Aerothermal Analysis and Design – A Hypersonic Application

Army Hypersonic Compact Kinetic Energy Missile
Laser Window Design

Dr. Gerald Russell*, Stephen Cayson, Mike Jones, Wendy Carriger, Robert Mitchell
U.S. Army Aviation and Missile Command, Redstone Arsenal, AL, USA 35898

Forrest Strobel, Michael Rembert
ITT Industries, Advanced Engineering Sciences

Dave Gibson
Summit Research Corp.

ABSTRACT

The U.S. Army Aviation and Missile Command's Aviation and Missile Research, Development and Engineering Center (AMRDEC) is currently developing the Compact Kinetic Energy Missile (CKEM) which achieves hypersonic velocities at sea level. This work is being presented as an example of the Aerothermal Analysis and Design Process required to ensure a successful hypersonic system design. While this analysis and design was conducted for a short hypersonic flight environment, the same process is applicable to all systems experiencing aerothermal heating. The primary steps in aerothermal analysis and design include

A. System requirements definition
B. Definition of aerothermal boundary conditions
C. Identification of candidate material technology
D. Coupled thermo-structural analysis and design
E. Ground test for validation and verification
F. Flight test application of flight qualification

These steps provide a means of identifying and mitigating risk prior to costly system component fabrication and flight-testing. This paper will present the CKEM Laser Window Design and Analysis effort as an example of a successful approach to hypersonic system thermal analysis and design.

Keywords: Hypersonics, Laser Window, Aerothermal Tests, Seals, Flight Tests, Aerodynamic Heating

1. INTRODUCTION

The objective of the Compact Kinetic Energy Missile (CKEM) Laser Window Design Program was to develop and experimentally validate a laser window design for use in the CKEM hypersonic flight environment. The window design requirements included:

a. Accommodating the severe highly transient aeroheating and resulting thermal gradients
b. Providing an effective seal to prevent gas flow into the laser guidance electronics volume
c. Surface flush mount to minimize aerodynamic loads
d. Minimize dynamic effects on the window due to launch and flight shocks
e. Provide an adequate surface finish and transmissibility for the laser wavelength of interest

The Missile Guidance Directorate initially developed a conceptualized baseline design from which the final detailed design was derived. After completion of the final design, window specifications were developed and laser windows were purchased from Meller Optics, and attachment hardware was fabricated for use in ground and flight testing. Aerothermal tests were conducted at the Naval Air Warfare Center (NAWC) T-Range Aerothermal Test Facility [1] where heat fluxes and resulting thermal responses were simulated on the laser window design and attachment hardware to assess thermostructural performance and seal integrity. A final verification was performed during flight testing conducted at Eglin Air Force Base. This report documents the design and analysis of the laser window as well as the test and evaluation effort that validated and verified the laser window design.

2. DISCUSSION

2.1 Geometry

2.1.1 Missile Configuration

The CKEM missile configuration is shown in Figure 1. The current design essentially represents a test bed for state of the art technology that includes guidance and control, propulsion, packaging of lethality mechanisms, thermal protection systems, and integrated system capability. The missile is comprised of a nose section, guidance section, and motor section. For the trajectory of interest, the missile nose and guidance sections are protected by a Chartek 4 [2] thermal protection system, and the motor section utilizes a sacrificial over wrap of fiberglass epoxy. The window is located just forward of the transition from the ogive to the motor case cylinder. The local surface angle is approximately 6° for this region, with the distance from the nose tip being 18 inches. The flight configuration and trajectory were used to design the ground test configuration to induce the same thermal gradients and peak temperatures and accurately assess the window design performance.

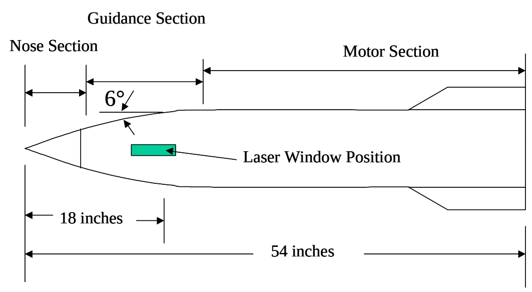

Figure 1. CKEM Missile Configuration

2.1.2 Window Configuration

The overall laser window configuration is provided in Figure 2. Each region of interest is labeled and includes the laser window, Grafoil™ seal, restraint frame, reflector section, and detector housing. These components make up the laser window flight and ground test hardware. The unique Grafoil™ seal [3] concept was developed by ITT Industries and represents a critical aspect of the design to limit hot gas flow from reaching internal components. The Grafoil™ was also used to reduce stress by allowing expansion of the window and frame and provide some level of dynamic isolation. The selected candidate window materials were polycrystalline aluminum oxynitride (ALON), sapphire, and fused silica (Dynasil™). These materials generally provide the highest performance in severe aerothermal environments and were well suited for the initial studies for the CKEM application. Specific trades were conducted to assess thermal stress effects that are generally the critical factor in the use of ceramics. The overall window dimensions were 0.88 inch wide by 2.89 inch long with a 0.1 inch wall thickness. Trades were performed for two bevel angles of 45° and 60° to reduce thermal stress and provide adequate surface contact with the Grafoil™ and steel attachment frame. As can be seen in Figure 3, the Grafoil™ seal is positioned to eliminate any direct contact with the housing hardware and is compressed to ensure adequate seal under ambient and elevated temperatures. The Chartek 4 heatshield is beveled into the flush mounted window to minimize flow disturbances.

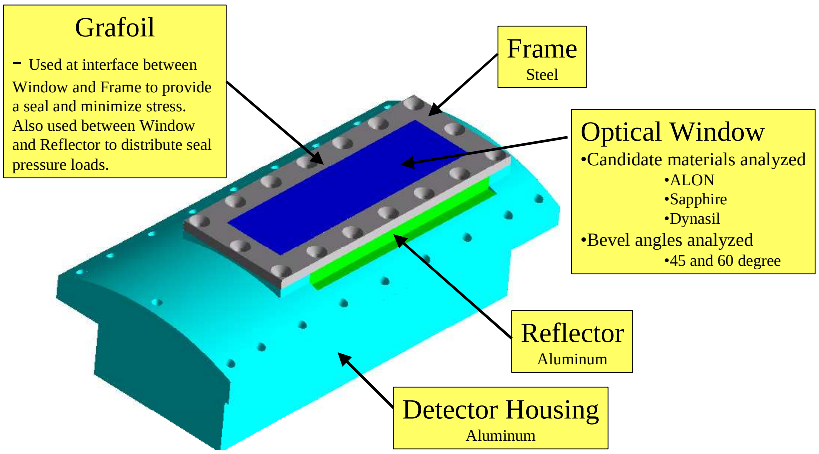

Figure 2. Overall Laser Window Hardware Configuration.

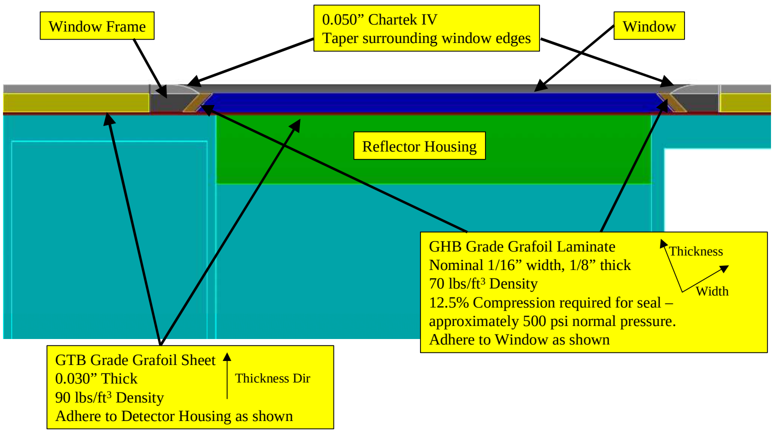

Figure 3. Cross-section of Laser Window Attachment Concept.

2.1.3 T-Range Test Configuration

Figure 4 provides a view of the aerothermal ground test configuration conducted at the NAWC T-Range facility. The test cone is assembled to an instrumentation cylinder, which contains all instrumentation lines, and the cylinder attaches to the translation hardware for injection of the test samples after facility flow stabilization. A 1.35-inch radius spherical steel nose tip was utilized along with a 0.05 inch Chartek 4 heatshield to match the flight configuration. The test configuration also includes the attachment frame, seal, and window. The calorimeter cone was configured in the same geometry as the window test cone shown in Figure 4, but is simply comprised of a solid stainless steel cone and calorimeter plate attachment (in place of the window). The size of the spherical nose tip, distance from the nose tip, and cone angle were analytically selected to match flight environments for the specific window station during flight. The window was located approximately 4.5 inches from the nose tip. The calorimeter was comprised of a 0.06-inch thin skin instrumented with four welded thermocouples to obtain a window location thermal response. Two static pressure gages were also used to obtain pressure at the window location. This data was utilized to verify the flow field conditions and aerothermal environment as well as validate the analytic predictions that were subsequently used for flight predictions. In addition to the calorimeter cone instrumentation, a thermocouple and pressure transducer were located in the volume below the actual laser window hardware to measure any temperature rise or pressure increase within the laser receiver volume. Any significant rise in either of these measurements might indicate a seal leak allowing hot gas to enter the temperature sensitive laser receiver volume. The holes in the instrumentation cylinder seen in Figure 4 identify where the injection arms mount. This assembly was positioned outside the test rhombus (or region of uniform flow) aft of the nozzle until flow conditions stabilized. When flow conditions stabilized, the test sting was injected into the high temperature flow and then withdrawn prior to facility shut down. This eliminated the effects of start up and shutdown shocks typically associated with aerothermal facilities.

Figure 5 provides an overall view of the test sting and nozzle exit. Initially the test sting was positioned in the center of the nozzle exit. However, through additional analysis, it was determined that an offset was required to ensure a uniform flow field over the length of the window. A 9-inch exit diameter Mach 3 nozzle was used to deliver the desired conditions. A standoff from the exit plane of 1 inch was selected to minimize injection concerns with the nozzle hardware. These conditions and configurations provided the most uniform flow and matched the desired convective thermal environment predicted for flight.

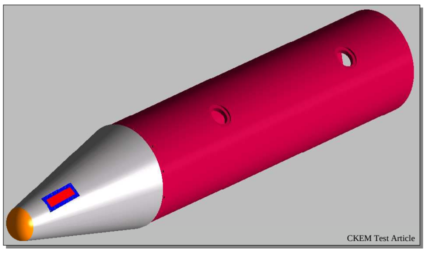

Figure 4. T-Range Test Sting and Laser Window Test Hardware.

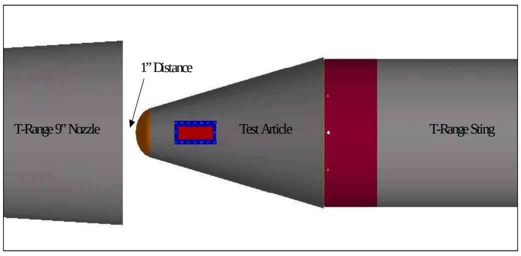

Figure 5. Overall Test Configuration after Injection.

2.2 Materials

The materials utilized in this design and test effort included the laser window material candidates, seal material, heatshield material, nose tip, attachment hardware, and housing hardware. The material candidates for the laser window included sapphire, polycrystalline aluminum oxynitride (ALON), and fused silica (Dynasil™). Sapphire was the initial material of choice for the window based on its high temperature capability and strength. In general, sapphire is typically a first candidate for high temperature applications until thermostructural analyses are performed exposing the thermal stress concerns typical of sapphire as well as concerns over the directionally dependent properties impacting fabrication. ALON is another high temperature optical material, but has reduced strength compared to sapphire, has a high thermal expansion coefficient, and is not as established in production. However, since the material is polycrystalline, homogeneous properties exist, and the material can be easily fabricated, reducing cost. While the fused silica has lower strength compared to ALON and sapphire, it has capability at very high temperatures due to its extremely low thermal expansion, and it experiences reduced thermal stress, making it the primary candidate for applications for high temperature environments. As a result of the use of the simplified rectangular flat configuration, the complexity of fabrication was reduced, and costs were approximately the same for each of the materials.

Stainless steel was used for the nose tip and window frame. Aluminum was used in the laser window reflector and housing. Grafoil™ was selected for the seal design due to the high temperature and compression capability. A pre-stress or compression on the seal was applied to maintain the leak proof volume and provide restraint for the window. Chartek 4 was applied in a 0.05-inch thickness on the outside surface of the steel cone to limit cone thermal response as well as replicate the actual flight missile heatshield design on the fore cone.

The thermal and mechanical properties used for the window design and evaluation are provided in Table 1. Room temperature values are provided for comparison in the table. However, temperature dependent properties were used for each of the materials where necessary. The window material properties were taken from Harris [4]. The Grafoil™ properties were taken from vendor data.

A primary concern for any optical material is the minimization of surface flaws to ensure a high probability of survival. To ensure an adequate window design, surface finish specifications were defined for polishing. It should be noted that weather survivability was not a requirement for the design and qualification test program.

Table 1. Room Temperature Thermal Properties.

Materials	Density (lbm/ft^3)	Thermal Conductivity (Btu/ft-hr-°F)	Specific Heat (Btu/lbm-°F)	Thermal Expansion (in/in-°F)	Young's Modulus (Mpsi)	Poisson's ratio	Mean Strength MOR** (ksi)
Sapphire	248	20	0.18	2.8e-6	50	.27	65.5
ALON	230	7.2	0.18	3.2e-6	47	.24	54.3
Dynasil	137	0.8	0.18	2.8e-5	11	.16	8.5
Grafoil	70	3.0	0.17	1.5e-5	0.029	0.3	0.01*

* compressive, ** Modulus Of Rupture (MOR)

2.3 Aerothermal Environments

Following the identification of the missile configuration of interest, it was necessary to define the aerothermal environments for which the window design must successfully function. Two flight trajectories were considered: a baseline trajectory imparting worst-case conditions, and the actual flight trajectory imparting a reduced level of severity and considered the more realistic environment for the flight test program. The ground test environments consisted of the T-Range conditions determined to best simulate the flight conditions. The Aeroheating and Thermal Analysis Code (ATAC3D) [5] was used to develop the transient aerothermal boundary conditions which were then mapped onto the three dimensional finite element analysis models for predicting stresses, both thermal and pressure induced.

The resulting aerothermal boundary conditions for the three test conditions of interest (baseline flight, actual flight, and T-Range test) are provided in Figures 6 through 8. Figure 6 provides a comparison of recovery temperature with peaks on the order of 2000 to 2600 °F. Again, the main objective was to match or exceed the actual flight conditions, which reached a peak of only 2100°F. Using a T-Range condition of 2200-2300 °F, ensured validation of a robust design, which could meet future performance enhancements. The resulting edge pressure conditions provided in Figure 7 show relatively good agreement in pressure loads. However, the finite element analyses indicated that the stress response of the window design was dominated by thermal gradients with pressure loads being negligible.

Figure 8 provides the resulting cold wall heat fluxes for the various test conditions. The peak heat flux rate matches well between the actual flight and T-Range conditions. The temperature response predictions from ATAC3D for the Dynasil™ window design are provided in Figure 9 for the three conditions of interest. As can be seen, the T-Range test conditions induce transient thermal gradients falling between the baseline flight and the actual flight results ensuring the validation of a robust design. The peak temperature and stress response during the actual flight test represents the criteria for selecting a T-Range test period. The test time was selected to ensure the peak stress experienced during the T-Range test exceeded that seen for the actual flight. The T-Range induced thermal response is similar in magnitude to the thermal gradients experienced during the baseline flight, and far exceeds the actual flight response.

2.4 Finite Element Analysis

Analyses were performed using the ATAC3D aerothermal analysis code to provide convective and pressure boundary conditions coupled with the ANSYS finite element analysis code to solve the three dimensional finite element problem. Shown in Figure 10 is the finite element analysis model of the window attachment design. Planes of symmetry were utilized to perform the analyses with the detector housing, window, seal, and frame included in the finite element model. The analytic model included transient temperature response, thermal expansion, and the appropriate constraints with respect to the remainder of the ogive assembly. The Grafoil™ seal was modeled with pre-stress loads of 500 psi or 12.5 percent compression to ensure an adequate seal at elevated temperature was maintained. A representative thermal response contour for the Dynasil™ window finite element analysis is provided in Figure 11. The

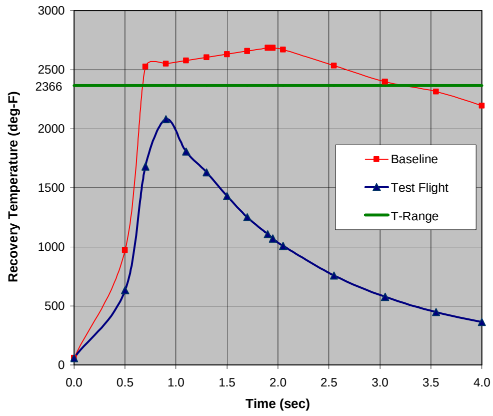

Figure 6. Recovery Temperature Comparisons.

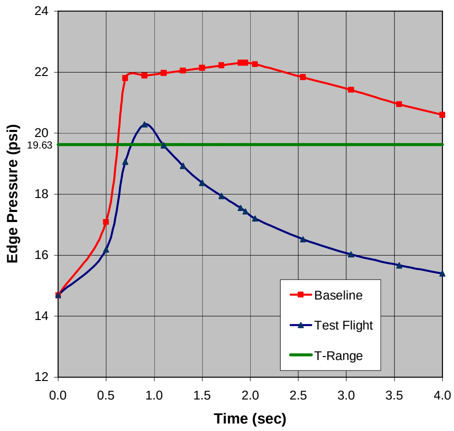

Figure 7. Edge Pressure Comparisons.

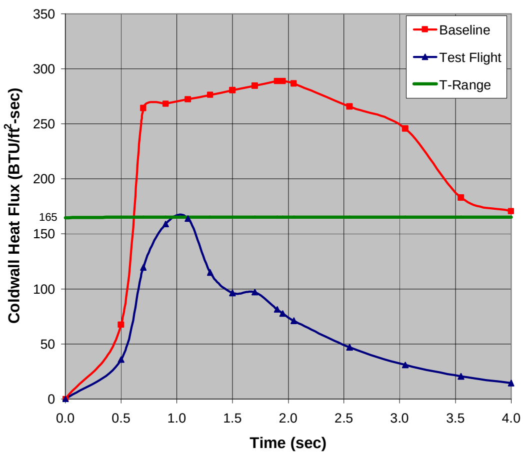

Figure 8. Cold Wall Heat flux Comparisons.

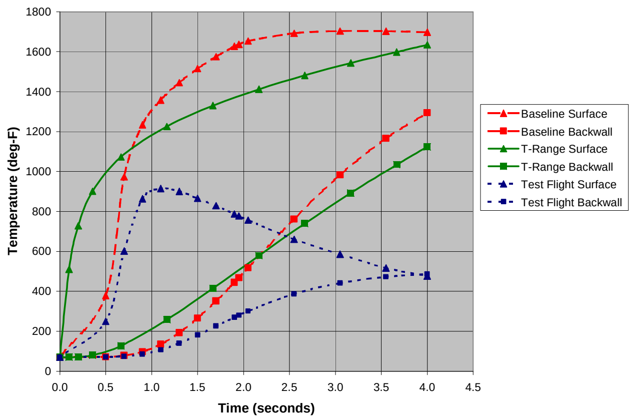

Figure 9. ATAC3D Predicted Dynasil Window Thermal Response Comparisons.

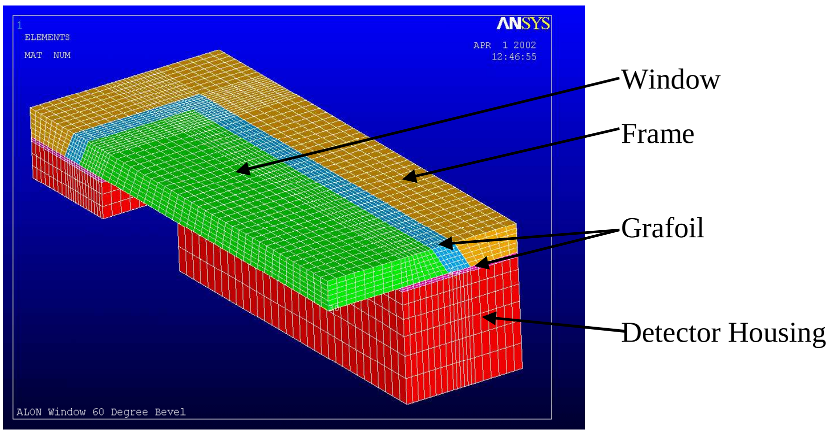

Figure 10. ANSYS Finite Element Analysis Model.

temperature contours are similar for the other window materials with edge temperatures being lower due to attachment conduction. Figure 12 provides the thermal response histories for the sapphire and Dynasil™ windows at the center top and bottom locations of the window section. The thermal response results for Dynasil™ can be compared to the ATAC3D one dimensional thermal response results shown in Figure 9. Very good agreement is achieved verifying the temperature dependent thermal boundary conditions calculated using ATAC3D. As can be seen, the Dynasil™ thermal response reaches 1600°F rapidly and the backside thermal response approaches 1300°F by the end of flight. An example of the resulting stress contours for the Dynasil™ window is provided in Figure 13 with the complete comparison of stress results for the various materials and bevel configurations provided in Table 2. The table contains the tabularized peak temperature and stress response comparison for the three window designs along with a comparison of bevel variation effects. Surface and backside temperature responses are provided for the three materials. As can be seen, larger thermal gradients are experienced for the Dynasil™ compared with those developed in the sapphire and ALON. However, considering the significant impact thermal expansion properties have, the resulting stress levels for the sapphire and ALON far exceed their strength levels and clearly eliminate them for use in this application. The room temperature strength of sapphire is approximately 65.5 ksi, which is relatively high for optical materials. The ALON strength is also relatively high at approximately 54.3 ksi, but less than that of sapphire. These strength values would suggest applicability for the CKEM environment. However, the thermal expansion properties of both sapphire and ALON result in exceedingly high thermal stress levels. The peak stress values for sapphire and ALON are 2 to 5 times greater than the materials' capability. The Dynasil™ peak stress is approximately 2.6 ksi, which is 20 to 25 times less than for the sapphire and ALON designs, and 3 times less than the Dynasil™ structural capability. Based on these, results Dynasil™ provides the only solution and performance to meet the CKEM flight requirements.

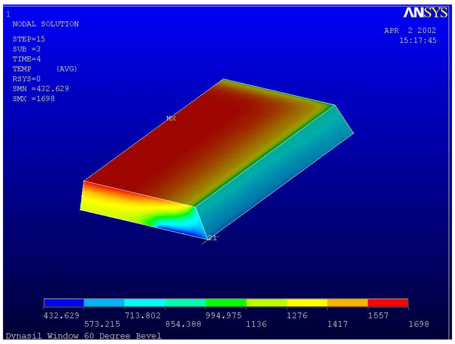

Figure 11. Dynasil Window Peak Thermal Response Contours.

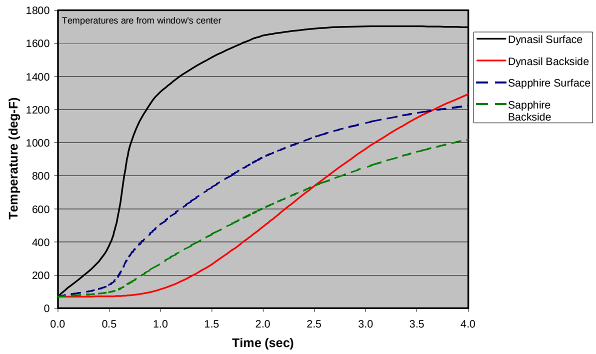

Figure 12. Finite Element Analysis Thermal Response Predictions.

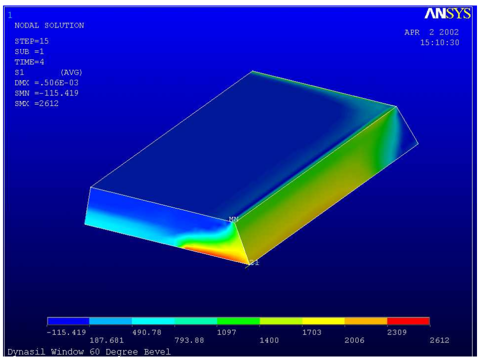

Figure 13. Dynasil Window Peak Stress Prediction.

Table 2. Thermostructural Response Comparison.

		Peak Surface Temperature (°F)	Backside Temperature (°F)	Peak Stress (psi)	Material Strength MOR (psi)	Margin of Safety
45° Bevel	**Sapphire**	**1250**	**1047**	**130525**	**65500**	**-**
	ALON	**1391**	**1093**	**94849**	**54350**	**-**
	Dynasil	**1709**	**1314**	**2620**	**8500**	**+**
60° Bevel	**Sapphire**	**1223**	**1020**	**114959**	**65500**	**-**
	ALON	**1385**	**1088**	**89492**	**54350**	**-**
	Dynasil	**1697**	**1293**	**2642**	**8500**	**+**

Figure 14 provides a comparison of the predicted stress histories for the baseline and actual flight conditions with two T-Range test conditions for Dynasil™. These two test conditions were analyzed to determine the range of capability at T-Range. As can be seen, the stress induced during the higher test condition matches well with the baseline flight peak stress response. Since the design qualification test objective was to meet the actual flight requirements, a successful test condition would be to ensure stress levels exceed the actual flight stress. These two test conditions induce peak stress levels, which clearly exceed the actual flight induced stress. These results provided an indication of the range of conditions possible at T-Range to provide qualification of the CKEM laser window design. It is interesting to note that the actual flight induced peak stress of approximately 1100 psi occurs at approximately 1.2 seconds into the flight. The lower and higher T-Range test conditions reach approximately 1500 and 1200 psi, respectively, in 1.2 seconds. To ensure added robustness in the verification test, a test period of 1.6 seconds was selected, which induced peak stresses between 1250 and 1600 psi, depending on the resulting simulated test condition.

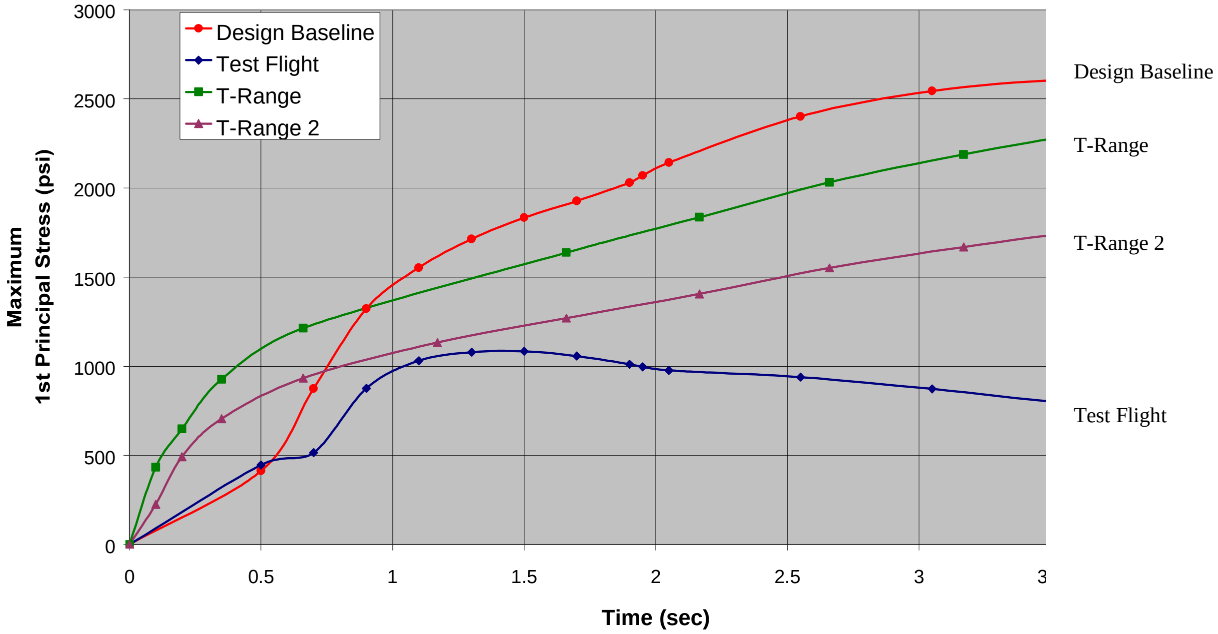

Figure 14. Predicted Baseline, Flight, and T-Range Stress Levels for Dynasil.

3. TEST RESULTS

3.1 T-Range Ground Test

As a result of the analytic conclusions for the window design effort, Dynasil™ was selected for fabrication and qualification testing, and a formal test plan was generated to provide test hardware drawings as well as required instrumentation specifications [6]. A variety of window fabrication houses were contacted and solicited for quotes to fabricate 10 windows having the optical surface finishing necessary to meet the laser receiver requirements. These requirements are less demanding than imaging requirements. The laser window only needs to pass the laser wavelength energy and stringent requirements for accurate imaging in the infrared are not necessary. Meller Optics was selected as the fabrication house for the windows with ground test and flight test hardware integration being conducted by AMRDEC. Shown in Figure 15 is an overview of the T-Range test facility. The previously tested sting can be seen in the background with the injection table in the front view. The nozzle is located to the left of the test sting. Figure 16 provides an aft looking forward view of the test section with the nozzle to the right. The test sting is translated out of the nozzle center for this view. Upon ignition of the burner and stabilized flow conditions, the test sting is translated into the nozzle flow. Real time infrared imagery was obtained of the window during the test to verify thermal response and model validation. The initial week of testing at T-Range involved the determination and verification of the necessary flow conditions to deliver the desired aerothermal heating environment. This effort required iterations on various flow

Figure 15. Overview of T-Range Facility.

Figure 16. T-Range Aft View of Nozzle and Injection Sting.

parameters such as propane flow rate, air flow rate, burner temperatures, and flow meter check out. The desired burner temperature and pressure conditions of 2200°F and 394 psi were achieved inducing worst case thermal environments to the window design. After completion of the facility check out runs, the calorimeter cone was tested to obtain edge pressure and thin skin thermal response for the specific window location. The calorimeter runs were conducted and resulting data compared to the predicted values. Figure 17 provides the measured backside thermal response of the steel thin skin for the calibration tests as compared to the predicted values. A peak temperature of approximately 1100°F was achieved during the 2.7-second test period that fell between the two test conditions considered. Additionally, the

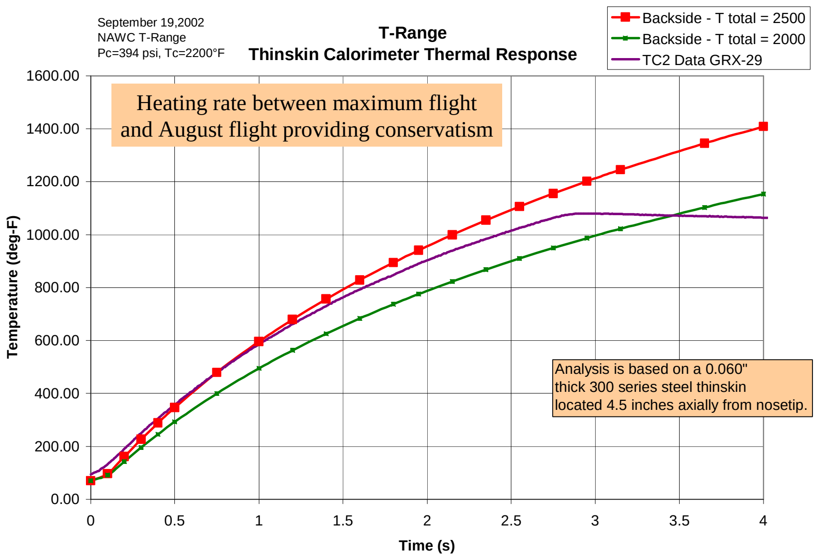

Figure 17. Thin Skin Backside Thermal Response Predictions versus Data.

edge pressure measurements matched the 19-20 psi predictions. These results provided confidence that the flow field and resulting aerothermal environments were accurate and the actual window test could be performed. The laser window test configuration is shown in Figure 18. The Chartek 4 insulation is applied to the steel cone and faired into the window frame to minimize flow disturbances and simulate the actual flight test hardware. The Grafoil™ seal can be seen around the Dynasil window. The posttest view of the laser window and heatshield can be seen in Figure 19. The window design successfully survived the severe aerothermal environment and resulting stress levels.

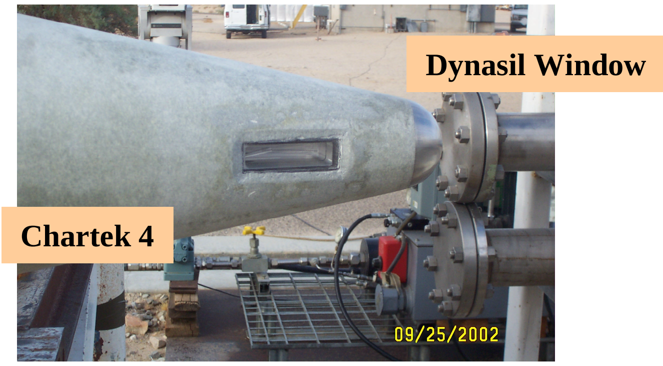

Figure 18. Pretest Cone Configuration.

Figure 19. Posttest Cone Response.

Figure 20 provides the infrared imaging thermal response for the test cone and window. The multiple blocked regions represent areas where thermal response was digitized. A variety of temperatures were collected for the window as well as the heatshield. The multiple window temperature measurements were taken in an attempt to identify possible gradients across the window along the centerline. Figure 21 provides the thermal response history of the window taken from the IR imaging data as compared with predictions. The initial "hump" in thermal response occurs during the injection period of the test. With the instantaneous exposure to conditions, the thermal rise rate is higher than for the actual flight and can be considered a "worst-case" test. The window reaches a peak thermal response of approximately 1200°F in 1.6 seconds. The resulting peak temperatures and thermal gradients for the test exceed the predicted thermal response of 900°F in 1.0 second for the actual flight. The magnitude of thermal response is in more agreement with the baseline peak response of 1500°F at 1.5 seconds and matches well with the predicted 1300°F response for the higher T-Range condition seen in Figure 9. Since thermal expansion is the critical factor in the stress response, the test induced thermal stress exceeds the actual flight stress and is near that achieved during the baseline flight. Based on these measured temperature responses, the laser window design has been successfully validated and verified for the actual flight condition. The design has also been shown to provide additional capability for higher velocity flight.

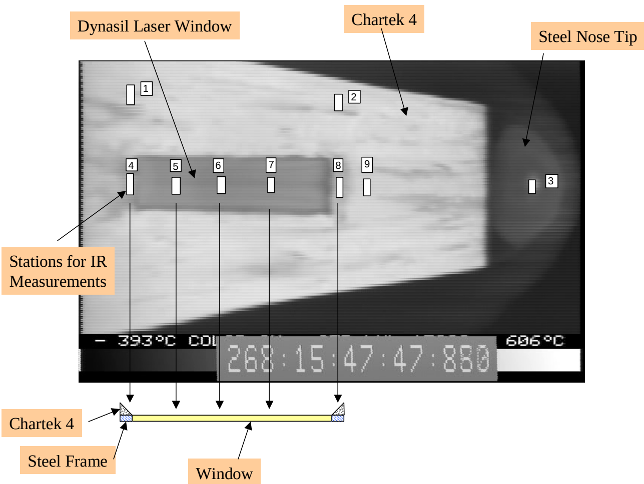

Figure 20. IR Image of Laser Window and Heatshield Near Peak Response.

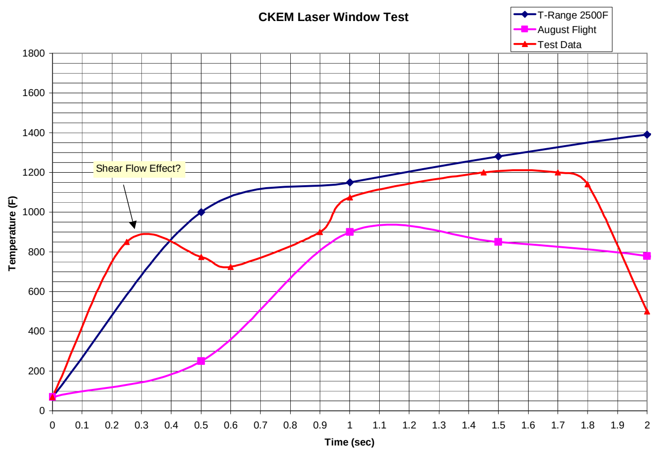

Figure 21. Comparison of Baseline, Flight, and Test Data for Window Thermal Response.

3.2 Flight Test

Figure 22 shows the launch of the CKEM Technology Demonstration Test (TDT) performed at Eglin Air Force Base, Florida in August 2002. The laser widow can be seen on the side of the missile ogive. The same configuration as validated during the ground test program was incorporated into the flight vehicle. The primary purpose of the test was to demonstrate a peak missile velocity in excess of Mach 4 so that a relevant flight environment could be created for the numerous experiments onboard the missile. These experiments included an isolation system for the missile inertial components, operation of the attitude control thrusters, and plume effects on guidance techniques. One

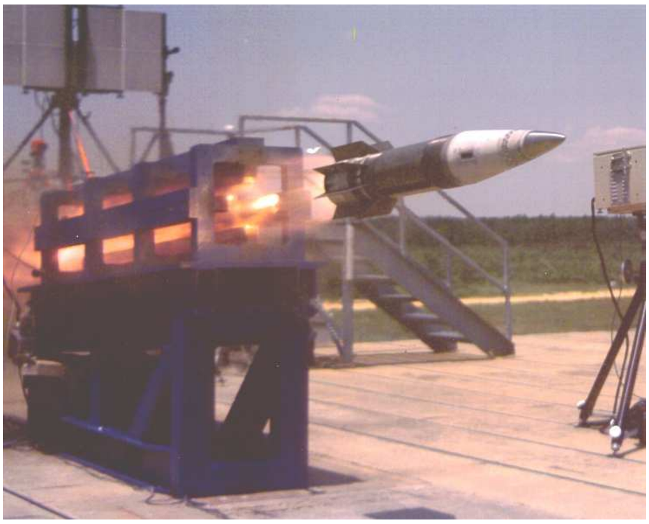

Figure 22. Flight Test of CKEM Laser Window Configuration.

of these guidance techniques was the Side-Scatter Laser Beam Rider (SSBR). Photos of the Side-Scatter Beamrider flight test hardware are shown in Figure 23. Although the guidance concept normally requires the use of four 4 receivers, mounted at 90 degree intervals laterally around the missile, only two were necessary to meet the guidance link test objective of TDT-1 to establish the signal-to-noise margin of the off-axis communication link to the missile during flight.

In Figure 23, one of the two laser widows can be seen on the side of the missile ogive. The same configuration as validated during the ground test program was incorporated into the flight vehicle. Although an early turn by the unguided missile precluded the establishment of launcher-to-missile communication, all photographic evidence and telemetered data indicates the window design functioned successfully. Test configuration refinements, including an extended guidance field to maximize probability of missile intercept, are under consideration for future flight tests including TDT-2

4. CONCLUSIONS

The initial objective of the CKEM laser window design and qualification program was to design and validate a window for use in flight testing to obtain laser receiver data during hypersonic flight. This objective has been successfully achieved and exceeded in that a window design has been developed which can meet the needs for future system enhancements and increased flight velocities. The design and analysis process and resulting analytic models are available for future design efforts, and test hardware is available for additional test and evaluation efforts, if system requirements change. The application of an uncooled optical window for hypersonic sea-level flight represents a unique application, and pushes the state of the art in window design technology.

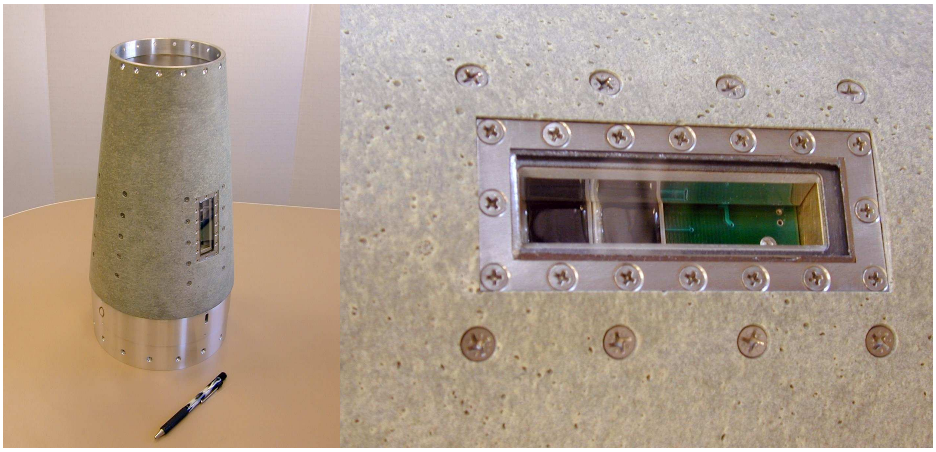

Figure 23. Side-Scatter Beam Rider Flight Hardware.

The analysis and design process utilized for the CKEM Laser Window provides a clear example of the critical processes for ensuring a successful flight system. The thermal analysis and design utilized the following steps:

A. System requirements definition
B. Definition of aerothermal boundary conditions
C. Identification of candidate material technology
D. Coupled thermo-structural analysis and design
E. Ground test for validation and verification
F. Flight test application of flight qualification

These steps ensured an accurate understanding was developed of the relevant aerothermal environment and its resulting effects on the laser window design. Through screening applicable material technologies, the best match was identified prior to funding being devoted to fabrication and flight. Finite element analysis provided insight to specific regions of concern such as thermal expansion and seal technology. Ground test and evaluation provided confidence the window design would survive the flight environment reducing risk to the overall flight system objective. The flight test verified the design and provides a means of identifying other areas of concern for future system enhancements. The existing analytic design model can now be utilized in future upgrades for increased velocity, angle of attack, and flight time.

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