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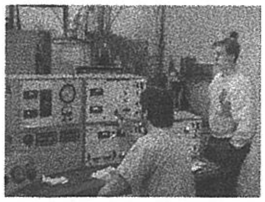

Effect of Altitude on Rocket Engine Performance

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Abstract

The goal of this project was to measure the performance of rocket engines at different altitudes.

To do this, I (a) designed, built and debugged a test stand using a Pasco force sensor and a personal computer; (b) put the stand in an altitude chamber and fired rocket engines; and (c) analyzed the data from firing the rocket engines.

My results showed that as altitudes increased: (a) the engines were more difficult to ignite, (b) thrust was higher and (c) delay trains burned longer.

The change in thrust and total impulse was very close to expectations based on nozzle theory. The ignition difficulties were unexpected. The change in delay trains was consistent with the results of other researchers.

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Theory and Hypothesis

- Hypothesis
  - Thrust and total impulse should increase as altitude increases
- Theory
  - Thrust = mdot*v+(P_2-P_3)A_2, where
    - mdot=Kg/s
    - v=m/s
    - P_2=nozzle pressure at exit
    - P_3=atmospheric pressure
    - A_2=nozzle area
  - Pressure=F/A=N/m^2=(Kgm/s^2) /m^2

Predicted Change in Average Thrust of Estes C6 engine with Altitude

Altitude (ft)	Pressure (kPa)	Average thrust (N)	ratio to sealevel
0	101.325	6.000	1.00
15,000	57.206	6.623	1.10
30,000	30.148	7.006	1.17
60,000	7.231	7.330	1.22

Nozzle	
Diameter (in)	0.167
Diameter (m)	0.0042418
Area (m2)	1.41316E-05

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I had heard that Vern Estes had tested engines up to 14,000 ft to see if altitude affected rocket engine performance when NAR S&T's data didn't agree with his. He concluded that the five thousand foot difference in altitude was the reason. I decided to test even higher with Aurora Flight Science's high altitude test cell. My hypothesis was that the engines should have a higher performance at higher altitudes. This is based on basic nozzle theory, which says that thrust is equal to the mass flow rate plus a pressure differential term between the exit area of the nozzle and the ambient pressure. If one assumes that model rocket engines are more or less optimized for sea level, then the thrust should increase as the ambient pressure decreases,. This effect should be large enough to be measurable (22% at 60,000').

Project Schedule

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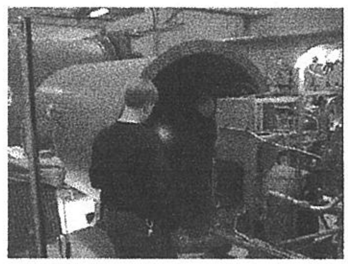
See the attached Gantt chart for an overview of my project.

Equipment

- Data System
  - Macintosh Computer w/ Science Workshop© software
  - Video camera
  - Analog-Digital converter box
- Altitude test chamber
  - 6' diameter steel bell w/ pumps that flow hundreds of cubic feet per minute at temperature an pressure profiles up to 60 thousand feet
  - designed, built and operated by Aurora Flight Sciences Corp.
- 12 C6-3 engines
- Various Igniters
- Test stand
  - Science Workshop© student force sensor
  - Ignition system
  - Oil
  - Cinder block
  - 2 C clamps
  - Soup can lid
  - Clothes hanger
  - Extender cable



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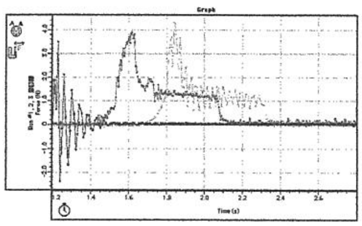
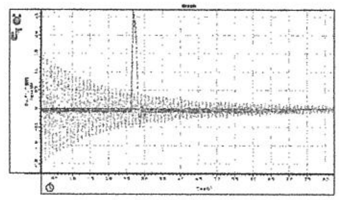
I constructed a test stand using a force sensor borrowed from my science teacher. I mounted it on a cinderblock to prevent it from moving when the engine was fired. I used a pot of oil to damp out the vibrations in the sensor. This information was read by my dad's computer witch I had installed a program called Science Workshop© (also borrowed from school) that recorded the data up to 200 times per second and plotted it. I took this setup to Aurora Flight Sciences where I placed it in their test chamber.

The test chamber is designed for running airplane engines at altitudes up to 100,000 feet. It has a a large vacuum chamber, big pumps to drive it, and a lot of plumbing and control mechanisms. There is also a dynamometer and lots of heat exchangers. I didn't use the dyno.

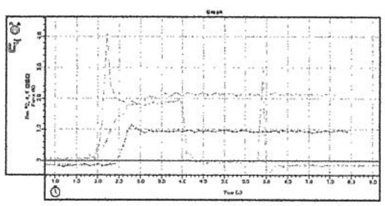
Test stand development



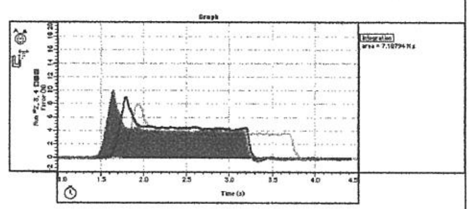
First attempt:10 Hz sampling and no damping



Response of beam before and after oil damping



10 Hz sampling with damping & calibration run



Final system: oil damping + 200 Hz sample rate

When I first built the test stand, its data was useless. There were all sorts of noises and vibrations that messed up the stand. It turned out that 60 Hz noise from the power supply was showing up on the data. I switched to battery power and the problem went away.

The next problem was vibrations in the load cell. I fixed this by adding an oil damper.

Finally, I had to play with the sampling speed to get reliable results. It turned out the fastest was the best. I ended up logging data at 200 samples per second.

With the battery power, oil damping, and high sampling rate, I was able to get thrust-time curves that looked like they came out of an Estes catalog!

Experimental Procedures

- Research
  - Theory of nozzles
  - Design of test stand
- Experiment
  - 15 test firings to debug test stand & establish procedures
  - Redesign required to damp out natural frequencies
  - 27 data runs
    - 7 good data samples at 3 altitudes
    - Xx misfires
    - Yy calibration runs
- Analysis
  - Comparison of theory & results
  - Unexpected results

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This is the outline of my procedures.

Data Summary

Run 1 - Calibration
Run 2 - Test 1 (engine 5)
Run 3 - calibration
Run 4 - calibration
Run 5 - Test 2 misfire (engine 3)
Run 6 - Test 2 misfire (engine 3)
Run 7 - Test 2 misfire (engine 8)
Run 8 - Test 2 misfire (engine 8)
Run 9 - Test 2 misfire (engine 8)
Run 10 - Test 2 (engine 8)
Run 11 - calibration
Run 12 - Test 3 (engine 7)
Run 13 - calibration
Run 14 - Test 4 (engine 9)

Run 15 - calibration
Run 16 - Test 5 misfire (engine 10)
Run 17 - Test 6 misfire (engine 11)
Run 15 - calibration
Run 19 - Test 7 (engine 12)
Run 15 - calibration
Run 15 - calibration
Run 22 - Test 8 (engine 3)
Run 15 - calibration
Run 15 - calibration
Run 25 - Test 9 misfire (engine 4)
Run 26 - Test 10 misfire (engine 10)
Run 27 - Test 11 (engine 11)

I did 29 runs to debug the sensor

Run #	Altitude (kPa)	Total Impulse (N-S)	Peak Thrust (N)	sustainer avg (N)	Burn Time (sec)	Delay time (sec)
2	100.8	8.02	10.65	4.25	1.89	2.06
14	100.8	7.73	9.41	4.05	1.96	2.23
22	100.8	7.02	7.88	3.79	1.88	1.38
AVG	100.8	7.59	9.31	4.03	1.91	1.89
27	60.0	8.40	9.02	4.34	1.96	4.44
10	30.0	9.85	9.75	5.00	2.19	11.18
12	30.0	9.47	9.77	4.64	2.21	11.02
19	30.0	8.98	10.26	4.73	1.91	4.42
AVG	30.0	9.43	9.93	4.79	2.10	8.87

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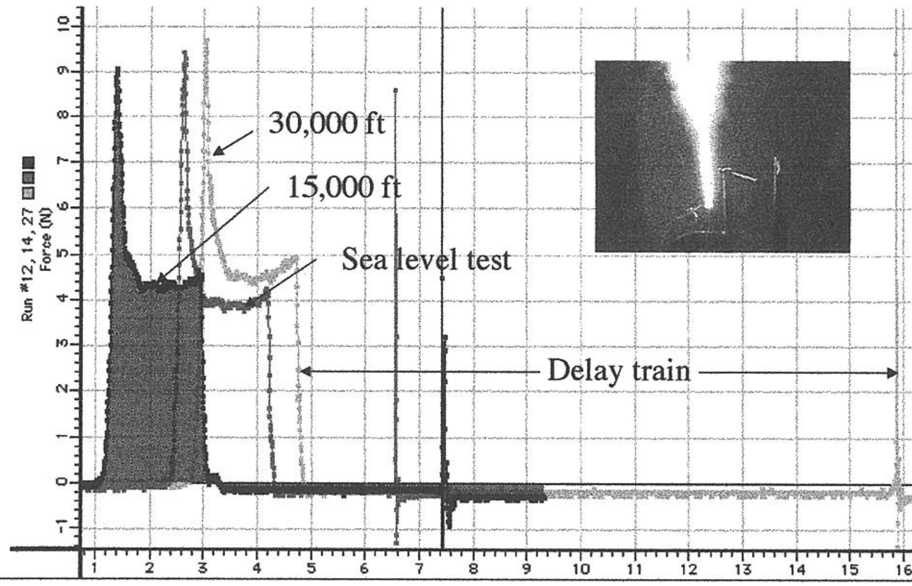
I made a lot of runs -- 27 in all. A number of them were misfires, which was a real pain since you had to pump the chamber back down to fix it.

The first run I had a really close call as it turned out there was some residual gasoline in one of the supply lines from the aircraft engines. At altitude it got sucked back into the chamber. If my engine had ignited I would have had a real problem. This was one time I was really glad for a misfire!

I was able to collect data at ground level, 15,000 ft ASL and 30,000 ft ASL. It took three days of testing to get this.

Comparison between 0, 15, & 30 k ft



This is a plot from Science Workshop showing a sea level test, the 15,000 ft test, and a 30,000 ft test. The inset picture is of an engine burning in the test chamber. If you compare it to multiple samples of burns at sea level, you can conclude that these differences are statistically significant.

I plotted them here so you can see the whole burn, including the delay train. The delay turned out to be very dependent on altitude.

Possible Sources of Error

- Altitude Chamber
  - Test chamber must be manually controlled
    - Seemed accurate to within +/-2kPa (+/- ≈1,000 ft)
  - Gases from engine increase pressure in cell
    - Operator noticed ≈ 0.5 kPa increase during burn
- Engines
  - Black powder engines vary slightly
    - I used all engines from the same batch
- Sensor
  - Calibration
    - recalibrated between each run with 1 kilogram and 500 gram weights
  - 6 gram resolution on A/D conversion

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The test chamber's altitude was only accurate to about +/-1,000 feet at altitude. Also, the chamber isn't very big, so when the engine lit, it decreased the altitude by several hundred feet.

All black powder engines are slightly different. To make them as close as possible to each other, I used engines all from the same batch.

The sensor could only measure differences of six grams or multiples there of. It was recalibrated between each test, but that was done by humans.

Still, even when you add up all these issues, I am pretty sure that I am seeing results that are real differences.

Conclusions

1. Ignition became much more difficult to achieve with altitude
   - This was unexpected
2. Total Impulse and average thrust increased with altitude
   - Measured results closely matched the theoretical predictions
3. Duration of smoke delay trains increased with altitude
   -Similar results have been reported for altitudes up to about 15 thousand feet
4. In all cases, measured performance was lower than advertised

   -These are really C4-2s at sea level

   -C4.5-12s at 30k ft

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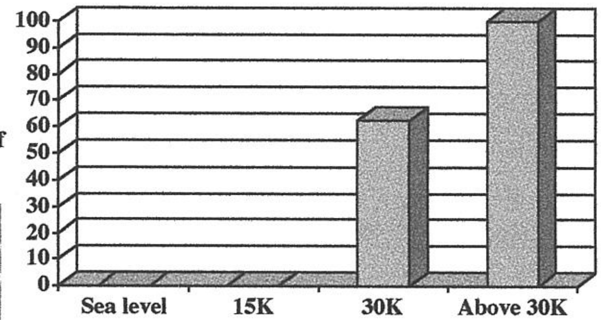
As I predicted, total impulse and thrust increased with altitude. In fact, my predictions were very close to the measured data.

Unexpectedly, lighting the motors became much more difficult at higher altitudes.

At higher altitudes, the delay train burned slower, so this year use shorter delays at NARAM.

Also, it appears that the stated (catalog) performance is much higher than actual. This could be a calibration error in my data, since I was more concerned about relative differences between my runs than on the absolute value. Or it could be real.

Ignition became much more difficult to achieve with altitude



- Four different types of igniters were tried.
- Increasing voltage helped at 30,000 ft
- Nothing worked above 30,000 ft

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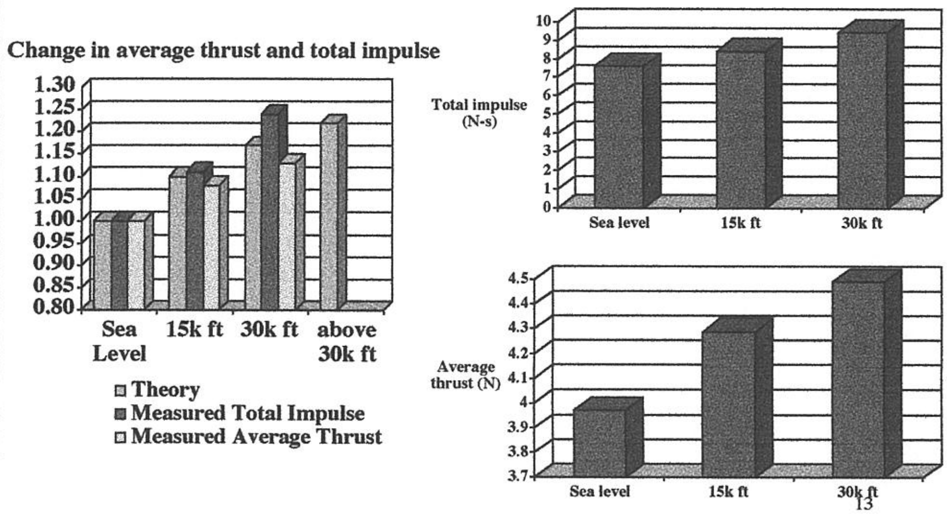
The ignition difficulties were the real surprise. This is an area for further research. The idea of even launching a black powder model rocket on the moon may be infeasible if the stuff won't light in a vacuum!

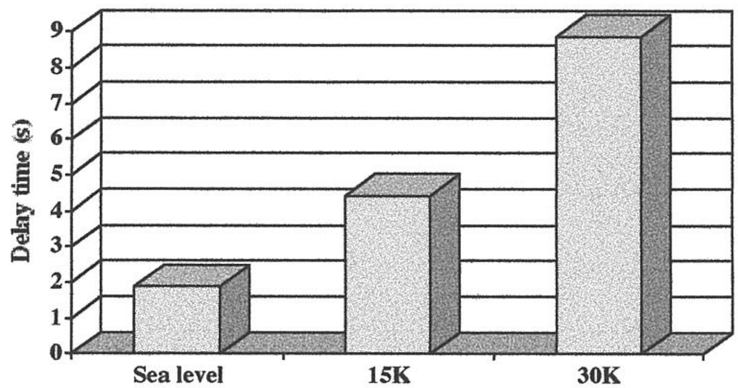
Total Impulse and average thrust increased with altitude



When I started I was warned that black powder engines were messy and that composites would be a better bet for these tests. I still used black powder, however, because of the cost.

This data is pretty amazing. It shows that even with black powder, the effects of altitude are visible.

Duration of smoke delay trains increased with altitude



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This was the biggest effect of all! Apparently, results from Estes and NASR S&T have disagreed for years and none one could understand it until they realized that Estes was at 5,000 feet and NAR S&T was at sea level. Still, I think my data is the most conclusive measurement yet of this effect.

Future Work

- Find igniters that work above 30k ft
  - This is an R&D project in itself
- Use composite engines instead of black powder engines
  - Composite engines have more consistency
- Collect data at 60k ft and 100k ft

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There is a lot to do. However, the test chamber is expensive and a real pain and so I am not sure it is worth the effort to continue the research. What do you guys think?

Bibliography

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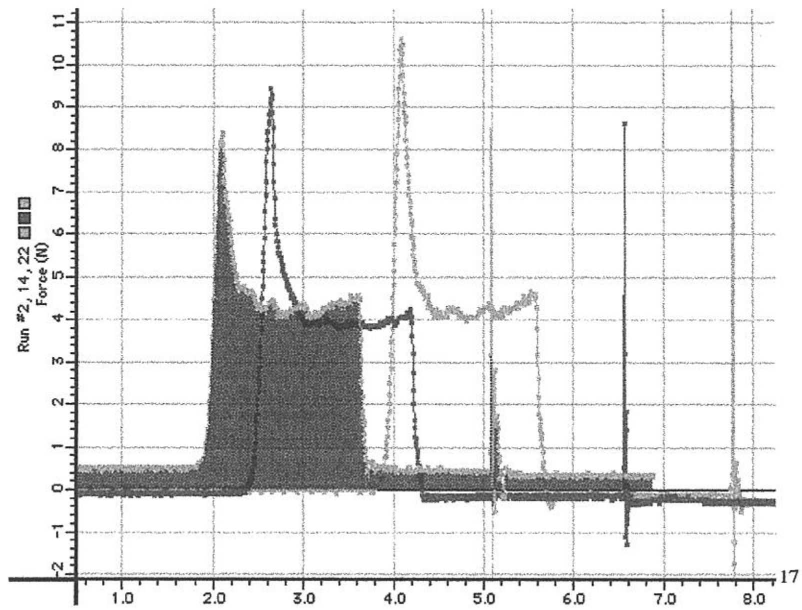
Thrust Time Curves: Sea Level



Thrust time curves: 30,000'