations of the HVAC (during an oscillation period of roughly 10 to 20 minutes).

Figures 6(c) and 6(d) display the thermal stability of the uninsulated OM with the water cooling system running continuously. Although the lab air temperature is seen to oscillate 1.5°C about a mean temperature of 20.50°C , the OM component temperatures all remain fairly constant in a 0.2°C band (between 20.05°C and 20.30°C). This is a fairly tight and uniform temperature band considering the accuracy of the thermocouples is 0.05°C . Figure 6(d) indicates that the OM walls and optical components are the coolest, while the vacuum window and air temperature near the venting port are the highest. This is to be expected since the large vacuum window and venting port are furthest removed (thermally) from the water cooling system and, hence, more susceptible to heating from the external laboratory air. Fortunately, the HVAC system in the NIF will be under tighter temperature control ($20.00^{\circ}\text{C} \pm 0.28^{\circ}\text{C}$) than the laboratory HVAC unit available for these tests. Consequently, the NIF operational temperature spread in the OM components should be even less than the 0.2°C band observed in this study.

To minimize the impact of the laboratory air temperature on the thermal upset and response of the OM in later tests, all exposed surfaces of the OM prototype were insulated with 5.08 cm of polystyrene. Upon insulating the OM, the water cooling system tests presented previously in Figures 6(c) and 6(d) were repeated. The quasi-steady temperature plots of the OM components for this later test are displayed in Figure 7(a) and 7(b). As expected, the addition of the insulation resulted in a slightly lower mean temperature for all of the OM components. In addition, the relative positions of the temperature curves with respect to one another have shifted slightly in comparison to the results of the uninsulated OM test (i.e., the vacuum window is now one of the coolest components). However, the 0.2°C band in the OM components still exists.

The thermal response of the OM to the water cooling system was the last feature of interest in these preliminary thermal stability tests. In this test, the insulated OM was pre-cooled to approximately 20.0°C over a 24 hour period. Following this time period, the water temperature in the chiller's reservoir was raised from 19.80°C to 20.80°C . The

Figure 7. Temperature histories of the OM and its components for (a)-(b) an insulated, water cooled OM, and (c)-(d) an insulated, water cooled OM with a 1°C water temperature rise, exposed to an oscillating HVAC system.

rapid rise in the OM's west wall (water cooled) and the corresponding slower response of the OM components is shown in Figures 7(c) and 7(d). After a period of 3 hours, the OM components are still far from reaching equilibrium.

These thermal stability tests revealed that the thermal mass of the OM and the lack of efficient heat conduction paths between components result in a very slow response of the OM to a thermal upset. Rapid fluctuations (on the order of 15 to 30 minutes) in the HVAC air temperature are too quick for the OM to respond to. The data also indicates that the water system can be used to effectively control and manipulate the OM component temperatures.

3.2 Results: Thermal Response of the Optics Module to Pump-Down and Venting

This section describes the thermal response characteristics of the OM and its optical components to various vacuum pump-down and venting scenarios of the OM chamber. First, the effect of vacuum pump-down rate on the thermal upset and recovery of the optics will be explored along with speculative discussions of the heat transfer mechanisms involved in the process. Next, the influence of the water cooling system and venting processes on the thermal recovery of the optics will be investigated. Following this, empirical temperature data of the thermal upset and recovery of the OM's optics will be compared to computational fluid dynamics (CFD) predictions generated in a previous study [7]. Finally, a comparison of the temperature measurement capabilities of a non-surface-contact infrared thermocouple will be compared to that of a standard surface mounted thermocouple.

3.2.1 Rapid Vacuum Pump-Down

Figures 8(a) – 8(c) display the pressure and temperature measurements made within the OM during a relatively fast vacuum pump-down. Figure 8(b) shows the rapid drop in air temperatures within the OM as the gas is expansively-cooled during the pump-down process. The magnitude and extent of these temperature excursions are shown in more detail in Figure 9(a). The largest drop in the OM's air temperature is roughly 15°C, which is well short of the 269°C temperature drop predicted for adiabatic expansion with

Figure 8. Transient plots of (a) optics module pressure, (b) optics module air and boundary temperatures, and (c) FOC optics temperatures during a rapid pump-down process.

(a)

(b)

Figure 9. Early temperature transients of the (a) optics module air and boundary components and (b) FOC optics during the rapid pump-down of Figure 8.

Equation (1). Obviously, as the gas is cooled during the evacuation process, it is removing heat by convection and conduction from the OM walls and optical components. As Figures 8(b) and 8(c) exhibit, this is indeed the case. The OM vacuum window, FOC frame, and the optics (SHG, THG, and final focus lens) temperatures all decrease during the first few minutes of the pump-down process.

Figure 9(a) indicates that the expansive cooling of the gas is complete within a few minutes of the initiation of the pump-down process. As the gas pressure approaches 100 Torr, the expansive cooling process begins to drop off, and the air that remains in the OM begins to warm up as it convects/conducts heat from the OM components. The walls of the OM do not drop much in temperature because of their large thermal mass and active temperature control. The vacuum window and optical components, on the other hand, undergo significant temperature disturbances as a result of the pump-down process. Before discussing the temperature histories of the optical components, however, some assessment of the interpretation of the temperature measurements must be made. How well do the surface mounted thermocouples capture the mean temperature of the components to which they are attached?

During the first few minutes of the rapid pressure/temperature transients, the temperature distributions in each of the optical components are nonuniform, both temporally and spatially. The temperature distribution near the surface of the SHG, $T(x, t)$, can be represented with a one-dimensional, semi-infinite body model with surface convection [8]:

$$T(x, t) = T_i + (T_\infty - T_i) \left\{ \operatorname{erfc} \left(\frac{x}{2\sqrt{\alpha t}} \right) - \left[\exp \left(\frac{hx}{k} + \frac{h^2 \alpha t}{k^2} \right) \right] \left[\operatorname{erfc} \left(\frac{x}{2\sqrt{\alpha t}} + \frac{h\sqrt{\alpha t}}{k} \right) \right] \right\}, \quad (6)$$

where, h is the surface convection heat transfer coefficient, k is the material thermal conductivity, α is the material thermal diffusivity, t is time, T_∞ is the gas temperature, T_i is the initial material temperature, and erfc is the complementary error function.

An analytical analysis, using Equation (6), indicated that the maximum spatial temperature variation within the SHG was approximately 0.2°C within 2 minutes of the

thermal upset. However, after roughly 2 minutes, convection heat transfer drops off considerably as the air density within the OM is reduced by over 90% from its initial value. At this point, heat transfer from the optical components to the gas occurs primarily by conduction heat transfer. This dramatic reduction in heat transfer between the surface of the optics and the cool surrounding gas gives the heat conduction within the optics time to catch up and allow the temperature gradients within the optics to gradually disappear. Within 5 minutes of the initial thermal upset, the temperature distribution in the SHG was determined analytically to be fairly uniform (within 0.05°C). Consequently, during the first few minutes of the transient thermal upset, the optical component thermocouple is recording the surface temperature, which is slightly different than the mean component temperature. Beyond 5 minutes, however, temperature gradients within the optics subside and the temperature measurements begin to correspond to a mean or uniform component temperature.

Inspection of the OM component temperatures prior to pump-down reveals that the components are not all at the same temperature. Part of this can be explained by measurement uncertainty ($\pm 0.05^{\circ}\text{C}$), while the remaining spread is due to temperature control limitations of the experimental apparatus (i.e., heat leaks to/from the environment). With these measurement issues in mind, the temperature histories of the optical components can now be interpreted.

Figure 9(b) displays the thermal upsets and corresponding recoveries of the SHG, THG, and focus lens. During the cool-down process, the surface temperature of the focus lens decreases the greatest, followed by that of the SHG and THG. This behavior agrees with the corresponding air temperature data of Figure 9(a), which shows that the air beneath the focus lens cools more than the air above the SHG (near the vacuum port or venting inlet) or the air in the gap between the SHG and THG. The THG is sandwiched between the SHG and focus lens and, thus, is somewhat insulated from the rapid temperature drop in the OM's internal gas temperature. Hence, its thermal upset is quite small. The rapid warming of the surface of the optical components, which follows the initial temperature decrease, results primarily from heat being conducted from the warmer interior portion of the optics. Radiation warming of the optics from the OM walls also

contributes, but to a lesser degree. This must be the case since the surrounding gas during this time period is still much cooler than the optical components [see Figures 9(a) and 9(b)].

As the temperature field in the optical components equilibrate (after 5 minutes from the initiation of the pump-down), it becomes apparent that the SHG has undergone the largest thermal upset, followed by the THG and focus lens. This is expected since the SHG has only half the thermal mass of the focus lens, and the THG is fairly well insulated from the external gas field by the SHG and focus lens. During the next 3 hours, the optical components begin to warm back up towards their temperatures prior to the thermal upset. Extrapolation of the temperature curves in Figure 8(c) reveals that complete temperature recovery would have occurred in 4 to 5 hours. However, the NIF operational thermal recovery, as defined earlier (optical component temperature within 19.70°C to 20.30°C and not varying by more than 0.1°C/hr), occurs approximately 2.5 hours following the initial thermal upset. This is well within the desired NIF operational laser shot period of 8 hours [1].

3.2.2 Slow Vacuum Pump-Down

The vacuum pump-down test was repeated with a pump-down rate that was roughly twice as slow as in the first case. The pressure and temperature data from this slow vacuum pump-down test is shown in Figures 10(a) through 10(c). The general temperature trends of the OM and its components are very similar to those obtained with the rapid pump-down test. However, the time duration of the thermal upset is prolonged with the slow vacuum pump-down process. The gas is expanded in a slower fashion and, hence, has more time to remove heat from the optical components. The net result is that the optical components are cooled to a greater degree as the pump-down rate is decreased, and consequently, their corresponding temperature recovery is prolonged. Inspection of the temperature histories in Figure 10(c) indicates that even though the optics take longer to reheat with the slower pump-down rate, they do satisfy the thermal recovery definition in about the same time frame as for the rapid pump-down case (2.5 hours). This particular test was repeated two more times with nearly identical results. Consequently,

Figure 10. Transient plots of (a) optics module pressure, (b) optics module air and boundary temperatures, and (c) FOC optics temperatures during a slow pump-down process.

vacuum pump-down rates, on the order of those used in this study, should satisfy the thermal recovery criteria for the OM's optical components.

3.2.3 Slow Vacuum Pump-Down Followed by a Water Temperature Increase

Figure 11 displays the pressure and temperature histories of the OM during a slow vacuum pump-down, followed by a 1°C increase in the coolant water supply temperature. The intention of this test was to investigate whether or not the water cooling system could be manipulated in such a way as to speed up the thermal recovery of the optical components following a thermal disturbance. The temperature data of Figures 11(b) and 11(c) indicate that the 1°C increase in coolant water supply temperature caused a significant increase in the reheat rate of the optical components as compared to the data discussed in Section 3.2.2 in which water temperature manipulation was not used. This latest test did not include active temperature control in which the water temperature would be continually decreased to its starting temperature to bring about the original steady-state temperature conditions. The data does indicate, however, that the water cooling system could be manipulated in such a way to speed up the thermal recovery of the optics if need be.

3.2.4 Rapid Venting Followed by a Rapid Vacuum Pump-Down

Prior to a typical maintenance procedure in which the OM components must be accessed, the OM must be vented to atmospheric pressure. Once the maintenance task is completed, the OM can be pumped down to its operating vacuum pressure. If the venting and pump-down processes are conducted within hours of each other, the corresponding thermal upsets of each process (heating from venting and cooling from pump-down) should nearly off-set one another, and the recovery time of the optical components should be rather short. The pressure changes and thermal upsets associated with the rapid venting of the OM, followed by a one hour lag (representing a maintenance process), and then a rapid vacuum pump-down, are displayed in Figure 12. As expected, the venting process causes a temperature rise in the air as it enters and gets compressed within the OM. This causes a corresponding increase in the temperature of the vacuum window and

Figure 11. Transient plots of (a) optics module pressure, (b) optics module air and boundary temperatures, and (c) FOC optics temperatures during a slow pump-down process and an elevated cooling water temperature (raised from 19.8°C to 20.8°C at the instant of pump-down).

Figure 12. Transient plots of (a) optics module pressure, (b) optics module air and boundary temperatures, and (c) FOC optics temperatures during a venting process followed after one hour by a pump-down process (to simulate maintenance procedure).

optical components. During the one hour lag, the temperatures of these components gradually decrease towards the 20.00°C OM wall temperature. After the one hour lag, the vacuum pump-down is commenced, and the OM components undergo a temperature decrease. Review of the temperature histories of the OM's optical components in Figure 12(c) reveals the recovery time is approximately 2 hours from the initiation of the venting process. As the maintenance period (or time lag between the venting and pump-down processes) increases, the benefit of the thermal upset off-set will decrease. In the extreme limit of a long maintenance period (roughly 3 or more hours), the thermal recovery of the optical components following the vacuum pump-down will be similar to those shown earlier in Figures 8 and 10.

3.2.5 CFD Model Predictions Versus Experimental Measurements

Prior to this current experimental study, a CFD model was developed using the commercial software package CFX 4.1 [9] to investigate the thermal recovery of the OM's optical components following a rapid vacuum pump-down scenario [7].

Before comparing the temperature histories displayed in Figure 13, the differences between the model and experiment must be reviewed. Table 2 summarizes the major differences between the CFX model and the OM prototype experiment. The most significant difference between the model and experiment is how each method reported the optical component temperatures. The CFX model displayed the volumetric average temperature for each optical component, whereas the experiment measured the surface temperature of each of the optics. These two methods can present appreciable differences during rapid thermal upsets. Next, the model used constant temperature (20.00°C) boundary conditions for the OM walls and vacuum window, while in the experiment, these components were allowed to thermally respond to the imposed conditions. For example, in the experiment, the vacuum window was found to change several degrees Celsius during the vacuum pump-down process. Since the vacuum window is located immediately above the SHG, its temperature value significantly impacts the amount of radiation heat exchange and recovery time of the optics.

(a)

(b)

Figure 13. Temperature histories of the SHG, THG, and Focus Lens (a) as predicted with a CFX model [1] and (b) as measured experimentally in the present study during a pump-down scenario.

The remaining differences listed in Table 2 are fairly self-explanatory. While their effects on the optical component temperatures are speculated to be less than the two parameters just discussed, they are still important.

Table 2. Major Differences Between the CFX Model and OM Prototype Experiment

Parameter	CFX Model Condition	Experiment Condition
Optical component temperature	The temperature that was reported for each optical component represented a volumetric average.	The temperature reported for each optical component was measured at one location of the surface of that corresponding component.
Boundary temperatures	All walls of the OM, including the vacuum window and bottom panel, were held at a constant 20.00°C.	The OM walls were held within 0.10°C of 20.00°C; however, the vacuum window and bottom panel underwent significant temperature swings with the thermal disturbances.
Pumping port location	The pumping port was located on the side of the OM, beneath the FOC	The pumping port was located on the side of the OM, above the FOC
Emissivity	The walls of the OM were modeled with an emissivity of 0.02.	The walls of the OM prototype were very rough and heavily oxidized. The emissivity of these surfaces was probably close to 0.5.
Time resolution	A time step of less than 1 second was used for tracing the temperature histories.	A 15 second resolution was used for recording all temperature data.
Convection heat transfer and fluid motion	The solution of the flow momentum equations was discontinued after 2.5 minutes of the pump-down process. Only conduction and radiation heat transfers were accounted for in the thermal recovery.	The net effects of all heat transfer processes were obviously accounted for.

Figures 13(a) and 13(b) show, respectively, the numerically predicted and experimentally measured temperature histories of the SHG, THG, and focus lens following a rapid pump-down of the OM. The magnitude of the thermal upsets in the experiment [Figure 13(b)] were roughly 1.0°C, 0.7°C, and 0.2°C for the focus lens, SHG, and THG, respectively. These are considerably larger than those predicted with the CFX model shown in Figure 13(a). The main cause of these discrepancies is the temperature

gradients developed within the optics during the early stages of the transient pump-down. The numerically predicted temperature values shown in Figure 13(a) are volumetric averages for each optical component. The experimental values, on the other hand, represent the optical component surface temperatures. As discussed previously, the rapid cool down of the OM gas creates a temperature gradient within each of the optical components during the first few minutes of the pump-down process. During the early stages of the thermal disturbance, the surface temperature of each optic is much lower than its volumetric average. Only after several minutes do the large thermal gradients within the optics disappear, and the experimental thermocouple measurements begin to represent the volumetric average temperatures of the optics. Consequently, during the first few minutes of the thermal disturbance, the experimentally measured and numerically predicted optical component temperatures represent different values and can not be directly compared. Roughly 10 minutes after the pump-down was initiated, the experimentally measured optical component temperatures are fairly representative of volumetric averages. With this in mind, the maximum volumetric average temperature decrease of the SHG, THG, and focus lens were found experimentally to be roughly twice that of those predicted numerically.

While the surface effect explains the discrepancy between the predicted and measured thermal upsets during the early part of the transient, it does not adequately explain the differences in the recovery times. The CFX model predicts a recovery time of less than 1 hour, whereas the experiment reveals a recovery time of roughly 2 hours. This difference can be attributed primarily to the temperature boundary condition of the vacuum window. In both the model and experiment, the reheat of the SHG is driven by radiation warming from the vacuum window and conduction heat transfer from the gas (once this gas has warmed up from its initial expansion cooling). The CFX model's vacuum window is at a constant 20.00°C, whereas the prototype's vacuum window cools to nearly 17°C and slowly re-heats over the next hour following the rapid pump-down process [see Figure 9(b)]. Consequently, the SHG in the CFX model receives significantly more radiation warming from the vacuum window and, hence, a shorter recovery time than the SHG in the experimental prototype.

In summary, the CFX model under-predicts the recovery time of the optical components in the OM prototype for a rapid vacuum pump-down scenario. This can be attributed to several of the parametric differences listed in Table 2 and discussed above. It is recommended that the experimentally measured recovery times be used for design and operation guidelines concerning the OM and its optical components.

3.2.6 *Non-Contact Infrared Thermocouple Versus Surface Mounted Thermocouple*

Figure 14 shows the SHG's temperature response to a rapid vacuum pump-down of the OM as measured with a non-surface-contact infrared thermocouple and a standard surface mounted thermocouple. Prior to the experiment, the infrared thermocouple was calibrated against the surface mounted thermocouple at a temperature of 20.15°C. The empirical data of Figure 14(b) indicates that except for the rapid early temperature transient, the infrared and surface mounted thermocouples displayed nearly identical temperatures for the duration of the thermal recovery. The discrepancies between temperature measurements during the first few minutes of the pump-down can be explained by a surface cooling effect and the measurement philosophy of both thermocouples. As the gas is initially expanded, the gas and surface temperature of the SHG drop quite rapidly. The surface mounted thermocouple tracks the surface cooling behavior quite closely because of its location and low thermal mass. The glass SHG is roughly 80% transparent in the 0.7 to 6 μm wavelength range and quickly becomes opaque with increasing wavelength (infrared wavelength range is 0.7 to 100 μm) [8]. Thus the infrared thermocouple measures the average temperature of the glass over a certain depth from which it receives infrared radiation. To determine this approximate depth, one can make use of the radiation transmissivity, which is the portion of incident radiation that passes through a particular medium. In this case, it is a measure of the amount of thermal radiation within the SHG that is generated uniformly within its depths and is emitted through its outer surface. Assuming the glass is a homogeneous isothermal medium, the transmissivity, τ , is defined as:

$$\tau = e^{-\kappa s}, \quad (7)$$

(a)

(b)

Figure 14. (a) Transient pressure plot and (b) comparison of SHG temperature measurements made with a non-contact, infrared thermocouple and a standard type T surface mounted thermocouple during a pump-down of the optics module.

where κ is the absorption coefficient and s is the thickness of the glass layer. In the wavelength range of 0.7 to 6 μm , where glass is fairly transparent ($\tau \approx 0.9$, [10]), the absorption coefficient is approximately 1.0 cm^{-1} [10]. Solving Equation (7) for s gives a value of 0.11 cm. This simple exercise demonstrates that the infrared thermocouple does not just see the outermost surface of the SHG. Rather, the infrared thermocouple receives infrared radiation over a depth of approximately 1 mm into the SHG. Thus, the temperature that is measured with the infrared thermocouple is an average glass temperature over this depth. During the early stages of the rapid pump-down process, the lower depths of this layer are warmer than the outer surface of the SHG. Consequently, the infrared thermocouple displays a warmer temperature than the surface mounted thermocouple does during the early transient.

While rapid surface temperature changes may not accurately be captured with the infrared thermocouple, the results of this study indicate that properly calibrated infrared thermocouples could be used to adequately monitor the average quasi-steady SHG temperatures in the NIF.

3.3 Results: Thermal Response of the Optics Module to a Simulated Laser Shot

This section describes the thermal response characteristics of the OM's optical components to a simulated laser shot. The first subsection discusses the thermal upset and recovery of the optics as a function of the amount of laser energy deposited in the SHG and THG. The second subsection compares the thermal response of the optics to a simulated laser shot as predicted numerically with a CFX model [5] to that measured experimentally in the present study.

3.3.1 Simulated Laser Shots with Variable Laser Energy Deposition

Figures 15(a) through 15(c) display the thermal responses of the SHG, THG, and focus lens to simulated laser shots. In particular, the Figures show the temperature rise and decay of the optical components for different laser energy absorption values by the SHG and the THG.

(a)

(b)

(c)

(d)

Figure 15. Transient temperature plots of the OM optical components during simulated laser shots with various energy depositions in the SHG and THG.

Figure 15(a) displays the thermal upset and recovery of the optical components for a simulated laser shot in which the SHG and THG have absorbed 1200 J and 400 J, respectively. Immediately following the simulated laser shot, the SHG and THG rise in temperature according to Equation (2). Using laser energy absorption values of 1200 J and 400 J for the SHG and THG, respectively, Equation (2) predicts corresponding temperature rises of 0.36°C and 0.12°C (using a density of 2200 kg/m³ and a specific heat of 686 J/kg/K for fused quartz). These temperature rises are consistent with the experimentally measured values depicted in Figure 15(a). Following the sudden rise in temperatures, the SHG and THG gradually cool by heat conduction to the surrounding air and radiation heat transfer to the OM walls. For the energy depositions given in Figure 15(a), the thermal recovery time for the optics is just over an hour. As Figures 15(b) and 15(c) reveal, the thermal upset and corresponding recovery times both decrease with a decreasing amount of energy deposited in the optical components. This trend is further demonstrated with Figure 15(d), in which the thermal response of the SHG is displayed for three different energy absorption values.

3.3.2 CFD Model Predictions Versus Experimental Measurements

Figures 16(a) and 16(b) show, respectively, the numerically predicted and the experimentally measured temperature histories of the SHG, THG, and focus lens following a simulated laser shot in which 1,200 J was deposited into the SHG and 400 J was deposited into the THG. In the numerical model [5], all three optical components were at 20.00°C prior to the laser shot; while in the experiment, the SHG and focus lens were initially at 20.15°C, and the THG was at 20.02°C. Regardless of this small initial discrepancy, similar temperature rises for the SHG (0.3°C) and THG (0.1°C) were reported by the numerical model and experiment. In addition, the numerical model predicted a thermal recovery of the optics nearly identical to that measured experimentally. Both studies predict a thermal recovery time of roughly 1 hour for a laser shot with the energy depositions given above. This recovery time is well within the desired 8 hour laser shot period for the NIF. Besides confirming the desired performance

Figure 16. Temperature histories of the SHG, THG, and focus lens (a) as predicted with a CFX model [2] and (b) as measured experimentally in the present study during a laser shot simulation.

of the OM, these results lend credibility to the previous numerical investigation [5] as well as to the experimental procedure used in the present study.

4. CONCLUSIONS

This experimental study was initiated to observe and characterize the temperature stability of the OM, as well as the magnitude and extent of various thermal upsets to the OM's optical components and the corresponding recovery times. The thermal upsets included temperature fluctuations of the external air temperature, expansion and compression heating due to vacuum pump-down and venting, respectively, of the OM, and laser energy absorption in the optical components. The primary goal of this study was to identify design and operational criteria that could be used to minimize the thermal upset and corresponding recovery times of the optical components and, thus, enhance the availability and performance of the NIF. From the experimental results and analyses, the following key conclusions can be drawn:

1. The OM was fairly stable (thermally) to the relatively rapid HVAC air temperature oscillations present in this study. For the sake of the precision temperature control of the OM and its components, an OM water jacket cooling system and polystyrene insulation were required. Since the HVAC system for the NIF will have more stringent controls than the one available for this study, insulation of the OM is not required. However, the use of a water jacket cooling system is recommended for control and manipulation of the OM's optical components.
2. The thermal upset generated by the vacuum pump-down of the OM was significant. However, the recovery times of the optical components were less than 2.5 hours for the pump-down rates used in this study. The recovery time was found to decrease if the vacuum pump-down was preceded with a venting process in which the OM pressure was raised from its standard vacuum level to atmospheric pressure.
3. Manipulating the water cooling system temperature could significantly decrease the recovery time of the optics.

4. The thermal upset of a simulated laser shot was dependent upon the amount of energy deposited in the SHG and THG. For the range of energy levels used in this study, the thermal recovery time of the optics was less than 1.5 hours.
5. For all types of thermal upsets investigated in this study, the corresponding thermal recovery times of the optical components were less than 2.5 hours. This recovery time is well within the desired 8 hour laser shot period for the NIF.

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