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BLAST INITIATION DETECTOR PROOF-OF-CONCEPT WIND TUNNEL TESTING OF OPTICAL/AEROSHELL INTERFACE

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BLAST INITIATION DETECTOR PROOF-OF-CONCEPT WIND TUNNEL TESTING OF OPTICAL/AEROSHELL INTERFACE

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Abstract

Interceptors with fragmenting warheads that detonate in proximity to target vehicles are being used in missile defense tests. As part of this effort, it is necessary to be able to measure the performance of an interceptor during the endgame and it is preferable that the measurements be recorded independently from the interceptor telemetry. Target-based instrumentation and telemetry are used to provide this independent performance measurement. A Blast Initiation Detector (BID) was developed for use onboard target vehicles to detect the initiation of the blast from the fragmenting warhead. The blast detection provides a target-centric temporal baseline for the final sequence of events during the intercept. The BID uses a circumferential array of six individual optical fibers attached to the surface of the target re-entry vehicle. The distal tip of each optical fiber protrudes beyond the surface of the aeroshell to provide the required optical field-of-view. Testing was used to address concerns of possible optical tip damage that could be induced by aerothermal loads. The optical fiber/aeroshell interface design of the BID was proven out by performing wind tunnel testing in a simulated aerothermal environment at the Avery Advanced Technology Development Laboratory by using two toggling laser beams at differing angles of incidence to simulate the blasts. The exposed distal tip of the optical fiber reached 1200°F during the worst aerothermal heating. The measured optical signals from the fibers indicated no significant degradation of performance and provided a proof-of-concept for the design of the optical/aeroshell interface of the BID.

Introduction

The Blast Initiation Detector (BID) is a target-based instrument that detects the optical signal from the warhead blast and provides a target-centric temporal baseline for the final sequence of events during missile intercept tests. This information, when used in conjunction with data from other instruments that are used to detect fragment impacts on the target vehicle, can be used to quantify the standoff distance at the time when the warhead exploded. The detection of the blast in the target data stream can also provide a temporal reference point for associating telemetry data from other sources, including the interceptor and the range.

The BID is comprised of a symmetrical arrangement of six multi-stranded borosilicate glass optical fibers that view the space surrounding the target vehicle and deliver the optical signals to a central electronics package. The large numerical aperture (NA=0.66) of the fiber material provides a wide field-of-view to ensure that all statistically likely blast locations will be detected by at least one fiber. The optical signals from the blast are coupled into high-speed photodiode amplifiers that register the blast initiation time into the telemetry stream. BID timing analysis indicates that the expected response time or latency of the BID will be less than 10 microseconds[1].

The BIDs consist of an AC-coupled electronics module with six optical fiber inputs. A block diagram is shown in Figure 1. The optical fiber/aeroshell interface design was known at the outset to be the area of highest risk for the system design since the application requires the exposed fiber distal tips to survive the flight re-entry environment with preservation of the optical field-of-view and throughput until the time of intercept. A drawing of the final optical fiber assembly is shown in Figure 2. Based on thermal and field-of-view requirements, borosilicate glass was chosen as the fiber material. A high temperature epoxy (RESBOND 950) based on high purity ceramic binders and aluminum powder was used to bond the glass fibers into the stainless steel connectors. Each fiber consists of eight parallel 50 micron diameter strands as shown in the expanded cross-sectional view in Figure 2. A stainless steel spiral wound outer sheath protects the fibers during handling.

The BID system is installed in the forward section of the target vehicle as a compromise between field-of-view and heating environment considerations. The distal tips of the optical fibers protrude through the aeroshell at six equally spaced circumferential locations to provide complete coverage. These locations imposed tight bend radius requirements on the fiber to prevent interference from other components of the target vehicle. Using eight individual smaller diameter fibers in lieu of one larger fiber reduced the minimum bend radius to approximately one inch. Based on a trade-off between field-of-view and bend radius concerns, the fibers were installed such that each fiber axis made a 45 degree angle with the axis of the target vehicle. For unrestricted field-of-view, it was found to be necessary for the distal tip of the optical fiber to protrude approximately 0.017 inches above the surface of the vehicle, Figure 3. There were concerns about excessive temperature augmentation at the protruding tip.

Proof-of-Concept Testing

Wind tunnel testing was used to address the concerns about high temperatures on the exposed fiber tip. The test hardware was fabricated to simulate the BID optical/aeroshell environment upon re-entry. The circular plate in Figure 4 shows the instrumented portion of the wind tunnel test hardware and is representative of a small section of the aft bulkhead of the Forward Section of the Target Vehicle. The materials and construction geometry were duplicates of the actual flight hardware. The test fixture was instrumented as shown in Figure 4 and installed into Cell 4 of the wind tunnel test facility at the Avery Advanced Technology Development Laboratory. During the tests, two laser beams were toggled onto the optical fiber at two differing angles of incidence, approximately 25° and 35° off-axis. Temperatures, pressure, qualitative infrared thermal images, Schlerien images, and relative optical throughput were recorded during four tests. The Schlerien images revealed the shock structure at the BID fiber distal tip protrusion. The infrared images showed the basic heating trend of the test fixture. The other data are discussed below.

Test 1

The first wind tunnel test (IRS1116) occurred 10 February 2000. The total pressure was 488 PSIA and the total temperature was 1406°R. This first test was the basic proof-of-concept test that validated the design of the fiber/aeroshell interface. The optical fiber tip protruded into the boundary layer 0.014 inches. The data plot is shown in Figure 5. The skin temperatures approached 800°F gradually during the three-minute exposure. The optical throughput remained relatively unchanged as indicated by the BID optical signal. The upper optical signal on the plot corresponds to the 35 degree off-axis laser and the lower optical signal corresponds to the 25 degree angle. The slight variation in throughput noted on the upper optical signal was due to the smaller spot size and the normal vibration of the wind tunnel and was not due to the degradation of the fiber. It is significant to note that the temperature of the protruding distal tip was only a few degrees higher than the hottest skin temperature. There was very little temperature augmentation on the protruding tip.

Test 2

During the second test (IRS1117), the protruding tip was extended from 0.014 to 0.018 inches normal from the surface of the plate. The increased protrusion was selected to afford some tolerance for thermally induced expansion and contraction of target vehicle components while preserving field-of-view. The same optical fiber was reused from the first test. The tunnel conditions were more severe than the first test and an attempt was made to thermally shock the protruding fiber similar to what would be expected on re-entry. The total pressure was 444 PSIA and the total temperature was initially 2654°R. As seen in the data plot of Figure 6, the distal tip temperature exceeded 1200°F for a few seconds. Then as the tunnel conditions were relaxed (total pressure of 479 PSIA and total temperature of 1296°R) the surfaces cooled and then reheated gradually approaching 800°F. Again the optical throughput was preserved for the full three-minute exposure. However, the increased protrusion distance was evidenced by the temperature augmentation of the tip relative to the skin. In this test, the tip peaked as much as 200°F warmer than the skin and ended up approximately 50°F warmer for the duration of the test. Also the shock structure at the protruding tip was easily visible within the Schlerien images.

Test 3

The thermal conditions were substantially worsened during the third test. The laser on-times were reduced from five seconds down to three seconds to ensure that data were acquired for at least several transitions under the more severe conditions. The same optical fiber was again used. The intent on this test was to induce optical failure of the fiber. The total pressure of the tunnel was 282 PSIA and the total temperature was 2576°R. The data plot is shown in Figure 7. The optical fiber throughput was lost approximately 50 seconds into the test. This was followed by a gradual ramping of the baseline optical signal for about 20 seconds until the wind tunnel conditions were relaxed. The measured protruding tip temperature was actually lower than measured skin temperatures during this test and this was attributed to non-symmetrical heating profiles within the tunnel under the stated run conditions. Subsequent inspection of the test fixture revealed that the sudden loss of optical throughput was due to the melting of solder that was used to bond thermocouple TC05 to the test fixture. The solder melting temperature was 1105°F, consistent with temperatures recorded on the test fixture skin surface. A track of ablated material was seen from the location of thermocouple TC05 to the protruding tip of the optical fiber and melted metal residue was evident on the fiber tip. The slow ramping signal measured after the abrupt loss of optical throughput was attributed to the glowing molten material on the fiber tip. This signal quickly vanished when the tunnel conditions were relaxed to cool down. When the molten material was removed from the distal tip after the test, the intact ends of the glass fiber strands could still be clearly seen under a microscope.

Test 4

The fiber manufacturer had experienced great difficulty in reliably reproducing the fibers with the high temperature epoxy used in the fiber from Tests 1 through 3. In production, many fibers were fracturing during the polishing process. To increase yield, a small amount of low temperature epoxy was added to the spaces between the 50 micron fiber strands and the surrounding epoxy was still all high temperature material. There were concerns that the addition of the low temperature epoxy would compromise the thermal survivability of the fiber tips. These concerns were validated in Test 4.

Test 4 was a repeat of Test 3 to optical failure with a fiber that used a small amount of the lower temperature epoxy. A review of the data shown in Figure 8 indicated that the optical throughput was lost within about 20 seconds. This was followed by a gradual exponential rising of the background optical signal (when the laser was off) and an erratic laser optical signal for the next 105 seconds. This was followed by immediate loss of background optical signal on transition to tunnel cool-down with optical throughput approximately 1/10 the original. Subsequent disassembly of the distal tip showed that the glass in the tip had melted. The exponentially rising background was attributed to the glowing/burning tip. The main conclusion from Test 4 was that no low temperature materials could be tolerated in the optical fiber distal tip.

After these test results were interpreted, APL went back to the fiber manufacturer and jointly solved the production yield problem by the following process changes:

(1) Use of only high temperature epoxy, but with a reduced aluminum particle size to improve fiber-to-fiber interstitial bonding;
(2) Use of a syringe rather than an open mixing pot to hold mixed epoxy and increase pot life;
(3) Use of a hand pick to push epoxy into the fiber-to-fiber interstices; and
(4) Use of a grinding/polishing process with reduced particle sizes on the polishing apparatus to reduce fiber jarring and fracturing.

The final production fibers were identical to those used during Tests 1 through 3, except for the manufacturing process changes noted above.

Conclusions

The wind tunnel tests were performed to guide the design process and to prove out the concept for the optical fiber/aeroshell interface. Test data indicate the temperatures experienced by the protruding distal tip are not significantly higher than the aeroshell skin temperatures and within the thermal survivability envelope of the materials used.

Based on data from Test 4, it was recognized that even small amounts of low temperature epoxy in the distal tip of the optical fibers greatly impaired performance. Based on data from Tests 1 through 3, the optical fiber/aeroshell interface that was designed for the Blast Initiation Detectors was shown to withstand the simulated thermal environment of re-entry for the required performance duration with little or no thermally induced loss of optical throughput or field-of-view.

Acknowledgments

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aeroshell thermal predictions, M. J. Neuenhoff for the Cell 4 support and the many others involved with the JHU/APL Blast Initiation Detector development effort.

References

1. Gauthier, L. R. Jr*., and Klimek, J. M., "Blast Initiation Detector for Target Vehicles," 2000 National Fire Control Symposium, Orlando, FL., August 2000

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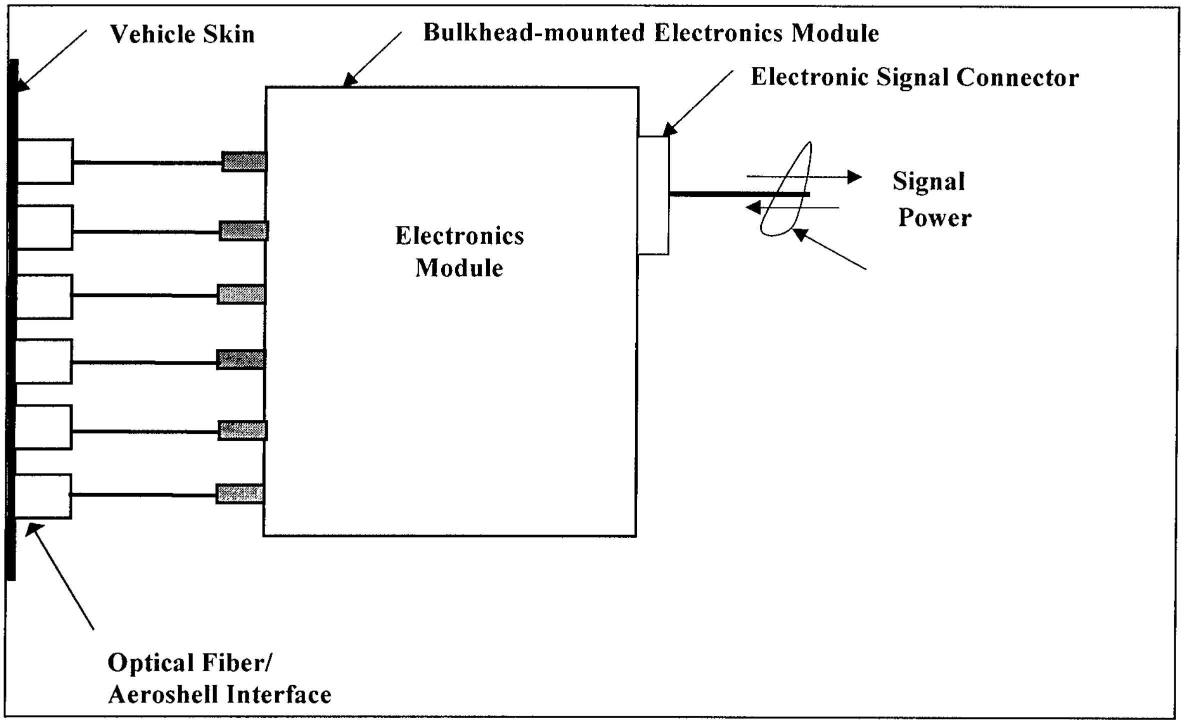

Figure 1 - Block Diagram of Blast Initiation Detector

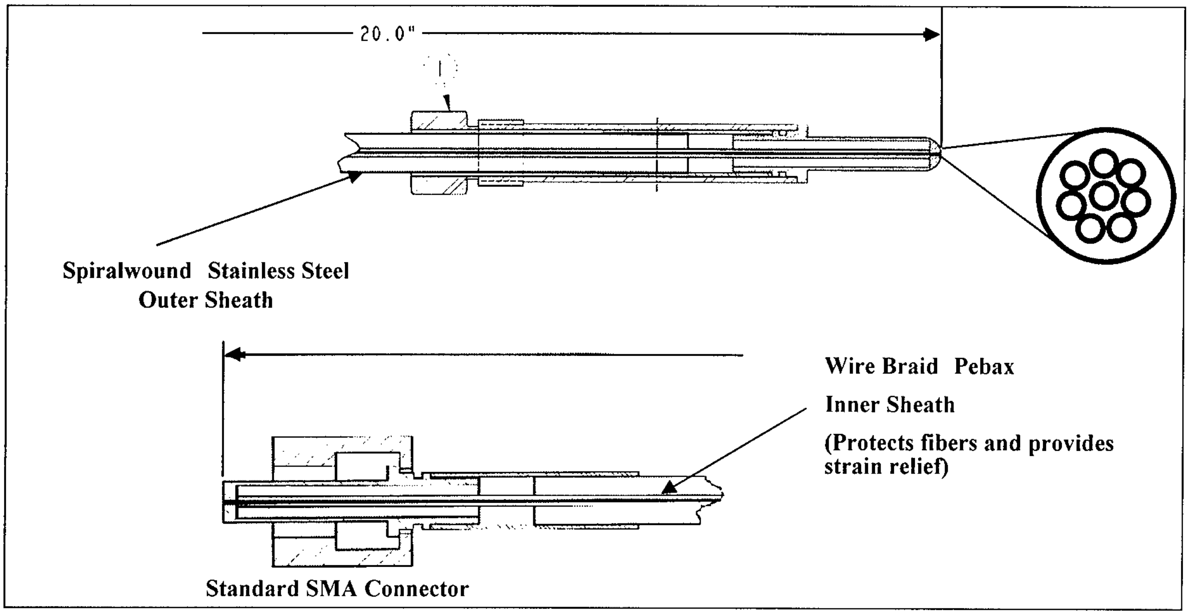

Figure 2 - Optical Fiber Assembly

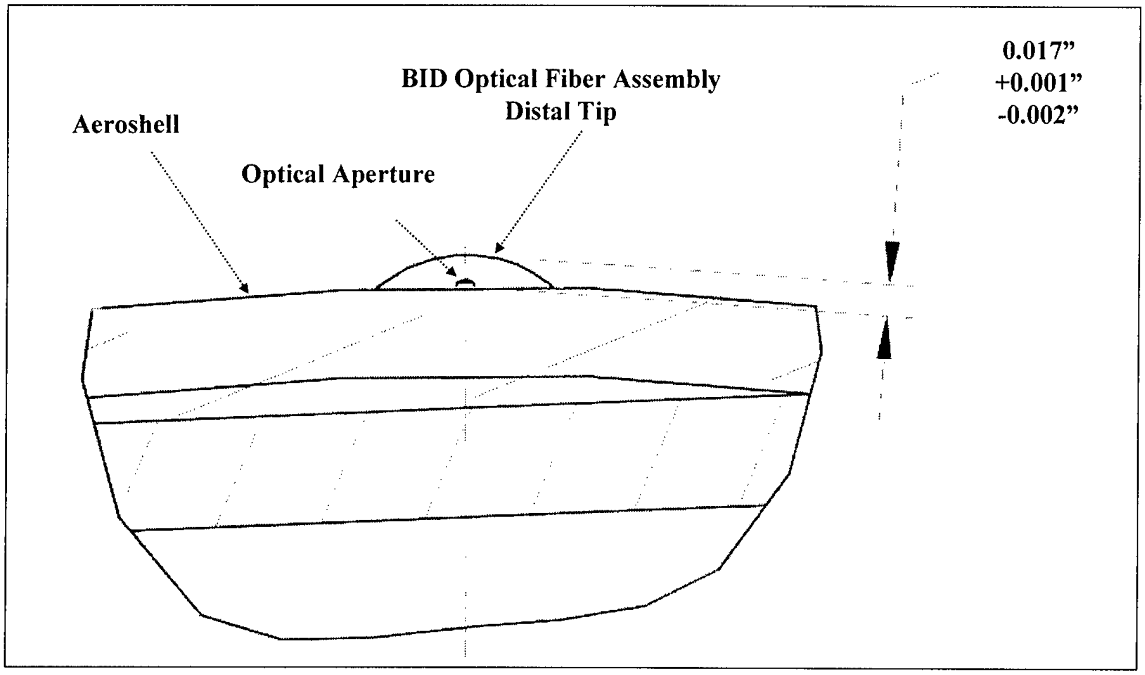

Figure 3 View Looking Aft Along Side of Target (1 of 6)

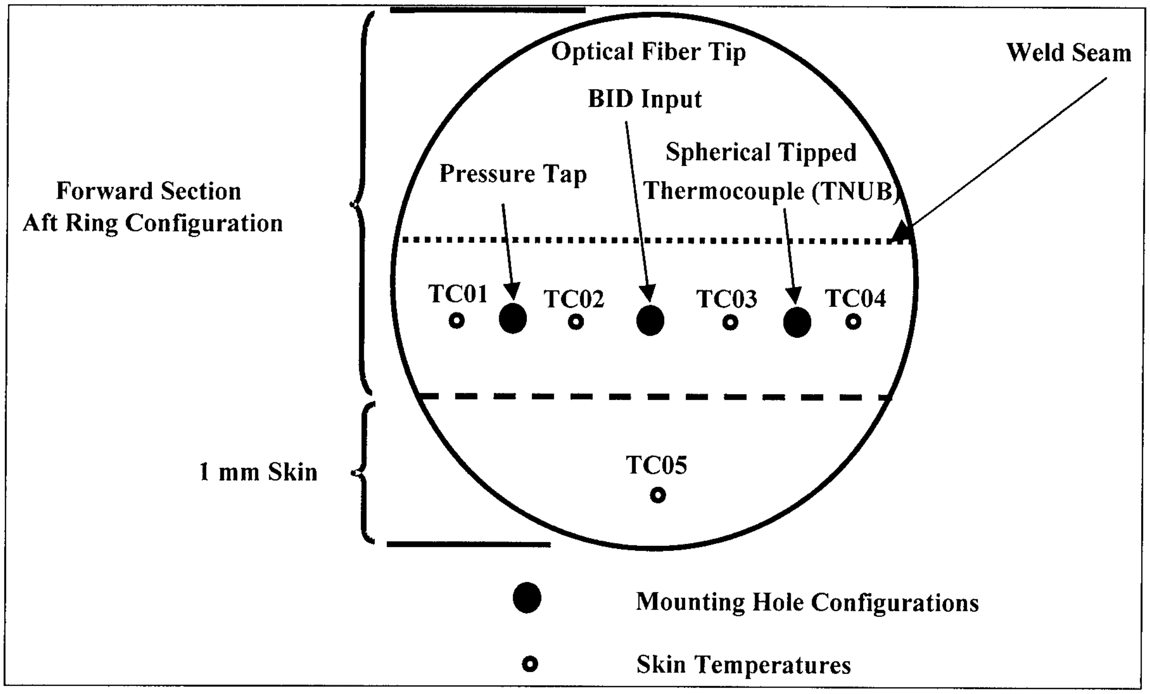

Figure 4 Instrumentation for Wind Tunnel Testing of BID

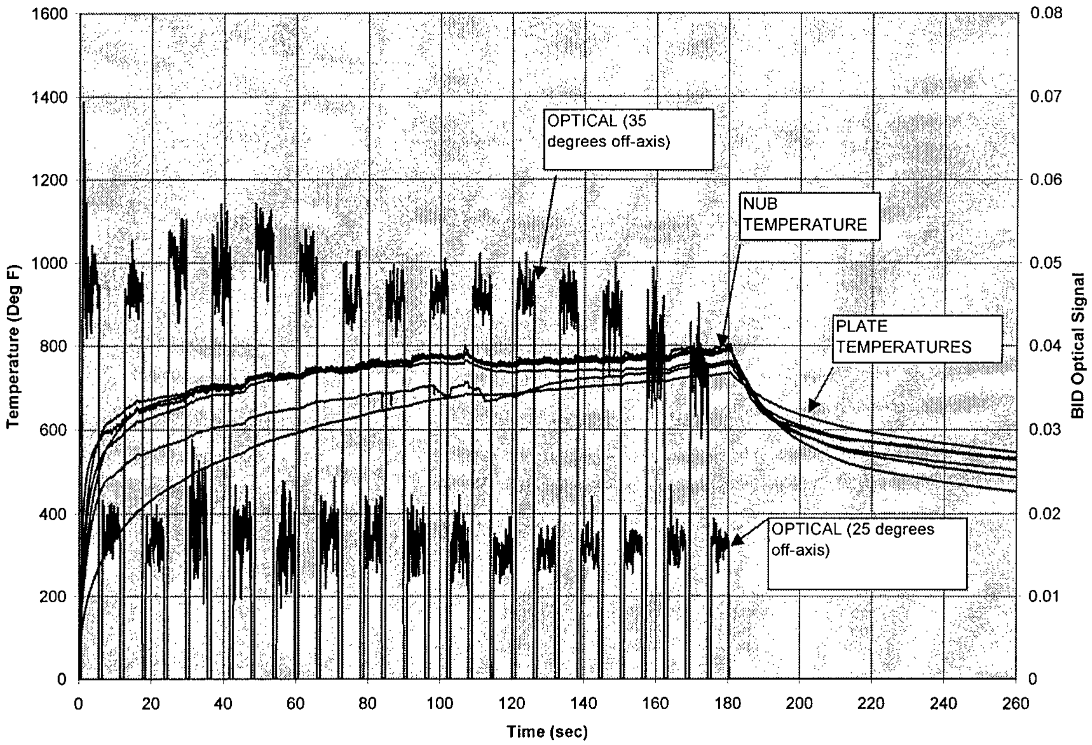

Figure 5 Test 1 (IRS1116) Data Plot

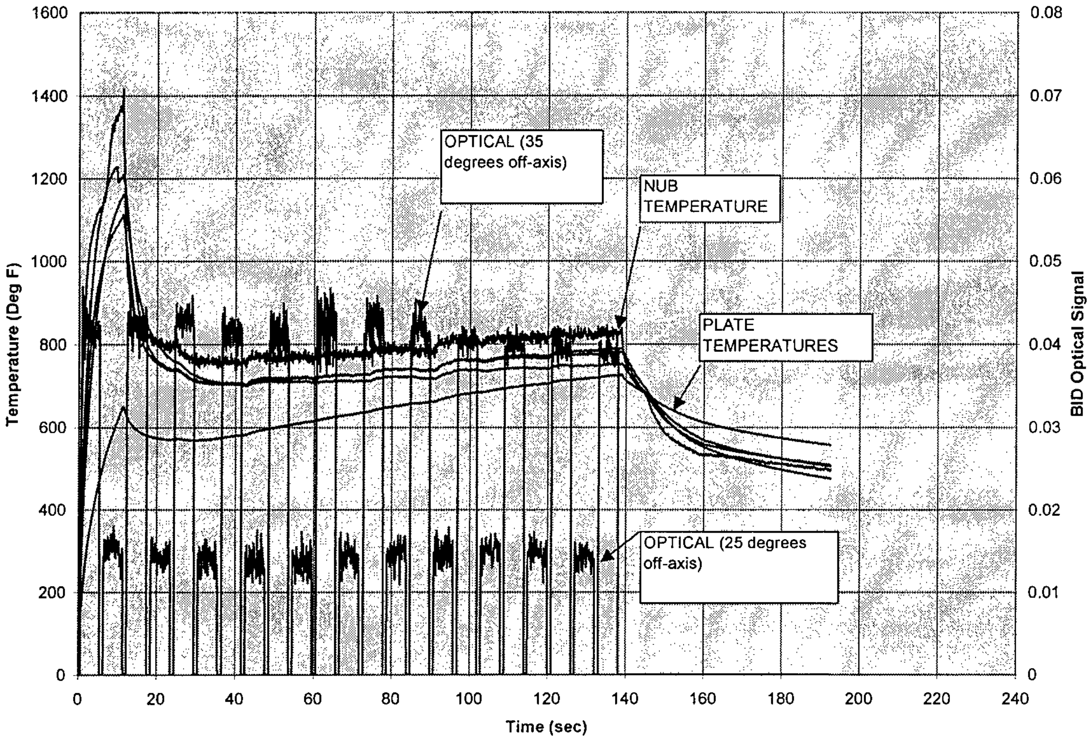

Figure 6 Test 2 (IRS1117) Data Plot

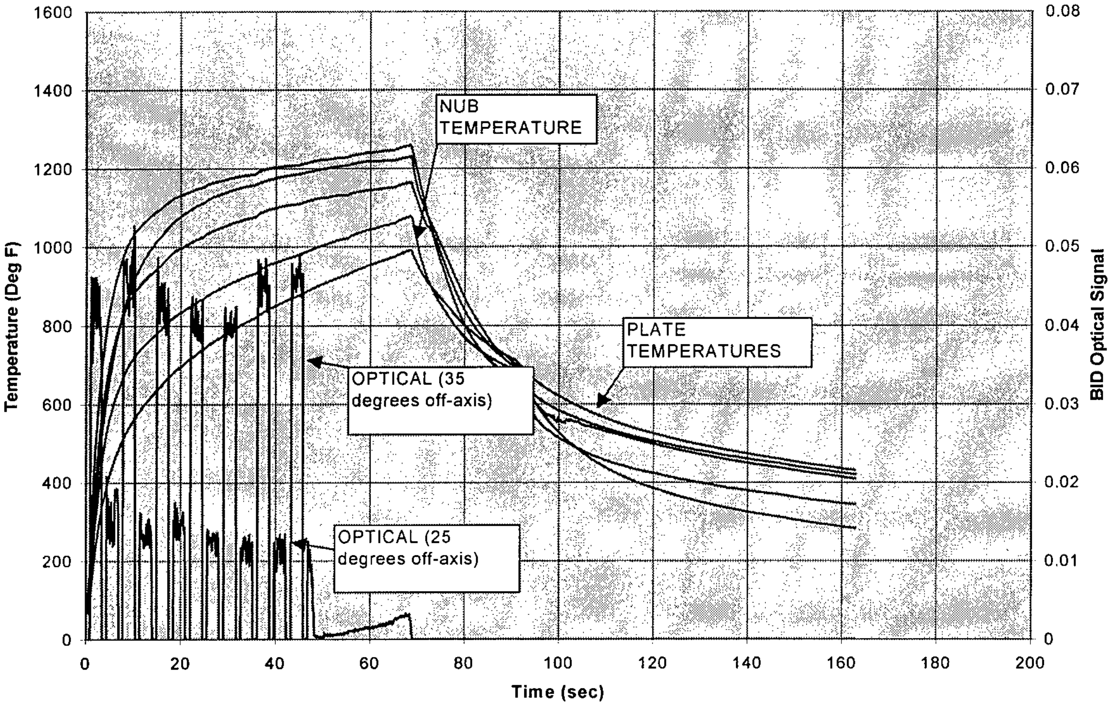

Figure 7 Test 3 (IRS1118) Data Plot

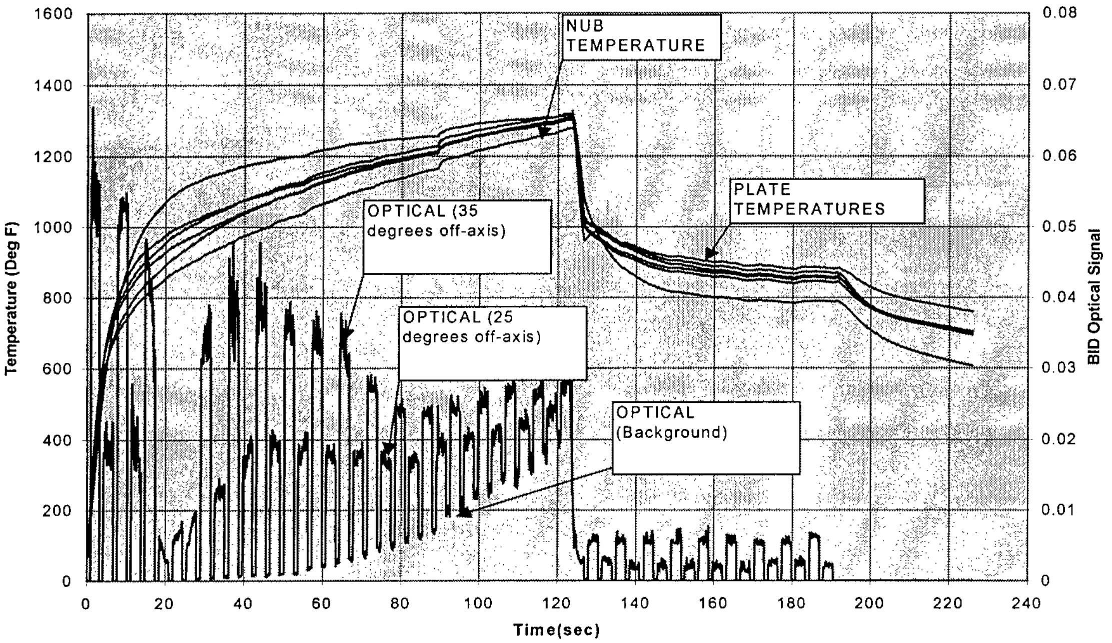

Figure 8 Test 4 (IRS1119) Data Plot

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