40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
11 - 14 July 2004, Fort Lauderdale, Florida

AIAA 2004-4148

DEVELOPMENT OF A 250 lbfv KEROSENE – 90% HYDROGEN PEROXIDE THRUSTER

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With the renewal of hydrogen peroxide usage in the last decade, many parties have become interested in using a non-toxic bi-propellant thruster for use in systems where weight and fast response (small impulse bit) are desired. GK has successfully developed a 250 lbfv RP-1/90% Hydrogen Peroxide thruster with very high thrust to weight and very short start times. The development test effort covers two years and test data is given from these tests.

Nomenclature

*C**	=	Characteristic Exhaust Velocity (ft/s)
O/F	=	Mass Based Oxidizer to Fuel Ratio (unitless)

I. Introduction

Near the end of WWII hydrogen peroxide began to be used as a rocket propellant both in the monopropellant mode and as an oxidizer in bipropellant rockets. This use was expanded through the years up to about 1970 when the favor began to shift to various hydrazines, some as monopropellants and some as the storable fuel in a bipropellant system with nitrogen tetroxide, also storable. These combinations became so popular that hydrogen peroxide was slowly phased out and manufacturing of rocket grade hydrogen peroxide stopped. In the 1990's with the advent of "clean" rockets, the popularity of hydrogen peroxide started to return. As the millennium turned, a number of systems were using hydrogen peroxide, manufacturing had restarted. This paper describes the development of an RP-1/H2O2 rocket that is a state-of-the-art example of what can be achieved with this remarkable propellant.

II. Test Stand

The test stand consists of an outdoor structure containing a 14 gallon oxidizer tank (pickle-passivated to be class 2[1] or better), a one gallon fuel tank, a pressurizing and propellant feed system for each, a pneumatically operated oxidizer fire valve, a fuel solenoid fire valve, a purge system for both oxidizer and fuel, suitable valves to remotely actuate the pressurization, the venting, the purge and the thruster operation and finally a fill and drain system for each propellant. Figure 1 shows an overall view of the test stand and Fig. 3shows the system schematic. Gaseous Nitrogen pressure was supplied by six packs while the oxidizer was loaded into the system from 30 gallon peroxide storage drums using an aspirator to evacuate the oxidizer tank to make the transfer possible. The thruster was mounted horizontally and consisted of a 90% H2O2 catalyst bed connected to a massive solid copper nozzle (for the first two phases) via the fuel injector plate which was sandwiched between them. Oxidizer is pressure fed from the oxidizer run tank to the thruster through a calibrated cavitating venturi and thus the proper flow rate is set by simply setting the oxidizer tank pressure. Initially fuel flow was to be controlled the same way using a calibrated cavitating venturi and fuel tank pressure. Early testing indicated that the double orifice effect of the spray holes in the injector made this impossible and contributed to ambiguity in the oxidizer to fuel ratio (O/F) determination. A small turbine meter was subsequently used to measure fuel flow and the injector was precalibrated at different fuel tank pressures. A certain amount of cut-and-try during actual operation was necessary because the fuel calibration did not have the combustion chamber pressure included but the presence of the turbine meter made it quite simple to adjust the fuel tank pressure between runs to get the O/F desired.

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III. Test Method

The test method used here was sequential like most successful development programs. The idea is to start very simple and progress on each step toward the end goal of a multiple pulse, high thrust-to-weight thruster with very short start transients. The catalyst bed was a flanged assembly bolted to an adapter downstream of the oxidizer fire valve. The oxidizer flow control cavitating venturi was located at this point. The downstream flange uses copper metallic seals in a known-to-work configuration for the high temperatures expected. The fuel injector was built into a flange plate which matched this seal arrangement as did the copper nozzle and the entire arrangement was held together by long through bolts (see fig 2 for close up side photograph of test article). The oxidizer fire valve was a pneumatically controlled ball valve located between the oxidizer tank isolation valve and the catalyst bed adapter. Oxidizer purge was supplied from a small solenoid valve through a check valve arranged so that the purge would check out when the chamber pressure would come up. The fuel fire valve was a three way solenoid valve arranged so that when it was normally closed fuel purge would flow but when it was opened purge would stop and fuel would flow.

Shown below in table 1 are the major tests which occurred in the program. Also indicated in the table are the intended parameters that were tested to determine performance envelope. Initial tests consisted of longer steady state fuel on times to determine "is it possible?" followed by more detailed performance tests. As can be seen later in the testing program the O/F was fixed at the optimum value of 7.5. A major goal of the test program was to determine if purge on the fuel and oxidizer were needed for the General Kinetics design and how fast the ignition process could be achieved. This is because the intended use was for a spacecraft wherein elimination or reduction of purge would be a great advance in reducing the system mass. Additionally, knowledge of the combustion response time is of use for steering.

Table 1. Test Matrix

Test Phase	**Description**	**Cat Bed Flux, lbm/ (in^2-s)**	**Fuel Flow Measurement**	**Chamber Material**	**Fuel Valve**	**Fuel Pulse Width (sec)**	**O/F**	**Ox Purge**	**Fuel Purge**
1st	Functionality	0.75	Venturi	Copper	Marotta, 3-way	2	-	Yes	Yes
	Functionality	0.75	Turbine Meter	Copper	Marotta, 3-way	2	5 – 22	Yes	Yes
2nd	O/F Sweep	0.75	Turbine Meter	Copper	Marotta, 3-way	2, 4	6-26	Yes	Yes
	Fuel Purge Elimination	0.75	Turbine Meter	Copper	Marotta, 3-way	<2	7.5	Yes	No
	Multi-Pulse	0.75	Turbine Meter	Copper	Marotta, 3-way	<0.1	7.5	Yes	No
Final	Higher Flux	1.0	Turbine Meter	Copper	Marotta, 3-way	2	7.5	Yes	Yes
	Inconel Chamber	1.0	Turbine Meter	Inconel	Marotta, 3-way	<0.25	7.5	Yes	Yes
	Inconel Life	1.0	Turbine Meter	Inconel	Marotta, 3-way	1.6	7.5	Yes	Yes
	Ox Purge Elimination & Flight Fuel Vlv	1.0	Calculated	Inconel	Moog	<0.1	7.5	No	No
	Ox and Fuel Simultaneous Shutdown	1.0	Calculated	Inconel	Moog	<0.1	7.5	No	No
	Shortest Pulse	1.0	Calculated	Inconel	Moog	<0.1	7.5	No	No

IV. Test Results

A. Initial Testing

The purpose of the initial testing was to see if bipropellant ignition could be achieved, to determine the performance of the bipropellant operation and generally to see how the whole apparatus and test setup would behave. This initial testing used a typical catalyst bed with a simple fuel injector and massive copper combustion chamber nozzle assembly (Fig. 2). The oxidizer and fuel flow were both controlled by their respective tank pressures using calibrated cavitating venturii. A typical test included pulse preheat followed by 10 sec of steady state monopropellant operation of catalyst bed during which time bi-propellant operation was initiated, typically starting at 5 seconds into monopropellant operation and lasting 1 to 4 seconds. The pulse preheat of the catalyst bed consisted of 3 pulses of H2O2 0.25 sec long, with a 1 sec off period between pulses. The last one second period is followed by the 10 second monopropellant period.

At this point purging was considered very important to prevent any untoward events between the fuel and the oxidizer before they were wanted. During the run sequence the oxidizer purge was started first. This purged everything from upstream of the catalyst bed all the way through the nozzle with nitrogen. Then the fuel purge was started through the normally open port of the fuel fire valve. The fuel purge pressure was set to be higher than chamber pressure in monopropellant mode so that it would continue on through until the bipropellant operation was initiated. The oxidizer purge system was configured so that the purge automatically checked out when stable monopropellant operation was established but came back on immediately when it was stopped.

As might be expected, the results of this testing were mixed. Ignition was achieved and bipropellant combustion was quite stable and very smooth. There was almost no orange color to the exhaust plume indicating very efficient combustion. The O/F was difficult to determine because the fuel venturi acted as a second orifice instead of a venturi. It was determined the pressure drop across the fuel injection ports was greater that first used to size the fuel venturi. As such the fuel venturi was out of cavitation during all the tests. Hence the flow rate calculation becomes more difficult since it now orifii in series. Various methods of calculation produce different O/F and hence C* efficiencies.

A second iteration of the initial testing was done using a slight modification to the fuel injector and a turbine meter for the fuel flow measurement. Measured C* efficiency of greater than 95% in bipropellant operation were found while the turbine meter allowed for increased confidence in the fuel flow measurements.

B. Second Generation Testing

The purpose of the second generation testing was to improve on the repeatability of the results and to map the performance at different O/F ratios. Finally, it was anticipated that a flight-like fuel valve would be available during this period offering an opportunity to check out the operation of it.

This testing began with ignition problems. A few ignition problems in the initial testing led to the idea that a lean mixture and possibly some minimum combustion chamber temperature was required to achieve reliable ignition. Comparison of the fuel data from the runs where a light was first achieved in the early work to these runs indicated that the fuel purge then was much smaller than that being currently used. Duplicating the purge pressure by valving down the pressure to the purge port achieved ignition at a high O/F. After that, a systematic increase in the fuel pressure to investigate the effect of lowering the O/F produced continued success. Ignition was then achieved with the reduced purge with the lowest O/F (6) and a cold copper chamber. An attempt to reduce the purge even further to possibly increase performance resulted in a successful run but no significant change in the performance. Since the turbine flow meter was adequately providing the flow data needed, the no longer required fuel venturi was removed to achieve a lower O/F, and a quicker response was also noted. A couple of runs were used to find the optimum O/F of 7.5 followed by a short and long pulse to observe the behavior of the copper chamber which demonstrated the capability of withstanding four seconds of operation at O/F of 7.5. For the last run of the series, the venturi upstream pressure transducer was removed and the fuel inlet transducer was coupled as closely as possible to examine the effect of decreasing these volumes on response as a precursor to short pulse operation. After all this testing the fuel injector was removed, examined and found to free of any cracking. Three major hurdles had been overcome: 1) Ignition was achieved over a range of O/F from 6.4 to 26, 2) The injector design can withstand operation without cracking with reduced fuel purge flow and 3) Ignition can be achieved with “cold” or warm hardware. During the course of this testing the thruster demonstrated outstanding performance during bipropellant operation. The combustion was very smooth having a roughness less than 1.5% zero-to-peak of mean on a 3-sigma basis. The General Kinetics Inc. fuel injector exhibited C-star efficiencies from about 92% to 95% at O/F ratios between 12 and 6.4, excellent for an L* of less than 7 in. The bi-propellant start transient appears to be around 30-50 ms for the given system depending on the O/F ratio. A minimum start time of 25 ms was achieved at O/F ~ 6.5 with the fuel venturi removed. Figure 4 shows a measured chamber pressure response for typical 2 sec bi-propellant run for this portion of the test series. Ahead of the 1 sec relative time the motor is running in monopropellant mode at a pressure around 150 psia. Fuel is then turned on and combustion achieved with a nice smooth rollover to steady state for two seconds. Fuel is then shut off and once the pressure drops to around 275 psia the fuel purge kicks in providing a somewhat prolonged tailoff back to monopropellant conditions. At around 5 seconds relative time the oxidizer is shut off and a sharp tailoff until the ox purge kicks in about 30 psia. Note that the data provide in the plot is sampled (and shown at) 1k Hz with an analog 250 Hz low pass filter applied. The observed combustion is very smooth. Figure 9 shows a still photograph of the plume during bi-propellant operation with a copper chamber at O/F~7.5. Note the very clear plume corroborating the high measured C* efficiency.

The flight-like valve (Moog) was obtained and installed. This valve, being very compact and having the capability of extremely rapid operation, is a pilot operated valve with a separate helium pressure supply for the pilot and an electronic valve driver to supply the power for operation. In addition, a fuel valve command electrical signal was added to the data acquisition system. The testing described here was conducted in the desert in the late summer giving rise to a number of heat related difficulties with the valve driver, including a complete cessation of the pulse modulation mode. This limited the valve on time to 100 milliseconds to keep the solenoid coil from overheating. Since this valve was not a three way solenoid the purge was changed to check out when the combustion chamber pressure rose. The monopropellant portion of the run was shortened from ten seconds to three with the 100 millisecond fuel pulse coming after two seconds of monopropellant operation. Fuel pressure was always set to maintain a constant O/F of 7.5. The first run was made with the purge and the second without. There seemed to be no difference so this was repeated but with two 50 msec fuel pulses, 0.5 sec apart to confirm no fuel purge on the second pulse. There was still no difference so the purge was abandoned. It became obvious at this point that the flow-meter integration time was too long for these short pulses so the flow rate was estimated from the fuel supply tank pressure and the known fuel injector performance on these and all subsequent runs. It was also noted that the flight-like valve was a lot faster than the former three-way valve. The start times were now almost the same based either upon start of fuel inlet pressure rise or the fuel fire valve command, but were still in the 30 – 35 ms range to 90% of mean chamber pressure as measured in pulses long enough to achieve steady state. Since the system seemed to respond favorably to multiple pulses, it was decided to close out this test series with ever shortening pulses. The two 50 msec fuel pulses, 0.5 sec apart sequence was repeated three more times with the pulse length set to 25, 10 and 5 msec, all 0.5 seconds apart. All tests were successful. The 5 msec pulses were actually 10 msec long because the test controller (not the valve driver) apparently could not deal with this short a time. The last test of the series was four 10 msec fuel pulses, 0.49 sec apart, first pulse 0.5 sec after oxidizer start. This was also successful and concluded the series on a high note. See figures 5 & 6 for the measured chamber pressure response versus fuel valve command for the 2nd and 4th pulses. As can be seen from these figures the fourth pulse rises faster than the second pulse to the maximum chamber pressure (~15 msec) and the pulse shapes are different. The reason for this is that the fuel injector starts the test unfilled and on the second pulse the injector is still not completely filled until approx the fourth (note no fuel purge until after test complete).

C. Final Testing

The intent of the last series of tests was to distinctly advance the state-of-the-art in a number of ways to serve as a precursor to the design of the final product. To this end, a significantly higher flux catalyst bed was employed as was a relatively light weight Inconel nozzle. The flanged joint arrangement was retained but the nozzle dimensions downstream of the flange were flight like. Other flight like factors in sequencing were to be investigated as well. Things like complete elimination of purging, simultaneous shut-off of both propellants and investigation of multi-pulse operation with fuel and oxidizer coming on at the same time.

Since a considerable time had passed since the last testing and a new high flux catalyst bed was being tried for the first time, the thruster was returned to the original configuration for the first tests of this series. This included both purges, the three-way solenoid valve and the copper chamber. The first set of runs was intended as bipropellant check tests to determine if the thruster would light connected to the new catalyst bed. Again ignition problems plagued the effort but fortunately the problems did not seem to be connected to the new catalyst bed but rather to the dramatic change in the weather. It was now winter in the desert and apparently the operation of the entire test setup was affected by a 50 deg Fahrenheit change in ambient temperature. To counter this problem, a “hot-house” was constructed around the setup. The wisdom of this was shown immediately when ignition and performance similar to previous runs in the summer was achieved in spite of the change of catalyst beds. Moving on to the higher flux runs showed good performance at the same optimum O/F. One of two Inconel chambers was run to destruction to put a real-life handle on the heat transfer issues involved with a flight-like uncooled thrust chamber nozzle assembly. Figure 7 shows the measured chamber pressure for the run to life test. As can be seen the throat begins to erode at approximately 1.6 seconds and the test is terminated at roughly 4.5 sec when the throat completely burned through. Installation of the Moog valve started the timing and pulse testing crucial to the final success of this thruster. After an initial successful run, a run was made with no oxidizer purge followed by runs in which attempts were made to shut off the oxidizer at the same time as the fuel. After a couple of tries this was basically successful. Starting and stopping the thruster with no purges seemed to be a non-issue as was stopping the fuel and oxidizer flows simultaneously. At this stage it started to become obvious that the enormous difference between the oxidizer valve, a pneumatically operated ball valve and the ulta-rapid flight-like fuel valve was going to make any solid conclusions regarding valve timing a little vague. Attempts to make the oxidizer flow and the fuel flow start together resulted in a number of ignition problems that could be attributed chiefly to the need for chamber preheat to achieve ignition and, quite possibly, timing problems, especially when the times became quite short. In all, however, the testing provided an enormous amount of information that could influence the design of a flight unit of this thruster and confirmed the ability for such a thruster to perform quite well and operate successfully in the short-pulse mode. Figure 8 shows a typical chamber pressure response for a 10 msec fuel pulse wherein there is no purge on both the fuel and the oxidizer. It can be seen that the time from fuel valve command to the peak is roughly 20 ms which for slightly longer pulses resulted in a start transient time of ~25 ms from fuel valve command to 90% of steady state chamber pressure. Also of note from figure 8 is that the fuel and oxidizer are shut off simultaneously hence the shutdown time is 50-70 msec.

V. Conclusions

Several important parameters associated with the propellant combination of 90% H2O2/RP-1 were proven in the development test program. In each case the system performed as expected or better. Some of the major conclusions that are drawn from the data:

- A General Kinetics Inc design high flux catalyst bed in combination with General Kinetics Inc. fuel injector achieved reliable auto-ignition for catalyst bed flux levels of 0.75-1.0 lbm/(in^2-s).
- Very stable (<5% zero-to-peak of mean on a 3-sigma basis) was achieved at optimum O/F of 7.5 and as low as 5 and as high 26.
- The bi-propellant start transient appeared to be around 25 ms for the given system using a cat bed flux of 1.0 lbm/(in^2-s), Moog fuel valve, Inconel metal chamber and optimum O/F ratio. This resulted in a bi-propellant chamber pressure of roughly 475 psia.
- Short, multiple pulse operation has been shown to be not only feasible but quite workable down to the electronic limitations of the valve and the valve driver. This limit was about 10 msec command widths.
- Combustion was very smooth in all cases, with and without purge, multi-pulses with various pulse durations having a roughness less than 1.5% zero-to-peak of mean on a 3-sigma basis.
- The combustion efficiency was consistently in the 92-94% range, which is excellent for a short L* at O/F ~ 7.5. A very clear plume with almost no orange is also indicating excellent combustion efficiency.
- Outdoor weather effects have considerable bearing on the start-up performance of a bipropellant thruster of this type and certainly cannot be ignored. It was found that hardware and propellant temperatures greater than 80 F were required.
- It was found that purge could be completely eliminated from both the oxidizer and fuel system with no adverse effects on the hardware.

Acknowledgments

General Kinetics would like to thank Lawrence Livermore Laboratories (LLNL) for funding the flux testing. Specifically, the LLNL members: Doug Dobie, Ken Skulina, Arno Ledebuhr, Don McMahon, Elon Ormsby, Lee Pittinger, & Jeff Robinson.

References

[1]Rocketdyne, North American Aviation, “Hydrogen Peroxide Handbook,” Air Force Rocket propulsion Laboratory Technical Report AFRPL-TR-67-144, July 1967.

Figure 1. Picture of Test Stand

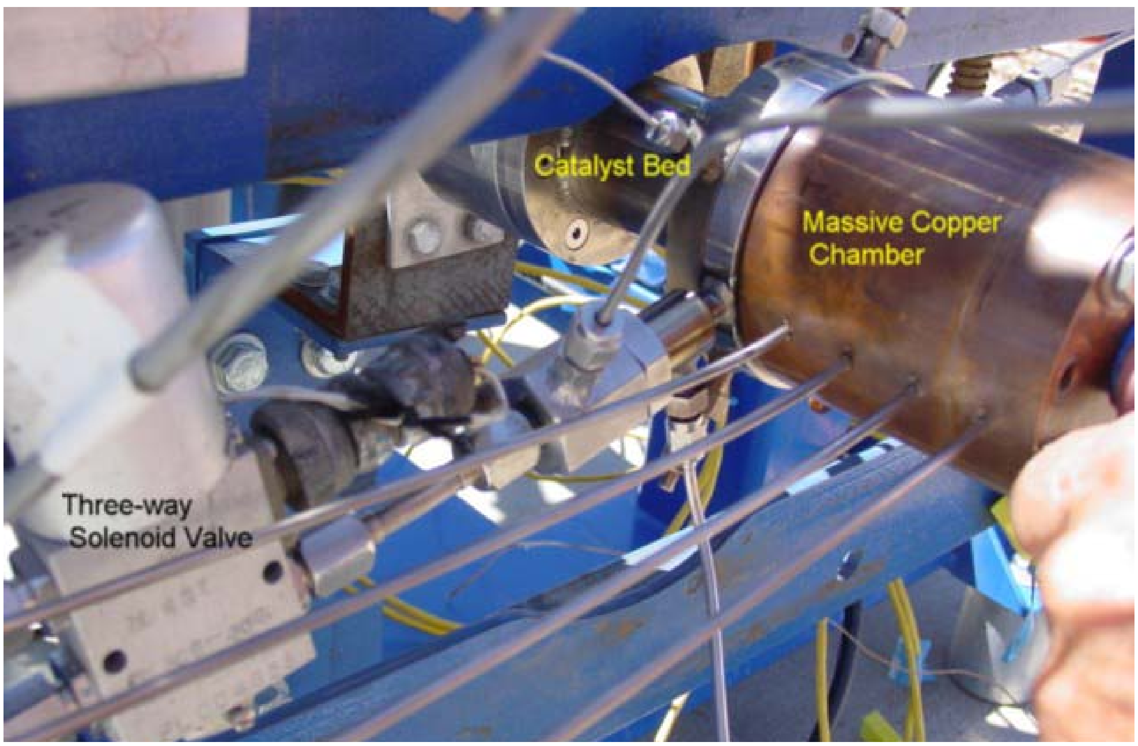

Figure 2. Details of Test Thruster

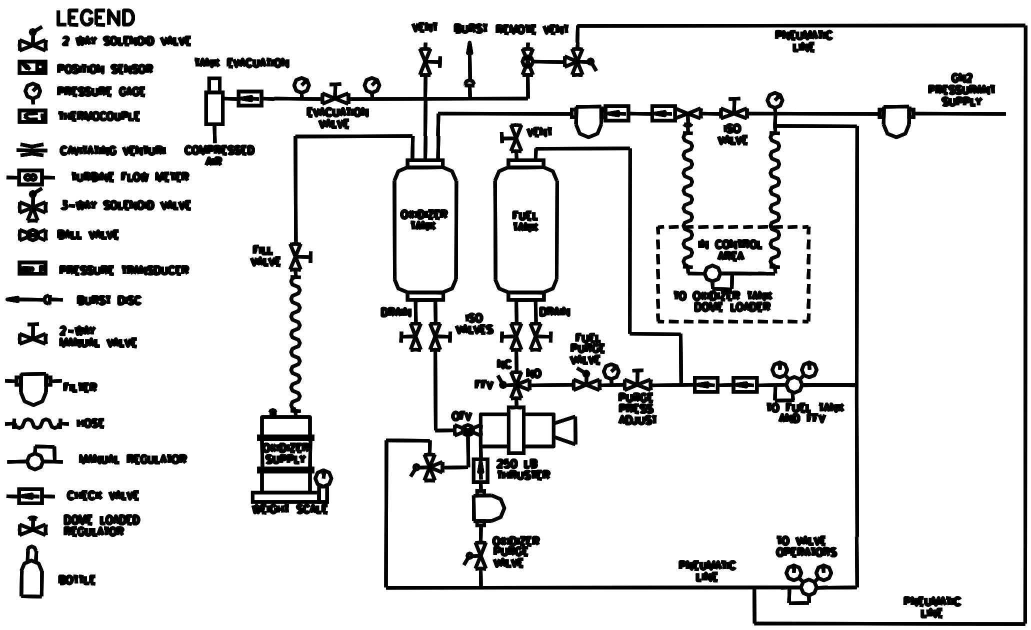

Figure 4. Test Schematic

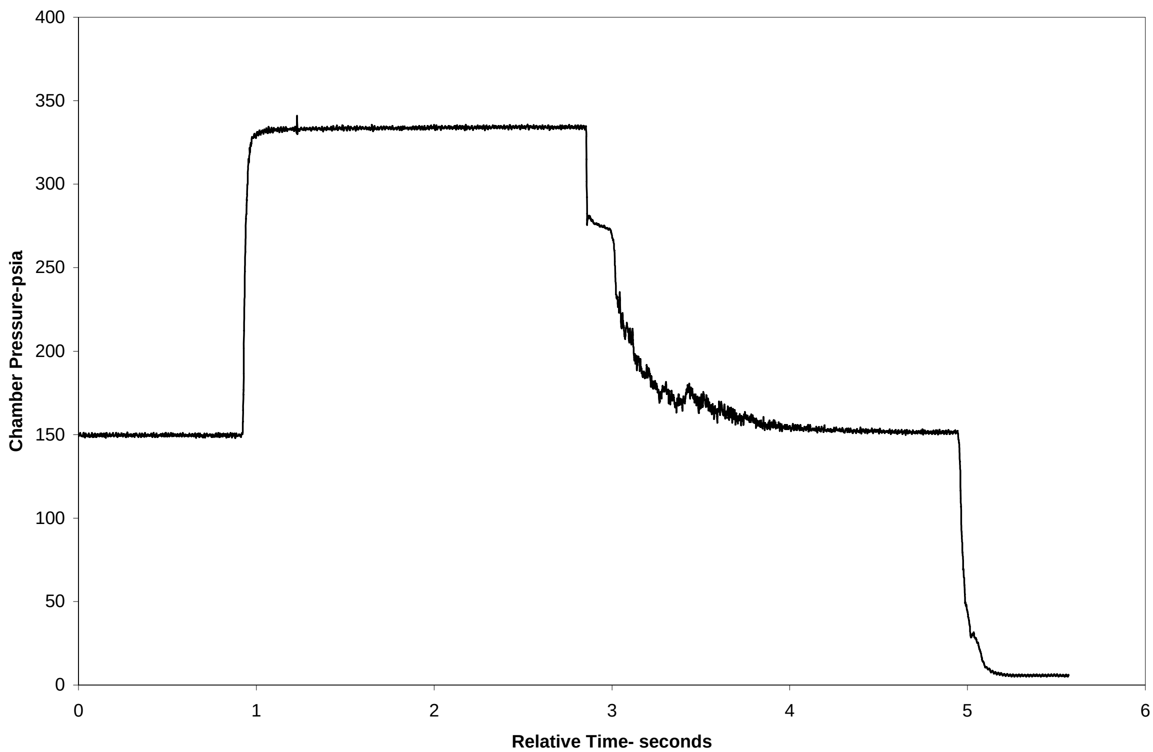

Figure 3. Measured Chamber Pressure Test 081203_006 – Copper Chamber, O/F~7.5

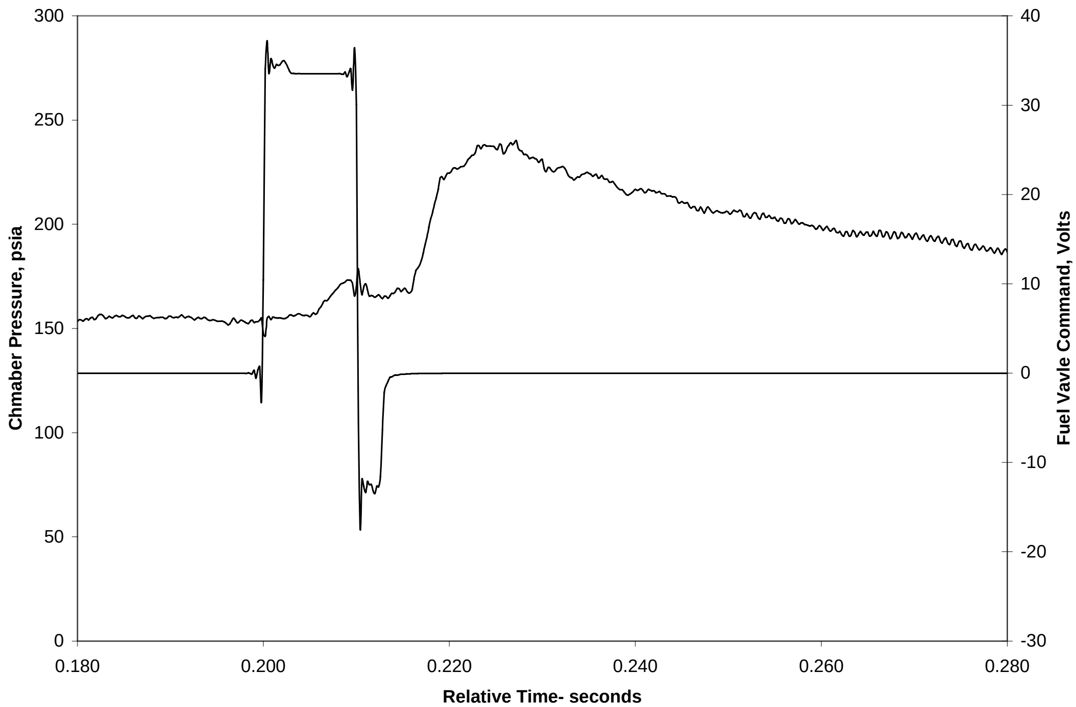

Figure 5. Measured Chamber Pressure for Test 090303_006 2nd Pulse

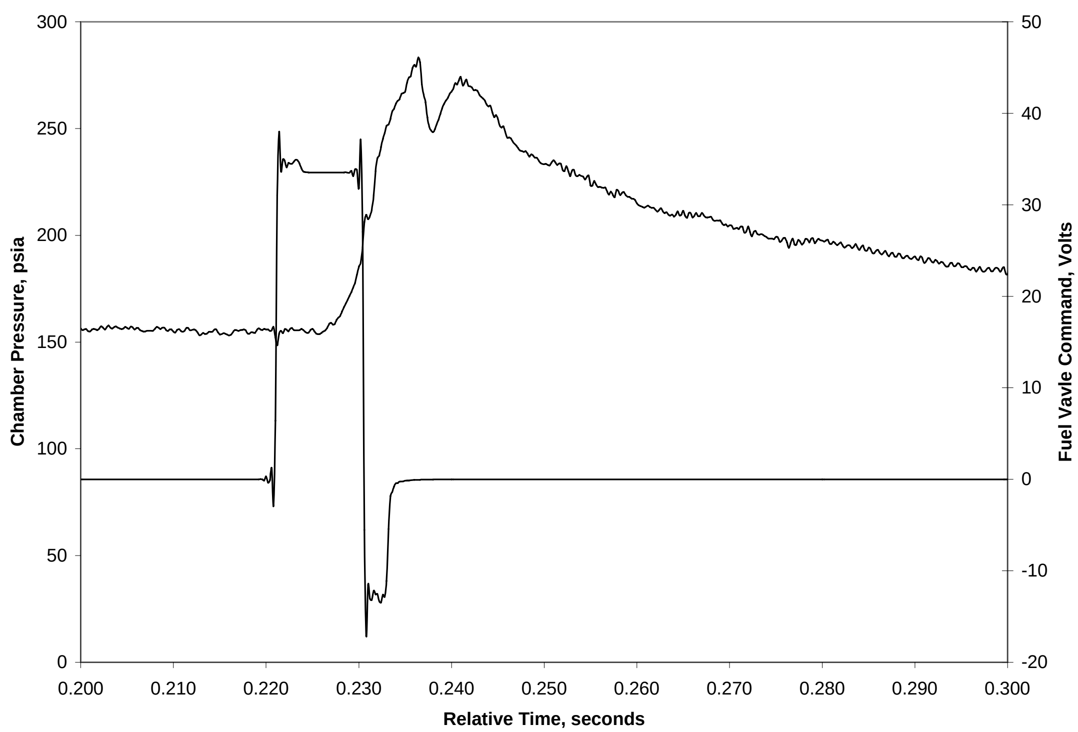

Figure 6. Measured Chamber Pressure for Test 090303_006 4th Pulse

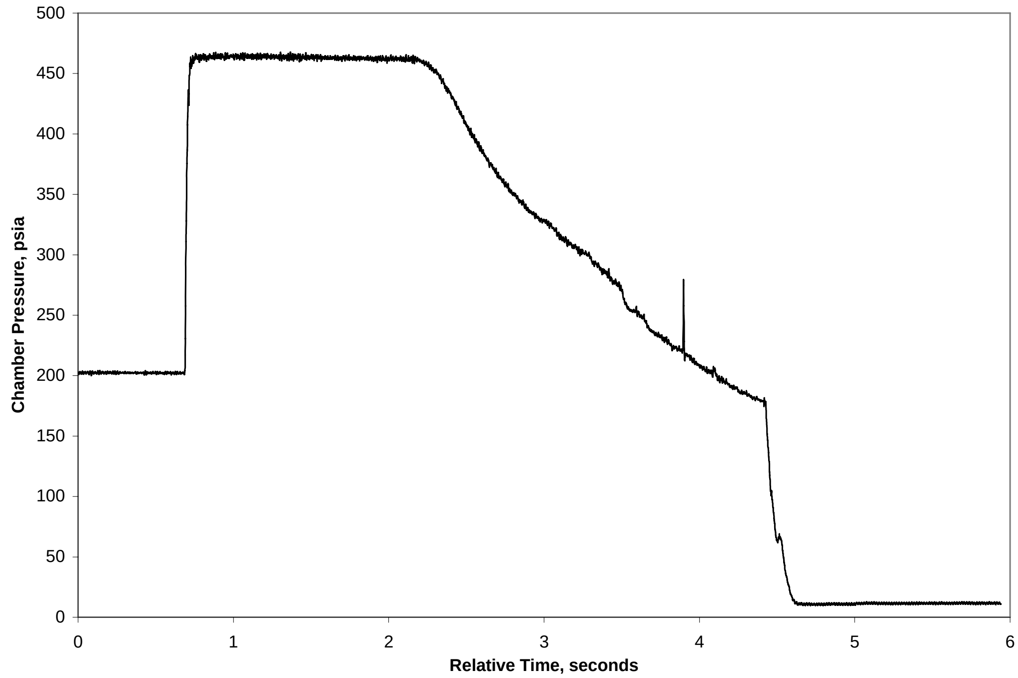

Figure 7. Measured Chamber Pressure for Test 112103_004

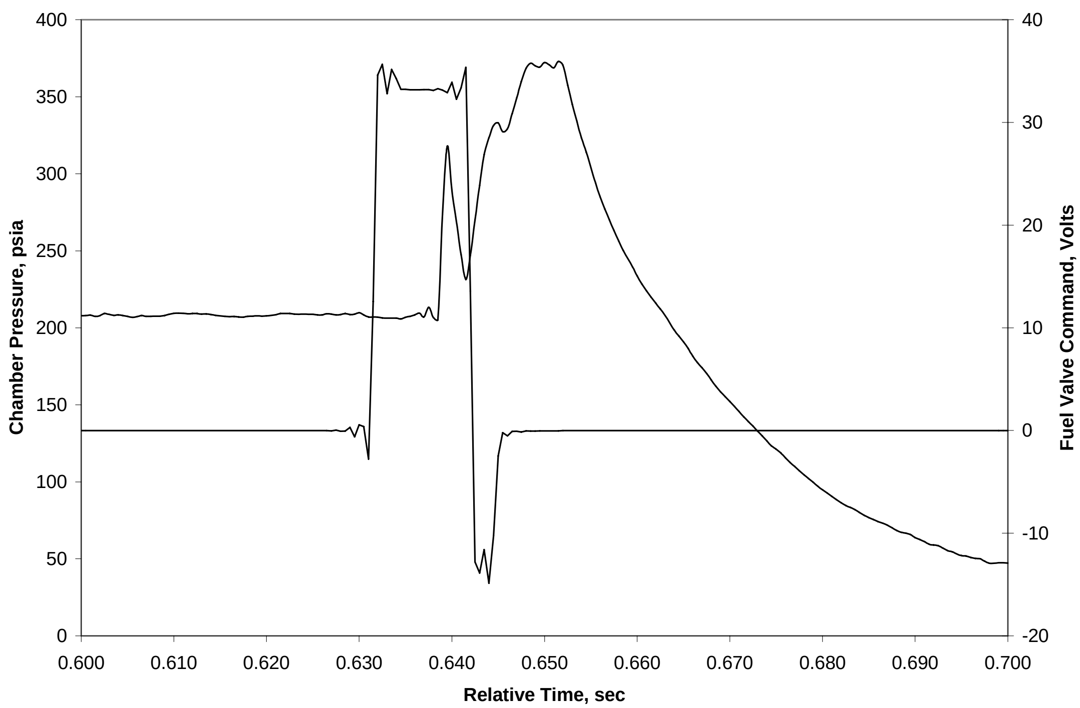

Figure 8. Measured Chamber Pressure for Test 112303_009

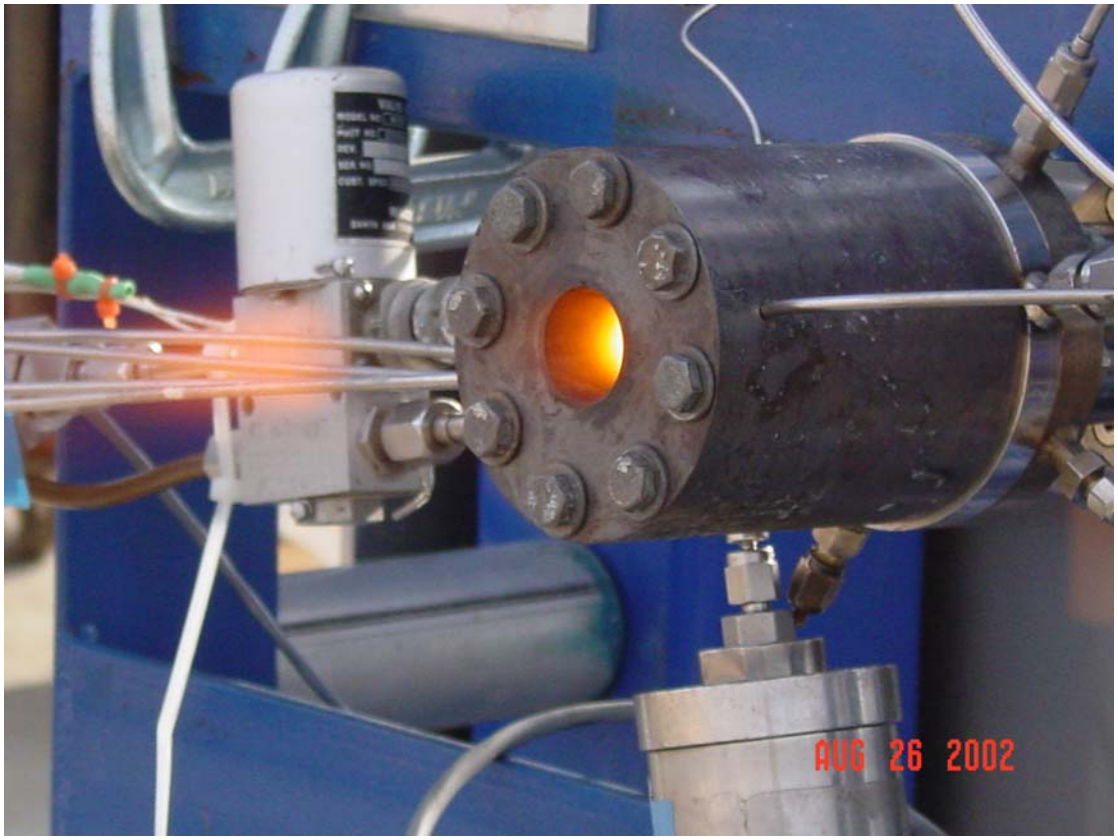

Figure 9. Plume Photo of Test 082303_007 During Bi-Propellant Operation