Insidious ICE

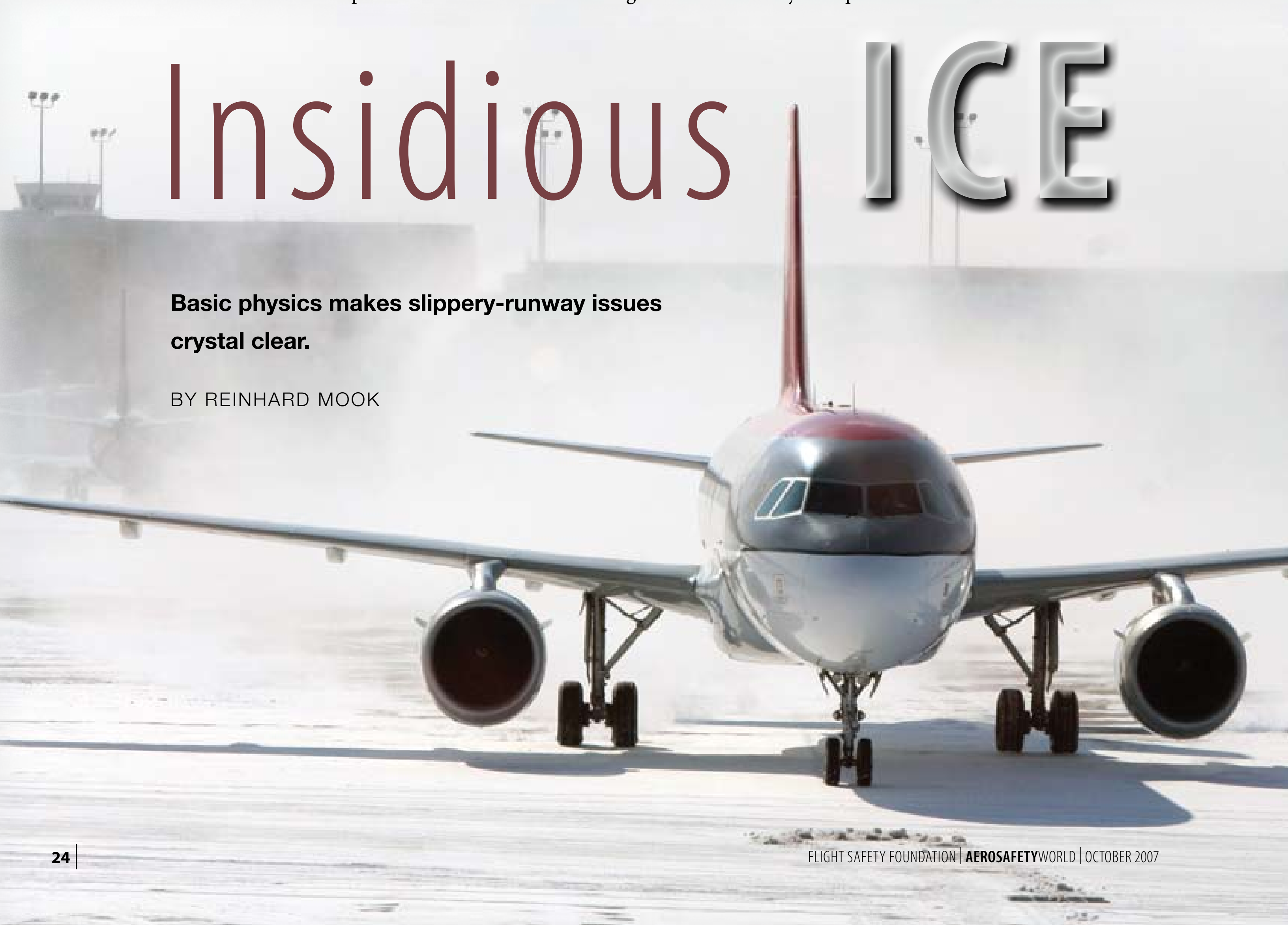
Basic physics makes slippery-runway issues crystal clear.

BY REINHARD MOOK

The wide range of slippery conditions on runways contaminated by frozen water still challenge even flight crews highly experienced in winter operations. But accident investigators in recent years have been pressing for a wider understanding of the basic ice physics responsible for catching pilots off guard (*ASW,* 2/07, p. 22). Runway-surface temperature — and its relationship with the dew-point or frost-point temperatures of the adjacent air — may indicate either the possibility of water freezing or the current state of the frozen water, and may improve flight crews' assessment of runway-friction properties, including times when the surface seems free of frozen contamination. Because freezing occurs on at least 30 percent of the Earth's non-glaciated land, such knowledge can reduce risk in takeoff and landing.

More realistic estimates of aircraft deceleration performance could be made if flight crews ideally were able to consider the correlation of aircraft braking friction coefficient with runway-surface temperature, the amount of water vapor close to the surface and the exact type of frozen contamination. Significant changes in the type of frozen contamination, such as rapid freezing of water, may happen in the course of minutes. Real-time broadcast of surface temperature for a dry or wet runway could be used to predict the likely freezing of liquid water or formation of frost from water vapor, as well as the microtexture of frozen contaminants.

Findings from recent accident investigations have urgent practical implications. One is that airport surface air temperatures reported to pilots via routine aviation weather reports (METARs) may be misleading with respect to actual runway-surface conditions. Another is that flight crews should interpret conservatively all reports of friction coefficients based



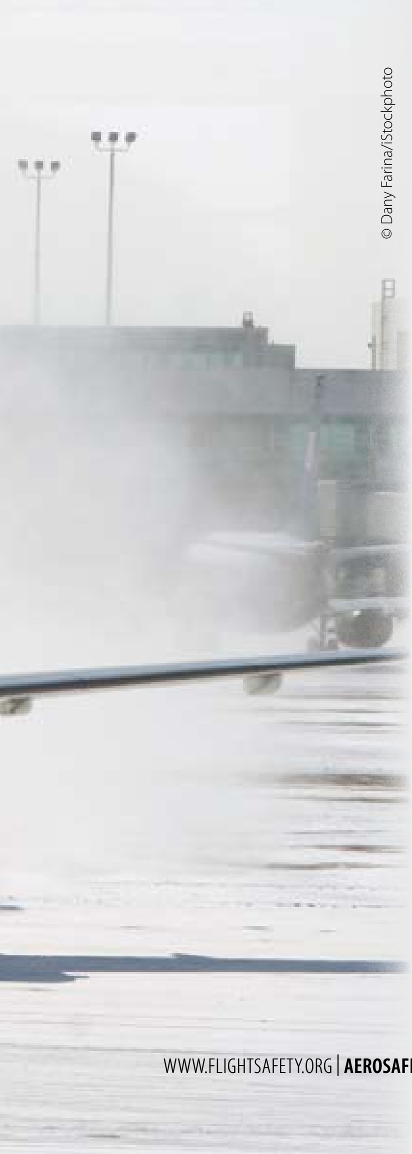
on data collected by the friction-measurement devices carried or pulled by airport vehicles — and consider these reports as qualitative information, not as quantitatively precise measurements.

These cautions are supported by my recent micrometeorological field work as an independent researcher at Norway's Svalbard Airport Longyear and analyses of slippery runway incidents for the Accident Investigation Board Norway (AIBN), SAS Scandinavian Airlines and the former Norwegian airline Braathens SAFE. In my research, the label "frozen contamination" on runways may mean compacted snow, "black ice" — transparent/invisible ice — or ice generated from sintered[1] snow, frozen slush, hoar frost and/or glaze from freezing rain, and may appear in various changing stages or as consecutive layers. Water freezing at 0 degrees C (32 degrees F) is assumed in this article.[2]

Current and accurate runway-surface temperature measurements are proving to be crucial to assessing frozen contamination.

At the International Society of Air Safety Investigators seminar in August 2007, Knut Lande of the AIBN reviewed unresolved issues concerning winter operations and friction measurements. The AIBN says that aircraft operators should not rely solely on runway friction coefficient reports generated by airports if frozen contamination is present or wet/damp conditions exist and the "spread" between dew point and METAR air temperature is 3 kelvins (K; 3 degrees C, 5.4 degrees F) or less. Scientists use the kelvin, formerly called degree Kelvin, as the unit of thermodynamic temperature. Based on an international agreement in 1873 about synoptic observations by weather stations — later including METARs — air temperatures are measured at 2.0 m (6.6 ft) above ground level to represent the general climate and to reduce the influence of the local microclimate.[3] To assess frozen contamination, however, accurate runway-surface temperature information is crucial.[4]

Air temperature at an airport can vary significantly from runway-surface temperature, especially when there are few clouds and the wind is light. In this situation, radiation becomes the dominant factor governing the local thermal state.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Phenomenal Friction

Friction, though not yet understood completely, is believed to be caused by electric force acting between molecules of two surfaces, and affects the interaction of materials on a molecular scale. "Kinetic friction" means the total friction of a "slider," essentially an object moving while in contact with another. For example, friction between an aircraft tire as the slider and a frozen contaminant depends on shear forces transferred by the actual contact area of their microscopic surface elevations, or high spots — which scientists call asperities — so deceleration depends on the microtexture of the frozen contamination. The slipperiness of frozen contamination on the runway also can be differentiated by how ice asperities' microscopic "peaks" and "valleys" vary within the microclimates of frozen contaminants because of adhesion and Kelvin effect, in which maximum evaporation occurs from these peaks, also called tips.

The special case of friction involving frozen contamination seems to deviate from classical laws of physics because it also depends on load and sliding velocity. Because the heat conduction within rubber is poor, most of the heat generated by friction — for example, while the aircraft tire contacts the runway surface — is conducted into the asperities of the frozen contaminant, such as ice. Rather high flash temperatures — maximum temperatures attributable to friction — occur in the contact area, which changes during the landing roll because the asperities of the ice are subject to mechanical deformation and melting as a result of the tire sliding.[5] This friction also is controlled by the volume of liquid water present due to processes such as precipitation and melting, and frictional heat. The size and dispersion of the asperities — each ranging in height from about a micrometer to a millimeter — and the adhesive characteristics of the frozen contamination also play a key role.

The mechanical tendencies of frozen contaminants — for example, that ice easily will creep[6] under load — are governed by the magnitude of the homologous temperature of each specific contaminant. Homologous temperature

"Black ice" on runways, closely resembling liquid water, surprises unwary pilots.

is the ratio of its absolute temperature to its melting-point temperature, expressed by scientists using kelvins. Expressed in METAR temperatures, ice at minus 30 degrees C (minus 22 degrees F) has a relatively warm homologous temperature of 0.89, its 243 K absolute temperature divided by its 273 K melting-point temperature. By comparison, the homologous temperature of titanium at minus 30 degrees C is 0.13.

One counterintuitive factor is that if the frozen contamination is near its melting-point temperature, the aircraft braking coefficient of friction decreases — that is, braking action becomes worse — with increasing load. Thus, the tires of a heavy aircraft may generate less friction than those of a much lighter aircraft.

Pilots also should be aware that the aircraft braking coefficient of friction decreases significantly in relation to increasing amounts of liquid water on top, inside and at the base layer of the frozen contaminant on the runway due to melting, which submerges the ice asperities and — by water lubrication — reduces their ability to transmit shear stress. As the volume of liquid water increases, this coefficient of friction depends increasingly on sliding velocity and load. Specifically, the water volume from frictional melting increases as a function of the square root of the sliding velocity.

There are exceptions. For example, at a low temperature, a low aircraft braking coefficient of friction may occur if frozen contamination on the runway surface has been "polished" by the vertical skipping and horizontal movements of drifting particles of ice or when the tire lifts because of an air-snow mixture in an intermediate layer.

Wet snow on ice may create a complex, but weak, pattern of transmitting shear stress during braking. The reason is that snowflakes contain liquid water — and near the sea, they may contain dissolved salt — promoting slippery conditions. At 0 degrees C, at least 10 percent of the weight of snow is liquid water, maybe more depending on local topography and the resultant vertical air movement in clouds. By definition, at least 30 percent of the weight of slush is liquid water. So the squeezing of such frozen contaminants under aircraft tires contributes significantly to water lubrication and slipperiness. Adding complexity are the dynamic crystalline and mechanical characteristics of frozen contamination, which change due to factors such as runway maintenance and metamorphism — transformations occurring between forms of frozen water, such as snow to granular ice, caused by a change of external pressure such as from tires — temperature, vapor pressure and ice-particle geometry.

Contact-Free Observations

The temperature of most materials can be measured by direct physical contact between the material and a heat-conducting probe, which senses temperature increases/decreases as changes of liquid volume or deformation of metal or the changes in voltage output from a thermocouple or electrical resistance thermometer. The surface temperature of a runway profile — a line designated for measurements where wheel braking typically occurs — cannot be measured conventionally. Instead, other methods have been developed. For example, the density of infrared radiation emitted from the runway surface depends on its temperature. So the temperature of a large area may be derived indirectly by moving an infrared radiation sensor above the runway profile.

To be reliable and valuable at the microtexture level, however, measuring temperature by sensing infrared radiation — whether at one spot over the runway or all along the runway profile — requires excluding the infrared radiation from extraneous sources. Surface temperatures of a runway profile can be recorded without erroneous readings by eliminating sources such as radiation from the measuring instrument, floodlights, warm exhaust from vehicles or blowing snow between the sensor and the surface.

The method currently used for taking runway-surface temperature readings is to install electrical resistance thermometers into the concrete or asphalt. Besides confining each reading to a fixed site only — not taking into account the thermal and micrometeorological differences along the runway pavement — this method has other inherent problems. Readings are dependent on heat flow through the runway pavement and, in some cases, through the layers of frozen contamination. Therefore, the indicated temperatures on these thermometers are damped, lagging behind actual conditions. Several minutes elapse on average before they reliably indicate a surface-temperature change.

Ground/Air Freezing

Because the ground is the major transformer of heat, from absorbed radiation to heat and from heat to emitted radiation, the microclimate with the most extreme temperature fluctuations actually is found at, or close to, the microtexture of the runway surface. Within this boundary layer of air, just fractions of a millimeter in thickness, vertical temperature gradients equivalent to several thousand kelvins per meter are common.

Many aspects of heat flow that influence changes in runway-surface temperature have to be considered. These include absorbed and emitted solar/terrestrial radiation, sensible heat flow — what people describe as temperature changes — in the air due to convection and shear stress turbulence, latent heat within or released by water vapor, heat absorbed by melting or released by freezing, heat conducted inside the pavement and heat content in the layers of frozen contamination. Other factors also may be significant, such as the heat content in freezing rain and the lateral heat transfer by air.

Scientists for decades have been able to calculate the amount of dew or hoar frost that will be deposited at the Earth's surface from the net radiation, the flow of heat and air temperature, without directly measuring the surface temperature.[7] To routinely monitor all the variables would be too complex and impractical for routine airport operations, but the underlying principles are valuable.

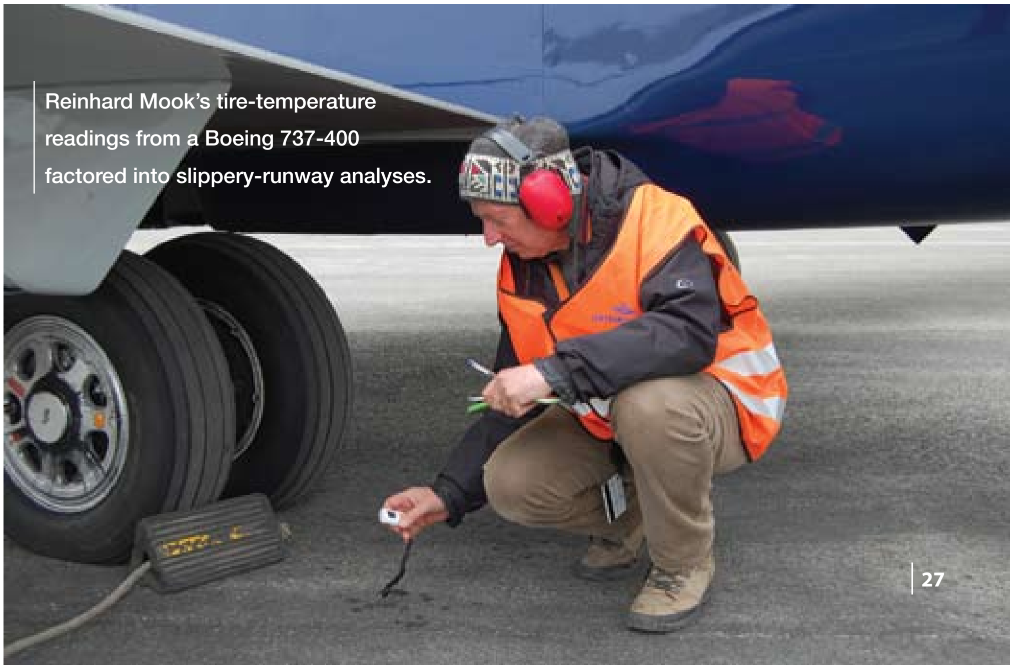
In particular, when the radiation balance between the ground and the atmosphere is negative — as on clear winter nights — the runway pavement cools by radiation deficit with the rate affected by the cooling of the adjacent air and the heat conducted from deep inside the pavement to the cooling runway surface. The air transfers heat to the radiation-emitting surface, and if formed, dew and freezing dew or hoar frost contribute by releasing heat. The resulting temperature inversion in the air layer adjacent to the runway surface easily may produce a surface 10 K (10 degrees C, 18 degrees F) colder than the airport's METAR air temperature.

Dew strongly contributes to melting because the heat released by one unit of dew theoretically can melt 7.5 units of ice at 0 degrees C. But, at this air temperature, ice melts only if the water vapor is saturated. In the early 1950s, one scientist calculated that for snow at 0 degrees C, the onset of melting does not occur at standard sea-level pressure until the air temperature exceeds 2.5 degrees C (36.5 degrees F) at a relative humidity of 60 percent or 4.2 degrees C (39.6 degrees F) at 40 percent because of the latent heat of evaporating water.[8]

Frozen dew or hoar frost reduce runway friction by water lubrication. If freezing is not a factor, dew forms when the dew-point temperature adjacent to the runway surface is warmer than the surface. When conditions conducive to freezing are involved, however, the frost-point temperature becomes most relevant. Because the saturation vapor pressure in relation to solid water — ice — is lower than in relation to liquid water, the saturation vapor pressure can be reached, causing frost formation despite a seemingly wide difference between the METAR air temperature and dew point, which is reported in METARs even at temperatures below freezing.[9]

Predicting Frost and Worse

A practical guideline for flight crews is that the frost point will be 1 degree C (1.8 degrees F) warmer than the airport's reported dew point while the airport's



Reinhard Mook's tire-temperature readings from a Boeing 737-400 factored into slippery-runway analyses.

surface temperature is minus 10 degrees C (14 degrees F), 2 degrees C (3.6 degrees F) warmer at minus 20 degrees C (minus 4 degrees F) and 3 degrees C (5.4 degrees F) warmer at minus 30 degrees C (minus 22 degrees F). That means that a METAR showing a 1 degree C temperature–dew point spread with a surface temperature of minus 10 degrees C already is a saturated vapor condition with respect to ice — so flight crews should expect frost on the runway. In fact, a runway at minus 10 degrees C might be coated with ice.

In the case of solar radiation or warm nocturnal clouds above a cool ground, both the runway pavement and the air gain heat by surplus radiation. On an uncontaminated runway surface, the temperature may exceed the adjacent air temperature. For example, even during summer in the Arctic, the runway-surface temperature may be 20 K (20 degrees C, 36 degrees F) warmer while METARs report the air temperature as freezing; far higher runway-surface temperatures may occur at lower latitudes.

Such transfers of heat to frozen contamination on the runway surface typically cause evaporation and warming to 0 degrees C followed by melting. Solar radiation through a transparent layer of ice can cause melting that begins from the bottom of the layer. In contrast, frozen contamination absorbing heat at its upper surface can attain 0 degrees C and melt beginning from the top layer, although the METAR air temperature is well below freezing.

Conversely, in conditions of warm air and little water vapor, with minimal or zero solar radiation, evaporation from a wet runway surface — combined with the radiation deficit — may result in ice forming on the runway surface despite an apparently large difference of 10 K to 15 K (10 degrees C, 27 degrees F) between METAR air temperature and runway-surface temperature.

In another scenario, lateral heat transfer by air at temperatures above freezing, with the runway surface covered by frozen contamination, may cause the air to cool. Since frozen contamination by definition cannot exceed 0 degrees C, dew formation and the melting process then may cause an extremely slippery runway despite a METAR air temperature well above freezing. ●

Reinhard Mook, Ph.D., who retired in 2006 as a professor at the University of Tromsø in Norway, is an independent consultant and researcher whose main interest is meteorological phenomena near the ground, including practical applications ranging from atmospheric effects on technology to demographic effects. Mook received his doctorate from the University of Innsbruck, Austria, after conducting research on radiation and heat data from Antarctica in 1961. His research in 2004 and 2005 was conducted with encouragement from the staff of Svalbard Airport Longyear and Avinor, the owner and operator.

Notes

1. Sintering is molecular-level bonding/fusion that can occur within clusters of snow grains, causing them to freeze into larger snow crystals; the process also occurs in ice and other aggregates.
2. In micrometeorology, scientists typically study weather-related processes on scales from a millimeter or less above ground level to heights of hundreds of meters — focusing, for example, on the air-ground exchange of heat and moisture at the shallow boundary layer of air next to the ground at a specific site.
3. Cannegieter, H.G. "The History of the International Meteorological Organization 1872–1951," *Annalen der Meteorologie [Annals of Meteorology],* New Series 1 (1953).
4. Lande, K. "Winter Operations and Friction Measurements." In proceedings of the 38th Annual International Society of Air Safety Investigators Seminar, Aug. 27–30, 2007, Singapore.
5. The following sources explain these factors. Bäurle, L. "Sliding Friction of Polyethylene on Snow and Ice." Dissertation no. 16517 (2006), Swiss Federal Institute of Technology, Zurich. Buhl, D.; Fauve, M.; Rhyner, H. "The kinetic friction of polyethylene on snow: The influence of the snow temperature and the load." *Cold Regions Science and Technology,* Volume 33 (2001), 133–140. Colbeck, S.C. "The kinetic friction of snow." *Journal of Glaciology,* Volume 34 (no. 116, 1988), 78–86. Eriksson, R.; Nupen, W. "Friction of Runners on Snow and Ice." *U.S. Army Snow, Ice and Permafrost Establishment* no. 44 (translated). U.S. Defense Technical Information Center. April 1955. Kuriowa, D. "A Study of Ice Sintering." *Tellus,* Volume 13 (1961), 252–259. Kuriowa D. "The kinetic friction on snow and ice." *Journal of Glaciology,* Volume 19 (no. 81, 1977), 141–152. Oksanen, P.; Keinonen, J. "The mechanism of friction of ice." *Wear,* Volume 78 (1982), 315–324. Persson, B.N.J. *Sliding Friction: Physical Principles and Applications,* 2000, Springer Verlag, Berlin. Petrenko, V.F.; Colbeck, S.C. "Generation of electric fields by ice and snow friction." *Journal of Applied Physics,* Volume 77 (no. 9, 1995), 4518–4521. Salm, B. "Mechanical Properties of Snow." *Reviews of Geophysics and Space Physics,* American Geophysical Union, Volume 20 (no. 1, 1982), 1–19. Sinha, N.K. "Grain Boundary Sliding in Polycrystalline Ice." *Journal of Glaciology,* Volume 2 (no. 85, 1979), 457–473.
6. Creep — most familiar in the slow movement of glaciers — also occurs in thin layers of ice; the cause is mutual displacement of ice crystals in response to shear stress.
7. Hofmann, G. *Die Thermodynamik der Taubildung [Thermodynamics of Dew Formation].* Berichte Deutscher Wetterdienst, Volume 18 (no. 3, 1955), Offenbach, Germany.
8. Müller, H.G. "Zur Wärmebilanz der Schneedecke [On the Heat Balance of Snow Cover]." *Meteorologische Rundschau.* Volume 6 (1953), 140–143.
9. Saturation vapor pressure, the maximum water vapor pressure that can exist in air at a given temperature, increases strongly with a rise in air temperature.