Tests of Paper as a Fuel in a Hybrid Rocket Engine

Lucas Beveridge
Independent Researcher
1009 Meadow Ave, Tillamook OR 97141, USA. Email: lucasbeveridge@yahoo.com

Abstract: *The goal of this investigation was to determine how common types of paper would perform compared to pure Cellulose as fuels in a hybrid rocket engine. Although most types of paper are largely Cellulose, it was unclear if the additional components of paper (such as Lignin and fillers) would significantly impact the performance. Soft-wood (and by extension wood-pulp based paper), bleached paper (the type used for printing/copying/faxing), and Kraft paper (which is >95% Cellulose by mass) were all tested in a hybrid rocket engine with Nitrous Oxide (N_2O) oxidizer. Thrust was measured, and the engine weighed before and after each test. The thrust curves were integrated to obtain the total impulse for each test and then divided by the change in weight to find an average specific impulse (I_{sp}). High-speed video was also taken of each test to provide another point of comparison.*

The data and video indicate that there is no significant difference in performance or burning characteristics between any of the paper/wood fuels. This would imply that fuel grains for hybrid rockets could be made from paper, and can be expected to perform as well as pure Cellulose. This not only simplifies chemical equilibrium analysis, but would also allow fuel grains to be made from a mixture of waste-paper.

Keywords: *hybrid rocket, propellants, Cellulose, paper, wood, engine testing*

1 Introduction

Hybrid rockets store their propellants in two different states, usually with a solid fuel and a liquid oxidizer. This combination provides a higher performance than conventional solid propellants, greater simplicity than liquids, and greater safety than either. This greater safety comes from the fact that the propellants cannot mix intimately being in different physical states, and because the solid fuels are usually inert, handling is much safer. Furthermore, they can be throttled, shutdown, and restarted. Imperfections in the fuel grain do not cause catastrophic failure because the fuel will burn only after it has vaporized and mixed with the oxidizer in the flow.

Because of this, hybrids can tolerate larger margins, use less expensive parts (i.e. not Mil-Spec), and have fewer failure modes.[1,2] Thus, hybrids can be far less expensive than other types of rockets.

The flexibility of fuels in hybrids might allow for the use of common waste, such as paper and cardboard as fuel. The most common types of paper are wood based, and are largely composed of Cellulose, but include other substances as well; such as Lignin and inert fillers. Cardboard (as used in corrugated shipping boxes) is made from pulp produced with the Kraft process, which removes nearly all of the Lignin leaving almost totally pure Cellulose,[3] and so would burn just like pure Cellulose. Bleached paper (as used for printing and faxing) is also produced with the Kraft process, but it also has some fillers and the bleaching process affects the Cellulose chemically,[4] and so it may not necessarily burn the same as Cellulose. Most other common types of paper (such as newsprint) use more of the original wood in the pulp to increase the yield,[5] and so would burn more like natural wood. Paper is usually assumed to be pure Cellulose for the purpose of chemical analysis,[6] but this assumption is not necessarily valid in a rocket engine since small changes in propellant

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composition can drastically change performance.

The test data were gathered to study the general burning characteristics and performance of the different fuels. The performance difference between pure Cellulose (unbleached Kraft paper), wood, and bleached paper was determined. These three fuels cover the range of the most common types of paper[7] and so they represent the most likely to be obtained as waste. This is important since the precise chemical composition of the waste paper is not known *a priori* without chemical analysis (which would have to be done with every new type of paper obtained). So, if it was found that they all perform the same, then they would not need to be separated prior to manufacturing fuel grains. The low cost and potential ease of processing could make waste paper very attractive as a fuel in hybrid rockets.

2 Testing methods

A single engine was tested with the various fuels, and each with an 8 gram Nitrous Oxide whipped-cream charger. These small chargers are ideal for testing due to their high manufacturing standards which provided consistency in feed pressure, and mass flow rate. The high food-grade purity also gave consistency in overall performance leaving the fuel composition as the only variable.

All fuel grains were made with the same length and port diameter regardless of composition. The reason for this was to allow direct comparison between all tests, since all three fuels had nearly the same density (which would affect regression rate, and thus oxidizer/fuel ratio (O/F) and performance). The engine was made commercially, and unfortunately its design did not allow for modification to accommodate sensors to measure quantities inside of it, such as chamber pressure and temperature. However, other measurements could be made that nonetheless provided the necessary performance data.

The engine was fired by turning a screw that pushed the N_2O charger onto a piercer pin. The piercer also served as the injector. The N_2O was then only released when a plastic burst disc was melted away when a preheater grain ignited. Figure 1 shows an illustration of the engine.

Thrust was measured during the duration of each test with a 20 kg loadcell and 14 bit data acquisition system with 10 V full-scale and sampling at 4 kHz. The weight of the whole engine was taken before and after each test (minus the weight of the preheater grain, which did not contribute to the total impulse). The thrust profile of each test was integrated to obtain the total impulse, and then divided by the change in weight Δw to obtain average specific impulses (I_{sp}) for the tests.

The engine was tested so that it fired upward, pushing down on the loadcell. This arrangement would, of course, cause the changing weight of the engine to influence the thrust measurement. However, the change in engine weight for all of the tests was very small compared to the thrust ($\approx$0.15 N for Δw *vs.* $\approx$15 N for thrust, and $\approx$1 N for the engine weight), so this had a negligible influence on the results.

3 Results

3.1 Experimental results

In total, 16 hot-fire tests were conducted; 5 with soft-wood, 5 with Kraft-paper (Cellulose), 3 with bleached paper, and 3 with Nylon. The Nylon tests were used as a control to observe the performance and qualitative burning characteristics of a fuel with a very different composition than the paper/wood fuels. The Nylon fuel grains had a larger port diameter, but were much denser (and so would have had a lower regression rate). As will be explained later, Nylon was expected to have a higher performance than Cellulose.

Each thrust curve was cut off at 0.1 s and 3 s, because the preheater produced thrust for about 0.1 s at the beginning of each burn, and the burn was complete after 3 s. Time zero (at ignition) was the first data point greater than 5% of peak thrust

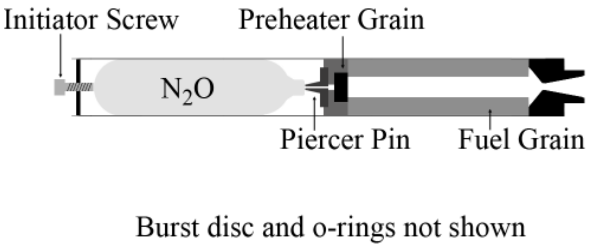

Figure 1. *Simplified diagram of the hybrid engine used for this investigation.*

above zero.

It should be noted that every burn continued for up to 30 s after ignition, but only the first 3 s produced any measurable thrust (see Figures 2 and 3). It was impossible to measure how much propellant was lost during this residual burn. So, since the measured Δw is greater than it would be for only the first 3 s, the calculated I_{sp} is somewhat lower than the actual I_{sp}. However, the residual burn lasted approximately as long for all tests, so there would be very little variation in lost propellant. Because all of the tests were consistent, a direct comparison could still be made between them.

Another problem encountered during testing was incomplete combustion. Obvious sparks were seen in all paper, wood, and Kraft-paper tests. Images of these are shown in Figure 4. This would have reduced the performance by slowing the exhaust.

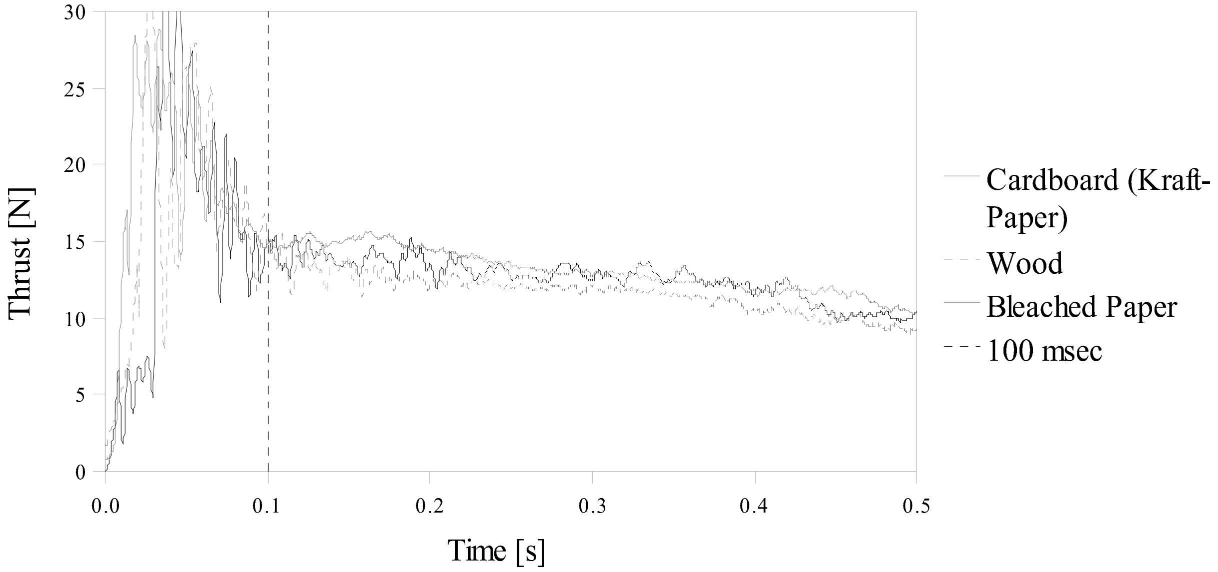

Figure 2. *Representative thrust vs. time data for the various fuels (truncated at 0.5 s for clarity).*

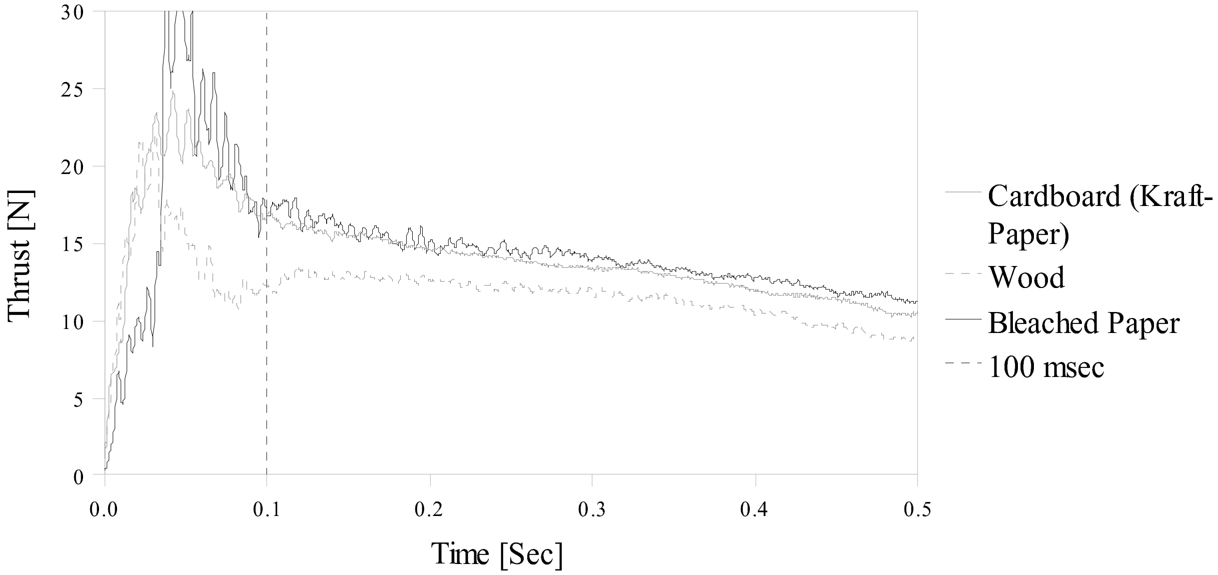

Figure 3. *Thrust vs. time averages for each test series (truncated at 0.5 s for clarity).*

Also, the bleached paper fuel grains appeared to partially delaminate during the burn, causing pieces of fuel to be ejected from the engine. This would have further lowered the measured I_{sp} for these tests. The test results are summarized in Table 1.

As can be seen from the data in Table 1, there was some variation in Δw in the bleached paper tests (probably caused by delamination); this of course caused the standard deviation of both Δw and I_{sp} to be larger than they would be otherwise. There was also some variation in total impulse in the Nylon tests due to rough burning, this caused its standard deviations to be larger also. However, both test series only had three trials, and if more trials could have been done, then perhaps they would be more consistent with the other tests (each of which had five trials).

It is clear from this that although there are some slight differences between the bleached paper, wood, and Cellulose fuels, they do approximately perform the same. Also, wood seemed to produce more sparks than the other propellants, so this may have reduced its apparent performance disproportionately. However, although the unburned fuel would contribute to a loss of performance, it appears that the residual burn was largely responsible for the loss in these tests. This does not change the results because it is the relative difference in performance between the fuels that was being studied. Figures 2 and 3 show plots of representative data and averages of all tests for each fuel respectively. Note, in Figures 2 and 3, every 4 data points were averaged to decrease noise.

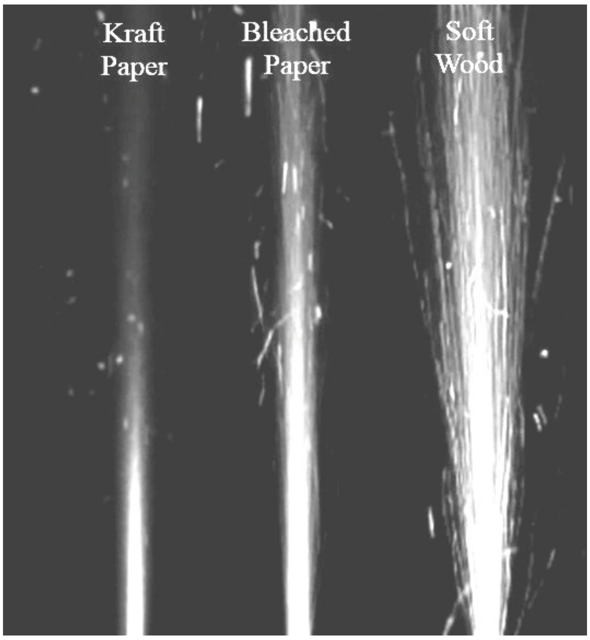

Figure 4. *Apparent sparks.*

Table 1. *Test series summary.*

Fuel	Quantity	Mean	Standard deviation
Bleached	Impulse [N s]	13.35	0.832
	Δw [N]	0.1343	0.0051
	I_{sp} [s]	99.5	7.3
Kraft	Impulse [N s]	12.81	0.504
	Δw [N]	0.1185	0.0019
	I_{sp} [s]	108.5	3.8
Wood	Impulse [N s]	10.92	0.389
	Δw [N]	0.1053	0.0025
	I_{sp} [s]	103.7	4.3
Nylon	Impulse [N s]	16.16	1.24
	Δw [N]	0.0968	0.0015
	I_{sp} [s]	170.5	10.9

3.2 Theoretical performance of cellulose

To determine the realistic performance of an engine, chemical equilibrium analysis was done with Propep. Propep is a rocket performance code using the chemical equilibrium algorithm presented by Gordon and McBride.[8]

First, the expected performance of the Nylon and Cellulose fuels was evaluated with N_2O in vacuum with various O/F ratios to see how they compared. Indeed, Nylon did perform significantly better (after taking the mean of shifting and frozen equilibrium) with a peak I_{sp} of 337.8 s, whereas Cellulose peaked at 300.3 s.

The performance of Cellulose and Liquid Oxygen was found *vs.* O/F in a vacuum for both shifting and frozen equilibrium (see Figure 5). In Figure 5, the average of frozen and shifting equilibrium is also plotted, and its peak I_{sp} is 351.8 s. Also, the I_{sp} does not vary significantly from the peak above an O/F $\approx$ 1. This is advantageous because the O/F shifts during the burn of any hybrid-fuel engine. Although the average may be optimistic, the peak I_{sp} for frozen equilibrium is still 326.3 s,

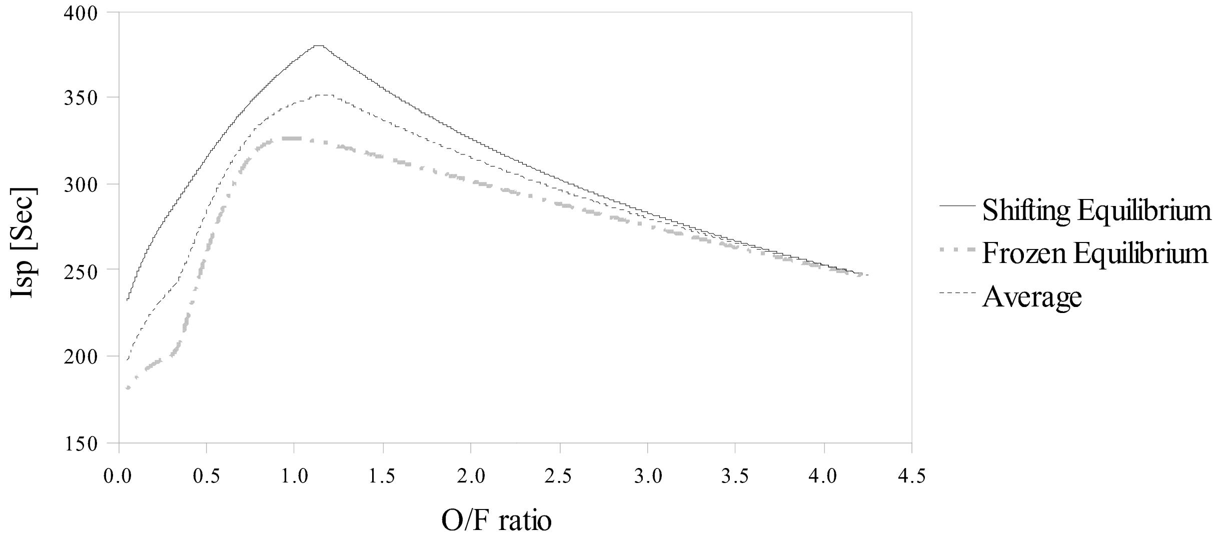

Figure 5. *Plot of vacuum* I_{sp} *vs. O/F ratio for Cellulose and Liquid Oxygen (done with Propep).*

and also does not vary significantly from the peak above O/F ≈ 1. The total change in velocity (Δv) required to place a spacecraft in low Earth orbit is approximately 9 km s^{-1}, which would mean a launch vehicle using these propellants could have an inert mass fraction (structure and payload mass divided by total liftoff mass) of 6%. This is comparable to existing launch vehicles.[1,2]

4 Conclusions

The unburned fuel that came out as whole pieces and sparks suggests that post-combustion chambers will be even more critical in a hybrid engine using paper than with other fuels.

The large difference between the predicted performance of Cellulose/N_2O and what was measured is, of course, largely due to the fact that the testing was not done in a vacuum. However, this would only account for some of the difference: the rest is likely due to a combination of off-optimum O/F, nozzle inefficiency, the aforementioned loss of fuel during burning (particularly during the residual burn), and solid particles in the exhaust.

Nonetheless, there was no significant difference between pure Cellulose (i.e. Kraft paper), wood, and bleached paper. This implies that Cellulose may be assumed to be the primary constituent of paper for the purpose of chemical equilibrium analysis in a rocket engine. Such analysis reveals that the specific impulse for a Liquid Oxygen/Cellulose engine could have a vacuum I_{sp} >> 300 s. Also, because waste paper is so readily available, safe to work with, and inexpensive, it could be an extremely attractive propellant for launch vehicles.

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