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SUITABILITY OF ICE FOR AIRCRAFT LANDINGS

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Abstract--The thickness of ice required for aircraft landings on skis can be calculated from the following formulas:

$$S_r = (15/4)\sqrt{W_t};\quad S_\ell = (27/8)\sqrt{W_t};\quad S_s = (27/4)\sqrt{W_t}$$

S_r is the thickness in inches for river ice, S_ℓ for lake ice, and S_s for old sea ice. W_t is the weight of the plane in tons. These formulas allow for the static weight of the plane and its dynamic impact at the time of landing. The thicknesses calculated are for ice formed at or below 16°F. For ice formed at higher temperatures the thicknesses must be increased by about 25 per cent. S_s is for old sea ice. Young sea ice is weaker and must be about three times as thick as river ice. Planes on wheels require about 20 per cent greater thickness than calculated from the above formulas. Ice is stronger at lower temperatures, and its strength increases about four times between 23°F and - 76°F. Salt, air bubbles, included vegetation, cracks, and heavy snow cover all make ice weaker. Ice also experiences elastic fatigue under constant heavy use and must be rested frequently.

Freeze-up usually takes place many days or even several weeks after the mean air temperature falls below freezing. After the water temperature reaches freezing, the rate of formation and growth of ice may be predicted from a curve of degree days of frost or calculated by formula.

Salinity retards freezing by lowering both the freezing point and the maximum-density temperature. Currents, waves, and snow cover also retard the growth of ice, but under proper conditions wind can be an asset. Ice continues to increase in thickness well beyond the period of minimum air temperature. Thereafter, it maintains its maximum thickness for a short time before showing a rapid decrease just prior to break-up. Ice deteriorates considerably in spring, and its strength decreases more rapidly than its thickness. This is particularly true of lake ice which "candles." Salty ice honeycombs extensively.

The surface of most frozen fresh-water bodies is usually suitable for landings, but sea ice is often rough and broken. However, many successful landings and take-offs have been made from the ice pack, and a suitable place can frequently be found. Firm, wind-packed snow can have a bearing strength of 100 to 200 lb/in^2, but wind-swept surfaces are often rough owing to drifts and sastrugi.

Introduction--The following is strictly an office compilation from a variety of sources. It contains no original material and is not based on the experiments or field observations of the compiler, who is no cryologist. These data were assembled during World War II and issued as a preliminary report of the Arctic, Desert, and Tropic Branch of the Army Air Forces Center. The report has been cleared for publication by the United States War Department and is reproduced here in essentially its original form.

The major aim is to provide information pertinent to some aspects of aircraft operations on ice, particularly landings. The formation of ice, some of its physical characteristics, and other factors affecting its suitability for aircraft operations are considered briefly. These matters are not treated from a geographical standpoint, although an attempt is made to provide some means by which approximate thicknesses of ice in remote regions can be predicted.

Problems of ice in relation to aircraft landings have been most fully studied by the Russians. Digests of this Russian information and considerable data from other sources have been made available through the cooperation of A. D. Bajkov, formerly of the Air Technical Service Command, United States Army Air Forces. Much of this compilation should be credited to Bajkov.

Formation of ice--It is now generally concluded that H_2O molecules are at least temporarily bonded together in twos and threes [see "References" at end of paper, DORSEY, 1940]. The single molecule, H_2O or hydrol, is water vapor; the double molecule, $(H_2O)_2$ or dihydrol, is water in the liquid form; and the aggregate of three molecules, $(H_2O)_3$ or trihydrol, is ice. With increasing temperature dihydrol (water) tends to change to hydrol (water vapor) and with decreasing temperature to trihydrol (ice). The significant relation here is that dihydrol (water) contains trihydrol (ice) in solution. At 100°F water is said to contain 16 per cent ice in solution, and this rises to 37 per cent approaching the freezing point [BARNES, 1928], although these figures may not be universally accepted [DORSEY, 1940]. At the freezing point water becomes a saturated solution, and ice is precipitated. Super-cooled water behaves essentially like any supersaturated solution.

Dissolved salts lower the freezing point and produce a significant difference in the freezing temperature of fresh and sea water as shown in Table 1. Average sea water has a salinity of 35 parts per thousand and freezes at 28°.6 F [WORDIE and ROBERTS, 1944].

Table 1--Salinity and freezing points

Salinity	Freezing points	
parts/1000	°C	°F
0	0	32
5	- 0.3	31.5
10	- 0.5	31.1
15	- 0.8	30.6
20	- 1.1	30
24.695	- 1.332	29.61
25	- 1.35	29.57
30	- 1.6	29.12
35	- 1.9	28.58
40	- 2.2	28.0

Salinity also affects the freezing point through its influence on density [WORDIE and ROBERTS, 1944]. Fresh water reaches its maximum density at 39°.2 F, so density currents do not develop with further cooling, and only the surficial layer need be cooled to the freezing point before a layer of ice can form. Conduction complicates this simplified picture to some degree. Water with a salinity of 5°/00 has its greatest density at 37°.2 F, so the entire body of water must be cooled to that temperature before density currents cease. The maximum-density temperature and the freezing temperature approach each other as salinity increases. They coincide when the salinity is 24°.695/00. This means that with a salinity of 24°.695/00 or more density currents operate clear down to the freezing point, and the entire water body must be cooled to this temperature before a layer of ice can form on the surface. The rapidity of cooling and the total drop in temperature are often so great and density currents so slow that ice probably does form in nature before the temperature of the entire body is lowered to the freezing point. Regardless of this, it is clear that salinity retards freezing by lowering the maximum-density temperature as well as by lowering the freezing point.

Heat is lost from water chiefly by conduction, convection, radiation, and evaporation, and any factors affecting these processes are significant in the formation and growth of ice.

Zenith angle of the sun, and therefore latitude, are important because with a low sun water surfaces reflect a considerable part of the solar radiation. The following information and figures are from DEVIK [1944]. In northern latitudes in winter the heat received from direct solar radiation and from diffused radiation is far below the amount of heat lost from the water. Loss of heat by infrared radiation is nearly three times as great with a clear sky as with a complete cloud cover. Heat loss by convection is controlled by temperature difference between the water surface and air and is increased by wind. At 14°F air temperature, water temperature 32°F, and no wind, the heat loss by convection is 18.1 cal/in^2/hr. With a wind speed of 1.12 mph the heat loss increases to 74.2 cal/in^2/hr. Heat lost by evaporation depends largely upon vapor pressure gradient and wind. At air temperature 14°F, water temperature 32°F, a vapor pressure 2.6 mm mercury, and no wind, the loss by evaporation is 10.9 cal/in^2/hr. Under the same conditions but with a wind speed of 1.12 mph it is 40.7 cal/in^2/hr [DEVIK, 1944]. Although wind aids cooling by increasing heat loss through convection and evaporation, it retards freezing by disturbing the surface of the water. However, freezing during a calm following a windy period is benefited by the cooling produced by the wind. Once a layer of ice is formed, wind can aid its growth by blowing away the snow that falls on its surface or by packing the snow more firmly and thereby reducing its power of insulation.

At 14°F, vapor pressure of 2.6 mm mercury, zero wind velocity, no cloud cover, sun altitude 5°, and water temperature 32°F, the total heat lost exceeds the heat gained by 94.8 cal/in^2/hr. With all conditions the same except for a wind velocity of 1.12 mph and cloudiness ten, the heat lost exceeds the heat gained by 150 cal/in^2/hr. In the first case ice will be produced at 0.079 in/hr and in the second at 0.126 in/hr [DEVIK, 1944].

Snow falling into water has a cooling effect, but this is likely to be relatively insignificant except when the water is already close to freezing. However, at this temperature snowflakes aid freezing both by cooling and by providing nuclei around which ice crystals develop.

Water cools slowly and its surface temperature always lags behind the rise and fall of the mean air temperature. In the Murmansk-White Sea area, rivers usually freeze about three weeks after the mean air temperature falls below 32°F. This is probably representative for many similar regions. Lakes usually freeze a little earlier. Inland waters containing much vegetation do not freeze as quickly as clear water, and swift currents in rivers obviously retard freezing and may even prevent it.

The following factors facilitate the formation of ice in the sea: (1) Freshening of the water by precipitation, rivers, or melting of ice; (2) hindrance of wave and other water motion; (3) presence of floating chunks of old ice which cool the water and reduce wave motion; (4) shallow water; (5) lack of currents; and (6) lack of storms [SMITH, 1932, and TRANSEHE, 1928].

Freezing of sea water is first indicated by a greasy or oily appearance and shortly thereafter small spicules and plates called "frazil ice" become visible. Frazil ice increases until the water is covered with a mush of crystals called "slush" or "sludge." This material gradually agglomerates into roughly circular flat masses called "pancakes," and the pancakes are eventually cemented together to form "floes" and "sheets" [WORDIE and ROBERTS, 1944]. Ice formed on bodies of fresh water is usually relatively clear and smooth, but in the sea such ice forms only in protected coves and narrow lanes or leads cutting through the ice pack. In fast-running streams spongy accumulations of frazil ice on the bottom and along the shores are usually the first phase in the freeze-up [DEVIK, 1944].

Growth and thickness of ice--Heat loss at the rate of 120 cal/in^2/hr causes ice to form at the rate of 0.1 in/hr if the water temperature is 32°F [DEVIK, 1944]. Newly formed ice may grow to a thickness of four or five inches in the first 48 hours. Thereafter growth is slower. Once a solid layer of ice is formed, further growth depends chiefly upon conduction of heat through the ice to the colder air above, and this in turn depends upon the steepness of the temperature gradient. The effect of an increasing ice thickness and a snow cover upon heat loss is illustrated in the following diagram, Figure 1. Evaporation from the ice surface and radiation, which takes place only when the ice is clear and its surface free of snow, play a small part. Convection currents in the water usually retard the growth of ice. Sea ice seldom grows to a thickness greater than five to seven feet in the first year. If unbroken through the second winter, the thickness may reach seven to eight feet at the most. Ice in the far northern rivers and lakes can grow to a thickness of six to eight feet in a single season. With rare exceptions this fresh-water ice disappears entirely in summer, but sea ice is perennial in the Polar Basin. Perennial sea ice may grow in thickness during the summer by the following means. Snow on the surface melts, and the water runs down through cracks and holes to form a layer of fresh water under the ice. Since the temperature of the underlying salt water is usually lower than the freezing point of fresh water, a layer of fresh-water ice is formed on the bottom of the sea ice [WORDIE and ROBERTS, 1944].

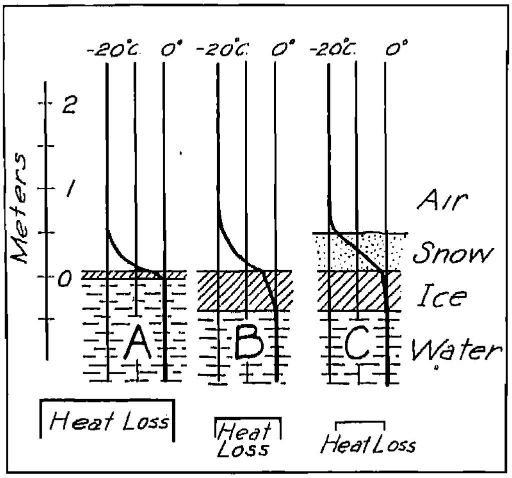

Fig. 1--Thermal gradient and heat loss through: A, thin ice; B, thick ice; C, thick ice and snow [after Devik]

Ice in the Polar Basin is seldom less than 3-1/2 to 4-1/2 feet thick, and Nansen [ZUBOV, 1940] reports a maximum thickness of 13 ft ten inches produced by about four years of normal growth. Much greater thicknesses can be formed by rafting, tidal overflow, other types of flooding, spray, and splashing. Ice in hummocks and pressure ridges sometimes attains a thickness of 50 to 100 feet.

The rate of growth of fresh-water ice may be calculated by Formula (1) [BARNES, 1928]:

$$t = (LSE/K\theta)(1 + E/2) \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which t is the time in seconds for the ice sheet to attain a thickness E in centimeters; L is the heat of fusion, 80 cal/gm; S is the density of ice, 0.9166; K is the conductivity of ice, 0.0057 cal per degree difference of temperature C, per cm^2, per sec; and θ is the difference in temperature, C, between the underside of the ice sheet, assumed 0°C, and the air temperature.

Table 2 provides examples of the results obtained from (1) with the above assumptions. Thicknesses are converted from centimeters to inches and temperatures from Centigrade to Farenheit.

Table 2--Rate of growth of an ice layer

Thickness of ice	Temperatures			
	14°F	- 4°F	- 22°F	- 40°F
in	day	day	day	day
1	0.086	0.043	0.029	0.021
6	1.95	0.98	0.65	0.49
10	5.19	2.60	1.73	1.29
12	7.38	3.69	2.46	1.85
24	28.60	14.30	9.53	7.15
36	63.69	31.85	21.23	15.92

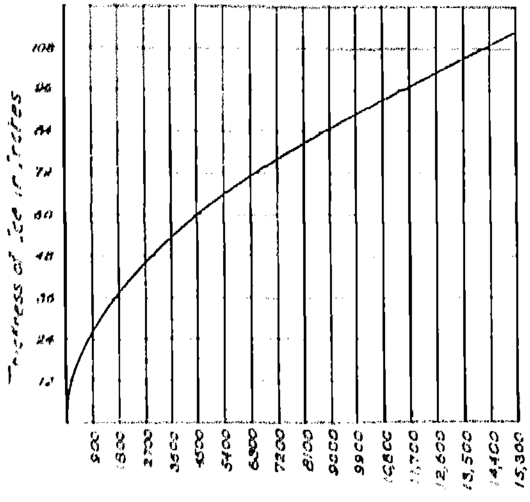

Fig. 2--Rate of growth of ice

The approximate thickness of ice may be predicted from the curve of Figure 2 if the temperatures at a specified locality are known. Even if exact temperatures are not available estimates can probably be made from a general knowledge of weather conditions in the region. In calculating the degree days of frost it must be remembered that 0°F is 32° of frost. Furthermore, it is better to add up the mean number of degrees of frost for each day or group of days having about the same mean degrees of frost than to make a single calculation using a large number of days and a mean figure for the degrees of frost for the entire period. Days on which the temperature was below freezing for only part of the 24 hours can be ignored unless exceptionally numerous, and excessive refinements in calculation of degree days of frost are neither necessary nor justified. Examples of calculations of degree days of frost follow. Assume a specified day had eight hours below freezing, and the mean temperature for those eight hours was 23°F. The degree days of frost for that day are 8/24 × 9 = 3. Suppose the next day had temperatures below freezing for the entire 24 hours, and the mean temperature was 20°F. The degree days of frost for this day are 12. If the next ten days had approximately uniform mean temperature, say - 20°F, and all hours were below freezing, the degree days of frost for the ten days are 520. The total degree days of frost for the 12-day period described above would be 535. A glance at Figure 2 shows that the curve permits considerable approximation in calculating degree days of frost without seriously affecting the final results. Obviously other factors such as wind, snow, and currents introduce complications difficult to evaluate and not allowed for in the graph. The lowermost end of the curve is none too reliable because freezing weather may exist for a number of days before ice starts to form. Once a layer of ice has begun to form, the curve is much more reliable unless thawing occurs.

Weekly measurements of ice thickness in far northern harbors [BERNIER, 1910, and LOW, 1906] give curves which rise steadily for two-thirds to three-fourths of the total period, flatten off briefly, and then drop abruptly just prior to breakup.

Physical nature and structures of ice--Ice is reported to precipitate as a colloid from water super-cooled by as little as a few thousandths of a degree [BARNES, 1928]. The colloidal particles agglomerate and form plate- and spicule-shaped crystals [BARNES, 1928]. In calm fresh water, ice forms long hexagonal prismatic crystals arranged perpendicular to the water surface. If undisturbed these crystals grow into long pencils equal to the thickness of the ice layer. Freshened sea ice may also develop this structure, but young sea ice is said to consist of an uppermost one-half-inch layer of thin horizontal ice plates about the size of a fingernail with the ice beneath consisting of vertical prismatic crystals [WORDIE and ROBERTS, 1944]. Some young fresh-water ice has a similar arrangement. Ice crystals have gliding planes parallel to the base, but experiments show that aggregates of parallel prismatic crystals may yield more readily along the prismatic face than along the base [MATSUYAMA, 1920].

New sea ice usually contains five to 15°/00 salt. Ice formed slowly or in calm weather has less salt than ice formed rapidly or in rough weather. For example, young sea ice formed at 14°F has four to 6°/00 salt, but that formed at - 40°F has ten to 15°/00 [WORDIE and ROBERTS, 1944]. As sea water freezes, a network of fresh-water crystals develops, forming pockets which contain salt water. The crystals grow at the expense of this brine, which becomes progressively heavier and more concentrated. Depending upon the temperature, this brine may or may not freeze, and even if it does freeze it thaws readily with rising temperature. Its high salinity and weight enable it to melt a path gradually downward through the ice, and the flushing-out process is facilitated by rising temperature and thawing. In this manner salt-water ice becomes fresh and changes from greasy, streaky and opaque to more or less granular, brittle, and clear, as well as increasing in strength. Hummocking hastens the freshening process by providing cracks for drainage and by lifting the ice above its surroundings so that the brine flushes out more easily.

Arctic sea ice contains three to ten per cent air, and fresh-water or brackish-water ice contains about two per cent air. Small air bubbles are spherical, but many of the larger ones are elongated vertically into thread-like tubes. Different horizontal layers of ice may contain differing amounts of air. Usually ice formed quickly or in rough weather contains more air than that formed slowly or in quiet weather [BAJKOV].

Several high-pressure forms of ice are known from laboratory studies, but none has been found in nature [DORSEY, 1940, and SELIGMAN, 1936].

Strength of ice--The strength of ice is dependent upon a wide variety of conditions, some of which will be treated following a simplified consideration of the thickness of ice required for aircraft landings.

Several empirical rules concerning the thickness of ice able to support various loads have been developed. Unfortunately, these do not usually specify the nature of the ice, its conditions of formation, or its environment. A familiar example of such rules are those stating that two inches of ice is considered safe for infantry, four inches for cavalry or light guns, six inches for heavy field guns, and eight inches for loads on sledges weighing not over 1000 lbs per square foot. Blind application of such empirical rules may lead to trouble. The Russians have done considerable work with the loading strength of ice and landings of aircraft thereon. Much of the following material has been derived from their reports [BAJKOV, MOSKATOV, 1938 a and b].

If some data are already available on the various loads borne by ice of known character and thickness, they can be extrapolated, for the required safe thickness of ice is directly proportional to the square root of its tolerable load. Thus, if it is known in a specific locality that a certain thickness of ice, S_1, will bear a load, L_1, then by simple proportion the thickness, S_2, needed to carry a load, L_2, can be calculated as:

$$S_2^2/S_1^2 = L_2/L_1 \text{ or } S_2 = \sqrt{L_2 S_1^2/L_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

For aircraft landings, both the static load of the plane and the dynamic load or impact at time of landing must be considered. The usual Russian practice is to take six times the static weight of the plane as safely equivalent to these loads combined. Therefore, to obtain the thickness of ice necessary for a plane landing from data for static loads the formula will be

$$S_2 = \sqrt{(S_1^2 \times 6W_p)/L_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

in which W_p is the static weight of the plane. If the thickness of ice for landing of a plane of specified weight is already known, the formula can be used in the form first given.

It is known that fresh-water ice is about three times as strong as salt-water ice. This introduces a factor $\sqrt{3}$ in the formula for converting data from fresh-water ice to salt-water ice, thus:

$$S_s = 1.732 \sqrt{(S_{fw}^2 \times L_2)/L_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

in which S_s = thickness of sea ice; S_{fw} = thickness of fresh-water ice.

From various accumulated data the Russians have developed the following simplified formulas for landings of aircraft with skis:

$$\left.\begin{aligned} S_r &= (15/4)\sqrt{W_t} \\ S_\ell &= (27/8)\sqrt{W_t} \\ S_s &= (27/4)\sqrt{W_t} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

S_r is the thickness of river ice, S_ℓ of lake ice, and S_s of sea ice, in inches, and W_t is the weight of the plane in tons. These formulas apply to ice formed at or below 16°F. For ice formed at higher temperatures the thicknesses should be about 25 per cent greater. Lake ice is generally about ten per cent stronger than river ice. Probably no airplane, even the lightest, should attempt to land on fresh-water ice less than six inches thick. The S_s in the third formula above is for old sea ice, which is stronger than young sea ice. The required thickness of young sea ice is about three times that of river ice.

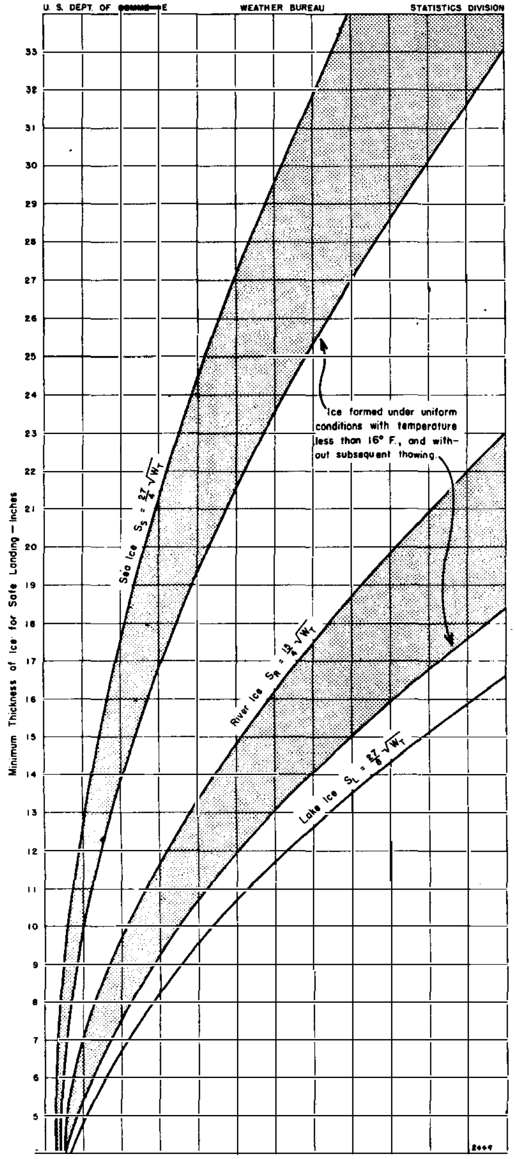

Fig. 3--Minimum thickness of ice required for safe landings of aircraft on skis [after U. S. Weather Bureau]

The curves of Figure 3 have been constructe from the above formulas. For planes on wheels the ice thickness should be about 20 per cent greater. Allowances must be made for major cracks and other structural weaknesses.

The above data can be checked by the following theoretical calculations. It is known that a roughly circular area with a radius of about 30 meters bears the load of an object the size of an aircraft on the ice surface. On this basis Formula (6) may be used to determine the ice thickness required for a specified load:

$$S_b = (18KP/\pi T^2)(1 - 2r_o/3r) \ldots \quad (6)$$

in which S_b is the maximum breaking strength taken as 30 kg/cm^2 for fresh-water ice and 15 kg/cm^2 for salt-water ice; K is a coefficient taken at 0.5; r is the radius of a circular plate bearing the load taken at 30 meters; r_o is the radius of circle upon which the load is concentrated--this is the size of the skis calculated as a circular area; P is weight of the plane in kg; and T is necessary thickness of ice for safe landing, in centimeters.

Substituting the figures for river ice and rearranging we get

$$T_r = \sqrt{3 \times 0.5[1 - (2r_o/3r)]6P/3.14(30)} \quad . \quad (7)$$

This can be simplified, since $(1 - 2r_o/3r)$ can be taken as unity. Then $T_r = 0.31\sqrt{P}$. This gives thickness of river ice in cm with weight of plane in kg, or $T_r = 3.68\sqrt{P}$ gives thickness in inches with weight in tons. This is very close to the $S_r = 15/4\sqrt{W_t}$ given above, as 15/4 = 3.75. Thus the theoretical and analogical methods check.

Salt makes ice plastic and weak [BRUCE, 1911], and sea ice becomes stronger as it freshens in the manner previously described. Newly formed sea ice less than six inches thick may bend under the weight of a man [BROWN, 1927]. It is probably unsafe for heavily loaded sledges and obviously unsuited for plane landings. Most sea ice has a breaking strength of ten to 15 kg/cm^2 in contrast to the 30 kg/cm^2 of fresh-water ice [MOSKATOV, 1938 a and b]. The crushing strength of ice ranges from 327 to 1000 lbs/in^2 and increases as the temperature falls, increasing four times between 23°F and - 76°F [BAJKOV]. Falling temperature, however, leads to contraction and cracking of ice and may weaken an ice layer even though water rises in the cracks and seals them. The tensil strength of ice is about one-third its crushing strength. Vegetation included within the ice makes it weaker.

Ice covered with a thick layer of snow is weaker because it is warmer, and ice becomes much weaker in spring for various reasons treated in more detail elsewhere. An abundance of parallel thread-like air bubbles in some ice decreases its strength considerably.

Ice shows the phenomenon of elastic fatigue and will bend or sag under continual stress [HAYES, 1937]. Constant travel of heavy loads over ice causes fatigue and further weakens it by opening and widening cracks. A fast-traveling plane on take-off or landing sends a wave through the ice before it and is followed by another wave. These waves cause fatigue and set up stresses which can be released by boring small holes through the ice [HAYES, 1937]. Heavily used runways on ice should be given frequent rest periods to allow recovery from fatigue and sealing of cracks.

Role of snow--Snow is important with regard to aircraft landings on frozen water bodies because more often than not it constitutes the surficial material. Since it is an excellent insulator it also exerts considerable influence on the rate at which ice forms and the thickness attained.

A common assumption in the North is that heavy snow in the fall means a rapid break-up in spring.

Snow constitutes an extra load on the ice and keeps it warmer, therefore weaker. These disadvantages are partly offset if the snow is well packed. Hard-packed snow does not retard the growth of ice nearly so much as loose snow and has a considerable bearing strength of its own. Wind-packed snow without benefit of thaw may have a bearing strength between 100 and 200 lbs/in^2 [BAJKOV]. Firm, wind-packed snow of this type is found chiefly in unforested northern areas where strong winds prevail. In such areas the snow tends to be firmly packed throughout, not just on the surface. In other regions a surficial crust on soft fluffy snow may give a misleading impression of the strength of a snow cover.

The snow on areas of ice to be used frequently for landings should be scraped or rolled. Scraping allows a greater thickness of ice to develop, but rolling is preferred in some quarters, possibly because of the bearing strength of firmly-packed snow, or because of unevenness in the underlying ice. In one instance the ice under an area scraped six days before was 16 inches thick and that under a nearby uncleared area was only 12 inches [HAYES, 1937]. Air temperatures during this period are not known. Another good reason for clearing snow from the ice is the prevention of slush formed if water gains access to the snow through cracks or by other means. Several inches of ice are destroyed by formation of the slush, which refreezes slowly even at air temperatures well below zero [HAYES, 1937]. If the snow cover is very thick, water forced up through holes and cracks in the ice forms a layer of slush with the lowermost snow which is entirely hidden by the overlying unaffected snow [DEPARTMENT OF NATIONAL DEFENSE, 1944]. The potential dangers of this situation are obvious. A snow cover on ice constitutes a further hazard by hiding weak spots which might otherwise be apparent from the air. Weak spots in the ice on inland water bodies can sometimes be identified by animal tracks leading up to but not across them. In any case the snow should be cleared from an area larger than that actually needed for operation, so that cracks and holes in the nearby ice have a chance to freeze. Snow should not be piled close to the runway, as it weakens the ice. If the surface of the ice beneath the snow is rough, scraping is obviously out of the question.

Even loose powdery snow changes progressively throughout the season without benefit of thawing. It becomes more granular and better packed. The increase in grain size is due to condensation of moisture from the atmosphere and the transfer of vapor from the vicinity of small grains to larger grains where ice is deposited. This takes place because the vapor pressure around ice grains is inversely proportional to the radius of curvature and is higher around small grains than large ones [SELIGMAN, 1936]. The surface of snow in wind-swept regions, although firm, is often rough in detail, owing to the formation of drifts, barchans, and sastrugi. Sastrugi are small ridges of hard-packed snow up to two feet high and ten to 15 feet long arranged parallel to the prevailing wind direction. They are capable of upsetting almost any plane on wheels or skis. Barchans are similar ridges lying transverse to the wind.

Nature of ice surface--The rough surface on sea ice more often limits its use for aircraft operations than thickness or strength. The surface of river and lake ice is usually smoother. Much sea ice is broken, rafted, pushed into hummocks and cracked by tides, winds, and currents in such a way as to make it wholly unsuited for aircraft operations. The open ice pack of summer consisting of separate ice fragments is obviously unsuited for aircraft landings unless some of the floes are exceptionally large. In winter much of this open pack refreezes with a surface that is too rough for aircraft landings until covered with snow. This is true in many of the fiords of East Greenland [WATKINS, 1932]. The closed pack may be suitable both winter and summer, 'although one polar flier has estimated that fully 90 per cent of the Arctic ice pack is unsuitable for aircraft landings [BYRD, 1928]. However, there have been many successful landings and take-offs from the Arctic pack, and suitable areas can usually be found [MOSKATOV, 1938 b, and ZUBOV, 1940]. Along low lagoon-fringed Arctic shorelines, like the north coast of Alaska, large areas of smooth flat ice are available for winter landings [WILKINS, 1928 a and b].

Springtime melting can make an ice surface very rough. Salty sea ice becomes soft and honeycombed in spring even though the air temperature remains below freezing [DEPARTMENT OF NATIONAL DEFENSE, 1944]. It is advisable to avoid areas of ice covered with melt water because the surface beneath is likely to be pitted and rough. However, it is true that melt water standing on ice is an indication of the soundness of that ice. As thawing progresses the water disappears into the ice, indicating that it is honeycombed and therefore weak and unreliable [DEPARTMENT OF NATIONAL DEFENSE, 1944]. After the melt water runs off, the ice surface is dry, white, soft, and sticky. Sometimes in spring, water on the ice refreezes surficially, leaving a layer of slush beneath. This bad condition is to be expected following a cold snap during break-up.

Fresh water, particularly in lakes, freezes to a firm smooth surface, but rivers may have areas of very rough ice if the current is swift and early ice has been broken up prior to final freezing. Ice on rivers may be dangerously thin over areas of fast-flowing water because of erosion on the underside. The surface on newly formed sea ice is sticky even at low temperatures, and sledges, skis, and other sliding surfaces do not move over it easily [BRUCE, 1911]. The Russians have been able to produce smooth surfaces on some areas of ice by pumping water onto the surface. This is likely to be unsatisfactory if the snow cover is at all heavy, for the snow and water form a slush which freezes slowly.

Melting and breakup--Ice and snow are melted by radiation from the sun and by heat conduction from the air, rocks, and water. Another less commonly recognized mode of melting is by condensation of warm moist air. This can be an important factor, for the moisture so condensed melts up to 7-1/2 times its own weight in snow [LIGHT, 1941].

Heat is more readily transferred through air by eddy diffusion than by molecular conduction. Thus, melting is likely to be greater with a wind than with calm air, and moist wind is a better melting agent than dry wind of the same temperature because of the melting caused by condensation. Cooling by evaporation in the case of dry wind helps to make it less efficient as a melting agent. Pressure facilitates melting by lowering the melting point, but below - 7°.6 F (- 22°C) pressure will no longer cause melting.

In spring, as the snow on the surface melts, the ice is covered with water. With continued thawing the ice becomes honeycombed with passages and holes into which the surface water drains.

Sea ice less than a year old is still somewhat salty and melts more readily than the older salt-free floes. It also honeycombs extensively as it melts. In spring, land-fast sea ice usually melts first near shore because of the relatively warm water which runs onto it from the land. Wind, waves, currents, and rivers aid break-up and melting by mechanical means.

In spring, lake ice "candles." That is, it separates into long pencil-like crystals by melting of intercrystal films [BUCHANAN, 1908]. These crystals slide past each other easily, and ice two feet thick may not bear the weight of a man. In spring, extreme caution must be used in making aircraft landings on lakes.

Break-up on rivers usually occurs three or four weeks after the mean air temperature has risen above 32°F. Ice on lakes breaks up two or three weeks later, and sea ice may break up about this same time.

Operations on ice--Landings on ice are easier to execute than take-offs owing to unevenesses in the ice surface. Planes operating on crusted snow should be careful not to break through the crust in turning.

Frequent measurements of ice thickness under and around a landing area should be made in spring, or even daily throughout the period of operation if the ice overlies flowing water. Measurements can be made by boring a hole through the ice with an auger. The lower part of such a hole is likely to be cone-shaped, so a hook or L-shaped rod should be used to measure thickness of the ice adjacent to the hole [HAYES, 1937]. Measurements made directly in the hole are likely to be in error. The breakup may be preceded by a rapid thinning of the ice, though break-ups can and do occur without any great amount of previous thinning. In high Arctic latitudes ice airdromes could be operated the year around, but any heavily used runway on ice should be given frequent periods of rest to permit recovery from fatigue and sealing of cracks.

Other things to be kept in mind are the notoriously poor depth perception in snow-covered terrain, and the tendency of skis to freeze immediately to ice or snow.

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