

Laser Schlieren and Ultraviolet Diagnostics
of Rocket Combustion

S. C. Fisher

Rockwell International/Rocketdyne Division
Canoga Park, California

Abstract

A low pressure oxygen/hydrogen turbine drive combustor hot-fire test series was conducted on the Turbine Drive Combustor Technology Program (Contract NAS8-34728). The first objective of the test series was to gather data on an axisymmetric combustion system to support anchoring of a new combustion/fluid dynamics computer code under development on the same contract. The second objective was to gain insight into low mixture ratio combustion characteristics of coaxial injector elements.

This paper discusses the diagnostic test setup used in the hot-fire test program and the results obtained. Most of the data collected is in the form of high-speed laser Schlieren cinematography and ultraviolet cinematography of the actual ignition and combustion process inside a combustion chamber system. Details of the 9000 frames/sec laser Schlieren system and the ultraviolet cinematography system are described. The combustion model utilized in the program was designed to simulate the Space Shuttle Main Engine (SSME) oxidizer preburner ignition conditions.

Introduction and Background

The present start requirements on the SSME dictate that the oxidizer preburner ignite at overall mixture ratios as low as 0.3 (o/f), which is substantially below the well mixed flammability limit (Fig. 1). The preburner coaxial elements have regularly accomplished ignition under these conditions, however, repeatability is sensitive to small engine flow control variations and some delayed ignitions

have occurred. The physical mechanisms that allow coaxial element ignition at very low mixture ratios, and subsequently contribute to this sensitivity, are not well understood.

The basic coaxial element injector design is fundamentally a high durability and high performance injector concept. In general, this has been well substantiated on the

SSME preburners. However, there have been a number of instances where injector face, liquid oxygen (LOX) post, fuel sleeve, liner wall, and baffle erosions have occurred. These anomalies appear to be related to contamination in the injector elements, but this has not been positively established in all cases and the physical mechanisms whereby these erosions occur is also not well understood. As a corrective measure, additional hydrogen coolant has been selectively added at several locations of the injector. This is undesirable since it potentially reduces injector mixing efficiency and can potentially contribute to non-uniformities in the temperature profile within the hot gas delivered to the turbine.

Technology advancements are required that will increase the understanding of the physical mechanisms that influence low mixture ratio coaxial element operation, leading to analysis and design techniques that will improve the ignition, durability, and performance characteristics of turbine drive combustors for current and future liquid rocket engine systems.

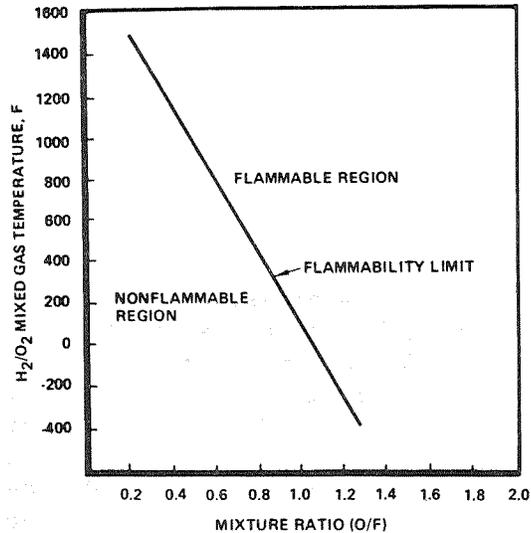


Fig. 1. Flammability Limits of Mixed Oxygen/Hydrogen

The Turbine Drive Combustor Ignition and Durability Technology Program includes a combination of computer modeling analysis and hot-fire testing that will lead to a better understanding of the physical mechanisms affecting turbine drive combustor ignition, durability, and performance. This paper discussed the high speed laser Schlieren and ultraviolet diagnostic setup and results of the first of two hot-fire test series to be performed on the Turbine Drive Technology Program. The low pressure ignition test series was conducted at the Thermodynamics Laboratory at the NAAO (North American Aircraft Operations) Division. All of the testing was done utilizing a 4-inch diameter solid wall combustor with 4-inch diameter fused silica windows on opposite sides of the combustion chamber. The ignition and combustion process was viewed through the windows and recorded on high-speed motion picture film utilizing both a laser Schlieren and an ultraviolet camera system.

A total of 115 ambient oxygen/ambient hydrogen ignition hot-fire tests were conducted. Ignition tests were run on both coaxial and micro-orifice type injector elements. The tests had chamber pressures ranging from 80 to 200 psia, flowrates ranging from 0.016 to 0.086 lb/sec, and mixture ratios ranging from 0.08 to 1.8 (oxygen/hydrogen).

Hardware Description

The combustor assembly used for the ignition test series is shown in Fig. 2 and 3. Three different injectors were hot-fire tested: a single SSME oxidizer preburner element injector, a four-inline SSME oxidizer preburner element injector, and a "micro-orifice" type injector. The coaxial design of the SSME oxidizer preburner element is shown in the cutaway view in Fig. 4. The micro-orifice injector was designed for a flowrate equivalent to three oxidizer preburner elements. The injector incorporates 27 elements that have a total of 163 individual orifices. The basic elements are a pentad type (four on one) with the center "showerhead" being an oxidizer hole. This pattern is shown in Fig. 5.

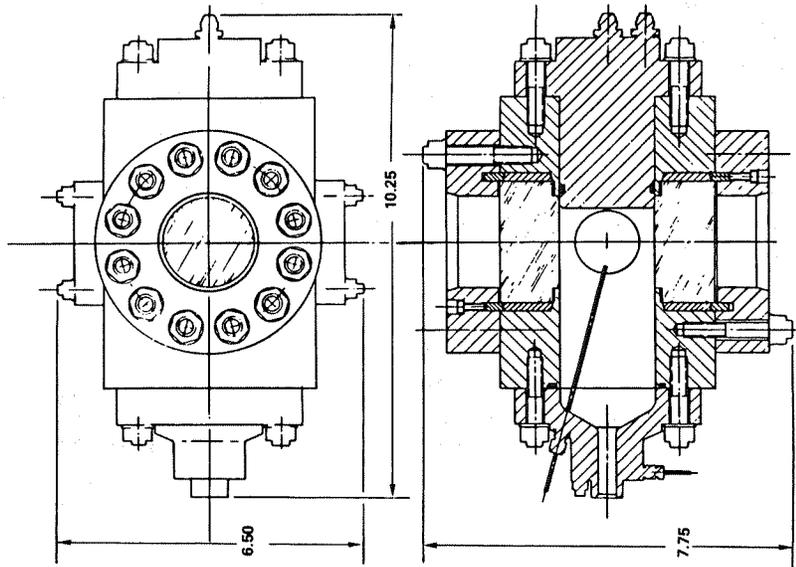


Fig. 2. Turbine Drive Combustor Technology Test Chamber

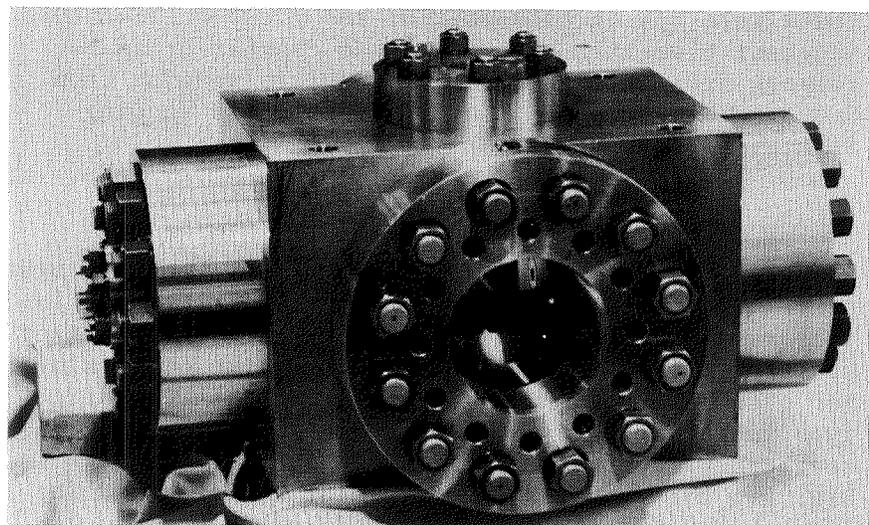


Fig. 3. Combustion Chamber Assembly

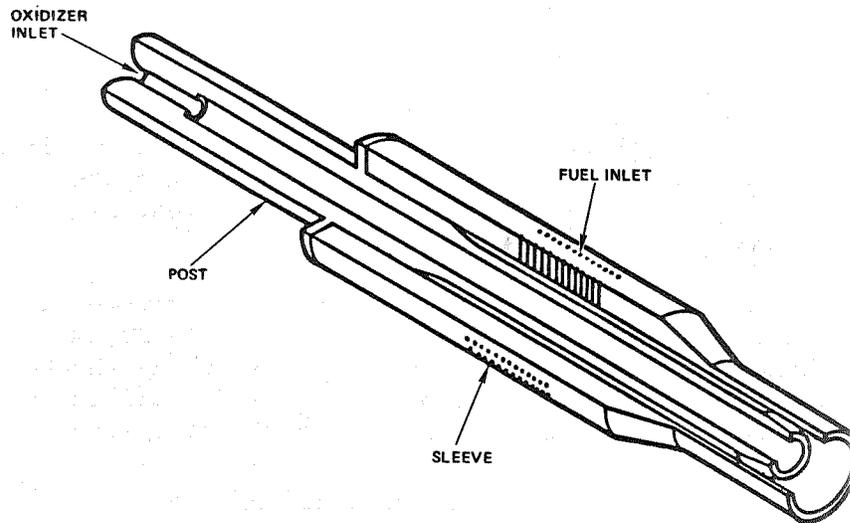


Fig. 4. Preburner Injector Element

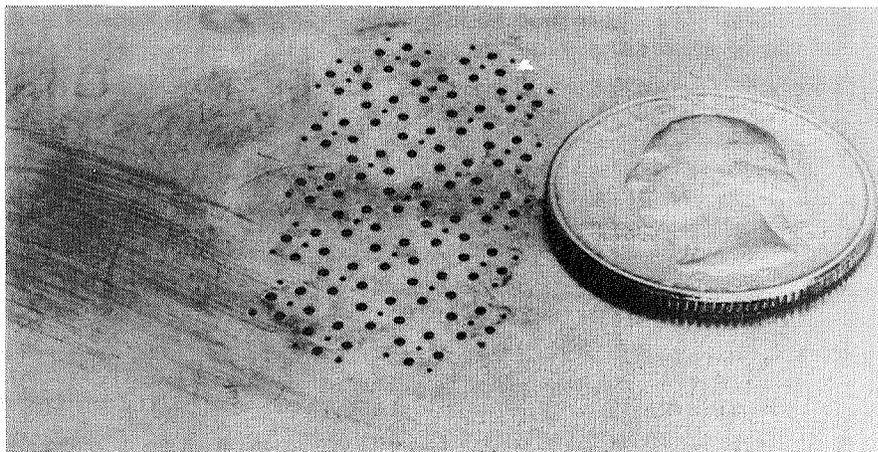


Fig. 5. Micro-orifice Injector

The chamber has two unique fused-silica window assemblies through which the combustion process can be viewed optically. Two instrumentation ports are located 90 degrees to both of the windows. These ports were used for special instrumentation requirements. Separate fittings were designed to accept pressure transducers, ignition probes, thermocouples, and thermocouple rake assemblies.

The chamber pressure was controlled by the back-pressure nozzle diameter. The nozzle is a nickel insert that is sealed to the exit housing by serrations machined into the housing and exit flange. Several nozzles of different diameters were fabricated for the various targeted mixture ratios and flowrates. All of the inlet flows were controlled externally by the facility utilizing calibrated critical venturis and regulated upstream pressures.

All of the combustor assembly details were designed to permit the test configuration to be easily changed. The facility mounting holes in the chamber body allow any detail to be removed and replaced without removing the assembly from the test stand.

Diagnostic System Description

The high-speed cinematography diagnostic system is shown in Fig. 6. The diagnostic system was made up of four separate subsystems:

1. High-Speed Ultraviolet Cinematography System

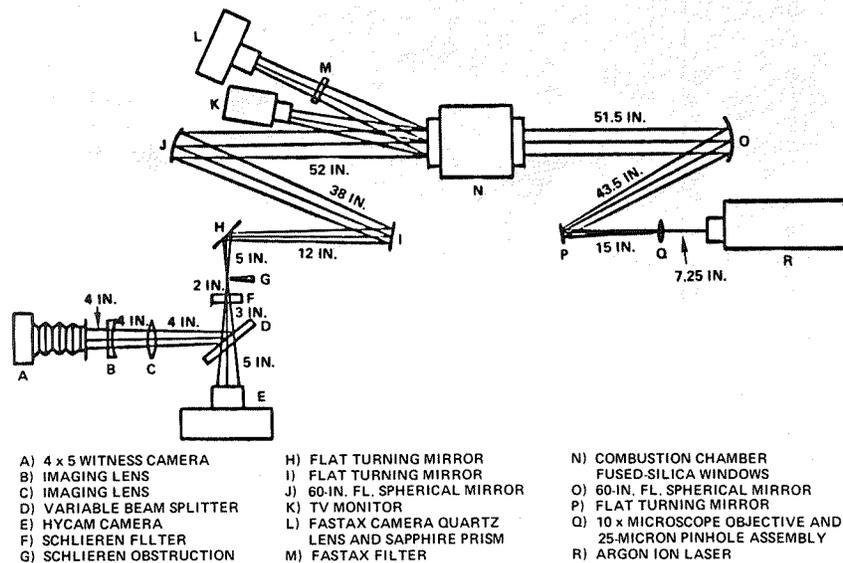


Fig. 6. Diagnostic Setup

2. High-Speed Laser Schlieren Cinematography System
3. Polaroid Laser Schlieren System
4. Vidicon TV Monitor System

High-Speed Ultraviolet Cinematography System

The High-Speed Ultraviolet Cinematography System was used to view the OH specie concentrations in the combustng flow. The ability to view only the OH concentrations is very useful in studying the oxygen/hydrogen combustion process. The OH radical is very short lived, kinetic (at the test conditions), and exists mainly as a part of the overall chain of reactions in the combustion process. Therefore, the OH concentrations are a direct indicator of the locations where the actual combustion reactions are taking place. At the low mixture ratios (temperatures) typically run, OH concentrations are insignificant in the equilibrium exhaust products.

In a typical oxygen/hydrogen combustion process, the reactions are in part characterized by various species that emit radiation between 0.2 and 1.2 micron wavelengths. As can be seen in Fig. 7, OH is a pre-dominate contributor to the radiation emitted from the combustion process.

The OH species emits at a wavelength of approximately 0.31 micron, which is the ultraviolet range and can be detected with standard color film. However, standard "glass" type optics typically will not transmit below a wavelength of 0.38 to 0.4 micron. Because of this, all of the optical components in the ultraviolet diagnostic system were either quartz, fused silica, or sapphire.

On some of the tests, a special ultraviolet filter (0.25 to 0.35 micron) was used. On later tests, because of exposure problems and the fact that the filter only transmitted 60 to 70 percent of the light in its narrow band, the filter was not used. Since

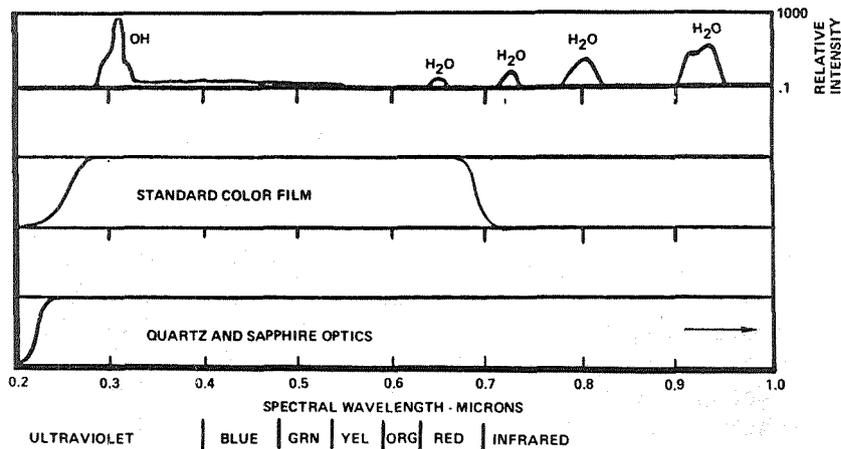


Fig. 7. Typical Spectral Transmission Response, and Optical Spectrum for Oxygen/Hydrogen Combustion System

the OH intensity is much higher than the H_2O_2 intensities (Fig. 6), the high framing rates effectively filtered all but the OH radiation. This was verified by comparing films of identical conditions with and without the filter.

On the early tests in the program, a Faxtax camera with a sapphire prism, quartz lens, and 400 ASA color film was utilized. The speeds ranged from approximately 5000 frames/sec down to 2000 frames/sec. The film exposure at these speeds was very poor. A Milikan camera with a quartz lens was used to replace the Faxtax system. The Milikan camera with the 400 ASA film and a speed of approximately 400 frames/sec gave very good results even on the lower mixture ratio tests.

High-Speed Laser Schlieren Cinematography System

The high-speed laser Schlieren cinematography system proved to be a very useful diagnostic for the oxygen/hydrogen combustion system. Run at very high framing rates (9000 frames/sec), the system was able to record flow patterns, spark heated gas "puffs,"

spark ignition, propagation of the ignition process, flame outs, and steady-state combustion/flow patterns.

The Schlieren system utilized a 0.5 watt argon ion laser, standard Schlieren/laser optics, and a Hycam camera with 400 ASA film. Figures 8 and 9 show the actual diagnostic setup. The use of a laser light source for the Schlieren work is advantageous for two

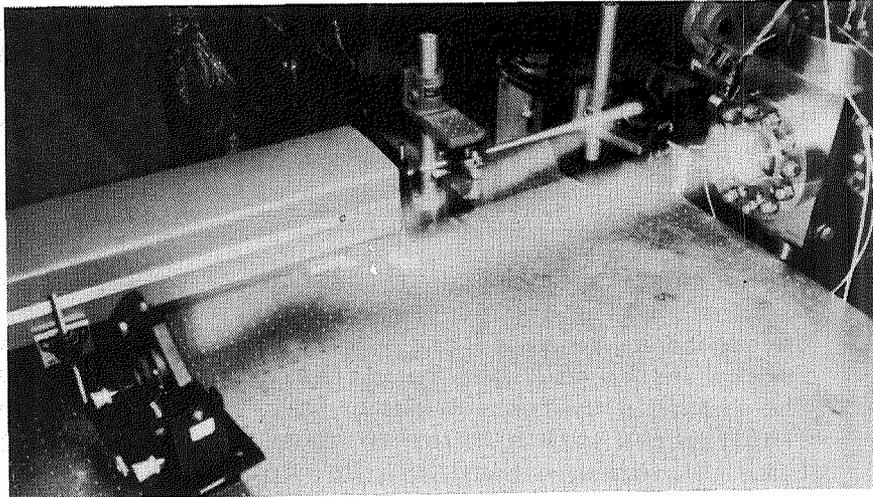


Fig. 8. Laser Schlieren Source

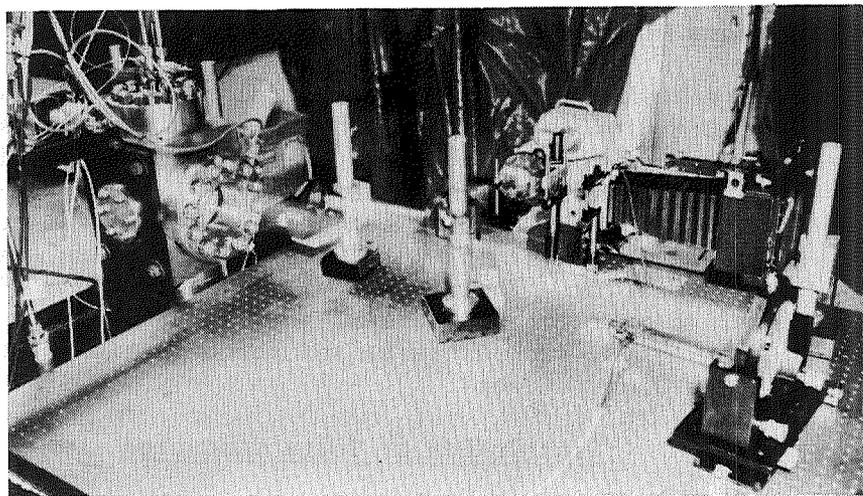


Fig. 9. Laser Schlieren Recording System

reasons. First, the intensity of the laser makes it possible to record Schlieren data at high framing rates on standard film. Second, it is a simple task to filter out the lumination created by the combustion process and view only the narrow band wavelengths of the laser/Schlieren system flow field data. An additional side benefit is that laser system is easier to work with optically.

Most of the tests were conducted with a camera speed of 9000 frames/sec and gave very good results. A few tests were conducted with framing rates of 11,000 frames/sec, but camera problems precluded running at these rates on a regular basis.

Polaroid Laser Schlieren System

To determine and correct setup or test problems without waiting for processed film from the Hycam camera to be returned and viewed, a parallel Polaroid camera system was used to witness the Schlieren tests. The Polaroid system was setup such that the exposure requirements were similar to those for the Hycam system. Following a test, the Polaroid film was reviewed to determine if the test should be rerun with different adjustments.

Vidicon Monitor System

A real-time TV monitor and recording system was set up to remotely monitor the hot-fire tests from the control room. No direct view of the test cell was available from the control room. The monitor was observed for real-time discrepancies during the tests. The tape was played back and studied following test stand securing. The monitor was very useful in discovering spark probe problems just prior to test, during tests, and posttest, and for detection of ignitions and flameouts.

Description of Tests Conducted

A total of 115 low-pressure ignition tests were conducted on three different injectors. The first

injector to be hot fired in the program was the single oxidizer preburner coaxial element injector. Following the single-element injector, the four-element coaxial injector was installed. The micro-orifice injector was the last injector to be hot fired in the ignition test series.

Seventy-seven single-element coaxial ignition tests were completed. Three different test sequences were used; fuel lead sequence, oxidizer lead sequence, and a sequence in which both propellants were flowing steady-state prior to initiation of the spark system.

All of the tests utilized a "point" ignition probe that was 1/8 inch in diameter and could be located anywhere within the chamber. This spark probe was placed in several different locations to determine ignition sensitivity of the coaxial elements to the spark location. Following completion of the "ignition" tests on the single-coaxial injector, the thermocouple rakes were installed to measure the temperature profile of the gas/gas combustion system.

Most of the tests were set up for a steady-state total flowrate of 0.02 lb/sec. However, a wide range of total flowrates (0.016 to 0.072 lb/sec) and mixture ratios (0.08 to 1.4 oxygen/hydrogen) were run.

Thirteen four-element coaxial low-pressure ignition tests were conducted. All of the tests utilized an oxidizer lead sequence. In addition to the ignition tests, thermocouple rake tests were also run. The total flowrates changed from 0.072 to 0.086 lb/sec with the mixture ratios varying from 0.10 to 0.62 oxygen/hydrogen.

Finally, the micro-orifice injector was subjected to a series of 25 low pressure tests. The 27 elements were sized for a flowrate equivalent to three SSME oxidizer preburner elements. Both oxidizer and fuel lead sequences were used. In addition to using the "normal" point ignition probe, the probe was modified to arc directly to the injector face on some tests.

The thermocouple rake assemblies were again used to map the temperature profile of the gas/gas combustion system.

The last tests to be conducted explored the ability of the micro-orifice injector to remain ignited as the mixture ratio was lowered. In all cases, the micro-orifice injector required a very high mixture ratio (compared with the coaxial injectors) for ignition and to remain ignited. The variable oxidizer flow was accomplished by opening a vent valve downstream of the sonic oxidizer venturi. The bypassed flow was regulated by an orifice and then vented to the atmosphere.

Diagnostic System Results and Conclusions

The review of the high speed laser Schlieren and ultraviolet films has yielded some new insights into the mechanisms of gas/gas coaxial element ignition which are listed below:

1. There appears to be a feature within the coaxial element flow stream that is acting as a flame holder near the injector face. This feature is able to flamehold even though the mean jet velocities are several times the theoretical flame propagation speed for a well mixed gas of similar mixture ratio.
2. Since the combustion process is unable to propagate upstream in the high velocity jet flow, another ignition mechanism is required to ignite the "flame holding feature" near the injector face. The observed mechanism appears to have two basic requirements. First, the gas/gas flow stream must be distributed, either slowed down, reversed, or blown sideways away from the element. Secondly, this disturbing action must take place while there is combustion (an ignition source) present in the recirculating gases surrounding the jet flow near the injector face. When the high velocity jet is disturbed, the flame holding feature becomes

exposed and can be ignited by the combustion in the surrounding gases.

3. Two forms of the required disturbance were observed:
 - a. The rapid flame propagation within the high mixture ratio recirculation gases present in the oxidizer lead tests provided the required disturbance. The rapid pressure increase from combustion in the recirculation gases actually reversed the element flow stream in some of the tests.
 - b. Ignition of a high mixture ratio flow stream, approximately 2 inches from the injector face, was also violent enough to disturb the element flow stream and allow ignition of the "flame holder" near the face. The phenomena was observed on fuel lead tests that had high enough mixture ratios in the recirculation zones to allow flame propagation within the slow moving recirculation gases that in turn ignited the element stream approximately 2 inches from the face. The ignition of this zone propagated rapidly and provided a pressure surge and the required disturbance of the element stream near the face. However, the flame did not propagate up the element stream. Only after the element stream was disturbed was the flame holding region able to be ignited.

In addition, the micro-orifice injector does not appear to have a flame holding mechanism at the conditions tested. The ultraviolet films show no indication of flame holding near the injector face. The recirculation gases appear to be the main source of combustion. Because of this, very high mixture ratios (1.4 or greater) are required to sustain combustion. A well mixed gas with this mixture ratio is ignitable, but the flame propagation speeds are much lower than

the injector velocities. Because of this, the bulk of the combustion is in the recirculating well mixed gases. This effect was seen in the thermocouple rake temperature profiles as well as the ultraviolet films.

Figure 10 is a collection of prints made from the high-speed laser Schlieren film from Test 10.1. Test 10.1 was a typical fuel lead test with a high mixture ratio (1.1 oxygen/hydrogen). This sequence of photos (only 15 frames out of a 400-foot roll) is presented to give a representation of the type of information available from the laser Schlieren films. Every fifth frame of the actual sequence was printed. The sequence goes from left to right. The actual framing rate was near 9000 frames/sec. The reproduction of the film for this paper unfortunately does not portray the quality and the information available from these films. To study any of the phenomena described, the actual test films must be reviewed. The author has all of the original test films (a total of 8 miles of film), which includes both the laser Schlieren and ultraviolet records.

Both the high-speed laser Schlieren and ultraviolet diagnostics have proven to be extremely useful tools in the study of the low-mixture ratio ignition and combustion of hydrogen and oxygen in a rocket combustion system. With the high speed laser Schlieren cinematography system flow patterns, the actual spark ignition process, combustion propagation, and "flame outs" can be visualized with great detail. The high-speed ultraviolet cinematography has allowed visualization of high OH concentrations and zones of the actual combustion process. Both of these very graphic visualization techniques go hand in hand and complement each other.

Because of the successful application of these techniques and the large amount of insight gained, additional refined studies into low mixture ratio oxygen/hydrogen ignition and combustion would be very productive in helping to further understand the mechanisms involved. The Turbine Drive Combustor

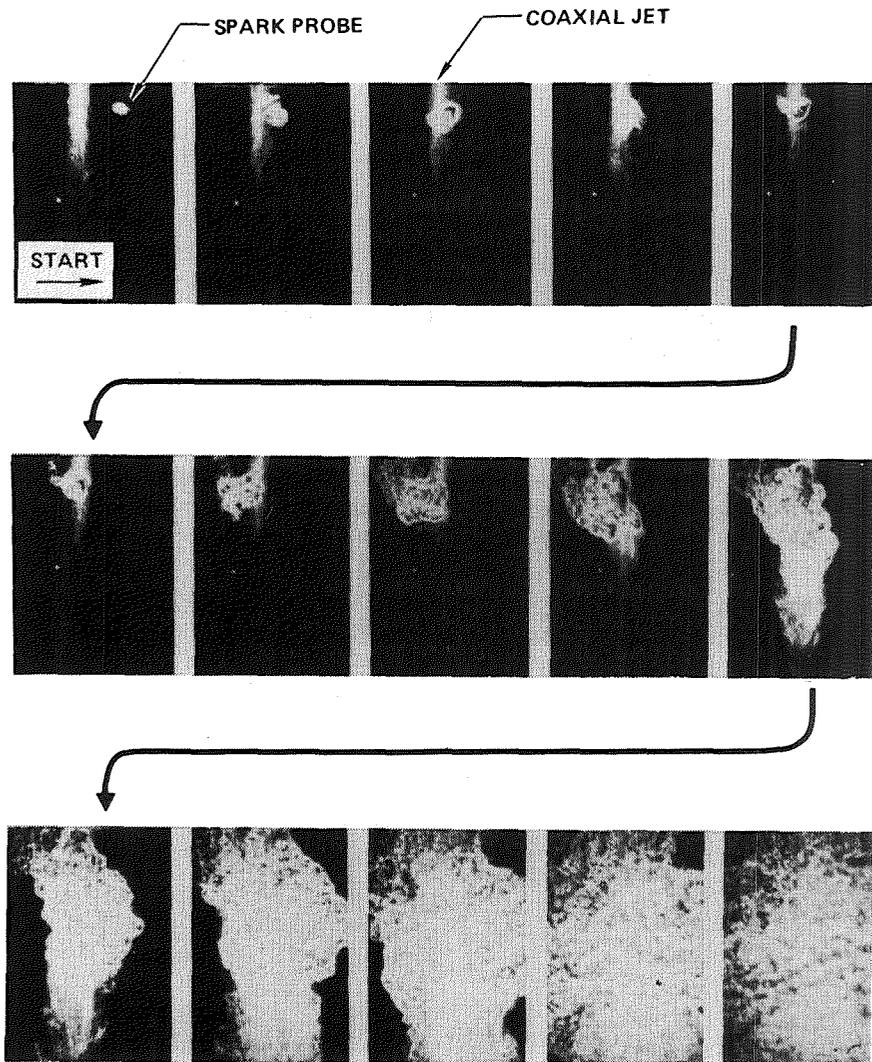


Fig. 10. Fuel Lead Ignition Sequence

Technology Program is currently making plans for additional tests that will study the flame holding aspects of the gas/gas coaxial element and study coaxial element oxygen/hydrogen combustion, using the same test hardware and diagnostics.