Sorbitol-Based Hybrid Fuel Studies with Nitrous Oxide for the Stratos II Sounding Rocket

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The low regression rate of plastic hybrid rocket fuels drives combustion chamber designs towards long and slender single-port options or multi-port geometries. Both options result in mass and geometry penalties for rocket applications with increasing system impulse, while maintaining short burn times. In order to make hybrid motors with single-port fuel grain geometries a viable option to power sounding rockets such as Delft Aerospace Rocket Engineering's flagship project Stratos II, novel fuel combinations are investigated using an engineering approach. Eleven tests on sorbitol-based fuels were performed on a 1,000 Ns lab scale motor and evaluated to assess the effect of fuel additives such as paraffin wax and aluminum micro particles as well as the influence of swirl injection on specific impulse, fuel density, average regression rate and oxidizer-to-fuel ratio. Furthermore production, operations and safety aspects are addressed. A mixture of 80% sorbitol, 10% paraffin wax and 10% aluminum micro particles by mass in combination with a 15° swirl injection angle is found to meet the fuel requirements to power Stratos II.

Nomenclature

G_{ox}	Oxidizer mass flux, kg/(m^2 · s)
I_{sp}	Specific Impulse at sea level, s
O/F	Oxidizer-to-fuel mass ratio
p	Pressure, bar
$\dot{r}$	Regression rate averaged over the grain length, mm/s
R	Combustion roughness in thrust, peak-to-peak relative to initial thrust, %
ρ	Density, kg/m^3
θ	Injection angle off the line of straight injection, °

Subscripts

avg	Average over total burn time
$fuel$	Fuel
$ideal$	Ideal value for maximum theoretical specific impulse
$init$	Initial
max	Theoretical maximum
$tank$	Run tank

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I. Introduction

Delft Aerospace Rocket Engineering (DARE) is an organization of students from Delft University of Technology. Its members are full time students from different faculties who design, construct, test and launch sounding rockets as an extracurricular activity. DARE strives to keep all development and production in-house. In its twelve years of existence, DARE has launched over 100 rockets from launch bases in several different countries including the Netherlands, Germany Sweden, Spain and South Africa.

In 2009, DARE broke the European altitude record for amateur rockets with the launch of Stratos I to 12.5 km. Stratos I was powered by a two-stage, sorbitol and potassium nitrate based, solid rocket propulsion system.[1]

Currently, DARE is developing its successor, the Stratos II rocket. Stratos II features a single-stage hybrid rocket motor designed to deliver a 15 kg scientific payload to an apogee of 50 km. Stratos II will require a propulsion system capable of delivering approximately 10 kN thrust and 200 kNs total impulse. Scaling up the propulsion system of Stratos I was considered infeasible due to the low specific impulse of 110 to 130 seconds of DAREs traditional solid rocket motors. To overcome this limitation, a team for the development of an alternative propulsion concept was established in 2010 by a group of international students within DARE.[2]

As an alternative a hybrid concept is being studied. Early investigations found that the low regression rates of traditional hybrid fuels such as high-density polyethylene (HDPE), poly(methyl methacrylate) (PMMA) and hydroxyl-terminated polybutadiene (HTPB) drive combustion chambers towards long and slender designs or multi-port configurations. Slender combustion chambers become less and less practical with increasing thrust level due to their unfavorably low volumetric efficiency in a rocket. Multi-port designs are practical, however they result in high sliver fractions of residual fuel as these motors need to be shut down before all fuel is burnt.[3] Stratos II will use a circular, single-port design in order to avoid mass penalties due to high sliver fractions.

Recently, there has been a focus on novel types of high-regression-rate fuels. These paraffin-based liquefying fuels form a melt layer during the combustion process. This sheet displays shear-driven waves that release droplets which physically enhance the mass transfer from the grain towards the flow, increasing the regression rate.[4, 5] These high regression rate fuels allow single port grain configurations for large motors, mitigating the disadvantages of multi-port geometries. A disadvantage of paraffin-based fuels is however the low mass density, poor structural properties and high ideal oxidizer-to-fuel ratio.

DARE exclusively uses nitrous oxide as an oxidizer due to its wide availability, non toxicity and self-pressurizing capability. Sorbitol is selected as baseline fuel due to the previous experience in handling within DARE and its experimentally proven regression rate in excess of traditional fuels such as HDPE, PMMA and HTPB.[6] Furthermore, it also offers a high theoretical mass density of 1489 kg/m^3, a low ideal O/F ratio in the order of 3,[6] it can be cast, and has structural properties in excess of comparable liquefying fuels such as paraffin wax. It does however have a slightly lower theoretical I_{sp} than traditional hybrid fuels.[7]

After the development of a lab scale propulsion system, sorbitol was validated as a practical fuel by the successful launch of a 1000 Ns rocket. It was however confirmed that pure sorbitol fuel gives rise to rough combustion behavior with high peak-to-peak spikes[6] and that the regression rate was not high enough to be used for a Stratos II sized motor. For that reason, a test campaign was conducted to develop a new sorbitol based fuel with increased performance. The focus of this investigation was to improve regression rate, specific impulse and combustion stability without compromising its density, O/F ratio and structural integrity (Table 1). Several additives to the sorbitol baseline and the impact of swirl injection have been investigated in order to achieve this. This paper presents the progress made and conclusions drawn from these experiments.

In Section II, the test rationale is introduced, the design constraints and scope of the experiments are described, and theoretical expectations of the experimental outcome are presented. Section III presents a description of the test setup including sensors and a summary of the test procedures. Section IV contains the safety, production and cost considerations of the experimental fuels. In Section V the test results are shown. Section VI contains a discussion on all results and outcomes. Remarks are given on the repeatability, accuracy and anomalies of the performed tests. The final conclusions are presented in Section VII. Finally, recommendations and future steps are presented in Section VIII.

Table 1. Top Level Fuel Requirements to successfully fly the Stratos II mission.

Parameter	Required value	Unit
Regression rate	>2	mm/s
Specific Impulse at sea level	>185	s
Combustion Roughness	less than pure sorbitol	-
Density	>1300	kg/m^3
O/F	<4	-

II. Methodology

The methodology presents the test goals and defines the parameters to be used for evaluation of the results. This section presents and discusses the different additives and injection methods used. Furthermore, theoretical predictions of all combinations tested are shown.

A. Test goals

The goal of these tests is to achieve the requirements set in the introduction. Furthermore, performance repeatability needs to be demonstrated such that the fuel can be characterized.

B. Constraints

All hybrid fuel tests of DARE use nitrous oxide (N_2O) as oxidizer. Despite its disadvantageous low mass density and specific impulse compared to other oxidizers, it is selected because it is widely available, non-toxic, non-cryogenic, and able to meet the modest performance requirements. Furthermore its self-pressurizing properties remove the need of a separate pressurant and thus decreases the complexity of the system. These properties make nitrous oxide an ideal oxidizer for student rocket projects such as Stratos II. Nitrous oxide mass fluxes in excess of 650 kg/(m^{2}s) have previously led to flame holding instabilities with single-port paraffin fuel grains.[8] In spite of using sorbitol as a baseline fuel, the oxidizer mass flux for all experiments is aimed to stay clear of this upper limit to avoid having to deal with this issue.

Sorbitol is used as a baseline fuel because of DARE's previous experience with processing it in solid rocket propellant, its previously observed regression rate in excess of traditional fuels,[6] its high density, low O/F ratio with N_2O, and its good structural properties. Due to its low O/F ratio, the I_{sp} performance is rather insensitive to changes in oxidizer mass flow. Its maximum theoretical I_{sp} only drops by 6% at O/F ratios ranging from 2 to 5 (Figure 1). All tests are conducted at 30 bar combustion chamber pressure and 60 bar initial oxidizer pressure.

C. Performance Parameters

The fuel selection for Stratos II is driven by the requirement to get the maximum thrust and total impulse out of a pre-defined maximum combustion chamber inner diameter of 19 cm. A fast regressing and high I_{sp} fuel will allow the fixed chamber cross-section to be used optimally.

The quality of a fuel for application in Stratos II can be measured by four critical performance parameters: Specific impulse, regression rate, oxidizer-to-fuel ratio with nitrous oxide, fuel density and combustion roughness. All of these parameters directly impact either the thrust or total impulse of the motor.

Specific Impulse The specific impulse at sea level is a direct measure for the efficiency of a rocket motor. As long as it does not greatly compromise any of the other performance parameters it is desirable to achieve the highest possible I_{sp}.

Regression Rate Regression rate effectively limits the combustion chamber diameter by imposing a maximum fuel web thickness directly related to the burn time. The port diameter is limited by the maximum allowable initial oxidizer mass flux at motor start up. A higher mass flux also has a positive effect on the regression rate.[9] Traditionally, regression rates of typical hybrid fuels are too low to allow for a Stratos II-sized, single-port geometry that can satisfy the mission requirement of reaching 50 km. High regression rates are thus a strong indicator for fuel performance. The time averaged regression rate is determined indirectly from total fuel mass flow and previously determined density. It should be noted that this results in a one-dimensional approximation. Local variations in regression rate are neglected. All tests are conducted such that the grains will not be regressed through to the liner, ensuring enough fuel is left to make accurate average regression rate estimations.

O/F RATIO WITH NITROUS OXIDE With a limit of 650 kg/(m^{2}s) set as the maximum oxidizer mass flux to avoid flame holding instabilities,[8] the total mass flow can still be kept high by using fuels that burn at a low ideal O/F ratio resulting in a significant fuel mass flow. The total system impulse density benefits from low O/F ratios as well[a].

FUEL DENSITY A dense fuel is generally desired to increase overall system density and higher fuel mass flows at the same regression rate. The density of each grain was determined from the initial fuel grain mass and its ideal volume (Table 6).

COMBUSTION ROUGHNESS Combustion roughness is an important parameter as it is an indicator of the overall stability of the motor performance. Large combustion instabilities create unnecessary vibrations, which can be detrimental to the rocket's payload and structure. The combustion roughness is determined primarily by combustion chamber pressure data as well as high-speed video analysis and thrust data. Combustion pressure data was not usable to quantify combustion roughness as the sensor was partially blocked during these tests, resulting in a highly damped signal, hence thrust is used by determining the peak-to-peak oscillations as a percentage of initial thrust.

Along with the five performance parameters all tested fuel combinations are assessed on their safety, cost and ease of manufacturing. These factors are of special importance for extracurricular student projects where resources are particularly limited.

D. Approach

The performance improvement of the sorbitol baseline fuel is approached in three ways. The effect of including varying fractions of aluminum micro particles (Table 3) and paraffin wax (Table 4) to the pure sorbitol baseline fuel (Table 2) is investigated with respect to the previously mentioned performance parameters. The effect of swirl injection, compared to axial injection, is also investigated.

Table 2. Sorbitol granules.

Sorbitol Granules		
Congealing Point	95	[°C]
Density at 25 deg C	typ. 1489	[kg/m^3]
Cost	2.90	[€/kg]

Table 3. Coated Flake Metal Aluminium Powder 90000/A Technical Data Sheet excerpt.[10]

Flake Metal Aluminium Powder 90000/A		
D10	1.5 - 3	[µm]
D50	4.5 - 6.5	[µm]
D90	14 - 17.5	[µm]
Settled powder density	200 - 260	[kg/m^3]
Density	2700	[kg/m^3]
Cost	13.60	[€/kg]

The main goal of introducing paraffin wax is to correct the rough combustion behavior of sorbitol.[6] Its high regression rate with respect to practically all other fuels is also expected to affect the sorbitol baseline positively. A mass fraction of 10% is added to all investigated fuels.

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[a] Given that the fuel density is greater than that of nitrous oxide

Table 4. Shell Sarawax SX70 Product data sheet excerpt.[11]

Shell Sarawax SX70		
Congealing Point	68 - 72	[°C]
Density at 70 deg C	typ. 780	[kg/m^3]
Cost	6.00	[€/kg]

Aluminum has a higher theoretical maximum I_{sp} as well as a higher density than sorbitol and is thus expected to improve both these performance parameters. Adding too much aluminum is expected to have impact on the combustion efficiency, effectively lowering the I_{sp}, and lead to excessive nozzle erosion. 10% and 20% mass ratios are tested.

Aside from the baseline of pure sorbitol, three different fuel combinations have been tested (Table 5).

Table 5. Theoretical characteristics of the four fuel combinations tested.O/F_{ideal} and $I_{sp_{max}}$ are computed using Cpropep with a combustion pressure of 30 bar, expansion to 1 atm, assuming shifting equilibrium flow.

Notation	Sorbitol	Paraffin	Aluminum	O/F_{ideal}	$I_{sp_{max}}$, s	ρ_{max}, kg/m^3	Bulk cost, €/kg
100:0:0	100 %	0 %	0 %	3.0	228	1489	2.90
90:10:0	90 %	10 %	0 %	3.5	232	1419	3.21
80:10:10	80 %	10 %	10 %	3.3	234	1540	4.28
70:10:20	70 %	10 %	20 %	2.9	237	1661	5.35

As the main objective of these experiments is to improve the performance characteristics for application in the Stratos II rocket, the influence of 15° swirl injection on the best performing candidate has been tested. An angle of 15° has been selected based on previous DARE studies.[2] As suggested by literature,[12] swirl injection can greatly increase the fuel regression rate. A moderate increase in regression rate is expected for all tests involving 15° swirl injection.

Tests 2 to 5 were carried out to devise a better performing fuel than pure sorbitol. Test 6 was carried out to determine the effect of swirl injection on the chosen fuel. Tests 7 to 11 were carried out to fully characterize the performance of the chosen fuel and injector configuration.

E. Theoretical Expectations

The theoretical, ideal densities for the four combinations derived from the densities of the constituents and their fractions are presented in Table 5. From experience, cast sorbitol fuel grains generally show a lower-than-ideal density in practice. This is also expected for the fuel combinations tested.

The theoretical maximum specific impulse at ideal expansion to sea level pressure (1 atm) has been computed for O/F ratios between 0.5 and 7 for all four fuel combinations using Cpropep. The results are shown in Figure 1 and have been summarized in Table 5. Whereas the theoretical maximum I_{sp} only changes by 9 s from lowest to highest, the optimum O/F ratio visibly shifts between 2.9 and 3.5

III. Experimental Setup

In order to validate the performance of different fuel combinations, an experimental test setup was developed. All eleven tests presented in this paper were performed on the setup presented in this section.

A. Motor Design

The combustion chamber consists of a 10 mm walled aluminum tube with an inner diameter of 44 mm. The grain is cast in a cardboard liner and placed inside the combustion chamber. A graphite nozzle is placed inside a steel sleeve, which sits up against the fuel grain without a post-combustion chamber. Sealing of both the sleeve and the nozzle is achieved by using a double o-ring seal and high-temperature silicone sealant.

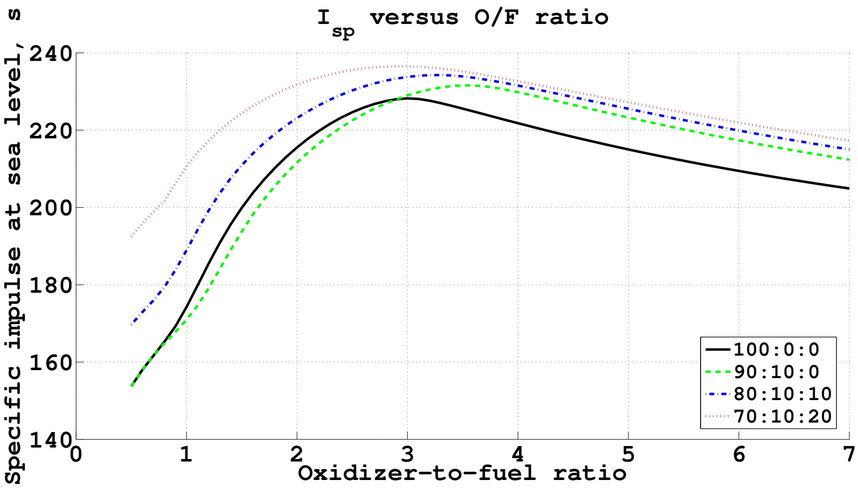

Figure 1. Theoretical maximum specific impulse at sea level with nitrous oxide at 30 bar combustion pressure assuming shifting equilibrium flow.

The injector housing features a pressure port, which allows for combustion pressure sensor, DPS-2, to be mounted to the motor (see Figures 2 and 3). The combustion pressure will thus be measured just downstream of the injector. A pre-combustion chamber of 20 mm length, in which the igniter is placed before firing is located directly downstream of the injector. A schematic overview of the test combustion chamber is presented in Figure 3. The injector and nozzle are held in place by two retainer plates and tensioning rods.

1. Injector

Nitrous oxide is injected through an injector plate with ports of 1 mm diameter. During the test campaign, two different types of injector plates are used with varying amounts of injector holes. The first type of injector plate features holes parallel to the center axis of the combustion chamber for straight injection. The second type has its holes inclined 15° from the line of straight injection to create a vortex. The plates are screwed in place inside the injector housing and can easily be replaced. This design enables injector plates to be swapped out to achieve the required oxidizer mass flow, without requiring a new injector.

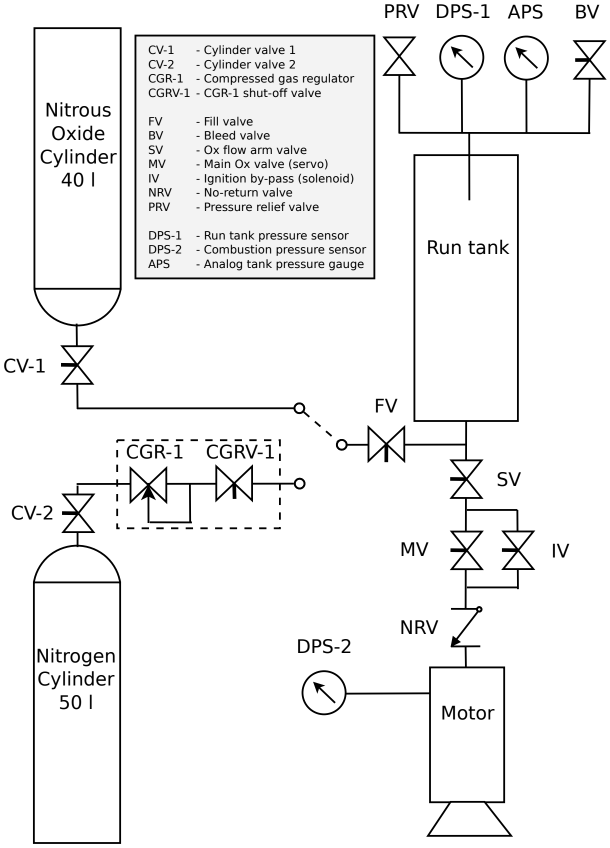

Figure 2. Feed System Schematic.

2. Igniter

Ignition is achieved by use of a pyrotechnic squib. The squib is rolled firstly in cotton-wool, then steel-wool. The igniter is placed upstream of the grain in the precombustion chamber, against the injector plate. The squib leads are routed out the nozzle and are ejected when the motor ignites. At 3 seconds before actual motor ignition, N_2O is bled into the chamber at a rate of less than 5 g/s[b] and the squib is fired, igniting the fuel grain. This generates subsonic hot flow through the nozzle and preheats the chamber for 3 seconds. The main oxidizer valve, MV, is opened afterwards for full motor ignition. The fuel mass flow before opening of the main valve is considered negligible in comparison to the fuel mass flow during the burn and is not accounted for in the data analysis.

B. Test Conditions

All fuel grains have been cut to the same dimensions indicated in Table 6. The nozzle geometry is individually adapted depending on the fuel tested. The throat area is designed to result in a combustion pressure of 30 bar. This combustion pressure has been selected to balance high-pressure performance with sufficient pressure drop over the injector. Nozzle expansion is optimized for sea-level. The oxidizer tank holds between 700 g and 800 g of N_2O[c] and is electrically heated until the N_2O reaches a vapor pressure of 60 bar. The motor was fired for 2.5 seconds for each burn except for test 1 where it was fired for 6 seconds. The entire feed system, without a motor attached, is purged with nitrogen before use.

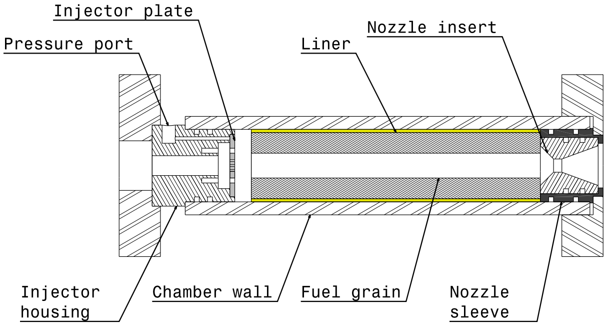

Figure 3. Test Motor Schematic.

Table 6. Fuel grain dimensions for all tests conducted.

Overall diameter	44	[mm]
Diameter excl. liner	40	[mm]
Port diameter	20	[mm]
Overall length	170	[mm]
Liner thickness	2	[mm]

C. Measurements and sensors

Four parameters are measured during each tests using a Dataq DI-710 datalogger and sensors listed in Table 7.

Table 7. Sensory equipment and its specifications.

Parameter	Sensor	Resolution	Sampling Rate
Thrust	Scaime ZFA S-Beam Load Cell 100 kg	2.6 N	240 Hz
Run tank mass	Scaime ZFA S-Beam Load Cell 25 kg	0.024 kg	240 Hz
Run tank pressure	Honeywell 13mm series	0.01 bar	240 Hz
Combustion pressure	Honeywell 13mm series	0.01 bar	240 Hz
Fuel mass	Laboratory Scales	0.001 kg	before and after test

IV. Fuel operational characteristics

A. Cost

As this fuel development is part of an extracurricular student project, resources are scarce. Therefore fuel components are selected with the modest budget in mind. This budget also brings the requirement that the

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[b] In tests 1 to 7, this was achieved by partially opening the main valve, however this was found to produce inconsistent N_2O flow and hence inconsistent ignition behavior. To correct this, the solenoid valve IV was introduced to bypass the main valve.

[c] Depending on ambient temperature at the time of filling

fuel grains can be produced without the acquisition of expensive hardware such as industrial mixers. The bulk cost of each component can be found in Tables 2, 3, and 4. Table 5 shows the bulk cost for the four combinations. A maximum increase in cost of 84% compared to the baseline is observed for 70:10:20.

B. Production and Handling

100:0:0 grains are cast by heating the granular sorbitol to 110 °C. The sorbitol is then poured into a cardboard liner. The port is formed by a greased aluminum mandrel, which can easily be removed after solidification. The grains are allowed to cool for 24 hours before the mandrel is removed and they are cut to length. The production of fuel grains with additives was found to differ only slightly from that of pure sorbitol. 90:10:0 requires a small amount of soap to allow the sorbitol and paraffin to become miscible. Soap was not required for 80:10:10 and 70:10:20 as aluminum powder proves to be an effective emulsifier. The grain quality was found to be similar for all fuel types by visual inspection of grain sections. All fuels and additives used are unrestricted materials and can be sourced commercially.

The handling of sorbitol-based fuels was quite consistent with pure sorbitol. All combinations with paraffin additives had a slightly waxy feel. All fuel combinations with aluminum additives would deposit a silver layer on any surface they contacted.

Both pure sorbitol with axial injection and 80:10:10 with 15° swirl injection have been flight tested. Both flights utilized the same flight hardware except for altered injector plates. Handling and flight operations of the fuels were found to be identical.

Two 80:10:10 grains were stored in an air conditioned workshop for 9 months without humidity control. The grains were found to maintain physical characteristics such as weight and surface texture after this time period. In the same period of time in the same workshop, pure sorbitol grains were found to absorb water and begin to crumble under handling loads.

C. Safety and Non-Toxicity

As all production is conducted in-house by students, the fuel must be safe to produce. Therefore no substances, which produce toxic fumes during production, such as HTPB, are allowed. Furthermore, due to the largely unknown risks related to inhalation and contamination of nano-particles, only additives larger or equal to 1 micrometer are used.

Aluminum powder can cause irritations of the respiratory system when breathed in. Powdered aluminum is also classified as a "Flammable Solid" according to Regulation (EC) No 1272/2008 and "Highly flammable" according to Directive 67/548/EEC or Directive 1999/45/EC. Upon contact with water it releases hydrogen gas.[10] Appropriate precautions are taken during production such as to limit the amount of time pure powder is exposed to open air, wearing respirators, working in a well-ventilated, dry workplace, and keeping the workspace free of ignition sources.

V. Results

Table 8 shows eleven fuel tests, which were performed between May and September 2012. A typical test fire can be seen in Figure 7. The performance of pure sorbitol can be seen as 'test 1'. It shows a very modest regression rate and I_{sp} of 1.33 mm/s and 172 s respectively, despite the motor having operated very close to the optimum O/F ratio of 3. The thrust data of test 1 can been seen in Figure 6, where there are peak-to-peak thrust spikes of up to 50 N or 25% of the initial thrust.

A. Fuel selection: Tests 2 to 5

Test 2 showed excellent I_{sp} performance despite the O/F ratio being slightly lower than the ideal ratio of 3.3. As Figure 4 shows, the test suffered from an incorrectly calibrated igniter bleed line, causing sonic flow and significant thrust from 2.5 s before main ignition of the motor. The regression rate found during this test was a minor improvement over test 1. Combustion roughness appeared less than test 1, although this could only be analyzed via thrust data and high speed video. For this test only, the regression rate was averaged over the entire burn time including the ignition phase to account for the igniter bleed line miscalibration.

During tests 3 to 6, there was a major error in the data acquisition system, hence data for thrust, chamber pressure, and tank pressure was not obtained. Despite this, all tests were performed at an initial

Table 8. Test series results in tabular form.

#	Composition, $S\%P\%A\%$	θ, °	ρ_{fuel}, kg/m^3	$\dot{r}_{avg}$, mm/s	$I_{sp_{avg}}$, s	R, %	O/F_{avg}	$G_{ox_{init}}$, $kg/(m^2 \cdot s)$	Comment
1	100:0:0	0	1404	1.33	172	25%	3.40	238	Initial $p_{tank} = 40$ bar
2	80:10:10	0	1367	1.52	196	22%	2.84	...	Premature ignition
3	90:10:0	0	1367	1.74	...	...	4.88	496	
4	80:10:10	0	1398	1.79	...	...	4.82	522	
5	70:10:20	0	1404	2.04	...	...	3.59	457	Sparks leaving nozzle
6	80:10:10	15	1386	2.74	...	...	2.72	495	
7	80:10:10	15	1373	3.30	185	13%	2.33	506	
8	80:10:10	15	1361	3.20	198	14%	2.72	564	Rough start up
9	80:10:10	15	...	...	...	...	...	...	Misfire
10	80:10:10	15	1379	2.99	195	13%	2.85	547	
11	80:10:10	15	1386	3.11	198	9%	2.52	513	Rough start up

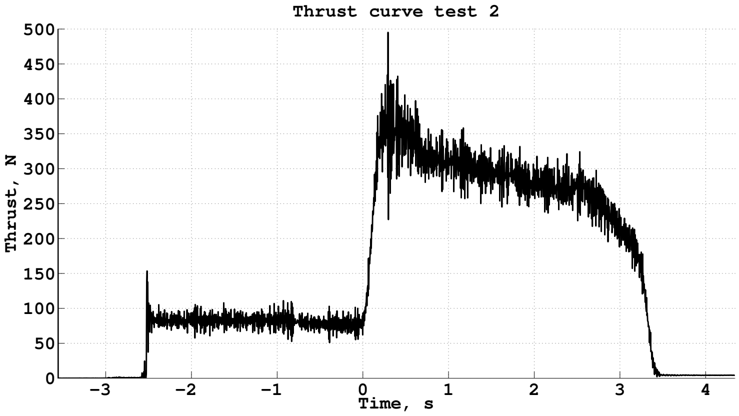

Figure 4. Thrust curve of test 2 showing an incorrectly calibrated ignition sequence.

tank pressure of 60 bar. This was determined with an analogue pressure dial. All comments on combustion stability for these tests come from analysis of high speed footage.

Test 3 shows marginally increased regression rate over test 2. Combustion roughness compared to test 1 was significantly reduced.

Test 4 shows very similar performance as test 3 in all respects.

Test 5 shows better performance than tests 3 and 4 in terms of regression rate, however video showed large amounts of aluminum being combusted outside the motor in the form of sparks.

B. Swirl injection and fuel characterization: Tests 6 to 11

Test 6, a repeat of test 4 except with 15° swirl injection, showed an increased regression rate of 53%. Combustion still appeared as stable as in test 4. Due to the high regression rate, the O/F ratio was somewhat lower than that of test 4.

At this point in the test series, it was determined that the combination 80:10:10 with 15° swirl injection is the best fuel candidate for further research, hence tests 7 to 10 all utilize this configuration.

Test 7 showed good regression rate performance of 3.3 mm/s but only marginal I_{sp} performance at 185 s. It is suspected that this is due to the low O/F ratio. This occurred due to the unexpectedly high regression rate and hence fuel flow.

Tests 8 to 11 were conducted in the same manner as test 7, except with an injector plate with 50% more injector holes to achieve an O/F ratio closer to the ideal 3.3. The O/F ratio of tests 8, 10 and 11 were marginally improved and hence the I_{sp} of these test is also marginally higher, between 195 and 198 s. Tests 8 and 11 both experienced a rough start up with large spikes in the thrust curves as can be seen in Figure 5. Test 9 flamed out at point of ignition.

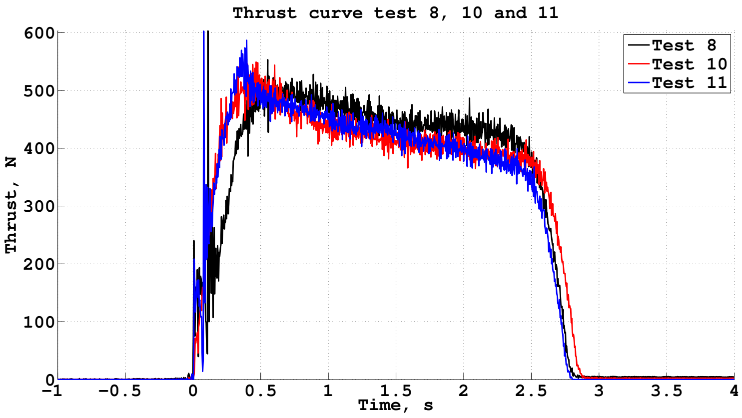

Figure 5. Thrust curves of tests 8, 10, and 11.

Figure 6 shows that the representative peak-to-peak combustion roughness of test 10 is around 50 N or 10% of the initial thrust. This is approximately the same magnitude as that in test one, however at a much higher total thrust level.

Test 4 shows that 80:10:10 has an increased regression rate of 35% over pure sorbitol for axial injection. Tests 2, 8, 10 and 11 show an average I_{sp} increase of 14 %. Additionally tests 8, 10 and 11 show that 15° swirl injection increased the regression rate by 73% from 1.79 mm/s in test 4 to an average of 3.1 mm/s.

VI. Discussion

The tests presented in this paper were performed as part of project Stratos, a student effort to launch suborbital rockets to space. The project is operating under limited human and financial resources and is on a tight schedule to launch in 2014. For these reasons, decisions about the performance of fuels often had to be made based on limited information to ensure that the project moved forward. This was certainly the case during tests where measurement data was lost such as in tests 3 to 6. This section discusses not only the test results but the decision rationale as well.

Between 2011 and 2012, several tests were conducted using pure sorbitol fuel. Test 1 is an example of

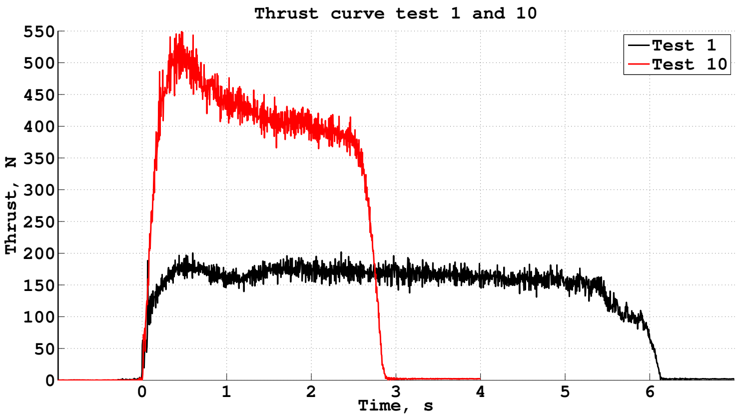

Figure 6. Thrust curves for test 1 and 10.

one of these tests, which showed modest performance and unstable burn characteristics where the flame would change from clear to bright yellow many times a second. This was observed using high speed footage captured at 300 frames per second. This rapid change in flame characteristics indicated that the O/F ratio was changing back and forth. This indicated that unburnt fuel was being ejected from the motor, causing a bright yellow flame and poor combustion efficiency. It was suspected that this would account for the mediocre I_{sp} performance found during these tests which were typically in the range of 170 s despite a near optimum O/F ratios.

In test 2, 80:10:10 was first used successfully and proved very promising. The I_{sp} performance was a marked improvement over that of test 1. For this reason, further investigation was directed to exploring this class of fuels.

Tests 3 to 5 were devised to analyze the effect of the aluminum additives. These 3 tests, despite the error in the data acquisition system, yielded useful results. The fuel combination of 90:10:0 significantly reduced the unsteady exhaust flame characteristics of 100:0:0 described earlier. This effect is also observed in 80:10:10. Aluminum powder was found to not only increase the density of the fuel but also the regression rate although only modestly, with 70:10:20 regressing 17% faster than 90:10:0.

70:10:20 expelled large amounts of unburnt aluminum powder, creating sparks outside of the combustion chamber. It was thought that this was an indicator of low combustion efficiency and hence low I_{sp}, despite 70:10:10 possessing a higher theoretical I_{sp} than 80:10:10. Unfortunately this theory could not be backed up with data.

From these 3 tests, it was decided that 80:10:10 was the best fuel to continue testing. This was largely because good I_{sp} data was already obtained for 80:10:10 from test 2. Although it could not be confirmed that 80:10:10 in fact performed better than 70:10:20, concerns about the combustion efficiency of 70:10:20 as well as fears that higher fractions of aluminum powder would lead to more nozzle erosion were enough to make the decision.

Figure 7. A typical lab scale motor test.

Test 6 was made to quantify the effect of swirl injection on 80:10:10. This test showed excellent regression performance, a 53% increase over test 4. This was a much larger improvement in regression than what had been achieved by altering the fuel combination. Due to the engineering goal of ultimately designing a propulsion system for the Stratos II rocket, it now became necessary to characterize the fuel under the conditions that it would be subjected to in flight hardware, hence all subsequent tests utilize 15° swirl injection.

At this point in the project, the team had decided that 80:10:10 coupled with swirl injection likely had the required performance as well as acceptable production, handling and operational characteristics to be an acceptable fuel for Stratos II. As a final test series, tests 7 to 11 were performed to properly characterize the fuel in terms of regression rate and I_{sp} such that a motor for Stratos II could be designed.

Test 7 suffered from a far too low O/F ratio and hence the motor was operating relativity far from its optimum. An attempt was made to correct this for tests 8 to 11 by using injector plates with more orifices. This was however found to be only partly effective, suggesting that the test bench feed system was approaching the limit of mass flow it could provide[d]. This is not entirely surprising as the feed system was designed for approximately 120 g/s, not 200 g/s as were required by tests 9 to 11. For this reason, a 50% increase in injector port area resulted in very little additional oxidizer mass flow and hence also O/F ratio. At these higher mass flows, the motors started to experience some ignition issues. Both tests 8 and 11 exhibit large thrust spikes 100 ms after ignition and test 9 flamed out entirely.

80:10:10 provides a substantially better I_{sp} performance than pure sorbitol, however the major regression rate increase is not due to the fuel combination but rather the change in injection configuration from axial to 15° swirl injection. The contributions of these effects were an increase of 35% and a further 73% respectively for a total increase in regression rate of 133% over the original pure sorbitol.

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[d] Specifically the available feed hoses were found to have insufficient cross-sectional area.

VII. Conclusion

Results from test campaigns using pure sorbitol fuel grains show low performance and rough combustion behavior. In order to address these issues 10 experiments with various combinations of additives mixed into the sorbitol baseline were performed. In this test campaign an addition of 10% paraffin wax, counteracting the rough combustion behavior, and 10% aluminum powder, improving the density, specific impulse and regression rate, was found to best meet the requirements for Stratos II.

Tests 2 to 11 were successful in obtaining better fuel performance through the combination of novel fuels as well as utilizing more effective methods of injection. However, given more time and resources, it is likely that a more optimum ratio of sorbitol, paraffin and aluminum as well as swirl angle could be found. This further research was not undertaken to free up human resources for the development of the Stratos II full scale motor.

80:10:10 achieved an increase in regression rate and I_{sp} of 35% and 14% respectively over pure sorbitol. Additionally it was found that 15° swirl injection increased the average regression rate a further 73% from 1.74 mm/s to 3.1 mm/s. A total regression rate increase of 133% was achieved.

80:10:10 was found to meet all the performance requirements and at the same time offer operational, safety, and cost characteristics for it to be an appropriate fuel for student use. Using this fuel, DARE can continue development of a propulsion system for Stratos II.

VIII. Recommendations

The tests presented in this paper were conducted with limited resources for equipment such as sensors. For future tests, useful combustion chamber pressure data should be obtained. Furthermore, it would be advantageous if this could be sampled at high frequency to measure combustion instabilities.

For further experiments related to the characterization of the fuels presented it is suggested to modify the test setup to allow for more oxidizer mass flow and less pressure drop over the feed system. Also better oxidizer mass flow predictions methods would facilitate reaching optimum O/F ratios. Both of these changes would help correct the problems of tests 8 to 11 by allowing optimum O/F ratios to be obtained.

A more extensive, scientifically oriented test series using constant initial conditions for all tests will allow for a better understanding of how the fuels presented fit into regression rate and combustion models. The structural strength variation of sorbitol with different additives needs to be quantified in order to assess its limits of suitability for sounding rocket applications.

Future research can also include an investigation into the flame holding ability of 80:10:10 at oxidizer mass fluxes greater than 650 kg/m^2s. This would allow for higher thrust and higher impulse density configurations, ultimately leading to higher performance propulsion systems.

As 80:10:10 is considered a sufficient fuel for Stratos II, DARE is developing a 200 kNs single port hybrid motor utilizing this fuel. As of June 2013, several static tests of this motor have been performed. This development along with the eventual integration into Stratos II will be the focus of DARE's hybrid propulsion team for the coming year.

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