EXPLOITING LUNAR NATURAL AND AUGUMENTED THERMAL ENVIRONMENTS FOR EXPLORAT AND RESEARCH

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INTRODUCTION

Near the poles of the Moon, there are permanently shadowed craters whose surface temperatures never exceed 100 K. Craters within craters, commonly referred to as double-shaded craters, have are en colder regions exist with, in many cases, temperatures that should never exceed 50 K. The presence of water ice possibly existing in permanently shaded areas of the moon has been hypothesized, discussed, and studied since W [1] predicted the possibility of ice on the moon. Ingersoll et al. [2] estimated that the maximum sublimation rate for ice is less than 1 cm per billion years for these types of environments. These potential ice stores have many uses xploration, potentially providing precious water and rocket fuel for any human exploration or future colonization.

The temperatures within these regions offer unprecedented high-vacuum cryogenic environments, which in their natural state could support cryogenic applications such as high-temperature supercor d associated devices that could be derived. The potential application of naturally occurring cryogenic environments in conjunction with simple methods to augment these environments to achieve even colder temperatures opens the p of many additional cryogenic techniques. Besides ice stores and the potential for continuous solar illumination for power production, the unique cryogenic conditions at the lunar poles provide an environment that could reduce t eight, and total mass that would have to be carried from the Earth to the Moon for lunar exploration and research.

BACKGROUND

Figure 1 shows a schematic of a lunar base that is exploiting single-shaded and double-shaded craters. Since we are near the poles, the sun is shown low in the horizon for two positions in the sky. Within single-shaded craters, some areas are shaded from all positions of the sun. Estimates by Carruba and Coradini indicate that the temperature ranges of single-shaded craters are in the 83-103 K range [3]. They also show that double-shaded craters can have temperatures in the 36-71 K range. These temperature ranges represent both the natural environment that is achievable and the types of cryogenic devices that can be used at these temperatures.

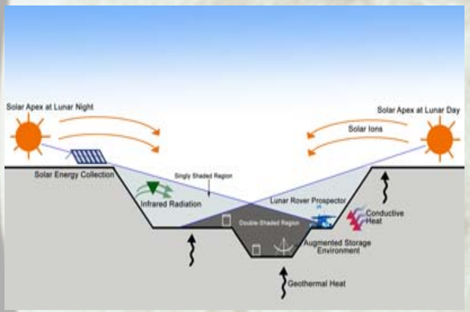

Figure 1. Schematic of polar single-shaded and double-shaded craters and associated thermal sources.

THEORY

Table 1. Heat sources and their magnitude.

Q	Flux $\frac{W}{m^2}$	Equivalent Temperature K	Reference
Q Conduction	Neglible after ~100m	NA	Langseth et al. [4]
Q Solar Wind (worst case ~2 days a month, aberration)	~ 1 E-3	10-12	Hardy et al.[5]
Solar wind (lower bound aberration)	~ 1E-5	4	Hardy et al.[5] Arnold [6]
Q Geothermal	2.5 E-2	25	Langseth et al. [5]
Q Radiation (Single Crater, direct thermal)	~ 2E0	84-103	Carruba and Coradini [3]
Q Double-Shaded Crater	1E -1 → 1E0	36-71	Carruba and Coradini [3]

The temperature on the surface of the moon T_{crater} is determined by expression (1), where σ is the Stefan Boltzman constant and Q_{total} is the total sources, described in Table 1.

$$T_{Crater} = \left[\frac{Q_{Total}}{\sigma}\right]^{\frac{1}{4}} \quad (1)$$

The low temperature within shaded craters is created by the elimination of direct solar radiation, whose normal incidence irradiance slightly exceeds 1 kW per m2. The heat sources associated with the sun are scattered visible and re-radiated gray body emission from direct solar heated surfaces and typically never exceed 400 K. The dominant heat source in single-shaded craters is the thermal re-radiation, which is on the order of a few W/m². By minimizing the heat transfer between an object and the lunar surface, temperatures approaching absolute zero can be produced. By reducing the heat flux of geothermal blackbody radiation, significant impacts on the achievable temperature can also be produced. The geothermal heat source is a fraction of a mW per m2, which by itself would limit the temperature of the surface in these regions to about 25 K. With a few manmade augmentations, permanently shaded craters located near the lunar poles can achieve temperatures even lower than those that naturally exist.

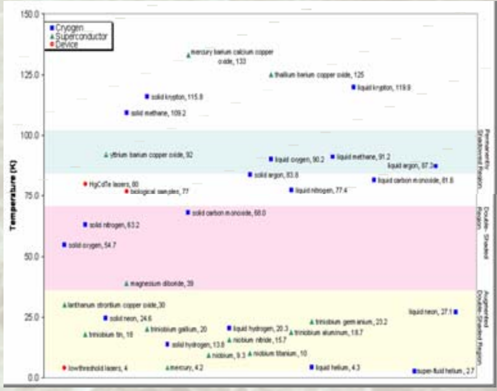

Figure 2. Various cryogenic devices and cryogens for natural and augmented thermal environments. Lide [7], Canfield and Bud'ko [8], and Carruba and Coradini [3].

Table 2 lists the expected temperatures for solar illuminated, permanently single-shaded craters, double-shaded craters, and two augmented architectures. The first augmentation is thermally isolating a device from the gray body emission and geothermal sources.

In effect, in a single- or double-shaded crater, if an object was isolated from a variety of thermal sources and was allowed to radiatively cool to space, the achievable temperatures would be limited only by 3 K cosmic background and the anomalous solar wind that would strike the object, thereby limiting the temperature to 10 K when the solar wind strikes the object. To get colder temperatures, a second augmentation with an active cooling device is added to the passive cooling architecture to achieve near absolute zero temperatures (also listed in Table 2).

Table 2. Various temperature ranges of different natural and augmented environments.

Temperature Ranges (K) of Lunar Environments		
Constant Illumination	250-396	Carruba and Coradini [3]
Permanently Shaded Crater	84-103	Carruba and Coradini [3]
Double-Shaded Crater	36-71	Carruba and Coradini [3]
Double-Shaded Crater with Augmentation 1	10-12	
Double-Shaded Crater with Augmentation 2 (cooler)	0.2-10	

The temperature ranges of both naturally shaded and thermally augmented craters could enable the long-term storage of most gases, low-temperature superconductors for large magnetic fields, devices, and advanced high-speed computing instruments. Therefore, augmenting existing thermal conditions in these craters could then be used as a basis for the development of an advanced thermal management architecture that would support a wide variety of cryogenic applications. The ranges of possible superconducting materials and selected phase transition temperatures are shown in Figure 2.

M ODS

Our analysis reveals that thermal shielding within shaded craters could create an en several Kelvin above absolute zero. Within the double-shaded spended thermal shield would reflect the nominal 50 K adiation back towards the lunar surface. A simple method ven a relatively large object would be to use a low thermal i spension structure that would hold both the thermal shield a t above the thermal shield. The naturally existing enviror levitate a thermal shield using high-temperature superc agnetic levitation, using the Meissner Effect as shown .

This would minimize the r (conduction and radiation) between the ground and a the Moon.

Magnetic levitation breaks thermal conduction paths

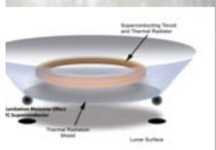

Figure 3. Thermal shield m vitated with a superconducting toroid.

SUMMARY CONCLUSIONS

Lunar exploration and ha abilities would significantly benefit if permanently shaded cr nted with thermal shielding, were used to support a wide va ogenic applications. This could be accomplished by using th s to enable the operation of near absolute zero instruments an array of cryogenically based propulsion, energy, comm sensing, and computing devices. By exploiting the unique ics of permanently shaded regions on the Moon, the power, total mass that are required to conduct research there co tantially reduced. Permanently shaded lunar craters coul reduce the required burden of carrying massive life-sup nents, mining tools, and research instrumentation from the Moon.

RE ENCES

[1] Watson K. et al. (196 s Res, 66(9): 3033–3045. [2] Ingersoll A. P. et al. (s, 100: 40–47. [3] Carruba V. and Coradini A. (1999) *Icaru* 413. [4] Langseth M. G. et al. (1976) *Proc Lunar Sci C* 3–3156. [5] Hardy D. A. et al. (1975) *Geophys Res Lett,* . [6] Arnold J. R. (1979) *J Geophys Res*, 84 (B10): 5 [7] Lide D. R. (2003) *CRC Handbook of Chemistry* [8] Canfield P. C. and Bud'ko S. L. (2005) *Sci Am*, 292 (4)

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