EXPLOITING LUNAR NATURAL AND AUGUMENTED THERMAL ENVIRONMENTS FOR EXPLORATION 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 areas where even 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 Watson et al. [1] predicted the possibility of ice on the moon. Ingersoll et al. [2] estimated the maximum sublimation rate for ice to be 0.9 cm per 10^9 years at 102 K. These potential ice stores have many uses for lunar exploration, 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 superconductors and associated devices that could be derived. In this vein, the potential application of naturally occurring cryogenic environments and simple methods to augment these environments to achieve even colder temperatures, opening the use of many additional cryogenic techniques, is discussed here. Furthermore, besides ice stores and the potential for continuous solar illumination, the unique cryogenic conditions at the lunar poles provide an environment that could reduce the power, weight, 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. 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.

Theory: The temperature on the surface of the moon T_{Crater} is determined by expression (1),

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

where σ is the Stefan Boltzman constant and Q_{Total} is the total heat sources, described in Table 1.

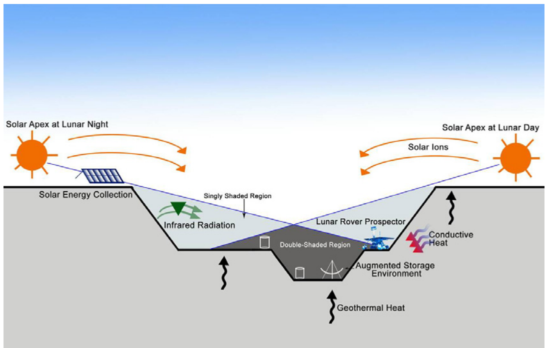

Figure 1. Schematic of polar single-shaded and double-shaded craters and associated thermal sources.

Table 1. Heat sources and their magnitude (Figure 1).

Q	Flux $\frac{W}{m2}$	Equivalent Temperature K	Reference
Q Conduction	Negligible after ~100 m	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. [4]
Q Radiation (Single-Shaded Crater, direct thermal)	~ 2E0	84-103	Carruba and Coradini [3]
Q Double-Shaded Crater	1E -1 → 1E0	36-71	Carruba and Coradini [3]

The low temperature within shaded craters is created by the elimination of direct solar radiation, whose normal incidence irradiance slightly exceeds 1 kW per m^2. 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 per m^2. 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 m^2, 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.

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.

Methods: Our analysis reveals that lightweight thermal shielding within shaded craters could create an environment several Kelvin above absolute zero. Within the double-shaded crater, a suspended thermal shield would reflect the nominal 50 K gray body radiation back towards the lunar surface. A simple method to isolate even a relatively large object would be to use a low thermal insulating suspension structure that would hold both the thermal shield and the object above the thermal shield. The naturally existing environment could levitate a thermal shield using high-temperature superconducting magnetic levitation, such as the Meissner Effect, as shown in Figure 3.

This would minimize the heat transfer (conduction and radiation) between the ground and an object on the Moon (where the gravity is relatively small).

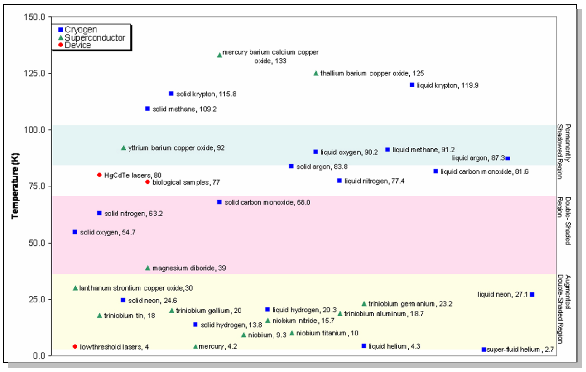

Figure 2. Various cryogenic devices and cryogens for natural and augmented thermal environments. Lide [7], Canfield and Bud'ko [8], and Carruba and Coradini [3].

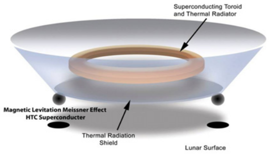

Figure 3. Thermal shield magnetically levitated with a superconducting toroid.

Summary and Conclusion: Lunar exploration and habitation capabilities would significantly benefit if permanently shaded craters, augmented with thermal shielding, were used to support a wide variety of cryogenic applications. This could be accomplished by using these locations to enable the operation of near-absolute-zero instruments, including an array of cryogenically based propulsion, energy, communication, sensing, and computing devices. By exploiting the unique characteristics of permanently shaded regions on the Moon, the power, weight, and total mass that are required to conduct research there could be substantially reduced. Permanently shaded lunar craters could potentially reduce the required burden of carrying massive life-support components, mining tools, and research instrumentation from the Earth to the Moon.

References: [1] Watson K. et al. (1961) *J Geophys Res*, 66(9): 3033–3045. [2] Ingersoll A. P. et al. (1992) *Icarus*, 100: 40–47. [3] Carruba V. and Coradini A. (1999) *Icarus*, 142: 402–413. [4] Langseth M. G. et al. (1976) *Proc Lunar Sci Conf 7th*, 3143–3156. [5] Hardy D. A. et al. (1975) *Geophys Res Lett*, 2: 169–178. [6] Arnold J. R. (1979) *J Geophys Res*, 84 (B10): 5659–5668. [7] Lide D. R. (2003) *CRC Handbook of Chemistry and Physics*. [8] Canfield P. C. and Bud'ko S. L. (2005) *Sci Am*, 292 (4): 81–87.