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X-Jet Ultrasonic Ablation Thickness Profile Gauging Instrumentation Design, Testing and Analysis

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Abstract

The objective of this project was to develop a test fixture for the X-Jet facility to measure recession of a Teflon coupon ablator using ultrasonic transducer technology. The current paper will present the mechanical design, testing and analysis of the X-Jet ultrasonic ablation thickness profile gauging test apparatus from its conceptual design to final hardware manufacturing and testing. The related acquisition and analysis software developed will also be presented. The necessary data acquisition system was developed in LabView to interface with the hardware and record data in real-time. Additional software was developed to process the signal and reduce a recession measurement to within 0.1 mm accuracy. The design work resulted in the development of a test fixture fully instrumented able to structurally support the test specimen, Integrate the test article with the pulser receiver and thermally protect the transducer and data acquisition cabling. The design requirements included Technician user friendliness. The system also allows for the Teflon coupon to be appropriately centered and oriented with respect to the torch flame. The main design constraint was that the apparatus fits within the volume boundaries of the X-Jet chamber and interfaces with its flange. The analysis and test results will be presented in detail in the paper.

Introduction

One of the most critical areas of space travel currently under research at NASA is in the Entry, Descent and Landing (EDL) portion of the spacecraft’s journey. The entry phase is especially dangerous because it entails withstanding the incredible heating which results from the high velocity compressed air that surrounds the spacecraft as it decelerates through the atmosphere. Because of these constraints, the structural goal of every spacecraft is to protect the payload during EDL and successfully land the spacecraft on the surface of the planet. The two main contributing factors to a successful design of a spacecraft’s exterior are the shape of the craft and the materials that it is made of, which go hand-in-hand and are essential components of a good design. The external structure of the spacecraft must be designed in a way that allows for maximum slowing of the spacecraft during entry, optimal heat protection, as well as the necessary aerodynamic controls for a safe landing. Likewise, as the shape of the spacecraft deflects the flow, the thermal protection system (TPS) must absorb or reflect the heat and act as the primary system responsible for maintaining an appropriate environment within the spacecraft.

While thorough design and test of various spacecraft shapes and materials is vital to the advancement of this field, it is very difficult for atmospheric entry conditions to be emulated on the ground. One of the premier facilities for testing atmospheric entry component is the Arc Jet facility at NASA Ames Research Center. In the Arc Jet, air is heated, expanded, passed through a nozzle and over the model, and the stream can obtain speeds upwards of 100,000 miles per hour and heat fluxes over 6000 kW/m^2. At present, the Arc Jet facility at ARC utilizes Teflon “coupons” in order to validate the air flow and calibrate the facility. Since Teflon ablates at high temperatures, the surface profiles of the test coupons provide an excellent indication of the flow quality.

Additionally, the ablative properties of Teflon are significant in TPS testing because ablative materials are currently being researched for used in entry vehicle heat shields. Thus Teflon is an important material in the development of TPS systems, and therefore the ability to quickly and accurately test Teflon under entry conditions is essential to the development of the space transportation and exploration industry.

The X-Jet chamber at NASA Ames is a laboratory-scale apparatus that is designed to mimic low pressure, high entropy atmospheric entry conditions. It is used for aerothermal testing of instrumentation that is integrated into various thermal protection systems, such as vehicle nose sections and high temperature surface insulation materials. The X-Jet operates in a low pressure environment and utilizes a flowing gas moving past an electrical arc to generate convective heat flux. In this regard, it is similar to an arc jet facility. The X-Jet chamber is essentially comprised of a plasma torch mounted inside a vacuum chamber, and is capable of generating cold-wall absorbed heat fluxes above 130 W/cm^2. The X-Jet has provides useful data regarding the design of new thermal sensor’s performance when exposed to plasma flows, and continues to aid in the improvement of TPS sensor integration performance.

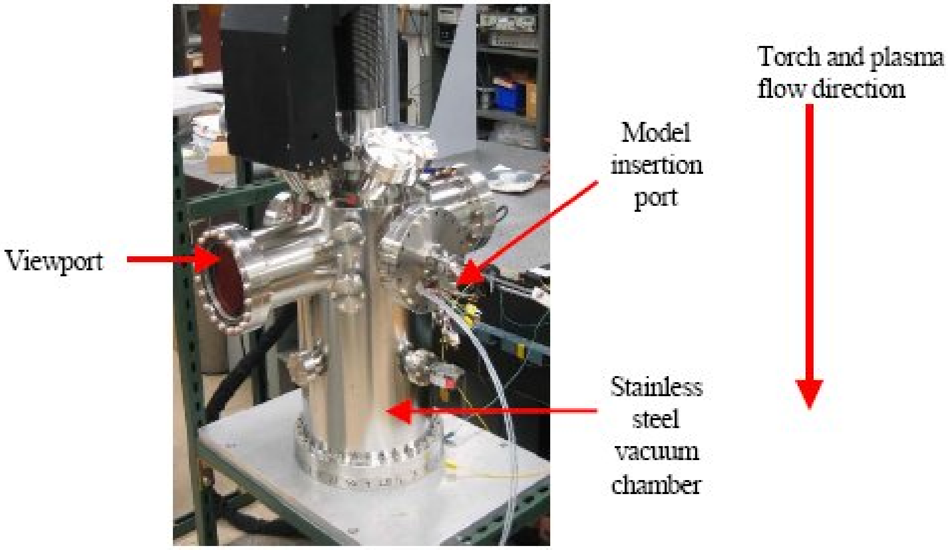


Figure 1 Photograph of the X-Jet test chamber at NASA Ames

Problem Statement

At present, the ablation testing and analysis of Teflon is a lengthy process and does not produce any real-time results. The Teflon and testing instrumentation must undergo a cool-down period before the test coupons may be accessed for analysis. Additionally, ablative tests of Teflon only provide data at one point in time – after the coupon has cooled post-test. These issues are major stumbling blocks in the advancement of TPS testing. A system that delivered real-time ablative data from Teflon coupons undergoing testing would be ideal.

Objective statement

Our overall objective was to design, build, test, and calibrate an independent system that can remotely monitor, report, and record thickness measurements in real time from a Teflon coupon undergoing ablation in the X-Jet chamber in real time. Our accuracy goal for this project was ±.1 mm.

Significance

Although data from X-Jet tests is not used directly in life-size TPS design, it provides very useful information about instrumentation and integration. In the case of Teflon, the X-Jet can provide excellent information regarding the ablative process, which can directly relate to other ablative materials. By monitoring the thickness of Teflon during testing, we can better understand the ablative process throughout the test phase, not just at

Approach

Our design philosophy for this project was to split the responsibilities for achieving the objective into three separate systems: the data handling system, the mechanical system, and the data analysis system. The data handling system was designated the task of generating and receiving the thickness measurement signals, transforming these signals into thickness measurements, and logging the raw and processed data. The mechanical system is responsible for the physical test apparatus, specifically the interface between the data handling system electronics and the X-Jet chamber. It supports the Teflon coupon, and protects the test instruments of the data handling system from the harsh X-Jet test conditions. It is also tasked with accurately and precisely traversing the coupon test assembly from a stowed test position (away from the plasma flame) to the test position, centered directly under the plasma flame. The data analysis system was responsible for data cleanup of the raw data collected by the data handling system and extracting quality, useful information from the test data.

Along with meeting our overall objectives, our system had to be designed within the limits of several constraints, most of which were derived from the operating conditions of the X-Jet chamber. Every component of the design that was to be inserted into the chamber for testing needed to be able to withstand the environmental conditions of the test (approximately 110 degrees C and 0.04 atm), as well as fit inside the physical boundaries of the chamber.

To refine our original design, we performed a series of tests in order to confirm the individual systems' compatibility with one another, to examine the overall system functionality, and for calibration. We adhered to an iterative design process, and made minor adjustments to our design following the results of each test. No major or universal changes were made to the overall original design.

Final design

The block diagram for the final design is illustrated in Figure . The setup includes the Teflon coupon, low frequency transducer, pulser-receiver, digital oscilloscope, and a computer with LabVIEW installed.

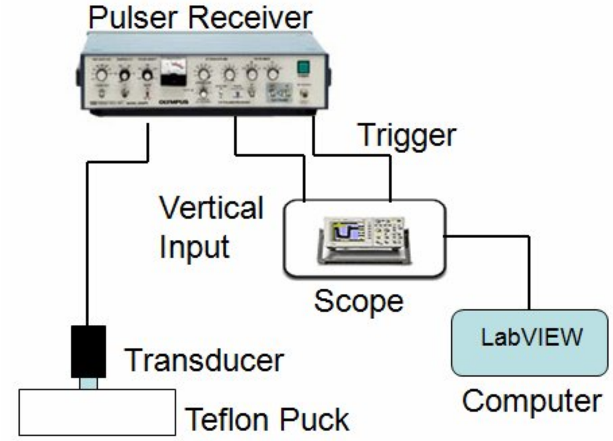


Figure 2 Preliminary Experimental Setup

Ultrasonic Transducer

The signal generation and collection system utilizes a single-element Olympus A103S-RB transducer, which produces ultrasonic signals at a frequency of 1 MHz and has an element diameter of 0.50”. It is classified as a contact transducer, which means it requires a sufficient amount of downward pressure in order to properly engage the test object, and it connects to the pulsar-receiver via a standard BNC cable. The size of the element is crucial to accurately resolving the recession area on the top surface of the coupon, since the recession area is localized. By using a transducer with a smaller element diameter, you are less likely to have a major portion of the signal interact with the recession area, and thus not a significant portion of the signal will be reflected back to the transducer for thickness readings. The 0.50” element diameter of the A103S-RB transducer, as well as the relatively low output frequency, solved this issue.

The responsibility of the signal generation and collection system is to both send and receive ultrasonic pulses in the Teflon coupon. The diameter of the plasma flame in the X-Jet is smaller than the diameter of the coupon. As a result, when the coupon is inserted into the chamber during a test, the jet creates a dimple in the top surface of the coupon, instead of a uniform ablation profile. As a result of the dimple, the transducer must be almost perfectly aligned with the center of recession. This can be easily achieved by centrally mounting the transducer on the bottom surface of the coupon, and using a permanent marker to indicate the center of the coupon on the top surface. Prior to testing, the Z-axis feed through on the Conflat flange assembly must be calibrated so that the “in” position aligns perfectly with the center mark on the coupon.

Olympus 5072PR Pulser/Receiver

The Olympus 5072PR is designed for low noise receiver response and high performance pulser control. When taking the thickness measurement, the pulser sends an electrical pulse to trigger the transducer, which converts the electrical input to mechanical energy (a vibrating piezoelectric crystal) creating ultrasonic waves. The ultrasonic wave travels through the material, and is reflected back to the transducer when it reaches the opposite surface of the material. The transducer then reverse-converts the waves back to electrical signals, and the pulser/receiver section receives the reflected signal and outputs the radio frequency (RF) to the oscilloscope for further analysis. When testing the measurement with the relatively thick Coupon, the pulser-receiver can be used to amplify the signal.

Tektronix 420A Oscilloscope

The Tektronix TDS 420A digitizing oscilloscope is used to acquire the signal from the pulser/receiver and send the acquired signal to LabVIEW. When acquiring the signal from the pulser-receiver, the digital oscilloscope converts the input signal from the pulser-receiver into digital data in the form of a series of numerical representation of the voltage level at regular time interval. Figure 2 **Acquisition: Input signal, sample, and**

digitizshown below illustrates an example of how the input signal is sampled and stored along with its corresponding timing information.

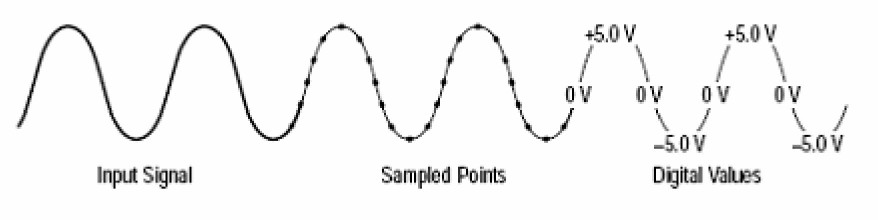


Figure 2 Acquisition: Input signal, sample, and digitization

To increase the accuracy and stabilize the input signal, we took 2500 samples of data during testing. The number of sample the oscilloscope takes may be larger than the actual recorded samples that the user defined. The digitizer uses the extra samples to perform the additional processing of averaging to stabilize the signal. This process helps to decrease the noise in the signal.

LabVIEW VI

LabVIEW was used to acquire, analyze, and display the signal from the oscilloscope. There are two ways to analyze the signal. One is to implement an algorithm into LabVIEW, using either Mathscript or series of sub-routines, to automatically compute the thickness as a function of time. The second method is to use LabVIEW to export the acquired data into a readable format, such as Comma Separated Value (CSV), and then use Microsoft Excel to analyze the data. In this project, the first method is used to acquire and analyze the signal. Figure 3 **Block diagram of LabVIEW signal processing vi**shown below illustrate the steps of acquiring and processing data in LabVIEW VI.

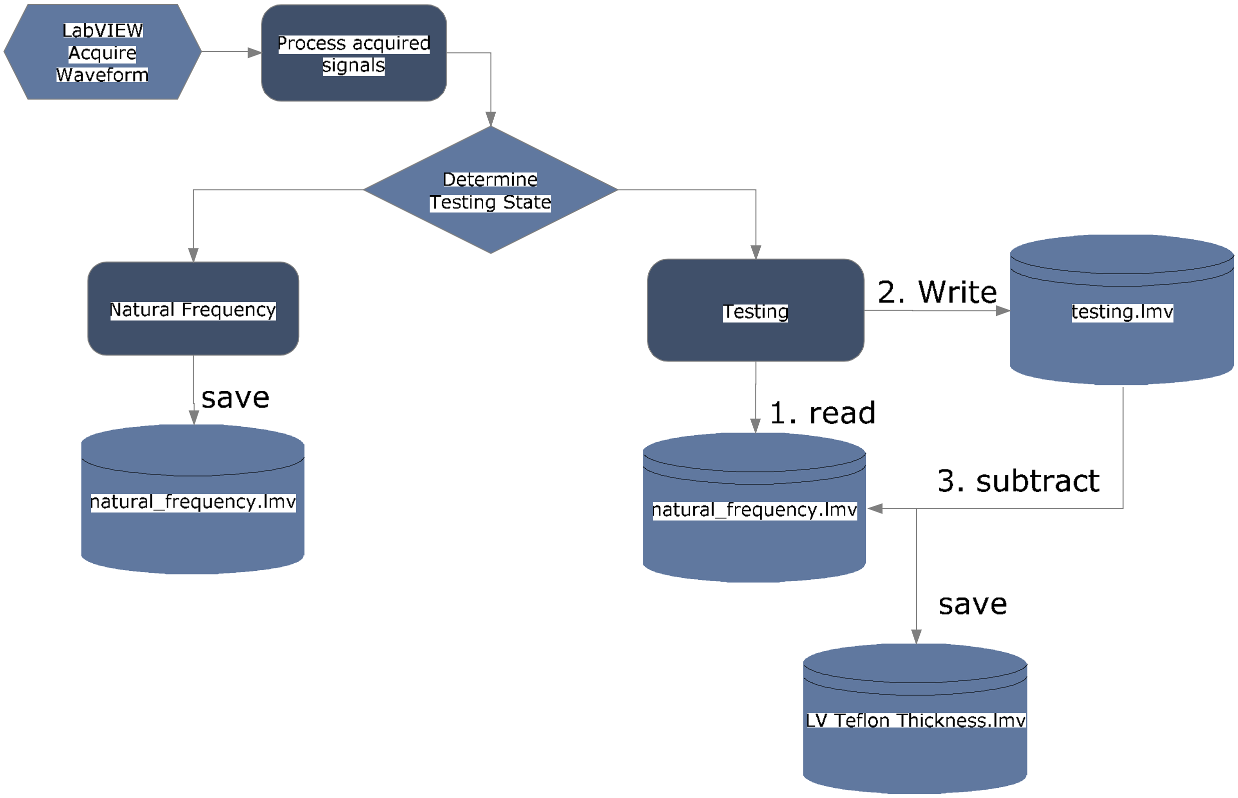
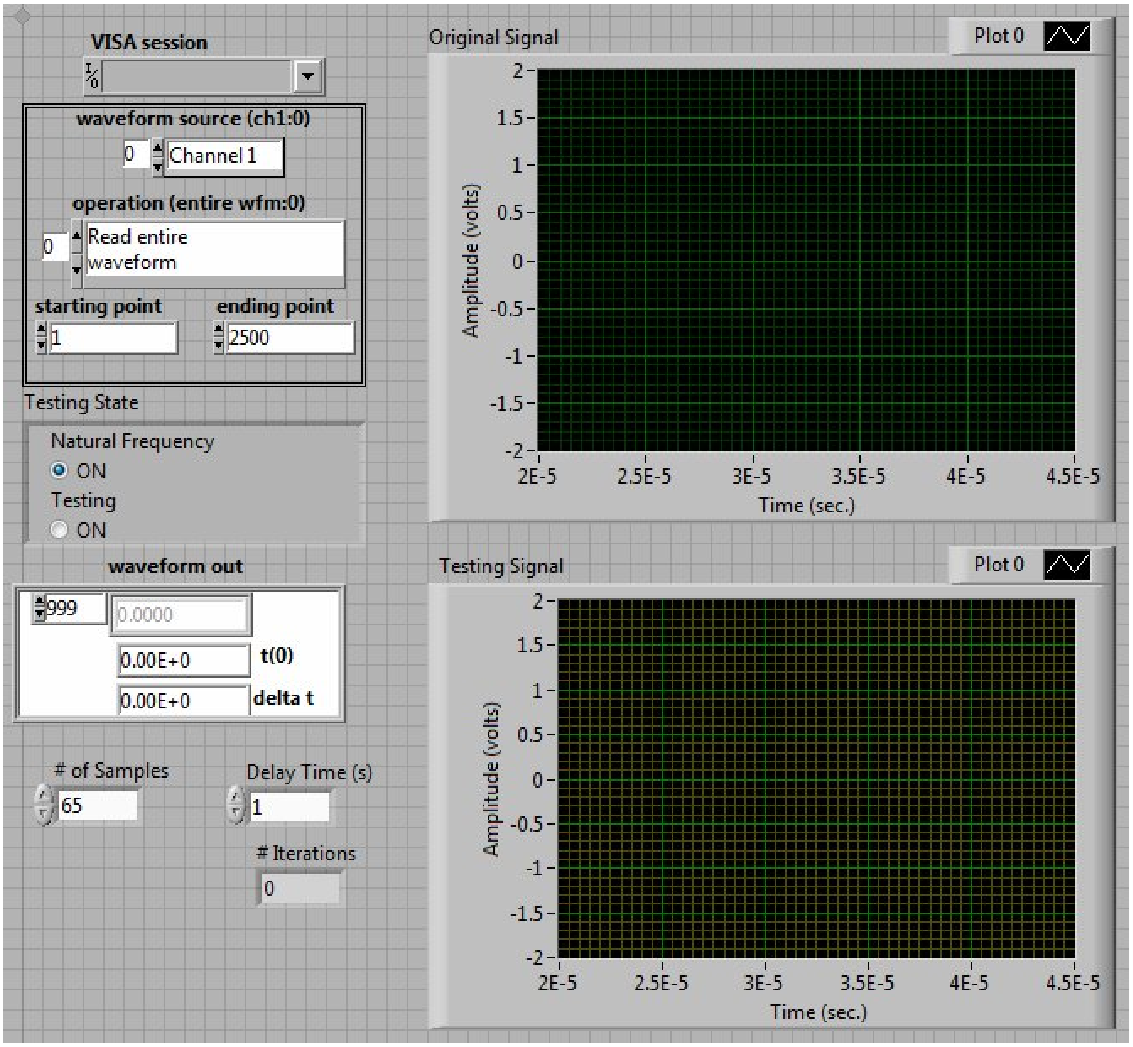


Figure 3 Block diagram of LabVIEW signal processing vi

LabVIEW uses Virtual Instrument Software Architecture (VISA) protocol to communicate with the instrument, specifically the Tektronix TDS 420A oscilloscope. The LabVIEW VI used to acquire the signals is shown in Figure 4 and Figure 5 **LabVIEW Block Diagram – TDS420A Oscilloscope**5.



VISA session

waveform source (ch1:0) 0 Channel 1

operation (entire wfm:0) 0 Read entire waveform

starting point 1

ending point 2500

Testing State

Natural Frequency
● ON

Testing
○ ON

waveform out
999 0.0000
0.00E+0 **t(0)**
0.00E+0 **delta t**

# of Samples 65

Delay Time (s) 1

Iterations 0

Figure 4 LabVIEW Front Panel – TDS420A Oscilloscope

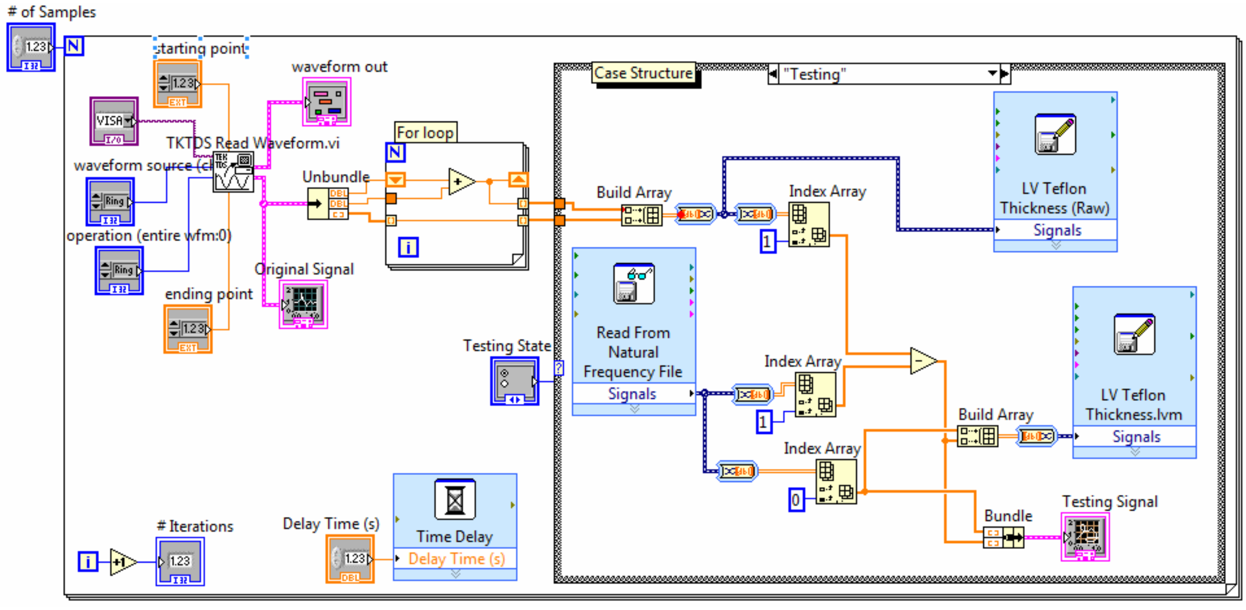


Figure 5 LabVIEW Block Diagram – TDS420A Oscilloscope

The VI shown in Figure 5 **LabVIEW Block Diagram – TDS420A Oscilloscope** used many different functions available in LabVIEW wired together to create a logical algorithm for acquiring and processing the signal.

Mechanical Assembly

The mechanical assembly is designed around the constraints of the X-Jet chamber. The chamber's configuration is set up in such a way that when in use, the torch flame is directed downward, perpendicular to ground, onto the surface of the test specimen in 0.4 atmosphere pressurization. The chamber is equipped with a 1.5-inch diameter plasma torch. The test specimen used in this setup is a 2.5-inch diameter and one inch thick Teflon coupon. The chamber diameter defines the design limits of the mechanical test piece. An off-the-shelf 8-inch Conflat Flange Mount that attaches to the chamber serves as the interface between the inside of the test chamber and the instruments located in the lab. An off-the-shelf Z-axis feed-through is implemented in conjunction with the Conflat Flange Mount to allow for variation of coupon position inside the chamber. All subsequent design and alteration of the mechanical assembly and any test instrumentation that was to be used inside the X-Jet chamber had to revolve around these key components.

Aluminum and steel were chosen to be the material entities to structurally support the affixed coupon, house the wiring from the transducer to the exterior of the chamber, and connect to the flange mount. This setup is designed to protect the transducer signal to the pulser/receiver and allow efficient relay to the oscilloscope for data analysis as well as structurally support the coupon in place for multiple test runs without need for disassembly.

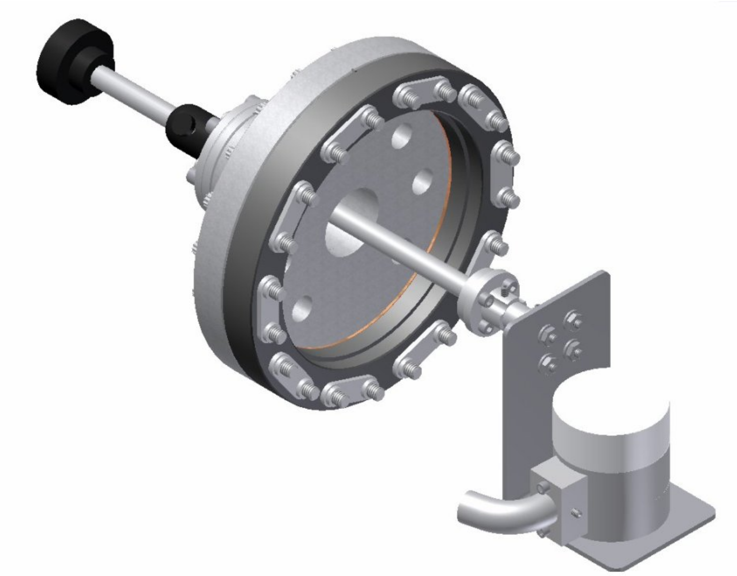


Figure 6 CAD drawing of the Conflat Flange Assembly, z-axis feed-through, and coupon mounting hardware

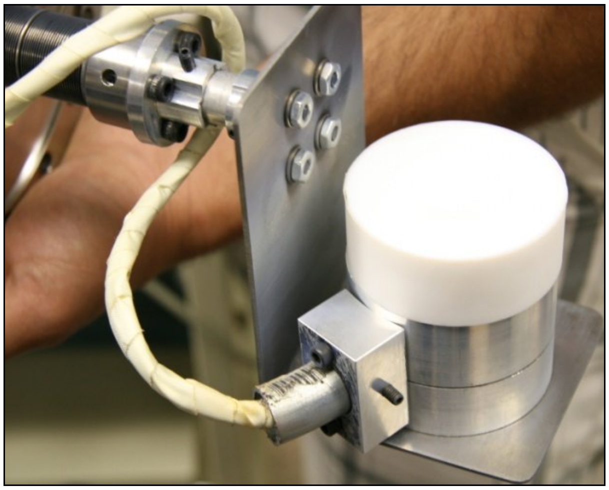


Figure 7 Photograph of actual coupon mounting hardware, and the BNC cable (protected with thermal tape)

Analysis and results

We performed several thickness gauging tests with our completed setup as part of our iterative design process. Our most successful test results were taken using the X-Jet with Teflon test coupon #5, performed at NASA Ames, on May 1, 2008. The test was performed with a 26 second exposure to the X-Jet flame beginning at approximately 9 seconds into the data acquisition. The flame was terminated at 35 seconds, relative to the start of the data acquisition. From the raw data, we calculated a recession depth of 4.48 mm.

Notable points in the data occur at approximately 10 and 35 seconds into data acquisition. Figure 8 shows a sharp thickness increase at approximately 10 seconds, and a sharp thickness decrease at approximately 35 seconds. From our analysis of the test data and video footage of the test, we determined that these two regions were caused by both thermal expansion of the Teflon coupon, as well as a liquid layer that formed at the top surface of the coupon. We observed that during the test, approximately 1 second after the coupon was inserted into the axis of the plasma flame, the surface of the coupon formed a thin liquid layer, which would then evaporate during the test. This is due to the fact that under the X-Jet's test conditions, Teflon is unable to sublimate and must pass through a liquid phase in order to evaporate. The coupon also undergoes thermal expansion at the beginning of plasma exposure due to the large change in heat flux. At flame shutoff, the coupon is rapidly cooled, the liquid layer hardens, and the coupon contracts, as denoted on the graph by the sharp decrease in thickness at approximately the 35 second mark.

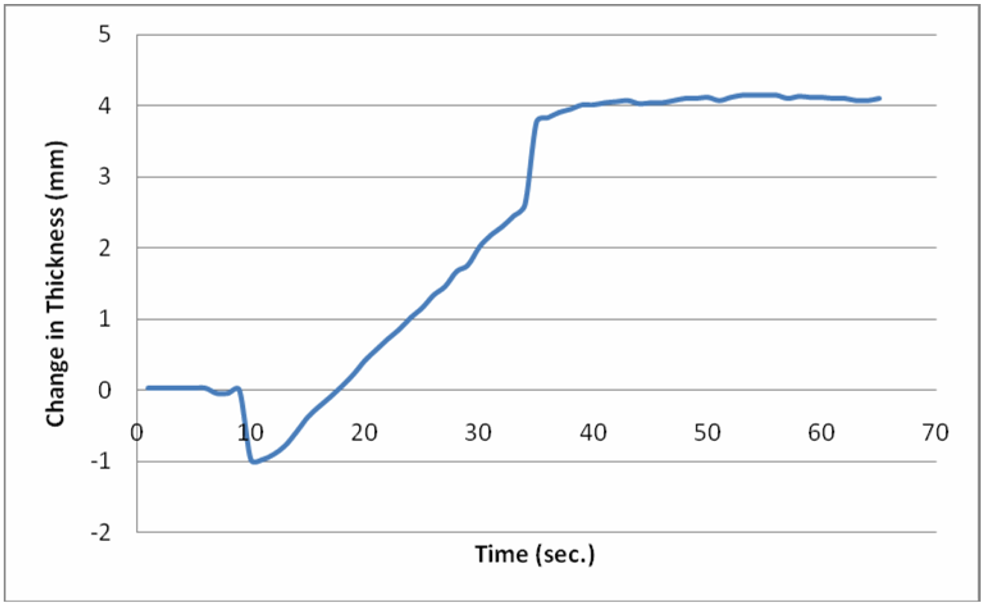


Figure 8 Plot of Raw Data for Recession

The data was further conditioned using a MATLAB script which eliminated signal noise and accounted for the thermal expansion and contraction of the test coupon. The recession of the coupon using the post-processed data was calculated at 4.88 mm.

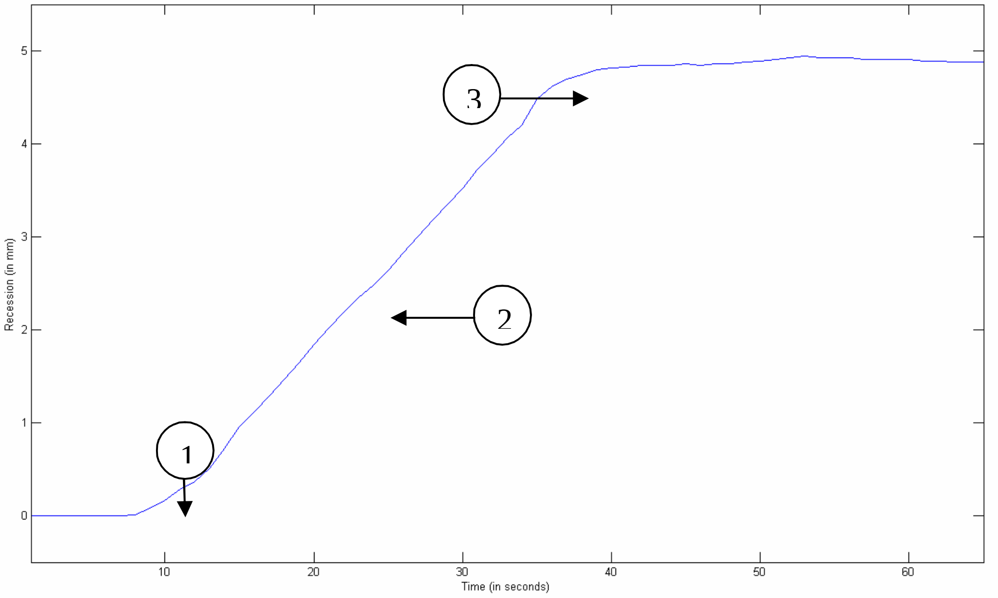


Figure 9 Recession test data post-processing via MATLAB

Benchmarking

A laser profilometer was used to perform surface metrology before and after the recession test in order to accurately benchmark our results. The profilometer measures the surface contours of the coupon by shining beams of laser light onto the coupon and measuring their reflections. This generates a cloud of 3D data points, which were then imported into ImageJ, an open source JAVA-based image generation application. The cloud was then transformed into surface contour plots, which were then converted into 3D images, as shown in Figure 11.

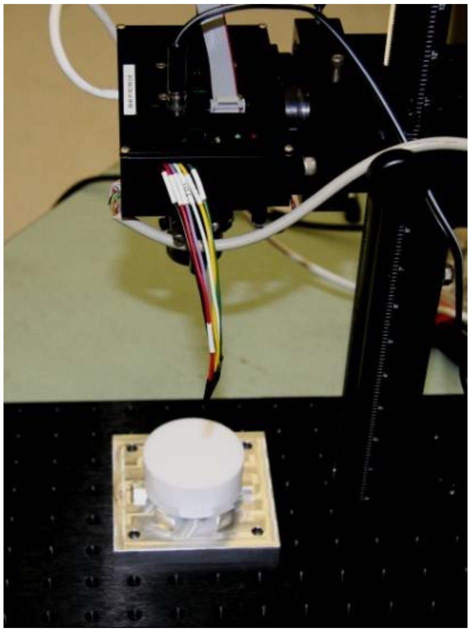


Figure 10 Laser profilometer and teflon test coupon

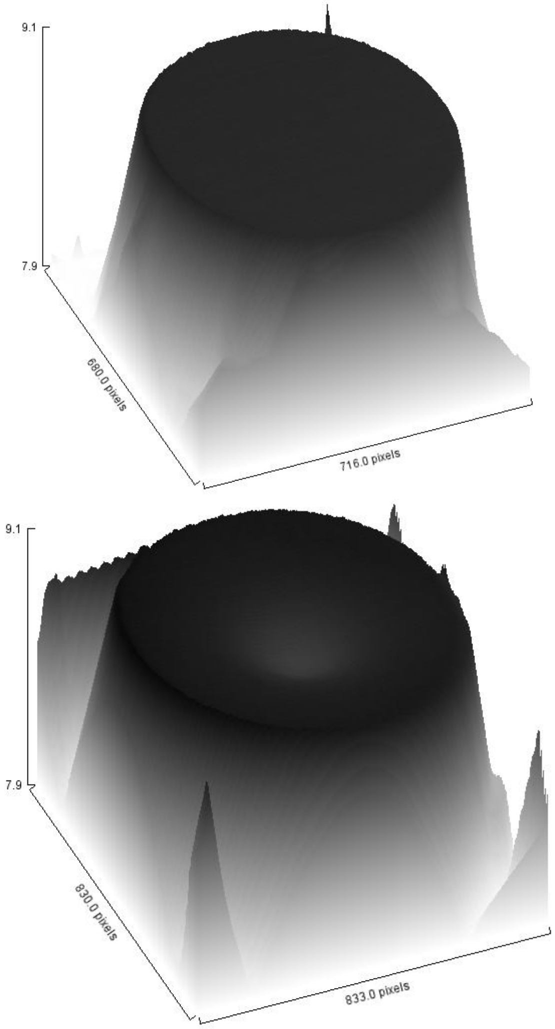


Figure 11 Surface Contours before (left) and after (right) X-Jet testing

In order to gather meaningful data which can be used for comparison, two cuts of plane data through the points of maximum recession are taken, and have their respective depths analyzed. One of the resulting 2D planes is shown in Figure 12.

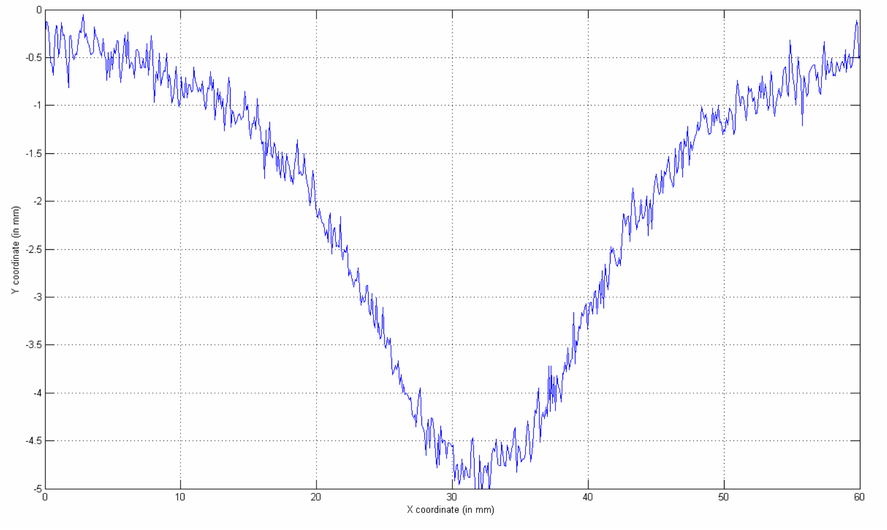


Figure 12 2D YZ plane cut of Surface Contour.

By utilizing a similar high-frequency noise filter as that was used to clean the ultrasonic signals, the data was conditioned, and a cleaner recession profile could be produced (as shown in Figure 13).

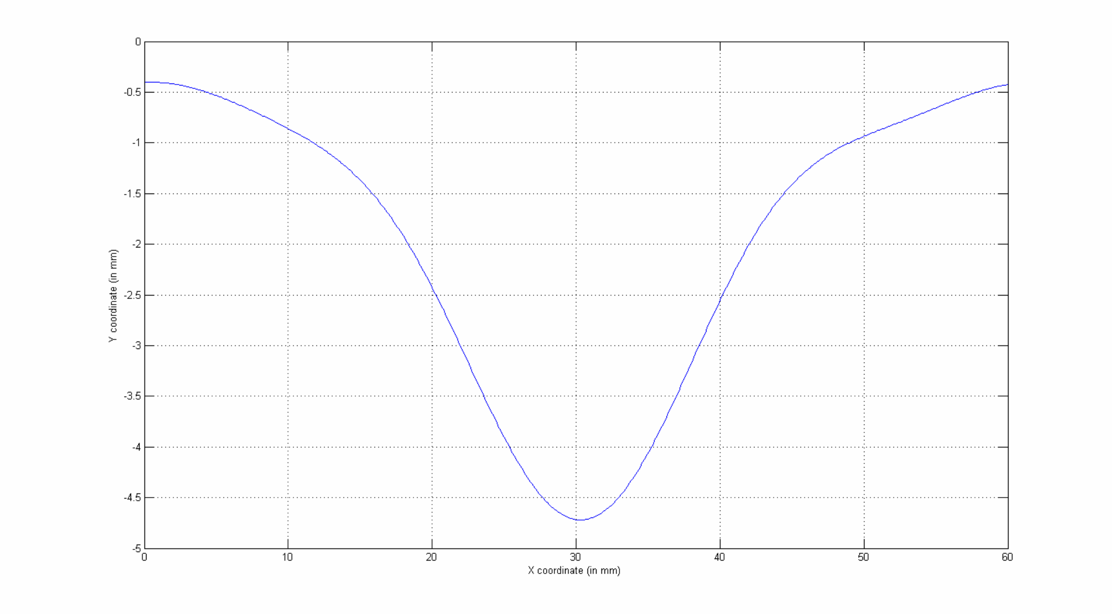


Figure 13 Filtered 2D YZ plane cut of Surface Contour.

Using these methods, the maximum recession was determined to be 4.8mm, from the comparison of the surface profile before and after recession, which results in an error of +1.7% for the ultrasonic measurement, or +.08 mm. This result satisfied our criteria of .1 mm accuracy for the ultrasonic measurement system.

Conclusion

Our objective was to design, build, test, and benchmark a system to perform thickness measurements of Teflon calibration coupons undergoing ablation in the NASA X-Jet chamber to within .1 mm accuracy. We completed this task by designing 3 sub-systems responsible for the data handling, mechanisms, and analysis respectively. Our final analysis shows that our system met all program objectives, and is ready to be implemented on a larger scale.