Valuable Intelligence

BY REINHARD MOOK

Temperature–dew point spread helps pilots anticipate slippery winter landing conditions.

The *3-Kelvin-spread rule,* an aviation rule of thumb for winter operations, can enhance pilots' sense of the actual landing risk level by calling attention to the likelihood that aircraft braking performance will not meet pre-landing calculations. The rule takes advantage of information readily available from aviation routine weather reports (METARs), and its potential value has been recognized in the recent report of an investigation of winter operations[1] by the Accident Investigation Board Norway (AIBN; *ASW,* 10/08, p. 14 and 11/10, p. 30). Nevertheless, its ease of adoption comes at the expense of absolute validity.

The rule emerged from several years of scientific research and analysis in Norway, including my contributions in the report's Appendix J, which explain the micrometeorology of the natural processes involved in water vapor saturation and ice on runways (see "Can You Stop?" p. 12). The impetus was that about two-thirds of the air transport accidents and serious incidents studied by the AIBN (21 of 30) occurred when a difference between air temperature and dew point (or *spread*) of 3 kelvin (K)[2] or less was reported by METARs (see Table 1, p. 17, and Table 2, p. 18 for Kelvin-scale conversions). The statistical probability of that proportion occurring by chance is 0.023 (2.3 percent).

Such a spread means that air containing water vapor is not very far from being saturated. The appendix discusses many factors involved; this article focuses only on saturated water vapor at freezing temperatures.

The rule states, "When the spread (air temperature minus dew point … read at 2-m [6.6-ft] level) is less than 3 K, compacted snow or ice may constitute slippery conditions." The rule has proved especially valuable when air temperatures are lower than 3 degrees C (37 degrees F), in cases of recent or current precipitation, when snow contains liquid water and/or when the surface of frozen contaminants is considerably colder than the METAR air temperatures collected 2 m above the runway indicate.

The rule's underlying research was first reported by an AIBN official in 2007.[3] Before then, insufficient friction on the runway during line operations in Norway often had been attributed only to precipitation or to liquid or frozen water deposited on the runway.

A spread of 3 K or less means the relative humidity is high — often 80 percent or higher, indicating likely precipitation. Often, such a spread occurs in precipitation, intermittent precipitation and precipitation in the vicinity of fog or in conditions conducive to fog.

Water Vapor in Air Above a Runway Affects Braking Friction

AIR TEMP/DP	SVP-W	SVP-I	SVP-DIFF	SVP-PCT	SMR-W	SMR-I	SMR-DIFF	FROST POINT	DP/FP-DIFF
–30°C (–22°F/243.2K)	0.509	0.380	0.129	25.3%	0.318	0.238	0.080	–27.2°C (–17.0°F/246.0K)	2.8°C
–27°C (–17°F/246.2K)	0.673	0.517	0.156	23.2%	0.421	0.323	0.098	–24.4°C (–11.9°F/248.8K)	2.6°C
–24°C (–11°F/249.2K)	0.883	0.699	0.184	20.8%	0.552	0.437	0.115	–21.6°C (–6.9°F/251.6K)	2.4°C
–21°C (–6°F/252.2K)	1.150	0.937	0.213	18.5%	0.720	0.586	0.134	–18.8°C (–1.8°F/254.4K)	2.2°C
–18°C (0°F/255.2K)	1.488	1.248	0.240	16.1%	0.931	0.781	0.150	–16.2°C (2.8°F/257.0K)	1.8°C
–15°C (5°F/258.2K)	1.912	1.652	0.260	13.6%	1.197	1.034	0.163	–13.4°C (7.9°F/259.8K)	1.6°C
–12°C (10°F/261.2K)	2.441	2.172	0.269	11.0%	1.529	1.360	0.169	–10.7°C (12.7°F/262.5K)	1.3°C
–9°C (16°F/264.2)	3.097	2.837	0.260	8.4%	1.941	1.778	0.163	–8.0°C (17.6°F/265.2K)	1.0°C
–6°C (21°F/267.2)	3.906	3.685	0.221	5.7%	2.450	2.310	0.140	–5.3°C (22.5°F/267.9K)	0.7°C
–3°C (27°F/270.2K)	4.898	4.757	0.141	2.9%	3.075	2.986	0.089	–2.7°C (27.1°F/270.5K)	0.3°C
0°C (32°F/273.2K)	6.108	6.108	0.000	0.0%	3.839	3.839	0.000	0.0°C (32°F/273.2K)	0.0°C
3°C (37°F/276.2K)	7.575	NA	NA	NA	4.769	NA	NA	3.0°C (37°F/276.2K)	NA

C = Celsius; F = Fahrenheit; K=Kelvin; hPa = hectopascals; NA = not applicable to ice; AIR TEMP/DP = air temperature (degrees C) for SVP and SMR columns; read as dew point temperature (degrees C) for FROST POINT and DP/FP-DIFF columns; FP = corresponding frost point temperature when air temperature in first column is read as dew point temperature (degrees C); SVP-I = saturation vapor pressure above ice (hPa); SVP-W = saturation vapor pressure above liquid water (hPa); SVP-DIFF = difference (SVP-W minus SVP-I); SVP-PCT = difference as percentage of SVP-W; SMR-I = saturation mixing ratio (grams of water/kilogram of dry air) above ice; SMR-W = SMR above liquid water; SMR-DIFF = difference (SMR-W minus SMR-I); DP/FP-DIFF = absolute difference (dew point minus frost point)

Notes:

Saturation vapor pressure, the maximum water vapor pressure that can exist in air at a given temperature, increases with a rise in air temperature. *Saturation mixing ratio* refers to the mass of water vapor relative to the mass of dry air above either liquid water or ice. This table assumes air temperature measured 2.0 m (6.6 ft) above the runway at an SVP of 1,000 hPa (29.53 in of mercury).

Source: Reinhard Mook

Table 1

Because lower saturation vapor pressure (SVP), the maximum water vapor pressure that can exist at a given air temperature, occurs above ice than above liquid water at a given air temperature, the air temperature–dew point spread exceeds the air temperature–frost point spread under the same physical conditions. Therefore, the spread reported to pilots by METARs is larger than the actual air temperature–frost point spread relevant to the physical processes by which ice forms on a runway. Specifically, air temperature–frost point spread can be close to zero while the METAR's air temperature–dew spread is 1 K or 2 K.

An air temperature–frost point spread will be less than the air temperature–dew point spread. Also, the surface temperature of the runway more often than not will deviate from air temperature. But due to lack of routine runway-surface temperature reports from airports, the 2-m level data must suffice for flight operations.

AIBN-directed research also found, however, that many exceptional cases of uneventful landings on ice or snow occurred even in conditions where a 3-K-or-less spread existed. Therefore, pilots should not assume that such small spreads always mean "definitely poor runway conditions" — instead, the METAR information should be interpreted as an early signal of possible threat.

Applied Micrometeorology

The latest AIBN research essentially recognizes that when the temperature of a solid surface (runway pavement) decreases below freezing and below the dew point of ambient air — that is, the temperature at which water vapor would be saturated above liquid water — water vapor pressure is directed from the air to the solid surface. The lower SVP above ice compared with SVP above liquid water means that hoar frost may appear before the spread drops to 0 K. SVP comes into play because the water vapor in an air mass may be saturated at a temperature 3 K colder than reported in the METAR. A frozen runway surface indicates that these SVP conditions exist in the air mass above the ice.

As hoar frost is crushed and partially melted by the tires of aircraft landing gear, frequently resulting in slippery conditions, the difference between reported dew point and effective frost

Saturation Mixing Ratio Effects

Air Temperature	SMR Change (above liquid water)[1]	SMR Change (above ice)[2]
3°C (37°F/276.2K)	0.930	0.930
0°C (32°F/ 273.2K)	0.764	0.853
–3°C (27°F/ 270.2K)	0.625	0.676
–6°C (21°F/ 267.2K)	0.509	0.532
–9°C (16°F/ 264.2K)	0.412	0.418
–12°C (10°F/ 261.2K)	0.332	0.326
–15°C (5°F/ 258.2K)	0.266	0.253
–18°C (0°F/ 255.2K)	0.211	0.149
–21°C (–6°F/ 252.2K)	0.168	0.114
–24°C (–11°F/ 249.2K)	0.131	0.114
–27°C (–17°F/ 246.2K)	0.103	0.085
–30°C (–22°F/ 243.2K)		

SMR = saturation mixing ratio; Hg = mercury

Notes:

Saturation vapor pressure (SVP), the maximum water vapor pressure that can exist in air at a given temperature, increases with a rise in air temperature. *Saturation mixing ratio* refers to the mass of water vapor relative to the mass of dry air. This table assumes air temperature measured 2.0 m (6.6 ft) above the runway at an SVP of 1,000 hectopascals (hPA; 29.53 in Hg). (1) These changes in SMR occur above liquid water on the runway; they are in grams of water per kilogram of dry air for a 32-kelvin decrease in temperature. (2) These changes in SMR, under the same conditions as the preceding column, occur above ice on the runway.

Source: Reinhard Mook

Table 2

point (the temperature at which the water vapor would become saturated above ice) might become significant to safe flight operations.

In addition to observations about SVP, consideration of saturation mixing ratio (SMR) — the mass of water vapor relative to the mass of dry air — also has helped to explain the 3-K-spread observations. SMRs in Table 2 show that air mass saturation with water vapor may occur with 0 K spread, 3 K spread or any spread between them (see "Interpreting Tables").

This is why the rule refers to a spread of "3 K *or less*" — to remind pilots that the whole interval from 3 K to 0 K is included. In terms of SMR, this means that saturation may occur at the reported air temperature, or in the most extreme case, saturation may occur when the air temperature has decreased by 3 K. With a 0-K spread prevailing, cooling of the air by 3 K means removing water vapor equal to the difference between the SMRs at any two temperatures having that spread.

More research is needed to provide a better understanding of how the transport of water vapor to or from the surface of frozen contamination affects the aircraft braking coefficient. The 3-K-spread rule may depend partly, with a few exceptions, on correlations with precipitation, the vertical gradient of air temperature, the distribution of water vapor close to the surface and the exchange of water at the air-ice interface.

One exception is that the rule does not account for close-to-the-surface, air temperature–dew point phenomena; that is, evaporation or deposition of dew or hoar frost are not explicitly considered by the rule.

Also, for simplicity, the rule does not consider factors such as the vertical gradient of vapor pressure between saturated vapor above liquid water and above ice at the surface, or the difference between air temperature reported at 2 m and surface temperature. Except for the effect of eddy mixing by wind, however, strong gradients in air temperature and vapor pressure will prevail close to any runway surface contaminated by frozen water.

Also affecting the rule's validity is that METARs use rounded numbers, so the actual spread may be even less than reported to pilots. Moreover, by international agreement, the dew point is reported even at temperatures below freezing.

Another exception is that at temperatures below minus 15 degrees C (5 degrees F) or so, the 3-K-spread rule may lose practical value during precipitation-free weather. The reason is that, as air temperature decreases, the frictional properties of ice or compacted snow actually improve considerably. In fact, at minus 30 degrees C, the aircraft braking coefficient on pure ice may be as good as when braking on ice embedded with grains of sand.

However, in the case of precipitation — including accumulations from blowing snow — such an improvement in runway frictional properties could not be expected because there would be an intermediate layer of loose, frozen material. Very slippery conditions may prevail whenever ice or snow has been exposed to the polishing effect of blown particles of ice, especially at low temperatures.

Interpreting Tables

Table 1 shows the SVPs, which are dependent on air temperature, above ice and above water on a runway. The table also shows that in the standard atmosphere, the largest absolute differences in SVP — those greater than 0.260 hectopascals (hPa) — occur from minus 10 to minus 14 degrees C (14 to 7 degrees F). The smaller differences in SVP above water and ice at air temperatures below minus 15 degrees C result from decreasing absolute SVPs.

However, the differences between SVP above liquid water and SVP above ice — expressed as a percentage of SVP-W in the SVP-PCT column — increase with decreasing air temperature. The SVP-PCT column values reflect the increasingly strong bonds of liquid water molecules to the ice with falling temperature.

An example of how close air can be to saturation is that at an air temperature of 0 degrees C (32 degrees F), the SVP above water is 6.108 hPa; the corresponding SVP at minus 3 degrees C (27 degrees F) is 4.898 hPa. That indicates relative humidity of 80 percent for this 3-K spread.[4] At the other extreme of the table — minus 27 degrees C (minus 17 degrees F) and minus 30 degrees C (minus 22 degrees F) — the corresponding SVPs are 0.673 and 0.509 hPa, so this 3-K spread yields a relative humidity of 76 percent, or possibly higher.

To quantify the range of the amount of water covered by the 3-K-spread rule, Table 1 also shows the SMR for air at 1,000 hPa above liquid water (SMR-W column) and above ice (SMR-I column). The largest differences (SMR-DIFF column) in gram water vapor (grams per kilogram of dry air) above liquid water and above ice are found between minus 10 degrees and minus 14 degrees C, that is, the interval with the largest differences in SVP.

The SMR-W and SMR-I columns show that the respective SMRs at minus 3 degrees C are approximately 10 times larger than those at minus 30 degrees C. For that reason, pilots should not expect that the 3-K-spread rule, or any rule based on a certain fixed spread, can be valid for any temperature.

If the SVP of the air above liquid water — and, logically, the SMR — exceeds the corresponding SVP above ice, the frost point for a certain mass of air will be higher/warmer than the dew point. Reading the Table 1 AIR TEMP/DP column values as dew points, the corresponding frost point temperatures are found under the FROST POINT column, and the spreads are found in the DP/FP-DIFF column. Typically, the dew point vs. frost point differences will be on the order of 0.1 K times the Celsius dew point, a negative number. For example, when a dew point of minus 15 degrees C is reported, the frost point will be about 1.5 degrees K warmer — that is, about minus 13.5 degrees C (7.7 degrees F).

The 3-K-spread rule only refers to dew point because, as noted, METARS report only dew point even at air temperatures below freezing. However, by extrapolating frost point from dew point as above, the spread in that example can be estimated to be 1.5 K. As dew point moves toward lower/colder values, however, the difference between dew point spread and frost point spread shrinks. With an extrapolated frost point, the rule becomes useful even at temperatures as low as minus 15 degrees C or so, although other effects should be considered.

Table 2 shows the maximum amount of water removed from air above the runway when the spread is 3 K or less and the air temperature then decreases by 3 K. If the spread is 3 K and the temperature drops by 3 K, no water will be removed. However, if the spread is 0 K, an amount of water equal to the difference of the SMR in the 3-K temperature interval will be the maximum amount of water removed. For example, at air temperature of minus 3 degrees C with a spread of 0 K, a 3 K drop in air temperature would mean water vapor removal of 0.625 g per kg above liquid water and 0.676 g per kg above ice. The actual amount will differ, depending on whether the spread is 3 K or less.

Table 2 also shows that the SMRs above ice decrease more strongly — that is, each change is larger per 3-K drop — than the SMRs above liquid water at temperatures warmer than minus 13 degrees C (9 degrees F). This is consistent with the relationships among SVPs in Table 1.

At temperatures even lower than these, a decrease of SMR above water on a runway will exceed a decrease of SMR above ice on a runway because the air above liquid water is dried less at higher/warmer temperatures than the air above ice. If we compare temperatures near the 0-degrees C freezing point with those near minus 30 degrees C, the SMRs decrease by a factor of about 0.1 for each 3K decrease. This underscores the basic principle that small amounts of water vapor exert significant effects on landing safety at low temperatures, even though the spread may be small.

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Notes

1. AIBN. "Winter Operations, Friction Measurements and Conditions for Friction Predictions." Statens Havarikommisjon for Transport, Lillestrøm, Norway. May 2011.
2. Each kelvin, the standard unit of measurement for expressing temperature differences in micrometeorology and other physical sciences, has the same magnitude as one degree C. Absolute zero — 0 K on the Kelvin scale — is equivalent to minus 273.15 degrees C (minus 459.67 degrees F).
3. Lande, K. "Winter Operations and Friction Measurements." In "International Cooperation: From Investigation Site to ICAO," Proceedings of the International Society of Air Safety Investigators 38th annual International Seminar (Vol. 11), Aug. 27–30, 2007, Singapore, pp. 31–45.
4. That is, 4.898 divided by 6.108 times 100.