Photodetachment Neutralizer Development - Laser Window Design Study

FINAL REPORT, Vol. II - WINDOW DESIGN DETAILS

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Lawrence Livermore National Laboratory
Livermore, California

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Three different material concepts were analyzed:

- o Single pane, edge cooled
- o Double pane, gas cooled
- o Double pane, liquid cooled

For the material and thermal analysis, the following requirements were specified:

- o Incident, one way flux 40 kW/cm²
- o Beam footprint 3 to 6 X 10 cm
- o Wavelength 1.315 micron

We concluded through the material comparison analysis that the best material candidate is clear sapphire (Al₂O₃). The thermal analysis showed that only the double pane, liquid cooled concept was feasible provided that the incident beam foot print is expanded to 10 X 10 cm. The laser beam expansion is done by combination of expanding and focusing mirrors on both sides of the window. This introduces at least four additional mirrors into the optical resonator. The beam shaping telescope reduces the one way flux to a level which can be thermally handled. The coolant recommended was Fluorinert Electronic Fluid (FC-104)

Previously Proposed Window Summary

Material	Al ₂ O ₃
Concept	Double pane liquid cooled
Coolant	FC-104 Fluorinert fluid
Irradiance	12 kW/cm ²
Footprint	10 X 10 cm
Expanding Telescope	Required

Double pane window transmissivity was still an open question because the absorption of FC-104 coolant was not precisely known. The transmissivity of FC-104 needed to be measured at 1.315 microns in the follow-on contract of the PDN development. The window material is transparent and antireflection coatings are required to reduce the losses to about 2×10^{-4} per pass per coating. Index matching concept for FC-104 will also be verified in the follow-on contract.

The following tasks were performed during the previous study in order to evaluate the PDN window concepts:

1. Evaluation and selection of candidate window materials.
2. Window mount design was established.
3. Thermal and Structural analysis was performed to evaluate GO-NOGO concepts.
4. Beam expanding/contracting telescope has been conceptualized.
5. Detailed description of the engineering analysis was performed on GO concepts.

The single window concept is shown in figure 1-3. This concept was not cooled and was evaluated for three thicknesses (1/4, 3/8, 1/2 inch). The beam footprint considered was 3 X 10 cm.

Double window concept is shown in Figure 1-4. This was chosen so that a coolant can be introduced between the windows. Two types of cooling were considered: gas and fluid. The fluid has a larger heat transfer capability and there is an additional advantage that the indices of refraction between the windows and the coolant can be matched thus minimizing one source of loss. Several window thicknesses were chosen (1/4, 3/8, 1/2 inch) and several window spacings were considered as well as various coolants. The beam foot print that was considered was 10 X 3 cm, the incident flux density was 40 kW/cm² one pass or 80 kW/cm² for total flux density passing through the window. This concept cannot be cooled at the full flux value, therefore, a double window/beam shaping telescope concept was developed as shown in Figure 1-5 in order to spread out the beam foot print which lowers the incident flux density. The expanded footprints considered were 10 X 10 cm and 15 X 15 cm.

The following conclusions and recommendations were generated as a result of this technology assessment program:

- o The single pane window concept is not acceptable.
- o The double pane window with gas coolant is not acceptable.
- o The double pane window with fluid and index matching is a feasible concept, but it requires experimental verification of important issues such as:
 - a. Coolant absorption measurement
 - b. Proper choice of index matching constituents and the effect on absorption
 - c. Deflection and associated beam degradation.

It was recommended that a Proof of Principle Test be performed in order to verify and characterize the material window conceptual configuration. Such test would incorporate the existing COIL laser with the appropriate hardware modifications to install the window with its appropriate instrumentations. This Proof of Principle project would include the fabrication of the proposed window which would be instrumented to give experimental data on all significant parameters i.e., coolant velocity, temperatures, deflection, etc. The results of this test would be used to characterize and to develop design and performance criteria for the conceptual design.

CURRENT STUDY

A summary of this follow-on laser window technology assessment contract is given in the following paragraphs.

The overall system requirement as proposed by TRW is to utilize a chemical oxygen iodine laser (COIL) operating at 1.315 microns to produce within a folded cavity, in a region isolated from the gain medium, a sufficient density of photons to neutralize by photodetachment a negative deuterium ion beam. A double paned cooled window was proposed as the means of isolating the gain medium from the vacuum in which the photodetachment process is to take place. A single pass steady state cavity flux of 40 kW/cm^2 (a double pass flux of 80 kW/cm^2) through a $10 \times 3 \text{ cm}$ beam footprint was specified. In order to reduce the intensity through the window it was proposed that the beam be expanded through the window with a system of expanding/contracting telescopes. The maximum expansion of the beam is limited by the size of sapphire available. It was determined that 8 inch sapphire can be procured. The largest beam footprint which could be passed through this size window (allowing a sufficient rim around the outside for mounting) is $12.36 \times 12.36 \text{ cm}$. This was thus chosen as the size of the operational window to analyze for use in the PDN application. It is noted that expanding the $3 \times 10 \text{ cm}$ beam to $12.36 \times 12.36 \text{ cm}$ and contracting it back to $10 \times 3 \text{ cm}$ requires 4 toroidal mirrors. A demonstrator window for technology verification testing purposes was designed and analyzed for use with an outcoupled COIL beam (10 kW, $10 \times 3 \text{ cm}$ picture frame). The demonstrator is a double paned sapphire window cooled between the panes with a flouorinert coolant.

In order to perform the analyses on the demonstrator and operational windows absorption coefficients of sapphire samples and of flouorinert coolants were measured. The measured values of β were 0.019 cm^{-1} and 0.0079 cm^{-1} for two sapphire samples and $.017 \text{ cm}^{-1}$ for the flouorinert coolant. The difference in β for the two sapphire samples led to an investigation which determined that there are several grades of optical quality sapphire with varying values of β . The measured values (which were both used in different analyses) are very conservative when compared to published data. It is recommended that similar measurements be done on premium quality sapphire. This could indicate increased safety factors and/or enable higher intensity power to be passed through the windows. It is anticipated that the absorption coefficient of premium grade sapphire will be low enough that expanding the beam to $10 \times 10 \text{ cm}$ rather than $12.36 \times 12.36 \text{ cm}$ will be sufficient. If this is found to be the case, the expanding/contracting telescoping system will be simplified since four cylindrical rather than four toroidal mirrors can be used.

The demonstrator window was designed for a $10 \times 3 \text{ cm}$ beam, and a coolant flow of 50 ft/sec, and coolant pressure at the window of 74 psi. The thickness of the sapphire window panes for the demonstrator was chosen to be 0.2 inches. This thickness was arrived at by minimizing the predicted combined thermal and pressure stresses. (A thicker window has higher thermal stresses while a thinner window has higher pressure stresses.)

It was suspected before the analyses that this window would have a large operating safety factor. Analysis of this beam therefore was performed using a β of sapphire of 0.019 cm^{-1} (the high measured value). The thermal/structural analysis showed a safety factor of 6.9.

Drawings of the operational window were not generated (they will be generated at the conclusion of the test phase). The operational window will however in principle be identical to the demonstrator except in size, and coolant gap. Analyses on the operational window assumed β of sapphire of 0.008 cm^{-1} (the low measured value) with double pass flux of 15.71 kW/cm^2 through a $12.36 \times 12.36 \text{ cm}$ footprint. A safety factor of 3.32 was determined for this case.

The computer models predict that the proposed window HEX will be capable of isolating the gain region from the photodetachment region. The proposed window will be able to withstand the high pressure stresses and thermal stresses involved in the PDN application.

2.0 REQUIREMENTS AND DESIGN CRITERIA

The overall system requirement is to perform photodetachment neutralization by stripping of a negative deuterium ion to produce a neutral atom. TRW's solution to this requirement is to utilize a chemical Oxygen Iodine Laser (COIL) which operates at 1.315 micrometers to produce a certain optical thickness of 1.315 micron photons in the path of a negative deuterium ion (D^-) in order that an electron gets stripped and a neutral atom is produced. This optical thickness will be produced inside a closed, folded COIL resonator. The ion beam interacts with the laser photons resulting in a neutralization by a photodetachment process. The produced neutral beam is used to heat the fusion devices. In a fusion device the neutral beam goes directly into the process vacuum chamber and therefore, the oxygen iodine gas mixture in the laser must be isolated by a window from the neutral beam channel with a minimal loss of light and no leakage of laser gas. The aerodynamic windows that have traditionally been used with chemical lasers are viewed as undesirable for the fusion application where any contamination of the fusion vacuum chamber by laser gas would be a big problem. The COIL laser gas medium (pressure 2 to 10 Torr) must therefore, be separated from the laser flux (10^{-6} Torr) beam interaction region by a material window.

The optical thickness of the laser energy needed to provide a certain neutral fraction is the first requirement imposed in the design of a PDN. The required optical thickness is large. In order to obtain a neutral fraction larger than 90% the required thickness is on the order of 10 to 15 MW/cm², depending on the beam energy. Considering the product of the intercavity flux and the length of the neutralizer, a single-pass incident flux of 40 kW/cm² was selected. A laser beam footprint of 3 X 10 cm was selected to carry this required flux along the neutralizer length. The required operating laser beam wavelength will be 1.315 micrometers. The design of the window heat exchanger will assume operation in a steady-state environment.

Design Criteria

The design criteria for the design of the double pane window are identified as follows:

1. Maximize incident flux transmission.
2. Minimize material window bulk absorption at 1.315 micrometers.
3. Minimize coolant bulk absorption coefficient at 1.315 micrometers.
4. Provide a window and heat exchanger mount assembly capable of resisting a coolant-vacuum pressure differences and isolating the gain medium region from the photodetachment region.
5. Size the window for the laser beam size, beam misalignment, beam diffraction, and mount interfacing allowances.

6. Determine required window pane thickness to resist coolant flowing pressures and pressure difference.
7. Select anti-reflective (AR) coatings that are compatible with the selected window coolant.

The detail development of these design criteria is discussed in the following paragraphs.

To maximize the incident flux transmission through the window panes, AR coatings will be used on both sides of each window pane. AR coatings are chosen to minimize reflection losses. The surface finish below the AR coating also affects the resultant scatter of the window surfaces. Al_2O_3 was selected in initial study contract as a material that can be super-polished to within 7 to 20 Å RMS.

Scatter losses off these superpolished surfaces will be minimal. Each element in the transmissive optic will have some amount of surface absorption. The amount of surface absorption may be controlled by the surface roughness due to the polishing process. However, there will continue to be an irreducible minimum of absorption that will result from nothing more than micro-roughness. The application of an anti-reflection coating on the surfaces will increase the absorption to some small degree. Measured values on highly polished surfaces (7-10 Å RMS) with AR coatings applied has resulted in absorption on the order of 2×10^{-4} .

Bulk absorption varies for different materials according to Beer's law, i.e.,

$$I = I_0 e^{-Bt} \quad \text{for transmission}$$

where: I = flux transmitted through medium
 I_0 = incident flux density
 B = bulk absorption, cm^{-1}
 t = window thickness, cm

Based on this equation and the published data Al_2O_3 was selected as the window material during the previous study contract. The bulk absorption of Al_2O_3 will be measured as part of this study contract to verify the published data prior to performing the thermal analysis.

The value of B becomes important not only for the window materials, but it is a very important consideration for the different liquid coolants. Because many of the standard liquids used for coolant materials have a high value of B at 1.315 microns and have good thermal transport properties as well. The absorption coefficient for three liquid coolants in the Fluorinert Electronic Fluid class (FC 104, FC-77, and FC-43) were measured to identify the coolant absorption.

The maximum window pane thickness is limited by absorption induced thermal stress. The minimum thickness is limited by pressure stresses caused by the pressure difference between the laser resonator cavity and the high vacuum in the PDN system, and the coolant flowing pressure between the panes. Window pane sizing must allow for beam misalignment (0.5 cm on a side) laser beam diffraction (0.5 cm on a side), and mounting (1 cm on each side).

AR coatings will be used on both sides of the window panes. The AR coatings selected must be compatible with the Fluorinert Electronic Fluids and undergo no performance degradation at temperatures below 600 degrees C. This AR coating temperature limit was defined by the coating vendor.

3.0 ABSORPTION MEASUREMENTS OF SAPPHIRE AND FLOUROINERT ELECTRONICS FLUIDS

In order to determine the required absorption coefficients, spectrophotometer transmission measurements were performed on three sapphire samples and on three candidate flouroinert cooling fluids (3M FC-104, FC-77, and FC-43). Some of the measurements were performed at Herron Optical using a Beckman U.V. Spectrophotometer, and the others were done at TRW using a Varian 2390 Spectrophotometer. Two of the sapphire samples were measured on both instruments to provide a measure of the correlation between the two machines. The results of these measurements are shown in table 3.1. The small difference between the two measurements could be due to variations within the individual samples.

3.1 Measurements on Sapphire Samples.

The method used to determine the absorption coefficients of the sapphire samples is described below.

By conservation of energy, or Kirchhoffs Law,

$$I = T + S + R + A, \quad 3.1 A$$

Where

I = incident power
T = transmitted power
S = scattered power
R = specularly reflected power
A = absorbed power

Transmitted power is recorded by the spectrophotometer as a fraction of incident power.

Scattered power of each surface was calculated as Total Integrated Scatter (T.I.S) from:

$$T.I.S. = \left(\frac{4 \pi X d \cos \theta}{\lambda} \right)^2 \quad 3.1 B$$

Where d is the RMS roughness of the surface (in angstroms) as determined by profilometer measurements, θ is zero degrees and λ is the wavelength (1.315 microns.) Specularly reflected light is not easily determined because there are multiple reflections between the surfaces. However, it can be assumed that two different samples will specularly reflect the same power.

The absorption, which is the quantity of interest can thus be determined if two samples of different thickness are available, as follows:

$$I1 = T1 + S1 + R1 + A1 \quad 3.1 C$$

$$I2 = T2 + S2 + R2 + A2 \quad 3.1 D$$

$$(I1-I2) = (T1 - T2) + (S1 - S2) + (R1- R2) + (A1 - A2) \quad 3.1 E$$

All quantities in parenthesis are known, except $(A1 - A2)$, which can now be solved for. The quantity $(A1 - A2)$ defines the fraction of power absorbed through a thickness of sapphire equal to the difference in thickness of the two samples. The absorption coefficient, α , is thus determined from Beer's Law as

$$1 - (A1 - A2) = e^{-\alpha(t1 - t2)} \quad 3.1 F$$

The thinnest sapphire sample (2mm) was used in 3.1 D above as the reference by which the absorption coefficients of the other two samples (9.5 mm and 13.5 mm thick) were calculated.

Using the method described above, the absorption coefficients of the two samples were determined as shown in Table 3-2.

The measured value of the absorption coefficients of the two samples differ by a factor of almost 2.5. This may seem surprising, but actually it just illustrates the fact that varying grades of optical quality sapphire can be procured. It is therefore very important to specify the required quality for a specific application.

A comparison of the absorption coefficients found in literature to experimentally measured values illustrates further the variation of quality among sapphire samples. Figure 3.1 is a published curve showing how β varies with temperature and wavelength. Figure 3-1 also shows the values of β at 20 degrees C of the samples which were measured as part of this report. As seen in the figure, the sapphire characterized by the data in this figure is of higher quality than that measured as part of this report. The measured values are therefore conservative since sapphire of higher quality is available. It is strongly recommended that prior to fabricating an operational window, the absorption coefficient of a premium grade sapphire sample be measured. If as expected the measured value of β is significantly lower, the design of the window and expanding telescope could be greatly simplified.

The published absorption coefficient increases significantly with temperature, however, the published coefficient at 1200 degrees C (which is hotter than the hottest predicted temperature) is still lower than the measured value which was used in the thermal models.

3.2 Measurements on Fluid Samples

3.2.1 Room Temperature Absorption Coefficients.

Spectrophotometer cells or cuvetts were used to hold the fluids in the beam paths of the instrument. A 1 cm path length cuvet containing the fluid was placed in the reference arm of the spectrophotometer. A 4 cm path length cuvette also containing fluid was placed in the other arm. Reflection losses were assumed to be equivalent for both cuvetts. The difference in transmission of the two cuvetts is thus equal to the absorption across a 3 cm thickness. The absorption coefficient is thus calculated from Beer's law as follows:

$$\frac{T_{4\text{cm}}}{T_{3\text{cm}}} = e^{-\beta 3\text{ cm}}$$

Table 3-3 shows the absorption coefficients of the three samples tested.

It is noted that FC-43 had an absorption coefficient smaller than the other two fluids (the exact absorption was too small to determine with the instrumentation used), but for simplicity the same coefficient was assumed for use in future analysis since the coefficient of the sapphire, not of the coolant, was found to be the critical value.

3.2.2 Change in Absorption Coefficient with Temperature.

An empty cuvet at 20 degrees C was placed in the reference arm of the spectrophotometer. An identical cuvet heated to 100 degrees C was placed in the other arm and its relative transmission was measured as it cooled.

This process was repeated with cuvetts filled with FC-43. The data was then compared to deduce the change in absorption coefficient with temperature of FC-43.

Figures 3-2 and 3-3 show change in transmission with temperature of an empty cuvet and an FC-43 filled cuvet respectively.

As can be seen in the figures, the decrease in transmission shown in figure 3-3 is thus primarily due to changes with temperature of the glass properties. The transmission (and thus the absorption coefficient) of FC-43 appears to be independent of temperature as shown in Figure 3-4.

4.0 MECHANICAL DESIGN OF WINDOW HEX

As explained in Section 1.0, two different windows were analyzed using thermal and structural computer models (a demonstrator and an operational window). The demonstrator will be used during the technology verification tests. Layout drawings, showing how the demonstrator interfaces with the existing COIL hardware, as well as level 1 drawings (prototype fabrication drawings) of the demonstrator window HEX were generated. These drawings are located in pockets onto the rear of this document.

Drawings of the operational window which will be used inside the COIL cavity for the actual PDN application, will be generated at the conclusion of the technology verification test program. The operational window will differ from the demonstrator in size, and coolant operating conditions, but in principle its design will be identical to that of the demonstrator.

As seen in the drawings of the demonstrator window HEX and mount, the design specifies a set of triple O-Rings between the window panes and mount to protect against coolant leakage. The sapphire window panes are held against the O-Rings with glass filled nylon wedges positioned between the panes on the outer rim of the window, and by the bolted window mount on the outside. The O-Rings are compatible with the fluoroinert coolant fluid. From the analysis, the maximum temperature the O-Rings will encounter is 302 degrees F. The O-Rings are rated to operate up to 350 degrees F.

The sapphire will be anti-reflection coated on each surface. The coatings will reduce reflection losses to less than 0.25% per surface and will have negligible absorption. The temperature encountered in the PDN application (302 degrees F) will have no negative effect on coatings as they can withstand temperatures of 600 degrees C. The fluoroinert coolant will also have no adverse effect on the coatings. The thickness of the sapphire panes was chosen to be 0.2 inches. The details of this thickness determination are discussed in Section 5.0.

The dimensions of the clear aperture of the windows are the same as the dimensions of the incident beam. Diffracted laser light and beam misalignment outside this clear aperture will be clipped to size the beam in front of the window. The cooling system is a closed loop design with cooled reservoir at approximately atmospheric pressure.

The manifolds and plumbing are designed for a fluid flow of 50 ft/sec across the window with a maximum pressure of 74 psi between the panes of the window. All coolant system manifolds and plumbing will be stainless steel which is compatible with the coolant and the expected temperatures.

5.0 THERMAL/STRUCTURAL ANALYSIS OF WINDOW HX

The design analysis of the PDN window consisted of a sizing analysis, the construction of thermal and structural models of the demonstrator (3 X 10 cm aperture) window suitable for testing with the present STP/COIL laser at outcoupled laser intensities and the construction of thermal and structural models of the operational (12.36 X 12.36 cm aperture) window usable for photodetachment neutralization at intercavity laser intensities.

Before either the demonstrator or operational windows were modeled, a preliminary hand analysis was performed to determine feasibility and optimize the window pane and coolant gap thicknesses. Synthetic sapphire and Fluoroinert liquids were selected for the window pane and coolant respectively based on References 1 and 2. (See below). These References are incorporated in the Final Report, Vol. II - Appendix for the September 30, 1983 contract No. W-7405-ENG-48, DOE.

REFERENCES:

1. IOC K324.83.5-303, "COIL Material Window Analysis", J. Williams & T. Hursman, 25 July 1983.
2. IOC K324.83.5-316, "Material Window Coolant Absorption Requirement, J. Williams & J. Palmer, 4 August 1983.

It was recognized at the outset that the selection of the proper thickness of a surface cooled window pane involves a compromise which minimizes the sum of thermal stresses from beam heating (which increase with pane thickness) and mechanical stresses from coolant pressure (which decrease with pane thickness). The thermal stresses in turn are strong functions of absorbed heat flux and beam footprint shape together with window thermal conductivity and degree of cooling. The detailed distribution of these thermal stresses was unknown without a finite element model, but their maximum tensile value was estimated to be about $0.2 E\alpha\Delta T$, where:

- E = modulus of elasticity (PSI)
- α = coefficient of thermal expansion (perdegree F)
- ΔT = maximum temperature difference existing within window pane

Accordingly, it was decided to choose a pane thickness which would minimize the sum of maximum tensile stresses produced by pressure and thermal stress, even if these maxima did not occur at the same point in the pane.

The sizing of the 3 X 10 cm aperture window commenced with assumption of a 50 ft/sec coolant velocity through a 0.06 inch interpane gap. The interpane gap dimension was set to as small a value as possible to minimize coolant supply system requirements with the understanding that if pressure drop and the consequent stresses in the window panes were too high, the coolant supply requirement would have to grow. The maximum pressure drop across a window pane is equal to the absolute inlet pressure, as the pane's outer surface is under vacuum. This absolute inlet pressure was estimated assuming a 0.8 velocity head drop in the interpane gap, a 1.0 velocity head expansion loss into the outlet manifold, an outlet line loss equal to 0.2 velocity heads at the interpane velocity and a one atmosphere pressure at the outlet sump. These assumptions imply an absolute inlet pressure of 74 psi across the sapphire pane for a 50 ft/sec coolant flow velocity.

Figure 5-1 shows a pane thickness tradeoff for the 3 X 10 cm aperture window. This curve assumes an upper bound on our measured sapphire absorption data of 0.019 cm^{-1} and the outcoupled flux of the present COIL/STP device of 1.67 kW/cm^2 . Since the magnitude of tensile thermal stresses are less certain than pressure stress magnitude, it is prudent to select a thinner pane than the strict minimum in the curve. A 0.20 inch thickness was selected for detailed modeling. The effect of 0.5 EaAT thermal stresses on the optimization is indicated. A safety factor of at least 4.0 on fracture can be achieved.

When the above assumptions are applied to design a window to operate at an intercavity heat flux of 80 kW/cm^2 over a 3 X 10 cm aperture for the PDN application, it is quickly found to be not feasible. At 48 times the heat flux, sufficient heat is absorbed to produce boiling in the coolant film and the sapphire is heated to a temperature where its thermal conductivity drops far below its room temperature value, producing further temperature increase. In order to produce a feasible design it was necessary to expand the beam to the maximum extent possible (as determined by size availability of a sapphire blank), widen the interpane coolant gap to offset the increased cooled length and assume the lowest value measured (0.0079 cm^{-1}) in our sapphire absorption tests. A much lower absorption can be achieved through careful specification and process controls for the sapphire blank. The largest single crystals available from our probable vendor are 8 inches in diameter. This limits the largest fabricable window panes to 14.36 X 14.36 cm. One centimeter around the periphery must be devoted to O-Ring seals, which sets the maximum expanded beam aperture to 12.36 X 12.36 cm. A 0.25 inch interpane gap will hold the effective pressure drop to no more than the two velocity heads used in the demonstrator design. Finally, the sapphire absorption can be lower than 0.008 cm^{-1} but the radial extent of this high quality region in maximum size crystals is presently unknown. Full size window panes must be fabricated and measured to verify this assumption.

Thermal Finite Difference Modeling

CADSINDA thermal models of one quarter of each of the two window sizes were prepared and run to provide temperature profiles for input to NASTRAN structural models.

A detailed temperature distribution within the sapphire demonstrator window is needed for an accurate stress analyses. A thermal model was constructed of the critical section of the window (Figure 5-2). The predicted beam footprint (Figures 5-2, 5-3, and 5-4) was used as input. A steady state solution was obtained (Figure 5-3) for cooling with FC-104 flowing at 50 ft/sec between the two window panes (Figure 5-2). A detailed map of the temperatures is presented in Figures 5-5 through 5-13. Moderate reduction in temperature gradients is possible if coolant velocity is increased. A section of the window was selected for the thermal model so that the entire window temperature distribution can be derived from the results, while maintaining the economic advantage of reduced size. It was expected that the temperature distribution in slice 9 (Figure 5-2) would be accurate for the section of the window extending from the right end of the model to the vertical centerline illustrated in Figure 5-1. This was proven when the results showed very little temperature gradient between slices 8 and 9. Hence it was possible to predict temperatures for an entire quarter section of the window with a model which is one half the size ordinarily required to accomplish this. The CAD/SINDA computer program was used to obtain the model steady state solution. The coolant is a "FluoroInert" liquid, FC-104, which is known to have a low absorptance for the laser radiation. It was measured to have an absorption of 0.017 cm^{-1} . A velocity of 50 ft/sec was selected in order to minimize pressure on the window while maintaining moderate temperature gradients. In the model results, 60% of the gradient from the hot surface of the window to the coolant bulk temperature was due to the coolant film gradient. The coolant temperature rise is 0.50 F at the right and left ends (Figure 5-2) and is 0.10 F in the center of the window. Hence coolant temperature rise was neglected in the model. The beam footprint has a rectangular window frame configuration, with the peak occurring at the inside edge. It is illustrated in part in Figures 5-2 and 5-3. Its sloping character is shown in Figure 5-4, where its relationship to slices 1 and 2 in the thermal model is indicated. Average values were used, as indicated for each slice in Figure 5-4. The value of 1.67 kW/cm^2 may be conservative for slices 3 - 9 since the heated width in the direction of the intensity build-up (Figure 5-3) is 30% of that indicated for slices 1 and 2. However, the beam dimension aspect ratio is also 30%; thus the buildup rate may be as great as 3.3 times as fast for slices 3 - 9. The thermal model results are summarized for the surface nodes in Figure 5-3. Heat conduction into the unheated region near the coolant inlet (location A) is such that the peak temperature occurs at the center of the broadest heated region at location B. Detailed temperature distribution in each model slice is presented in Figures 5-5 through 5-13. The slice orientation is defined in Figure 5-3. The peak temperature is seen in slice 2. It is on the surface at the center of the window and is 107 degrees F. At this location a maximum gradient of 11.3 degrees F

exists across the window thickness and an added drop of 18.8 degrees F occurs across; the coolant film.

As noted above, the thermal profiles input from CADSINDA to NASTRAN represent an absorption of 0.019 cm^{-1} of a 1.67 kW/cm^2 incident flux for the $3 \times 10 \text{ cm}$ aperture demonstrator window and an absorption of 0.008 cm^{-1} of a 15.71 kW/cm^2 incident flux for the $12.36 \times 12.36 \text{ cm}$ aperture operational window. Both models assume cooling with a 50 ft/sec stream of FC-104. The infrared absorption of this coolant was measured to be 0.017 cm^{-1} . The coolant bulk temperature rise from absorption in both sapphire panes and the coolant itself was found to be less than 0.5 degrees F in all cases and hence was neglected in the modeling.

As shown in Figure 5-3 the outcoupled beam footprint for the demonstrator window contains a rectangular hollow and is sawtooth shaped with the peak toward the inner edge. The intercavity beam footprint for the operational window in Figure 5-4 is solid and was assumed to be uniform in intensity.

A detailed temperature distribution within the sapphire operational window is needed for stress analysis. A steady state solution was obtained for cooling with FC-104 flowing at 50 ft/sec between the two window panes. A detailed map of the temperatures is presented in Figures 5-15 through 5-21.

the maximum predicted temperature of 302 degrees F (Figures 5-15 through 5-21) at the center of the large aperture window is fairly moderate compared to the material's melting point or its thermal stress limitations.

This group of figures represent the temperatures occurring in slices through the window. Slice 1 is taken along the centerline of the beam footprint while slice 7 is taken along the cooled but not illuminated edge of the window just outside the beam footprint. Slices 2 through 6 are equally spaced between these extremes. Each slice shown temperatures at 7 points through the thickness of the sapphire pane. The cooled surface is at the bottom of the picture, while the surface exposed to vacuum appears at the top. The left hand side of each slice is bounded by the beam centerline, the right hand side by the window edge. Thus the 302 degree C peak temperature occurs at the top left corner of slice 1, i.e. the center of the beam farthest from the coolant stream.

Structural Finite Element Modeling

NASTRAN structural models of one quarter of each of the two cooled window pane sizes were prepared. The actual multiple O-Ring support of the pane was modeled as a simple support at the centroid of the O-Ring bearing area.

Figures 5-22 and 5-23 show the distribution of 8 node NASTRAN HEXA elements used in the 3 X 10 cm and 12.36 X 12.36 cm aperture window models respectively. Coolant pressure was modeled at 74.32 PSI which is equivalent to two velocity heads of FC-104 coolant at 50 ft/sec.

Figure 5-24 summarizes the peak stresses shown by the NASTRAN models. The maximum stresses shown are compared to a tensile fracture stress of 64000 psi for sapphire. For safety critical hardware in ground test a minimum safety factor of 4.0 would be required. For the subject window, surrounded as it is by vacuum chambers and isolated from other optical components by safety shutters, a minimum safety factor of 1.5 may be allowed. Both the demonstrator and operational window designs successfully meet this criteria. The demonstrator window, operating at only out coupled heat flux, has particularly high structural margins. The safety factors, while adequate for the specific conditions assumed, will decrease much faster than linearly for increasing absorption. This parameter, together with coolant pressure and incident flux should be carefully monitored in subsequent development programs.

FIGURE 1-2 DESIGN AND ANALYSIS MATRIX

FIGURE 1-1 COIL PDN WINDOW HEX DEVELOPMENT LOGIC FLOW CHART

SINGLE WINDOW

FIGURE 1-3

DOUBLE WINDOW

FIGURE 1-4

BEAM SHAPING TELESCOPE

FIGURE 1-5

TRANSMITTANCE
(REFLECTIVE
LOSSES INCLUDED)

BECKMAN 5240		VARIAN 2390
2mm SAMPLE	86.5	86.5
9.5mm SAMPLE	85.7	86.1

TABLE 3-1 COMPARISON OF TOTAL
TRANSMITTANCE OF TWO
SAPPHIRE SAMPLES AS MEASURED
BY THE BECKMAN 5240 AND
VARIAN 2390 SPECTROPHOTOMETERS

	9.5mm THICK SAMPLE	13.5mm THICK SAMPLE
ABSORPTION COEFFICIENT B	0.0079 cm ⁻¹	0.019 cm ⁻¹

TABLE 3-2 ABSORPTION COEFFICIENT OF SAPPHIRE
SAMPLES AS MEASURED BY THE
BECKMAN 5240 SPECTROPHOTOMETER

FIGURE 3-1 ABSORPTION COEFFICIENT, β , FOR SAPPHIRE IN THE INFRARED AS A FUNCTION OF TEMPERATURE.

θ AND X INDICATES THE MEASURED VALUES OF TWO TESTED SAMPLES AT 20°C

(JOURNAL OF THE OPTICAL SOCIETY OF AMERICA, VOL.55, No.6, JUNE 1965
 "OPTICAL AND INFRARED PROPERTIES OF Al_2O_3 AT ELEVATED TEMPERATURES"
 BY DAVID A. GRYVNAK AND DARRELL E. BURCH)

FLUID	3M FC-104	3 M FC-77	3 M FC-43
ABSORPTION COEFFICIENT (β)	0.017 cm^{-1}	0.017 cm^{-1}	<0.017 cm^{-1}

TABLE 3.3 MEASURED ABSORPTION COEFFICIENTS OF THE CANDIDATE COOLANT FLUIDS AT 1.315 MICRONS

FIGURE 3-2 RELATIVE TRANSMISSION OF EMPTY CUVET COOLING FROM 100° C TO 20° C VS CUVET AT 20°C

FIGURE 3-3 RELATIVE TRANSMISSION OF CUVET FILLED WITH FC-43 VS IDENTICAL CUVET FILLED WITH FC-43 AT 20°C

FIGURE 3-4 RELATIVE TRANSMISSION OF FC-43
VS FC-43 AT 20°C

FIGURE 5-2 Laser Window assembly with thermal model section indicated by heavy lines. Dimensions are in inches.

FIGURE 5-3 - LASER WINDOW THERMAL MODEL CONFIGURATION AND RESULTS. ALL DIMENSIONS ARE IN INCHES. SURFACE TEMPERATURES SHOWN ARE IN DEGREES F.

FIGURE 5-4 Predicted intensity versus distance from outside edge of beam and intensity values used in the thermal model.

EXTERNAL SURFACE

104.85	104.13	102.11	98.36	94.83	90.35	83.82	80.12	78.79
104.85	104.13	102.11	98.36	94.83	90.35	83.82	80.12	78.79
104.53	103.82	101.82	98.11	94.60	90.05	83.73	80.08	78.76
103.21	102.54	100.55	97.13	93.76	89.33	83.38	79.92	78.67
101.01	100.40	98.68	95.48	92.39	88.28	82.81	79.55	78.52
97.92	97.40	95.92	93.15	90.46	86.86	82.03	79.30	78.32
94.95	94.50	92.13	89.55	86.53	83.57	81.32	78.84	78.12
94.95	94.50	92.13	89.55	86.53	83.57	81.32	78.84	78.12

←
COOLANT

INLET
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B

FIGURE 5-5 3x10CM window thermal model results for slice 1. Temperatures are in degrees F.

EXTERNAL SURFACE

107.14	106.53	104.80	101.31	97.30	90.42	83.55	79.98	76.71
107.14	106.53	104.80	101.31	97.30	90.42	83.55	79.98	76.71
106.03	105.23	104.52	101.07	97.10	90.24	83.46	79.94	76.69
105.54	104.98	103.37	100.09	96.28	89.83	83.13	79.79	76.60
103.40	102.88	101.41	98.42	94.89	88.58	82.58	78.54	76.46
100.76	99.82	98.56	95.96	92.85	87.17	81.66	78.20	76.28
97.05	95.58	93.91	91.18	87.75	83.79	80.18	76.98	76.82

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COOLANT

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FIGURE 5-6 3x10CM window thermal model results for slice 2. Temperatures are in degrees F.

FIGURE 5-7 3x10CM window thermal model results for slice 3. Temperatures are in degrees F.

FIGURE 5-8 3x10CM window thermal model results for slice 4. Temperatures are in degrees F.

FIGURE 5-9 3x10CM window thermal model results for slice 5. Temperatures are in degrees F.

EXTERNAL SURFACE

81.65	81.81	82.28	83.22	84.13	82.48	80.23	78.72	78.18
81.65	81.81	82.28	83.22	84.13	82.48	80.25	78.72	78.18
81.60	81.75	82.21	83.14	84.05	82.42	80.21	78.70	78.08
81.36	81.50	81.94	82.65	83.37	82.17	80.05	78.61	78.03
80.96	81.08	81.50	82.36	83.27	81.74	79.78	78.47	77.84
80.43	80.54	80.90	81.68	82.55	81.34	79.41	78.27	77.81
79.74	80.04	80.35	81.02	81.82	80.55	79.97	78.93	77.77

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COOLANT

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FIGURE 5-10 3x10CM window thermal model results for slice 6. Temperatures are in degrees F.

FIGURE 5-11 3x10CM window thermal model results for slice 7. Temperatures are in degrees F.

EXTERNAL SURFACE

78.40	78.69	80.44	81.73	82.86	81.47	79.62	78.40	77.81
78.40	78.69	80.44	81.73	82.86	81.47	79.62	78.40	77.81
79.37	79.65	80.40	81.68	82.82	81.42	79.58	78.39	77.80
79.25	79.51	80.29	81.46	82.60	81.22	79.46	78.32	77.86
79.05	79.29	79.94	81.10	82.21	80.87	79.24	78.20	77.78
78.77	78.98	79.55	80.58	81.64	80.39	78.95	78.04	77.68
78.52	78.78	79.18	80.08	81.03	79.92	78.67	77.89	77.58
78.45	78.66	79.08	80.00	80.74	79.74	78.51	77.84	77.54

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COOLANT

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FIGURE 5-12 3x10CM window thermal model results for slice 8. Temperatures are in degrees F.

EXTERNAL SURFACE

78.05	78.38	80.16	81.50	82.68	81.30	79.51	78.35	77.88
79.05	78.36	80.16	81.50	82.68	81.30	79.51	78.35	77.88
79.03	78.33	80.12	81.45	82.62	81.26	79.48	78.33	77.87
78.92	78.21	79.98	81.24	82.41	81.08	79.38	78.26	77.82
78.75	78.01	79.70	80.90	82.04	80.73	79.16	78.16	77.75
78.51	78.74	79.34	80.41	81.45	80.27	78.88	77.99	77.65
78.30	78.53	79.01	80.34	80.89	79.81	78.59	77.85	77.85

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FIGURE 5-13 3x10CM window thermal model results for slice 9. Temperatures are in degrees F.

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FIGURE 5-14 12.4x12.4cm window thermal model configuration; all dimensions are in inches.

FIGURE 5-15 Laser Window Thermal Model Results for Slice 1. Temperatures are in Degrees F.

FIGURE 5-16 Laser Window Thermal Model Results for Slice 2. Temperatures are in Degrees F.

FIGURE 5-17 Laser Window Thermal Model Results for Slice 3. Temperatures are in Degrees F

EXTERNAL SURFACE

302.3	302.3	302.2	301.5	297.5	279.5	256.7	146.9	117.1	105.2
302.3	302.3	302.2	301.5	297.6	279.5	256.7	146.9	117.1	105.2
296.6	296.6	296.6	295.8	292.1	274.7	252.1	142.3	118.2	104.5
274.3	274.3	274.2	273.7	270.4	256.2	210.7	138.6	112.5	102.0
238.9	238.9	238.6	238.4	235.8	224.1	195.4	126.6	106.7	97.5
191.1	191.1	191.0	191.1	186.2	181.4	171.4	110.3	91.0	82.5

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COOLANT

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FIGURE 5-18 Laser Window Thermal Model Results for Slice 4. Temperatures are in Degrees F.

EXTERNAL SURFACE

FIGURE 5-19 Laser Window Thermal Model Results for Slice 5. Temperatures are in Degrees F.

FIGURE 5-20 Laser Window Thermal Model Results for Slice 6. Temperatures are in Degrees F.

FIGURE 5-21 Laser Window Thermal Model Results for Slice 7. Temperatures are in Degrees F.

FIGURE 5-22 - QUARTER MODEL OF 3 X 10 cm
APERTURE WINDOW (NASTRAN)

FIGURE 5-23 - QUARTER MODEL OF 12.36 X 12.36 cm APERTURE WINDOW (NASTRAN)

WINDOW PANE	MAX. TENSILE STRESS, PRESSURE ONLY (PSI)	MAX. TENSILE STRESS, THERMAL ONLY (PSI)	MAX. TENSILE STRESS, THERMAL PLUS PRESSURE (PSI)	MINIMUM SAFETY FACTOR
3 X 10LM APERTURE, 6.86 X 13.92 X 0.508 CM EXTERNAL DIMENSIONS UNDER 16.1 WATT/CM ² ABSORBED FLUX	+5574 (AT CENTER)	+4512 (AT EDGE)	8689 (AT CENTER)	6.90
12.36 X 12.36 CM APERTURE 14.36 X 14.36 X 0.508 CM EXTERNAL DIMENSIONS UNDER 63.9 WATT/CM ² ABSORBED FLUX	+14714 (AT CENTER)	+31213 (AT BEAM CORNER)	+18071 (AT BEAM EDGE)	3.32 *

*1.92 IF COOLANT PRESSURE LOST DURING OPERATION AND "THERMAL ONLY" CONDITION APPLIES

FIGURE 5-24 - NASTRAN WINDOW MODEL RESULTS

SECTION B-B

SECTION C-C

REVISIONS			
LTB	DESCRIPTION	DATE	APPROVED

NOTES: UNLESS OTHERWISE SPECIFIED

- 1 PART IDENTIFICATION MARKING PER PR12-6-0110, LOCATE APPROX AS SHOWN.
- 2 INSTALL INSERTS PER PR 9-110.
- 3 WELD PER PR3-1.

205 R 6 PI

32

669 +.005
-.030 FOR -10

10	12		NAS1395C3	INSERT					
	4		-17	TUBE	4150 R 600W 600T 74 AL ALT	COMML			
	2		-15	SPACER	10% GLASS FILLED NYLON6	COMML			
	2		-15	SPACER	10% GLASS FILLED NYLON6	COMML			
	2		-14	WINDOW	.200 THK AL ₂ O ₃	COMML			
1			-13	PLATE	1.00 THK 6061-T651 AL ALT	00-A-250/11			
	1		-12	PLATE	1.00 THK 6061-T651 AL ALT	00-A-250/11			
		1	-11	PLATE ASSY					
		1	-10	PLATE ASSY					

FORM NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPEC	REV	DATE
-11	10-1					

GP -11

UNLESS OTHERWISE SPECIFIED				CONTRACT NO.		THE FOLLOWING IS A PART OF THE DRAWING	
1. DO NOT SCALE DRAWING 2. DIMENSIONS ARE IN INCHES 3. DIMENSIONS ARE IN INCHES 4. SURFACE TEXTURE SHALL BE 5. REMOVE BORDERS AND SHARP EDGES 6. DIMENSIONS APPLY BEFORE PLATING 7. DIMENSIONS APPLY BEFORE PLATING 8. DIMENSIONS APPLY BEFORE PLATING 9. DIMENSIONS APPLY BEFORE PLATING 10. DIMENSIONS APPLY BEFORE PLATING				DRAWN: [] CHECKED: [] DATE: []		DATE: []	
PR 9-110 PR 12-1 PR 3-1				ON THE DRAWING DIMENSIONS 1. 1.00 2. 1.00 3. 1.00 4. 1.00 5. 1.00 6. 1.00 7. 1.00 8. 1.00 9. 1.00 10. 1.00		WINDOW, COOLED PDN	
APPLICABLE SPECIFICATIONS THE ABOVE TWO (2) SPECIFICATIONS FORM A PART OF THIS DRAWING.				E 11982 X434613		SHEET 1 OF 1

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INSTRUCTIONS			
LTB	DESCRIPTION	DATE	APPROVED

BOX

PAPER PLATE

LABORATORY CALORIMETER

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