ICING ON AIRCRAFT

by

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Submitted in Partial Fulfillment of
Requirements for the Certificate in
Meteorology.

Meteorology Dept.
Calif. Inst. of Tech.
February 3, 1942

INTRODUCTION

Icing on aircraft becomes a factor of major importance in these days of all-weather flying. In certain circumstances aircraft may become heavily loaded with ice, particularly, but not entirely, over leading edges of wings and other parts, and the effect on flight may be serious. In mild cases it may only render the radio useless by coating the antenna and causing it to break away. In other cases the carburetor intake may be choked or the controls jammed by it, but the greatest danger probably lies in the effect on the performance of the aircraft, due to the sheer weight of accumulated ice, or mainly to the disturbance of the aerodynamical properties of the supporting surfaces causing loss of lift and setting up vibrations sufficient in magnitude to throw the aircraft out of control or even to cause structural failure. While not all icing is as violent as this, mild cases can be very dangerous in that it may cause vital instruments to become useless.

I

THE PHYSICS OF ICE FORMATION

In studying icing, there are three different types of ice to be considered.

One is clear or glaze ice which is clear and hard with a smooth and glassy appearance, although when mixed with sleet or snow it may have a rough appearance. It is very difficult to dislodge when formed to any appreciable thickness. This type of ice is the most dangerous because of the above reason and also because of the blunt shape it assumes as it freezes on the leading edge of the wing or strut with its frontal area enlarged.

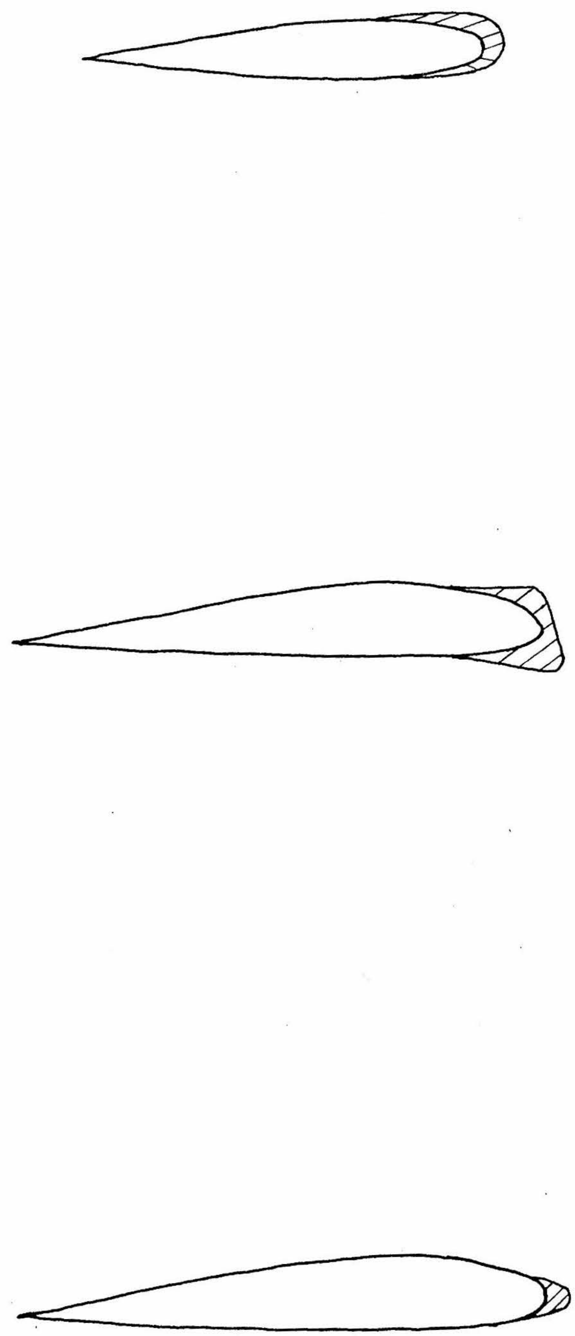
The second type of ice is called rime ice. It is pure white, opaque, and granular in structure. It consists of tiny ice pellets which have little cohesion or adhesion. Rime builds up into sharp nosed deposits on leading edges and does not alter the form of the airfoil to any extent, although its additional weight and the increase in drag caused by it building up very much will be noticed. Ordinarily this type of ice does not build up to large amounts because it is easily shaken off by vibration. For that reason if is seldom a dangerous type of ice. However, at low temperature, the tenacity of this form of ice increases and the formation, if prolonged, soon reaches dangerous proportions.

The third and least dangerous type of ice is frost. It is a light crystalline formation and never assumes any degree of magnitude. There are certain cases where this type will be slightly dangerous because of a light, rough deposit on an airfoil, destroying some of its lifting characteristics. However, the length of time that this deposit will remain is short, because as soon as the airfoil reaches a temperature equilibrium with the surrounding atmosphere, the frost will melt, providing the temperature is above freezing.

The types mentioned above are the pure types. In the case of the first two there can be, and are, many intermediate grades between the transparent ice and pure white rime. The most common type is of a semi-opaque nature, similar to partially melted and refrozen snow. Diagrams showing the characteristic shapes of rime and clear ice will be found on the following page.

Most meteorologists agree that there are two prerequisites for any type of serious icing on aircraft. One is that there must be liquid water present and the other is that the temperature must be 34°F. or below. There are special cases in which these conditions do not hold, but the type of ice formed is not dangerous to any large extent.

Liquid water must be present because precipitation in the frozen or solid form before striking the aircraft will not adhere to it but will be blown away. In order for this liquid water to be present, it must usually



SOME IDEALIZED FORMS

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be in the form of supercooled water. This is an important fact because, as it is known from experiments, agitation of this supercooled water will cause solidification. The necessary agitation in this case is accomplished by an airfoil moving through this subcooled water and the resultant impact of the drops on the airfoil.

In determining the type of ice to be formed, the icing time, or the time it takes for the ice to form is of prime importance. If the time is relatively large, clear or glaze ice will be formed, while conversely, if the time is small, rime will be the end product. Bleeker has shown that the icing time is directly proportional to the radius of the droplet of sub-cooled water and that the proportionality factor involved is dependent mainly on the vapor pressure existing in the air surrounding the droplet.

In order to demonstrate the processes involved in the formation of ice on aircraft, let it be assumed that there is water in liquid form, either as a cloud, or, perhaps, falling rain, at a temperature of -8°C. As soon as the plane strikes such a sub-cooled droplet, there is provided the necessary agitation and freezing begins. All of the droplet will not freeze at once, however. For illustrative purposes, which will not invalidate the results in any way, assume the droplet consists of one cubic centimeter of liquid water. It is known that to freeze one c.c. of water 80 calories must be removed therefrom. It is also known that at the instant the droplet begins to freeze, the temperature of the mixture of ice and water will immediately rise to 0°C. This rise in temperature can only be accomplished as a result of heat being added, while at the same time heat is being taken away from a portion of the droplet in order to bring about the freezing. Assuming that no heat is added from without, this added heat must be removed from that portion of the droplet which freezes. Thus the rise in temperature of the mixture from -8°C. will give a measure of the number of calories required to produce this heating and thereby indicate the fraction of the droplet which is immediately frozen on impact. In this example, since it requires 1 calorie to raise the temperature of 1 c.c. through 1 degree C., it will require 1 x 8 or 8 claories to bring the mixture up to $0^{\circ}C.$ And, since it requires the expenditure of 80 calories to freeze 1 c.c., cooling has been provided sufficient to freeze 8/80 c.c. or 10% of the volume of the droplet. Thus it can be said that the amount of water encountered by the plane in the form of cloud particles or rain drops, and which is immediately frozen, is directly proportional to the degree of under-cooling of the droplets. This point will be considered later with respect to the size of the droplet (as mentioned earlier).

If it was only that portion of the droplet which freezes on impact that concerned us, and the remaining portion was permitted to run off as water, the icing of aircraft would not be of much importance. It is because a very large part of the remaining water also freezes that the icing conditions are considered such a hazard to flying. It is through the operation of the process of evaporation that the remaining portion of each droplet is largely turned to ice.

Consider again, the original droplet, 10% of which has been changed into ice, while the remaining 90% exists as water at a temperature of $0^{\circ}C.$ It is here that the vapor pressure of the surrounding air is very important. Over this water at $0^{\circ}C.$ there is a saturation vapor pressure of 6.11 mb., whereas the surrounding cloud air will have a saturation vapor pressure corresponding to the temperature of $-8^{\circ}C.$, or only 3.12 mb. Thus evaporation will take place from the water surface because of its higher vapor pressure as compared to the surrounding air. To accomplish the evaporation of 1 c.c. of water it requires the addition of approximately 600 calories of heat. To freeze the remaining 90% of the original droplet, only 1x80x.9 which equals 72 calories needs to be removed. Hence it is only necessary to evaporate 72/600 or 12% of the original droplet. However, as all heat is added or subtracted from this droplet itself, some of the water will be lost, and even less heat will be required to be taken away. This amounts to about 2% so that the total amount of the drop to be evaporated is approximately 10%. Under these conditions it is seen that, roughly 90% of the water encountered by the plane would be frozen, nearly nine tenths of which is caused by evaporation, and this part that is formed through evaporation is the most dangerous clear or glaze ice. Thus it is evident that the process of evaporation is of first importance in any consideration of icing conditions of aircraft, particularly because of the strong ventilation afforded by their rapid relative movement through the air.

The size of the cloud particle or the sub-cooled water droplet has no influence on the part of each that is frozen either on impact or through subsequent evaporation. As was stated before, the portion of each droplet frozen on impact is directly proportional to the degree of undercooling, and so it is true that the rate of evaporation of the remaining liquid portion, and the total amount to be frozen, will be directly proportional to the degree of undercooling.

At this point it is well to begin considering at what degrees of subcooling certain size droplets can and ordinarily do exist. The different types of ice have been observed to form most frequently from 34°F. to 0°F., although pilots have found ice at higher and lower temperatures. But, it was not of sufficient amount to be hazardous.

About 80% of the clear ice formation occurs above a temperature of 20°F. while about 55% of the rime occurs below that temperature. Temperature is a minor consideration as compared with other factors, though, in determining the type of ice, as long as it is within the 34°F. to 0°F. range. Air turbulence is an important factor however, because larger drops will be able to exist with increases in turbulence. One explanation advanced for the fact that most glaze occurs above 20°F. is that at lower temperatures large drops of water tend to freeze spontaneously. Therefore, only the smaller drops in which rime forms are in abundance. Below 0°F. the water droplets usually become so small because of the rarity of water in the liquid form that they are deflected with the air around the airfoil and other parts of the plane. The reason they are deflected is because of their smallness they have not sufficient inertia to penetrate the airstream at enough of an angle to make contact with the plane.

In going on from here vapor pressure and icing time will have to be considered along with other factors. In theillustration given above it was seen that the difference in vapor pressure was an important factor in the evaporation of the liquid water and the resultant freezing of the droplet. In this illustration the air was assumed to have a relative humidity of 100%. Observations have shown that in such clouds where clear ice formations were reported, the relativehumidities ranged from 51% to 100% with the average being about 90%. With lower relative humidities, it can be seen that the vapor pressures will also be lower so that there would exist a still greater difference in vapor pressure between that for the water on the wing of the plane and that in the free air. Hence evaporation and the resultant freezing would take place more rapidly. This explains the observed rapid formation of ice as a plane emerges from a moist cloud into the comparativ-ely clear, dry air above or below.

Under certain conditions such as that of heavy undercooled rain, aircraft will fail to pick up large deposits of ice. If the drops have large radii and are undercooled only a few degrees, and the relative humidity is great, the icing time will be large. The part of the droplets not frozen on impact have time to be blown away and if heavy enough rain is falling, the water will even have time to collect and wash some of the allready frozen ice away. As can be seen, this will definitely not give the airfoil a load of clear ice, as clear ice depends upon many thin layers of water to be successively frozen over each other.

At temperatures below 20°F. rime iec is most predominant because the small droplets enable the icing time to become very small, almost instantaneous. Upon impact only a part of the drop freezes, but there is so little water in the drop that it does not spread over an appreciable area. Consequently the formation is of a granular structure.

The rate at which ice forms on an airplane part varies greatly according to icing time, which varies with other factors as mentioned, and with the speed of the plane through the free air. Observations differ over wide ranges from less than 0.5 in. per hour to as high as 2 in. per minute. Pilots observations have indicated that a rate of one in, per minute is not at all unusual.

At the beginning of this paper frost was mentioned as a type of ice that aircraft are troubled with at times. A few common causes for frost are: (1) a plane flying through free air which is below the freezing point long enough to assume the temperature of the cold air, and then suddenly going into warmer air so that the water vapor in this warmer air is condensed on the plane as small ice crystals known as frost. This occurence is not at alldangerous because as soon as the plane comes to the same temperature as thesurrounding air, the frost will melt off; (2) If a plane has been standing in the open air long enough to collect a deposit of frost, it should be brushed off before take-off is attempted because the collection of frost produces a surface that is not smooth and destroys the aerodynamical properties of the airfoil to some extent. This can become quite important in the case of heavily loaded planes that do not have too much room in which to take-off; (3) This third case is very similar to the first case and is usually only come across in the high latitudes. If there is an inversion near the ground so that the temp. is below freezing, it is possible for an airplane to take-off and climb rapidly enough to still be very cold when it reaches the inversion and commences to collect frost due to the lowering of the temp. of the warmer air to the dew point which is 32°F. or less. If the plane is at maximum rate of climb, this occurence may cause the airfoil to become inefficient enough to cause the plane to stall because the formation is quite rapid.

Summary

Points to remember about icing are:

(1) Icing is likely to be heaviest at temperatures fairly close to the freezing point.

(2) Clear ice may be expected in clouds with appropriate temperatures, where vertical currents strong enough to support the larger cloud droplets, are found, i.e. instability clouds or turbulent air.

(3) Clear ice predominates above 20°F.

(4) Rime predominates below 20°F.

(5) Rime may be expected in clouds, with appropriate temperatures, wherein vertical currents are not strong enough to support the larger droplets, i.e. stable type clouds.

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II

THE METEOROLOGY OF ICE FORMATION

If a pilot is familiar with the physical processes causing an encountered or forecasted icing condition, his plans for avoiding the region can be logically made. In this section of the paper, a number of meteorological situations with which ice is commonly associated are analyzed and the practical application of these studies to flight plans is suggested.

In general, the following practical considerations should be realized for icing in addition to previously mentioned theoretical considerations:

1. The danger of icing in regions above cloud forms is not great.

2. Ice may be formed in rain below a warm front provided the lower cold air has cooled the aircraft surfaces below 32°F.

3. Clear ice may be expected with appropriate temperatures and when sufficient vertical currents are realized from the following:

(a) Convective action resulting from the heating of surface layers.

(b) Convective overturning or the forcing aloft of warm air at the forward portion of the cold front.

(c) Active upglide of warm moist air over a cold front.

(d) The lifting of cold moist air under the warm front due to the convergence of streamlines along the warm front.

(e) The lifting of unstable air over mountain ranges.

(f) All of the above conditions will be shown on the diagram as being within a layer of unstable air, or if in a stable layer, immediately above an unstable zone.

4. The diagram will indicate stable conditions within the zone of rime formation, wherein vertical currents are not strong enough to support the larger droplets.

It should be noted here that in addition to the absolute amount of liquid water a cloud contains, the rate of deposition of ice depends upon the mass of liquid water traversed per minute by an airplane, and increases with the velocity of the plane. A free balloon, moving with the wind, rarely experiences icing. Captive balloons and kites exposed to prevailing winds undergo serious icing only when exposed to the falling of supercooled rain.

Similarly, in forecasting the 32°F boundary from the ground, it is absolutely essential to remember that the boundary also varies with airplane velocity. Because of the impact and friction of air particles on the plane, other factors being equal, the temperature of the plane is always higher than the air temperature and the differential increases as the plane velocity increases. Due to this fact, the 32°F level of a plane in flight is higher than the meteorological 32°F level.

In <u>cloud</u> flying at altitudes between 3,000 and 7,000 feet, the following figures are applicable:

Flying speed (mph)	100	150	200	250	300
Approx. lifting of 32°F boundary (feet)	350	800	1500	2350	3400

During flight, the pilot should watch the free air temperature closely and remember that it does not indicate the meteorological but the increased temperature due to plane velocity.

This increased temperature rise in flight through a cloud is about 40% lower than in clear air. Therefore a pilot, before flying into dangerous ice clouds, should seek an altitude where the thermometer reads 1°F to 5°F above 32°F (depending upon air speed). This is in order to stay below the "velocity cloud freezing level" as differentiated from the "velocity clear air freezing level."

As has been suggested previously, one of the most striking things shown by material assembled is that not one case of icing was recorded in which lifting by some method was not taking place. These cases, however, were recorded in the Western States. It has happened in other places that a plane flying through a relatively warm moist cloud--without icing--has immediately picked up ice upon passing into relatively colder clear air due to the difference in vapor pressures in the warmer and colder air. This has been explained earlier in this paper and noted as not very important.

Of 218 cases on which United Air Lines have definite information up to 1938, the following occurred:

2 in instability showers over flat territory.

34 in currents over mountains with no fronts nearby.

182 through or in close proximity to fronts (with orographic and instability effects added in most cases).

The times when ice is formed from thick fog or from rain falling into colder air are extremely rare in the Western U.S. region. Ice occurred only twice in air that was definitely known to be stable, and in a few more that may have been.

FRONTAL EFFECTS

Since about 85% of the observed icing of aircraft occurs in frontal zones, it is evident that considerable study must be given to the distribution of ice forming properties in those zones.

COLD FRONTS

Ice formation along and in advance of cold fronts increases as the instability and moisture content of the air in the warm sector increases. Because of the unusually steep slope of cold fronts, the horizontal extent of the ice area is generally smaller than along warm fronts, but because of the more rapid lifting, vertical currents are usually greater and the larger liquid droplets will cause severe ice formation. A safe flight path to avoid dangerous ice conditions is illustrated in Figure I. Where temperatures are below 15°F, ice particles will predominate in the cloud mass, and even if the frontal cloudiness extends to higher altitudes than shown, only light ice will be encountered unless convection is very strong. The advisability of flying west to avoid the icing areas adjacent to the cold front is evident, for in climbing to the east, the area of severe ice formation would be encountered. The maximum altitude would, of course, depend on the direction of flight and the top of the clouds.

An icing situation that is frequently observed along the eastern slope of the Rocky Mountains occurs when the cold front of a Pc air mass moves southwest and west against higher ground. The example shown in Figure II is from actual reports of pilots flying between Albuquerque and Kansas City on morning of December 8, 1937.

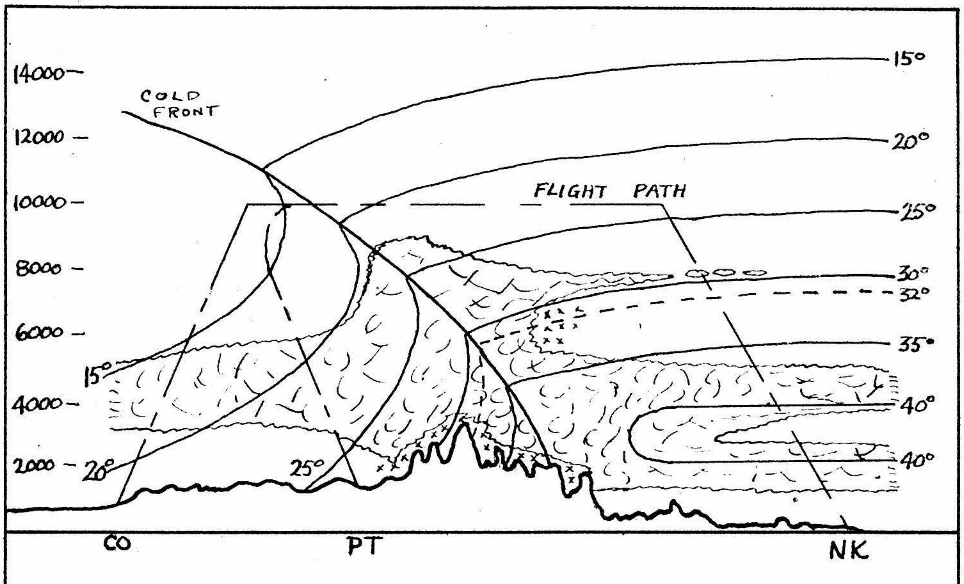

FIGURE I

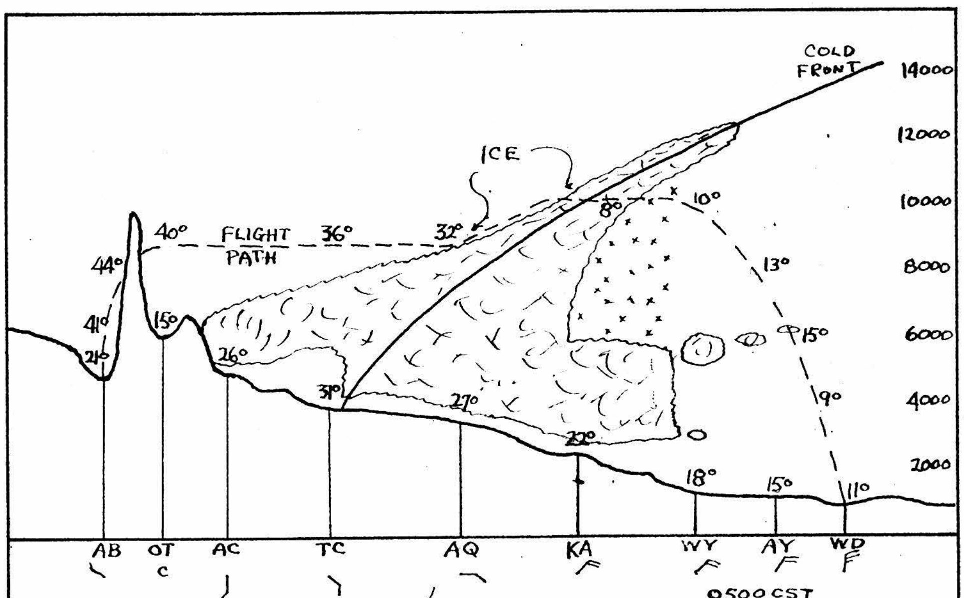

FIGURE II

In this situation, a modified Pc air mass is lifted to above its condensation level by the encroaching cold air, and in this unstable state, sustains adequate liquid particles at freezing temperatures. The pilot of an eastbound flight reported that when he attempted to let down from 8000 feet through the cloud mass at Amarillo, a 1/4" of ice formed in 50 seconds. Flight was then continued above the cloud mass until the cold front was intercepted at 10,500 feet where breaks in the cloud deck were observed, and only light ice formed. The frontal clouds in this case were only 20 - 30 miles in extent. After the flight reached the fresh cold Pc sector, no ice was deposited, although snow continued to fall from the higher clouds along the frontal surface.

WARM FRONTS

In Figure III is a cross section of a warm front as described by Byers in his "Synoptic and Aeronautical Meteorology," and is similar to an actual condition which occurred between Pittsburgh and Newark on December 11, 1933. The important features to be considered in this example are the temperature distribution, the regions of the cloud mass where liquid particles and ice particles predominate, and the precipitation forms. The heavy black line marks the limit of ice formation; its position in the cold sector is predicated on the freezing isotherm in the rain area, and in the warm sector includes all of the cloud layer below freezing up to where liquid cloud particles cease to exist and only ice needles, flakes or dry snow prevail. Ordinarily, this change in form occurs between 15°F and 10°F unless strong convection prevails to above this level.

In flying through a warm front of this type, it is evident

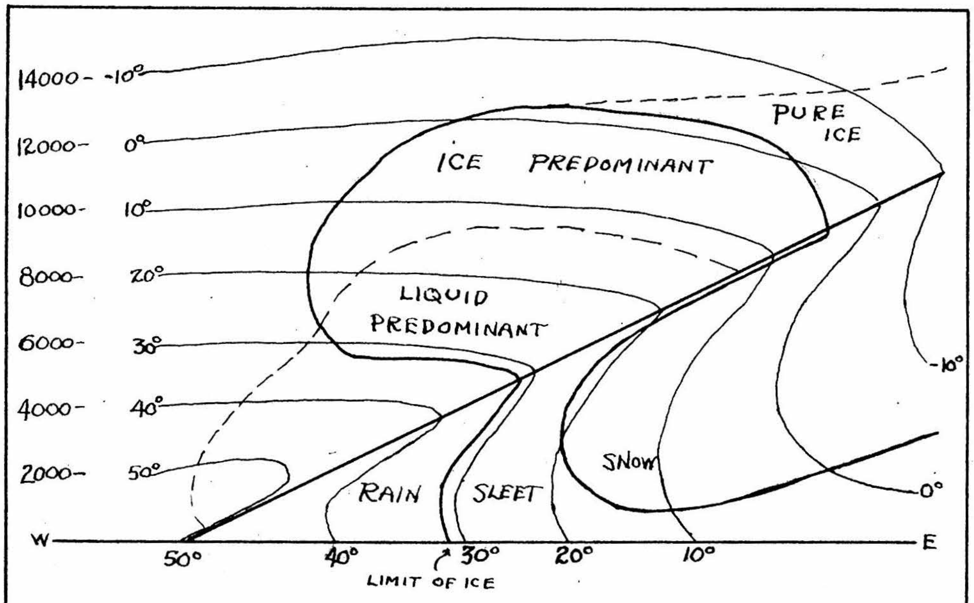

FIGURE III

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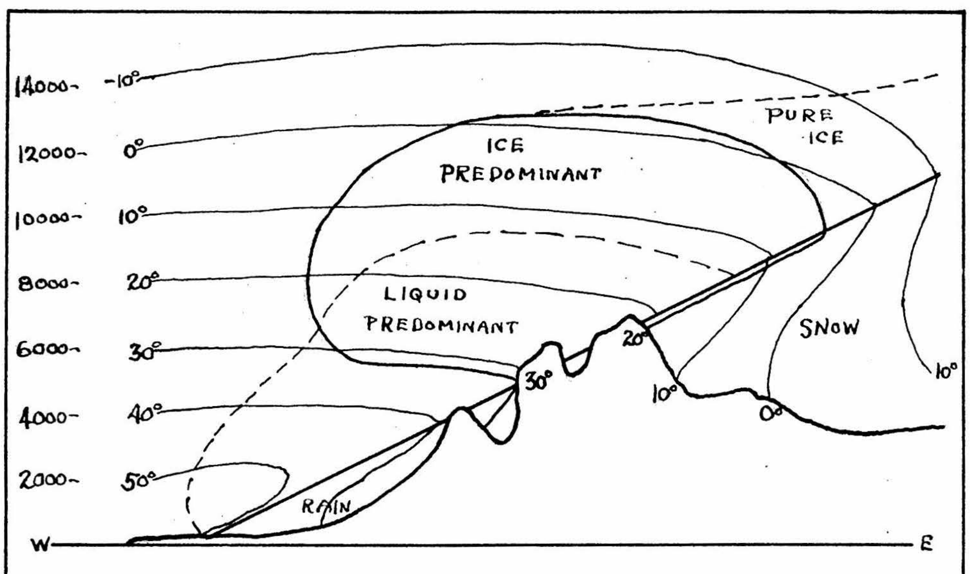

FIGURE IV

W.E.S.

that the only safe flight path is one that will avoid the area where liquid cloud particles predominate. This can be accomplished only by flying at high levels, at 10,000 - 12,000 feet, or in ice particles above 9,000 feet. At any level below 9,000 feet where supercooled liquid predominates severe ice will be encountered.

In the case of a plane flying below a warm front, if freezing rain is encountered severe icing could be avoided by climbing only if that portion of the inversion above freezing is intercepted. It is important to remember that only when near the surface front should the inversion be sought by climbing, or well in advance of the front where the region free of liquid particles can be reached without encountering the area where liquid droplets do predominate.

WARM FRONT WITH OROGRAPHIC INFLUENCES

The warm front condition just considered may be transposed into mountainous country as illustrated by Figure IV. The most prominent difference is the loss of the lower section of the warm front surface. This brings the freezing isotherm and the area of the cloud mass in which liquid predominates closer to the surface. More rapid convection, induced by the steeper slope of the ground, will tend to sustain larger cloud droplets and consequently increase the ice deposit per unit time.

A higher mountain range results as shown in Figure IV. The important resulting change is the concentration of the icing zone against the windward side of the mountain and its extension across the top of the range. Safe flight remains possible only at high altitudes.

Widespread areas of icing conditions frequently exist in modified air masses over mountainous regions with no definite warm front, but in advance of a cold front. Figure V shows this condition as it would be indicated on the weather map, and in cross section. The air in advance of the cold front is NP_p in which the moisture content has been increased through the evaporation of moisture from the earth's surface. Under such conditions, this air would have a conditionally unstable lapse rate, and once condensation starts, mild turbulence will hold the resulting liquid droplets in suspension. Thus in those levels above the freezing isotherm, a severe icing condition would result, as liquid water would be available in the cloud mass.

As Figure V shows, each range of mountains will act as a warm front, causing ice forming cloudiness to extend over the area, and with strong wind, ice formation would exist to the top of the clouds.

The combined effects of cold front and orographic lifting of an air mass rapidly lowers the temperature of the ascending warm air mass and produces moderate to severe ice, since the cooling and condensation process is intensified, and liquid cloud droplets will predominate in the cloud mass.

OCCLUSION

A cold front type occlusion existed in the Chicago area on the night of December 7, 1937, and the cross section (Figure VI) is based on data recorded by a pilot flying through the frontal surfaces. The most outstanding feature of this situation is the

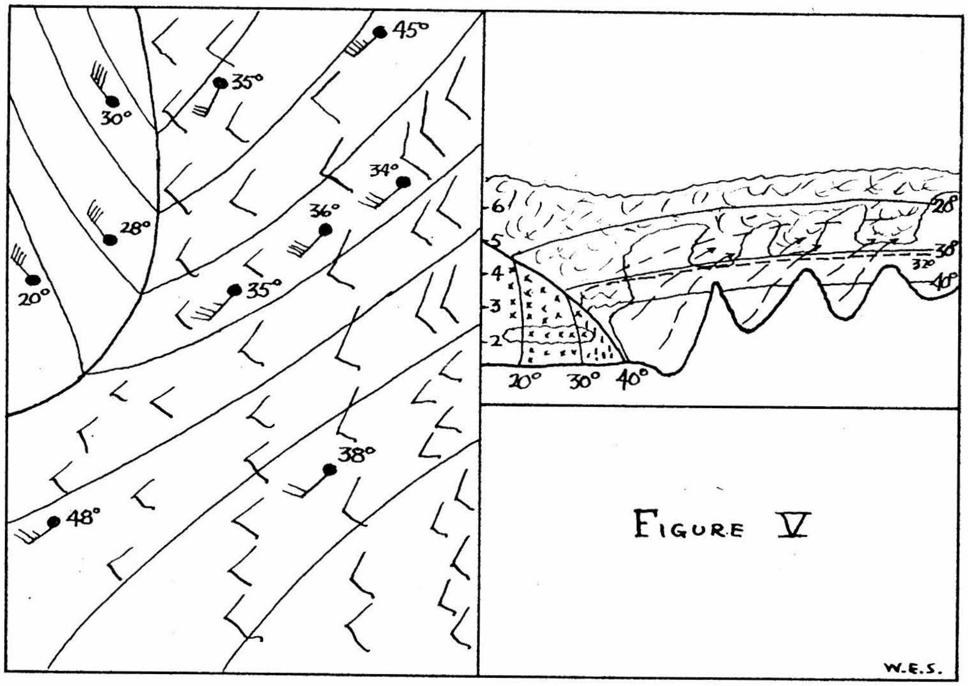

FIGURE V

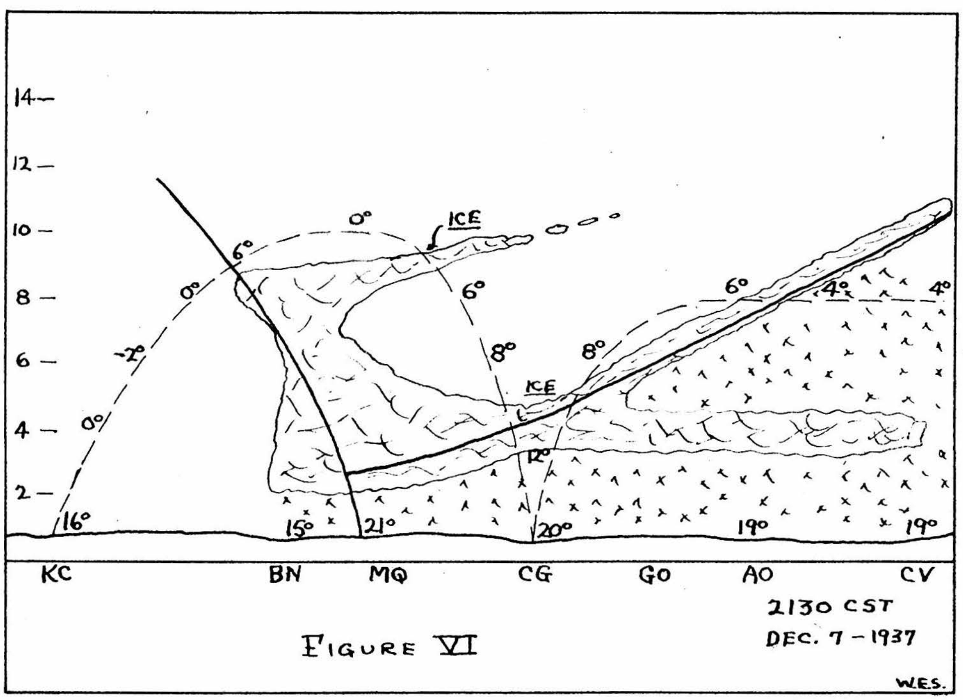

FIGURE VI

low temperatures, below 10°F, in which icing occurred. As is to be expected, ice occurred only along the frontal surfaces, where the necessary conditions for formation are realized. Due to the low temperatures of the warm air mass, the amount of available water vapor is small, but it is evident that even with the low temperatures, liquid droplets predominated in the cloud mass.

Flight through such frontal surfaces should be conducted in a manner that will reduce the time of passage to a minimum, that is, a rapid climb and descent through cloud masses. This is good practice, providing the thickness of the cloud deck is known with a fair degree of accuracy. If the warm sector had been solid cloud, heavy snow would ordinarily be reported at stations below that sector. In the absence of such reports, a relatively thin cloud stratum is to be expected.

CONCLUSION

From the analysis of these situations, certain precepts to be used in avoiding ice formation aloft are derived:

1. The regions of most severe icing are associated with frontal surfaces.

2. Vertical convection sustains large water droplets and thereby induces severe icing, providing temperatures are below freezing. Cloudiness associated with strong convection should therefore be avoided.

3. Temperature inversions to above freezing do not always exist above ice forming regions, even when freezing rain occurs. Escape from ice by climbing should not be attempted unless existence

of above freezing temperatures at higher levels is definitely known.

4. Ice evaporates very slowly in clear cold air and an accumulation of ice induces rapid collection of more ice if descent is made through a cloud deck in which liquid droplets predominate and the temperature is 32°F or lower.

5. When uncertain of ice distribution in clouds, flight in clear air above the clouds is the safest flight path. The flight run on climb and descent should be through broken or thin clouds remote from the frontal surface.

6. A thorough study of the latest synoptic chart to determine the position, slope and tendency of fronts before flight is attempted is the only means by which ice forming regions may be located and the probable intensity of icing determined.

7. The falling of precipitation (especially, mist, snow, sleet, etc.) from a cloud is indicative of ice formation therein if the cloud is presumably or known to be at or below 32°F.

PRACTICAL SUMMARY

I

Sources of Icing on Aircraft

1. Flight through subcooled clouds: This is the most common source of rime.

2. Freezing rain aloft or on ground: A temperature inversion is usually found aloft with temperatures above 32°. This is most common source of glaze.

3. Freezing drizzle aloft or on ground: Temperature inversion to above 32° aloft not dependable in this condition.

4. Mixture of freezing rain, snow and occasionally sleet: This may be encountered either aloft or on ground. Rough glaze results.

5. Wet snow aloft or on ground: Dry snow can also cause dangerous ice if the plane is removed from warm hanger. The initial melting, then refreezing of snowflakes may produce a rough surface, preventing plane from reaching safe flying speed on takeoff.

6. Carburetor icing: This may occur with free air temperature as high as 70° if heat is not applied. Considered important today with present type of carburetor in the larger and heavier aircraft.

7. Splashing of airport runway puddle water on plane during takeoff when temperature is below freezing: This may produce rough coating on control surfaces which can seriously affect control of plane.

8. Frost formed on wings and control surfaces while plane is on ground: This can produce serious difficulty on an early morning takeoff due to rough surface.

9. Frost aloft: This may form on a cold plane flying into a warmer moist stratum of air. This melts or evaporates quickly and is unimportant.

10. Propeller icing during runup and takeoff in dense subcooled fog on ground: Unimportant only so long as flight minimums restrict takeoffs in dense fog; otherwise power loss.

11. Flight through clouds or rain with apparent temperatures 32° to 35°F: This is occasionally reported and is probably due to expansional cooling above leading edge of wing. But thermometers are often in positive error by as much as 5° due to frictional heating.

II

Weather Map Type Associated with Icing

1. Cold front: The icing may be quite severe through a narrow zone if the warmer air mass is conditionally or convectively unstable and therefore producing a line of dense cumulus clouds. The worst arrangement is a cold front of this type which strikes the plane course broadside. If icing becomes severe in this case, the heaviest icing zone may generally be avoided by detouring slightly to the rear of the front.

2. Warm front in which the overrunning warmer air is unstable: The heaviest icing should be found immediately above the surface of discontinuity aloft; i.e., in the upper part of the transitional air between the two air masses (in stable air the heaviest water

particles tend to settle to the bottom). Severe icing is often escaped by changes of altitude of only 1,000 or 2,000 feet under these conditions as the clouds are often well stratified. In changing altitude the direction of slope of the frontal surface must be kept in mind, e.g., with a steep frontal slope produced by blocking of air on western side of the Sierra Nevada or Rocky Mountains, a pilot climbing eastward might climb at nearly the same rate at which the frontal surface sloped upwards.

3. Warm front in which the overrunning warmer air is convectively unstable: In this case cumulus clouds will form on the frontal slope, as well as the stratus type, and moderate to heavy icing may extend up to 15,000 feet or higher. In general, the least icing and smoothest air is found beneath the frontal surface.

4. Upper fronts: Heavy icing may nearly always be avoided by flying underneath the frontal surface aloft and in the lower layer of stable air across the top of which the upper front is moving.

5. "Point of Occlusion" or Eye of Low: This is often a zone of relatively heavy icing resulting from convergent lifting (surface winds converge on this area from all sides), and from frontal effects. If icing becomes too severe in this zone, the only definite out or alternative is to turn back or to climb to a very high level.(?) Cumulus clouds may build up to 15,000 feet or higher over a fairly wide zone at this time. Development is generally sudden and without warning.

6. Orographic lifting: Some examples of this source of icing are: W and NW winds carrying moist and unstable air of Pc origin up the west slopes of the Alleghenies; E winds carrying unstable

P_A air up the east slopes of the Alleghenies in late winter and spring; and E winds blowing upslope from GI to CX and DV. According to studies made by J. A. Riley of the U.S. Weather Bureau, westerly gales over the Sierra Nevada in winter often cause a zone of severe icing to extend from Summit to 11,000 feet and to extend from 25 miles W of the mountains to 10 miles E of the mountains. At these times, ice is generally not a problem at 12,000 - 14,000 feet. Thickness of the icing zone is greatest with highest temperatures and highest wind velocities at Summit.

7. Air Mass Instability: Some examples are: Pc air which has had heat and moisture added to the bottom layers in crossing the Great Lakes in winter; P_A air with the same characteristics which moves in from the Atlantic Ocean in late winter and spring over the LG - KY sector (this air is often more unstable than the Pc type on the western slopes of the Alleghenies); any cold Pc air mass which moves southward over increasingly warmer ground surfaces.

8. Stagnant Map with weak occlusion or obscure fronts: Characteristic of a once active low which has filled in. Freezing drizzle quite characteristic with this type and an inversion in temperature to above freezing aloft should not be expected. Tops of clouds are generally 10,000 feet to 14,000 feet msl and definite layers are generally present.

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