DRILL DON'T DIG: SUBTERRANEAN LAKES ON THE MOON AS AN ECONOMIC RESOURCE T. Marshall Eubanks[1], W. Paul Blase[1], Manasvi Lingam[2] and Andreas Hein[3] [1]Space Initiatives Inc , Newport, Virginia 24128 USA [2]Department of Aerospace, Physics and Space Sciences, Florida Institute of Technology, Melbourne, FL 32901, USA [3]Luxembourg University, Luxembourg ; tme@space-initiatives.com;

Introduction: The Moon has a hot interior and a relatively cold surface, with a cooler crust on top of a warmer mantle. The thermal gradient can be estimated from the Fourier equation [1, 2]

$$\mathrm{F_z} = -\mathrm{k}\,\frac{d\mathrm{T}}{d\mathrm{z}} \tag{1}$$

where F is the internal heat flux, k the thermal conductivity, and z the depth (here increasing downwards). The thermal conductivity measured by the Apollo ALSEP experiments [3] was very low, with k of order 10^{-3} W K^{-1} m^{-1} in the top 2-cm of the regolith, and order 10^{-2} W K^{-1} m^{-1} at a depth of 1 meter [4], which produces thermal gradients of order 1 K m^{-1} at z $\sim$ 1 m in both the Apollo 15 and 17 heat flow measurements.

These measured near surface thermal gradients are much too large, and the ALSEP thermal conductivities much too small, to be present throughout the lunar crust (they would imply a mantle depth of $<$ 1 km!). Instead, below a regolith layer of order 10 - 20 meters depth, the lunar crust must approach the much larger thermal conductivity of its constituent rocks, thought to be plagioclase feldspars. With current estimates for the temperature of the upper mantle being 705.5 K at a mean depth of 38.5 km [5], the bulk crustal thermal gradient beneath the Apollo 17 site is 11.2 K km^{-1} giving a bulk crustal thermal conductivity of 0.94 W K^{-1} m^{-1}, in reasonable agreement with the measured thermal conductivity of the plagioclase feldspar labradorite, with $\mathrm{k}_{labradorite}$ under lunar conditions being between $\sim$1 and $\sim$2 W K^{-1} m^{-1}, depending on the temperature [6].

Temperatures in the Lunar Crust: With its very small thermal conductivity, the upper lunar regolith is a very good insulator, and the large thermal variations present on any sunlit lunar surface have disappeared at a depth of 0.5 to 0.75 meters [7]. The temperature at a depth of $\sim$0.75 meters (which we call the Immediate SubSurface, or ISS) is roughly constant and depends on both the internal heat flow from below, the energy deposited on the surface above by solar heating, and the energy lost at the surface by radiation. Assuming the two layer model of [4], together with Apollo conductivity and recent satellite albedo models, then the zonally averaged ISS temperature is given by Figure 1.

The one dimensional heat equation of Equation 1 can be solved given boundary conditions on either boundary, in our model the ISS temperature (which is given by the model shown in Figure 1) and thermal conditions at the crust-mantle boundary (CrMB). Two types of static boundary conditions are appropriate in this case; Dirichlet boundary conditions (where the temperature is given at both the upper and lower boundary, with the CrMB temperature being fixed at 705.5 K), and mixed boundary conditions (where the temperature is given at both the upper boundary, and the CrMB heat-flux is fixed at 0.011 W m^{-2}. Given the general lack of knowledge of conditions at the CrMB, we assume that both boundary conditions are independent of latitude and longitude, with the CrMB being at a uniform depth of 38.5 km [5]. Note that while thermal conductivities are material properties, the thermal gradient and heat flux are related by Equation 1, so that with Dirichlet boundary conditions the heat flux varies with latitude, while with mixed boundary conditions the CrMB temperature varies with latitude.

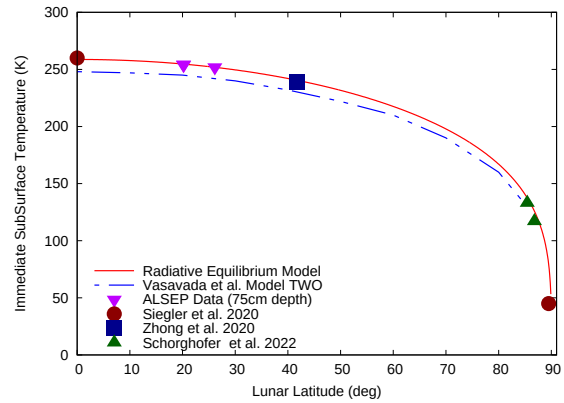

Figure 1: Zonally averaged models for the ISS temperature (the temperature at a depth of $\sim$0.75 m, just beneath the diurnally varying surface layer). The Vasavada Model TWO is from [4]; our model (the solid red line) is similar but is fit to the Apollo temperature data. The triangles are Apollo heat flow measurements [3]; also shown are predicted subsurface temperatures from [8] and [9]. Note that the ISS temperature is everywhere below the freezing point of water.

While surface ice is thought to be geologically stable in practice only in regions with surface temperatures $\lesssim$ 110 K, which amounts to only in the Permanently Shadowed Regions (PSRs) close to the poles, underground ice will be stable at higher temperatures [10], and thus can survive in a wider latitude range. Figure 2 shows the depth of a temperature of 0° C for the two 1-D thermal equation models. As the temperature below the surface regolith is monotonically increasing with depth, water ice can exist above the indicated curves, and liquid wa-

ter below each curve. Note that near the poles, water ice could form very thick subterranean layers, potentially km thick [11]. This water would be delivered to the Moon by the impacts of comets and meteorites [12], possibly during periods of a transient lunar atmosphere [13], be distributed on the lunar surface, and subsequently buried by later meteorite impacts or even lunar volcanism.

Conditions for Underground Lakes: Underground lakes of liquid water on the Moon require both a reservoir of underground water and a barrier sufficient to stop the water from being lost to space over geologic time. As the lunar crust has likely been extensively fractured by repeated impacts, we assume that the survival of subterranean liquid water will likely require a water ice cap above it, to block the loss of the liquid water. Subterranean 'lakes" may thus be possible underneath any region with surface or subsurface ice. With our thermal models, they could potentially be found as far from the poles as $\pm$ 30° latitude.

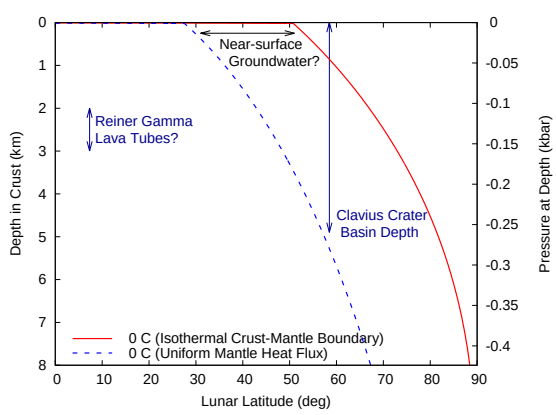

Figure 2: The depth at which pure liquid water would freeze assuming a 1-D heat equation and two types of boundary conditions: Dirichlet boundary conditions (with an isothermal crust-mantle boundary) and mixed Dirichlet-Neumann boundary conditions (with a uniform crust-mantle boundary heat-flux). In both cases the upper boundary condition is given by the zonal-mean temperature estimates in Figure 1. With these subsurface temperatures, liquid water (under a cap of ice) may be found even at mid-latitudes.

Two interesting lunar areas that might be connected to subsurface water are also shown in Figure 2. Clavius Crater apparently has surface water [14, 15], which might arise from subsurface water leakage. It is interesting that Clavius, which is a deep crater, in at a latitude where liquid water might be relatively close to the surface. The estimates of the depth of the hypothesized lava tubes in Reiner Gamma are from [16]. If the Reiner Gamma caves exist, and are below the depth of meteorite gardening and so can contain some water, that water should be liquid. Near-equatorial lava tubes with skylights, pits, or other openings [17] are likely to be relatively warm ($\gtrsim$250 K) and thus would have likely lost any internal water long ago. Open caves would have to very near the poles are to be able to retain much water over geologic ties.

Liquid Water as an Economic Resource: Subsurface water lakes are clearly a potential economic resource. It is clear to extracting surface water from lunar PSRs will be very difficult and expensive, requiring the development of mining technologies capable of operating at liquid nitrogen temperatures and constant darkness. Extracting subsurface liquid water, by contrast, will be a drilling problem, and humanity has a long experience with drilling and pumping water. Figure 2 indicates that ground water may be found relatively near the surface at latitudes of 30° to 60 °, depending on the actual internal temperature distribution of the lunar crust. It will be relatively easy to operate drilling facilities in these relatively warm and well-lit mid-latitudes, where both solar power and communications with Earth should be relatively available.

We will discuss the problems of finding sub-surface ice and lakes, and also to technical problems extracting subsurface water in a vacuum environment.

References: [1] A. Jiménez-Díaz, et al. (2021) *Icarus* 353:113635 doi. [2] M. Lingam, et al. (2020) *Ap J Lett* 901(1):L11 doi.arXiv:2008.08709. [3] M. G. Langseth, et al. (1976) *Lunar and Planetary Science Conference Proceedings* 3:3143. [4] A. R. Vasavada, et al. (1999) *Icarus* 141(2):179 doi. [5] O. L. Kuskov, et al. (2014) *Physics of the Earth and Planetary Interiors* 235:84 doi. [6] M. L. Linvill, et al. (1984) *Bulletin de Minéralogie* 107(3-4):521. [7] P. O. Hayne, et al. (2017) *Journal of Geophysical Research (Planets)* 122(12):2371 doi. arXiv:1711.00977. [8] M. Siegler, et al. (2020) in *Lunar Surface Science Workshop* vol. 2241 of *LPI Contributions* 5140. [9] Z. Zhong, et al. (2020) *Remote Sensing* 12(4) ISSN 2072-4292 doi. [10] N. Schorghofer, et al. (2007) *Journal of Geophysical Research (Planets)* 112(E2):E02010 doi. [11] K. M. Cannon, et al. (2020) *Geophys Res Lett* 47(21):e88920 doi. [12] B. D. Stewart, et al. (2011) *Icarus* 215(1):1 doi. [13] D. H. Needham, et al. (2017) *Earth and Planetary Science Letters* 478:175 doi. [14] S. G. Pugacheva, et al. (2021) in *52nd Lunar and Planetary Science Conference* Lunar and Planetary Science Conference 1411. [15] C. I. Honniball, et al. (2021) *Nature Astronomy* 5:121 doi. [16] D. J. Hemingway, et al. (2018) *Journal of Geophysical Research (Planets)* 123(8):2223 doi. [17] R. V. Wagner, et al. (2014) *Icarus* 237:52 doi.