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Development and Testing of SP7 Fuel for Mars Ascent Vehicle Application

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A new solid fuel formulation called SP7 was developed for application in a hybrid rocket propulsion system for a potential Mars Ascent Vehicle (MAV). The new fuel offers good propulsive performance (I_{sp}) while meeting the storage and operation requirements placed upon the proposed mission. Mixed Oxides of Nitrogen (MON) are selected for the oxidizer due to the low freezing points possible with these materials. The low temperature capabilities of the fuel and oxidizer reduce the required energy associated with thermal management systems. Evaluation of the propulsive performance of SP7 was completed with two oxidizers, N_2O and MON, in a 2.7-in hybrid rocket motor. In addition to the baseline fuel, metallized formulations with 20% by weight aluminum particles were also tested. Ignition and stable combustion was demonstrated with both oxidizers over a wide range of operating conditions. Static test firing of SP7 demonstrated the ability for this fuel to meet the propulsion requirements of the as designed potential MAV mission.

I. Introduction

The Mars Sample Return mission is being planned to be the first mission to return rock, soil and atmosphere samples from Mars for further study on Earth. Samples will be collected by rover on the Mars surface and placed inside the Mars Ascent Vehicle (MAV). The MAV will shuttle the samples from the Mars surface and place them in orbit for the return trip to Earth upon a secondary vehicle.

As currently planned, the MAV will remain on the surface of Mars for upwards of 2 years. This places special thermal requirements on the propulsion system in addition to the propulsive performance.[1] A major obstacle for the MAV propulsion system is the thermal requirements of the propellants. The propulsion system must be rated for temperature variations between 60°C and -60°C, based on the maximum temperature for launch from Earth and storage conditions on the surface of Mars.

This large temperature change eliminates many propellants from consideration including the baseline SPG fuel, SP1x. In addition, the long storage duration also requires that the propellants be capable of withstanding multiple thermal cycles associated with Mars surface temperature variation throughout the potential mission. The addition of metal particles to the baseline fuel was considered for propulsive performance and packing reasons. The low temperatures that the propulsion system are exposed to during

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storage and operation also necessitate an oxidizer capable of withstanding the environment. For this reason, Mixed Oxides of Nitrogen (MON) was selected for the candidate oxidizer.

Though a number of thermoplastic materials exhibit the capability to withstand the large temperature variations required by the MAV, the propulsive performance is usually inadequate. Most thermoset polymers (e.g., hydroxyl-terminated polybutadiene) have a glass transition temperature above the required storage temperatures, which also eliminates them from consideration. A novel solid fuel formulation was developed that meets both the propulsive and thermal requirements.

To identify plausible fuel candidates for additional screening and static motor testing, a series of qualitative and quantitative measures were identified for quick evaluation of a given fuel. The selected fuel formulations were then evaluated in a series of sub-scale rocket motor firings using N_2O as a simulant oxidizer prior to proceeding to testing with MON-3 (3% NO concentration) oxidizer.

II. Technical Approach

The primary objective of the study is to advance the state of readiness of the propulsion system for the MAV. Initial efforts focused on the development of novel solid fuel formulations that meet the stringent storage and operation requirements for a MAV system. In addition to the thermal requirements, the inclusion of metal particles was also a selection criteria for the initial formulation testing. The overall objectives of the fuel formulation development program were:

1. Establish the feasibility of using hybrid rocket propulsion for the extreme temperature ranges and long storage requirements of the MAV application.
2. Formulate several candidate liquefying fuels that would be suitable for the MAV application, capable of withstanding storage and operation at low ambient temperatures.
3. Demonstrate the operability of the hybrid rocket propulsion system under Mars conditions by conducting motor tests with a cold, but non-cryogenic, oxidizer.
4. Develop a fuel formulation with the desired ballistic performance for the desired trajectory of the MAV.

Selected metallized and non-metallized fuels were then tested with N_2O oxidizer as a simulant for the MON-3 oxidizer. Following the initial testing with N_2O oxidizers, the fuel formulation was down selected to the non-metallized fuel.

After the successful fuel development and demonstration testing with N_2O, continued testing with MON-3 oxidizer was completed. The primary objectives of the SP7/MON-3 testing can be summarized as:

1. Evaluate the regression rate of SP7/MON-3 and determine the capability for robust ignition and flame holding
2. Measure the regression rate of SP7/MON-3 and determine the curve fit relationship with average oxidizer mass flux
3. Compare the relative regression rate behavior to the existing data of SP7/N_2O
4. Investigate the low mass flux regime to determine if there exists an instability related to flame holding
5. Determine the capability for the operation of SP7 at diameter ratios (b/a) of 3

III. Fuel Formulation Development

Methodology

The fuel formulation requirements were based on three defining criterion; 1) the fuel could withstand the storage and operating condition requirements, and 2) the fuel must be capable of including aluminum particles, and 3) the regression rate was in an acceptable range based on trajectory calculations. Based on these requirements, a systematic study was carried out to evaluate various fuel formulations, where both the baseline fuel and additives were varied. To identify plausible candidates for static motor testing, a series of qualitative and quantitative measures were identified for quick evaluation of a given fuel.

For each fuel formulation, the high and low temperature requirements (60°C and -60°C, respectively) were evaluated qualitatively. A small sample, ~12 g, was cast in a sample pan and heated or cooled to the desired temperature. At the high temperature limit, the sample was pressed on to test for rigidity. At low temperatures, the sample was dropped to the ground. Samples that were both rigid at high temperature and withstood being dropped at low temperature were considered for additional screening.

The next evaluation criterion was the inclusion of metal particles. Mixtures containing metal particles at a desired concentration were mixed and the same high and low temperature tests outlined above. The inclusion of particles in fuels also proved to be a useful selection criteria as certain formulations did not mix well with particles, inhibiting the uniform distribution of particles in the fuel matrix.

Fuel formulations that met the above requirements were then evaluated for regression rate performance. The requirement of the regression rate was determined based on trajectory calculations completed by NASA-JPL personnel. Based on previous study at Space Propulsion Group, Inc. (SPG), the relative regression rate of a new fuel can be quickly evaluated through measurement of certain liquid-phase properties. These properties were measured for each candidate fuels. Formulations were tailored to meet the determined liquid-phase properties for achieving the desired fuel regression rate. Once meeting the liquid-phase property requirements, the fuels were again tested for high and low temperature behavior.

In total more than 60 fuel formulations were evaluated with the above process. As a result of the evaluation a new fuel formulation was developed that met the requirements for regression rate, temperature, and aluminum inclusion and was called SP7.

Thermochemical Calculations

With an initial fuel formulation specified, the theoretical thermodynamic performance of the fuel was evaluated. Calculations were completed to compare SP7 to $C_{32}H_{66}$ (the exact composition of SP7 is not given here for proprietary reasons). The resulting mixture properties were determined using the ABC Method.[2] The thermochemical calculations were completed using NASA-CEA thermochemical equilibrium code[3] with the "Rocket" problem and assuming equilibrium species. The oxidizer was N_2O for all cases. The pressure was specified at 3.45 MPa (500 psi) and all fuel and oxidizer were both at 298K. The nozzle was expanded to an exit pressure of 83 kPa (12 psi), which is local atmospheric pressure in Butte, MT. Both baseline and metallized fuels were considered. The aluminum particles were assumed to contain an oxide layer that was 15% by mass of the total particle.

For the comparison between fuel formulations, the characteristic exhaust velocity (C^*) and the specific impulse (I_{sp}) were compared as a function of the oxidizer-to-fuel ratio (O/F). The O/F ratio was varied from fuel rich (O/F = 5) to oxidizer rich (O/F = 9)

Figure 1 shows the comparison of the C^* values for non-metallized SP7. The overall trend between the two curves is quite similar. This is expected since the fuel formulations are similar in nature. The main difference occurs at high O/F ratios where there is effectively a constant offset between the two curves. The difference between the two curves is quite small, with a maximum difference in velocity being approximately 2 m/s.

The calculated I_{sp} is shown in Figure 2. Similar behavior is observed compared to that of the C^* values, as shown in Fig. 1. The curves follow closely at fuel-rich operating conditions and then slightly offset at oxidizer rich values, where paraffin wax has a slightly higher value. The maximum difference in the I_{sp} of SP7 and $C_{32}H_{66}$ is near 1 second.

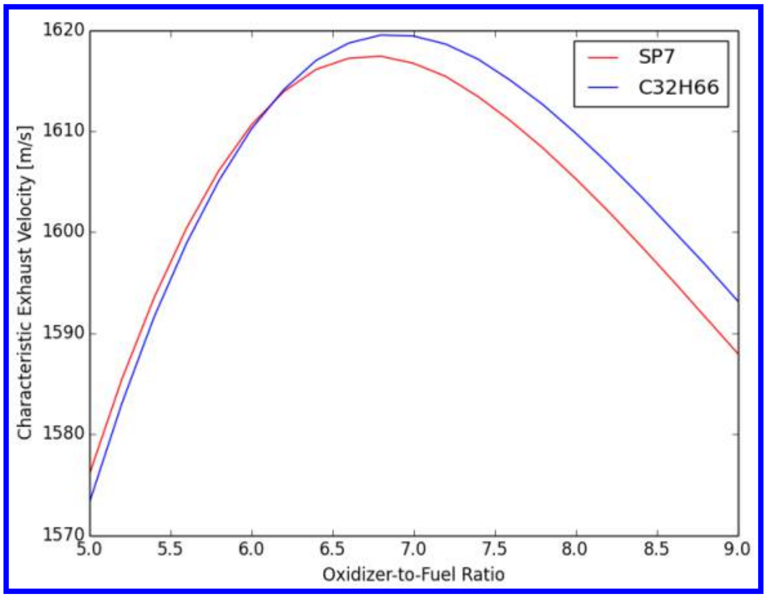

Figure 1. Comparison of characteristic exhaust velocity for SP7 vs. SP1x

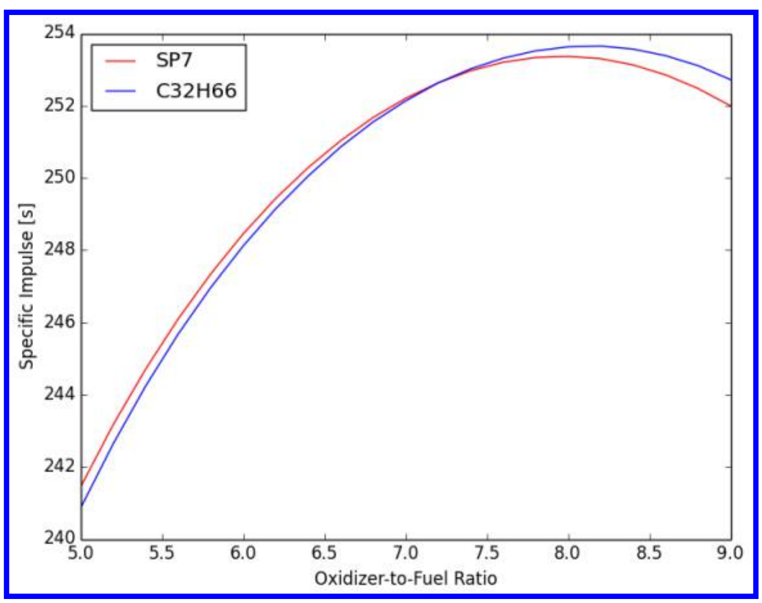

Figure 2. Comparison of specific impulse for SP7 vs. SP1x

Figure 3 shows the percent difference of C^* and I_{sp} performance for SP7 and SP1x, relative to SP7 values. Over the O/F range considered, the maximum difference of 0.3% occurred at oxidizer-rich conditions. The baseline paraffin fuel performs better at high O/F values and SP7 has higher performance at low O/F values, though this difference is very small across the entire range of interest.

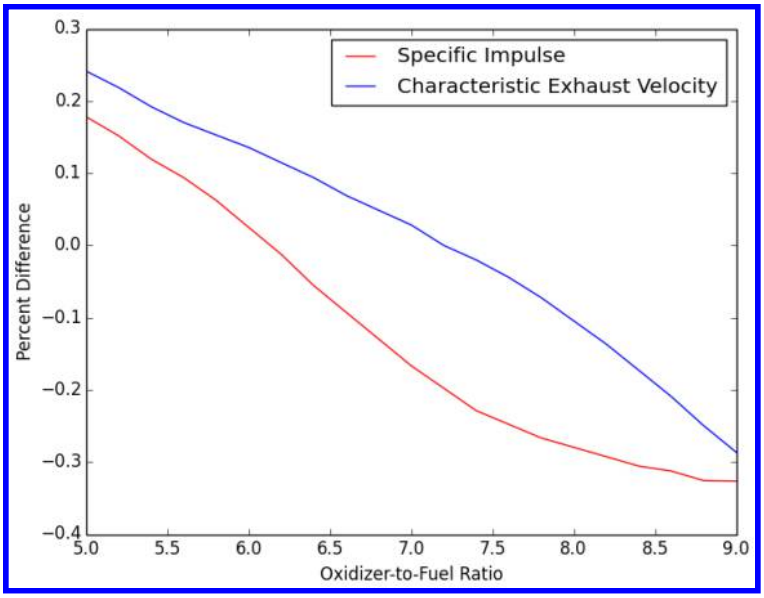

Figure 3. Percent difference of I_{sp} & C^* for SP7 vs. SP1x

Similar results in C^* and I_{sp} are observed when comparing the metallized formulations. Maximum differences of 2 m/s for C^* and less than 1 s I_{sp} is calculated.

These small differences in thermochemical performance indicate that SP7 can potentially deliver similar ballistic performance levels to that of SP1x and the pending regression rate determination would meet the requirements for a MAV mission.

IV. Experimental Setup and Characterization

The promising outcome of fuel formulation screening led to the selection of formulation SP7 for hot-fire testing with N_2O. Initial screening was completed at room temperature conditions for a direct comparison of the regression rate to the SPG baseline fuel SP1x. Subsequent testing was completed with both the fuel grain and oxidizer conditioned to desired low temperatures to evaluate ignition and combustion characteristics of the new fuel. The lowest oxidizer and fuel temperatures tested were -60°C.

Two formulations of SP7 were evaluated, one with the addition of 20% by weight aluminum and one non-metallized. The initial size of the aluminum used for metallized fuels was a 30 μm spherical particle. Later test series evaluated the influence of particle morphology on the regression rate and combustion efficiency.

Testing conducted with MON-3 oxidizer was all conducted at ambient conditions. Two objectives of this testing were to demonstrate ignition and combustion of SP7 with MON-3 and to develop a preliminary regression rate correlation based on average oxidizer mass flux. 13 tests were completed with this propellant combination.

Tests were completed at the Butte AeroTec Facility located in Butte, MT. Testing was conducted in a 2.7-in motor. In total, 45 tests were conducted at a range of operating conditions including two oxidizer types, fuel and oxidizer temperature, average oxidizer mass flux, and oxidizer flow rate.

2.7-in Motor Test Facility

The 2.7-in motor (Figure 4) used was composed of a heavy-wall aluminum chamber designed for a maximum allowable working pressure of 6.9 MPa (1,000 psi). The fuel grain is cartridge loaded in the motor and graphite insulators are used for the pre-combustion and post-combustion chambers. The injector and retaining plate were made from brass for testing conducted with N_2O and Alloy X with MON-3. A nozzle insert made of graphite is used to control the chamber pressure. A pyrogen ignition system was attached to the injector retaining plate and was initiated by hot wire. The motor has been used for more than 300 test firings using N_2O oxidizer.

Fuel grains had an OD of 2.6-in and various initial port diameters. The fuel grains were housed in a phenolic liner with an OD of 2.75-in. Motor burn times were up to 11 seconds in duration and maximum chamber pressures of 500 psi were used. The oxidizer flow rate was measured with a turbine flow meter and was verified with the difference in pre-test and post-test tank weights.

During initial tests, the oxidizer used was N_2O and the maximum oxidizer flow rate was 450 g/s. The N_2O was pressurized in the run tank using gaseous oxygen. For N_2O testing at cold conditions, the run tank was chilled using an ethylene glycol & dry ice coolant system that circulated through tubes around the run tank. Prior to conducting the test, the oxidizer temperature was measured with a thermocouple located in the bottom of the run tank.

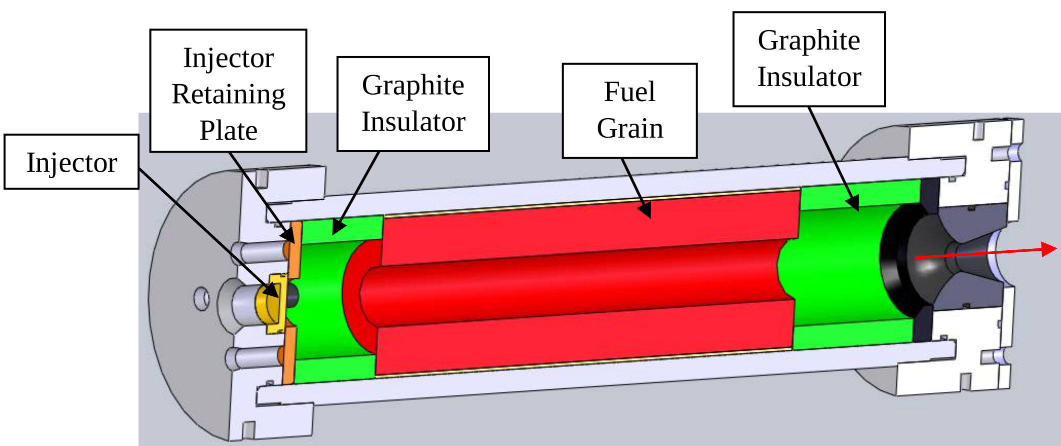

Figure 4. Schematic diagram of 2.7-in motor used for fuel formulation testing

Pressure measurements were taken in the run tank, upstream of the injector inlet, and two measurements were taken in the combustion chamber. The oxidizer temperature was also measured upstream of the injector. The pressure and temperature of the oxidizer were used to determine the mass flow rate of oxidizer in combination with the turbine flow meter measurement.

Operations with MON-3 oxidizer were conducted at a newly constructed test cell located at the Butte AeroTec Test Facility. The test cell was designed with the capability for full-scale motor operations (MON-3 flow rates up to 2.5 kg/s). Tests presented in this paper were conducted at much lower flow rates. The current tests with MON-3 as an oxidizer, maximum flow rates of 146 g/s were achieved. The MON-3 was pressurized with UHP Helium and all tests were conducted at ambient temperatures.

Experimental Evaluation of SP7/N_2O

The objective of tests conducted with N_2O was to determine the regression rate of SP7 with the target rate of 70% the burning rate of SP1x. Average oxidizer mass fluxes from 100-325 kg/m^2-s were evaluated. Three formulations were tested:

1) Baseline SP1x,
2) Non-metallized SP7, and
3) Metallized SP7 with 20% aluminum content

Three different particle types were considered for the metallized SP7; 30 μm spherical, 30 μm flake, and 5 μm spherical.

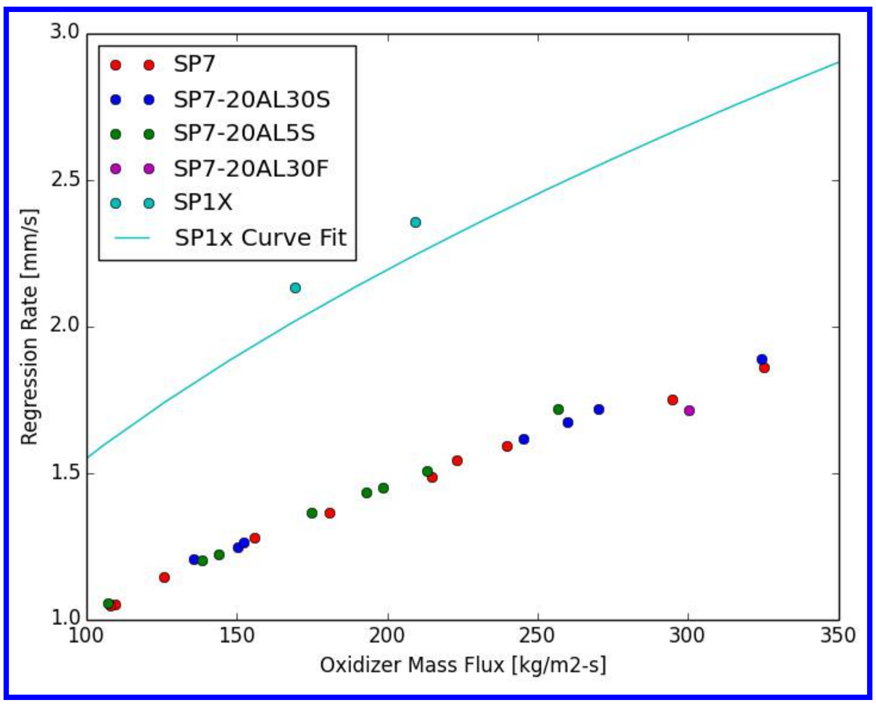

Figure 5. Regression rates for baseline & aluminized fuel formulations with N_2O oxidizer

The measured regression rates as a function of average oxidizer mass flux are shown in Figure 5. Also shown is the regression rate curve for SP1x with N_2O that has been validated with more than 300 test firings. The addition of aluminum particles has a very minor effect on the regression rate compared to baseline SP7. The particle morphology does not significantly influence the regression rate either. The fuel regression rate was unaffected by initial temperature of the fuel and oxidizer; with no difference in performance measured where the fuel grains and oxidizer were initially conditioned to -60°C.

From this round of testing it was demonstrated that the regression rate of SP7 is 60-70% of that of SP1x. The regression rate parameters were deduced together for non-metallized and metallized fuels since there is no difference within measurement uncertainty. The regression rate correlation was developed accounting for O/F variation using Eqn. 1 and the resulting parameters are given in Table 1.

$$\frac{\bar{\dot{r}}}{a\bar{G}_{ox}^{n}} = \frac{1-n}{\left[\left(1+{}^{1}/_{O/F}\right)^{1-n}-1\right]O/F} \tag{1}$$

Table 1. Deduced regression rate parameters for non-metallized and metallized SP7/N_2O

$r_b = aG_{ox,ave}^{n}$	SP7/N_2O
Units: r_b [m/s], G_{ox} [kg/m^2-s]	
a	0.0000781
n	0.545

Experimental Evaluation of SP7/MON-3

Testing was completed using the baseline, non-metallized SP7 fuel in a newly developed MON test cell at the Butte Aerotec Facility. Grains were fabricated at the SPG facility in Butte, MT. Testing was conducted using the same 2.7-in motor as was used for N_2O testing with the noted changes in materials for compatibility reasons.

A primary objective of the testing with MON-3 was to demonstrate ignition and stable combustion. In total, 13 tests were conducted with 8 successful ignitions. A summary of all test data is provided in Table 2. An image captured from a hot-fire test is shown in Figure 6. Stable and efficient operation was demonstrated using MON-3 as the oxidizer at a wide range of initial oxidizer mass flux values, ranging from 66 – 268 kg/m^2-s, and average oxidizer mass flux values, ranging from 47-164 kg/m^2-s. These tests proved that the fuel tested can operate at conditions pertinent to the proposed MAV mission.

Tests where ignition failed occurred at low b/a ratios, for a b/a ratio of 1.85 ignition and sustained combustion would not occur. In these tests, the fluid dynamics in the head-end region did not facilitate the flame attachment during the attempted ignition. No flame attachment was observed in these tests. Tests that ignited and burned to a port diameter where the diameter ratio was smaller than the cases of non-ignition did not demonstrate the onset of flame-holding or other instabilities. This emphasizes the importance of head-end geometry for flame attachment during the ignition transient.

Recorded pressure-time traces from Test 3in_MON_SP7_01 are shown in Fig. 7, which are representative of the stability level for all tests with successful ignition. The four pressure measurements shown are the run tank pressure (black), the pressure upstream of the injector element (green), and two chamber pressure measurements (blue and red). The test was successful in igniting the propellants, with ignition occurring quickly and the burn was quite steady. There was a longer than expected burn because of a long shutdown transient associated with the large volume in the feedline between main run valve and motor. The large feedline volume was a direct result of sizing the feed system to future testing objectives requiring significantly higher flow rates. The commanded burn duration was 3 seconds followed by a shutdown transient of approximately 3.3 seconds. The total measured burn duration was based on pressure-time trace was 5.88 seconds.

Figure 6. Image captured during static test firing with MON-3 oxidizer

Table 2. Summary of test conditions

Test Name	Initial Port Diameter [in]	Diameter Ratio (b/a)	Grain Length [in]	Gox,ave [kg/m2-s]	rb,ave [mm/s]	%SP1 fit	eta C*	O/F	Outcome
3in_MON_SP7_01	1.259	2.06	8.40	46.7	0.97	0.66	0.98	2.3	Ignition
3in_MON_SP7_02	0.976	2.66	7.00	121.5	1.13	0.66	0.69	4.7	Ignition
3in_MON_SP7_03	1.088	2.39	8.40	84.4	1.07	0.66	0.72	3.4	Ignition
3in_MON_SP7_04	1.250	2.08	8.40	55.4	0.77	0.65	0.92	3.3	Ignition
3in_MON_SP7_05	1.405	1.85	8.40	--	--	--	--	--	Non-Ignition
3in_MON_SP7_06	1.405	1.85	8.40	--	--	--	--	--	Non-Ignition
3in_MON_SP7_07	1.405	1.85	8.40	--	--	--	--	--	Non-Ignition
3in_MON_SP7_08	1.405	1.85	8.40	--	--	--	--	--	Non-Ignition
3in_MON_SP7_09	0.860	3.02	8.40	117.0	1.10	0.68	0.68	3.0	Ignition
3in_MON_SP7_10	0.861	3.02	8.40	163.5	1.27	0.63	0.71	4.5	Ignition
3in_MON_SP7_11	0.855	3.04	8.40	151.0	1.11	0.67	0.70	4.9	Ignition
3in_MON_SP7_12	1.266	2.05	8.40	--	--	--	--	--	Non-Ignition
3in_MON_SP7_13	0.855	3.04	8.40	128.7	1.12	0.63	0.73	4.6	Ignition

The measured oxidizer mass flow rate from the turbine flowmeter data was 60.1 g/s, which agreed well with the value of 64 g/s that was predicted with an in-house injector performance code calculated under similar conditions. The oxidizer flow rate also remained relatively constant during the shutdown transient based on the injector pressure level and the calculated values from the injector design code. A slight decrease in calculated oxidizer mass flow rate, at a level of 62.3 g/s, occurred during the shutdown transient.

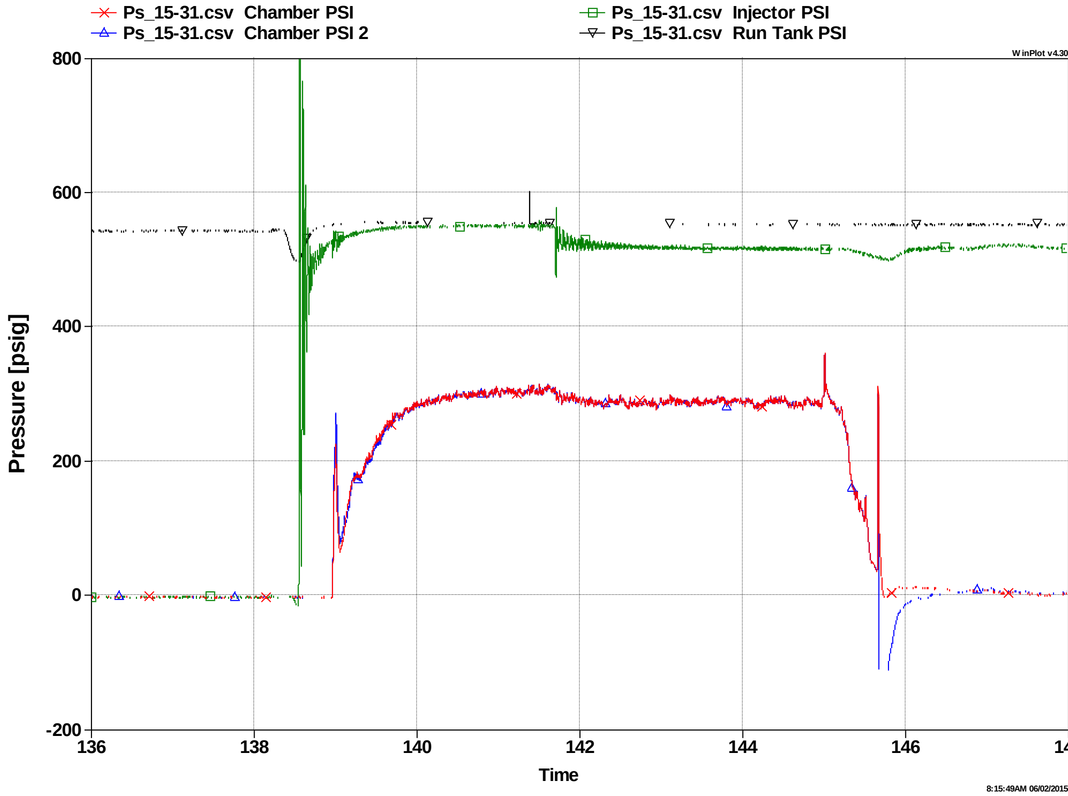

Figure 7. Pressure-time traces for Test 3in_MON_SP7_01

The regression rate was measured at 0.97 mm/s with an average oxidizer mass flux of 46.7 kg/m^2-s. The predicted value from the existing SP7/N_2O curve fit was 0.63 mm/s, which gave a 54% increase in the regression rate at this particular flux level for SP7/MON-3. The average O/F ratio for this test was 2.3, which was well below the ideal value near 3.5. The combustion was very efficient, with an average C^* efficiency of 98%. This was not unexpected for the low O/F operating condition of this test. Average C^* efficiencies tend to be quite high due to the decrease of the C^* curve at low O/F ratio.

There are 8 data points from the performed testing, the correlation that best fits the data was not that robust because of the relatively small oxidizer mass flux range evaluated and also, to a lesser extent, the tests conducted at off-nominal O/F ratios. The curve parameters resulting from the eight parameters gave the results of a = 2.80e-4 and n = 0.297, where G_{ox} is in kg/m^2-s and $\dot{r}$ is in m/s. Even accounting for the O/F variation with a three parameter curve fit using Eqn. 1 produced results that were skewed by the small oxidizer mass flux range considered (a = 2.53e-4 and n = 0.311).

It was best to compare the data to the existing curve fit for SP7/N_2O to see if the new data fits well with the existing curve fit. Applying Eqn. (1) with the existing curve parameters for SP7/N_2O (a = 7.81e-5 and n = 0.545) gave the results shown in Figure 8. Also shown is the regression rate curve for SP1x with N_2O that is validated with more than 300 test firings. It is seen that the regression rate for SP7/MON-3 agrees very well with the data for SP7/N_2O. At this point, the existing curve fit parameters for SP7/N_2O should be used when calculating the regression rates for SP7/MON-3.

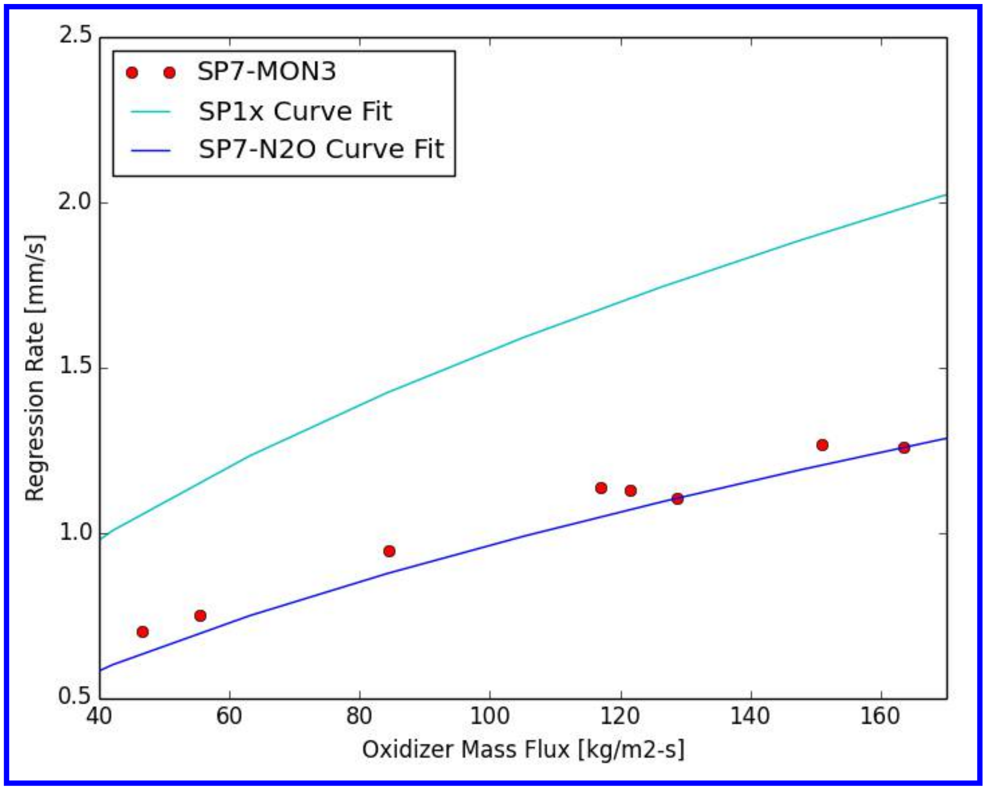

Figure 8. Comparison of regression rate data for SP7/MON-3 with the curve fits for SP7/N_2O and SP1x/N_2O

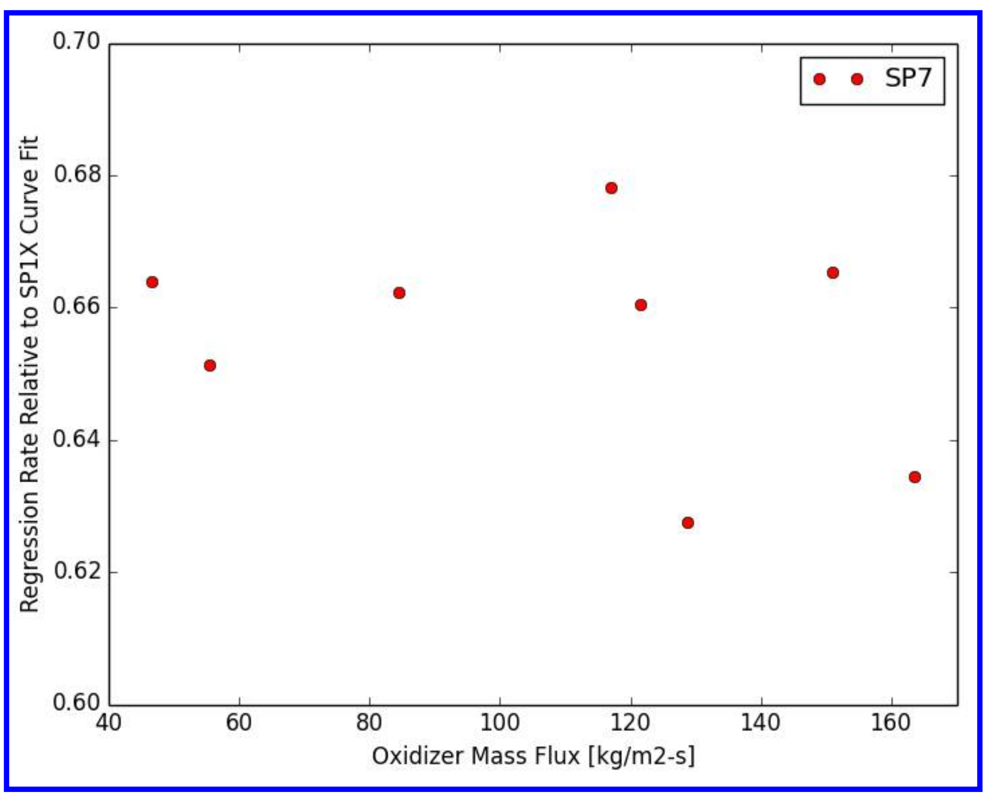

Figure 9. Relative regression rate of SP7/MON-3 with SP1x/N_2O

The relative regression rate, in percent of SP1x, is shown in Figure 9. The regression rate values are first corrected for average O/F ratio prior to comparison to SP1x. SP7 demonstrated a regression rate ranging from 62-68% that of SP1x. The variation in relative regression rate was quite small and shows that the fuel-oxidizer combination was meeting the desired regression rate for a potential MAV application.

The C^* efficiency for these tests ranged in value from 65-98%, which are typical of a motor this size using graphite insulators. It is fully expected that with larger motors the C^* efficiency values of 95% plus can be reached in a full-scale vehicle.

V. Summary and Conclusions

A new wax-based fuel formulation, called SP7, was developed that meets the storage and propulsive requirements for a potential MAV mission. The ignition and stable combustion with both N_2O and MON-3 oxidizers has been completed at a 2.7-in scale. Fuel grain and N_2O oxidizer temperatures as low as -60°C were tested, showing no variation of propulsive performance at these temperature levels relative to ambient test conditions. A regression rate curve fit correlation was developed for SP7/N_2O from 32 tests over an average oxidizer mass flux range of 100 to 325 kg/m^2-s. The resulting curve fit parameters are a = 7.81e-5 and n = 0.545, where G_{ox} is in kg/m^2-s and $\dot{r}$ is in m/s

The ignition and stable combustion of the previously developed SP7 fuel was demonstrated with MON-3 oxidizer in a series of 13 test firings. Of the 13 test firings, 8 successful hot fires were completed. A port diameter-to-injector diameter limit was found for the current 3-in motor configuration. A port-to-grain OD ratio of 1.85 would not ignite, which corresponds to a port diameter-to-injector element ratio of 3.2. Additionally, these tests demonstrated the importance of head-end motor fluid dynamics on the ignition processes.

Test firings that burned to beyond the port diameter where ignition would not occur were completed. Combustion was stable throughout the burn, with no flame-holding instability observed. This shows that once attached, the flame is very stable. Burn durations of 9 seconds were completed with no measured change in combustion stability.

The regression rate of SP7/MON-3 was evaluated over a range of average oxidizer mass flux levels of 47 to 163 kg/m^2-s. The correlation of data with the existing SP7/N_2O data showed good agreement. The relative regression rate to that of SP1x/N_2O was 66%, which is at the desired level for MAV application. At this point, it is suggested to use the existing SP7/N_2O curve parameters of a = 7.81e-5 and n = 0.545, where, G_{ox} is in kg/m^2-s and $\dot{r}$ is in m/s, for calculation purposes.

VI. Acknowledgements

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