**ARCHIMEDES' ENGINE: BUOYANT UNSPOOLING GENERATOR FOR PLANETARY MISSION POWER APPLICATIONS.**

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**Introduction:** The need for long term (days to months) power (one to several watts) for planetary missions where solar power is difficult and other alternative power sources are expensive, risky, or complex is a challenge for missions to targets such as the surfaces of Venus and Titan [1,2,3]. We propose a new, yet very old, technology that does not require radioactive materials, high capacity batteries, or other fuels, and does not rely on incompletely understood, possibly stochastic processes like surface or near-surface winds. Surface pressure on Venus and Titan (and other planets with atmospheres, and at the bottom of lakes and oceans) is relatively constant, with well-characterized lapse rates. For environments with gas or fluid mediums, we can take advantage of the upward force of buoyancy to drive a mechanical generator to power a variety of long-term missions.

**Buoyant Power:** This method uses the buoyant force of a balloon (in an atmosphere) or float (in a liquid such as an ocean) to unspool a cord attached to a generator to provide electrical power. The primary uses for this power system are planetary surface probes on planets with atmospheres, and deep lake/ocean environments where solar power is difficult and battery or radioisotope sources are challenging.

Figure 1 shows a conceptual system block diagram. A buoyancy device provides an upward force $F_b$, which is transferred to a drum, rod, or spool by the cord attached to the buoyancy device. The drum rotates slowly, and is mechanically stepped to an alternator/generator. The generator feeds through a boost regulator to the equipment and/or a battery/capacitor storage or modulating system, possible with voltage control.

The system is similar to a ripcord-type generator, with the addition of using buoyancy for the pulling force. The system is a low-mass, low-risk, and simple power source for places where conventional power is unavailable or challenging. This basic design offers other advantages over traditional power sources. The system can be idle indefinitely without losing stored energy. The balloon rise speed can be adjusted in real time by controlling the electrical load on the generator, thus allowing for higher power when tasks require it and saving energy during idle periods. It can be used to generate short bursts of power much greater than RTGs or batteries can provide, for intermittent tasks such as transmission.

**Application to Planetary Scenarios:** To understand the amount of energy available from this technique, a very simple calculation suffices. The buoyant force is $F_b$:

$$F_b = (\rho_o - \rho_b)Vg \qquad (1)$$

where $\rho_b$ is the density of the gas filling the balloon, $\rho_o$ is the density of the surrounding atmosphere or fluid, $V$ is the balloon volume, and g is the local acceleration due to gravity.

The total energy available from the balloon is $F_b$ integrated over the rise of the balloon. For a first order energy estimate in various atmospheres (Table 1), we assume a 100-$m^3$ balloon (5.8 m diameter), 1 km rise, and a negligible change in atmospheric density and pressure over that 1 km. For the case of undersea generation on Earth, we assume a start at 4 km depth with a rise of 1 km, constant seawater density and temperature, and linearly decreasing pressure. For the undersea case, 100 $m^3$ is the initial balloon volume; the balloon expands as it rises. In all of these applications, the mass of the balloon itself and the cord that connects it to the lander are small compared to the buoyant force. For the examples in Table 1, 1 km of a modern high-performance cord of appropriate tensile strength will weigh about 1% of the buoyant force.

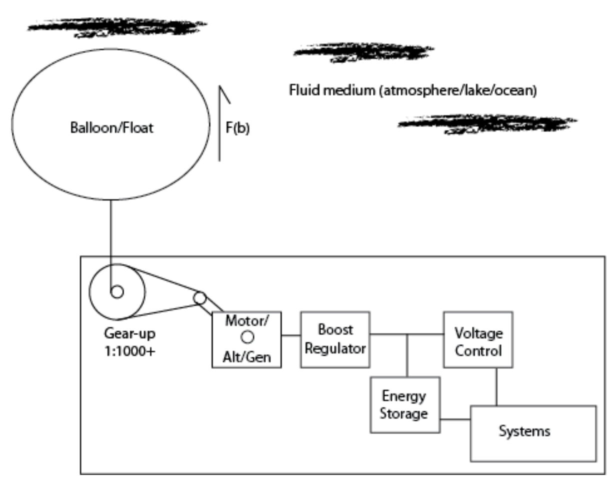


Figure 1. Schematic of buoyant unspooling power system.

Table 1 shows that the technique is viable in locations with reasonably dense atmospheres, and of little utility in sparse atmospheres like Mars. The last column shows reasonable mission durations in time units relevant to planetary scientific missions. It is important to note that energy scales linearly with balloon volume, but balloon diameter scales as a 1/3 power of volume. Thus, to increase the Table 1 durations (or average power) by a factor of 10 requires a balloon of diameter 12.4 m, which is still reasonable. Also, the 1 km rise is arbitrary. For Venus and Titan, 5-10 km of balloon rise could likely be used without risk of damaging winds or other atmospheric challenges.

| | Atmospheric Density (kg/m$^3$) | Energy (kJ) / (kWh) | Mission duration @ 1 W avg. power consumption |
|---|---|---|---|
| Earth | 1.2 | 1100 / 0.30 | 13 Earth days |
| Earth - undersea | 1058 | 1.2 x $10^9$ / 321 | 37 Earth years |
| Venus | 65 | 55000 / 15 | 2.8 Venus years |
| Titan | 5.7 | 720 / 0.20 | 0.52 orbits of Saturn (8.3 Earth Days) |
| Mars | 0.02 | 4.7 / 1.3 x $10^{-3}$ | 1.3 hours |

Table 1. Energy available from example buoyant power source in several planetary scenarios.

The main technical challenge in implementing this approach is the high reverse gear ratio required. For the Venus mission of Table 1 generating a constant 1 W, the rate of rise of the balloon is 1.8 x $10^{-5}$ m/s, which must be geared up by a very large factor (>1:50000) to drive a conventional generator at a reasonable rate. A purpose-built generator, with of order 100 poles and designed to turn very slowly, could reduce the gearing required by up to two orders of magnitude.

Another approach would be to operate the generator a small fraction of the time, perhaps 0.1%-1%, with a more rapid rise rate, and store the energy for a short period of time. This reduces by orders of magnitude the gear ratio required, at a cost of requiring short-term energy storage in the form of supercapacitors or batteries. There is a large engineering trade space to be explored in order to optimize these parameters for maximum power efficiency and minimum system mass. However, from commercial off the shelf components, we have built a proof-of-principle system that converts mechanical to electrical energy at 25% efficiency while providing 10 mW of power (unspooling at 8.5 x $10^{-4}$ m/s under a force of 254 N).

**Example Scenarios:** With power availability as described in Table 1, low power instrumentation (e.g. weather stations, gas sensors, seismic sensors), and power control to allow occasional transmission to relay data, long lived planetary surface probes may be enabled.

For a Venus landed probe [2], buoyant power competes very favorably with radioisotope power generation [2,3,4] and high temperature batteries [1] for long duration (months- to year-long) missions.

For a Titan surface and/or lake probe [6, 7] the energy return, and thus mission duration, are lower, but still potentially viable (and potentially a locomotion source as well for a lake probe).

Sluggish surface winds (~1 m/s or less) on both Venus [8] and Titan [9] should not pose risks to balloon deployment. The system will operate in much higher wind speeds; for the Earth and Venus atmospheres, the balloon will fly at approximately 45 degrees away from straight up in wind speeds of 11 m/s, and on Titan in a wind speed of 4.4 m/s.

**Conclusion:** Buoyant unspooling power provides the potential for a low complexity, lower cost, and possibly lower overall risk "clockwork planetary probe" for long sojourns on solar system targets with dense atmospheres. An "Archimedes engine" could apply 3rd century (BCE) physics and 19th century technology to solve problems in 21st century exploration applications.

**References:** [1] E. Kolawa et al. (2007) *JPL Pub. D-32832.* [2] G.A. Landis & K.C. Mellott (2007) *Acta Astronomica* 61, 995-1001. [3] J.R. Greer et al. (2011) *Keck Titan Wkshp Study Rept.* http://www.kiss.caltech.edu/study/titan/report.pdf. [4] R.W. Dyson & G.A. Bruder (2011) NASA TM-2011-217018. [5] A. Yavrouian et al. (1995) *11th LTAT Conf.* [6] Stofan et al. (2010) *41st LPS* #1236. [7] O. Urdampilleta et al.(2012) *2012 EPSC*, Vol. 7 EPSC2012-64. [8] R. Greely et al. (1992) *JGR* 97 E8 13319-13345. [9] M.K. Bird et al. (2005) *Nature* 436 800-802.