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Abstract

The University of Arkansas at Little Rock (UALR) labscale hybrid rocket injector head was redesigned to incorporate fiber optics to study the chemistry and fluid flow inside the combustion chamber during firings. An imaging fiber optic (boroscope) was used to capture the image of the burning fuel grain and transmit it to a CCD camera. Slow motion video capture of the firings was used to study the fluid flow patterns during combustion. Swirling and pulsating flow fields were observed, which indicate that one-dimensional flow model assumptions are not valid. A quartz fiber, which can pass ultraviolet, visible, and near infrared light, was placed in the measurement port. The light was passed to a UV-Vis spectrograph, and spectral studies using fuels doped with metals were conducted.

Introduction

In 1993 a labscale hybrid rocket facility, complete with computer control and data acquisition system, was designed and constructed at the University of Arkansas at Little Rock (UALR) (see Figure 1). This facility has served to aid the aerospace community in studies on hybrid rockets for future use as boosters on the Space Shuttle Main Engine (SSME). [1] Studies to characterize the physical parameters of the hybrid rocket such as: pressure, plume flicker, acoustical output, and thrust have been performed at the UALR facility.[2,3] Exhaust plume spectroscopy has been an area of focus for hybrid rockets. NASA's John C. Stennis Space Center (SSC), a leader in exhaust plume diagnostics, utilizes plume spectroscopy for vehicle health management (VHM). [4] Diagnostics for VHM are provided by atomic spectral emissions techniques. The relationship of excited atomic species in the motor plume to the amounts introduced by failures in the system provide good diagnostics.

Hybrid rockets provide a high source of energy for atomization and excitation of elements involved. Hydroxyl-terminated polybutadiene (HTPB), an unconditional fuel, is utilized in the hybrid. The hybrid has an oxygen to fuel ratio (O/F) of 1.5 to 4.5. HTPB burns stoichiometrically to CO and H_2O at an O/F ratio of 2.074.[1] The temperature in the combustion chamber is above 3000°C providing good energy for the atomization process. [5] Molecular band and atomic line emissions have been studied to determine interference, infractions of species present as molecular versus atomic.[6]

Gas emission, particle detection, and spectral analysis studies have been conducted at the UALR facility. Spectral emission have been detected in the ultraviolet-visible (300-750nm), near infrared (750-1100nm), and mid infrared (2-16um) of the hybrid rocket plume.[5] Infrared studies have been conducted with a Fourier transform infrared (FTIR) spectrometer.

Although UALR, SSC, and other rocket facilities have conducted extensive research on the external parameters of the hybrid rocket plume, no studies have been conducted viewing, characterizing, or collecting data from the internal combustion chamber during firings. Internal combustion studies would support previous plume studies and offer information for comparative analysis. Viewing the inside of the motor will provide oxygen to fuel ratio data and internal flow characteristics of a healthy engine. Spectral analysis of internal combustion chamber can be correlated with plume spectral analysis.

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The goal of this project was to redesign the UALR labscale hybrid rocket motor to include an optical port. An imaging fiber optic is utilized to capture the image of the burning fuel grain and transmit it to a CCD camera. An ultraviolet fiber optic is utilized to collect spectral data and transfer it to a spectrograph.

Design

Injector Head

The original injector head was redesigned to incorporate fiber optics (see Figure 2) while maintaining the oxygen flow requirements of the original injector head.[6] The length, diameter, mounting to the motor, and other physical characteristics were not changed.

The new injector head design consists of two sections: the injector head shaft (IHS) and the fiber optic plug (FOP). The length of the injector head was increased to relocate the oxygen/nitrogen inlet port. The oxygen/nitrogen inlet port, which was originally located along the motor centerline, was moved to the side so that the FOP could be axially located (see Figure 3).

Protecting the fiber optics from the combustion chamber temperature and pressure was a primary design concern. A fiber optic plug, with either a quartz or sapphire window, was bolted into the IHS. This design was chosen so that the window could be inspected or replaced without disassembling the motor. O-rings were used to seal the FOP and the window, so that hot combustion gases cannot escape through the rear of the motor.

The FOP has a channel into which the fiber optic instrumentation is inserted and which is protected from the interior of the motor by the window. This allows the instrumentation to be inserted or adjusted.

The FOP provides the imaging fiber optic a view through the center of the hybrid rocket motor combustion chamber. This allows visual and spectral studies of the combustion process.

Optical Systems

There are two different optical setups: imaging (boroscope) and UV-vis. The imaging optical system includes an imaging fiber optic (boroscope), coupling devices, neutral density (ND) filters, a CCD camera, a video cassette recorder (VCR), and a television monitor (see Figures 5 & 6). A Hawkeye 17 focusing boroscope is used to collect visual images. The boroscope eyepiece is inserted into a ND filter holder. The ND filter holder mounts to a bracket which supports the boroscope and maintains the distance between the boroscope eyepiece and the FOP window. Kodak Wratten gelatin film is used as the Neural Density filter. The ND filter reduces light intensity across visible spectrum without altering the spectral image.

The CCD camera lens fits into the other side of the ND filter holder. A black and white CCD camera with NTSC output transmits the image to a VCR or TV.

The UV-Vis system is made of a quartz window, a UV quartz fiber optic, a spectrograph, and a PC based portable computer (see Figure 5). For maximum transmittance efficiency a 3ft UV quartz fiber optic with 10:1 core/clad ratio is used. The UV quartz fiber optic passes 300nm to 750nm light without distortion. The UV quartz fiber optic is attached to two coupling devices: a donut ring and a barrel extension. The UV quartz coupling setup is interfaced to a SPEX270 spectrograph. The output of the spectrograph is connected to a portable PC computer.

Experimental

Imaging

The fiber optic imaging system was set up as shown in Figures 4 and 5. HTPB fuel, which was doped with 1% carbon, was used to generate the visual images. Several firings, each lasting 4 seconds, were performed at increasing oxygen mass flows (0.04 - 0.081bm/sec). The VCR image was transferred from the tape to computer via an ATI-TV wonder video capture card.

UV-Vis

The UV-Vis spectral system was assembled as shown in figure 6.

Since manganese produced a distinctive spectrum in the plume emissions,[5] the HTPB fuel was doped with 100, 200, and 400ppm manganese. Four second duration firings at an oxygen mass flow of 0.06 lbm/sec were conducted. The spectrograph scanned the UV-Vis range 75 times for each experiment. Scanning was initialized two seconds before firing and continued after shutdown. This shows the initial ignition event and the shutdown event. Data was saved and transferred to a desktop PC for analysis.

Results and Discussion

Imaging

Baseline studies indicated a clockwise swirling, rotational, pulsating flow pattern. This flow pattern was observed in the combustion chamber (mixing region) (see Figure 7). The center of the flame looked similar to the optical Fraunhofer white light pattern (see Figure 8). The flow pattern resembled a fan at the end of a dark tunnel with a bright light shining through. Toward the end of the experiment, the light at the center of the motor intensified. This may be due to the system becoming fuel rich as the oxygen is terminated. As the firing ends the flame may be propagating in the direction of the oxygen. Before extinguishing the flame swirled, similar to a spinning pinwheel.

The firings conducted at low and mid oxygen mass flow offered good visual data. The high oxygen mass flow did not provide good visual information. This could be due to an increase in pressure and oxygen flow ratio. This could also be due to what is characterized as disordered state in combustion. The firings with 1% carbon doped fuel highlighted the swirling effect. The swirling appeared more intense for used fuel grains, fuels which had been fired once, than new ones, fuels which are fired for the first time. This could be due to the char layer deposited from previous firings acting as an opacifier. The soot particles may add to the swirling affect. The increased inner diameter may also increase the swirling due to what is known as ratcheting state, a state where one or more rings drift in a circular path, speeding up and slowing down in a characteristic manner.

Combustion chaos studies conducted with burner stabilized premixed flames aid in identifying the mechanisms which create the various fluid dynamic effects observed in the hybrid rocket. A bright glowing pattern is characterized as a solid cell and the hottest region. The ordered state which resembles pulsating movement is characterized by concentric rings of equal-size cells. Heavy hydrocarbon-air mixtures on a circular porous plug burner produced ordered states.

The hopping state is characterized by a hopping motion in which individual cells change their angular position. This state visibly resembles the swirling pattern. It is typically observed in isobutane $[(CH_3)_3CH]$ -air cellular flames.

The spinning pinwheel at the end of the firing may be characterized as a rotating state. This would result from the propagation of a nonsymmetric pattern from a broken symmetric pattern. The intermittent state describes to entire flow pattern as seen by an observer. It is observed when an ordered pattern appears at irregular intervals of time. Thus, it is a combination of states.

UV-Vis

Molecular band emissions or atomic line emissions may be formed in the UV-Vis spectral region. In this study band emissions were seen. As detected in the hybrid plume, baseline emission detected sodium in the combustion chamber. Figure 9 shows sodium emission in the 590 wavelength. This correlates with the data from plume emission. Manganese was detected in the metal seeded firings. Figure 10 shows manganese emission at 550 nm. This spectral data confirms plume emission data.

Conclusion

The swirling pulsating flow observed in the combustion chamber indicates that the one-dimensional flow assumptions are not valid. This study provided visual information that characterizes the internal combustion chamber flow as 3-D. The imaging data offers insight on the effects oxygen to flow ratio to the combustion process. The UV-Vis experiments correlate with the hybrid rocket plume emission studies.

Acknowledgments

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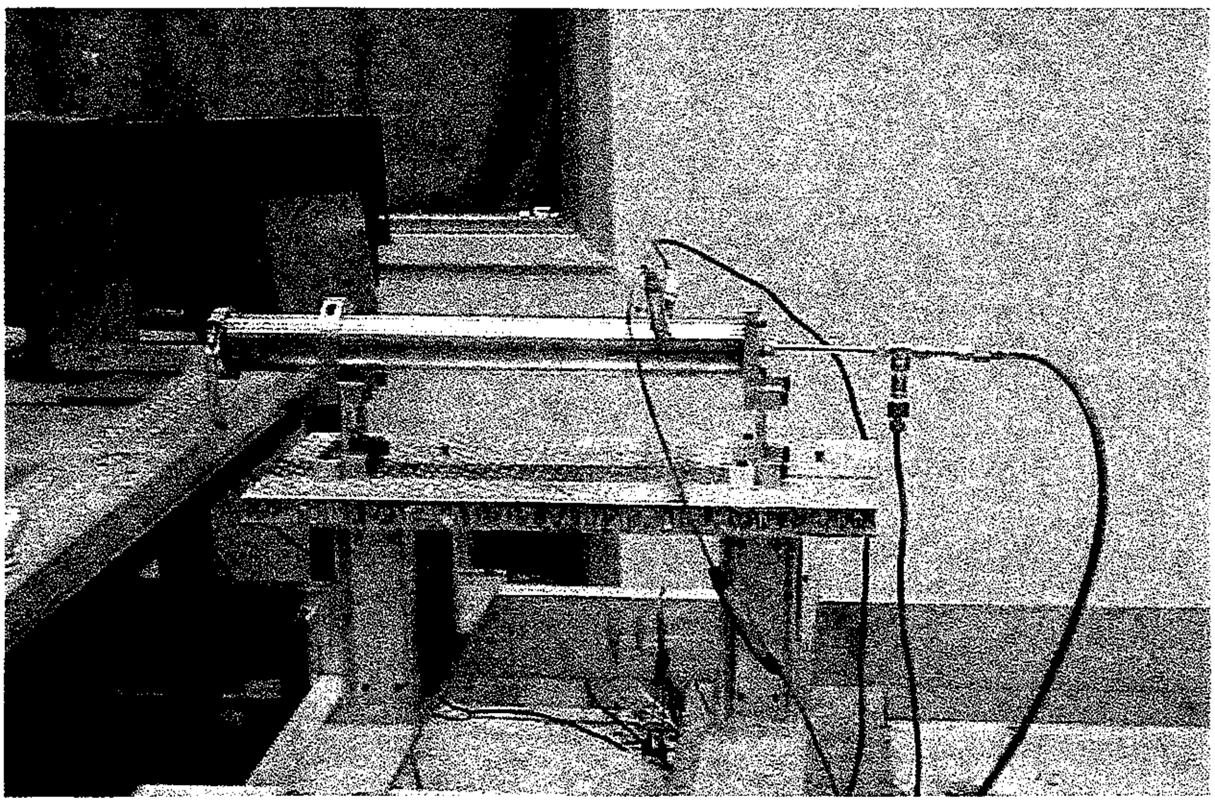

Figure 1. UALR Hybrid Rocket Facilty

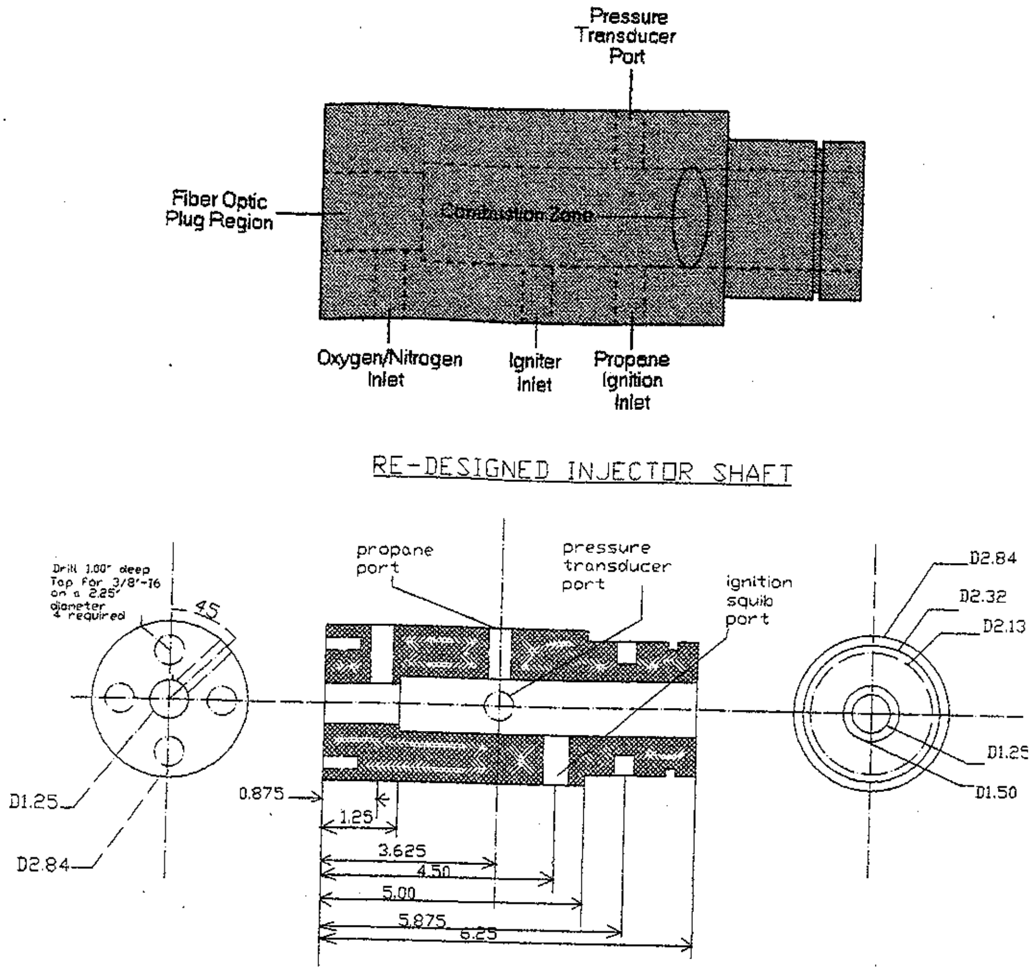

Figure 2. New Injector Head Design

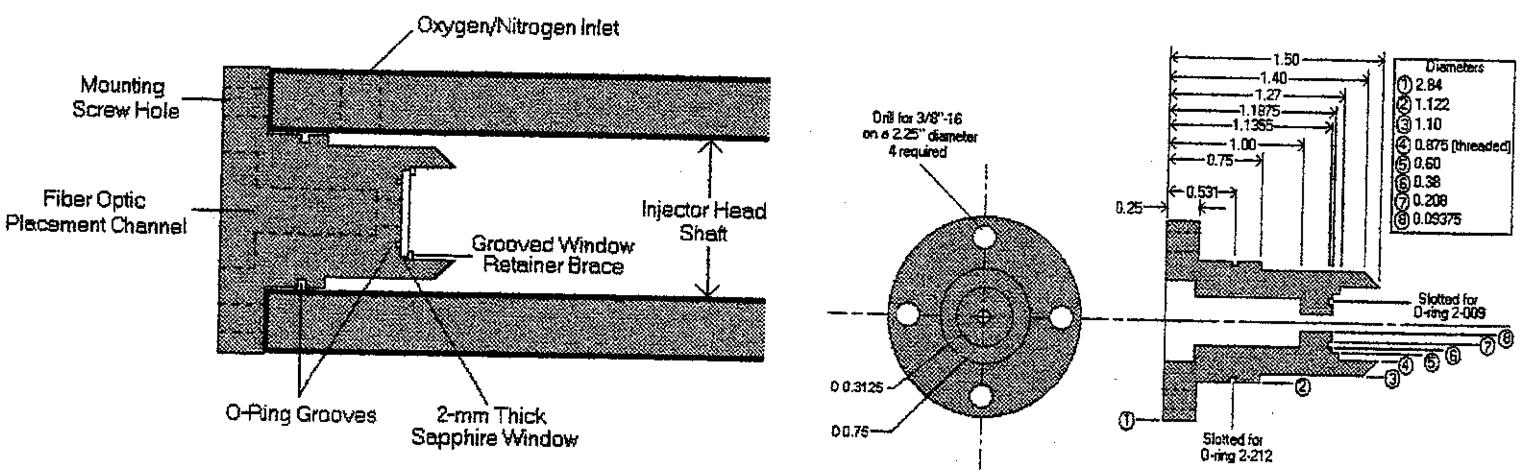

Figure 3. Fiber Optic Plug Design

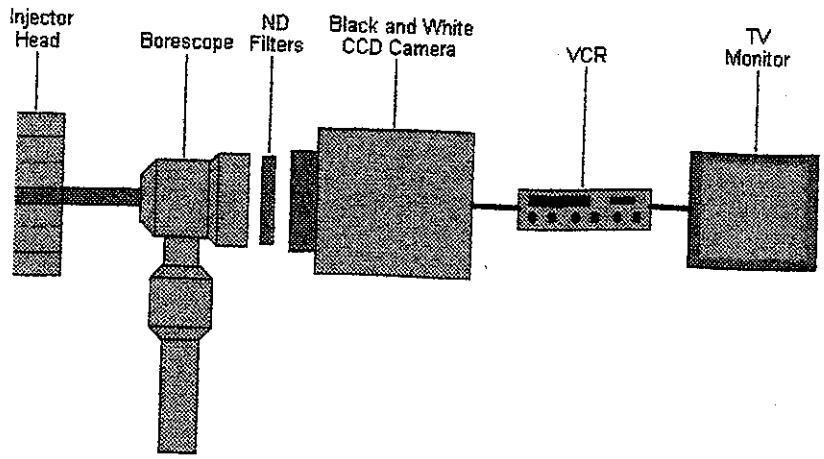

Figure 4. CCD Camera Optical Setup

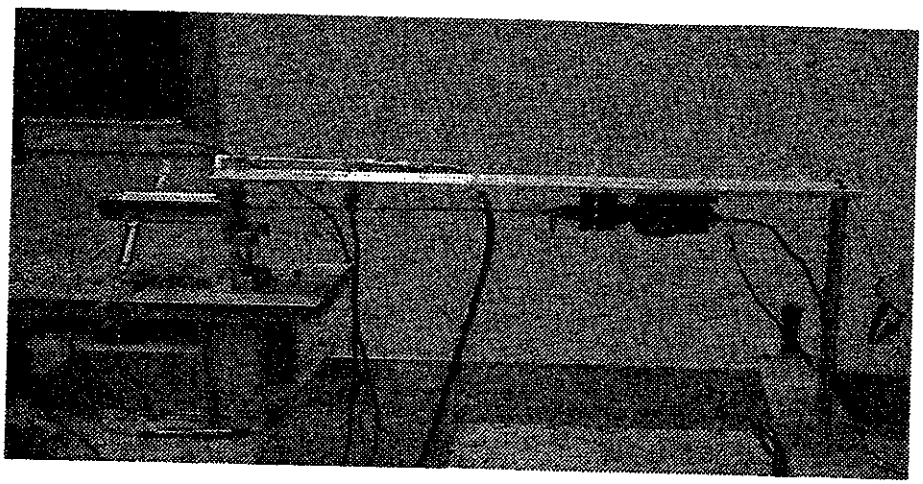

Figure 5. CCD Camera Optical Measuring System

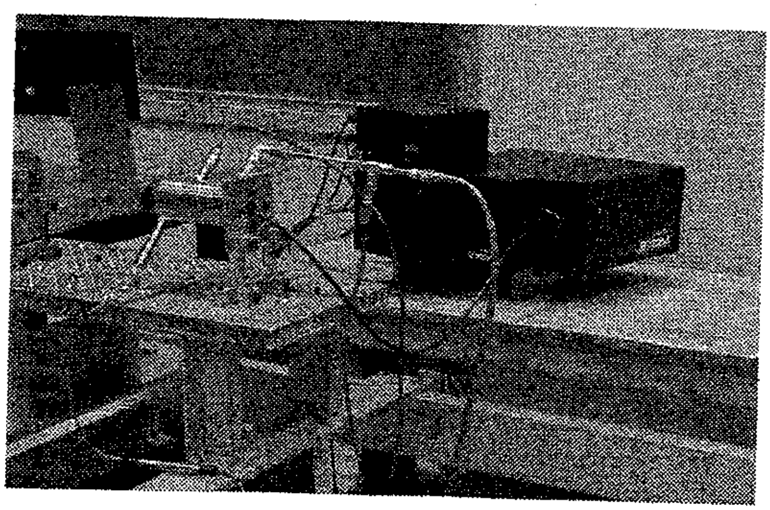

Figure 6. UV Quartz Fiber Optic Measuring System

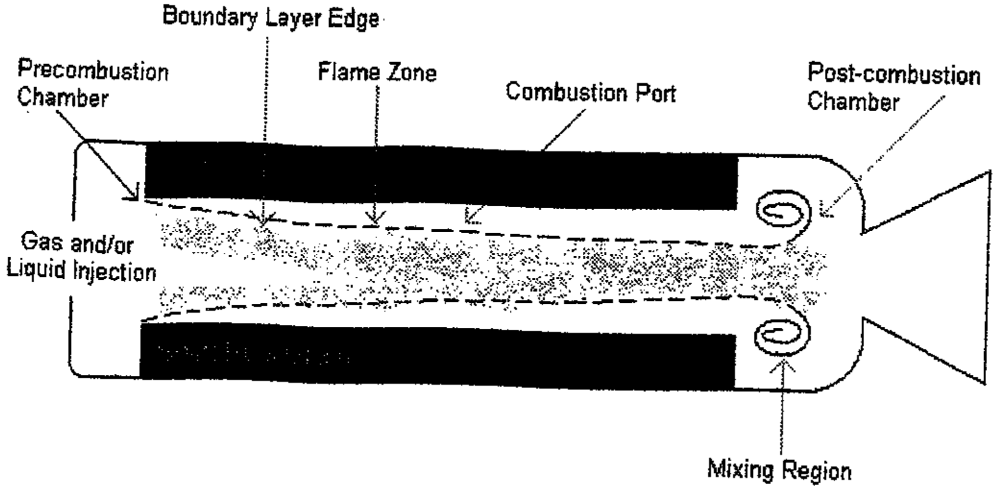

Figure 7. Oxidizer & Fuel Grain Burn Process

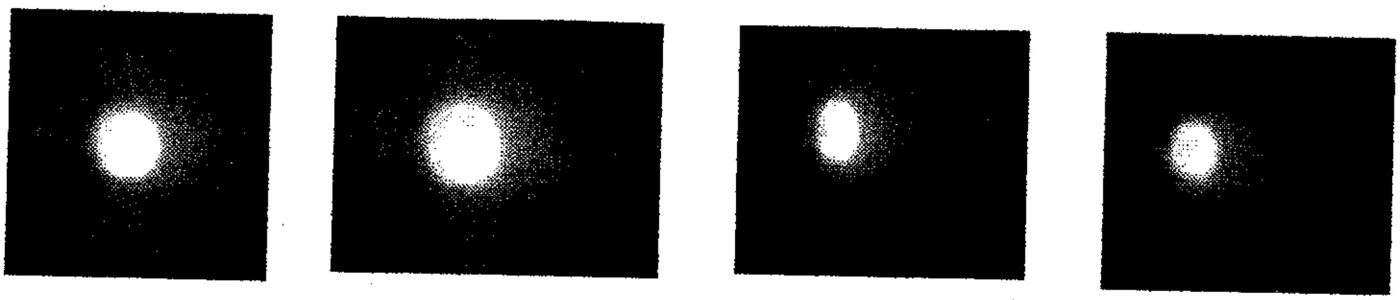

Figure 8. Combustion Chamber Images

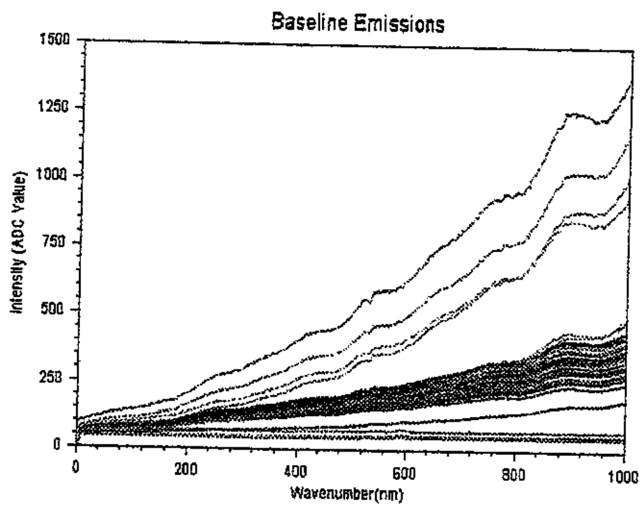

Figure 9. Baseline Undoped HTPB

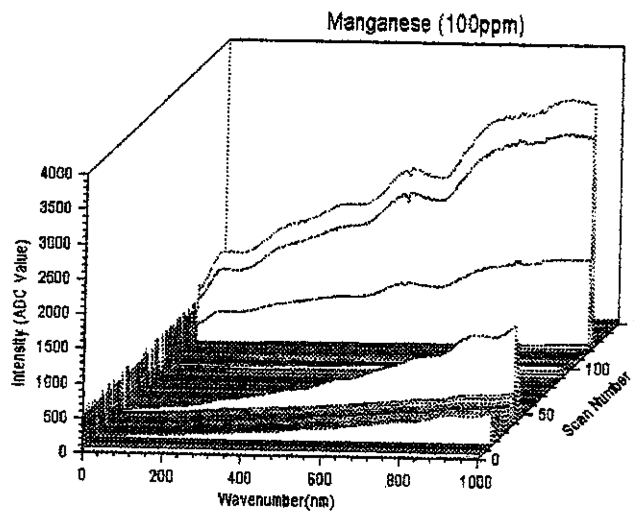

Figure 10. 100 ppm Manganese