Electronic Survival Past The Lunar Night

An Analysis

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April 20, 2021

Abstract

This work outlines a electronics chamber concept designed to allow electronics to survive the Lunar night. The harsh thermal environment of the Lunar surface has long been known to be the most significant issue for the design and operation of extended period Lunar experiments and stations. The Lunar surface provides two separate thermal extremes which are during the Lunar day and Lunar night. in the following we address a solution for maintaining the temperature of electronics at 23 °C for the entirety of the Lunar night by using lithium ion 18650 batteries and a vacuum insulated thermal enclosure. We discuss how the design scales to the needs of the electronics as well as the possible implementation of the concept to a human habitat at the lunar surface.

1 Introduction

1.1 Motivation

With recent motivation from NASA and other space agencies, an increased interest has begun once again at the prospect of human occupation of the Lunar surface. Meeting that goal however comes with many new found challenges. One such immense challenge is known as the Lunar night problem. At the Lunar surface during the day, temperatures have been known to reach near 127 °C and near −173 °C during the Lunar night. Each of these periods lasts 14 Earth days, which poses a significant thermal challenge for any systems with limited temperature range.

During the Lunar night period when temperatures drop to a low of −127 °C, electronics and batteries will cease to function and whilst the Sun is out of view photovoltaics will also not function. To maintain the electronics during this night period a solution must be capable of maintaining the temperature of the electronics to within operation. Typical solutions for generating heat during the Lunar night are to use radio isotope thermal generators (RTG); However, this is both a costly and controversial solution.

We discuss how the design scales to the needs of the electronics as well as the possible implementation of the concept to a human habitat at the lunar surface.

1.2 Lunar Environment

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1.3 Past designs for surviving the Lunar night

Early attempts to survive the lunar night came from NASA's Surveyor program (1966-1968), the precursor to Apollo missions. Five Surveyor probes gathered lunar data which was then sent to Earth; during lunar night these probes stopped transmitting information. Following lunar night conditions, two probes could be revived and continued transmitting information; no probe survived beyond the second lunar night(11). In order to withstand the harsh temperatures, these probes were outfitted with two thermal insulating chambers kept at temperatures between $-20\,^{\circ}\mathrm{C}$ and $50\,^{\circ}\mathrm{C}$. Chambers were equipped with electric heaters, thermally insulating blankets, conductive heat paths, and thermal switches(9).

Further attempts to +survive lunar night conditions came from Lunokhod 1 and 2 which used polonium-210 radioactive heaters](8) (7). These radioactive heater units (RHUs) are similar in function to RTGs, though they are more focused on heating electronics to survive harsh lunar night conditions(10). Following the Lunokhod missions, RTGs were also used to provide heat so electronics could survive the lunar night. 70 Watt Plutonium-238 RTGs were incorporated as part of the Apollo Lunar Surface Experiment Packages (ASLEPs) from Apollo missions 12, 14, 15, 16, and 17. This enabled the ASLEPs to operate until intentional shutdown in 1977(11).

More recently, the China National Space Administration (CNSA) has launched Change'e 3 (2013) and Change'e 4 (2019) which include rovers Yutu-1 and Yutu-2, respectively. Both of these use Plutonium-238 RHUs to cope with the severe temperatures(1)(11). Both survived lunar night conditions; Yutu-1 lost mobility after a month but took data for several years(5) and Yutu-2 continues to take data and rove about the lunar surface(6).

We propose creating a thermal enclosure which can be attached to small-scale lunar craft and does not require radioactive isotopes to function. This solution will allow electronics on these rovers to stay warm and therefore survive the lunar night without using nuclear power. This thermal enclosure will consist of a warm electronics chamber (WEC) and a larger vacuum chamber which surrounds the WEC. During lunar night conditions with temperatures reaching $-173\,^{\circ}\mathrm{C}$, the WEC will keep the electronics warm at $23\,^{\circ}\mathrm{C}$, allowing them to resume normal activity following this period. As a result, this will allow lunar spacecraft to extend their operational lifetimes and sustain exploration longer than two months.

2 Lunar night survival chamber

2.1 Vacuum insulation

Vacuum insulation is an ideal method for maintaining temperature on the Moon. This is true because of the natural hard vacuum present on the moon. The hard vacuum present at the Lunar surface is of an order of magnitude greater than that present inside the vacuum tubes of the Large Hadron Collider (3). Beyond the easy access to hard vacuum at the Lunar surface, vacuum insulation provides the mitigation of conduction heat transfer from a warm object to a cold object. instead the conduction heat transfer can be mitigated to travel only along the support beams of a vacuum chamber. Moreover, the only other method of heat loss with vacuum insulation is through black body radiation. A significant magnitude of any black body radiation heat loss can be removed by use of multi layer insulation (MLI). By placing MLI around the entire surface of an electronics chamber, a large portion of photon radiation can be redirected back to the electronics chamber. Detailed work of these topics is covered in the following sections.

2.2 Electronics Chamber

The electronics chamber consists of (ADD STUFF)! A more precisely detailed explanation of how the electronics will function in the thermal insulation unit will be outlined in the experimental paper following our study.

====After discussing of the chamber we talk in the following sections about grey body radiation and of heat conduction transfer =====

2.3 Heat Loss Through Multi-layer Insulation

Due to the presence of hard vacuum and large temperature differences between the warm electronics ($\Delta T = 196K$) and the cold vacuum outside the chamber, we are in the position to take full advantage of the Lockhead Martin equation 1 which calculates the heat loss through MLI made of mylar and silk nets. As discussed by Ross **??**, the Lockheed equation takes into account heat loss through blackbody radiation(q_r) and conduction(q_r) per m^2 to calculate the total heat loss (q) per m^2 though the MLI.

$$q = q_c + q_r = \frac{C_c N^{2.56} T_m}{n}(T_h - T_c) + \frac{C_r \epsilon_o}{n}(T_h^{4.67} - T_c^{4.67}) \tag{1}$$

The first part of the equation, q_c, comes from the heat lost per m^2 due to the conductance through the mylar layers. Assuming the temperature difference between the hot and cold side is divided equally among the layers of the MLI **??** which gives,

$$q_c = k_c \Delta T / n$$

where k$_c$ is the conductance constant of an MLI spacer layer. This was found to be

$$k_c = C_c N^{2.56} T_m$$

q_r comes from the heat lost due to blackbody radiation. Materials that are not perfect blackbodies have a characteristic emissivity ϵ which is found in the Stefan-Boltzman Law

$$j = \epsilon \sigma T^4$$

for ϵ=1. This is why q_r is approximately proportional to the difference of the hot and cold side temperatures to the fourth power.

The constant C_c is the conduction constant through the MLI and is $8.95x10^{-5}$. C_r is the radiation constant and is $5.39x10^{-7}$. ϵ_o is 0.031 and is the MLI shield-layer emissivity.

In our model, the hot side of the MLI is T_h = 296 K and the cold side is T_c = 100 K. This gives a T_m = 198 K which is the mean MLI temperature. The layer density(N) is calculated by dividing the number of layers(n) by the space between the inner chamber and outer chamber which is 3.81 cm. When these values are plugged in, an optimal number of layers can be solved for after multiplying the Lockheed equation by the surface area of the inner chamber(A = 0.017 m^2) to get an equation of heat loss as a function of the number of layers2.

$$Q(n) = qA = \frac{0.017}{n}[(3.37)(\frac{n}{3.81})^{2.56} + 5769] \tag{2}$$

A graph of the expected heat loss as a function of layers can be seen in fig. 1. With n = 10 layers of MLI, the heat loss is in the mW range with a value of 9.61 mW.

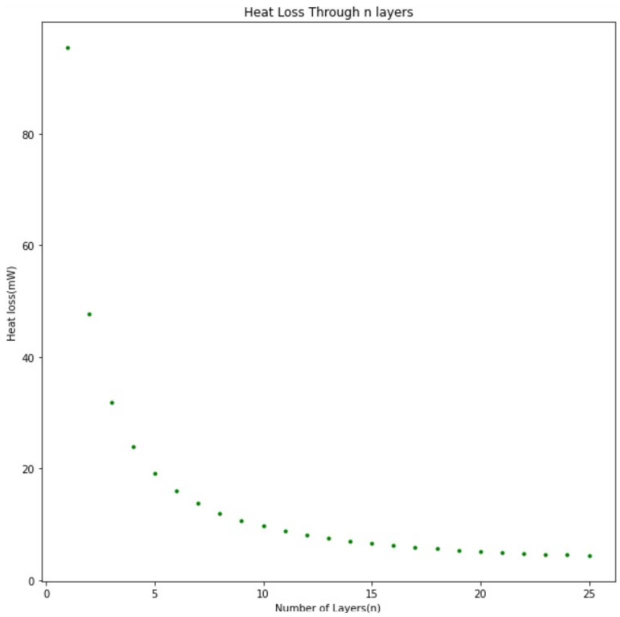

Figure 1: The Lockheed equation is used to model the amount of heat loss expected from the inner chamber as function of the number of layers.

2.4 Heat Loss Through Stainless Steel Pipe

Another source of heat loss from the inner chamber is the 304 stainless steel pipe that is used as a support for the inner chamber and as housing for the serial communication wire that is used to monitor the electronics.

Through thermal conductivity, the stainless steel support will leak heat(P) according to the equation:

$$P = \frac{A}{L}\int_{T_1}^{T_2} k(T)dT \tag{3}$$

The cross sectional area of the support beam is defined as A, and L defines the length. k(T) is the thermal conductivity as a function of temperature. An equation used to fit k(T) takes the form

$$k(T) = 10^{a+b(log_{10}T)+c(log_{10}T)^2+d(log_{10}T)^3+e(log_{10}T)^4+f(log_{10}T)^5+g(log_{10}T)^6+h(log_{10}T)^7+i(log_{10}T)^8} \tag{4}$$

Experimentally, the values that fit 304 stainless steel are shown in figure 2.

Solving for equation 4 involves integrating k(T) from T_1 = 296K to T_2 = 100K. The visual interpretation of the integral can be seen in figure 3. The value obtained is -2445.78 Watts/meter. The support beam's characteristics must be chosen to produce power loss in the milli-Watt range in order for the electronics not to fail.

For the support in this model, the diameter(d) is 2 millimeters, the thickness(t) is 100 micrometers, and the length(l) is 43 cm. The cross sectional area of the support is calculated using

$$A = \pi dt$$

which gives a cross-sectional area of 6.28 x 10^{-7} m^2. Plugging these values into equation 3 gives a power loss value of 3.57 mW.

	Thermal Conductivity	Specific Heat
UNITS	W/(m-K)	J/(kg-K)
a	-1.4087	22.0061
b	1.3982	-127.5528
c	0.2543	303.647
d	-0.6260	-381.0098
e	0.2334	274.0328
f	0.4256	-112.9212
g	-0.4658	24.7593
h	0.1650	-2.239153
i	-0.0199	0
data range	4-300	4-300
equation range	1-300	4-300
curve fit % error relative to data	2	5

Figure 2: Values found by National Institute of Standards to fit equation 4 for 304 stainless steel.

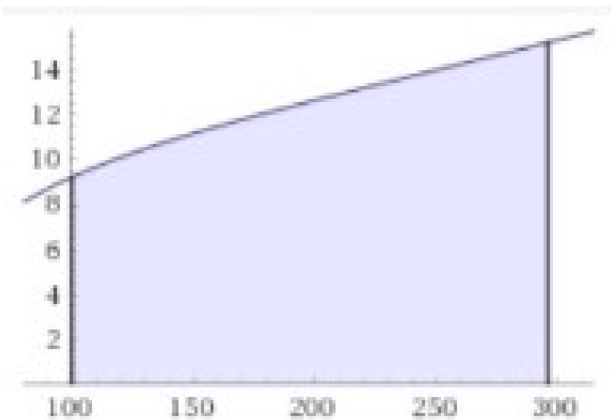

Figure 3: The area under the curve represents the value of integrating k(T) for 304 stainless steel.

3 Electronics

4 Housing

4.1 Measurements

The thermal insulation chamber is designed with both an inner and outer cylinder which are separated by a vacuum. Both cylinders have a length which is significantly larger than the cylinder wall width; this was used in order to perform calculations to determine the minimum safe wall thickness. The outer cylinder experiences an exterior pressure from atmospheric conditions and an interior vacuum condition and is therefore more likely to implode due to buckling. In order to calculate the minimum wall thickness required the Windenburg and Trilling's buckling pressure equation(**?**) was used

$$P_{cr} = \frac{2.42E\frac{t}{2a}^{2.5}}{(1-\nu)^2(\frac{l}{2a} - 0.447\frac{t}{2a}^{0.5})}$$

where E stands for Young's Modulus for the material, t is the cylinder wall thickness, a is the cylinder radius, ν is Poisson's ratio for the material, and l is the length of the cylinder. Given the values $E = 97\,\text{GPa}$, $P_{cr} = 0.101\,\text{MPa}$, $\nu = 0.31$, $l = 254\,\text{mm}$, and a=30 mm for 272 brass alloy, the minimum thickness, t, for the cylinder is 0.294 mm. In contrast, the inner cylinder will experience an explosion case as the inside of the cylinder has a higher pressure than the outside. Following design conditions, the inside is pressurized with one atmosphere and the outside experiences vacuum conditions. Therefore, the minimum wall thickness required is calculated by using the hoop stress equation(**?**),

$$\sigma_y = \frac{PR}{t}$$

where σ_y stands for the yield stress, P stands for the interior pressure, R stands for the radius, and t represents the thickness. For 272 brass alloy, σ_y=410 MPa, P=0.101 MPa, and R=12.25 mm, resulting in a minimum wall thickness of 3.02 µm.

4.2 Design

The experimental design of WEC is made from piping for ease of fabrication and labratory testing in the cryogenic dewar. Both the inner and outer chambers are to consist of 272 brass alloy—chosen for its low thermal conductivity in order to maintain a proper temperature of approximately 25 °C for electronics housed in the inner chamber. The inner chamber is composed of a 6 inches long tube with an outer diameter of 1.25 inches and an inner diameter of 0.995 inches (wall thickness of 0.1275 inches), designed to maintain an internal pressure of approximately 1 atm. Brass caps with diameter 1.75 inches and length of 0.5 inches will enclose the pipe to support the the main body of the inner chamber. An end cap will be welded onto he bottom end of the tube while the top end will be fabricated to be bolted with an indium O-ring (chosen for its malleability and use in cryogenic applications) to further seal the chamber. The outer chamber is composed of a 12 inches long brass tube, with outer diameter of 3 inches and inner diameter of 2.75 inches (wall thickness of 0.125 inches). Similarly to the inner chamber, brass caps with diameter of 3.5 inches and length of 0.6 inches will enclose the outer pipe to support the internal vacuum to replicate the relevant environment. Between the two chambers, multiple layers of aluminized mylar sheets surround the outer surface of the inner chamber in order to provide additional insulation in conjunction with the vacuum established between the two chambers to minimize heat flow. In addition, the top caps for both chambers will have a 2 mm hole drilled directly in the center in order to support a connecting tube.

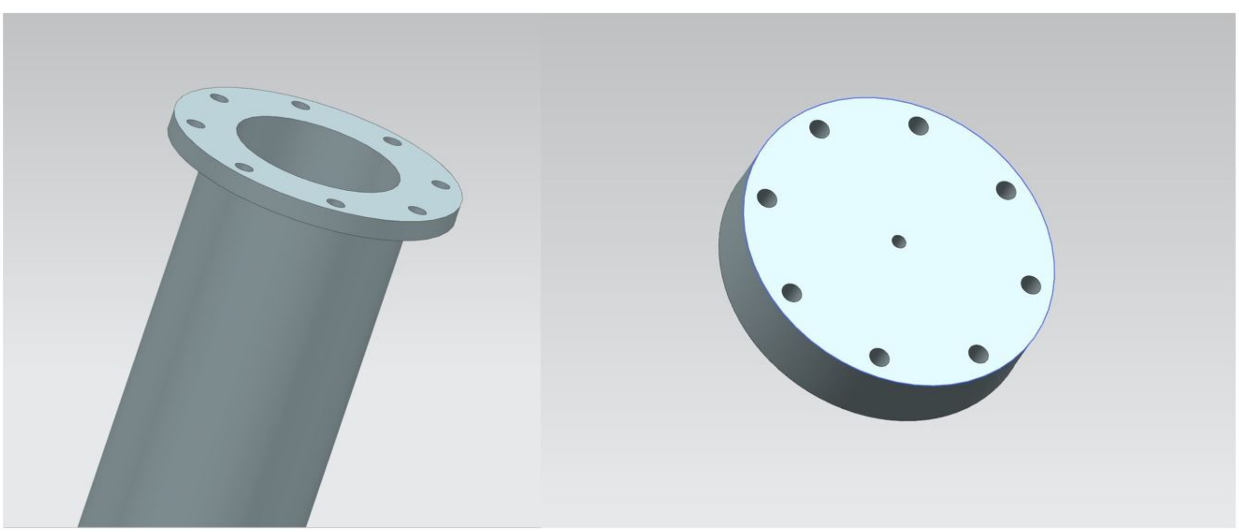

Figure 4: Closeup view of the inner chamber and its weldable end cap.

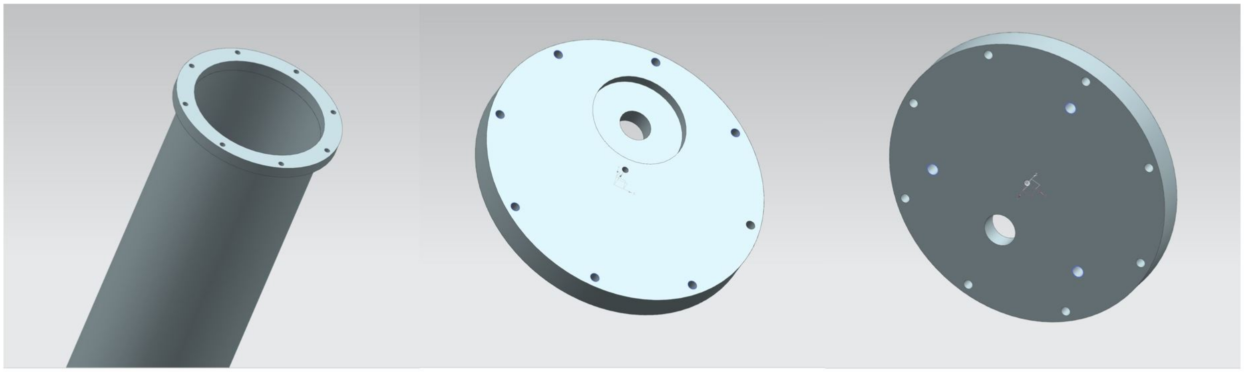

Figure 5: Outer chamber, and its lid (top and bottom respectively).

Together, the inner chamber is suspended in the center of the outer chamber, connected by a 2 mm diameter, 4 inch long stainless steel tube to relay wires into and out of the inner chamber. Three eye tab bolts will be secured to both lids of both chambers to provide additional support to the 2 mm stainless steel pipe holding the wires. These bolts will screw into the top of the inner chamber lid and the bottom of the outer chamber lid. Then, Kevlar thread will be woven through the tabs on the inner and outer chambers to fully support the wiring tube from crimping or buckling. The outer chamber cap, in addition, supports an additional imprint to fit the vacuum bellows hose. This enables the vacuum environment to remain between the two chambers to reflect conditions in the relevant lunar environment. Due to the pressure differential between the two chambers, a finite element analysis was completed to ensure the structural integrity of the tubes would not be affected. The results are shown below.

5 Conclusions

6 Acknowledgements

The authors would like to thank Dr. Philip Lubin for his continued support and advice in this project. Furthermore, they are grateful to technical advice from Mr. Nicholas Rupert. The team would also like to thank Mr. Alexander Cohen for his advice on content and formatting of this paper.

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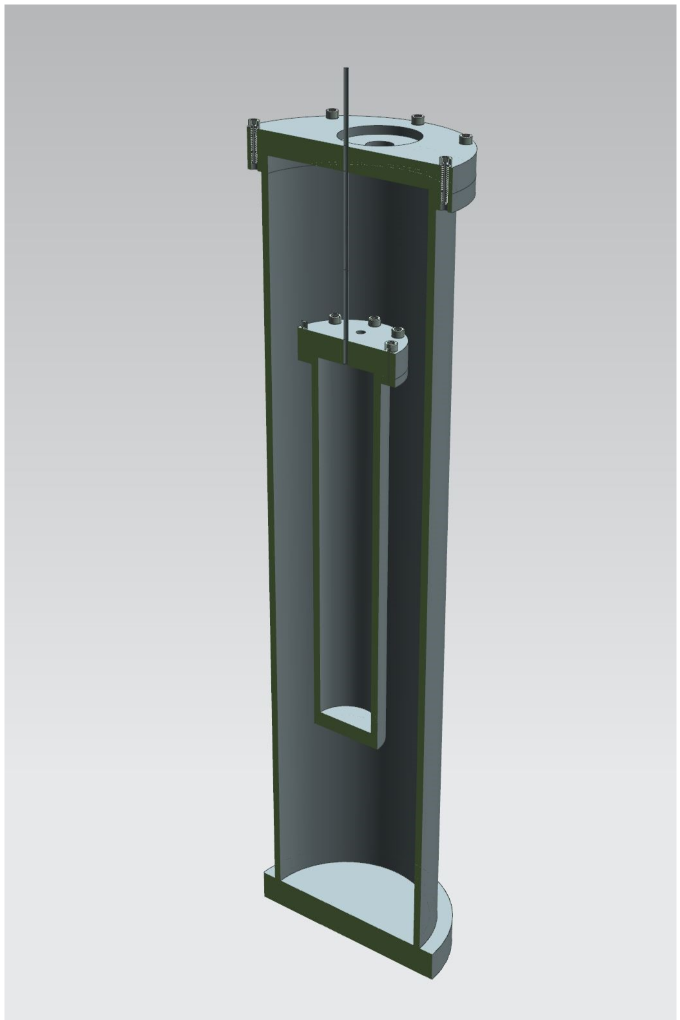

Figure 6: Cutaway view of both chambers.

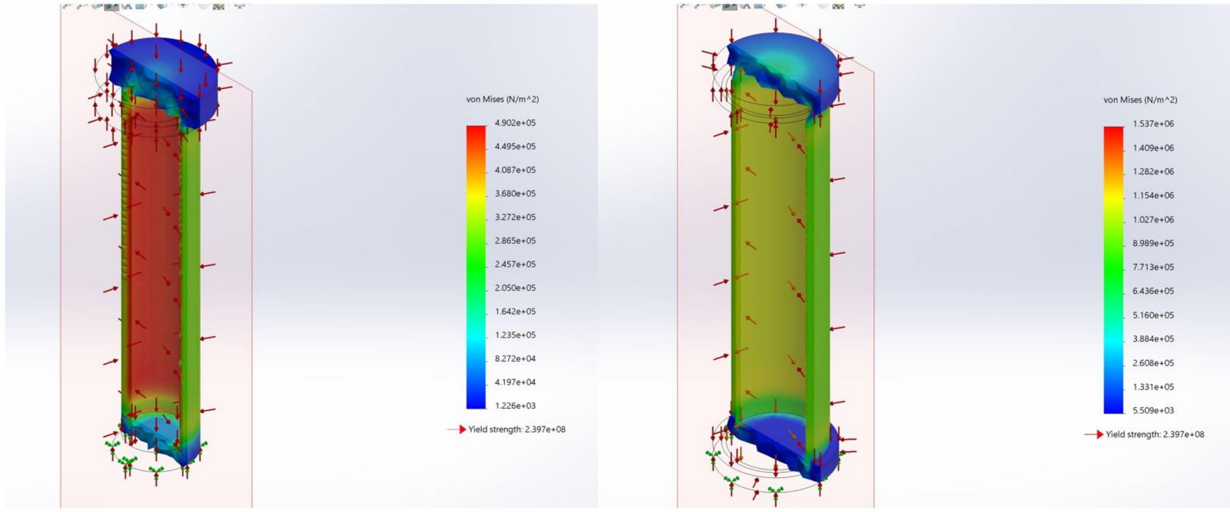

Figure 7: Stress on the inner and outer chamber (respectively). The inner chamber has an external pressure of 10^{-15} Pa (vacuum) and internal pressure of 101,325 Pa (1 atm). The outer chamber has an external pressure of 101,325 Pa (1 atm) and internal pressure of 10^{-15} Pa (vacuum). As seen in the graph, no spots in the simulation exceed the yield strength, meaning there will be negligible deformation.

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