# YAW GOING TO MARS?

## **Can a micro drone fly on Mars?**

Jerrod Harris

# Can a micro drone fly on Mars?

- In 2020, NASA will send a helicopter to Mars to test flight feasibility on Mars.
- This study will investigate the possibility of flying a drone on Mars and other planets with different atmospheres and gravity.
- The general applicability of the propeller lift equation will also be checked at low pressures.

# Experimental Variables

- Independent Variables:
  - Air pressure
  - Motor power=voltage*current
  - Propeller selection
- Dependent Variables:
  - Lift force
  - Propeller rotation rate

# Background: Terms

- Pressure: The force per unit area exerted by a gas (kPa or k-Newtons/$m^2$)
- Gas Density: The mass/volume ratio for a gas (kg/$m^{3)}$.
  - **Pressure (P) is proportional to density** for fixed temperature (T).
  - Ideal Gas Law: P*M=density*R*T where M is the molar mass of the gas and R is the universal gas constant, 8.31Joules/(Kelvin*mole).
- Weight: The gravitational force on a mass (Newtons).
  - W=mass*g, where g is the acceleration due to gravity in m/$s^2$ (Earth=9.8, Mars=3.7m/$sec^2$)
- Propeller Lift: Force generated by propeller pushing down on air or other gas (mN).
- Power:
  - Power=Voltage*Current (Energy consumed per time measured in Watts.)
  - Power determines how fast the propeller motor spins for different pressures and propeller types.
- Propeller Rotation Rate: The number of revolutions in a given time (revolutions/sec).
- Tachometer: An instrument to measure rotation rate.
  - In this experiment, electrical pulses (frequency) are counted when a laser pointer beam is interrupted by the propeller blades (two blades per revolution).

# Background (continued)

- Propeller Equation
  - The lift (L) equation for a small section of a propeller: **$L=(C_{lift})*(density)*(area)*(velocity)^2$**
  - $C_{lift}$ is an experimentally determined coefficient
  - velocity=(rotation rate)*2* $\pi$ *r, where r is the radial distance from the propeller axis

- Mars Facts
  - Gravitational acceleration relative to Earth:
    - **0.38**=$(3.71 m/s^2)/(9.8 m/s^2)$
  - Atmospheric density relative to Earth
    - **1.66%**=$(0.02 kg/m^3)/(1.2 kg/m^3)$

# Hypothesis

- If one optimizes the motor speed, the propeller area, and the propeller pitch of a helicopter or drone, then it should be possible to fly in a reduced atmospheric pressure environment intended to simulate the density on Mars.

# Materials List

1. 1 metal steel (empty) tank (30.5 cm diameter x 35.6 cm high) for vacuum chamber
2. 1 2 stage Harbor Freight dual stage air conditioning vacuum pump
3. 0.6 cm x 25.5 cm x 10 cm sheet of plexiglass
4. 15 ml of epoxy
5. 20 piece long pin “strip” headers of electrical connector for vacuum feedthrough
6. 200 ml General Electric silicone caulk
7. 2.54 cm x 10 cm copper pipe
8. 0.6 cm x 60 cm copper pipe
9. 0.6 cm x 80 cm plastic tubing
10. 1 Lead-free plumbing soldering wire roll
11. 1 Soldering torch
12. 1 Sargent Welch mechanical vacuum gage
13. 1 meter of Teflon tape for sealing threaded pipe connections
14. 100 ml Dow Corning silicone vacuum grease
15. 50 ml soldering flux for copper pipe soldering

# Materials List (cont.)

16. 2 Hewlett Packard DC power supplies
17. 1 Metex multi-meter & frequency meter to measure rotation speed
18. 1 MH-Series Pocket Scale up to the hundredth gram
19. 1 5 mm x 15 mm Mini Quadcopter drone motor
20. 1 43 mm propeller (A)
21. 1 x mm propeller (B)
22. 2.5 mm diameter x 3 meters insulated copper wire for electrical connections
23. 100 ml vacuum pump oil for manometer
24. 2 plumbing valves
25. 30 cm x 30 cm piece of plastic wrap
26. 2.54 cm diameter pipe fitting
27. 1 mm diameter 10 cm long iron wire
28. 1 roll of masking tape
29. Dollar Tree laser pointer for motor & propeller speed sensor/tachometer
30. Solar cell to generate electrical signal when propeller blocks laser light
31. Computer speaker amplifier to amplify electrical pulses from solar cell

# Procedure: Vacuum Chamber Construction

1. Cut a 23 cm tall x 8 cm wide hole about 18 cm from the bottom of the steel tank.
2. Take the plexiglass sheet and heat it so it conforms to the shape of the curvature of the tank.
3. Place the plastic wrap on the tank and put silicone caulk on the plexiglass and press onto the tank. Let cure for one day to form the gasket.
4. Solder the 2.5 cm pipe into the pipe fitting then crush one end and solder it shut.
5. Drill a hole into the side of the 2.5 cm pipe and then solder in the 0.6 cm copper tube.
6. Drill holes into tank for header pins, place in the header pins in the holes and then use the five-minute epoxy to seal.
7. Connect the 0.6 cm plastic tubing to the end of the 0.6 cm copper tube then connect the plastic tubing to Sargent Welch vacuum gauge.
8. Take a segment of the 0.6 cm copper tube and then connect the Sargent Welch gauge to the Vacuum pump
9. Remove the plastic wrap from the chamber and then place the plexiglass with silicone gasket back onto the chamber with vacuum grease to make a vacuum tight seal.
10. Test the vacuum chamber: turn on the vacuum pump. If there are any leaks, patch them with epoxy or by other means. To vent the chamber, unscrew the vent port on the pump.
11. Now the vacuum chamber is complete and leak tested.

# Vacuum Chamber Set-Up

Pictures of Construction

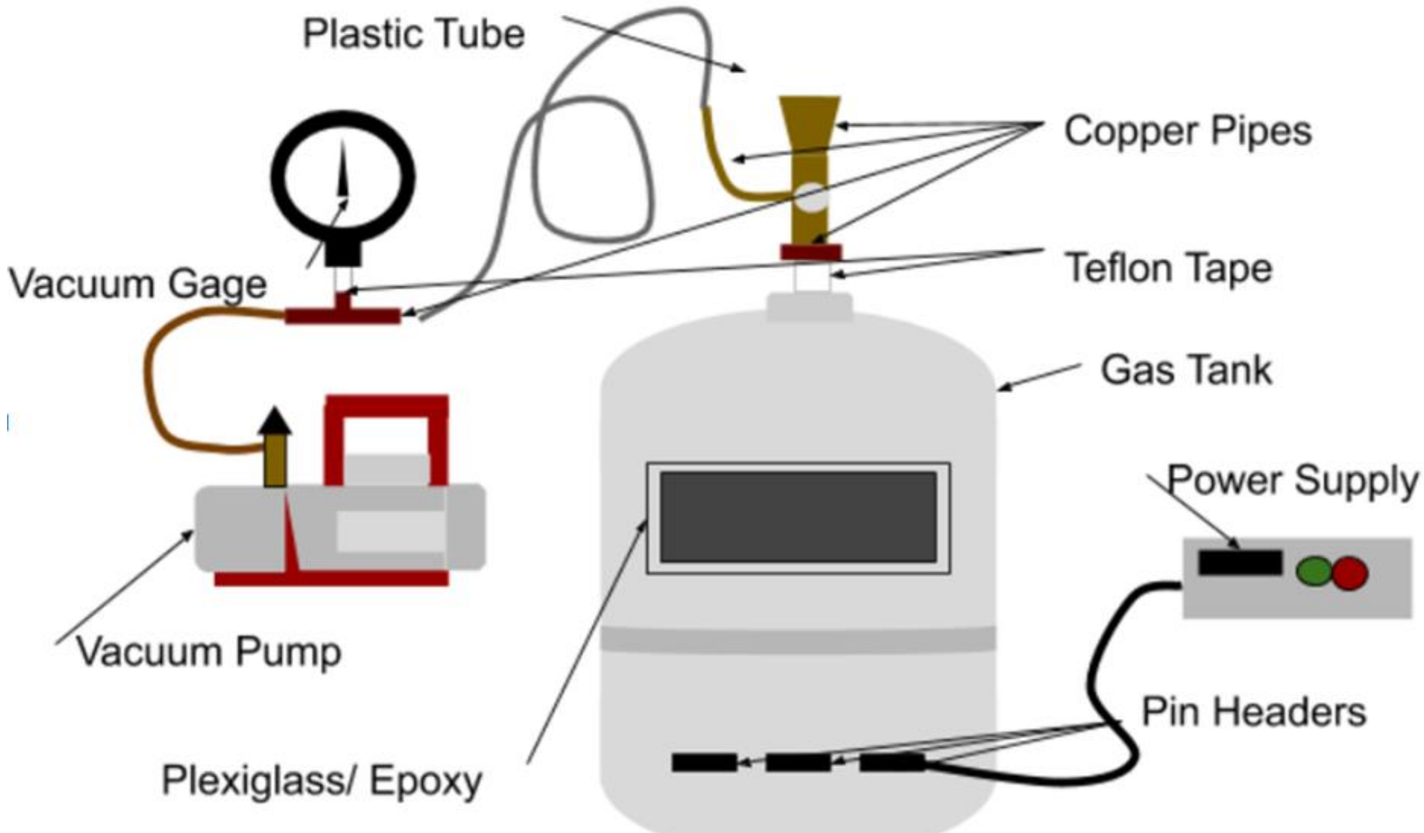


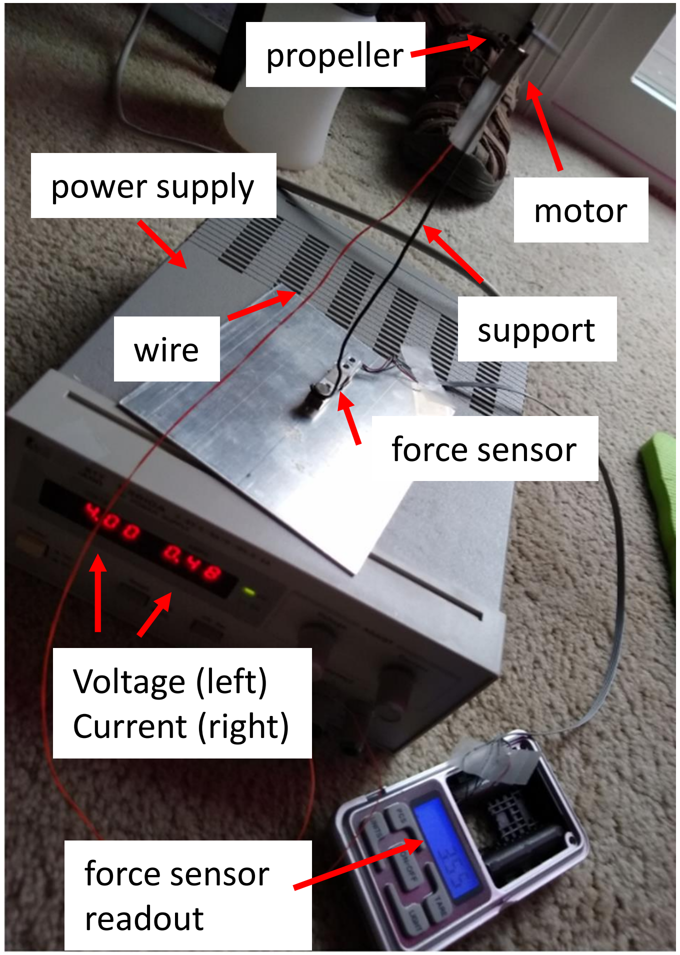

Diagram of Vacuum Chamber Set-Up

# Procedure: Propeller Mounting System

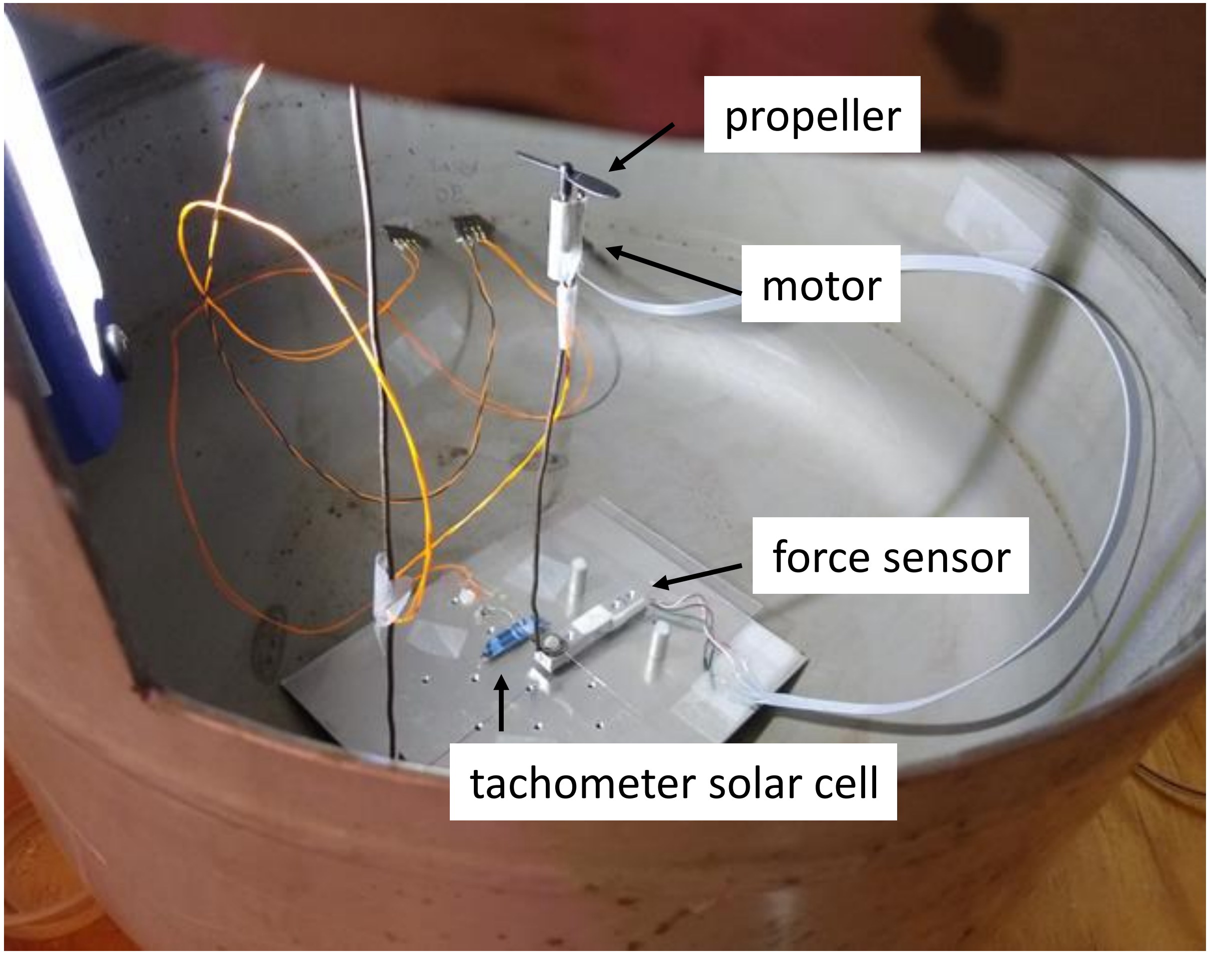
Construction of the motor/propeller mounting system and scale

1. Mount the motor with the propeller to the iron wire with a strip of masking tape. This will allow easy interchange of the motors.
2. Remove the top portion of the pocket scale and the plate that goes on top of the sensor that measures the weight. This is done so that the sensor (strain gauge) that measures the force is inside the chamber. The electronics that gives the readout is on the outside.
3. Screw the iron wire motor mount into the pocket scale’s sensor.
4. Put the motor, propeller, iron wire mount, and the sensor part of the scale into the vacuum chamber.
5. Solder the wires to the motor and the scale sensor to header connectors.
6. Connect the Readout part of the scale to the corresponding prongs of the header connecters.
7. Solder the laser pointer and solar cell to headers and place inside the vacuum chamber so that the propeller will break the light from the laser to the solar cell. This will provide an electrical signal for the rotation rate of the motor and propeller.

# Motor/Propeller Mounting System




Measuring power consumption of drone motor with 3.55g = 34.8mN of lift.




Everything assembled in the vacuum chamber.

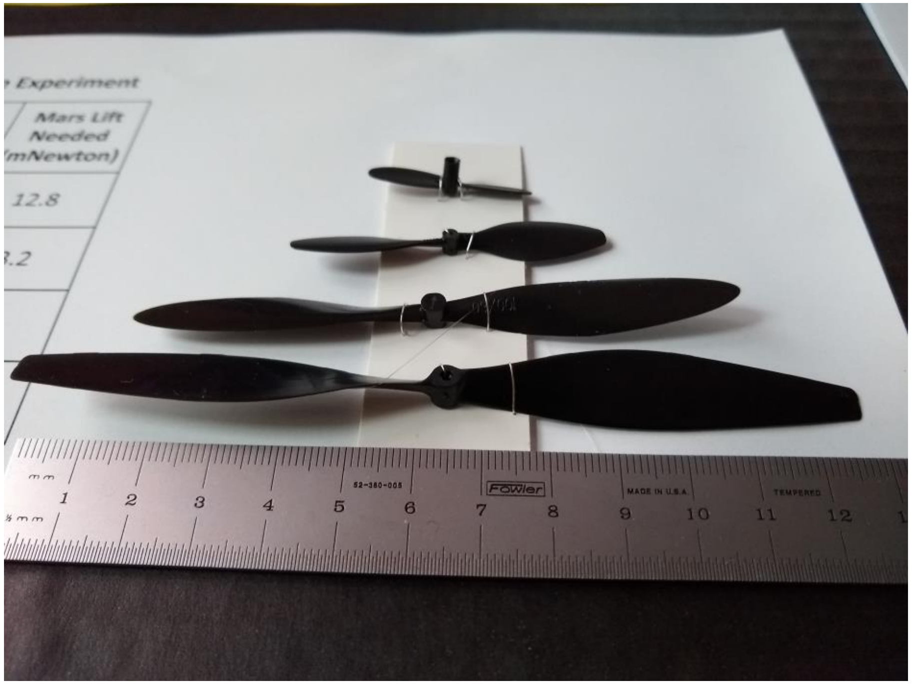
# Procedure: Measurements

1. Hook up power supply to motor and laser through the feedthrough headers and hook up the solar cell to the amplifier and Metex frequency meter. The frequency in Hertz will measure as twice the rotation since the beam is interrupted by each half of the propeller.
2. Make reference measurements of lift force versus motor speeds for the original propeller (A) in Earth's atmospheric pressure of 101.6 kPa.
3. Repeat measurements under the same nominal conditions to determine repeatability.
4. Pump out chamber to approximately 1.7 kPa to simulate the atmospheric density of Mars (0.02kg/m$^3$); repeat measurements in step (3b) for other pressures and propellers (B, C, D).

# Propellers Used in the Experiment

- Propeller length, width, mass measured
- Mars lift calculated based on lift needed for ¼ weight of the micro drone (assuming a 4 propeller micro drone)

| Propeller | Length (mm) | Largest Width (mm) | Mass (grams) | Mars Lift Needed (mNewton) |
|---|---|---|---|---|
| A (original) | 31 | 4.5 | 0.12 | 12.8 |
| B | 60 | 9 | 0.22 | 13.2 |
| C | 100 | 10 | 0.37 | 13.7 |
| D | 130 | 13 | 0.97 | 16.0 |



# Data: Sample Table for Propeller A

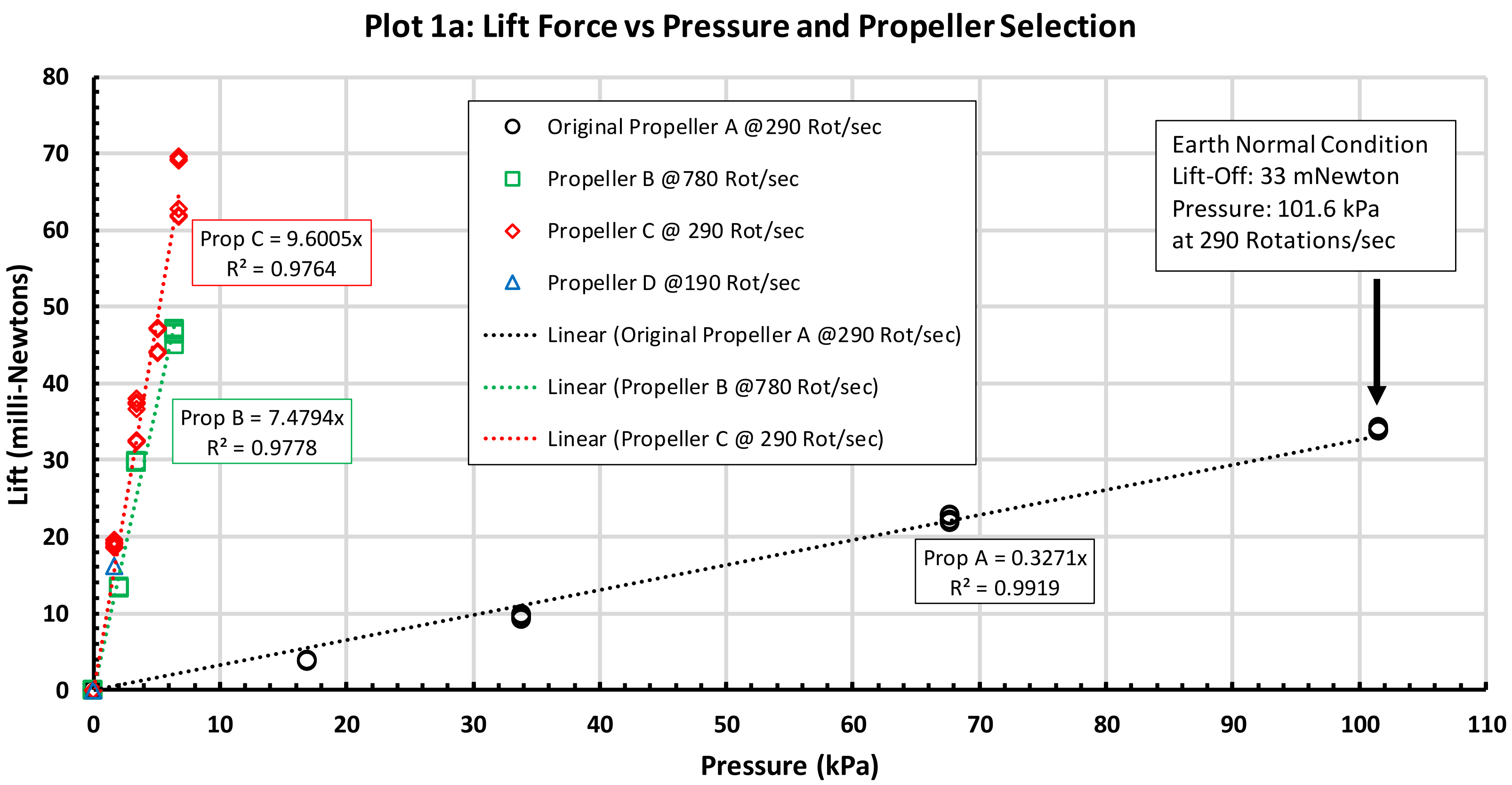
- Measurements:
  - Lift and Power vs Pressure at fixed rotation speed

| Table1A | 0 =atmosphere | | | | | 0=vacuum | | | metric conversions | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Trial | Pressure (in Hg) | Frequency (kHz) | Voltage (V) | Current (I) | Lift (grams) | pressure | power (Watt) | | rotations/sec | lift (m-Newton) | pressure (kPa) |
| 1 | 0 | 1.04 | 2.77 | 0.27 | 3.45 | 30 | 0.7479 | | 520 | 33.81 | 101.58 |
| 2 | 0 | 1.043 | 2.77 | 0.27 | 3.5 | 30 | 0.7479 | | 521.5 | 34.3 | 101.58 |
| 3 | 0 | 1.046 | 2.77 | 0.27 | 3.46 | 30 | 0.7479 | | 523 | 33.908 | 101.58 |
| 4 | 0 | 1.042 | 2.77 | 0.27 | 3.45 | 30 | 0.7479 | | 521 | 33.81 | 101.58 |
| 5 | 0 | 1.047 | 2.77 | 0.27 | 3.46 | 30 | 0.7479 | | 523.5 | 33.908 | 101.58 |
| 1 | 10 | 1.057 | 2.58 | 0.2 | 2.25 | 20 | 0.516 | | 528.5 | 22.05 | 67.72 |
| 2 | 10 | 1.052 | 2.58 | 0.2 | 2.26 | 20 | 0.516 | | 526 | 22.148 | 67.72 |
| 3 | 10 | 1.045 | 2.58 | 0.2 | 2.23 | 20 | 0.516 | | 522.5 | 21.854 | 67.72 |
| 4 | 10 | 1.054 | 2.58 | 0.2 | 2.31 | 20 | 0.516 | | 527 | 22.638 | 67.72 |
| 5 | 10 | 1.05 | 2.58 | 0.2 | 2.32 | 20 | 0.516 | | 525 | 22.736 | 67.72 |
| 1 | 20 | 1.057 | 2.36 | 0.11 | 0.97 | 10 | 0.2596 | | 528.5 | 9.506 | 33.86 |
| 2 | 20 | 1.056 | 2.36 | 0.11 | 0.97 | 10 | 0.2596 | | 528 | 9.506 | 33.86 |
| 3 | 20 | 1.053 | 2.36 | 0.11 | 1 | 10 | 0.2596 | | 526.5 | 9.8 | 33.86 |
| 4 | 20 | 1.063 | 2.36 | 0.11 | 0.99 | 10 | 0.2596 | | 531.5 | 9.702 | 33.86 |
| 5 | 20 | 1.054 | 2.36 | 0.11 | 0.94 | 10 | 0.2596 | | 527 | 9.212 | 33.86 |
| 1 | 25 | 1,051 | 2.24 | 0.07 | 0.39 | 5 | 0.1568 | | 525500 | 3.822 | 16.93 |
| 2 | 25 | 1.03 | 2.24 | 0.07 | 0.37 | 5 | 0.1568 | | 515 | 3.626 | 16.93 |
| 3 | 25 | 1.029 | 2.24 | 0.07 | 0.37 | 5 | 0.1568 | | 514.5 | 3.626 | 16.93 |
| 4 | 25 | 1.018 | 2.24 | 0.07 | 0.37 | 5 | 0.1568 | | 509 | 3.626 | 16.93 |
| 5 | 25 | 1.05 | 2.29 | 0.07 | 0.4 | 5 | 0.1603 | | 525 | 3.92 | 16.93 |
| 1 | 30 | 1.058 | 2.17 | 0.042 | 0 | 0 | 0.09114 | | 529 | 0 | 0 |
| 2 | 30 | 1.049 | 2.17 | 0.042 | 0 | 0 | 0.09114 | | 524.5 | 0 | 0 |
| 3 | 30 | 1.053 | 2.17 | 0.042 | 0 | 0 | 0.09114 | | 526.5 | 0 | 0 |
| 4 | 30 | 1.051 | 2.17 | 0.041 | 0 | 0 | 0.08897 | | 525.5 | 0 | 0 |
| 5 | 30 | 1.05 | 2.17 | 0.04 | 0 | 0 | 0.0868 | | 525 | 0 | 0 |

# Data Analysis

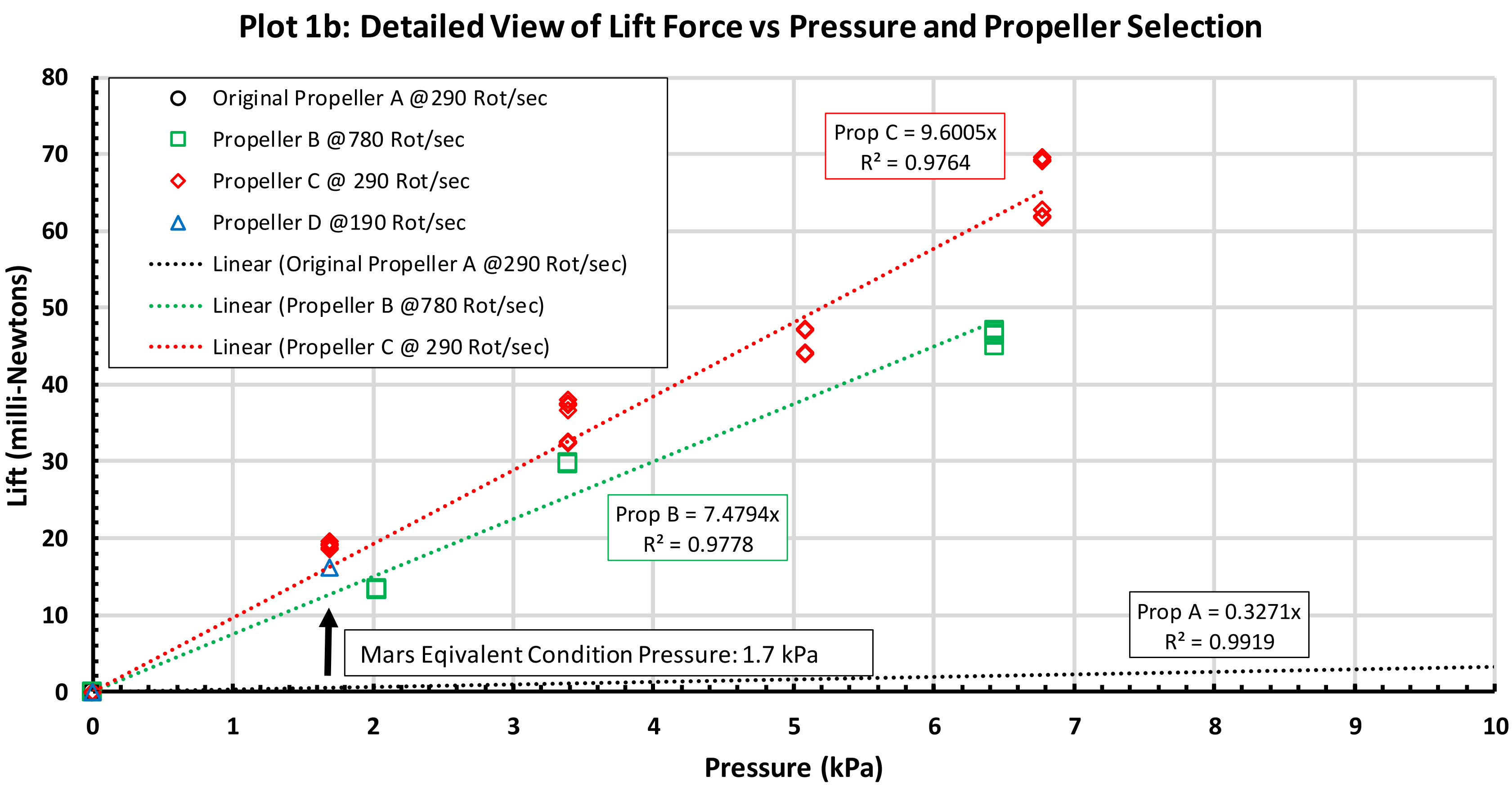
- All raw data converted to standard metric units.
- The digital scale measuring lift reported mass (m) which was converted to force (F), using Newton's Law: F=ma, where a is the acceleration due to gravity, $9.8 m/s^2$.
- Pressures from "inch Hg" (mercury) gauge were converted to kPa using 3.38 kPa/inch Hg
- Motor power (Watts) is computed from motor (voltage)*(current). (Watts=Volts*Amperes).
- Excess Lift is the measured lift (for one propeller) subtracting the lift required for ¼ of the drone weight for Earth or Mars.
- To check linearity of data, the Excel linear fit function is used, reporting $R^2$ as goodness of fit.

# Lift Force vs Pressure for 4 Propellers



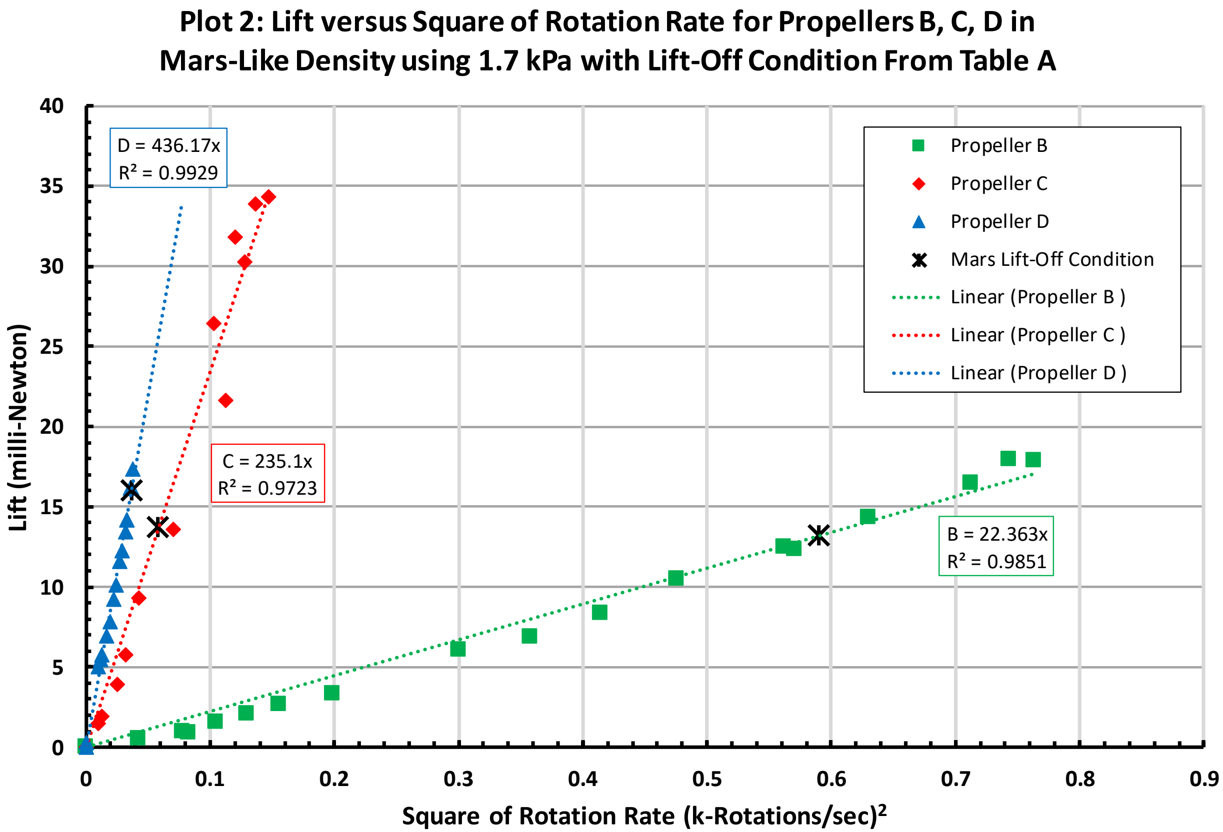

- Lift data shows strong linear relationship to pressure
- Note that Lift equation states that lift is proportional to density
  - **$L=(C_{lift})*(density)*(area)*(velocity)^2$**
  - Density is proportional to pressure by the Ideal Gas Law

# Detailed View: Lift Force vs Pressure



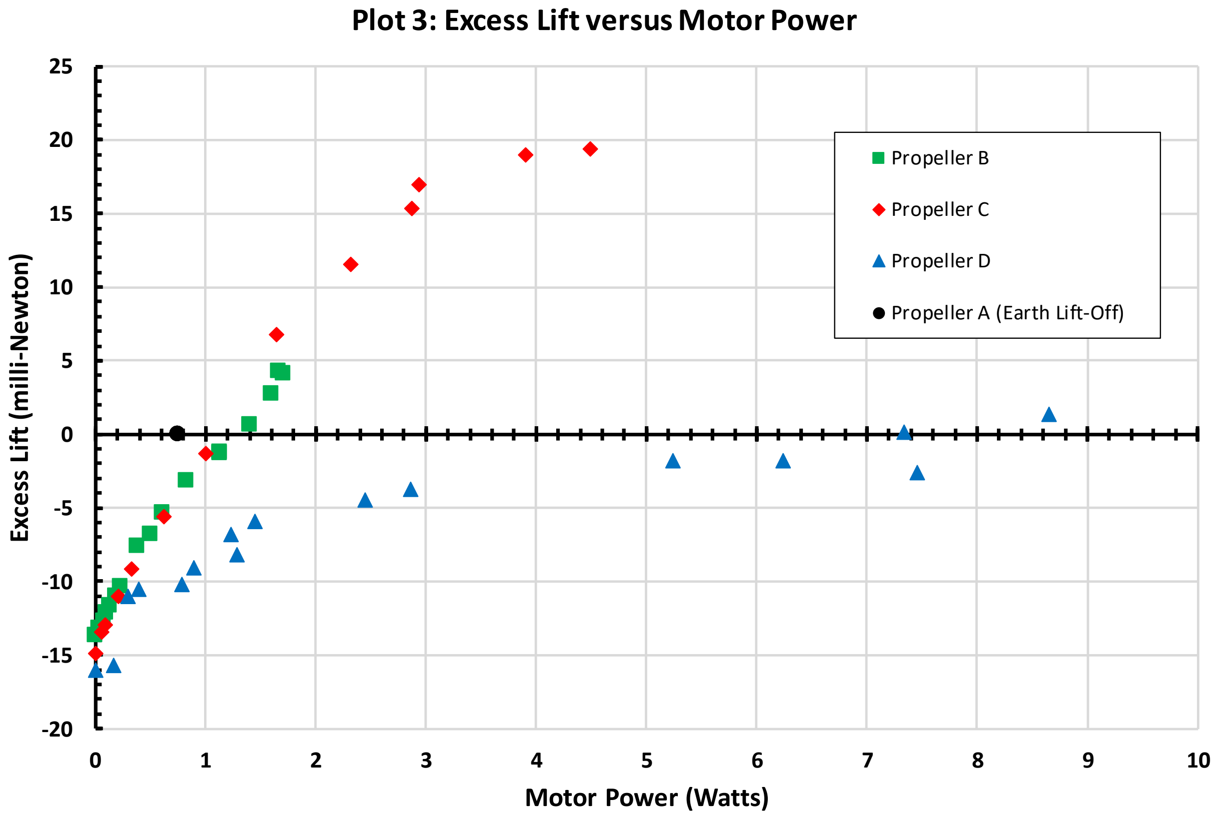

- Linear relationship of lift and pressure
- Propeller D only has two pressure points since the motor failed when going above 3kPa pressure due to excessive motor power.

# Lift vs Square of Rotation Rate at 1.7kPa




- Lift data shows strong linear relationship to (rotation rate)$^2$
- Note that Lift equation states that lift is proportional to (velocity)$^2$
  - **L=($C_{lift}$)*(density)*(area)*(velocity)$^2$ , velocity=2$\pi$r*(rotation rate)**
- **Propellers B, C, D all show lift beyond the Mars lift-off condition!**

# Excess Lift vs Motor Power at 1.7kPa




- Power required for Mars atmospheric density lift-off was almost 2X higher for Propellers B, C compared to Propeller A in Earth normal condition
- Power required was 10X higher for Propeller D compared to the original propeller, A, in Earth normal conditions.

# Conclusions

- **Can a drone fly on Mars? <u>YES, with proper selection of propeller and rotation rate.</u>**
- The original drone propeller, A, was unable to achieve Mars lift-off with the available rotation rate.
- The data showed a linear relationship for lift vs pressure and lift vs (rotation rate)$^2$, consistent with the Lift equation.
- Propellers B, C, D all achieved the Mars lift-off condition, **<u>confirming the hypothesis!</u>**
- The power required for Mars lift-off was almost 2X higher for Propellers B, C and 10X higher for Propeller D compared to the original propeller, A, in Earth normal conditions. Drag and possibly motor friction is greater for larger propellers.

# Possible Sources of Errors

- Vibrations due to propeller imbalances affecting lift, power, and tachometer readings.
- Inaccurate pressure readings (estimate 15% variation at low pressure).
- Lift scale with only two digits of precision (0.01g).
- Vacuum chamber size may have some impact because of internal air currents.

# Potential Solutions/Future Experiments

- Obtain or fabricate better quality propellers with better balance to reduce vibration.
- Add mass and vibration damping to scale to reduce vibration.
- Fabricate or purchase propellers with known specifications for more systematic studies of propeller lift vs power consumption.
- This experiment did not investigate the changes needed in the overall design of a micro-drone: structural changes to accommodate larger propellers, using better materials to reduce weight, batteries and battery flight time. These could all be studied in the future.

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# THANK YOU!

# Appendix: Propeller B Data

Table 1B. Lift and power vs Pressure at fixed rotation rate for Propeller B: raw data and metric conversions.

| Table 1B | 0 =atmosphere | Tachometer | Motor | Motor | Propeller | 0=vacuum | Motor | Metric Conversions | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Trial | Pressure (in Hg) | Frequency (kHz) | Voltage (V) | Current (I) | Lift (grams) | pressure (in Hg) | power (Watt) | rotations/sec | lift (m-Newton) | pressure (kPa) |
| 1 | 29.4 | 1.55 | 3.955 | 0.32 | 1.37 | 0.6 | 1.2656 | 775 | 13.426 | 2.0316 |
| 2 | 29.4 | 1.544 | 3.955 | 0.43 | 1.35 | 0.6 | 1.70065 | 772 | 13.23 | 2.0316 |
| 3 | 29.4 | 1.535 | 3.955 | 0.44 | 1.36 | 0.6 | 1.7402 | 767.5 | 13.328 | 2.0316 |
| 4 | 29.4 | 1.551 | 3.955 | 0.44 | 1.35 | 0.6 | 1.7402 | 775.5 | 13.23 | 2.0316 |
| 5 | 29.4 | 1.542 | 3.955 | 0.44 | 1.36 | 0.6 | 1.7402 | 771 | 13.328 | 2.0316 |
| 1 | 28.1 | 1.567 | 4.77 | 0.64 | 4.75 | 1.9 | 3.0528 | 783.5 | 46.55 | 6.4334 |
| 2 | 28.1 | 1.56 | 4.77 | 0.64 | 4.59 | 1.9 | 3.0528 | 780 | 44.982 | 6.4334 |
| 3 | 28.1 | 1.563 | 4.77 | 0.64 | 4.79 | 1.9 | 3.0528 | 781.5 | 46.942 | 6.4334 |
| 4 | 28.1 | 1.565 | 4.77 | 0.64 | 4.8 | 1.9 | 3.0528 | 782.5 | 47.04 | 6.4334 |
| 5 | 28.1 | 1.561 | 4.77 | 0.65 | 4.73 | 1.9 | 3.1005 | 780.5 | 46.354 | 6.4334 |
| 1 | 30 | 1.572 | 3.42 | 0.13 | 0 | 0 | 0.4446 | 786 | 0 | 0 |
| 2 | 30 | 1.569 | 3.44 | 0.13 | 0 | 0 | 0.4472 | 784.5 | 0 | 0 |
| 3 | 30 | 1.574 | 3.44 | 0.13 | 0 | 0 | 0.4472 | 787 | 0 | 0 |
| 4 | 30 | 1.574 | 3.44 | 0.13 | 0 | 0 | 0.4472 | 787 | 0 | 0 |
| 5 | 30 | 1.571 | 3.44 | 0.14 | 0 | 0 | 0.4816 | 785.5 | 0 | 0 |
| 1 | 29 | 1.565 | 4.31 | 0.48 | 3.05 | 1 | 2.0688 | 782.5 | 29.89 | 3.386 |
| 2 | 29 | 1.558 | 4.31 | 0.49 | 3.05 | 1 | 2.1119 | 779 | 29.89 | 3.386 |
| 3 | 29 | 1.546 | 4.28 | 0.48 | 3.03 | 1 | 2.0544 | 773 | 29.694 | 3.386 |
| 4 | 29 | 1.557 | 4.28 | 0.48 | 3.03 | 1 | 2.0544 | 778.5 | 29.694 | 3.386 |
| 5 | 29 | 1.555 | 5.78 | 1.21 | 3.03 | 1 | 6.9938 | 777.5 | 29.694 | 3.386 |

# Appendix: Propeller C Data

Table 1C. Lift and power vs Pressure at fixed rotation rate for Propeller C: raw data and metric conversions.

| Table 1C | 0 =atmosphere | Tachometer | Motor | Motor | Propeller | 0=vacuum | Motor | | Metric Conversions | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Trial | Pressure (in Hg) | Frequency (kHz) | Voltage (V) | Current (I) | Lift (grams) | pressure (in Hg) | power (Watt) | | rotations/sec | lift (m-Newton) | pressure (kPa) |
| 1 | 28 | 0.583 | 3.77 | 3.07 | 7.05 | 2 | 11.5739 | | 291.5 | 69.09 | 6.772 |
| 2 | 28 | 0.586 | 3.77 | 3.07 | 7.07 | 2 | 11.5739 | | 293 | 69.286 | 6.772 |
| 3 | 28 | 0.587 | 3.77 | 3.07 | 7.1 | 2 | 11.5739 | | 293.5 | 69.58 | 6.772 |
| 4 | 28 | 0.586 | 3.77 | 3.08 | 7.07 | 2 | 11.6116 | | 293 | 69.286 | 6.772 |
| 5 | 28 | 0.588 | 3.77 | 3.08 | 7.11 | 2 | 11.6116 | | 294 | 69.678 | 6.772 |
| 1 | 29 | 0.603 | 2.48 | 1.86 | 3.87 | 1 | 4.6128 | | 301.5 | 37.926 | 3.386 |
| 2 | 29 | 0.596 | 2.48 | 1.87 | 3.83 | 1 | 4.6376 | | 298 | 37.534 | 3.386 |
| 3 | 29 | 0.59 | 2.48 | 1.88 | 3.81 | 1 | 4.6624 | | 295 | 37.338 | 3.386 |
| 4 | 29 | 0.592 | 2.48 | 1.88 | 3.82 | 1 | 4.6624 | | 296 | 37.436 | 3.386 |
| 5 | 29 | 0.596 | 2.48 | 1.88 | 3.74 | 1 | 4.6624 | | 298 | 36.652 | 3.386 |
| 1 | 30 | 0.561 | 1.03 | 0.38 | 0 | 0 | 0.3914 | | 280.5 | 0 | 0 |
| 2 | 30 | 0.554 | 1.03 | 0.38 | 0 | 0 | 0.3914 | | 277 | 0 | 0 |
| 3 | 30 | 0.575 | 1.03 | 0.37 | 0 | 0 | 0.3811 | | 287.5 | 0 | 0 |
| 4 | 30 | 0.564 | 1.03 | 0.38 | 0 | 0 | 0.3914 | | 282 | 0 | 0 |
| 5 | 30 | 0.584 | 1.03 | 0.38 | 0 | 0 | 0.3914 | | 292 | 0 | 0 |
| 1 | 28.5 | 0.575 | 2.7 | 2.08 | 4.49 | 1.5 | 5.616 | | 287.5 | 44.002 | 5.079 |
| 2 | 28.5 | 0.573 | 2.7 | 2.08 | 4.49 | 1.5 | 5.616 | | 286.5 | 44.002 | 5.079 |
| 3 | 28.5 | 0.575 | 2.7 | 2.08 | 4.49 | 1.5 | 5.616 | | 287.5 | 44.002 | 5.079 |
| 4 | 28.5 | 0.576 | 2.7 | 2.08 | 4.51 | 1.5 | 5.616 | | 288 | 44.198 | 5.079 |
| 5 | 28.5 | 0.575 | 2.7 | 2.08 | 4.51 | 1.5 | 5.616 | | 287.5 | 44.198 | 5.079 |
| 1 | 29.5 | 0.596 | 1.75 | 1 | 1.99 | 0.5 | 1.75 | | 298 | 19.502 | 1.693 |
| 2 | 29.5 | 0.596 | 1.75 | 1.01 | 1.96 | 0.5 | 1.7675 | | 298 | 19.208 | 1.693 |
| 3 | 29.5 | 0.596 | 1.75 | 1.01 | 1.95 | 0.5 | 1.7675 | | 298 | 19.11 | 1.693 |
| 4 | 29.5 | 0.595 | 1.75 | 1.01 | 1.91 | 0.5 | 1.7675 | | 297.5 | 18.718 | 1.693 |
| 5 | 29.5 | 0.593 | 1.75 | 1.01 | 1.9 | 0.5 | 1.7675 | | 296.5 | 18.62 | 1.693 |
| 1 | 29 | 0.583 | 2.24 | 1.54 | 3.3 | 1 | 3.4496 | | 291.5 | 32.34 | 3.386 |
| 2 | 29 | 0.587 | 2.24 | 1.54 | 3.3 | 1 | 3.4496 | | 293.5 | 32.34 | 3.386 |
| 3 | 29 | 0.58 | 2.24 | 1.54 | 3.32 | 1 | 3.4496 | | 290 | 32.536 | 3.386 |
| 4 | 29 | 0.582 | 2.24 | 1.54 | 3.32 | 1 | 3.4496 | | 291 | 32.536 | 3.386 |
| 5 | 29 | 0.583 | 2.24 | 1.54 | 3.32 | 1 | 3.4496 | | 291.5 | 32.536 | 3.386 |
| 1 | 28.5 | 0.574 | 2.87 | 2.21 | 4.82 | 1.5 | 6.3427 | | 287 | 47.236 | 5.079 |
| 2 | 28.5 | 0.574 | 2.87 | 2.21 | 4.82 | 1.5 | 6.3427 | | 287 | 47.236 | 5.079 |
| 3 | 28.5 | 0.574 | 2.87 | 2.21 | 4.82 | 1.5 | 6.3427 | | 287 | 47.236 | 5.079 |
| 4 | 28.5 | 0.574 | 2.87 | 2.21 | 4.82 | 1.5 | 6.3427 | | 287 | 47.236 | 5.079 |
| 5 | 28.5 | 0.572 | 2.87 | 2.21 | 4.81 | 1.5 | 6.3427 | | 286 | 47.138 | 5.079 |
| 1 | 28 | 0.577 | 3.5 | 2.85 | 6.32 | 2 | 9.975 | | 288.5 | 61.936 | 6.772 |
| 2 | 28 | 0.576 | 3.5 | 2.85 | 6.31 | 2 | 9.975 | | 288 | 61.838 | 6.772 |
| 3 | 28 | 0.579 | 3.5 | 2.85 | 6.4 | 2 | 9.975 | | 289.5 | 62.72 | 6.772 |
| 4 | 28 | 0.578 | 3.5 | 2.86 | 6.41 | 2 | 10.01 | | 289 | 62.818 | 6.772 |
| 5 | 28 | 0.578 | 3.5 | 2.85 | 6.3 | 2 | 9.975 | | 289 | 61.74 | 6.772 |

# Appendix: Propeller D Data

Table 1D. Lift and power vs Pressure at fixed rotation rate for Propeller D: raw data and metric conversions.

| Table 1D | 0 =atmosphere | Tachometer | Motor | Motor | Propeller | 0=vacuum | Motor | | Metric Conversions | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Trial | Pressure (in Hg) | Frequency (kHz) | Voltage (V) | Current (I) | Lift (grams) | pressure (in Hg) | power (Watt) | | rotations/sec | lift (m-Newton) | pressure (kPa) |
| 1 | 29.5 | 0.384 | 5.32 | 1.38 | 1.65 | 0.5 | 7.3416 | | 192 | 16.17 | 1.693 |
| 1 | 30 | 0.39 | | | 0 | 0 | | | 195 | 0 | 0 |

Limited Data…. Motor Failed from Excess Power

# Appendix: Propeller B Data

Table 2B. Lift and power vs rotation rate and (rotation rate)$^2$ at fixed pressure of 1.7kpA for propeller B: raw data and metric conversion

| Table 2B | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 =atmosphere | Tachometer | Motor | Motor | Propeller | 0=vacuum | Motor | metric conversions | | | | |
| Pressure (in Hg) | Frequency (kHz) | Voltage (V) | Current (I) | Lift (gram) | pressure (in Hg) | power (Watt) | pressure (kpA) | (k-rot/sec)^2 | rotations/sec | Lift (mNewton) | Excess Lift (mN) |
| 29.500 | 1.724 | 4.500 | 0.370 | 1.830 | 0.500 | 1.665 | 1.690 | 0.743 | 862.000 | 17.934 | 4.234 |
| 29.500 | 1.748 | 4.500 | 0.380 | 1.820 | 0.500 | 1.710 | 1.690 | 0.764 | 874.000 | 17.836 | 4.136 |
| 29.500 | 1.688 | 4.320 | 0.370 | 1.680 | 0.500 | 1.598 | 1.690 | 0.712 | 844.000 | 16.464 | 2.764 |
| 29.500 | 1.588 | 4.120 | 0.340 | 1.460 | 0.500 | 1.401 | 1.690 | 0.630 | 794.000 | 14.308 | 0.608 |
| 29.500 | 1.500 | 3.790 | 0.300 | 1.270 | 0.500 | 1.137 | 1.690 | 0.563 | 750.000 | 12.446 | -1.254 |
| 29.500 | 1.511 | 3.790 | 0.300 | 1.260 | 0.500 | 1.137 | 1.690 | 0.571 | 755.500 | 12.348 | -1.352 |
| 29.500 | 1.379 | 3.450 | 0.240 | 1.070 | 0.500 | 0.828 | 1.690 | 0.475 | 689.500 | 10.486 | -3.214 |
| 29.500 | 1.287 | 3.070 | 0.200 | 0.850 | 0.500 | 0.614 | 1.690 | 0.414 | 643.500 | 8.330 | -5.370 |
| 29.500 | 1.196 | 2.810 | 0.180 | 0.700 | 0.500 | 0.506 | 1.690 | 0.358 | 598.000 | 6.860 | -6.840 |
| 29.500 | 1.096 | 2.520 | 0.150 | 0.620 | 0.500 | 0.378 | 1.690 | 0.300 | 548.000 | 6.076 | -7.624 |
| 29.500 | 0.892 | 2.100 | 0.110 | 0.340 | 0.500 | 0.231 | 1.690 | 0.199 | 446.000 | 3.332 | -10.368 |
| 29.500 | 0.789 | 1.850 | 0.100 | 0.270 | 0.500 | 0.185 | 1.690 | 0.156 | 394.500 | 2.646 | -11.054 |
| 29.500 | 0.720 | 1.680 | 0.080 | 0.210 | 0.500 | 0.134 | 1.690 | 0.130 | 360.000 | 2.058 | -11.642 |
| 29.500 | 0.647 | 1.500 | 0.070 | 0.160 | 0.500 | 0.105 | 1.690 | 0.105 | 323.500 | 1.568 | -12.132 |
| 29.500 | 0.558 | 1.290 | 0.060 | 0.100 | 0.500 | 0.077 | 1.690 | 0.078 | 279.000 | 0.980 | -12.720 |
| 29.500 | 0.412 | 0.940 | 0.040 | 0.050 | 0.500 | 0.038 | 1.690 | 0.042 | 206.000 | 0.490 | -13.210 |
| 29.500 | 0.577 | 1.300 | 0.150 | 0.090 | 0.500 | 0.195 | 1.690 | 0.083 | 288.500 | 0.882 | -12.818 |
| 29.500 | 0.000 | 0.000 | 0.000 | 0.000 | 0.500 | 0.000 | 1.690 | 0.000 | 0.000 | 0.000 | -13.700 |

# Appendix: Propeller C Data

Table 2C. Lift and power vs rotation rate and (rotation rate)$^2$ at fixed pressure of 1.7kpA for propeller C: raw data and metric conversion

| Table 2C | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 =atmosphere | Tachometer | Motor | Motor | Propeller | 0=vacuum | Motor | metric conversions | | | | |
| Pressure (in Hg) | Frequency (kHz) | Voltage (V) | Current (I) | Lift (gram) | pressure (in Hg) | power (Watt) | pressure (kpA) | (k-rot/sec)^2 | rotations/sec | Lift (mNewton) | Excess Lift (mN) |
| 29.500 | 0.766 | 4.540 | 0.990 | 3.500 | 0.500 | 4.495 | 1.690 | 0.147 | 383.000 | 34.300 | 19.400 |
| 29.500 | 0.740 | 4.240 | 0.920 | 3.460 | 0.500 | 3.901 | 1.690 | 0.137 | 370.000 | 33.908 | 19.008 |
| 29.500 | 0.694 | 3.500 | 0.840 | 3.250 | 0.500 | 2.940 | 1.690 | 0.120 | 347.000 | 31.850 | 16.950 |
| 29.500 | 0.715 | 3.640 | 0.790 | 3.090 | 0.500 | 2.876 | 1.690 | 0.128 | 357.500 | 30.282 | 15.382 |
| 29.500 | 0.642 | 3.270 | 0.710 | 2.700 | 0.500 | 2.322 | 1.690 | 0.103 | 321.000 | 26.460 | 11.560 |
| 29.500 | 0.670 | 2.780 | 0.590 | 2.210 | 0.500 | 1.640 | 1.690 | 0.112 | 335.000 | 21.658 | 6.758 |
| 29.500 | 0.530 | 2.190 | 0.460 | 1.390 | 0.500 | 1.007 | 1.690 | 0.070 | 265.000 | 13.622 | -1.278 |
| 29.500 | 0.411 | 1.740 | 0.360 | 0.950 | 0.500 | 0.626 | 1.690 | 0.042 | 205.500 | 9.310 | -5.590 |
| 29.500 | 0.360 | 1.300 | 0.250 | 0.590 | 0.500 | 0.325 | 1.690 | 0.032 | 180.000 | 5.782 | -9.118 |
| 29.500 | 0.320 | 1.040 | 0.200 | 0.400 | 0.500 | 0.208 | 1.690 | 0.026 | 160.000 | 3.920 | -10.980 |
| 29.500 | 0.225 | 0.710 | 0.130 | 0.200 | 0.500 | 0.092 | 1.690 | 0.013 | 112.500 | 1.960 | -12.940 |
| 29.500 | 0.202 | 0.570 | 0.100 | 0.150 | 0.500 | 0.057 | 1.690 | 0.010 | 101.000 | 1.470 | -13.430 |
| 29.500 | 0.000 | 0.000 | 0.000 | 0.000 | 0.500 | 0.000 | 1.690 | 0.000 | 0.000 | 0.000 | -14.900 |

# Appendix: Propeller D Data

Table 2D. Lift and power vs rotation rate and (rotation rate)$^2$ at fixed pressure of 1.7kpA for propeller D: raw data and metric conversion

| Table 2D | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 =atmosphere | Tachometer | Motor | Motor | Propeller | 0=vacuum | Motor | metric conversions | | | | |
| Pressure (in Hg) | Frequency (kHz) | Voltage (V) | Current (I) | Lift (gram) | pressure (in Hg) | power (Watt) | pressure (kpA) | (k-rot/sec)^2 | rotations/sec | Lift (mNewton) | Excess Lift (mN) |
| 29.500 | 0.000 | 0.000 | 0.000 | 0.000 | 0.500 | 0.000 | 1.690 | 0.000 | 0.000 | 0.000 | -16.000 |
| 29.500 | 0.056 | 0.720 | 0.230 | 0.030 | 0.500 | 0.166 | 1.690 | 0.001 | 28.000 | 0.294 | -15.706 |
| 29.500 | 0.203 | 1.080 | 0.270 | 0.510 | 0.500 | 0.292 | 1.690 | 0.010 | 101.500 | 4.998 | -11.002 |
| 29.500 | 0.219 | 1.270 | 0.310 | 0.560 | 0.500 | 0.394 | 1.690 | 0.012 | 109.500 | 5.488 | -10.512 |
| 29.500 | 0.229 | 1.700 | 0.460 | 0.590 | 0.500 | 0.782 | 1.690 | 0.013 | 114.500 | 5.782 | -10.218 |
| 29.500 | 0.256 | 1.820 | 0.490 | 0.710 | 0.500 | 0.892 | 1.690 | 0.016 | 128.000 | 6.958 | -9.042 |
| 29.500 | 0.279 | 2.180 | 0.590 | 0.800 | 0.500 | 1.286 | 1.690 | 0.019 | 139.500 | 7.840 | -8.160 |
| 29.500 | 0.298 | 2.130 | 0.580 | 0.940 | 0.500 | 1.235 | 1.690 | 0.022 | 149.000 | 9.212 | -6.788 |
| 29.500 | 0.314 | 2.330 | 0.620 | 1.030 | 0.500 | 1.445 | 1.690 | 0.025 | 157.000 | 10.094 | -5.906 |
| 29.500 | 0.329 | 2.990 | 0.820 | 1.180 | 0.500 | 2.452 | 1.690 | 0.027 | 164.500 | 11.564 | -4.436 |
| 29.500 | 0.340 | 3.250 | 0.880 | 1.250 | 0.500 | 2.860 | 1.690 | 0.029 | 170.000 | 12.250 | -3.750 |
| 29.500 | 0.355 | 5.400 | 1.380 | 1.370 | 0.500 | 7.452 | 1.690 | 0.032 | 177.500 | 13.426 | -2.574 |
| 29.500 | 0.363 | 5.030 | 1.240 | 1.450 | 0.500 | 6.237 | 1.690 | 0.033 | 181.500 | 14.210 | -1.790 |
| 29.500 | 0.361 | 4.520 | 1.160 | 1.450 | 0.500 | 5.243 | 1.690 | 0.033 | 180.500 | 14.210 | -1.790 |
| 29.500 | 0.377 | 6.580 | 1.540 | 1.650 | 0.500 | 10.133 | 1.690 | 0.036 | 188.500 | 16.170 | 0.170 |
| 29.500 | 0.384 | 5.320 | 1.380 | 1.650 | 0.500 | 7.342 | 1.690 | 0.037 | 192.000 | 16.170 | 0.170 |
| 29.500 | 0.387 | 5.970 | 1.450 | 1.770 | 0.500 | 8.657 | 1.690 | 0.037 | 193.500 | 17.346 | 1.346 |