PENITENT ICE ON EUROPA? LABORATORY TESTING OF CRYOGENIC ICES RELATED TO ICY MOON SURFACES

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Introduction: High altitude equatorial glaciers on Earth often grow ice penitente structures on the meter scale [1]. Landing spacecraft on icy solar system bodies may require accommodating the morphologies of such structures [2]. We have performed a series of laboratory tests to investigate the factors affecting penitente growth over a wide range of conditions, ranging from Earth-like (273 K, 0.1 MPa, 1 AU solar irradiance) to Europa-like (~100 K, near vacuum, 5.2 AU solar irradiance). We present two different experimental setups: The first is a static configuration, where thermal and illumination conditions remain constant to facilitate quick turnaround and comparison of different factors. The second approximates the full Europan environment, including cryogenic shrouding and diurnal illumination variation.

Figure 1. Penitentes on Mt. Kilimanjaro

Static Testbed: The static test apparatus consists of a vertical-axis aluminum cylindrical vacuum chamber with a welded outer jacket. The outer jacket contains fluid ports that connect to a recirculating fluid chiller or liquid nitrogen supply to provide cooling of the inner chamber sidewalls and floor. To minimize thermal gradients in the chamber, the cold fluid flows into this inter-wall volume through a single port in the center of the bottom surface, and out through two ports on opposite sides of the chamber sidewalls.

Similar to the work in [3], the light source consists of an 80W halogen flood lamp mounted vertically outside the chamber. Light enters via a quartz window in the chamber lid, which transmits (>90%) of wavelengths between approximately 0.2 and 2.8 μm. Optical power reaching the ice can be varied by adjusting the height of the lamp and the size of the aperture, up to a maximum of 3kW/m^2.

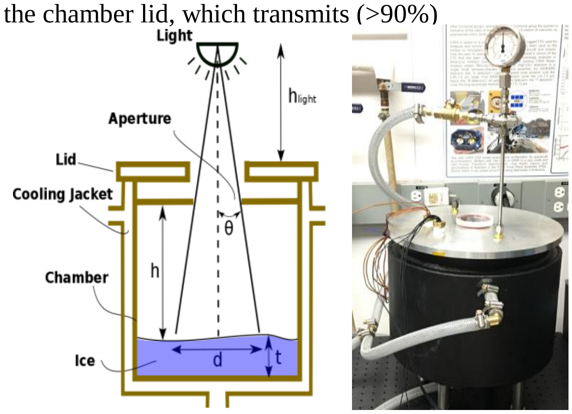

Figure 2. Static Testbed

The inner chamber contains a welded flange on the upper inside surface, which provides a mounting surface for a cold aperture plate. This plate can contain an aperture of any size, and is conductively coupled to the chamber walls to cool the plate. This cold aperture limits the incoming radiation from the light source to a desired spot size on the ice surface, and prevents direct illumination of the chamber walls. It also helps reduce incident thermal radiation from the warm chamber lid and ambient room. The upper surface of the aperture plate is coated with single-layer aluminized mylar insulation (effective emissivity approximately 0.05) to reflect much of the incident radiation and limit the heat load on the plate.

The chamber connects to a vacuum pump via a port in the lid through an adjustable vacuum regulator in line between the chamber and pump. This regulator controls the chamber pressure, with a dry nitrogen supply feeding the regulator vent port to prevent moist air from entering the system.

Dynamic Testbed: The Europa Penitente Ice Experiment (EPIX) chamber simulates the diurnal solar radiation environment for the surface of solar system icy moons. Figure 3 on the next page shows a diagram and photograph of the apparatus, which can maintain bulk ice samples at temperatures ranging from 70K to 200K.

A welded aluminum cold box with a bolt-on lid contains the ice and provides cold shrouding to block incident thermal radiation from the warm chamber walls reaching the ice. A single-stage Gifford-McMahon cryocooler draws heat from the cold box floor via a flexible copper thermal strap. Electrical resistance heaters attached to the thermal strap provide heat for thermal control of the coldbox temperature using an external PID controller with feedback from a temperature-sensitive diode mounted at the heater interface.

The light source for the EPIX chamber consists of a linear array of visible and near-IR LED's mounted to a metal-core printed circuit board. The LED's emit a cone of light that produces a range of illumjnation angles on the ice, simulating different times of day as the light source moves. Because LED's emit over a

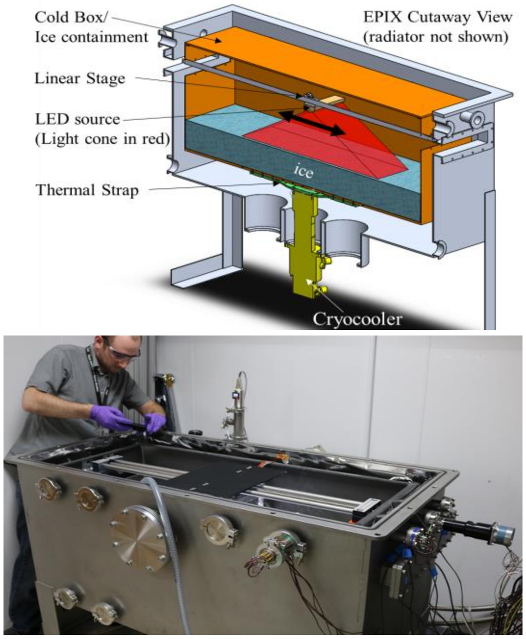

Figure 3. EPIX Diurnal Illumination Testbed

narrow spectrum, we selected the individual elements based on the spectral reflection characteristics of terrestrial snow [4]. We separated the snow reflectivity spectrum into three distinct bands: highly reflective (UV-visible), moderately reflective depending on grain size/surface morphology (near-IR), and highly absorbing (thermal-IR). The LED array emits total power in each of these three bands in approximately the same ratio as the solar spectrum. By varying current applied to the array, this system can simulate solar fluxes at the ice surface from approximately 1 to 1000 W/m2.

A flat plate radiator mounts atop the LED array, and provides cooling for the assembly. Aluminized mylar insulation covers the radiator bottom side to minimize thermal radiation to the ice. The radiator top side is coated with high-emissivity black paint to provide radiative thermal coupling to the coldbox lid. Heat radiated to the lid conducts through the coldbox walls to the cryocooler, which removes it from the system at the coldbox floor.

The LED array and radiator assembly mounts to a mechanical linear motion stage to provide the diurnal light variation. The stage mounts at each end to the coldbox interior wall and is driven by a lead screw, which passes through a hole in the coldbox. An externally mounted stepper motor drives the leadscrew through a vacuum rotary feedthrough. The stepper motion can be programmed to sweep slowly in one direction for appropriate day and night time simulation, and return quickly to the starting position. This allows the experiment to run indefinitely for many day/night cycles.

Preliminary Results and Discussion: Preliminary tests in the static chamber at fully Europan cryogenic conditions have not produced any observable penitentes over a three week period. At Earth-like conditions, mm-scale penitentes formed in less than one hour.

As a rough scaling estimate, we assume that penitente growth rate scales linearly with ice surface sublimation rate, which is a strong nonlinear function of surface temperature as predicted by [5, 6]. For a Europa surface temperature of 130K [7], we expect a growth rate of at least 10 orders of magnitude lower than that on Earth (-5ºC). This would imply roughly 1 Myr to form a 1cm penitente.

This does not account for vapor pressure gradients near the surface, variations with surface morphology evolution, etc. [8]. However, it suggests that experiments at fully cryogenic temperatures and under irradiance and vacuum conditions directly comparable to Europa are not likely to produce observable results in reasonable timescales for laboratory experiments. Therefore, both sets of experiments are designed to operate over a wide range of conditions, permitting e.g. trading time for irradiance. Ongoing work involves many experiments to fulfill a test matrix of varying conditions from Earth-like to Europa-like. The data from these tests will help develop empirical scaling relations for penitente growth rate as a function of ice temperature, background pressure, incident solar flux, and ice composition. Extrapolation of these scaling relations to fully cryogenic conditions will give insight to help bound the possible size for ice penitente structures on Europa, Enceladus, Pluto, and other icy moons and ocean worlds.

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