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Evaluation of Photodiode Arrays for Use in Rocket Plume Monitoring and Diagnostics

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Abstract

The spectroscopic analysis of plume emissions is a non-intrusive method which has been used to check for fatigue and possible damage throughout the pumps and other mechanisms in a rocket motor or engine. These components are made of various alloys. Knowing the composition of the alloys and for which parts they are used, one can potentially determine from the emissions in the plume which component is failing. Currently, Optical Multichannel Analyzer systems are being used which utilize charge coupled devices, cost tens of thousands of dollars, are somewhat delicate, and usually require cooling. We have developed two rugged instruments using less expensive linear photodiode arrays as detectors. A high resolution system was used to detect atomic emission lines while a low resolution system was used to detect molecular emission bands. We have also written data acquisition software and built electronic circuits to control the arrays and collect data. While NASA has used similar systems for characterization of the Space Shuttle Main Engine, the emissions from other rocket systems have not been surveyed as well. The two instruments described will be utilized to study hybrid rocket emissions at the UALR hybrid rocket facility.

Introduction

Over the past decade, the National Aeronautics and Space Administration (NASA) has been plagued with several manned and unmanned mission mishaps costing taxpayers millions of dollars. The most infamous of these mishaps was the *Challenger* disaster in 1986. Because these events cause negative public opinion toward NASA, coupled with the need to cut federal spending and the effect of increasing foreign competition, more pressure has been put on NASA needs to be assured that its boosters will perform satisfactorily at each launch.

One way to assure the proper performance of launch vehicles is to employ extensive engine ground testing on test stands designed for this purpose at research facilities. Using spectroscopic analysis of plume emissions, the "health" of the engine (that it is performing well, not failing), particularly combustion efficiency and the existence of component fatigue, can be determined. The high temperatures and pressures found in a rocket plume make excellent sources for atomic line and molecular band emissions from the near ultraviolet to middle infrared. Currently, monitoring systems are being used which employ charge coupled devices and/or Fabry-Perot interferometers, cost tens of thousands of dollars, are somewhat delicate, and usually require cooling.

A spectrometer using a rugged photodiode array mounted in the focal plane of an imaging spectrograph can be used for the analysis of UV-V is emissions from

rocket plumes. Gases such as CN, CO, N₂, and NH₃, and molecular species such as OH, C₂, and CH₂, emit in the visible region and can potentially be monitored. Also, most metals emit in the visible region, which is beneficial for detecting component fatigue or failure. Prior research conducted on the liquid-fueled Space Shuttle Main Engine (SSME) has shown the ability to detect wear from several alloys along the hot gas path.

Plume emission technology can also be applied to jet engines, especially military jets with afterburners. Other military applications include increasing the stealth capabilities of aircraft by reducing air-to-air and air-to-ground missile emission, which is possible through analysis of this type of data. Furthermore, high speed monitoring of the emissions produced by the combustion of propellant in all types of guns and explosives can be used to enhance their performance. Additionally, emission spectroscopy can be used to monitor the efficiency of oil-or coal-fired power plant furnaces.

Materials and Methods

Low Resolution Spectrometer.--A low resolution spectrometer for molecular band emission studies was constructed as shown in Fig. 1. The components for the spectrometer were positioned in a similar manner as a standard flame emission spectrometer (Ingle and Crouch, 1988). The components include the photodiode array

with associated timing and output electronics, the collection optics, an imaging spectrograph, an oscilloscope, and a computer.

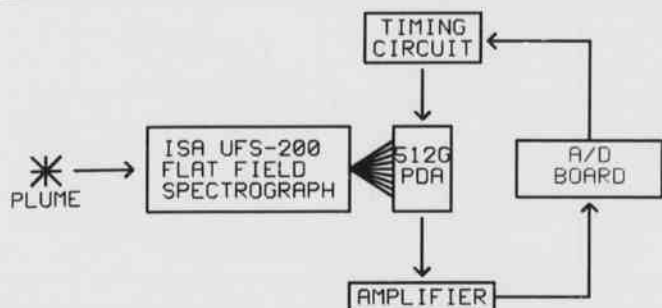


Fig. 1. Block diagram for the low-resolution spectrometer.

The photodiode array used in the low-resolution spectrometer was an EG&G Reticon 512G monolithic, self-scanning, linear array. This array has 512 photodiodes on 25 μm centers, thus giving a sensitive length of 12.8 mm. Each photodiode is 26 μm in height, which is relatively small when compared to the height of the slit on the spectrograph. Because of the array's monolithic, dual-inline-package (DIP) design, it was mounted into an 18-pin DIP socket that in turn was mounted to a circuit board. According to the manufacturer, this array was designed for use in low-cost facsimile and optical character recognition applications. While not optimized for spectroscopy, it offered a low cost alternative and was readily available.

Timing signals needed to drive the array were generated externally. The three required signals, clock, start, and reset, are shown in Fig. 2 and were produced by the circuit in Fig. 3. The circuit that produced the timing signals was mounted on a circuit board separate from the board to which the photodiode array was mounted. Pins 8 and 9 on the 512G array produce a video and dummy output respectively. These outputs were sent to a differential amplifier to extract the video signal and then through a low-pass filter before being sent simultaneously to the oscilloscope and to the Channel 0 High input on the analog-to-digital converter board installed in the computer. Fig. 4 shows the circuit board with the array and video output circuit (G Series, 1992).

The detector circuit board was positioned so the photodiodes in the array are in the focal plane of an Instruments SA UFS-200 Flat Field Spectrograph (UFS-200). The UFS-200 employs an aberration corrected concave holographic grating. This grating is 70 mm in diameter and is blazed with 200 grooves/mm. Its spectral range is from 200 to 800 nm with a dispersion of 24 nm/mm. The entrance slit is 3.8 mm high and 100 μm wide.

The collection optics were simply a convex lens and aperture stop. The lens was made of glass and housed in

an aluminum bracket. It was 10.1 cm in diameter and had a focal length of 23 cm. This lens was able to focus a small part of the flame on the entrance slit. Using a glass collection lens was justified since the window on the photodiode array was also made of glass. The aperture was mounted to the lens housing and used to control the amount of light reaching the entrance slit. It had a maximum diameter of 9.78 cm and a minimum diameter of 0.56 cm.

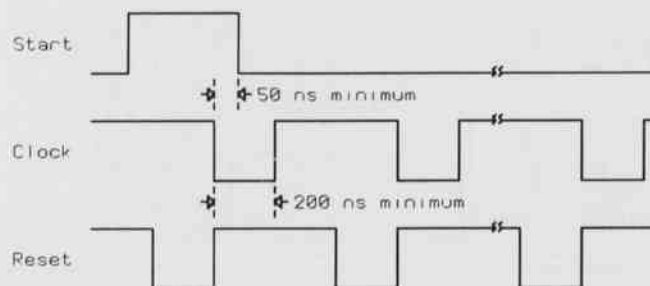


Fig. 2. Timing signals required for operation of the 512G.

A Zenith 80286AT personal computer equipped with an 80287 math coprocessor, and Computer Boards CIO-AD16JR-AT analog-to-digital conversion board (A/D board) was used to collect and store data. Data acquisition was controlled by a Borland Turbo C program. The program first prompts the user for the name of the file to which the data were to be written, the number of scans to be taken, and the amount of time delay between scans. Next, a TTL pulse was sent out from the Digital Output 0 (Dig Out 0) to the circuit on the array board shown in Fig. 4. The signal produced by this circuit was sent to the Digital Input 0/Trigger (Dig. In/TRIGGER) on the A/D board. The signal to the Dig. In 0/TRIGGER was in sync with the clock pulses, however, they only occur after the start pulse and only for 512 pulses. Therefore, there was one sample collected per pixel. The program stopped data collection after 512 pulses and resets the LS7474 flip-flop to await the next scan. A timing diagram for these pulses is shown in Fig. 5 (Schildt, 1990; CIO-AD16JR, 1991). The collected data for each scan was stored via Direct Memory Access (DMA) to a specified memory segment. After all scans had been taken, the data were saved, along with all corresponding pixel numbers, to a file on the computer's internal hard disk drive. The data were written to an ASCII file in a format that allows them to be read and plotted by the graphing program. SPLOT.

High Resolution Spectrometer.—The high-resolution spectrometer for atomic line emission and detailed molecular band studies was constructed as shown in Fig. 6.

Again, the components for the spectrometer were positioned in a similar manner as a standard flame emission spectrometer (Ingle and Crouch, 1988). The components include a photodiode array with associated timing and output electronics, the collection optics, an imaging spectrograph, an oscilloscope, and a computer.

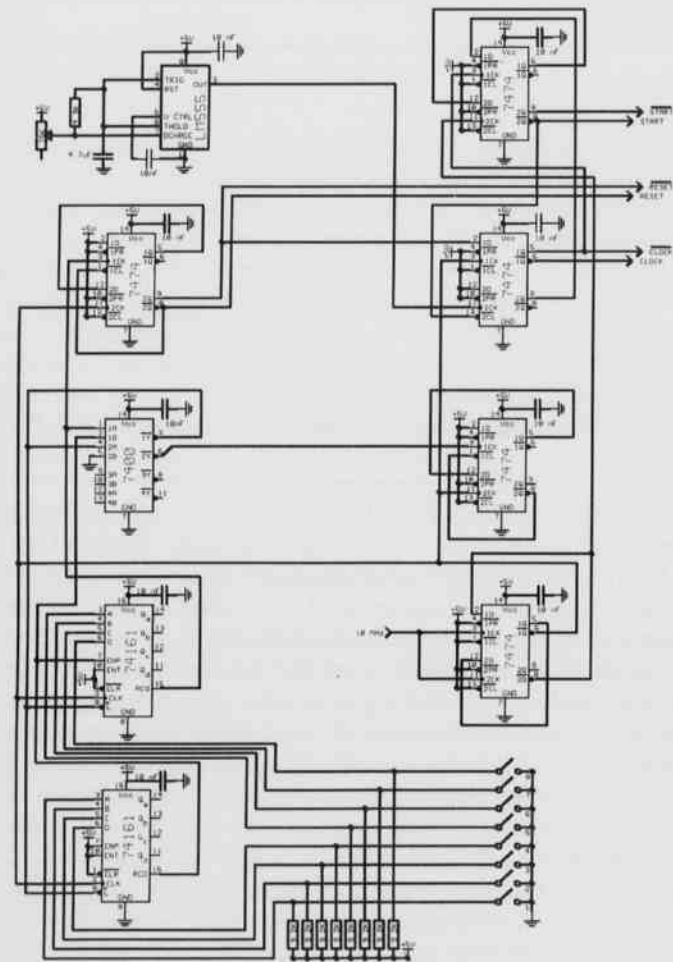


Fig. 3. Circuit to produce the timing signals in Fig. 2.

The photodiode array used in the high-resolution spectrometer was an EG&G Reticon 1024S monolithic, self-scanning, linear array. This array had 1024 photodiodes on 25 μm centers, thus giving a sensitive length of 25.6 mm. Each photodiode array was 13 μm wide and 2.5 mm high. According to the manufacturer, the 1024S was designed for spectroscopic studies. The slit-like geometry of each photodiode allows for the maximum amount of light possible to strike the photodiodes (S Series, 1991). The photodiode array was set in an EG&G Reticon RC1001 Satellite Board.

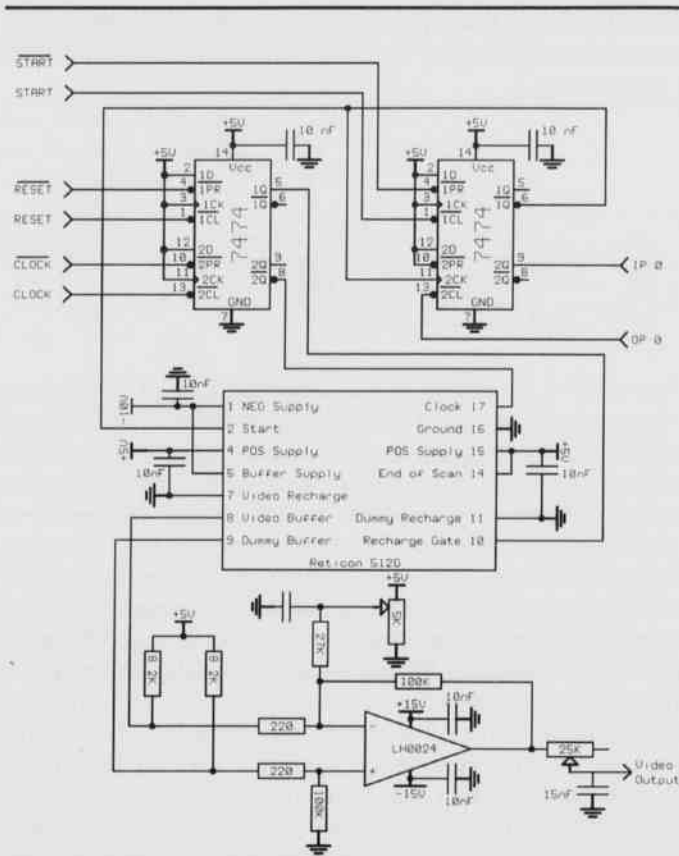


Fig. 4. Sensor board schematic.

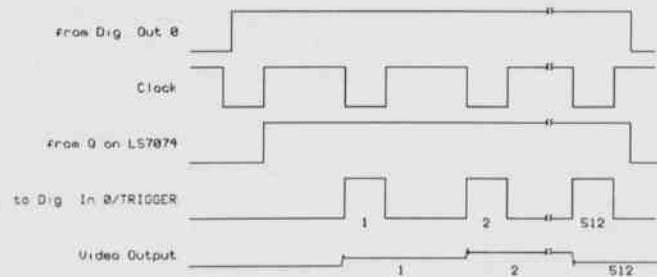


Fig. 5. Timing diagram for interfacing the 512G and A/D board.

The satellite board was connected to an EG&G Reticon RC1000 Mother Board via a 16-pin ribbon cable for digital signals and a six lead cable for analog signals. The RC1000 produces the required timing signals for the array, and it also has the necessary video processing circuitry. A single BNC connector allows the video signal to be output to an oscilloscope. In this setup, the video signal was sent to an oscilloscope and the computer as used previously (RC1000/RC1001, 1991).

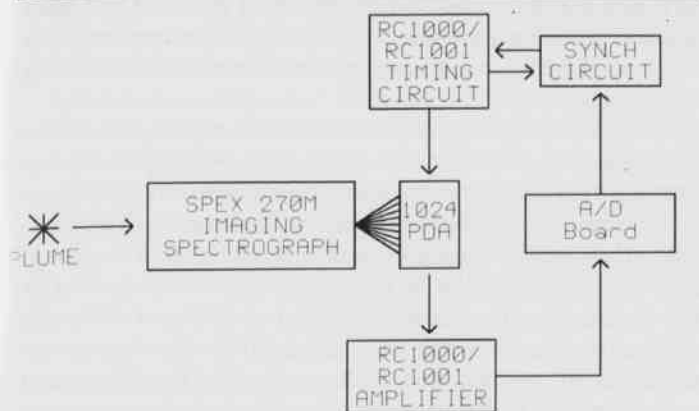


Fig. 6. Block diagram for the high-resolution spectrometer.

The combination of the EG&G Reticon RC1000 and RC1001 was designed for evaluation of photodiode arrays. It comes from the manufacturer ready to be hooked up to an oscilloscope, but not to a data acquisition system. A circuit was designed to interface between the RC1000 and a Computer Board CIO-AD16Jr-AT analog-to-digital converter board. This interface circuit is shown in Fig. 7. It produces a start pulse which was sent to the external start input on the RC1000. The circuit also produces active high TTL signals to the Dig. In O/TRIGGER input on the A/D board. These signals were synchronized so that one sample was taken for each pixel of the 1024S photodiode array. Fig. 8 shows the timing diagram for the interface circuit. In order for the interface circuit to perform properly, the start pulse input jumper on the RC1000 had to be set from internal to external. The timing and signal processing circuitry that was designed and built for the low resolution system (Figs. 3 and 4) was not necessary for the high resolution unit because of the outstanding performance of the RC1000/RC1001.

The 1024S photodiode array was positioned in focal plane of a SPEX 270M Imaging Spectrograph. The 270M employs two holographic gratings mounted on a motorized turret, so the optimum grating could be chosen depending on the wavelength to be analyzed. Both gratings have 1200 grooves/mm, one blazed for 250 nm and the other for 630 nm. Its spectral range was from 0 to 1100 nm with a dispersion of 3.1 nm/mm. The flat field area in the focal plane was 25 mm wide by 12 mm high, which gives 77 nm of coverage over the 25-mm width. The motorized turret allows a specific range of wavelengths to be observed. The entrance slit was 1.52 cm high and its width variable in 12.5 μm steps. The settings on the 270M were selected using the SPEX Hand Scan hand-held controller. This controller allows the user to select the desired grating, wavelength range, and entrance slit width (270M, 1993; Hand Scan, 1993).

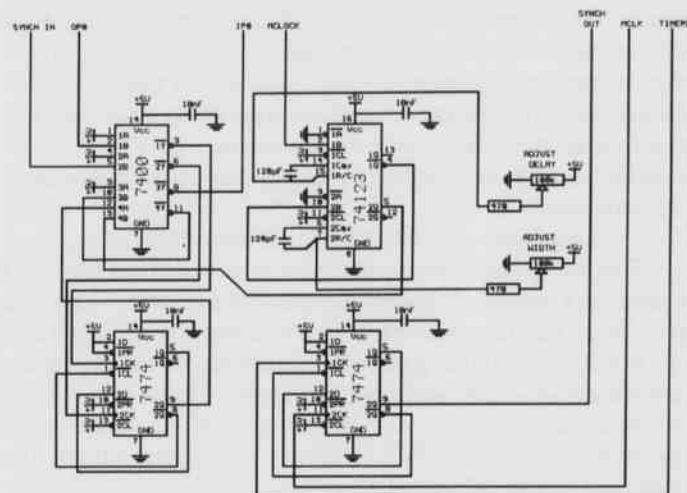


Fig. 7. Schematic for the interface circuit.

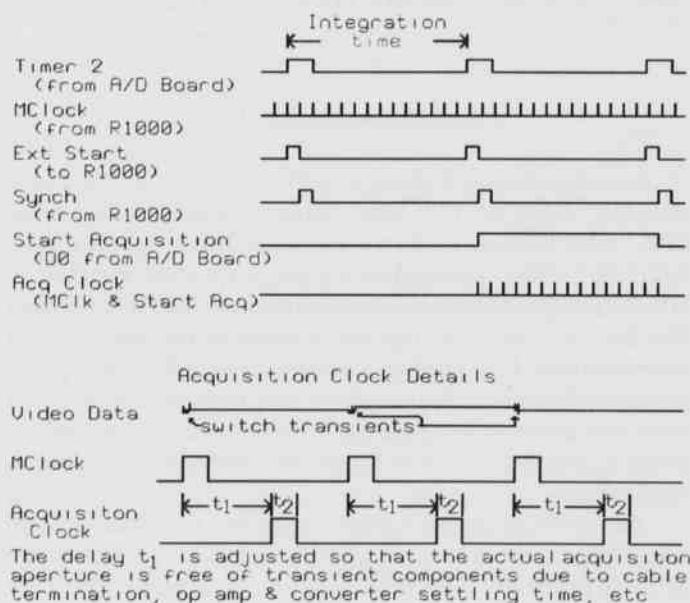


Fig. 8. Timing diagram for interfacing the 1024S and A/D board.

A BK Precision 20 MHz Model 2120A was used for alignment and calibration of the instrument. It was also used to set the proper integration time to attain a maximum signal without saturation. Channel 1 was used to monitor the video output. The sync output from Pin M on the RC1000 was sent to Channel 2 to provide a trigger pulse.

A Gateway 2000 486 personal computer with Computer Boards CIO-AD16JR-AT A/D board was used to collect and store data. Data acquisition was controlled by a Borland Turbo C program. The program first

prompts the user for the name of the file to which data was to be written, the number of scans to be taken, and the amount of time delay between scans. The program then prompts the user for the integration time or exposure. The value entered for the integration time was not the actual exposure time, but was the value written to Counter 2. To determine the integration time the following equation was used:

$$\text{Integration time} = (256 * \text{Counter 2 value}) / 1,000,000.$$

The integration time pulse was sent out from the A/D board on Counter 2 out to the interface board. The pulse sent from the interface board to the Dig. In 0/TRIGGER on the A/D board triggers the sampling of the video signal which was coming in on Channel 0 High. The collected data for each scan was stored via DMA to a specified memory segment. After all scans have been taken, the data was saved, along with its corresponding pixel number, to an ASCII file on the computer's internal hard disk drive. The data was written to the file in a format to be read and plotted by the graphing program SPLOT (Schildt, 1990).

Results and Discussion

Low Resolution Software.--The Reticon 512G has a sensitive width of 12.8 mm. When mated with the UFS-200, which has a dispersion of 24 nm/mm, the 512G/UFS-200 combination gives a spectral window of 307.2 nm. Because this window does not cover the entire 200-800 nm range of the spectrograph, the array board was positioned in varying locations along the focal plane to see different portions within the UV-Vis region. Each time the array was repositioned, a scan of the emissions from a Pen-Ray mercury lamp was taken for wavelength calibration.

To obtain a useful spectra from the raw data, several steps have to be taken, all of which are carried out in the SPLOT program. The first step was to subtract the dark signal from the data. This step takes out most of the fixed pattern noise, which is common in photodiode arrays operating at room temperature. Being able to do this allowed us to decrease costs because the array does not have to be cooled. The next step was to convert the x values of the data from pixel number to wavelength. This was accomplished by scaling the x value by an amount determined by the following equation:

Scaling factor = $-(\text{Dispersion} * \text{Sensitive Length}) / \text{Number of Pixels}$ which has a value of -0.6 for the 512G/UFS-200 combination. The scaling factor was negative because the data was collected in decreasing values of wavelength with increasing values of pixel number. After multiplying by this negative value, the data has increasing wavelength values along the increasing x-axis of the plot. The next step was

to offset the x-axis by 307.2 so the first point of the spectra was at zero nanometers. Finally, the appropriate amount of offset on the x-axis was determined by the Hg lamp spectra.

Initial studies were conducted by analyzing the flame produced by a Perkin-Elmer Atomic Absorption (AA) burner. The acetylene/air mix was adjusted to produce a lean flame with a bright blue interconal region. The spectra of this interconal region is shown in Fig. 9. The molecular bands centered at 463, 509, and 559 were created by the C_2 species. The bands centered at 382 and 427 were created by the CH series (Gaydon, 1974). The hump centered at 587 is not due to an emission band but was caused by fixed pattern noise.

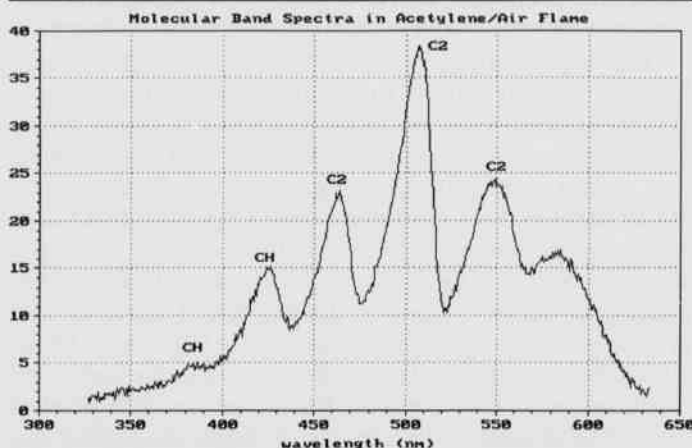


Fig. 9. Spectra of the interconal region of a C_2H_2 /air flame recorded with the low-resolution spectrometer system.

Studies have also been done by aspirating NaCl solutions of varying concentration into the AA burner to determine how well the low resolution unit could detect atomic emission lines. Fig. 10 shows the Na emission line at 598 nm for concentrations of 5, 10, 15, and 20 ppm. As expected, the peak intensity at 598 nm increased linearly with increasing Na concentration (Fig. 11).

High Resolution Spectrometer.--The Reticon 1024S has a sensitive width of 25.6 mm. When mated with the SPEX 270M, which has a dispersion of 3.1 nm/mm, the 1024S/SPEX 270M combination gives a spectral window of 79.36 nm. Because of this narrow window, the wavelength selector on the 270M was always set to center the atomic line emission wavelength of the species to be observed.

For the high-resolution spectrometer, only two steps have to be taken to obtain a useful spectra from the raw data. Again these steps were carried out in the SPLOT program. Unlike the low-resolution unit, the dark signal does not have to be subtracted because of the reduced fixed pattern noise and high quality video signal output of the RC1000/1001. The first step was to convert the x

values of the data from pixel number to wavelength. This was accomplished by scaling the x values by an amount determined by the following equation:

Scaling Factor = (Dispersion * Sensitive Length)/Number of Pixels which has a value of 0.0775 for the 1024S/SPEX 270M combination. The scaling factor was positive for the high-resolution unit because the data was collected in increasing values of wavelength with increasing values of pixel number. The next step was to offset the x-axis by the value for the wavelength selector minus 39.68. This was done because the wavelength selector determined the wavelength falling on the center pixel, so half of the spectral window, 39.68 nm, must be subtracted, to allow the proper wavelength values to be assigned to the spectra.

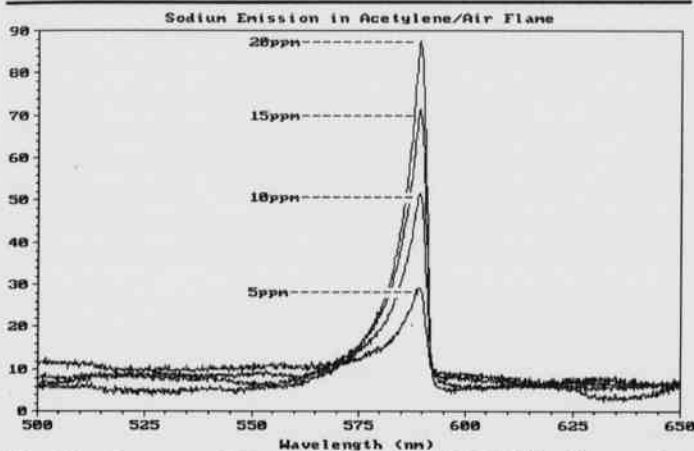


Fig. 10. Spectra of Na emission in a C₂H₂/air flame with varying concentrations of Na recorded with the low-resolution system.

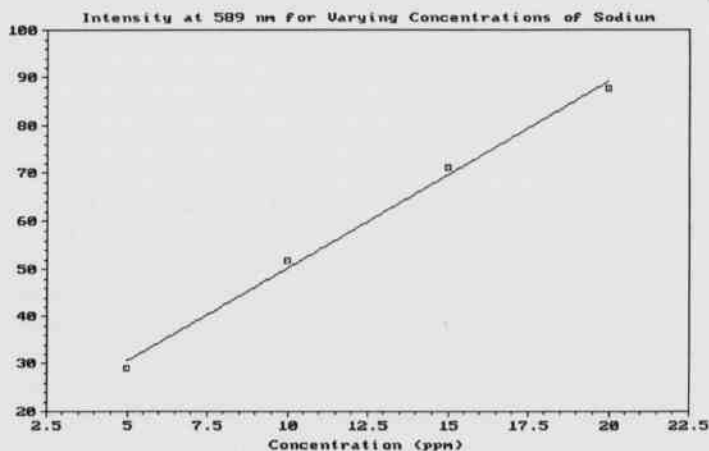


Fig. 11. Plot of peak intensity vs. concentration at 579 nm showing a linear increase in intensity with increasing Na concentration.

Several studies were being conducted on the emissions radiating from the plume of the hybrid rocket

motor at the University of Arkansas-Little Rock's Combustion Diagnostics Facility. During initial tests of the high resolution unit, data was collected on the Na emission line at 589 nm and K emission lines at 763 and 766 nm. Na and K are evidently present in the hydroxyl-terminated polybutadiene fuel grain as contaminant's from the manufacturing process. Data for Na and K were taken for three-second burns.

Figure 12 shows that the Na emission gradually rises throughout the burn. After the oxidizer was shut off at three seconds, the blackbody curve rises which is indicative of fuel rich combustion. After four seconds, the N₂ purge gas extinguishes all combustion.

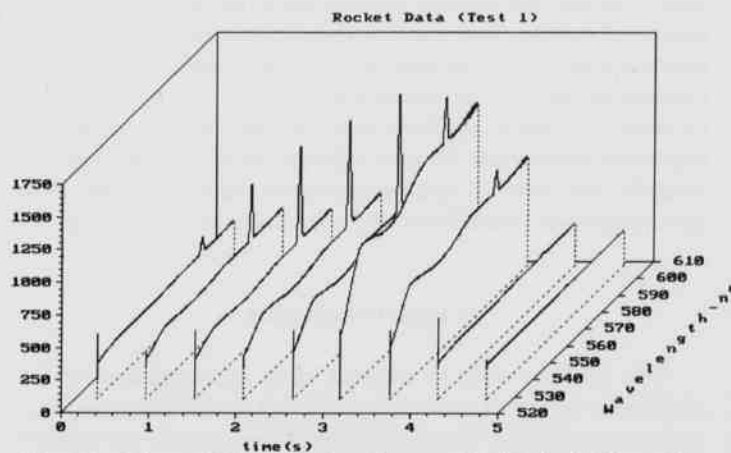


Fig. 12. Plot of Na emission from a HTPB hybrid rocket grain during a three second firing.

Figure 13 shows that the K emission starts off strong, but was overwhelmed by the blackbody radiation. Part of this was due to the fact that the region in which the K lines are present is approaching the near IR where blackbody radiation curves are more predominant.

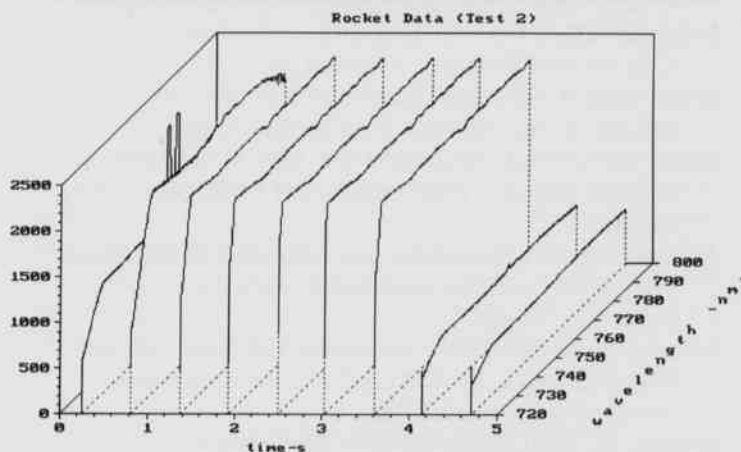


Fig. 13. Plot of K emission from a HTPB hybrid rocket grain during a three second firing.

Conclusions

Future studies will involve casting hybrid rocket fuel grains with known concentrations of metal salts to simulate wear within a launch scale hybrid rocket motor. We have seen that the 512G detector in the low resolution spectrometer is effective for characterizing band spectra, however, the signal-processing electronics need to be modified to decrease the fixed pattern noise which could be interpreted as a nonexistent emission band. Additionally, an improved low-resolution unit could be build by replacing the 512G photodiode array with a 1024S.

The 1024S detector has provided excellent results. By speeding up the timing and decreasing the integration time, we should have an instrument that can perform, in many applications, as well as or better than commercial Optical Multichannel Analyzers, without the higher cost or need for cooling. The planned improvement of the high-resolution unit by controlling the 270M through its RS-232 port should also enhance the spectrometers performance and capabilities.

Acknowledgements

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