Cryogenic ISRU Robot Survival in Lunar Permanently Shadowed Regions. C. Purrington[1] and K. Fergusen[1], [1]Colorado School of Mines, Center for Space Resources GRL 234 A, Golden, CO 80401, cpurrington @mymail.mines.edu

Introduction: Lunar Permanently Shadowed Region (PSR's) contain valuable resources vital to space exploration for future launch vehicles. However, PSR temperatures range from 25 K to 45 K, rover engineers and operators need additional thermal models to execute successful thermal management strategies to survive in a thermally harsh environment.

Literature Review: Specific papers addressing thermal survival of rovers in a Lunar PSR, currently do not exist. However, survival techniques to survive a Lunar night, have been explored extensively in [1],[2]. These papers outline the thermal conductivity of lunar regolith at the surface, 0.00115 W/m-K and as function of depth to 2 m, at only 0.225 w/m-K. Thermally conductivity this low, acts as a thermal barrier and we don't expect to lose significant thermal energy through the regolith. These papers assume an equatorial landing, not one in the water rich PSR's. The PSR's are believed to be 5% water content, [3], which dramatically changes the thermal conductivity. Reviewing permafrost thermal conductivity with similar water weight percentage provides a thermal conductivity of 3.04 W/m-K, [4]. Although, false, this provides an estimate for thermal properties of regolith with 5% water weight. An analyses on both regolith conditions will be accomplished in this model.

Concerns that ice in the regolith would sublimate as heat is transferred from the wheel, forced us to review cryogenic sublimation rates. Sublimation could impact thermal conductivity and possibly add a convection heat loss. However, according to [5], a 4 ng sample of ice heated to 150 K, showed neglible signs of submilimation after two hours. For this reason we'll assume a constant thermal conductivity with icy regolith, unless our regolith approaches the vapor barrier of 273 K.

The environmental conditions within a PSR have been studied primarily with remote sensing. The PSR regolith temperature ranges from 45 K to 25 K, [6]. This model will presume a worst case condition of 25 K. While radiation loss to space will assume a background temperature of 2.74 K, [7], which we expect our greatest heat loss.

Each material of the wheel has a specific emissivity. However, due to the natural locomotion mechanisms of lunar dust and due to a theoretical local mining operation, it is assumed lunar dust will coat almost all surfaces, [8]. Correcting the emissivity of surfaces to the emissivity of Lunar dust to 0.41 [9]. We will assume the outer surface of the wheel to have an emissivity of 0.41 to account for this effect.

Assumptions: To simplify our problem we'll focus on an external rover wheel as shown in figure 1. The source of heat to the wheel motor is out of the scope of our project, so we will simply assume the motor has an arbitrary heat source, and then quantify, *how much* heat must be supplied to the wheel motor rather than *how* it is supplied to the wheel. We'll also assume no heat is lost through the chassis and heat is only transferred from the wheel, out to the environment. We'll assume no radiation heat is transferred within the interior of the wheel.

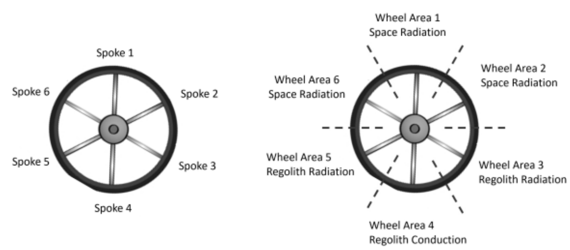

Figure 1: Wheel Diagram

Equipment Limitations. We are basing our rover wheel on the Mars Science Laboratory (MSL) Curiosity, martian rover, we are also using the same equipment limitations. Nominal operating temperatures sits at 273 K, components are allowed to operate without degradation to temperatures at 233 K, otherwise known as the Operational Limit. If component temperatures continue to drop below 233 K, the components will need to be warmed before operation, but if the temperature falls below 213 K, the component has suffered to much thermal damage and is considered lost.

Modeling Approach: Our modeling approach is an analytic analysis of the motor, wheel spokes, rover wheel and nearby regolith. By dividing the wheel components up into a multiple bodies, we can apply assumptions to each body and then combine the components for a final model. We'll separate the wheel structure into multiple components as shown in figure 1.

By applying an energy balance to the motor we work our way out to the surrounding components. As can be seen in equation 1, we have heat loss through the spokes and heat generated from a localized heat source in the motor. The motor is treated with the Lumped Thermal Capacitance method.

$$E_{storage} = -E_{Spoke1} - E_{Spoke2} - E_{Spoke3} - E_{Spoke4} - E_{Spoke5} - E_{Spoke6} + E_{HeatGeneration} \quad (1)$$

$$mc\frac{dT}{dt} = -kA_{spoke}(T_m - T_{A1} + T_m - T_{A2} + T_m - T_{A3} + T_m - T_{A4} + T_m - T_{A5} + T_m - T_{A6}) + q_{Generated} \quad (2)$$

Each area of the wheel undergoes different heat loss paramaters. As can be seen in figure 1 areas 1, 2, and 6 experience heat loss via radiation with space. Areas 3 and 5 experience radiation heat loss to surrounding regolith. Finally area 4 experiences no radiation heat loss, but instead conducts heat loss to the regolith. Applying an energy balance to each area we form the following equations.

As time permits and the model develops, more and more complexity will be incorporated into the model. For example, physical properties will depend on temperature, and individual components will be modeled to take into account their geometry rather than a lumped body. Numerical methods such as 'ode45' and 'ode15i' will be used to help perform integration forward through time, so that part temperatures can be tracked in a transient manner.

Preliminary results: Based off preliminary results (0D, transient, multi-body problem) and utilizing data from our literature review, we expect a rover motor to remain operation for 45 minutes with no heat source before exceeding the operational threshold. Furthermore, the survivability limit of -60 C is reached in only 15 additional minutes, as can be seen in figure 2. This does not allow a lot of time to recover a rover-gone-awry if there is a thermal system failure. An exploration of ways to increase the survivability of the rover drive wheel motor will be investigated through parametric studies.

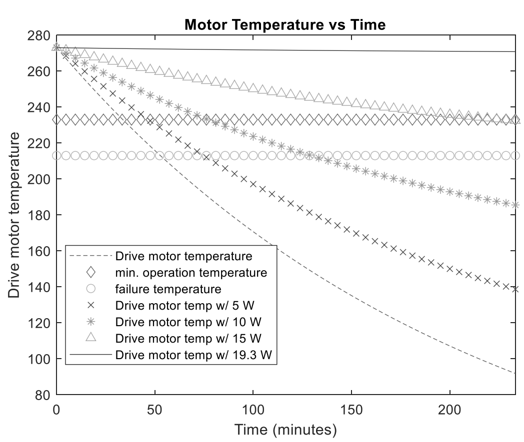

Figure 2: Preliminary Results

For normal operation, refering to figure 2, a constant heat source of 19.3 watts predicted to maintain a nominal operation temperature of 0 C. If a known 'down time' is scheduled, say 2 hours, less energy could be used to maintain the operational temperature, shown in figure 2, 10 watts could extend the survival temperature to 2 hours. Once, a rover begins to move, thermal heat generated from motor operation then provides the primary heat generation. By adjusting the input heat generation to see how long our motors would last. Values less than 19.3 watts are still useful for building an efficient strategy to maintaining operation in a PSR. The preliminary study, so far, has given an approximate values for useful to a thermal management strategy. Moving forward, heat generation required to maintain operational and survival conditions will be answered with the preliminary model. Next, the complexity, and accuracy, of the model will be increased so that more geometric effects and modes of heat loss can be accounted for when meeting/answering project objectives.

By quantifing the amount of heat that is lost to each heat sink in the system (radiation to space, and radiation and conduction to the regolith). The sublimation rates can be better explored if driving over 'icy regolith'. We expect the majority of heat to be lost via radiation, but if the regolith exceeds or reaches 273 K, we will need to consider sublimation rates of ice changing the thermal conductivity of regolith.

References: Use the brief numbered style common in many abstracts, e.g., [1], [2], etc. References should then appear in numerical order in the reference list, and should use the following abbreviated style:

[1] S. Ulamec, J. Biele, and E. Trollope, Planetary and Space Science, 2010. [2] K. Sacksteder, R. Wegeng, and N. Suzuki, AIAA–2010–8731, Tech. Rep., 2012. [3] A. Ricco et al. Science, 2010. [4] J. F. Batir, M. Hornbach, and D. Blackwell, Global and Planetary Change, 2017. [5] E. Andreas, Icarus, 2007. [6] J. Gamsky. P. Metzger, Earth and Space 2010: Engineering, Science, Construction, and Operationsin Challenging Environments, 2010. [7] E. Fixsen, The American Astronomical Society, Tech. Rep., 1996. [8] C. Katzan and J. Edwards, NASA Contract 4404, Tech. Rep., 1991. [9] J. Gaier, S. Ellis, and N. Hanks, Journal of Thermophysics and Heat Transfer, 2012. [10] T. Mcclanahan et al., Lunar and Planetary Science, vol. XLVIII, 2017. [11] P. Berkelman et al., Carnegie Mellon University, Tech.Rep., 1995.

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