Buoyancy Estimation of a Titan Aerostat (Montgolfière)

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Titan Montgolfière

- NASA Titan Explorer mission study (2008)
- Joint NASA/ESA Titan-Saturn-System Mission (TSSM) Flagship mission study (2009)
- Both studies advocated Montgolfière balloon using the ‘waste heat’ from Multi-Mission Radioisotope Thermoelectric Generator (MMRTG): 100 W electrical power and thermal output, $\boldsymbol{Q}$ = 2 kW
- Permits equatorial circumnavigation at 8 km altitude

Some Key Research Issues

1) Accurate prediction of aerostat buoyancy in quasi-steady equilibrium
2) Worse case prediction of downward force arising from storms and precipitation
3) Buoyancy modulation

Buoyancy Estimation

- Lift capability for given thermal power depends explicitly on heat transfer. Radiative heat transfer dominates on Earth, but at Titan cryogenic conditions convection dominates (e.g. Lorenz 2008 linear theory)
- Samanta et al. (2010) conducted experiments in cryogenic nitrogen gas
- For single wall envelope, buoyancy varies with MMTRG output

$$B \propto Q^{0.75}$$

- But experimental data showed significant departure (or deviating errors) and there is some disagreement over the choice of the best heat transfer correlations

Similarity Conditions

- For small temperature differences $B \cong \rho_a g V \Delta T / T_a$

- The Grashof number for the internal free convection heat transfer process is

$$Gr = \frac{gL^3 (T_b - T_w) \rho_b^2 \beta}{\mu_b^2}$$

- If the dominant thermal resistance is internal free convection, then

$$Gr \approx B \rho_a / \mu_a^2$$

Similarity Conditions (cont.)

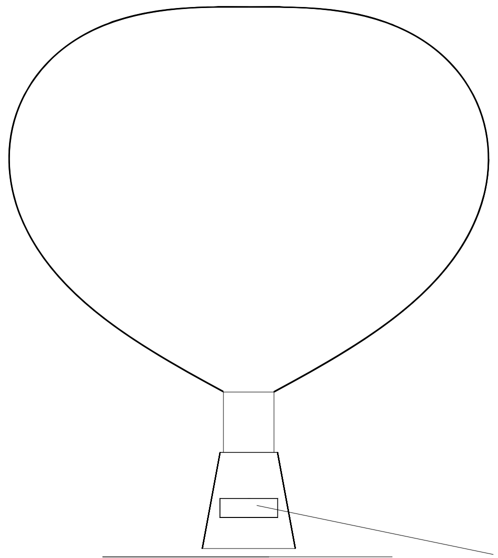
- For a system with a total mass of 200 kg

$$B\rho_a / \mu_a^2 \cong 2.7 \times 10^{13}$$

- Could be matched by heating 20 m radius envelope, 5 K, on Earth (at sea level conditions), but radiation transfer is dominant
- Niemela et al. (2000) reported internal free convection measurements of cyrogenic helium gas at Rayleigh numbers up to 10^{17},

$$Nu = 0.124 Ra^{0.309}$$

Experiment (Configuration 1)



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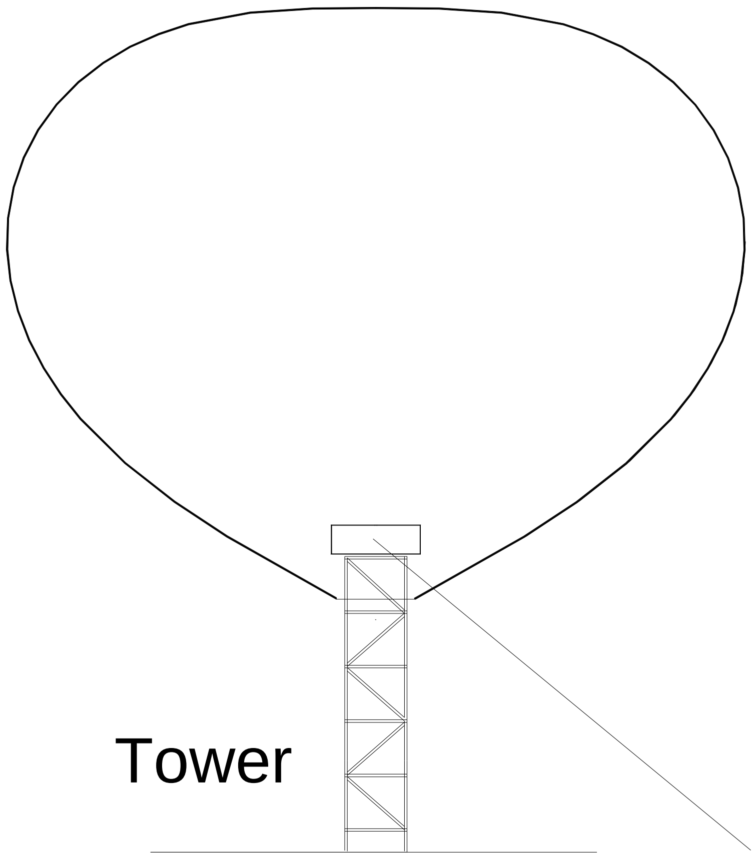
Revised Experiment (Configuration 2)



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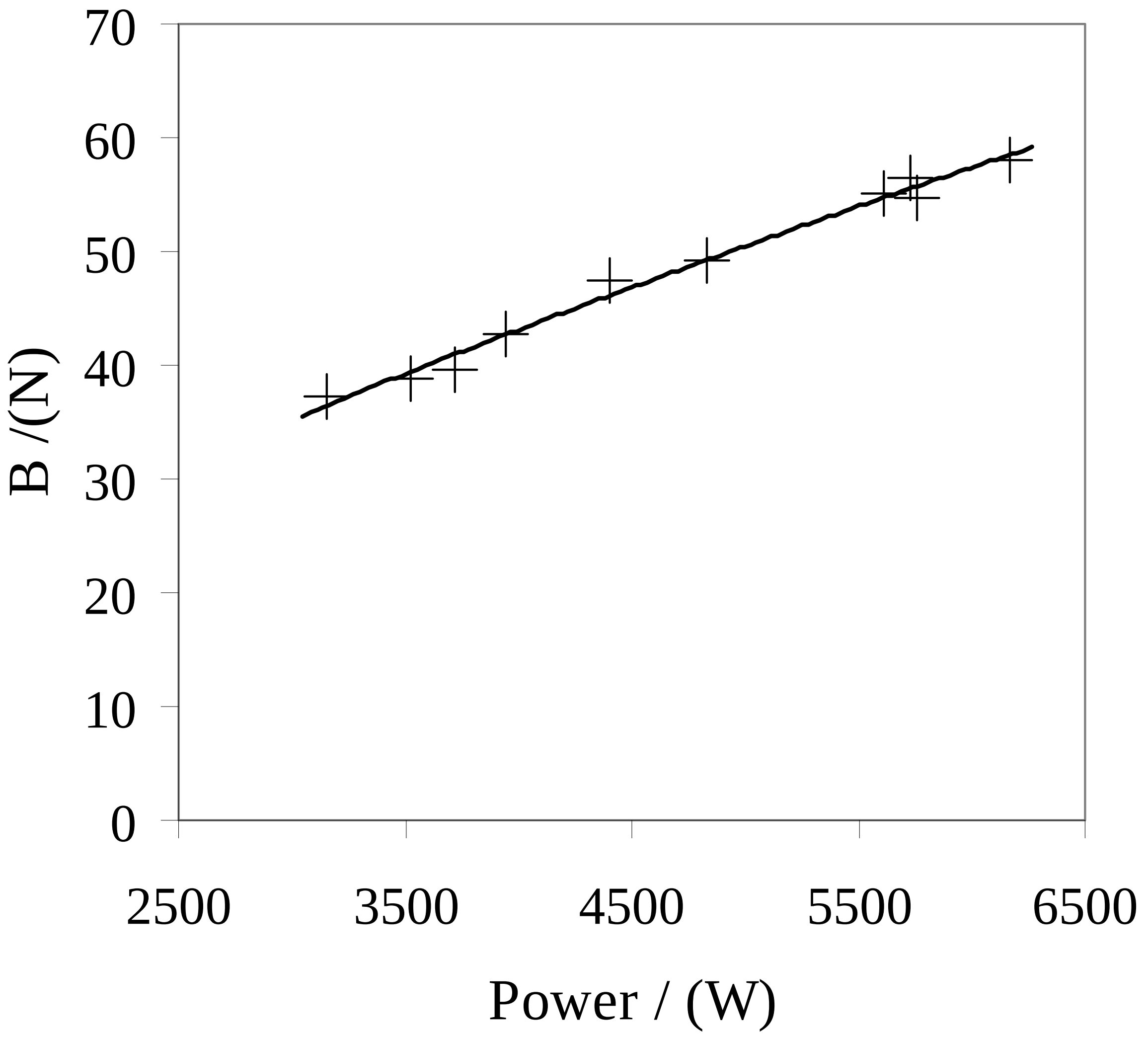
Measured buoyancy vs. power input



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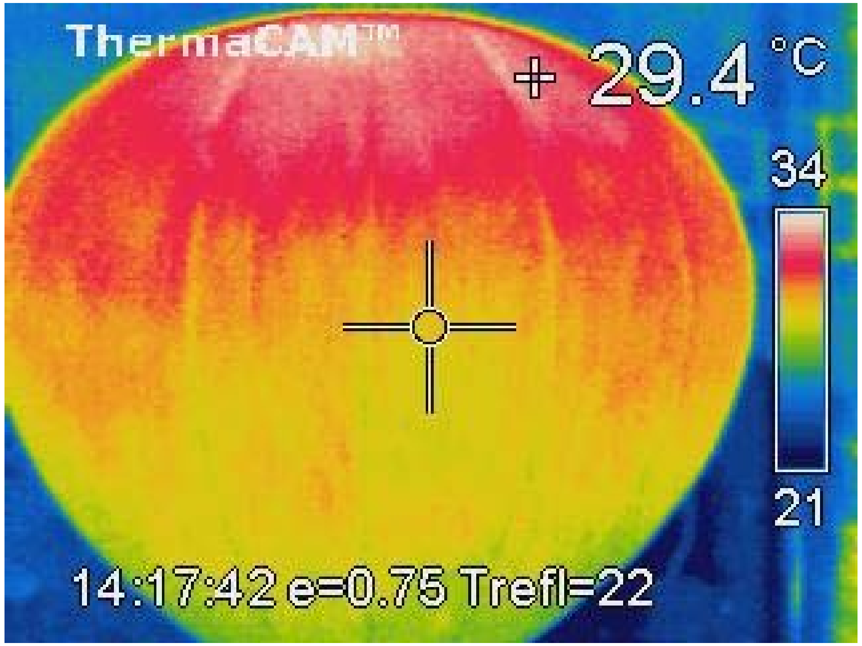
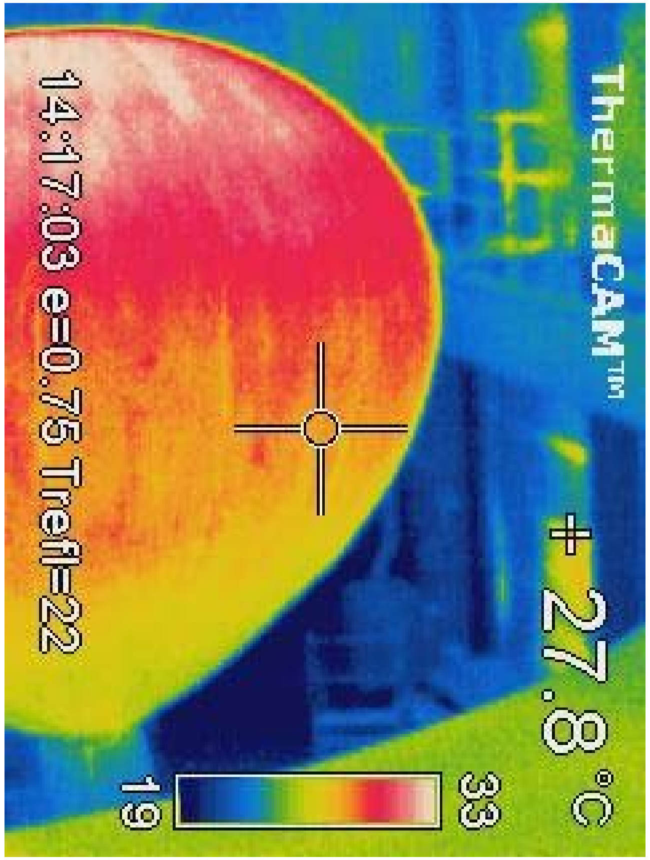
Infrared Images (Configuration 2)





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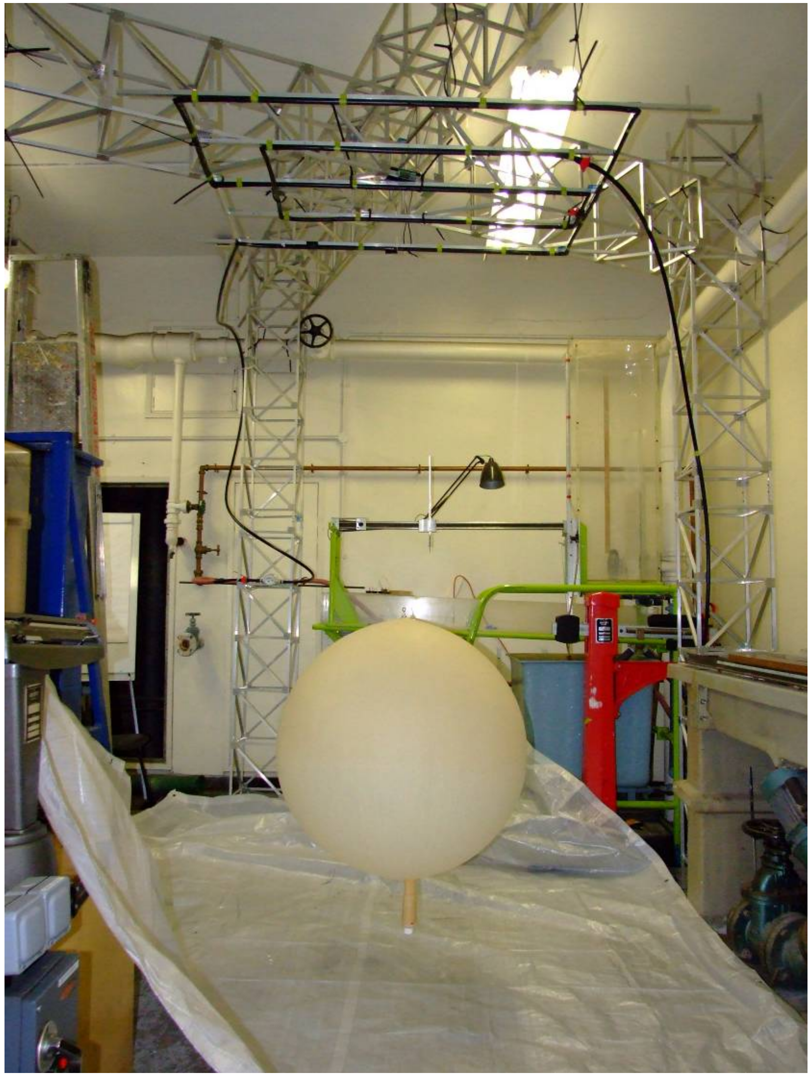
Deductions from Buoyancy Experiment

- Internal free convective heat transfer about 1/3 of that Samanta et al. (2010), but not as low as predicted using correlation of Niemela et al. (2000)
- Radiation losses can be estimated, but results still dependent on confirmation of envelope emissivity
- Past correlations used for external free convective heat transfer doubtful, since wall temperature is non-uniform (also internal and external convection processes are coupled)
- Accepting model deficiencies, extrapolation to Titan conditions (8 km altitude) predicts that a 17 m diameter single-wall envelope would lift 200 kg

Buoyancy Margin

- Required to overcome downdrafts
- To counter heaviness caused by precipitation

Water drizzle experiment



Flow pattern
(thin sheet with transition to trickle flow)

Preliminary Model

Dimensional analysis used to estimate accumulation mass

$$m_L = \dot{m}_A r^2 \left(\frac{\mu_L}{\rho_L g^2} \right)^{1/3} f(N)$$

$$N = \frac{\dot{m}_A}{\rho_L \mu_L g}$$

And from experiment $f(N) \cong 161 N^{-0.244}$

Extrapolation to Titan Storm Conditions

At 0.008 $kgm^{-2}s^{-1}$ (Barth and Rafkin, 2007)

(~7cm / hr ; ~1/ century storm, depending on location)

0.25 mm methane film accumulates on 17 m dia. balloon,

i.e. an accumulated mass of 50 kg

Downdraft -3 m/s downdraft (Barth and Rafkin, 2007)

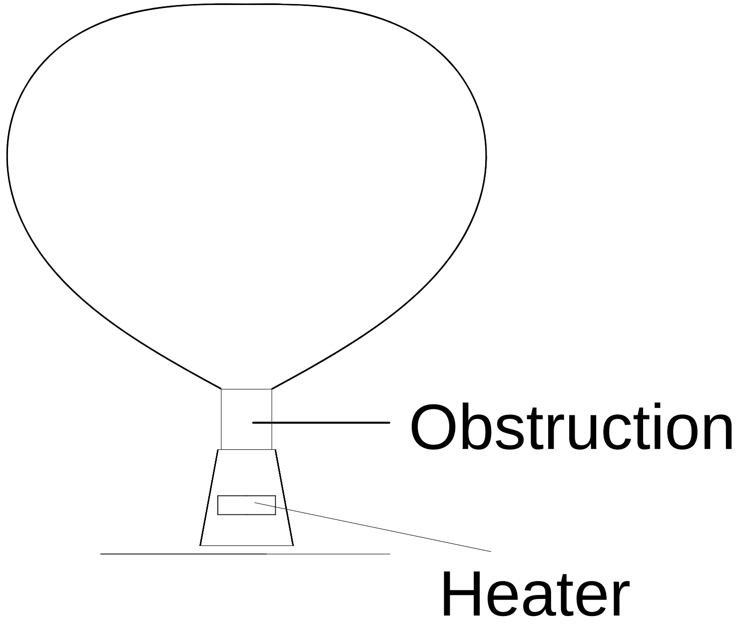
Total down force cannot be countered

Implies Titan Montgolfière needs to avoid polar summer storms

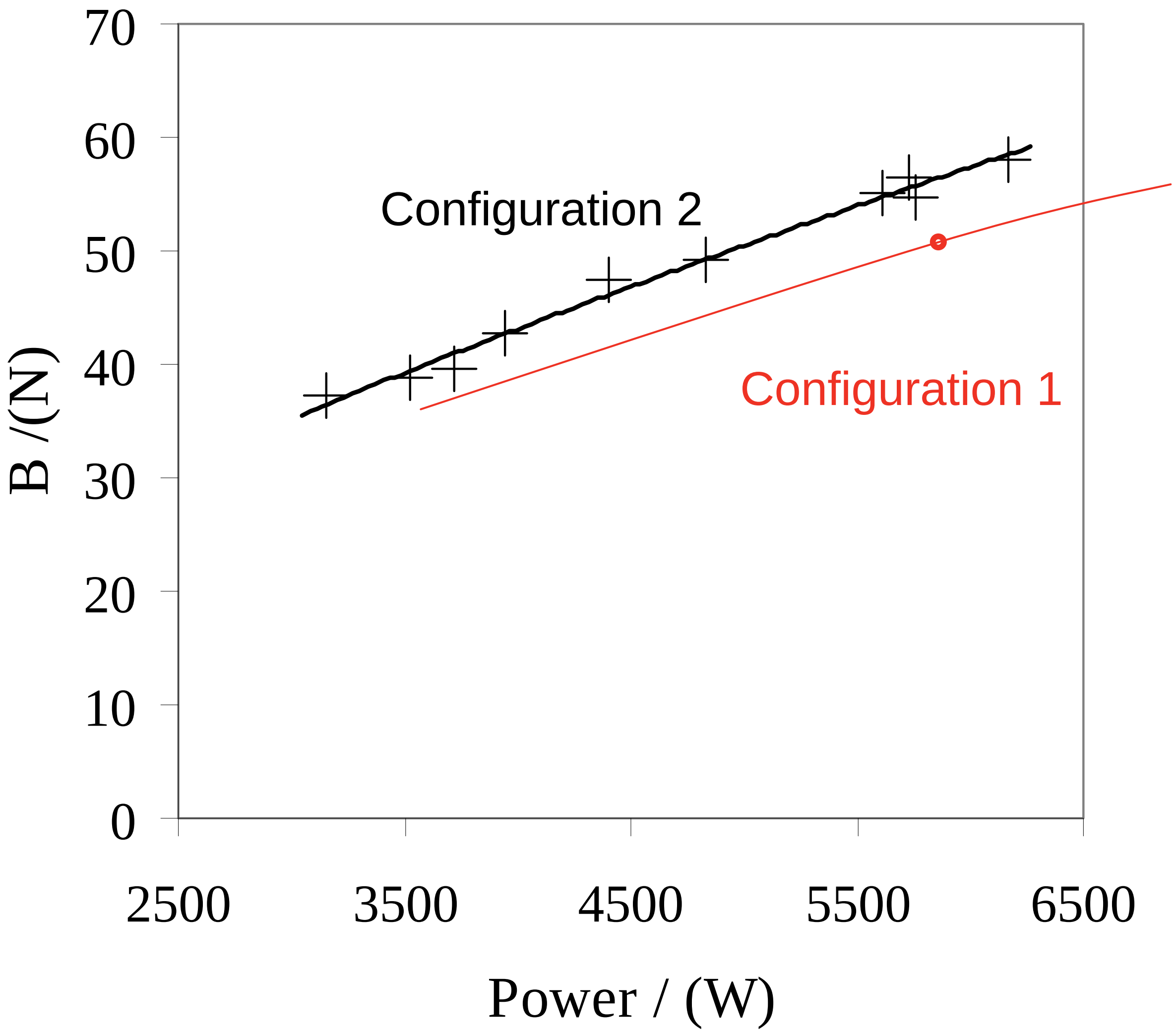
Experiment (Configuration 1)

Buoyancy modulation possible by diverting neck flow

Crown valve not needed



Measured buoyancy vs. power input



Concluding remarks

- University-based amenable experiments
- More buoyancy tests needed (by others)
- Verification of drizzle model needed
- Our experiments represent just a small step towards providing quantitative foundation to support realistic design efforts

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