THERMAL ANALYSIS OF EXPERIMENTAL APPARATUS SIMULATING ICY WORLD CONDITIONS. Z. F. G. Wong[1,2], D. F. Berisford[2,3], D. B. Goldstein[1], L. M. Trafton[1], P. L. Varghese[1], K. P. Hand[2], J. T. Foster[1], B. I. Furst[2], T. Daimaru[2], A. Macias[2,4], A. Hsu[1,2] [1]The University of Texas at Austin, Austin, TX, (zoelle.wong@utexas.edu), [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, (kevin.p.hand@jpl.nasa.gov), [3]Airborne Snow Observatories, Inc., Mammoth Lakes, CA, [4]Georgia Institute of Technology, Atlanta, GA

Introduction: The possible centimeter- to meter-scale surface morphology of Europa is currently unknown, but is an important consideration for sampling and investigating Europa's surface. Ice penitentes, thin spikes of hardened snow or ice, are formed on Earth from a combination of sublimation, vapor layer interactions, and self-illumination driven by incident solar radiation within a background atmosphere [1]. Incident solar flux warms the ice at and beneath the penitente's surface, thus releasing water molecules and excavating the surface. After a penitente field is initiated, a positive feedback cycle between sublimation and incident radiation is formed. As the troughs between penitentes continue to deepen, the scattering of incident photons between sidewalls increases, which raises internal temperatures and further deepens troughs [2]. Some recent work has raised the possibility about the potential existence of these structures on Europa, which has become a relevant question for landing spacecraft on its icy surface [3].

To gain a deeper insight into the mechanics of penitente formation, the Ocean Worlds Laboratory (https://oceanworldslab.jpl.nasa.gov/) at the Jet Propulsion Laboratory (JPL) has developed a variable temperature and solar irradiance testbed, capable of simulating Europan or other icy world environmental conditions [2]. Also known as the "Ark", this experimental apparatus consists of a rectangular vacuum chamber with an anodized aluminum inner chamber (cold box), LED bar, radiator, and cryocooler (Figure 1).

Previous experimental results from measuring the sublimation rate of an ice cake with sinusoidal surface profile at free molecular conditions have shown penitente troughs to be colder than the peaks, despite visibly brighter troughs than peaks. The preformed penitente-like ridges eroded with time in the experiment [4].

Recent computational models have shown that the temperature gradient between penitente peaks and troughs may invert when the experimental wall temperatures are at roughly 100 K [5]. That is, below wall temperatures of 100 K, the model showed warmer trough temperatures than peaks. Because the Ark's walls were between 150-220 K this implies an experiment with colder walls may drive penitente growth instead of erosion. The warm walls were likely due to LED waste heat and radiative thermal loads from the outer chamber walls. Tests may have been done in a regime where sidewall heating of the test article led to

a reversal of what would be expected on Europa. We note that a quasi-steady state ice surface temperature between 170 and 174K must be maintained for tractable penitente growth in the Ark: the ice surface must be around this temperature to obtain measurable deformation over a few weeks [4]. The finding of sidewall heating implies a need for a more robust thermal cooling system, and this paper seeks to explore methods for minimizing the effects of sidewall heating on the ice cake's evolution. Hence, we explored ways to: (1) maintain a quasi-surface temperature at 173 K by separating the ice cake from the cold box bottom wall with a suitable thermal barrier plate and (2) cool the cold box below 100 K by introducing additional thermal controls.
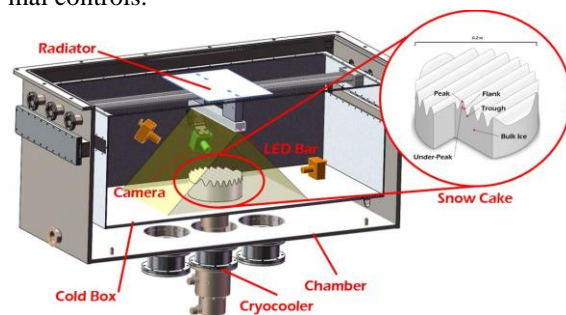

Figure 1: "Ark" CAD design; the front wall and lid of the chamber (1.3 m × 0.6 m × 0.6 m) and cold box (1.2 m × 0.5 m × 0.44 m) are removed to show the interior [2].

Methods: ThermalDestkop (TD), a CAD-based thermal engineering tool suite, was used to predict the temperature results of the experimental apparatus and its modifications. The ice cake was modeled as a cylinder with 0.07 m height and 0.115 m radius. The thermal conductivity of the ice cake was based on previous experimental data [2,6]. The cold box walls, LED bar, and chamber were also modeled using the same material properties and dimensions from the experiment. Finally, TD's transient solution for the heat equation was used because the cryocooler (SHI cryogenics CH-110) was modeled as a temperature dependent heat sink. For model validation, the temperatures of the Ark walls, top ice cake surface, and LED bar in the thermal model were compared to thermocouple data in the same locations from Berisford et. al [4] and matched within 1K.
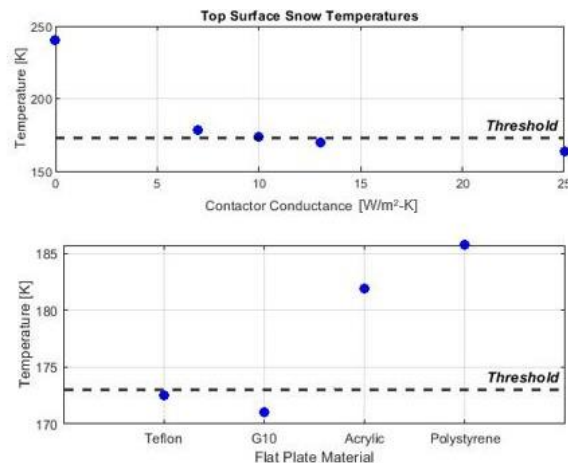
Figure 2: Thermal model results simulating the addition of a thermal barrier plate between the ice sample and cold box floor. Top subplot: average simulated snow temperatures with varied plate conductance. Bottom subplot: average simulated snow temperature with different flat plate materials of 0.0127 m thickness
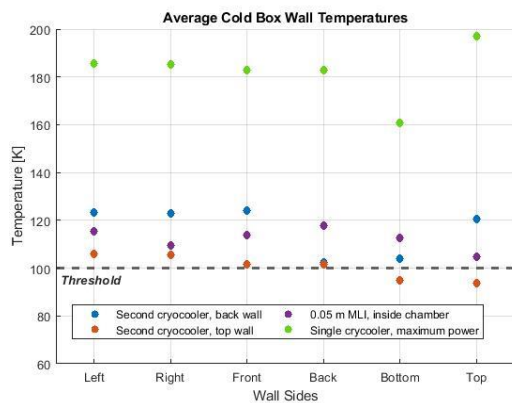

Figure 3: Simulated cold box wall temperatures when adding additional thermal controls.

Results:

Thermal Barrier Results: The temperature distribution within the ice cake depends upon the radiation absorbed from the LED and sidewalls, the scattered light from within, the thermal emission, and the conduction through the cold box floor. If we cool the cold box walls and floor to well below 100 K, we will need to add a thermal barrier between the ice cake and the floor to maintain an ice temperature of 173 K. The bulk ice temperature can be readily controlled by placing a thermal barrier between the ice cake and the floor. We explored several materials suitable for such a barrier (Steel, Teflon, G10 etc.) of different thicknesses and concluded that a 0.3048×0.3048 m $\times 0.0127$ m flat plate would need a conductance value of roughly 10 W/m^2-K. Figure 2 shows that the ice surface temperature increases as the flat plate conductance decreases. Teflon has a conductivity of 0.25 W/m-K, a specific heat of 1004 J/kg-K and density of 2170 kg/m^3 at 118K. Using these properties, the model predicts a

Teflon flat plate of $0.3048 \times 0.3048 \times 0.0127$ m will maintain the surface temperature of 173 K.

Thermal Controls Results: Earlier experiments demonstrated colder trough temperatures and warmer peaks. It was concluded colder trough temperatures arose from poor thermal conduction between the ridges in bulk ice [4], however computational models showed that warmer troughs may occur for wall temperatures below 100 K [5]. The remaining problem is, to lower the temperature of the sides of the cold box to below 100 K so that their thermal radiation to the ice cake is negligible.

We considered adding 0.05 m of multi-layer insulation (MLI) around the cold box as a solution. The outer chamber temperature is roughly 300 K and a 0.05 m gap exists between the cold box and outer chamber. Wrapping additional MLI around the cold box would decrease temperatures. However, our model results show peak wall temperatures of about 120 K. Achieving wall temperatures much lower than 120 K require MLI with near 0 emissivity which is not physically possible.

Figure 3 shows that adding an additional cryocooler on the top wall would lower the temperature sufficiently. Because the LED bar is nearest to the cold box lid, adding a second cryocooler to top wall would remove heat from the system most efficiently. A disadvantage is that adding a cryocooler on the top wall would require a customized mechanical assembly. This assembly would be difficult to fabricate and potentially introduce new heat leaks.

Conclusion: Methods for improving the Ark's thermal performance for future experiments were explored. Computational models were used to identify apparatus wall temperatures for penitente growth, and TD was used to predict the apparatus wall temperatures for given hardware changes. A $0.3048 \times 0.3048 \times 0.127$ m Teflon flat plate was found to best maintain a quasi-surface temperature of 173 K. Adding 0.05 m of MLI around the cold box produced wall temperatures of 120 K. Therefore this method alone is not sufficient to reach wall temperatures below 100 K and so we will need to introduce additional active cooling (a second cryocooler).

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