"Ice Spike Formation Induced By Dendritic Ice Sheets"

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Two years ago, about the time Helene Perry raised the question "Ice Spikes - Can You Explain Them?" in the *TPT*, I began to see spikes on ice cubes that seemed to defy gravity. They looked liked icicles that grew in the wrong direction! Since then, I have been communicating with Professor Stephen Morris at the University of Toronto to obtain documentation and try to explain the phenomenon. From the start, I saw the ice spikes on a daily basis. The ice spikes grew best when undisturbed and always stopped (or never started) just by opening the doors to the refrigerator, so going into the kitchen during spike growing hours was out of the question. The only other precaution taken to help the growth of spikes was to reduce the running time of the refrigerator by lowering the freezer setting. The freezer setting ranges from one to ten and is set on five and a half, which translates into $-10°$ C $\pm$ $6°$ between running times. Whenever the ice cubes were left alone (usually two hours), spikes formed. In most cases, I checked the freezer after the spikes stopped growing and observed the melting stage of the spike. The melting of the spike deforms its shape into a more rounded spike that complicated earlier attempts to explain the phenomenon. It is now known that the spikes possess triangular cross sections, as most of the readers of *TPT* have observed. The spikes have no preference to which tray compartment to occupy or to where the tray is positioned in the freezer. Sometimes, a single tray would have spikes in four or five different compartments! The spikes also had random growth orientations with different angles of inclination ranging from vertical to thirty degrees with respect to the cube surface (Fig. 1).

The first question everyone asked was, "Where does the water that forms the spike come from?" Most people suggested that the water dripped down from the ceiling of the freezer. Dripping seemed very unlikely to happen in a frost-free freezer and the could not account for the triangular shape of the spikes I saw. The other possibility for the source of the water either condenses from the air, like dew, or rises from beneath the surface of the cube. The condensation hypothesis suggests that the origin of ice spike is independent of the water in the cube. I decided to test this by tainting the water with powdered tea that turned the water brown. The spikes that grew from the tea samples were distinctively brown. If the ice spike had condensed out of the atmosphere, it should have been clear. From this observation, the majority of the water in the spikes must come from the ice cube itself. Therefore, the formation of the spikes must depend on the internal structure of the ice cube as it freezes.

In order to observe the spike formation process, I began to check the ice cubes before the usual two hours it took for the spikes to form. My freezer takes about an hour and a half to initiate the freezing of water straight from the tap. I tried using hot water but spikes never formed. So within an hour and a half, before the freezing of the surface layer, I began to notice sheets of ice crystallizing within the tray compartments (Fig. 2).

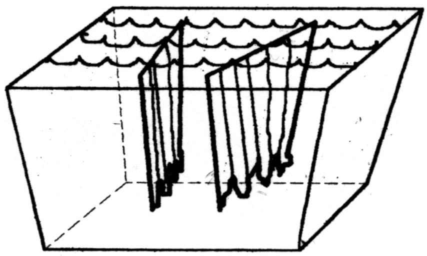

Fig. 2. Liquid compartment with two dendritic sheets of ice suspended vertically.

These dendritic sheets randomly crystallize within the tray compartments. They are oriented vertically, horizontally or at any angle in between. This happens after about an hour in the freezer and is not really visible unless the water is drained. The formation of the sheets is the fundamental process that governs the shape and size of the spikes.

As the surface of the water gradually freezes, it comes in contact with the dendritic sheets and locks them in place (Fig. 3.). If the random orientations of two or three dendritic sheets are close enough to intersecting, the surface of the ice cube will acquire a triangular shape and create the triangular pocket schematically drawn in Fig. 4.

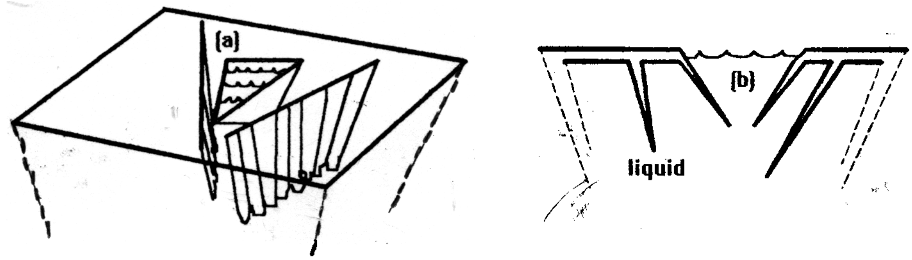

Fig. 4. (a) Triangular pocket created by two dendritic sheets at the top surface of the cube. (b) Side view of triangular pocket frozen or locked onto the surface.

As the surface of the cube freezes, the region between the dendritic sheets will freeze towards each other until a triangular hole is formed. The triangular hole will remain liquid until ice begins to grow into the cube from the edges of the hole (Fig. 4 b), thus creating a pocket. The enclosed pocket resembles an inverted pyramid with the top and bottom open. The pocket might remain liquid by providing a channel for the latent heat of freezing to be released and contains enough energy to maintain the liquidity of the water inside the pocket as the rest of the cube freezes. The growth of ice spikes requires that the center of the pocket remains in the liquid phase. If the pocket closes at the top or bottom, the spike will not form, but triangular indentations can be seen on the surface of the cube when it is completely frozen. I tried using a metal, ice cube tray and the rate of freezing at the surface was very fast due to the conduction of the metal. The freezing was quick enough to completely freeze and enclose the surface of the cube before any pockets could form.

The base of the spikes sits directly on top of the triangular pocket create in between the dendritic sheets of ice (Fig. 5). The pocket acts as a funnel and channels the water pushed upwards from below the surface as the ice expands due to freezing and creates a bulge. The base of the spike is created by freezing the water clinging to the edge of the pocket at the surface of the bulge (Fig. 6). In the few minutes that the growth takes place, the expansion of ice must be slow enough for the water to cling to the edges of the triangular pocket so that the bulge of water cant be maintained for the edges to continue to freeze upwards.

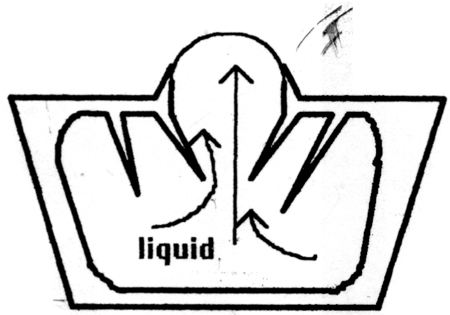

Fig. 6. Upward bulge of water acquires a triangular base at the edge of the pocket where the water clings and freezes.

If the expansion rate is too fast, the water will just flow out of the top and freeze over the hole. Once an upward direction is established, the vertical growth of the spike continues in the direction specified by the dendritic sheets. If all the sheets are slanted towards an angled direction, then the spike will also acquire the same direction, thus accounting for the angled spikes in Fig. 1. Figure 7 shows an angled spike while still in formation. At the moment the freezer door was opened, the bulge of water at the top of the spike was disturbed and the water level of the spike began to drop. The picture should clearly show that the spike is a hollow ice cylinder that pipes water from within the ice cube.

All of the ice spikes that I have observed from the freezer are spikes with wide bases that taper off at the top (Fig. 8 and 9). But that does not seem to be the only possibility, especially when the spikes are produced outdoors. Helene Perry from Loyola College sent me a picture of a spike that seems to continue the growth in all three directions of the triangular pocket extending beyond the surface (Fig. 10). It does not taper off, but expands outwardly from the bottom up while maintaining its triangular shape.

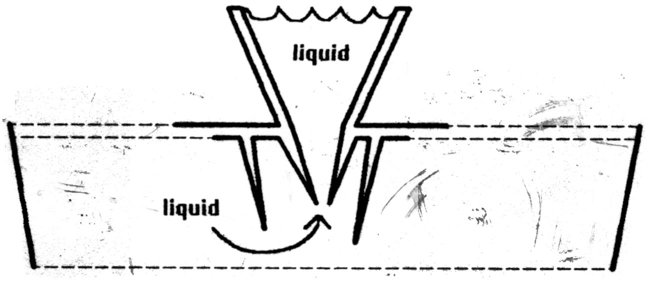

Fig. 10. Possible schematic of non-tapering spike using a large pan.

Professor John Hallet provided a paper that he wrote almost thirty-five years ago from the *Journal of Glaciology*, Vol. 3, No 28, 1960 on "Crystal Growth and the Formation of Spikes in the Surface of Supercooled Water" that included pictures of triangular prism spikes that do no taper or expand on the surface of glaciers. The spike growth processes I have observed are identical to the ones described in his paper. The differences in our spikes lie in the fact that my spikes are grown indoors and with a small container, whereas, Helene Perry's and Professor Hallet's observations were done outdoors with large or no containers. My freezer is probably capable of maintaining a constant temperature for only one or two hours before the temperature drop is enough for the refrigerator to start running again. I suspect that outdoor freezing has the ability to maintain a constant temperature for a longer period of time or at least vary slowly with time. Why should using a large or no containers outdoors produce spikes that do not taper? The increased surface area of a larger container should increase the rate of freezing, thus increase the rate of expansion. If the rate of freezing of the spike outside is slightly less than the rate of expansion of the water inside due to the increased surface area, the force of the upwards moving water may be enough to push the bulge of the spike in an upwards and outwards direction, as in Helene Perry's case. The spikes from the freezer might have expansion rates inside the cube that are slightly less than the rate of freezing of the freezer environment and produce spikes that must taper off at the top. I hope that the readers of the *TPT* continue to observe the ice spikes and find more interesting Physics in our freezers to amaze us!

Acknowledgments

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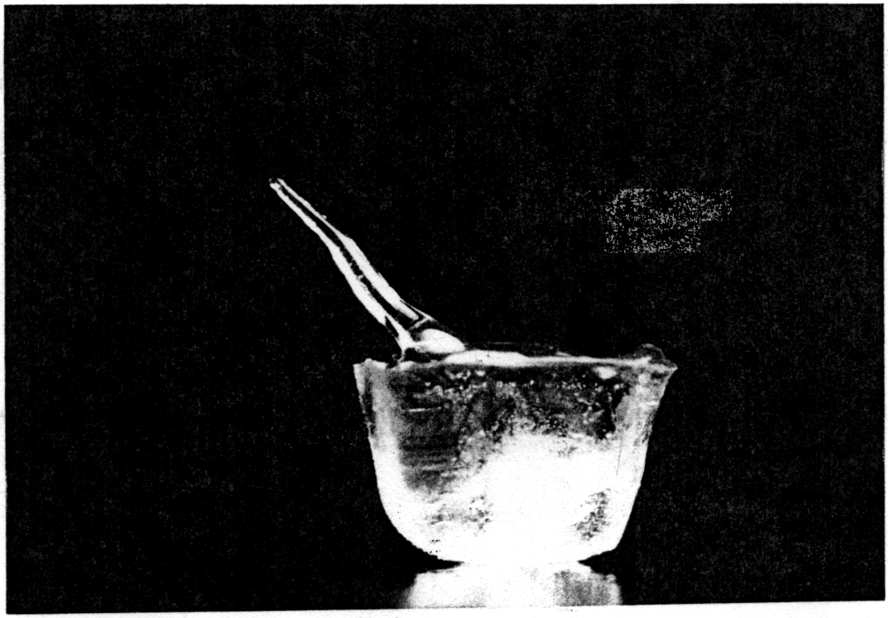

Fig. 1. Inclined ice spike.

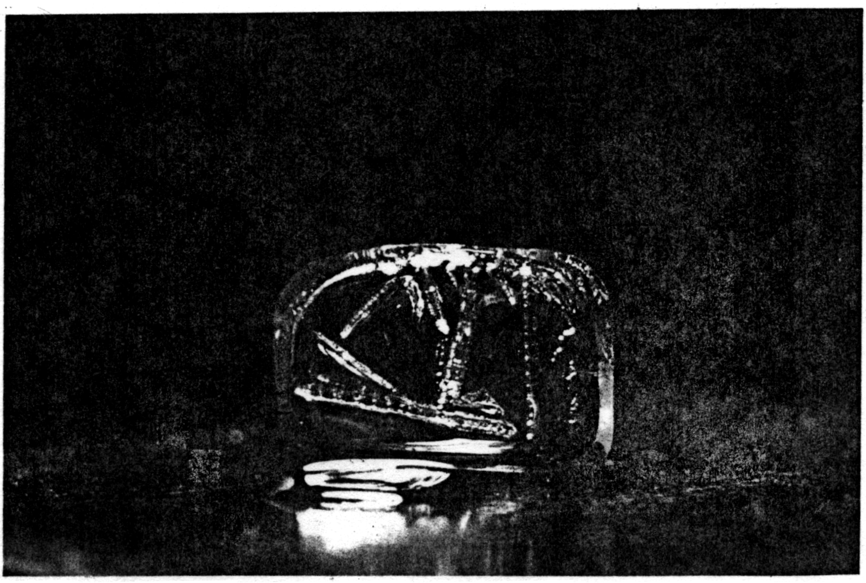

Fig. 3. Top view of ice cube with vertical dendritic sheets locked onto the surface in a triangular configuration.

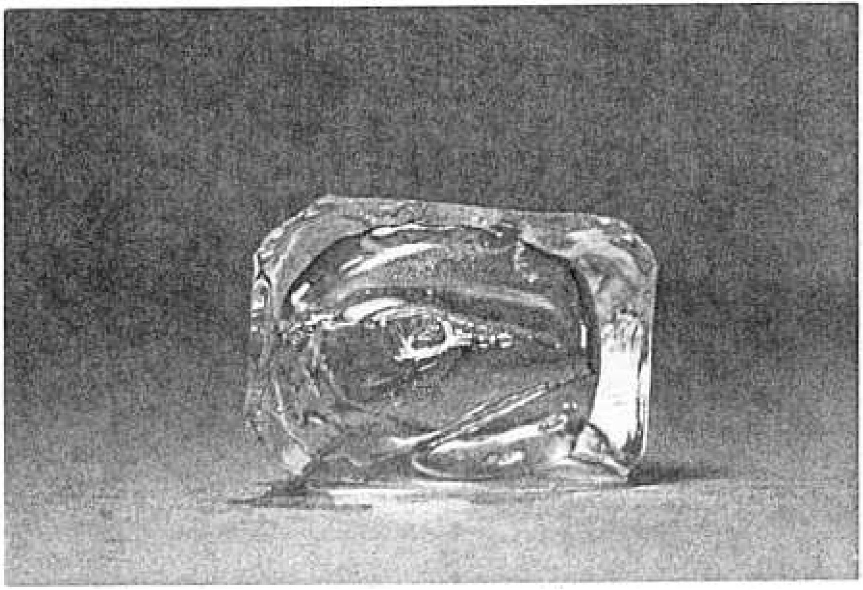

Fig. 5. Top view of ice cube with a triangular spike between two dendritic sheets.

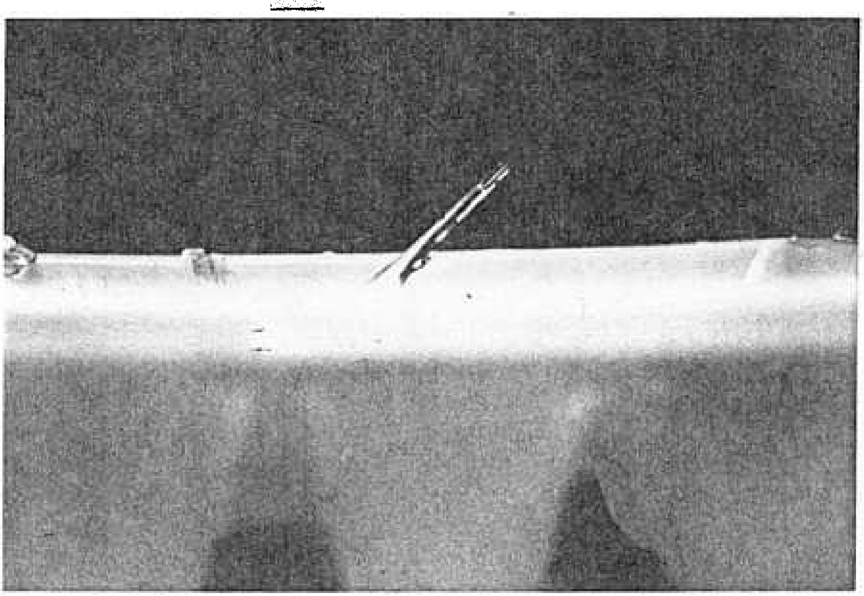

Fig. 7. Interrupted ice spike formation with dropping water level.

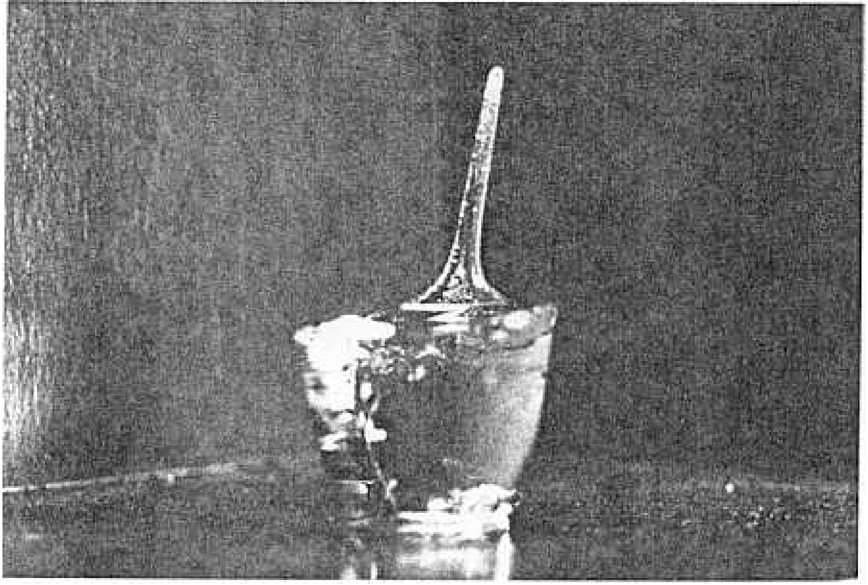

Fig. 8. Tapered spike with a wide base compared to the top.

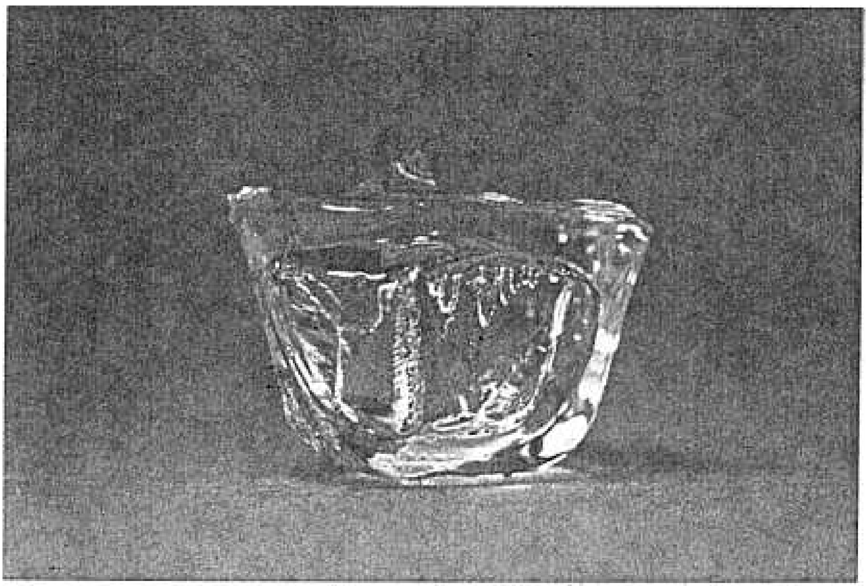

Fig. 9. Side view of fig. 5 with one side sectioned out. The short pyramidal spike sits on top of the dendritic sheets.