

**THERMAL DIFFUSIVITY-CONDUCTIVITY MEASUREMENTS ON ICE SAMPLES OF MAGNESIUM SULFATE AND SODIUM SULFATE SOLUTIONS: IMPLICATIONS FOR EUROPA'S ICE SHELL.** S. Nagihara<sup>1</sup>, P. Ngo<sup>2</sup>, and K. Zacny<sup>2</sup>, <sup>1</sup>Department of Geosciences, Texas Tech University, Lubbock, TX 79409 (seiichi.nagihara@ttu.edu), <sup>2</sup>Honeybee Robotics, Pasadena, CA 91103.

**Introduction:** Remote observations from Earth-based telescopes and spacecraft flybys over the icy satellites of Jupiter and Saturn show that thermal inertia of their surfaces is about two orders of magnitude lower than what is expected for solid water ice [1]. Thermal inertia is defined as the square root of the product of the material's volumetric heat capacity and thermal conductivity. Previous researchers have proposed possible causes for the low thermal inertia. For Europa, the surface ice may be highly porous or fractured [1, 2]. It may also consist predominantly of amorphous ice [3], which is less thermally conductive than crystalline ice. Presence of salts (i.e., magnesium sulfate, sodium sulfate) and clathrate hydrates has been detected [4]. These salts and hydrates are also less thermally conductive than crystalline water ice [5, 6]. It is likely that more than one of these (and possibly additional) factors contribute to the low thermal inertia. Further quantification and identification of these factors are needed for improving the models of the thermal structure and evolution of Europa.

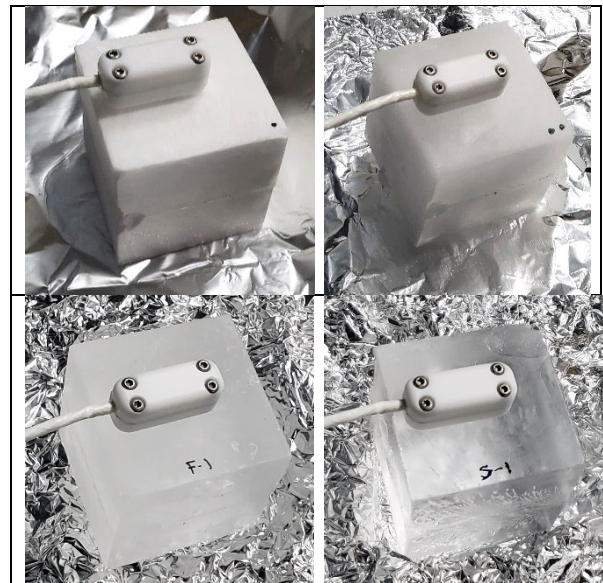
The aforementioned salts likely originate from the liquid ocean under the ice shell [4]. The material of the ice shell is more likely to be ice of their water solutions than that of pure H<sub>2</sub>O ice. The previously reported thermal measurements on the salts [5, 6] were performed on specimens of hydrated solids. Here we report the results of thermal conductivity and diffusivity measurements on ice samples of magnesium sulfate (MgSO<sub>4</sub>) solution and sodium sulfate (Na<sub>2</sub>SO<sub>4</sub>) solution.

**Ice Samples:** We first produced a 16%wt solution of MgSO<sub>4</sub>, and a 3.5%wt solution of Na<sub>2</sub>SO<sub>4</sub> in deionized water at room temperature. For each of the solutions, the liquid was poured into silicone molds with 5-cm cubic chambers, and the whole assembly was placed in a walk-in freezer whose temperature was set at -16°C. Three cubic ice pieces were made from the MgSO<sub>4</sub> solution and another three were from the Na<sub>2</sub>SO<sub>4</sub> solution (Fig. 1). The MgSO<sub>4</sub> cubes had solid white appearance, while the Na<sub>2</sub>SO<sub>4</sub> were more translucent.

We believe that we largely avoided precipitation of the salts during the freezing process by setting their concentration slightly below the eutectic values [7, 8]. No salt crystals were visible on the surfaces of the cubic ice samples extracted from the molds. In addition, after the completion of the thermal measurements, we heated the ice samples up to 225°C to evaporate the water, and weighed the anhydrous salt residues from them. The salt concentration values matched the initial values within

~4%, with all but one matching within 2%. It is still possible that some of these salts existed in crystal forms within the ice samples. Because of their opaqueness, it was not possible to visually confirm whether or not such crystals were absent.

Some of the opaqueness of the samples may have resulted from entrapment of air bubbles, which should not occur on the surface of Europa. We froze these samples overnight in the freezer. Slower freezing would have allowed time for more of the bubbles to escape, but it would have also increased the chance of salt precipitation. For comparison, we froze deionized water with no salt using the same method, and found it to be also somewhat opaque (Fig. 1), though to a lesser degree than the Na<sub>2</sub>SO<sub>4</sub> ones. We also froze deionized water more slowly by applying additional thermal insulation to the same cubic molds, taking more than 24 hours, and were able to produce clear ice cubes (Fig. 1). In assessing the effect of the trapped bubbles, we made thermal measurements on both the clear and the opaque water ice samples and compared the results.

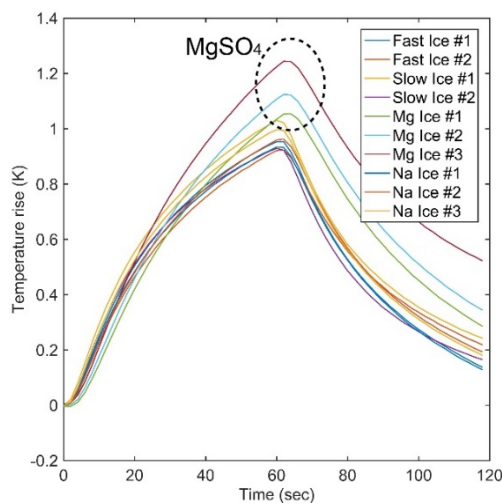


**Figure 1.** Photographs of the thermal diffusivity-conductivity probe inserted into the 5-cm cube samples of the MgSO<sub>4</sub> solution (top left), the Na<sub>2</sub>SO<sub>4</sub> solution (top right), the fast-cooled water (bottom left) and slow-cooled water (bottom right).

**Thermal Diffusivity-Conductivity Measurements:** We used the dual-probe method [9] for simultaneous determination of thermal conductivity and thermal diffusivity of each of the samples. Thermal diffusivity is defined as the material's thermal conductivity divided by volumetric heat capacity. The simultaneous determination of thermal diffusivity and thermal conductivity thus allows estimation of volumetric heat capacity as well.

We used the dual-probe system of Decagon Devices (now METER Group). The probe (SH-1) uses two needles, each 30-mm long with 1.3-mm diameter, separated by 6 mm [10]. One of the needles contains an electric heater and the other contains a temperature sensor. Thermal conductivity and diffusivity are determined by monitoring the heat conducting from the heater to the temperature-sensing needle through the medium of interest.

We drilled a pair of holes into each sample for inserting the probe (Fig. 1). Because of the difficulty working in the freezer, we did not apply thermal grease to the probes, and that may have resulted in some contact resistance between the probes and the surrounding ice. The heater was activated for one minute for a constant power of 17.5 W/m. The samples were kept in the freezer during the entire time. Three samples of the  $\text{MgSO}_4$  solution ice, three samples of the  $\text{Na}_2\text{SO}_4$  solution ice, two samples of the slow-cooled (24+ hours) water ice, and two samples of the fast-cooled (< 12 hours) water ice were measured. Figure 2 shows the temperature rise (relative to the pre-heating temperature) versus time graph for the heating experiments performed on the individual ice cubes.



**Figure 2.** Temperature rise versus time plots for the thermal diffusivity-conductivity measurements on the ice samples.

**Discussion and Conclusions:** The temperature-versus-time records for the fast-cooled water, the slow-cooled water, and the  $\text{Na}_2\text{SO}_4$  solution ice samples are almost identical, reaching  $\sim 0.9$  K above the pre-heating temperature at the end of the heating. They yielded similar thermal conductivity and diffusivity values (Table 1). It is not certain whether or not the small differences between the two groups of  $\text{H}_2\text{O}$  ices ( $\sim 5\%$ ) are due to the absence/presence of the air bubbles, given that the number of samples was small (2 pieces for each group) and that contact resistance between the needles and the ice may have affected these measurements. The  $\text{MgSO}_4$  solution samples reached their peak temperatures at considerably later times and at higher values (1.0 to 1.2 K), indicating that they are considerably less thermally conductive than the others. The thermal conductivity and diffusivity values for the  $\text{Na}_2\text{SO}_4$  solution ice are comparable to those of the  $\text{H}_2\text{O}$  ice samples. This may be due to the low concentration of the salt (3.5%wt). Solubility of  $\text{Na}_2\text{SO}_4$  is much lower than that of  $\text{MgSO}_4$ .

In conclusion, because of the difference in solubility,  $\text{MgSO}_4$  may have a greater impact on the thermal properties of Europa's ice shell than  $\text{Na}_2\text{SO}_4$ . Especially in deep subsurface ( $> \sim 1$ -km depth), where ice is expected to be much denser than on the surface [11], the sulfate type and its concentration in the water may be major factors controlling the thermal structure of the ice shell.

**Table 1:** The group averages of the thermal conductivity and diffusivity values of the ice samples at  $-16^\circ\text{C}$ .

	Thermal Conductivity (W/mK)	Thermal Diffusivity ( $\times 10^{-7} \text{m}^2/\text{s}$ )
Fast-cooled water	2.0	6.1
Slow-cooled water	2.1	7.2
16 wt% $\text{MgSO}_4$ solution	1.3	3.9
3.5 wt% $\text{Na}_2\text{SO}_4$ solution	1.9	6.1

The average values for each sample type are shown.

**References:** [1] Ferrari, C. and Lucas, A. (2016) *A&A*, 588, A133. [2] Nimmo, F. and Giese, B. (2005) *Icarus*, 177, 327-340. [3] Hansen, G. B. and McCord, T. B. (2004) *JGR-Planets*, 109, E01012. [4] Carlson, R. W. et al. (2009) *Europa*, Univ. Arizona Press, 283-327. [5] Ross, R. G. and Kargel, J. S. (1998) *Solar System Ices*, Kluwer Academic Pub., 33-62. [6] Prieto-Balasteros, O. and Kargel, J. S. (2005) *Icarus*, 173, 212-221. [7] Peterson, R. C. and Wang, R. (2006) *Geol.*, 34, 957-960. [8] Angeli, M. et al. (2010) *Geol. Soc. London Sp. Pub.*, 35-42. [9] Bristow, K. L. et al. (1994) *Soil Sc. Soc. Am*, 58, 1288-1294. [10] Decagon Devices (2011) *KD2 Pro Operator's Manual, ver.10*, 68 p. [11] Moore et al. (2009) *Europa*, Univ. Arizona Press, 329-349.