Design of a Hybrid Rocket Motor Injector Head for Internal Combustion Chamber Studies using Fiber Optics

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ABSTRACT

An interest in the combustion chamber area has led to the redesign of the University of Arkansas at Little Rock (UALR) labscale hybrid rocket motor injector head. The goals of the project are to view the combustion chamber area using an imaging fiber optic and to obtain Ultraviolet-Visible spectroscopic data using a fiber optic. An injector head fiber optic plug was designed to hold the imaging fiber optic in place and to isolate the delicate optics from the high temperatures and back pressure of the combustion chamber. The injector head fiber optic plug allows for the imaging fiber optic to view through the center of the combustion chamber area. This will allow for a better study of how the fuel grains burn, and a better characterization of the effects of chemical elements inside the combustion chamber area during the firing of the labscale hybrid rocket motor.

ABBREVIATIONS

CCD	Charged-Coupled Device
DSP	Digital Signal Processing
DTF	Diagnostic Testbed Facility
H	Horizontal
HTPB	Hydroxyl-Terminated PolyButadiene
Na	Sodium
NASA	National Aeronautics and Space Administration
ND	Neutral Density
PDA	Photodiode Array
psi	pounds per square inch
PVC	polyvinyl chloride
SRMs	Solid Rocket Motors
TV	television
UALR	University of Arkansas at Little Rock
UV	Ultraviolet-Visible
V	Vertical
VCR	video cassette recorder

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INTRODUCTION

The University of Arkansas at Little Rock (UALR) has developed a labscale hybrid rocket motor testbed facility for measurement of combustion parameters and characterization of chemical and mechanical phenomena. The Hybrid Rocket Facility, completed in September of 1993, was originally constructed for plume spectroscopic and combustion studies.[1,2] Some previous work has been done to characterize the physical parameters of the hybrid rocket motor and study spectral plume emissions in the ultraviolet-visible and infrared regions on UALR hybrid rocket motor. To this point, all spectral studies on the UALR hybrid rocket motor have focused on plume emissions.

The hybrid rocket motor is of interest to the aerospace community. The interest lies with using hybrid rockets as boosters, for example, with the Space Shuttle. Before this can be done, studies using ground test hybrid rocket motors must show that it is capable of providing adequate performance in a safe manner.

This project was designed to collect data from the combustion chamber of the hybrid rocket motor using imaging and ultraviolet quartz fiber optics. To accomplish this, a new hybrid rocket motor injector head had to be designed to allow for fiber optic placement. An imaging system using a CCD camera was constructed to study fuel grains as they burned. Also, a spectral system was constructed for collecting spectral emissions from the combustion chamber of the hybrid rocket motor. The spectral emissions collected from the combustion chamber can provide useful data for studying motor component breakdown, and perhaps reveal information on combustion parameters.

HISTORICAL REVIEW

Introduction to Hybrid Rockets

Liquid Rockets

Liquid rockets use a liquid fuel and liquid oxidizer that are stored in separate tanks. Liquid propellant engines operate by feeding the pressurized liquid oxidizer and liquid fuel into a thrust chamber. In the thrust chamber, the liquid oxidizer and liquid fuel combine and are ignited. The combustion gases expand into a nozzle, causing thrust. Liquid rocket motors give good thrust, have the ability to start, stop, and restart, can be throttled and are fairly environmentally friendly. The liquid rocket has drawbacks. It has a very complex system using precision valves, pressure regulators, injectors, and pumps that must all work together in sequence to perform adequately. Also, high cost and weight provide drawbacks as does storage problems with the liquid propellants.

Solid Rockets

Solid Rocket Motors (SRMs) powered the initial flight of the Space Shuttle and Titan IV rocket.[3] In solid rocket motors, the fuel and oxidizer are chemically premixed to form a solid fuel grain. By igniting this substance, the oxidizer and fuel in the intimately mixed solid grains react and produce the high-energy combustion gases for its thrust. Solid rockets provide good thrust and provide a simple system. Solid rockets do have some drawbacks. Solid rockets are inefficient fuel burners, cannot be throttled, and are not capable of start, stop, and restart. Storage is difficult, because they can be explosive since the oxidizer and fuel are not separated. They produce toxic exhaust fumes, such as hydrogen chloride gas.

Hybrid Rockets

Hybrid rockets combine features from both the liquid and solid rockets. The hybrid rocket uses a gaseous or liquid oxidizer that is stored separately from the solid fuel grain. The fuel grain is placed inside a pressure chamber between an oxidizer injector the motor nozzle. The solid fuel grain is hollowed out to produce a central combustion port, similar to that of a solid rocket motor. An ignition system is used to start the fuel vapor. By injecting the oxidizer at a high mass flow rate and pressure into the pressure chamber, the oxidizer and fuel are allowed to react in a thin boundary layer above the surface of the fuel grain. The energy released and the high temperature attained both increases the energy and sustains the solid fuel vaporization (See Figure 1). The combustion gases pass through the remainder of the combustion port and are expanded through the nozzle. By changing the flow rate of the oxidizer, the energy can be increased or decreased, allowing for throttling. Hybrid rockets have the capability of start, stop, and restart. Table 1 shows the advantages and disadvantages for liquid, solid, and hybrid rockets.

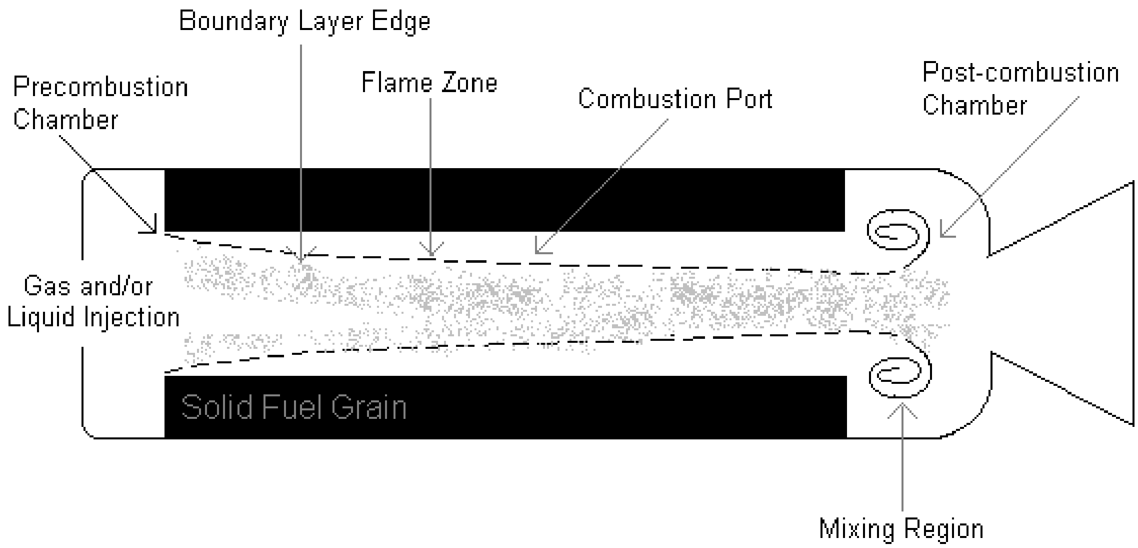


Figure 1: Oxidizer and Fuel Grain Burn Process

Type	Advantages	Disadvantages
Solid Rockets	Provides good thrust using a simple firing system and have high propellant density.	Inefficient fuel burners, cannot be throttled, are incapable of start, stop, and restart, explosive, and produce toxic exhaust fumes.
Liquid Rockets	Provides good thrust, can be throttled, capable of start, stop, and restart, and environmentally safe.	Uses a complex firing system with many valves, low propellant density, high cost to maintain, heavy in weight, and storage problems with liquid propellants.
Hybrid Rockets	Can be throttled, capable of start, stop, and restart, cost of oxidizers are cheap, environmentally safe, and safe to run.	Low propellant density, combustion efficiencies are lower, and mixture ratio and thrust vary during operation.

Table 1: Advantages and Disadvantages of Liquid, Solid, and Hybrid Rockets

History of the UALR Hybrid Rocket Facility

The UALR Hybrid Rocket Facility was designed in September 1993 (See Figure 2).[1,2] The design of the test facility was based on the Diagnostic Testbed Facility (DTF) at NASA's John C. Stennis Space Center and other test units, such as those for solid motors.[1,2]

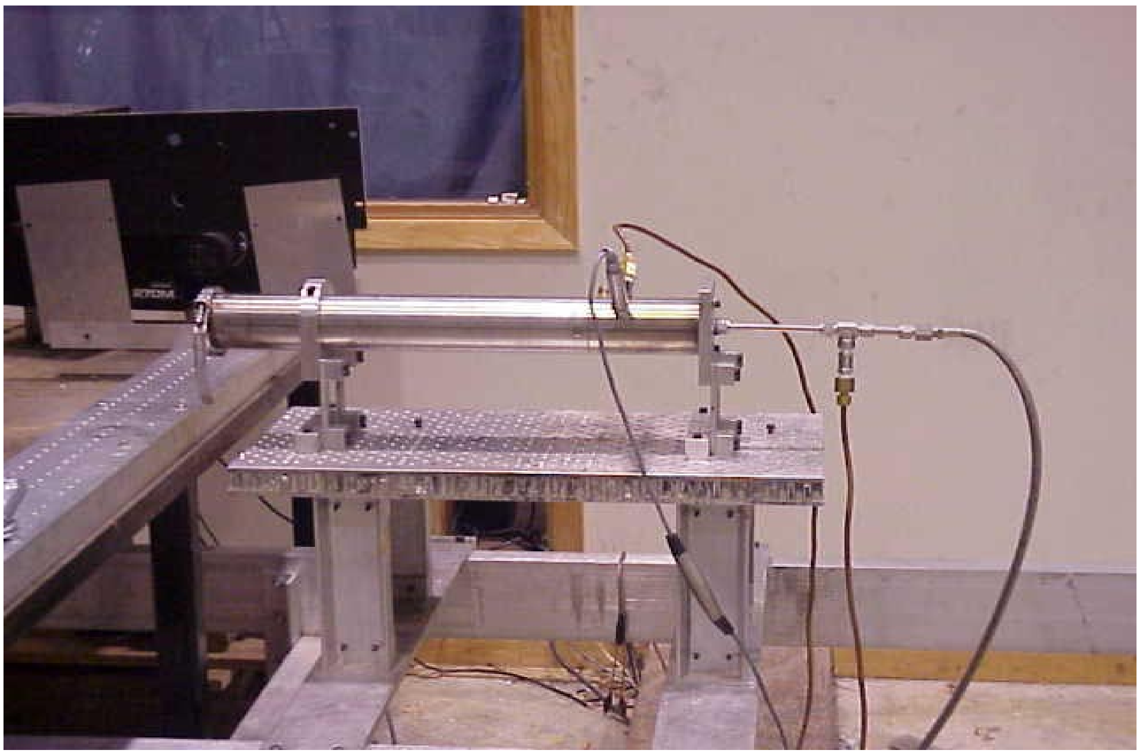


Figure 2: UALR Hybrid Rocket Motor Testbed Facility

In the past seven years, a number of studies have been performed using the UALR Hybrid Rocket Facility. A large number of these studies have focused on the spectral emissions in the Ultraviolet-Visible (300 – 750 nm), Near Infrared (750 – 1100 nm), and Mid Infrared (2 – 16 μm) regions in the hybrid rocket plume.[4-8] Regression rate studies have been performed using different types of fuel additives to the standard hybrid rocket fuel, Hydroxyl-Terminated PolyButadiene (HTPB). These studies have been performed to see if the additives increase the regression rate and improve the performance of the hybrid rocket fuel.[9-12] Studies have been performed to characterize the physical system parameters of the hybrid rocket motor. The physical system parameters studied are the pressure, plume flicker, acoustical output, and thrust force.[13-17] Studies using a multiple wavelength laser opacity system have been performed for monitoring the relative particulate loading of hybrid rocket plumes.[18,19] With each new study done on this facility, an improvement in the measurement systems has been performed to allow for more complete studies on the hybrid rocket motor.

UALR Hybrid Rocket Motor Facility Setup

Preexisting Hybrid Rocket Motor[1]

The labscale hybrid rocket motor was designed with two main sections, the chamber body and the injector head. The chamber body is made from 304 stainless steel, 2-1/2-in schedule 80 pipe. Inside the chamber body, a fuel grain, two graphite tube spacers, and a nozzle and its assembly are used to make up the motor assembly (See Figure 3). The fuel grain is 10-in in length and 2-in in diameter, the fuel grain is cast inside a paper phenolic tube with 1/8-in wall thickness.

The graphite tube spacers were used to supply space for precombustion and postcombustion. A graphite tube spacer that is 1-in in length is positioned in the precombustion chamber area, located between the injector head and the fuel grain. The precombustion chamber allows the oxidizer flow to stabilize before entering the fuel grain port. The postcombustion chamber area uses a 2-in in length graphite tube spacer that is positioned between the fuel grain and the nozzle. The postcombustion chamber allows for complete mixing of the vaporized fuel and oxidizer, ensuring complete combustion and increasing performance.

The nozzle, made of graphite, is fitted into a steel sleeve.[20] The steel sleeve has a 3/16-in o-ring groove around its outside for sealing with the chamber body. A steel retaining ring with eight 1/8-in diameter holes at 45 degrees apart is placed on the steel sleeve for holding the nozzle in place. The steel retaining ring is held fixed to the chamber body by brass shear pins that are placed into the holes through the chamber body.

The injector head was made from grade 303 stainless steel round stock. The injector head was designed to allow ports for the various gases, ignition squib, and pressure transducer (See Figure 4). Four ports were incorporated into the injector head design. Of the four ports, two ports are used for the gas system, one for the oxygen/nitrogen gas line and one for the propane gas line. Another port is used for the ignition squib, which creates the spark for ignition. The last port is the pressure transducer port, which reads the chamber pressure during a firing.

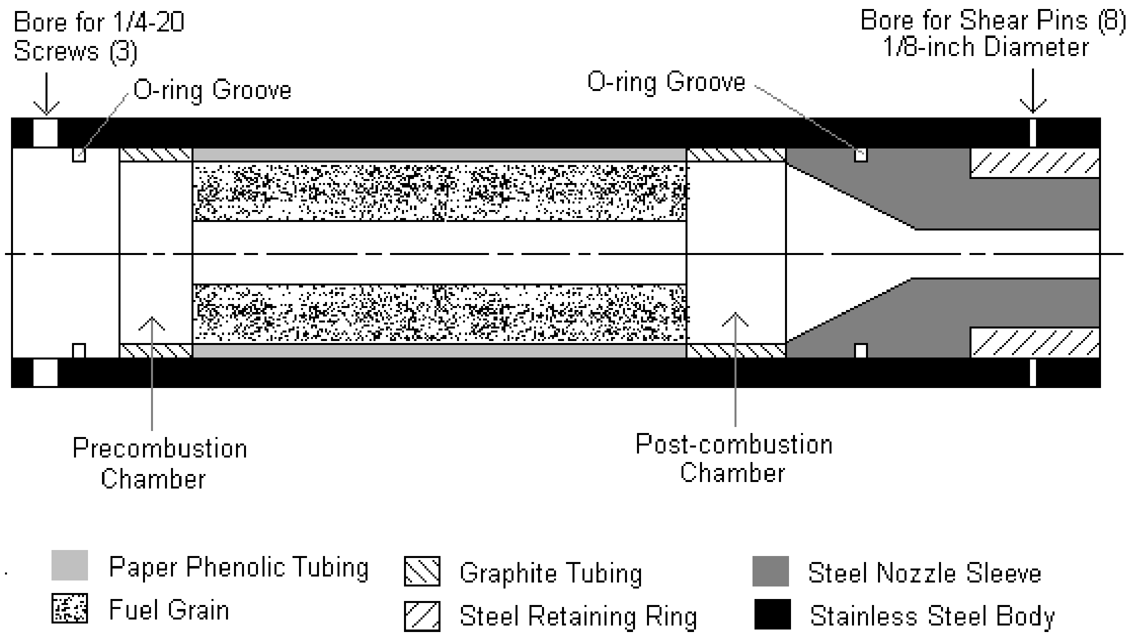


Figure 3: Chamber Body Housing

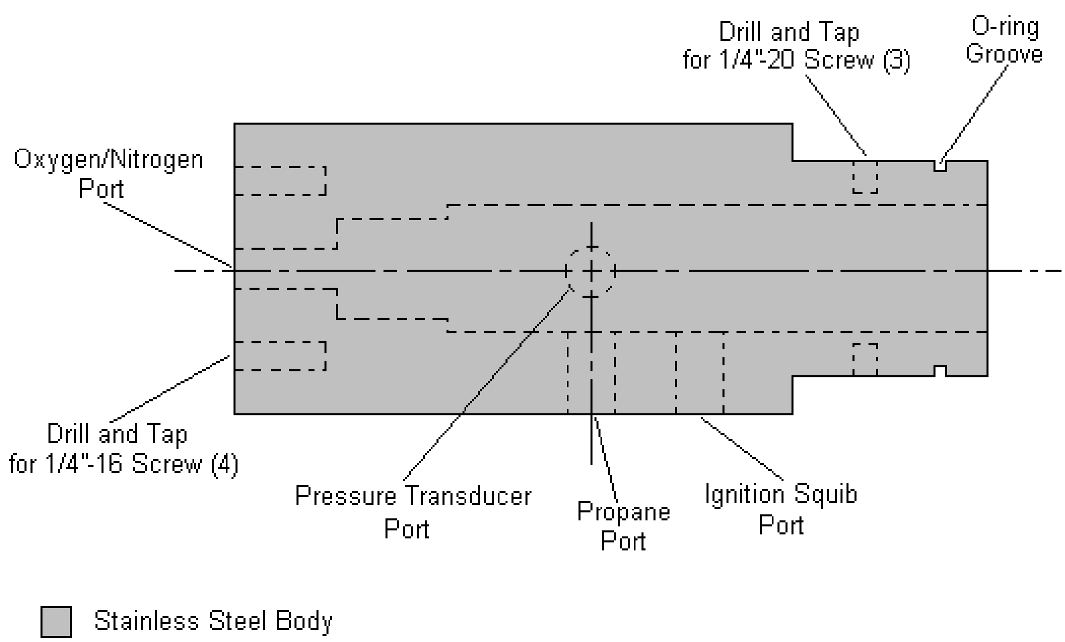


Figure 4: Original Injector Head Layout

The project was designed to develop a system for collecting data in the combustion chamber using an imaging fiber optic (borescope) and an ultraviolet-visible (UV) quartz fiber optic. A new injector head was designed for the hybrid rocket motor to allow for fiber optic observation down the centerline of the combustion chamber. This allows data from the combustion chamber to be collected.

Two imaging systems were developed for collecting data from the combustion chamber. The first imaging system used a black and white charged-coupled device (CCD) camera for viewing and collecting combustion chamber images. A second system was developed to view and collect combustion chamber images using a color CCD camera. Both imaging systems used the Hawkeye 17 borescope for viewing the combustion chamber. Both imaging systems provided images that increase the understanding of how fuel grains burn.

A spectroscopic system was developed to collect spectral data from the combustion chamber. The spectroscopic system used an UV quartz fiber optic to collect spectral data in the 475 nm to 625 nm region in the combustion chamber. The spectral data collected from the combustion chamber can be correlated with previous plume emission studies done at the UALR Hybrid Rocket Motor Facility.

DESIGN

Injector Head Design

The goal of the project is to collect imaging and spectral data from inside the combustion chamber area of the UALR hybrid rocket motor during fuel grain burns. To obtain the imaging and spectral data, a new injector head had to be designed.

The design needed to meet several requirements. It needed to have the same oxygen mass flow rate as the original design. For steady, incompressible flow, this is accomplished by maintaining the same cross sectional area as the original oxygen inlet. This would allow for the same combustion characteristics to be achieved as the previous design and allow comparisons to be made with prior results.

The new injector head design consists of two main sections, the injector head shaft and the fiber optic plug. The shaft and plug were both machined from a grade 303 stainless steel round stock.

Injector Head Shaft

The shaft contains ports for the oxygen/nitrogen inlet, the propane inlet, the igniter inlet, and the chamber pressure transducer port (See Figure 5). The shaft is 6.25-in in length, which is 0.50-in longer then the previous injector head (See Figure 6). The extra length provides space that is used in relocating the oxygen/nitrogen inlet from the front of the injector head to the side of the shaft.

The relocation was done to accommodate the plug and allow images along the centerline of the motor to be obtained.

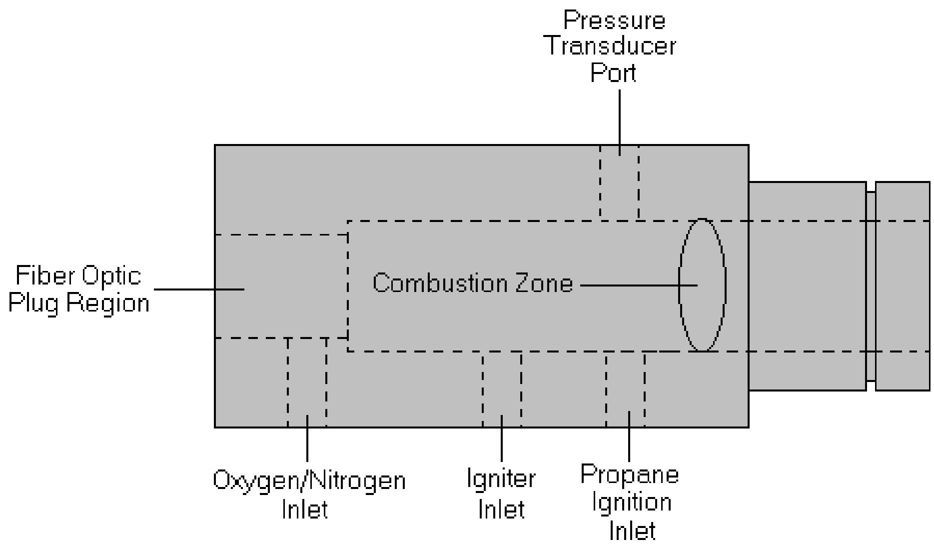


Figure 5: Injector Head Shaft Layout

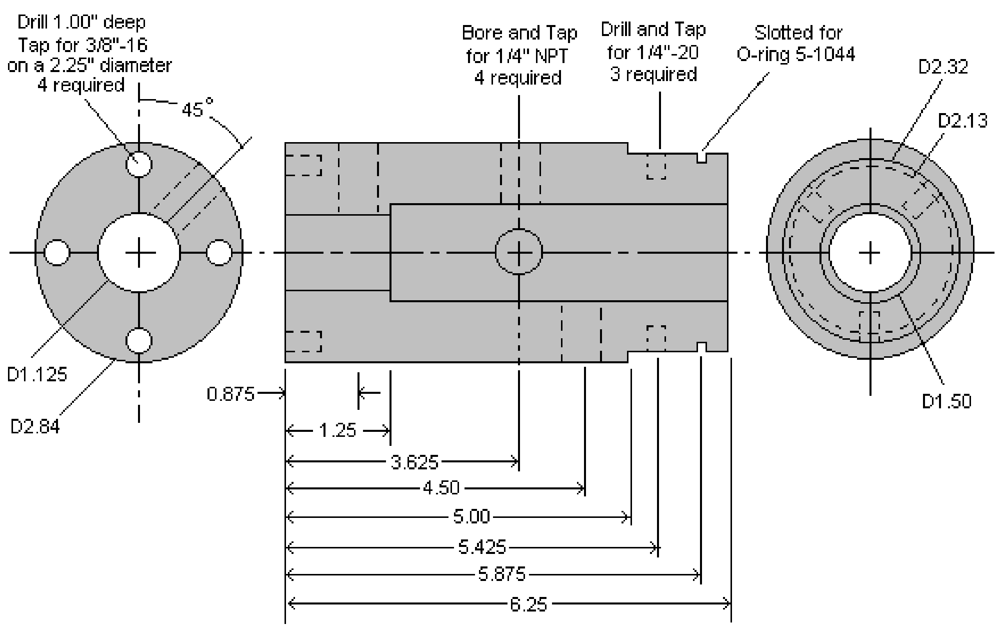


Figure 6: Injector Head Shaft Schematic

Fiber Optic Plug

The imaging fiber optic had to be mounted forward of, but directly on, the centerline of the combustion chamber area. A window was used in the plug to provide protection for the fiber optic against high temperatures and back pressures that occur during motor firings. The plug contains a window, fiber optic channel, and a grooved retaining ring brace device (See Figure 7).

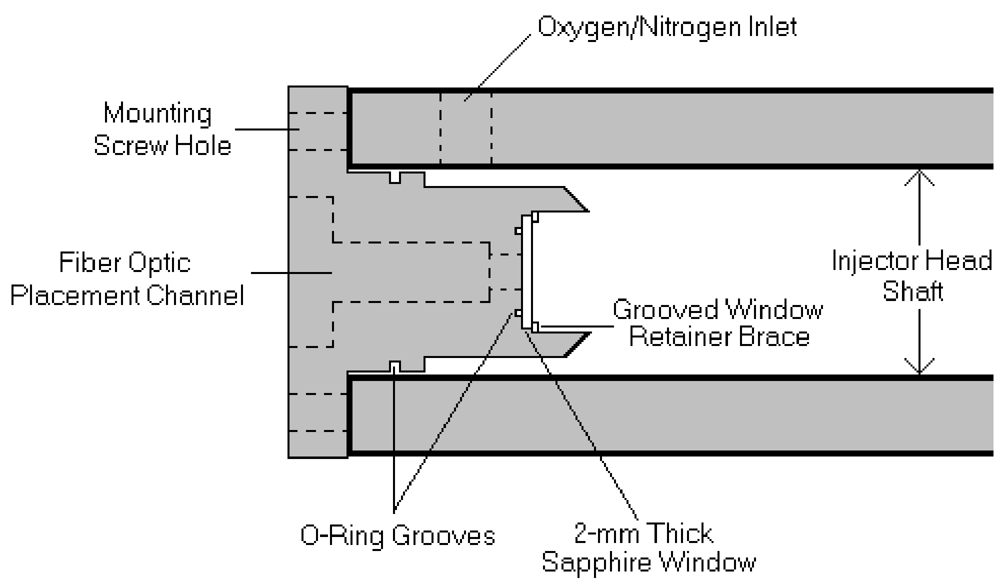


Figure 7: Fiber Optic Plug Layout

The plug was designed to fit into the 1.125-in diameter bored hole in the front of the modified injector head (See Figure 8). The plug was tapered so that the plug's outside diameter of 1.122-in was 0.003-in smaller than the shaft's inside diameter. An o-ring groove was milled into the plug, where the shaft slides over it. The o-ring size was a Parker Series 2-212. It has an inside diameter of 0.859-

in and a width of 0.139-in, giving it an outside diameter of 1.137-in. The seal design was made per Parker's specifications.[21]

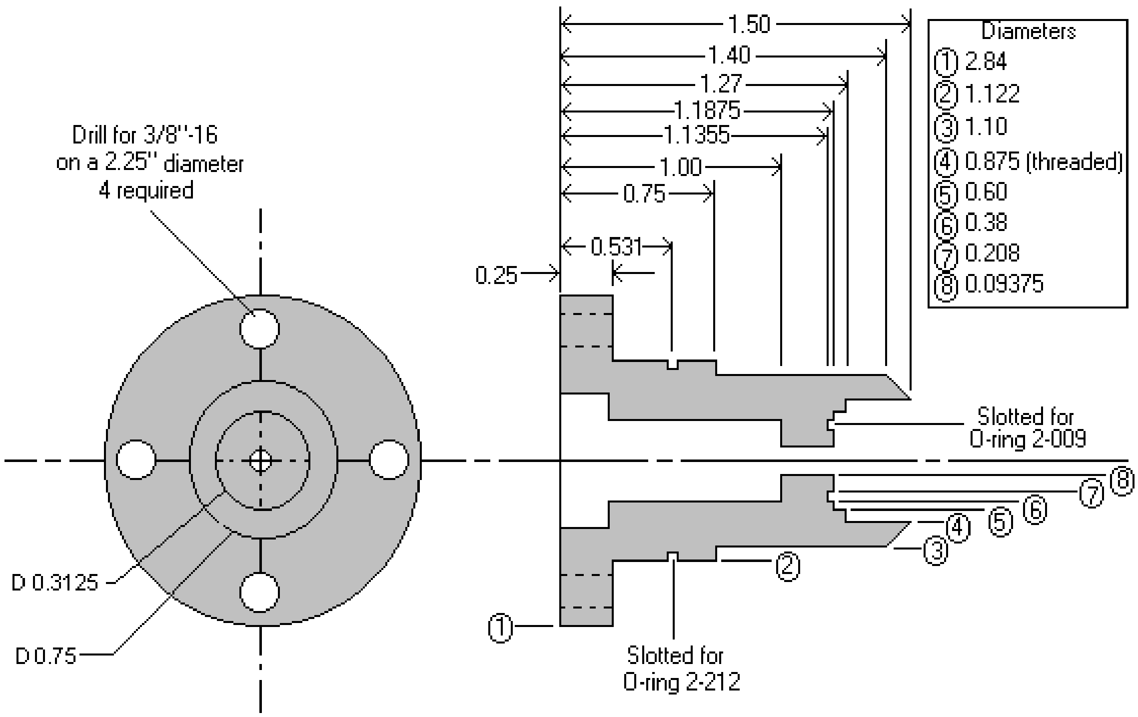


Figure 8: Fiber Optic Plug Schematic

The diameter of the plug was reduced to 1.10-in allowing a 0.025-in channel between the shaft and the plug. The oxygen/nitrogen inlet is located in this region of the shaft. This allows enough space for the oxygen/nitrogen to flow into the combustion area. The oxygen/nitrogen inlet and the plug cross-sectional area were designed to allow the same oxygen flow rate during firings to occur as for the standard design. The original designed oxygen/nitrogen inlet had a 0.50-in diameter hole giving an area of 0.196-in^2. The new oxygen/nitrogen inlet design is an annulus with an outside diameter of 1.125-in and an inside diameter of 1.10-in. The new area of the inlet was calculated to be 0.199-in^2. This gives approximately the same flow rate through the motor as previously designed. The oxygen/nitrogen flows through the inlet into this annular region. The flow direction is turned 90 degrees and forced into the combustion area. The distance between the oxygen/nitrogen inlet and the combustion chamber is such that fully developed flow results prior to the combustion zone.

The plug is designed with a centerline channel for the insertion of the imaging fiber optic and UV fiber optic. The channel diameter is made so that the imaging fiber optic or UV fiber optic can easily be removed without disassembling the injector head.

The centerline channel starts with a 0.75-in diameter bore that is reduced to a 0.3125-in diameter bore at a point 0.25-in into the plug. The 0.75-in diameter bore is used to allow access to the fiber optic for removal from the centerline channel. The 0.3125-in diameter is bored an additional 0.75-in into the plug. The reduction to a smaller diameter was made so that there would be a snug fit between the fiber optic and the centerline channel wall. This fixes the fiber optic in place so that the image is centered and the focal length does not change during a firing.

Mounted 0.25-in in front of the fiber optic is a 2-mm thick sapphire window. A sapphire window was chosen because of its surface hardness and high temperature resistance. The sapphire window was used to prevent back pressures and high temperatures from reaching the more delicate fiber optics. The window is held in place by a grooved retainer brace device on one side and against the wall on the other side (See Figure 9). The grooved retainer brace device was designed to allow the window to be removed for cleaning in between runs in case soot from the motor firing had collected on it. On the wall side, an o-ring is used to seal the plug to prevent gases from blowing out through the front of the motor. The o-ring size was a Parker Series 2-009. It has an inside diameter of 0.208-in and a width of 0.70-in, giving it an outside diameter of 0.348-in. Groove dimensions were chosen per Parker's specifications.[21]

The plug slides into the shaft. The shaft has four 1-in deep tapped holes at 90 degrees apart. The holes are tapped for 0.375-in 16 screws on a 2.25-in diameter. The plug has four 0.375-in holes on a 2.25-in diameter at 90 degrees apart to mount to the test stand brace. Four 0.375-in by 1.50-in 16 screws are used in constructing the testbed brace with the injector head assembly.

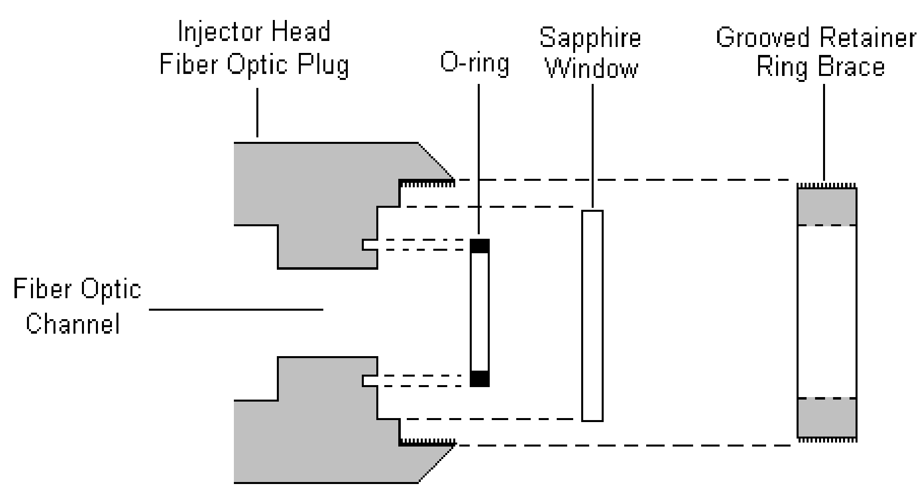


Figure 9: Sapphire Window Setup

Imaging Systems Design

A goal of the project was to design an imaging system to collect imaging data from inside the combustion chamber area. Two different imaging systems were designed: a black and white CCD camera system and a color CCD camera system. The black and white CCD camera system consists of an imaging fiber optic (borescope), a combustion of neutral density (ND) filters, a video cassette recorder, and a television (TV) monitor (See Figure 10). The color CCD camera system consists of an imaging fiber optic (borescope), a combination of ND filters, a microscope eyepiece, a VCR, and a TV monitor (See Figure 11).

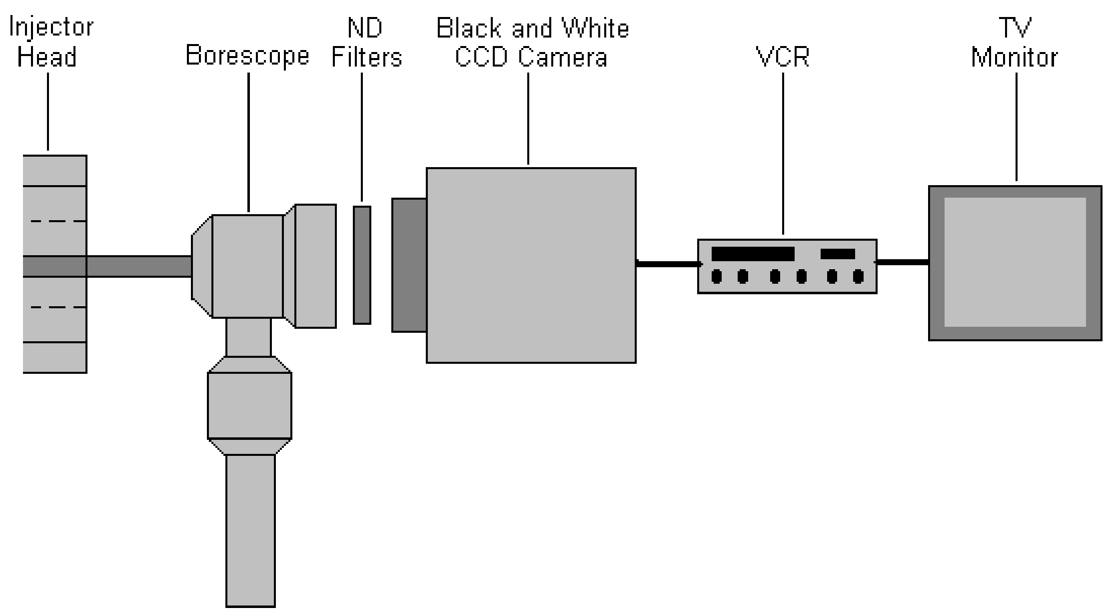


Figure 10: Black and White CCD Camera System

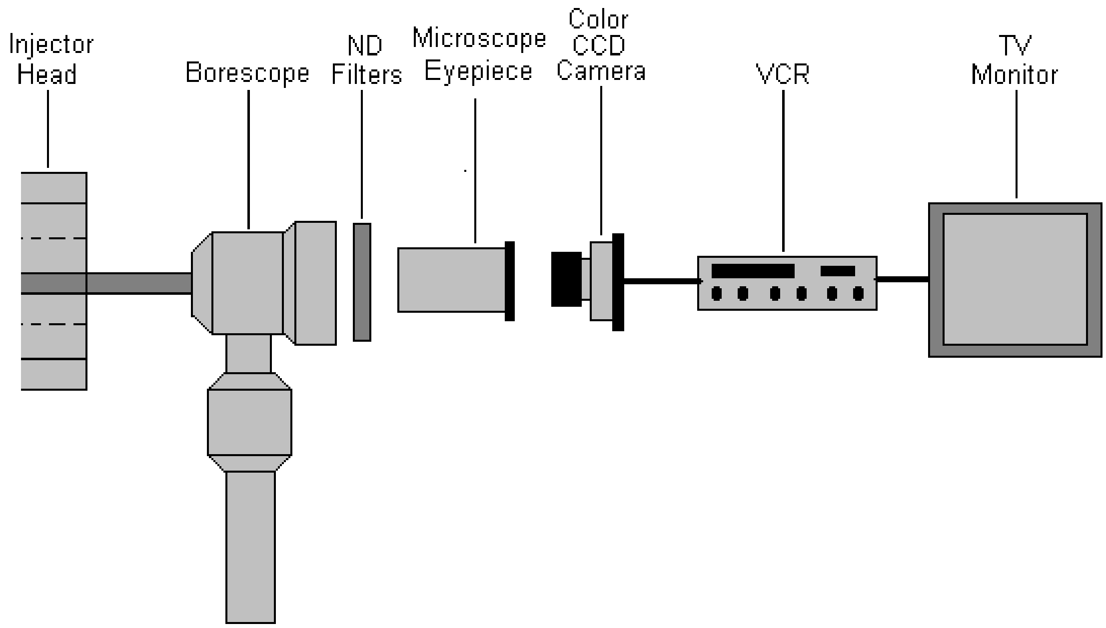


Figure 11: Color CCD Camera System

Black and White CCD Camera System

The black and white CCD camera was removed from a circuit board laser trimmer donated to the Applied Science Department at UALR. The black and white CCD camera provides a 6.6 mm (vertical) and 8.8 mm (horizontal) scanning area and a minimum sensitivity of 1.5 lux (See Appendix A). A 12-volt power supply was used to power the CCD camera. The CCD camera has a standard NTSC format output to transmit the image to a VCR or TV.

A mounting system was built for all of the optical components. An aluminum bracket was fabricated to bolt to the injector head mounting plate (See Figure 12). Two aluminum rods supported the other end of the CCD camera mounting bracket (See Figure 13). This allowed for a level surface to be created between the injector head assembly and the front of the test stand brace (See Figure 14).

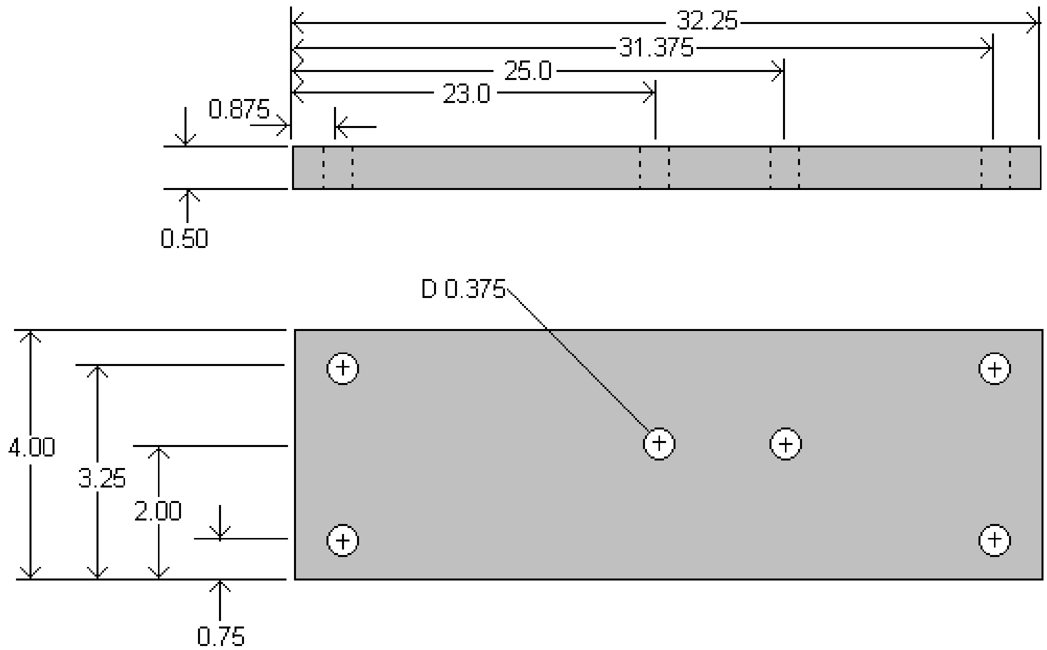


Figure 12: Aluminum Mounting Bracket System

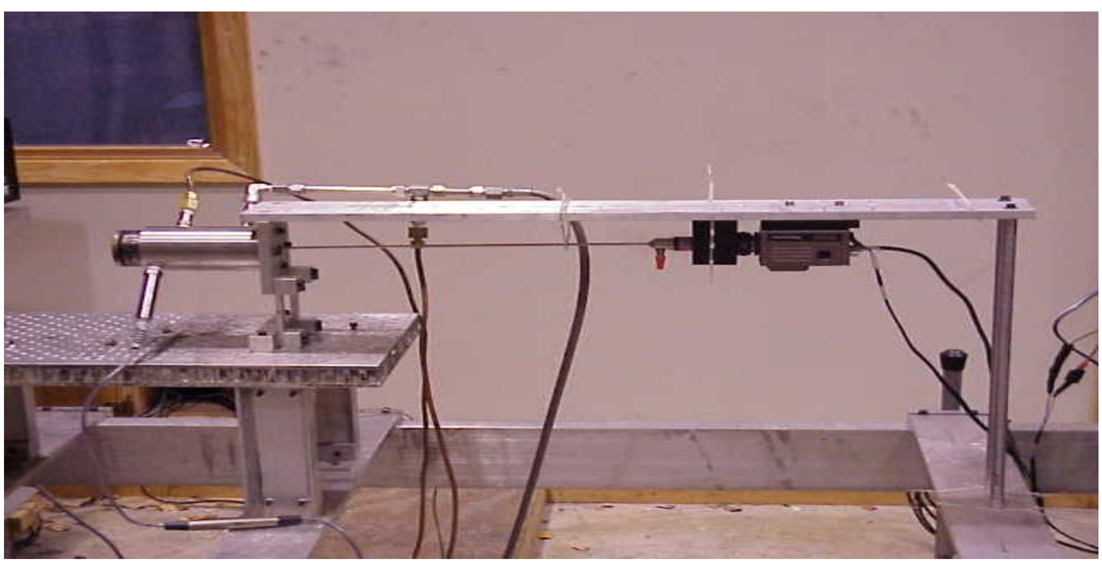


Figure 13: Black and White CCD Camera Optical Measuring System

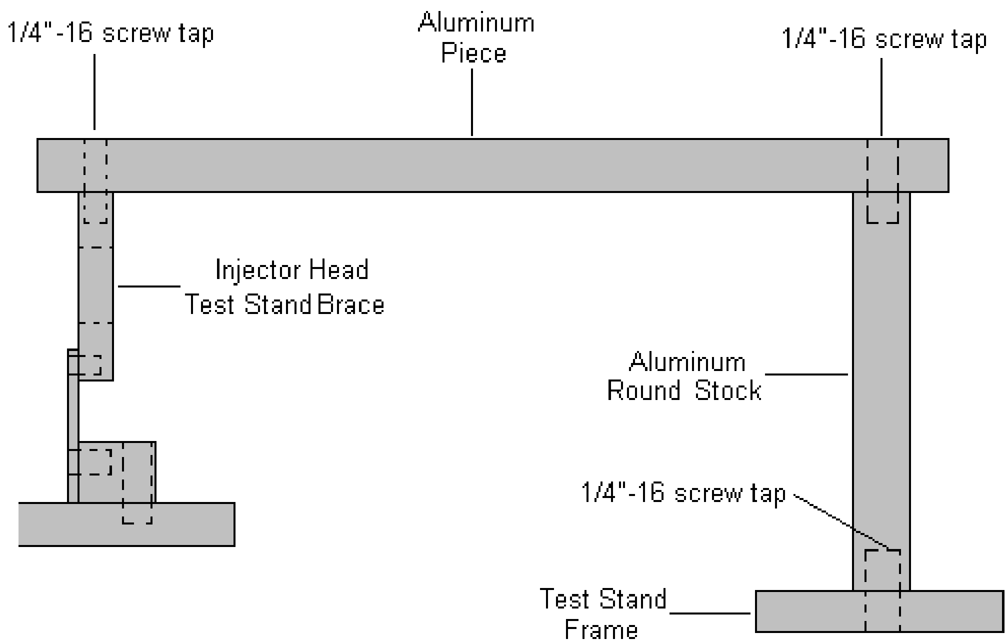


Figure 14: CCD Cameras Mounting Bracket

The Hawkeye 17 focusing borescope uses a single imaging fiber optic that is housed inside a stainless steel tube to pass the virtual image from the borescope tip to the eyecup. Inside the eyecup, a lens is used to convert the virtual image from the imaging fiber optic to a real image. The borescope stainless steel tube has a 0.165-in diameter. A 1.25-in piece of 0.25-in vacuum hose was placed around the stainless steel tube for protection, separating the stainless steel tube from the plug channel wall. The vacuum hose was used as a buffer to reduce contact with the plug and to hold the borescope centered in front of the sapphire window.

ND filters were used between the borescope eyecup and the black and white CCD camera lens. A holder/mount made of delrin material was designed to house the ND filters as well as supply a coupling system with the borescope eyecup and black and white CCD camera lens (See Figure 15). A special ring brace made of delrin material was designed to hold the ND filters in place (See Figure 16).

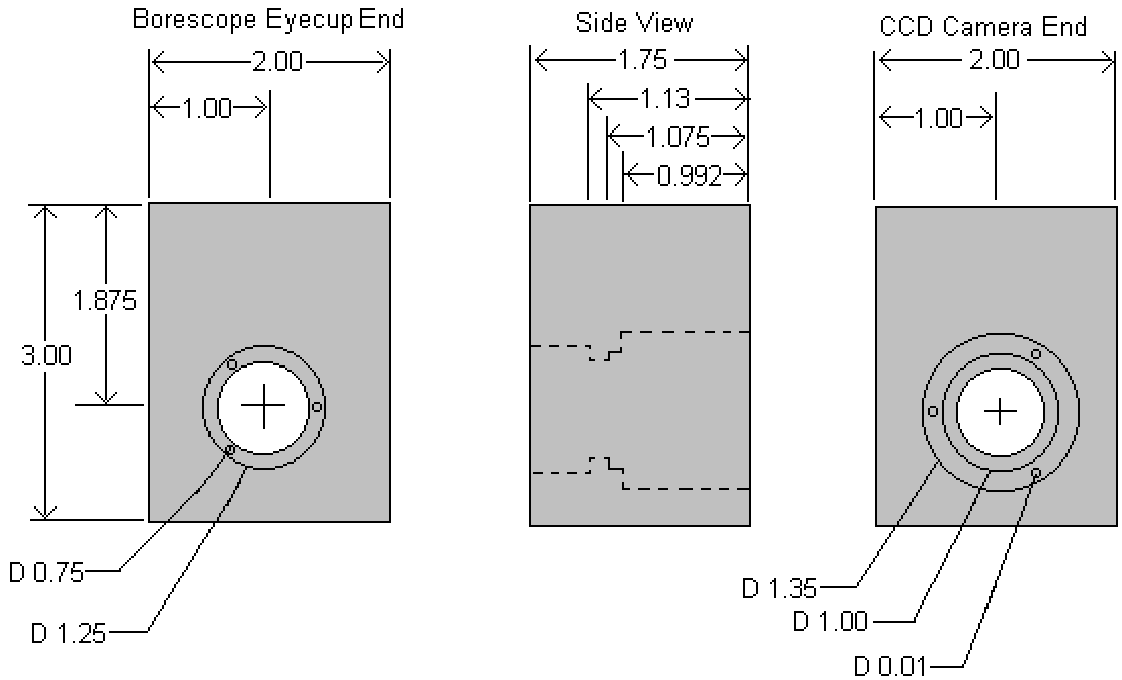


Figure 15: Neutral Density Filter Holder/Mount

The ND filter holder/mount was designed with a 0.75-in diameter bore on the borescope eyecup side. The borescope eyecup slides into the 0.75-in diameter bore of the ND filter holder/mount. On the black and white CCD camera lens side, a 1.35-in diameter bore was made for holding a ND filter ring brace and sliding the black and white CCD camera lens into place. On the inside edge of the 1.35-in diameter bore, three 0.01-in diameter taps were made for the ND filter ring brace screws. The ND filter ring brace was made for holding the ND filters securely in place and allowed the ND filters to be easily changed. Three 0.01-in diameter bored holes were machined a 120 degrees apart on the ND filter ring brace. A 0.18-in diameter bore with a 0.12-in depth was made in the front of the ND filter ring brace where the 0.01-in diameter bored holes were incorporated. This allowed for the 0.11-in 32-screw heads to be flush with the brace surface.

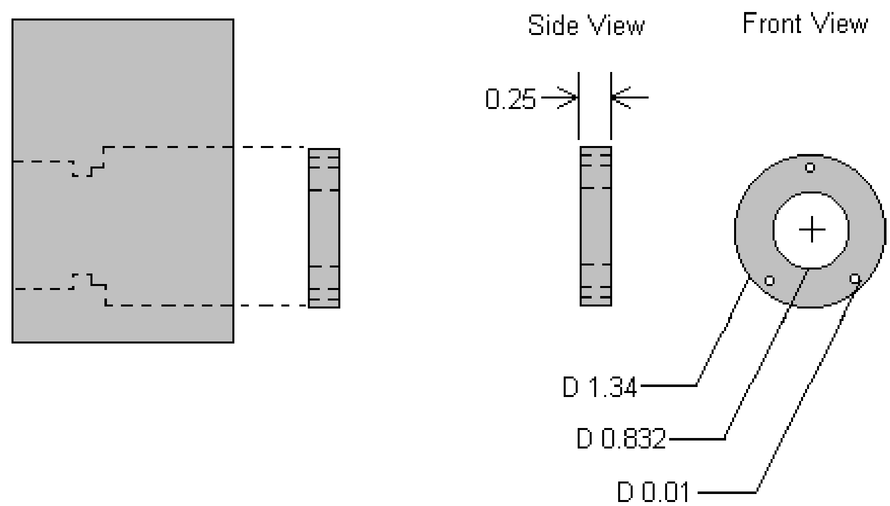


Figure 16: Neutral Density Filter Ring Brace

The black and white CCD camera lens slides into the 1.35-in diameter bore up to the ND filter ring brace to create a snug fit. A 1.00-in diameter bore was made after the 1.35-in diameter bore supplying a region for the ND filters. The ND filter holder/mount was positioned against the bottom of the CCD camera mounting brace. The ND filter holder/mount was held in place using cable ties to eliminate vibration caused during the motor firing.

The ND filters were used to reduce the light intensity across the visible spectrum without altering the spectral image from the combustion chamber area.

A variety of Optometrics Group ND filters consisted of filters with neutral densities of 0.3, 0.5, 1.0, 1.3, and 1.5. As the ND filter number increases, less light is passed. Two Kodak Wratten™ ND filters of 1.0 and 4.0 were purchased. These filters were made out of gelatin material and came in 3-in by 3-in film sheets. A circle cutter was used to cut the ND filter film to 1-in diameter circles.

The black and white CCD camera was mounted to the CCD camera bracket. The CCD camera had a sliding mount with two 0.25-in diameter tapped holes at 2-in apart. The sliding mount gave the CCD camera a 0.75-in horizontal sliding capability. On the CCD camera mounting bracket, two 0.26-in diameter holes were bored into the injector head test stand brace. This allowed the CCD camera to slide in and out of the ND filter holder/mount. Two 0.25-in 16-screws were used in mounting the CCD camera to the bracket.

A 6-ft coax cable was used between the black and white CCD camera and the Zenith 13-in color TV monitor with VCR. The Zenith TV/VCR was used to record and view the combustion chamber area image. By recording the image to a videocassette, the image data was stored, and could be viewed at a later date.

Color CCD Camera System

The color CCD camera system setup is similar to the black and white CCD camera system setup. The color CCD camera system uses the same borescope, ND filter holder/mount, Zenith TV/VCR. The changes include adding a microscope eyepiece, substituting a color CCD camera for the black and white CCD camera, and adding another mount for coupling the microscope eyepiece with the color CCD camera (See Figure 17).

The Panasonic OEM Board Camera GP-CX151 single-board, micro size color CCD camera supplies a 44 degree field of view, a horizontal resolution greater than 330 TV lines, a minimum sensitivity of 5 lux (40 lux with lens), Digital Signal Process (DSP) color with analog-to-digital conversion, and color processing (See Appendix A). A 5-volt power supply was used to power the camera.

A goal for the color CCD camera testing was to increase the image size being recorded from the combustion chamber. By incorporating a 15x microscope eyepiece between the ND filters and the color CCD camera, a larger image was focused to the color CCD camera lens. Before the 15x microscope eyepiece was used, many different optical setups had been tried.

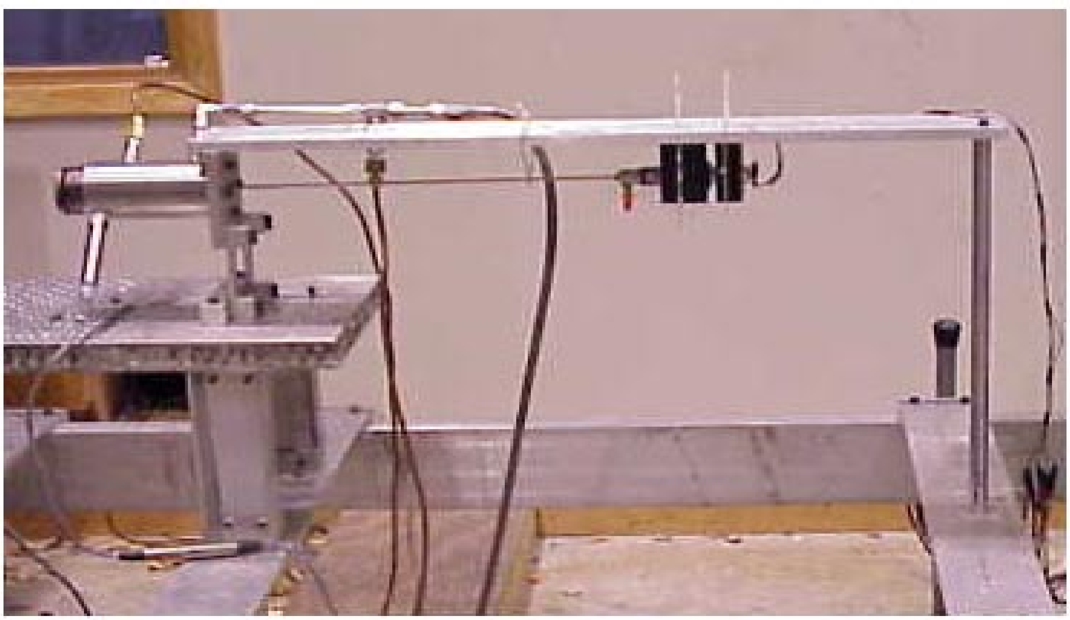


Figure 17: Color CCD Camera Optical Measuring System

The first optical setup involved a 1-in diameter symmetric bi-convex lens, borescope, and color CCD camera. All optical components were mounted to an optical bench in the Optics Lab at UALR to create a straight-line optical system.

The radius of curvature for the symmetric bi-convex lens was 11.25, the focal length was calculated from the radius of curvature to be approximately 4.44 cm. The symmetric bi-convex lens magnification was calculated from the focal length to be approximately 5.6 times (See Appendix B). The lens was placed approximately 4.44 cm from the borescope eyecup and approximately 4.44 cm from the color CCD camera lens.

The symmetric bi-convex lens was configured into the color CCD camera system. Before firing, a flashlight test was performed to make sure that the image size had been increased. The flashlight test involves a flashlight being placed at the nozzle end of the motor and shined down the center of the motor. This provides a light image similar to the one in the combustion chamber area. The image collected by the color CCD camera showed no significant increase like the one created previously in the optics lab. The color CCD camera system was measured again to make sure that the lens was placed at the correct distance from the borescope eyecup and the color CCD camera. The measurements showed that the lens had been placed a correct distance from the borescope eyecup and color CCD camera lens.

The optical system was reconstructed in the optics lab and provided the same magnified image as before. The symmetric bi-convex lens was configured again in the color CCD camera setup but failed to give a magnified image again. After going back through calculations a different approach was taken. This still leaves the concern of why this particular system did not work. A conclusion was made that the optical system in the lab was under different parameters than when it was set up with the motor assembly. When constructed in the lab the borescope was able to use its full field of view. When constructed with the shaft, the field of view of the borescope was limited by the 1.50-in diameter bore made in the shaft. By taking this into consideration a lens system can be created by using a symmetric bi-convex lens with a larger magnification.

The next approach was to use a microscope lens to magnify the image. This approach did not show good image magnification when setup in the optics lab. The next set up used a microscope eyepiece for magnifying the image. A 15x microscope eyepiece was tested in the optics lab with success. The microscope eyepiece was configured into the color CCD camera system. The flashlight test was performed and the microscope eyepiece provided a magnification of the flashlight image.

A microscope eyepiece/color CCD camera mount was designed for coupling the microscope eyepiece with the color CCD camera (See Figure 18). The microscope eyepiece/color CCD camera mount was designed with a 1.15-in diameter bore with a depth of 0.50-in on the microscope eyepiece side. The microscope eyepiece slides into the 1.15-in diameter bore region of the microscope eyepiece/color CCD camera mount. On the color CCD camera side of the microscope eyepiece/color CCD camera mount, a 0.875-in diameter bore was made to a depth of 0.50-in depth. The color CCD camera is allowed to slide into this region all the way up against the microscope eyepiece. The bored diameters of the microscope eyepiece and color CCD camera are centered at 1.875-in from the top and 1.00-in from the side of the microscope eyepiece/color CCD camera mount. The microscope eyepiece/color CCD camera mount is positioned flat against the bottom of the CCD camera mounting brace. The microscope eyepiece/color CCD camera mount is held in place using cable ties to eliminate vibration caused during the motor firing. The material used for making the microscope eyepiece/color CCD camera mount was delrin.

Since the outside diameter of the microscope eyepiece is 0.912-in and the ND filter holder/mount has a 1.35-in diameter bore, a coupling ring brace had to be made to make up the difference between the two diameters to keep the measuring system centered. The coupling ring brace was made with a 1.345-in outside diameter and bored with an inside diameter of 0.913-in. The coupling ring brace has a length 0.883-in. The microscope eyepiece was guided into the coupling ring brace that was then guided into the ND filter holder/mount.

Another coupling ring brace had to be made for the color CCD camera. This coupling ring brace was made to supply a buffer between the color CCD camera lens and the microscope eyepiece/color CCD camera mount. A 0.75-in piece of polyvinyl chloride (PVC) tubing material was used to make this coupling ring brace. The PVC tubing has an outside diameter of 0.8745-in and an inside diameter of 0.725-in. The color CCD camera lens was guided into the coupling ring brace and then into the microscope eyepiece/color CCD camera mounting brace for a snug fit (See Figure 19).

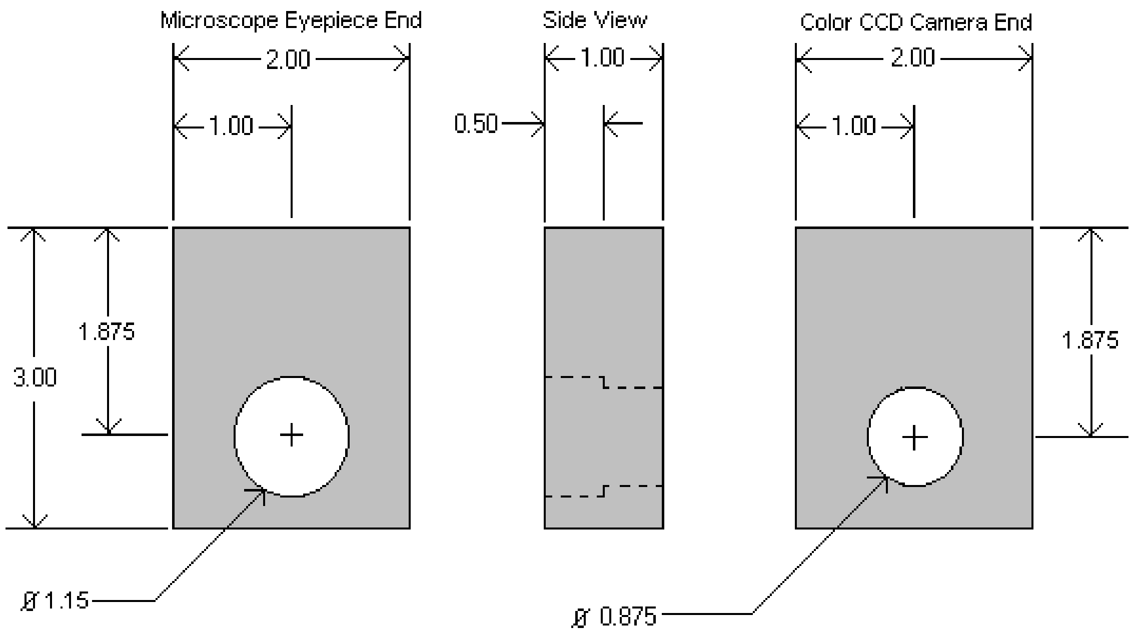


Figure 18: Microscope Eyepiece/Color CCD Camera Mount

A Compens 15x microscope eyepiece was used between the ND filters and the color CCD camera. The microscope eyepiece supplied the color CCD camera with a larger image out of the borescope. This increases the combustion chamber image that was viewed on the TV monitor.

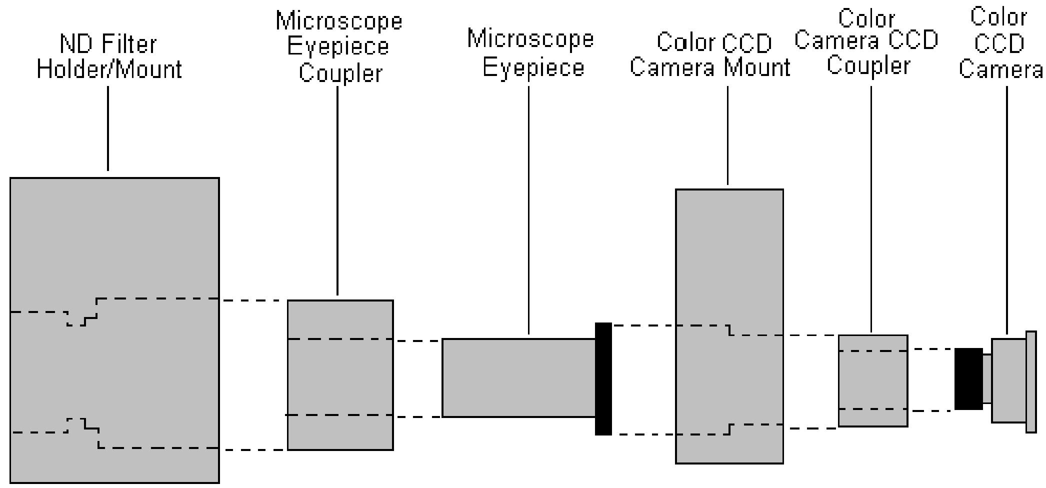


Figure 19: Color CCD Camera Coupling Setup

Spectral System Design

A spectral system was designed using a quartz fiber optic that passes light in the Ultraviolet-Visible range (300 nm to 750 nm). The fibers have a core of high-purity, nonfluorescing quartz clad with an ultraviolet transmitting plastic material. The spectral system consists of an UV quartz fiber optic, a quartz window, a spectrometer, and a PC based portable computer (See Figure 20 and Figure 21).[22]

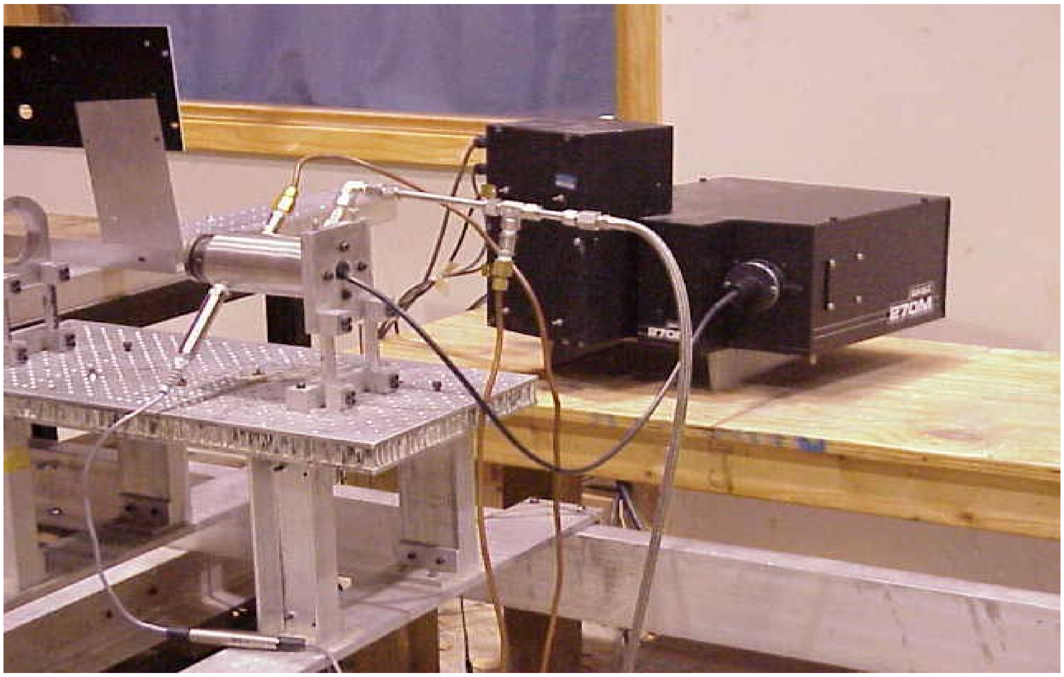


Figure 20: UV Quartz Fiber Optic Measuring System

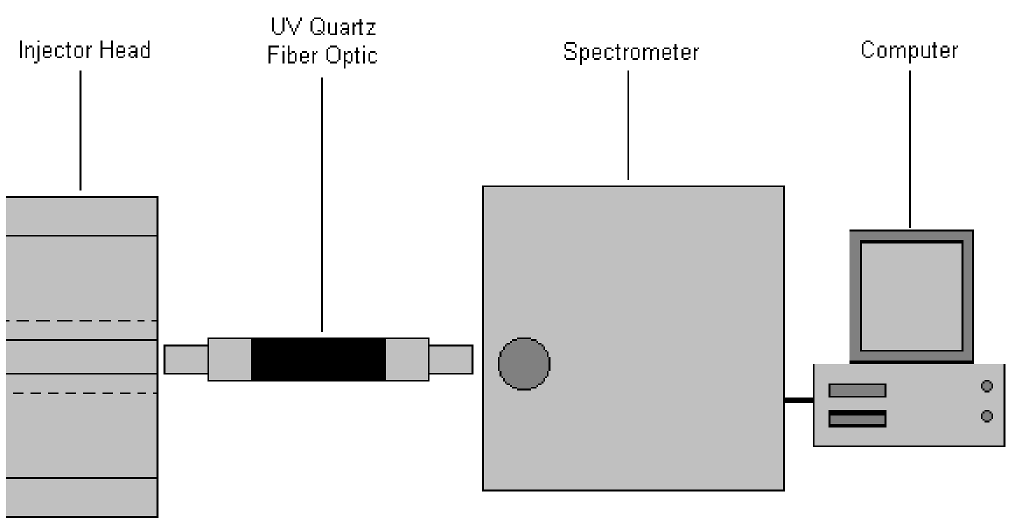


Figure 21: UV Quartz Fiber Optic System

Ultraviolet (UV) Quartz Fiber Optic System

The UV quartz fiber optic has a 10:1 core/clad ratio, which provides maximum transmittance efficiency. The UV quartz fiber optic is used to collect visible light in the 300 nm to 750 nm wavelength region. The UV quartz fiber optic is sheathed in PVC covered monocoil. A stainless steel termination is used 1.125-in from each end of the UV quartz fiber optic. The stainless steel terminations have a 0.185-in diameter. A 0.50-in piece of 0.25-in vacuum hose was placed around the stainless steel termination that plugs into the plug. The vacuum hose provided protection by separating the stainless steel termination from the plug channel wall. The vacuum hose was used as a buffer to reduce contact with the plug and to hold the UV quartz fiber optic centered in front of the quartz window. The other end of the UV quartz fiber optic has a 2-in barrel extension with a 1-in threaded inside diameter placed around the UV quartz fiber optic. A 1-in threaded outside diameter donut ring with a 0.3125-in diameter bore in the center is placed over the UV quartz fiber optic 1.185-in in from the end. The barrel extension is screwed onto the donut ring approximately 1.25-in. The barrel extension is then screwed onto a 1-in threaded tube adapter on the spectrometer (See Figure 22).

A SPEX 270M spectrometer is used to collect the spectral data from the UV quartz fiber optic. The incident light from the UV quartz fiber optic is focused onto the entrance slit of the spectrometer. The entrance slit width was set to 22 µm. This slit width was chosen based on the slit widths used with previous plume emission studies at UALR.[4-8] The spectrometer uses a grating to spread the incident light onto a 1024 pixel silicon photodiode array (PDA). A PC computer was issued to collect the PDA output for analysis.

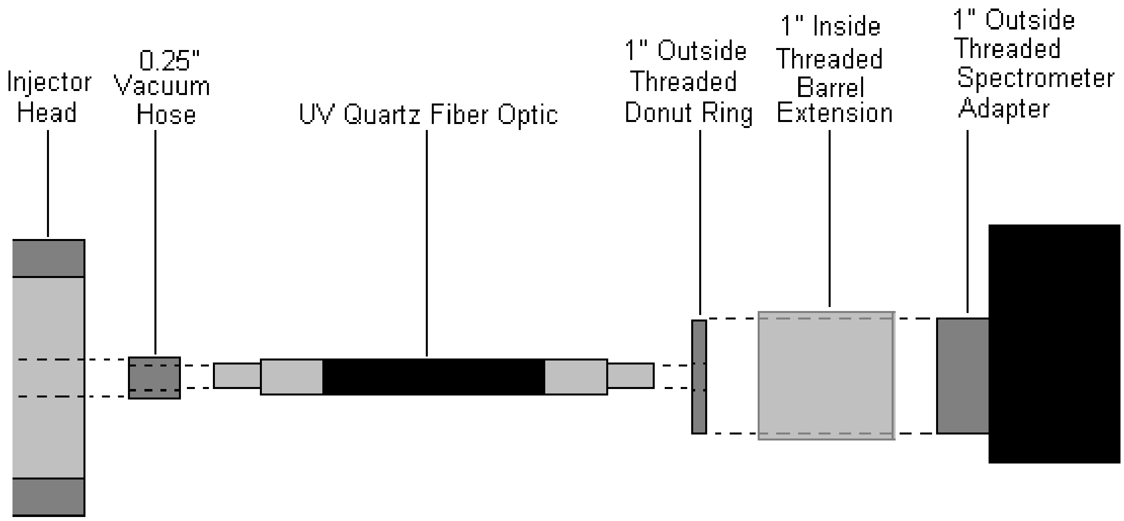
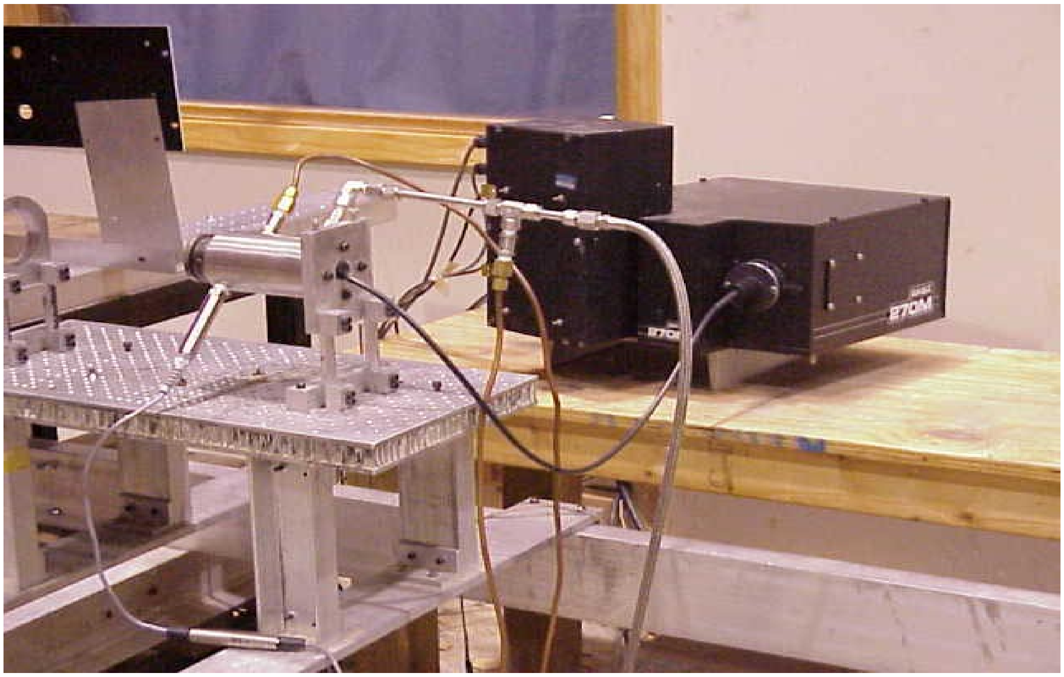


Figure 22: UV Quartz Fiber Optic Coupling Setup



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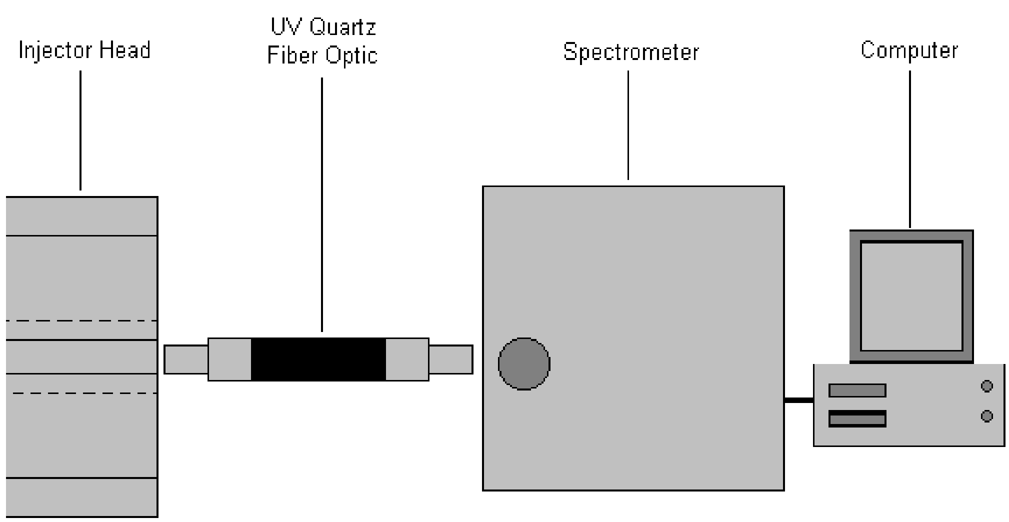

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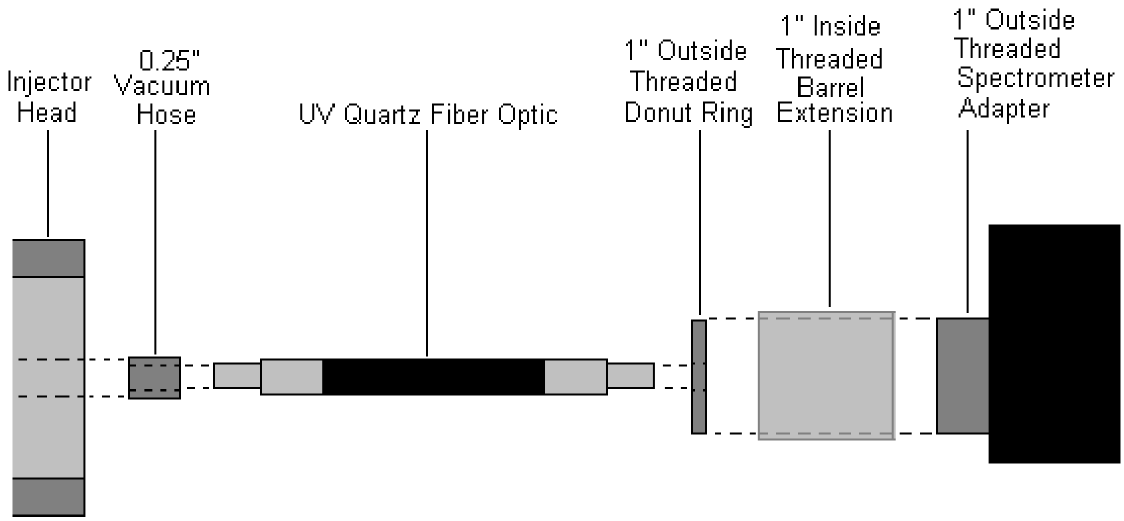

Figure 22: UV Quartz Fiber Optic Coupling Setup

EXPERIMENTAL

Injector Head Design Safety Testing

Once the injector head assembly had been constructed, it was necessary to pressure test the unit to ensure proper o-ring seals and to verify that the sapphire and quartz windows could withstand the pressure. The shaft and the plug were assembled together with the motor. The shaft's four-inlet ports were plugged with stainless steel Swagelok® plug fittings. The assembly was then filled with water under atmospheric pressure. Examination of the two o-rings showed no leakage in the plug. The nozzle end of the motor was sealed with a plug, which had an inlet fitting. A dead weight tester was connected to the plug inlet and the chamber was pressurized to approximately 50 psi. The o-rings were examined for leakage and the window for cracks. This process was repeated at 50 psi increments until the chamber pressure reached 650 psi. Each examination showed that the o-rings had no water leakage and the windows showed no signs of cracking.

Knowing that the windows could withstand the chamber pressure, the injector head assembly and motor were mounted to the labscale testbed for temperature testing. This testing would reveal if any soot would build up on the window during firings. All temperature testing was done using previous fired hydroxyl-terminated polybutadiene (HTPB/N-100) fuel grains. The quartz window was tested first at a low chamber pressure of approximately 210 psi for a duration of 3 sec. The plug was disassembled to examine the quartz window. The quartz window showed no signs of cracking, temperature deformation, or soot. This process was repeated at 100 psi increments until the chamber pressure reached approximately 500 psi (See Appendix C). The same temperature testing process was repeated for the sapphire window (See Appendix C). Each examination showed that the windows had no signs of cracking, temperature deformation, or soot.

Black and White CCD Camera Neutral Density Filter Testing

The black and white CCD camera system was set up with the motor to do ND filter tests. The tests were done to find the best neutral density for collecting clear images from the combustion chamber area. A neutral density that passed too much light would saturate the CCD camera. On the other had , a filter that did not pass enough light would result in a black CCD camera image. The objective was to find a neutral density that allowed an d]adequate amount of light to be passed for collecting clear images from the combustion chamber using the CCD camera.

The 1.3 Optometrics Group ND filter was placed into the ND filter holder/mount and coupled with the borescope and black and white CCD camera lens. The black and white CCD camera was saturated from the amount of light being passed by the ND filter from the combustion chamber area. A neutral density of 2.8 was made by adding a 1.5 Optometrics Group ND filter with the 1.3 Optometrics Group ND filter in the ND filter holder/mount. The same result occurred with the black and white CCD camera being saturated. This led to the purchasing of the 1.0 and 4.0 Kodak Wratten™ 3-in by 3-in gelatin material film ND filter sheets from Edmund Scientific.

Three 1-in diameter circles for each neutral density were cut from the Kodak Wratten™ sheets. Since the light intensity was so bright in the previous tests, a neutral density of 12.0 was chosen using the new filters. The 12.0 neutral density was made by stacking three 4.0 ND filters against each other in the ND filter holder/mount. This resulted in almost no light being transmitted through the ND filters to the black and white CCD camera. The process of changing neutral densities was done until a good neutral density was found for collecting imaging data using the black and white CCD camera (See Appendix D). A 5.0 ND filter setup proved to give the best neutral density for collecting the combustion chamber area images. All ND filter tests were done using HTPB/N-100 fuel grains for 3 second fuel burns. The sapphire window was used in all ND filter tests.

Black and White CCD Camera Combustion Imaging

The black and white CCD camera imaging system was set up to record combustion chamber images at different chamber pressures. An experiment was performed using eight HTPB/N-100 fuel grain firings. The experiment was setup to take two firings each at chamber pressures of 200 psi, 250 psi, 350 psi, and 450 psi. This was done to see if there were any similar characteristics between low, mid, and high chamber pressure firings (See Appendix E). Each motor firing was duplicated to ensure that the same imaging data was being collected at each chamber pressure. All motor firings lasted a duration of 3 seconds and were done with the HTPB/N-100 fuel grain.

The next set of firings using the black and white CCD camera system involved different types of fuel grains: HTPB/PAPI and HTPB/N-100 doped with graphite. A six firing experiment was performed to see if a different fuel grain would supply the same characteristic observed in the previous eight firings in the combustion chamber area (See Appendix F).

Color CCD Camera Neutral Density Filter Testing

The color CCD camera system was set up with the motor to do ND filter tests. The tests were done to find the best neutral density for collecting clear images from the combustion chamber area. The previous ND filter tests could not be used because the sensitivity of the black and white CCD camera was not known. No, sensitivity comparisons could be made between the two cameras.

The first ND filter test was done at a neutral density of 5.3. This neutral density supplied an image that was too dark. Next, a neutral density of 4.0 was tried; this provided an image that was still too dark. This process was repeated until a clean image was collected at a neutral density of 3.8 at a low chamber pressure of 200 psi (See Appendix G).

UV Quartz Fiber Optic Testing

The UV quartz fiber optic system was setup to collect internal combustion chamber area spectral data in the 475 nm to 625 nm ultraviolet-visible region at chamber pressures of 200 psi and 250 psi. Two motor firings were done at each chamber pressure to ensure that combustion chamber spectral emissions data could be duplicated and verified with previous plume spectral emissions studies performed on the UALR hybrid rocket motor.

RESULTS AND DISCUSSION

Injector Head Design

The new injector head was designed to allow for fiber optic studies while keeping the same combustion characteristics as the previous injector head design. The new injector head was designed with two sections: the injector head shaft and the fiber optic plug. The shaft was designed with the minimum amount of changes being done to the previous injector head design. The only significant change came where the oxygen/nitrogen port was incorporated into the original design.

The fiber optic plug o-ring seals and sapphire window were pressure tested prior to any firings. This was accomplished by pressure testing the injector head and motor using a dead weight tester. The o-ring seals and sapphire window were pressure tested up to 650 psi, which is 18 percent greater than a maximum firing. The o-ring seals were checked for leaks and the sapphire window for cracks. Both showed no signs of failure during the pressure tests.

The oxygen/nitrogen port in the injector head was then tested. The chamber body was not coupled to the injector head shaft for this test. The nitrogen was turned 'on' to verify that there was flow coming out of the port between the shaft wall and the plug. The injector head design was considered safe for firings.

Black and White CCD Camera Measurements

All images that were collected from the combustion chamber area were not inverted mirrors or lenses in anyway by the borescope or the camera lens. In every firing in the low, mid, and high chamber pressure firings a clockwise rotation was found in the combustion chamber area. In one of the 450 psi chamber pressure firings a large enough particle was captured to provide an angular velocity to be calculated for this firing. The particle moved a distance of 45 degrees or $\pi/4$ radians over a 0.13 second duration (See Figure 23). The angular velocity for the 450 psi chamber pressure was calculated to be 6.04 rad/sec which is approximately 1 rev/sec. The clockwise rotation was more visible in the higher chamber pressure firings due to hotter fuel grain burns. This provided a brighter image to be viewed by the black and white CCD camera (See Figure 24).

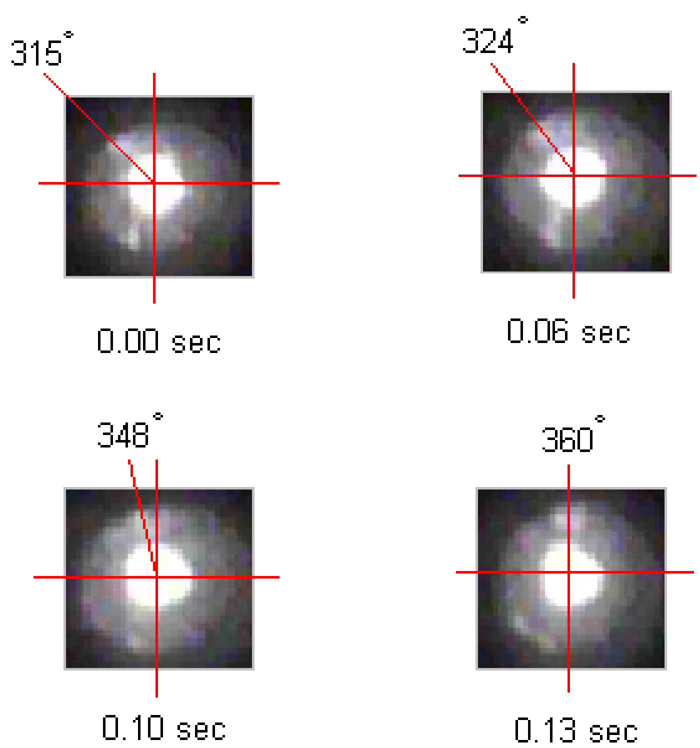

Figure 23: Rotational Movement of a Particle during a 450 psi Chamber Pressure Firing

Figure 24: Different Chamber Pressure Images

Color CCD Camera Measurements

All images that were collected from the combustion chamber area were not inverted mirrors or lenses in anyway by the borescope, microscope eyepiece or the camera lens. The ND filter tests are the only firings that have been recorded to this point for the color CCD camera system. A HTPB/N-100 fuel grain doped with aluminum chloride was used in three of the ND filter tests. An interesting discovery came from firing the aluminum chloride doped fuel grains. It was discovered that the chloride salt when heated during the hybrid rocket firing produced moisture inside the injector head. The moisture produced a mist that covered the sapphire window in the fiber optic plug. This caused the recorded image from the combustion chamber to be blurry.

The ND filter test firings have shown the same clockwise rotation that was recorded previously with the black and white CCD camera system. While doing the ND filter testing a 15x microscope eyepiece was used to provided a much larger image than the black and white CCD camera setup (See Figure 25).

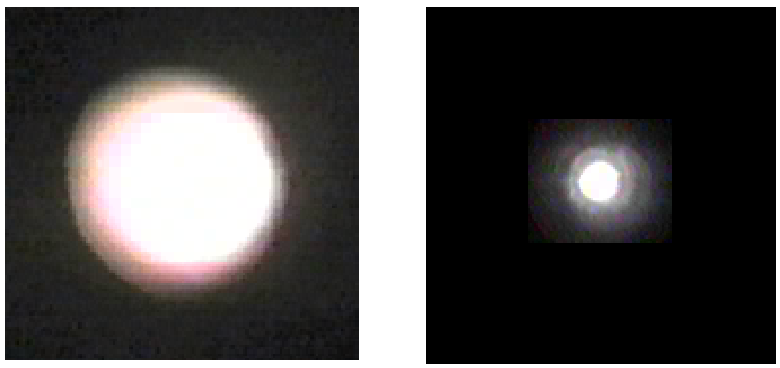

Figure 25: Magnified Color CCD Camera Image (Left Side) and Original Size Black and White CCD Camera Image (Right Side)

Ultraviolet Quartz Fiber Optic Measurement

The UV quartz fiber optic spectral data was collected in the ultraviolet-visible 475 nm to 625 nm region. A spectral peak at approximately 590 nm was detected in the combustion chamber area (See Figure 26 and Figure 27). The spectral peak at 590 nm corresponds to the sodium (Na) atomic line emissions. Sodium is present as a trace element in the HTPB fuel grain. This spectral peak was verified by other studies performed at UALR dealing with plume spectral emissions.

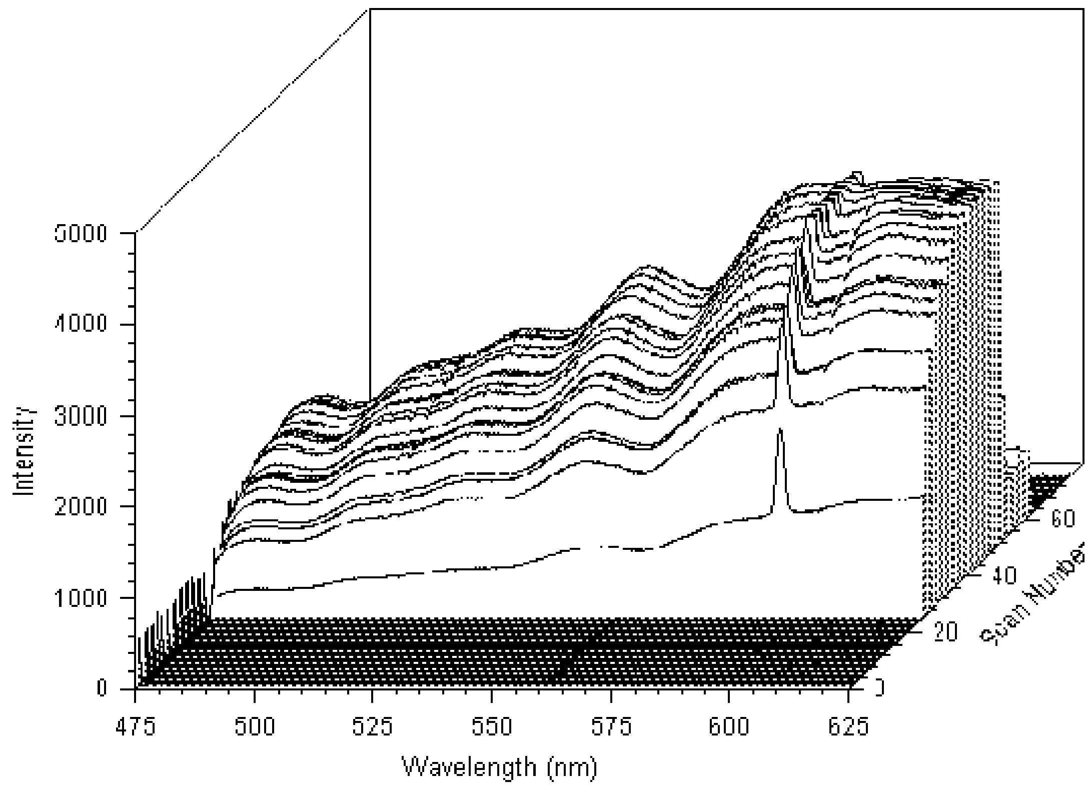

Figure 26: Cascade Plot of Sodium Emissions

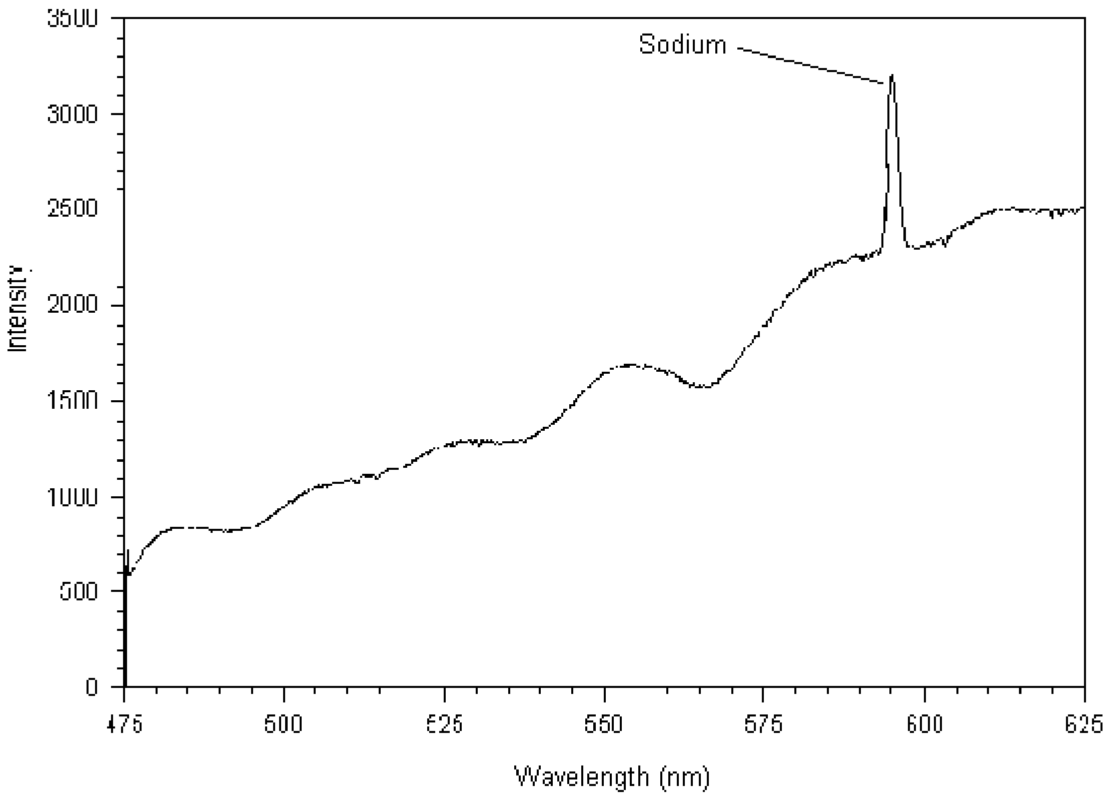

Figure 27: Sodium Emissions in the 590 nm Region

CONCLUSION

This project resulted in the design of an injector head that allows fiber optics to be incorporated into the hybrid rocket motor for internal combustion chamber area studies. The new injector head provides the ability to perform imaging and spectral studies in the combustion chamber area during a motor firing. The two imaging systems provided ways of collecting imaging data from the internal combustion chamber area. The imaging systems provided images showing a clockwise rotation in the combustion chamber area that was not previously known.

The spectral system provides quality ultraviolet-visible spectral data from the internal combustion chamber area that can be used to study atomic and molecular emission. This could be used in monitoring engine health and for comparative combustion diagnostics.

Future work for this project can be done studying the rotation in the combustion chamber area. This phenomenon needs to be studied in more detail to correlate the angular velocity with the oxygen mass flow rate during a rocket motor firing. That relationship could provide information on how a fuel grain is burned over a duration of time and if there are different rotation speeds with doped fuel grains compared to the standard HTPB/N-100 fuel grain. In order to achieve this, an optical system for the black and white CCD camera needs to be designed that will magnify the image between the borescope and the black and white CCD camera lens. The groundwork for this was performed during the color CCD camera system setup.

Also, future work can be done with the spectral system to collect emissions from the internal combustion chamber area with doped fuel grains of known chemical element concentrations. A new study using infrared fiber optics can be done with the new injector head design to study spectral emissions in the near infrared (750 – 1100 nm) and the mid infrared (2 – 16 μm) regions. Only changes in lens materials and the fiber materials would be necessary. The basic design and layout of this study can be used.

REFERENCES

1. Shanks, R. B., “A Labscale Hybrid Rocket Motor and Facility for Plume Diagnostic and Combustion Studies”, A Doctoral Dissertation, University of Arkansas at Little Rock, Little Rock, Arkansas, 1994.

2. Shanks, R. B. and Hudson M. K., “The Design and Control of a Labscale Hybrid Rocket Facility for Spectroscopy Studies”, AIAA Paper No. 94-3016, June 1994.

3. George, B., “Local Effects of Solid Rocket Motor Exhaust on Stratospheric Ozone Concentrations”, Internet Posting at http://www.au.af.mil/au/database/research/ay1996/afit_en/gee-env-96d-04.htm, 1997.

4. Hudson, M. K., Shanks, R. B., Snider, D. H., Lindquist, D. M., Luchini, C., and Rooke, S., “UV, Visible, and Infrared Spectral Emissions in Hybrid Rocket Plumes”, International Journal of Turbo and Jet Engines, 15, 71-87 (1998).

5. Hudson, M. K., Shanks, R. B., Snider, D. H., and Lindquist, D. M., “Spectroscopic Survey of Hybrid Plume Emissions”, AIAA Paper No. 94-3015, June 1994.

6. Underhill-Shanks, K., and Hudson, M. K., “Infrared Radiometric Instrumentation for Rocket Plumes and Combustion Studies”, AIAA Paper No. 94-2986, June 1994.

7. Shanks, R., Rooke, S., and Hudson, M. K., “Quantization Study of Metals in the Hybrid Rocket Plume”, AIAA Paper No. 95-2791, July 1995.

8. Maxwell, K. L., Chouinard, A. P., and Hudson, M. K., “Investigation of Metallic Molecular Bands in Hybrid Rocket Plumes”, AIAA Paper No. 99-2137, June 1999.

9. Wright, A., Wynne, P., Rooke, S., and Hudson, M. K., and Strong, M., “A Hybrid Rocket Regression Rate Study of Guanidinium Azo-Tetrazolate”, AIAA Paper No. 98-3186, July 1998.

10. Wright, A., Wynne, P., Rooke, S., and Hudson, M. K., “A Hybrid Rocket Regression Rate Study of AminoGuanidinium Azo-Tetrazolate”, AIAA Paper No. 98-3187, July 1998.

11. Luchini, C. B., Wynne, P., and Hudson, M. K., “Investigation of GAT as a High Regression Rate Hybrid Rocket Fuel”, AIAA Paper No. 96-2592, July 1996.

12. Luchini, C. B., Wynne, P., Hudson, M. K., and Rooke, S., “Hydrocarbon Hybrid Rocket Fuel Regression Rate Studies”, AIAA Paper No. 96-2595, July 1996.

13. Desrochers, M., “Instrumentation Of A Labscale Hybrid Rocket”, A Masters Thesis, University of Arkansas at Little Rock, Little Rock, Arkansas, 1997.

14. Wright, A. B., Tomany, A. M., Wright, A. M., and Hudson, M. K.,” Pressure Measurement in the Post-Combustion Section of a Hybrid Rocket Motor”, AIAA Paper No. 99-2536, June 1999.

15. Desrochers, M. F., Olsen, G. W., Luchini, C., and Hudson, M. K., “Correlation of Pressure, Plume Flicker, and Acoustics in Labscale Hybrid Rockets”, AIAA Paper No. 96-2834, July 1996.

16. Desrochers, M. F., Olsen, G. W., and Hudson, M. K., “Investigation of Pressure, Plume Flicker, and Thrust in a Labscale Hybrid Rocket”, AIAA Paper No. 97-3036, July 1997.

17. Wright, A. M., Dunn, L., Alford, B., Patton, J., Maxwell, K., and Hudson, M. K., “A Thrust and Impulse Study of Guanidinium Azo-Tetrazolate as an Additive for Hybrid Rocket Fuel”, AIAA Paper No. 99-2538, June 1999.

18. Chouinard, A. P., Adams, A., Wright, A. M., and Hudson, M. K., “Multi-Wavelength Opacity Study of a Hybrid Rocket Plume II”, AIAA Paper No. 98-3992, July 1998.

19. Hudson, M. K., Chouniard, A. P., Adams, A., Luchini, C. B., and Willis, J. D., “Multi-Wavelength Opacity Study of a Hybrid Rocket Plume”, AIAA Paper No. 96-2833, July 1996.

20. Hudson, M. K., Personal Communication, Professor of Applied Science and Chemistry, University of Arkansas at Little Rock.

21. Parker O-Ring Handbook, Parker Hannifin Corporation, Cleveland, OH, 1991.

22. Snider, D., Hudson, M. K., Shanks, R., and Cole, R., “Evaluation of Photodiode Arrays for Use in Rocket Plume Monitoring and Diagnostics”, Proceedings Arkansas Academy of Science, Vol. 48, 1994.

23. Melles Griot 95/96 Catalog, The Bibby Electro-Optics Company.

BIBLIOGRAPHY

Chouinard, A. P., Adams, A., Wright, A. M., and Hudson, M. K., "Multi-Wavelength Opacity Study of a Hybrid Rocket Plume II", AIAA Paper No. 98-3992, July 1998.

Desrochers, M., "Instrumentation Of A Labscale Hybrid Rocket", A Masters Thesis, University of Arkansas at Little Rock, Little Rock, Arkansas, 1997.

Desrochers, M. F., Olsen, G. W., Luchini, C., and Hudson, M. K., "Correlation of Pressure, Plume Flicker, and Acoustics in Labscale Hybrid Rockets", AIAA Paper No. 96-2834, July 1996.

Desrochers, M. F., Olsen, G. W., and Hudson, M. K., "Investigation of Pressure, Plume Flicker, and Thrust in a Labscale Hybrid Rocket", AIAA Paper No. 97-3036, July 1997.

George, B., "Local Effects of Solid Rocket Motor Exhaust on Stratospheric Ozone Concentrations", Internet Posting at http://www.au.af.mil/au/database/research/ay1996/afit_en/gee-env-96d-04.htm, 1997.

Hudson, M. K., Shanks, R. B., Snider, D. H., Lindquist, D. M., Luchini, C., and Rooke, S., "UV, Visible, and Infrared Spectral Emissions in Hybrid Rocket Plumes", International Journal of Turbo and Jet Engines, 15, 71-87 (1998).

Hudson, M. K., Shanks, R. B., Snider, D. H., and Lindquist, D. M., "Spectroscopic Survey of Hybrid Plume Emissions", AIAA Paper No. 94-3015, June 1994.

Hudson, M. K., Chouniard, A. P., Adams, A., Luchini, C. B., and Willis, J. D., "Multi-Wavelength Opacity Study of a Hybrid Rocket Plume", AIAA Paper No. 96-2833, July 1996.

Hudson, M. K., Personal Communication, Professor of Applied Science and Chemistry, University of Arkansas at Little Rock.

Luchini, C. B., Wynne, P., and Hudson, M. K., "Investigation of GAT as a High Regression Rate Hybrid Rocket Fuel", AIAA Paper No. 96-2592, July 1996.

Luchini, C. B., Wynne, P., Hudson, M. K., and Rooke, S., "Hydrocarbon Hybrid Rocket Fuel Regression Rate Studies", AIAA Paper No. 96-2595, July 1996.

Maxwell, K. L., Chouinard, A. P., and Hudson, M. K., "Investigation of Metallic Molecular Bands in Hybrid Rocket Plumes", AIAA Paper No. 99-2137, June 1999.

Melles Griot 95/96 Catalog, The Bibby Electro-Optics Company.

Parker O-Ring Handbook, Parker Hannifin Corporation, Cleveland, OH, 1991.

Shanks, R. B., “A Labscale Hybrid Rocket Motor and Facility for Plume Diagnostic and Combustion Studies”, A Doctoral Dissertation, University of Arkansas at Little Rock, Little Rock, Arkansas, 1994.

Shanks, R. B. and Hudson M. K., “The Design and Control of a Labscale Hybrid Rocket Facility for Spectroscopy Studies”, AIAA Paper No. 94-3016, June 1994.

Shanks, R., Rooke, S., and Hudson, M. K., “Quantization Study of Metals in the Hybrid Rocket Plume”, AIAA Paper No. 95-2791, July 1995.

Snider, D.

Underhill-Shanks, K., and Hudson, M. K., “Infrared Radiometric Instrumentation for Rocket Plumes and Combustion Studies”, AIAA Paper No. 94-2986, June 1994.

Wright, A., Wynne, P., Rooke, S., and Hudson, M. K., and Strong, M., “A Hybrid Rocket Regression Rate Study of Guanidinium Azo-Tetrazolate”, AIAA Paper No. 98-3186, July 1998.

Wright, A., Wynne, P., Rooke, S., and Hudson, M. K., “A Hybrid Rocket Regression Rate Study of AminoGuanidinium Azo-Tetrazolate”, AIAA Paper No. 98-3187, July 1998.

Wright, A. B., Tomany, A. M., Wright, A. M., and Hudson, M. K.,” Pressure Measurement in the Post-Combustion Section of a Hybrid Rocket Motor”, AIAA Paper No. 99-2536, June 1999.

Wright, A. M., Dunn, L., Alford, B., Patton, J., Maxwell, K., and Hudson, M. K., “A Thrust and Impulse Study of Guanidinium Azo-Tetrazolate as an Additive for Hybrid Rocket Fuel”, AIAA Paper No. 99-2538, June 1999.

APPENDIX A:
Black and White CCD and Color CCD Specifications

CCD Camera	Black and White	Color
Effective Pixels	510 (H) x 492 (V)	512 (H) x 492 (V)
Pick-Up Area	6.6 μm (H) x 8.8 μm (V)	3.61 μm (H) x 2.72 μm (V)
Pixel Dimensions	17 μm (H) x 13 μm (V)	7.2 μm (H) x 5.6 μm (V)
Horizontal Scan Freq.	15.734 kHz	15.734 kHz
Vertical Scan Freq.	59.9 Hz	59.94 Hz
Frames per Second	30 Frames	30 Frames
Horizontal Resolution	380 Lines	> 330 Lines
Vertical Resolution	350 Lines	> 350 Lines
Signal-to-Noise Ratio	50 dB	> 40 dB
Min. Required Illumination	1.5 lux	40 lux
Power Supply Voltage	12.0 V DC	5.0 – 6.0 V DC

Table 2: CCD Camera Specifications

APPENDIX B:
Symmetric Bi-Convex Calculations

All equations used in this appendix are from the Melles Griot 95/96 catalog.[23] The power diopter equation was used in determining the diopters of a symmetric bi-convex lens with a radius of curvature of 11.25 cm. Diopters are a way of expressing focal length. The diopters of the lens was calculated to be 22.5 cm. The 22.5 cm was then used to calculate the focal length of the lens, by using a focal length equation that incorporated diopters into the equation. The focal length for this lens was calculated to be approximately 4.44 cm. To find what the magnification for this lens was, a magnification equation was used that used the focal length of the lens. The magnification of the lens was calculated to be approximately 5.6 for a symmetric bi-convex lens with a radius of curvature of 11.25 cm.

Equations:

diopters = 2 • radius of curvature (2 times radius of curvature because symmetric bi-convex)

diopters = 2 • 11.25 cm

diopters = 22.5 cm

focal length = 100 / diopters

focal length = 100 / 22.5 cm

focal length ≅ 4.44 cm

magnification = 250 mm / focal length (mm)

magnification = 250 mm / 44.4 mm

magnification ≅ 5.6

APPENDIX C:
Quartz and Sapphire Window Temperature Tests

Date	Window	Chamber Pressure (psi)	Time (sec)	Fuel	Flow (lbm/sec)	Pass or Fail	Soot
7-12-99							
1	Quartz	~ 210	3	HTPB	0.0439	P	No
2	Quartz	~ 330	3	HTPB	0.0714	P	No
3	Quartz	~ 370	3	HTPB	0.0902	P	No
4	Quartz	~ 510	3	HTPB	0.1880	P	No
7-16-99							
1	Sapphire	~ 110	3	HTPB	0.0436	P	No
2	Sapphire	~ 200	3	HTPB	0.0756	P	No
3	Sapphire	~ 380	3	HTPB	0.0750	P	No
4	Sapphire	~ 475	3	HTPB	0.1120	P	No

Table 3: Quartz and Sapphire Window Temperature Tests

APPENDIX D:
Black and White CCD Camera Neutral Density Filter Tests

Date	Neutral Density	Chamber Pressure (psi)	Time (sec)	Fuel	Flow (lbm/sec)	Result of Image (Dark, Light, or Correct)
7-30-99						
1*	12.0		~ 1	HTPB		Dark
8-3-99						
1	6.0	~ 100	3	HTPB	0.0423	Dark
2*	5.0	~ 170	3	HTPB	0.0737	
3	5.0	~ 320	3	HTPB	0.0652	Correct
4	4.0	~ 300	3	HTPB	0.0644	Light
5*	5.3	~ 250	3	HTPB	0.0639	
6*	5.3	~ 270	3	HTPB	0.0624	
7*	5.3	~ 240	3	HTPB	0.0609	
8	5.0	~ 240	3	HTPB	0.0591	Correct

- - indicates a problem occurred during test.

Table 4: Black and White CCD Camera Neutral Density Filter Tests

Problems

7-30-99
Run 1 – Firing had to be shut down early due to a computer problem. A data sheet was not able to be collected showing chamber pressure, duration of firing, or flow for this run. A positive is that imaging data was collected and recorded showing that the neutral density was too dark.

8-3-99
Run 2 – No imaging data was collected due to the black and white CCD camera not being turned ‘on’.

Run 5 – No imaging data was collected. Don’t know cause of problem. Did a flashlight test, image was recorded.

Run 6 – No imaging data was collected. Don’t know cause of problem. Reexamined all optical system equipment, everything checks out to be working. Did a flashlight test, image was recorded.

Run 7 – No imaging data was collected. Found problem, coax cable from black and white CCD camera to VCR was loose.

APPENDIX E:
Black and White CCD Camera Duplication Firings

Date	Neutral Density	Chamber Pressure (psi)	Time (sec)	Fuel	Flow (lbm/sec)	Window
8-4-99						
1	5.0	~ 200	3	HTPB	0.0537	Sapphire
2	5.0	~ 200	3	HTPB	0.0536	Sapphire
3	5.0	~ 250	3	HTPB	0.0724	Sapphire
4	5.0	~ 250	3	HTPB	0.0722	Sapphire
5	5.0	~ 450	3	HTPB	0.0962	Sapphire
6	5.0	~ 350	3	HTPB	0.0954	Sapphire
7	5.0	~ 350	3	HTPB	0.1140	Sapphire
8	5.0	~ 450	3	HTPB	0.1010	Sapphire

Table 5: Black and White CCD Camera Duplication Firings

APPENDIX F:
Black and White CCD Camera Different Fuel Grain Firings

Date	Neutral Density	Chamber Pressure (psi)	Time (sec)	Fuel	Flow (lbm/sec)
8-11-99					
1	5.0	~ 140	4	PAPI	0.0595
2	5.0	~ 180	4	PAPI	0.0800
3	5.0	~ 430	4	Graphite	0.0794
4	5.0	~ 350	4	Graphite	0.0789
5	5.0	~ 300	4	PAPI	0.0863
6	5.0	~ 250	4	PAPI	0.0997

Table 6: Black and White CCD Camera Different Fuel Grain Firings

APPENDIX G:
Color CCD Camera Neutral Density Filter Tests

Date	Neutral Density	Chamber Pressure (psi)	Time (sec)	Fuel	Flow (lbm/sec)	Result of Image (Dark, Light, or Correct)
10-19-99						
1	5.3	~ 100	3	HTPB	0.0386	Dark
2	3.5	~ 100	4	HTPB	0.0386	Dark
3	3.5	~ 100	4	HTPB	0.0399	Light
4	2.5	~ 100	4	HTPB	0.0399	Light
11-8-99						
1	3.0	~ 200	4	HTPB	0.1070	Light
2*	3.3	~ 200	4	Aluminum	0.1060	Dark (Fuzzy)
3*	4.0	~ 180	4	Aluminum	0.1050	Dark (Fuzzy)
4*	3.3	~ 150	4	Aluminum	0.1.30	Dark (Fuzzy)
12-6-99						
1	3.3	~ 200	4	HTPB	0.0390	Light (Fuzzy)
2	4.0	~ 300	4	HTPB	0.0591	Dark
3	3.0	~ 200	4	HTPB	0.0395	Light
4*	3.3					
5	3.3	~ 200	4	HTPB	0.0418	Light
6	3.5	~ 200	4	HTPB	0.0417	Light
7	4.0	~ 210	6	Graphite	0.0415	Dark
8	3.8	~ 210	6	Graphite	0.0412	Correct

- - indicates a problem occurred during test.

Table 7: Color CCD Camera Neutral Density Filter Tests

Problems

11-8-99
Run 2 – Aluminum fuel grains caused moisture inside the combustion chamber area that caused the window to become misted over. Caused fuzzy image to be collected from the combustion chamber area.

Run 3 – See Run 2.

Run 4 – See Run 2.

12-6-99
Run 4 – Record button on VCR was not pushed.