Original idea from Captain Mike Bowyer

Aircraft Icing

Many rejected take-off accidents occurred before closer examination of the certification criteria revealed some of the shortcomings. A number of pilots had possibly believed that they were within the certification criteria to reject a takeoff, only to find out afterwards that, in fact, they had no chance of stopping within the distance available. First, the icing certification standards were established some forty years ago, before the advent of jet and turboprop transport aircraft. Second, they were not meant to be an exhaustive description of the icing environment but rather a statistical representation of icing conditions that may be encountered. The certification standards only cater for droplet sizes with diameters up to 40 microns, whereas, in the real world that we fly in, droplet sizes 100 to 1 000 times larger than this are not that uncommon. Freezing drizzle, snow, frost or mixed conditions are NOT addressed by the certification standards. According to an FAA test pilot, icing certification should be considered as a licence to fly *through,* rather than in icing conditions….

TAKE-OFF ICING ACCIDENTS

Mr. Jerome Lederer, founder of the Flight Safety Foundation made the statement shown in the centre box which, in the light of what we now know, may not seem remarkable..

What is remarkable, however, is that he made that statement in 1939, long before our present super-efficient (when uncontaminated) Laminar Flow and Super Critical aerofoils. Here are some examples of the sort of things he was warning about :

RYAN DC9-15, FEBRUARY 1991 (CLEVELAND, USA)

The aircraft was on a night mail flight with an en-route stop at Cleveland. Moderate rime icing between 7000 feet and the surface had been reported so the crew probably used anti-icing for the approach. The aircraft stood in dry blowing snow for the 35 minutes that it was on the ground. Failing snow melted on the initially hot wings before refreezing as the wings cooled to below freezing. As more snow fell onto this ice layer it was also frozen and formed a thin rough layer of "sand paper" ice which the crew were unlikely to have seen even if they had done a walk-around - they did not leave the aircraft.
On take-off, shortly after the positive rate call, sounds of compressor surges were heard on the CVR. This was followed by the stick shaker and the sound of impact with the ground.

The Tower Controller said the aircraft had reached a height of about 100 feet before it made a quick bank left, followed by a quick bank right, after which a " fireball " came out of the rear of the aircraft. The aircraft banked right to 900, increased pitch attitude and continued to roll past 900 before impacting the runway inverted. The NTSB noted that this combination of events was consistent with an abrupt and asymmetrical stall as the aircraft left ground effect. Tests by the manufacturer showed that compressor surges occur due to the disruption of the airflow aft of the wing when it is stalled. The stall occurred 27 knots above the theoretical stall speed. The 30 percent reduction in lift was due to a snow / ice accumulation that may have been less than 0.5 mm thick and barely perceptible by visual examination.

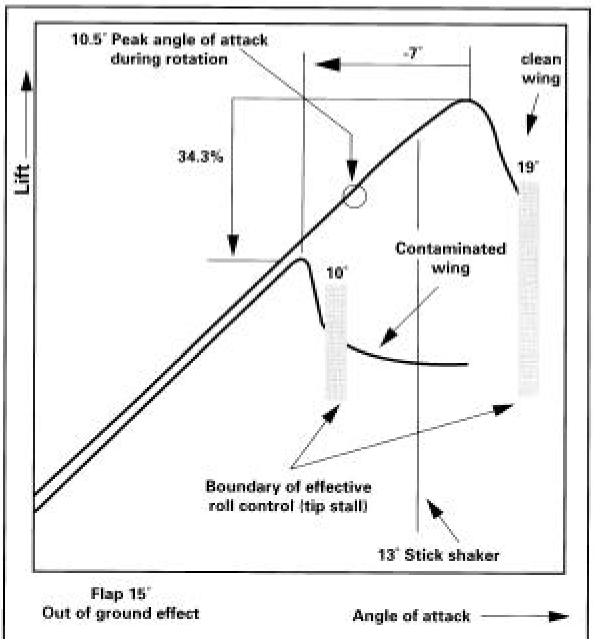

Figure 1. Effect of wing contamination on aircraft lift and roll

BOEING 737, JANUARY 1982 (POTOMAC RIVER)

In this well-publicized accident the delay between de-icing and takeoff exceeded the hold-overtime of the de-icing fluid. In spite of a sub-zero temperature and moderate-to heavy snow the crew did not use engine anti-ice during ground operations or take-off. As a result, both engine inlet pressure probes became blocked with ice before take-off. This caused erroneously high EPR readings which, in turn, resulted in a thrust deficiency of 3750 pounds per engine. This lower than normal thrust setting was aggravated by snow and/or ice contamination of the airframe.

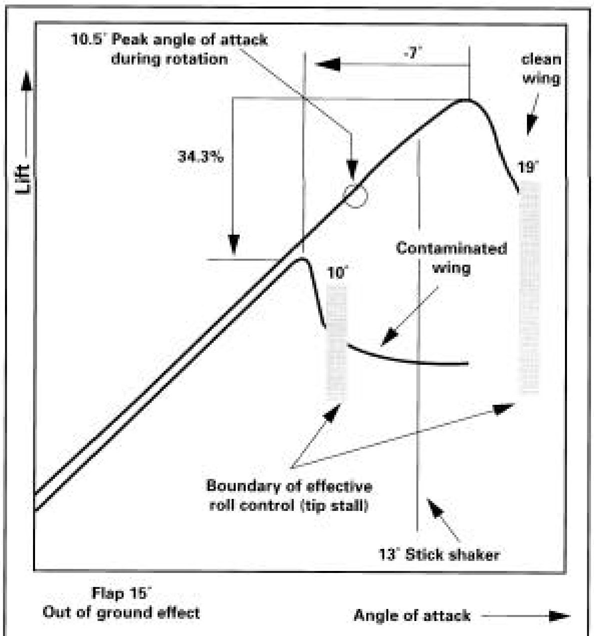

Figure 1. Effect of wing contamination on aircraft lift and roll

During the investigation of this accident it was learned that there had been 22 reported cases of B737s experiencing severe pitch up or roll off after take-off in icing conditions. This proved that although hard wing aircraft such as the DC9-15 series and the Fokker F28 are particularly vulnerable to small amounts of aerofoil icing on take-off, it requires just a little more ice for aircraft with leading edge high lift devices to display very similar characteristics.

The combination of reduced thrust, increased drag due to the airframe icing, subsequent stall and ensuing crash into the river are perhaps best explained by the two graphs (figures 1 and 2) obtained from flight and wind tunnel tests on a Fokker F100. The data was obtained from wind tunnel tests on models with various sizes of uniformly distributed roughness over the entire wing upper surface, as well as from flight tests with simulated rime ice and sandpaper roughness on the leading edge.

As with all aircraft types, wing contamination can reduce the maximum lift by up to 34 percent and, simultaneously, reduce the angle of attack for maximum lift by up to 7°.

When the clean aircraft is rotated smoothly at Vr with a pitch rate of 3°/sec the peak angle of attack will be approximately 10.5°. An uncontaminated wing will still have a 25° margin before activation of the stick shaker and a 5.5° margin before maximum lift is reached. With a contaminated wing, however, the stall will occur at about 9°, which is about 1.5° lower than the angle of attack already achieved by the aircraft and well below the 13° at which stick shaker activation will occur. Aggravating the situation is the fact that the stalling of a contaminated swept wing is usually accompanied by a pitch-up tendency which pitches the aircraft deeper into the stall.
Wing stall under these conditions is extremely dangerous because the inherently good-stalling characteristics of a clean wing are lost, since the wing is beyond the boundary of effective roll control.

As can be seen in Figure 1, the boundary of effective roll control for a clean wing is 19° compared to only 10° for the contaminated wing. Aggravated by the probable asymmetric contamination of the wings, an asymmetric stall may be accompanied by a violent, uncontrollable roll.

In Figure 2 the drag of the aircraft with clean wings is such that the climb capability is ensured at the required climb angle at V2 with one engine inoperative. However, with a stalled contaminated wing the drag may be more than doubled to the point where even with both engines at take-off thrust, climb capability may be lost.

The study concluded that, with no means of relating the amount of ground icing contamination to its effect on the aerodynamics of an aircraft, no take-off should be attempted unless it is first ascertained that all critical surfaces are free of ice snow or frost deposits. A further simulator study done by Fokker on alternative take off methods such as reduced rotation rate, lower pitch angle, increased rotation speed and combinations of these three methods showed a considerable increase of up to 43 percent in runway distance required to the screen height of 35 feet. Furthermore, the simulator trials only considered the symmetrical wing contamination case. The more severe case of non-symmetrically contaminated wings was not even considered. Perhaps the following extract from a letter by Douglas to the NTSB best sums the situation up :

In most take-off accidents, the ice contamination has not been in the form of large ice accretions on the leading edges or thick layers of snow adhering to the tops of wings. Rather, dangerous reductions in handling qualities and stall margins can occur because of icing roughness equivalent to medium grit sandpaper. This seemingly modest amount of contamination can result in pitching movement changes during take-off that cause the aircraft to increasingly behave as if it were mistrimmed in the nose-up direction. Following lift-off, degraded lateral stability requires larger and larger control wheel inputs to keep the aircraft from abruptly rolling off, possibly followed by premature stall at lower than normal angles of attack. Additionally, the airflow into the engines may become disturbed causing compressor surges and momentary losses of power.

Couple this to asymmetric lift induced rolling moments, followed by pilot initiated aileron and spoiler deflections which can very quickly set up roll oscillations, and the chances of a safe, successful take-off become very slim indeed.

FINNAIR DC9-51, MAY 1985 (HELSINKI, FINLAND)

The aircraft arrived in Helsinki after a 3 hour 40 minute flight and then spent six hours on the ramp in rain and snow with about 2400 kg of fuel in each wing tank. Temperatures were near zero. The aircraft was de-iced before departure. The Captain rejected the take-off at 80 knots due to reduced acceleration and a momentary EPR fluctuation. Inspection revealed a layer of clear ice about 20 mm thick in the wing root area above both wing tanks. Some ice from each wing had separated from the wing and been ingested by the engines damaging fan blades.

The Finnair investigation determined that if fuel in a full, or nearly full, wing tank is exposed to the cold of high altitude cruise for a long period (generally two hours plus), it becomes cold soaked.

If the aircraft then lands at an airport with a readily available source of moisture such as rain, drizzle, heavy fog, high humidity, etc. and an ambient temperature between -40 and +10° Celsius (even up to +15°C), the moisture will freeze on contact with the top surface of the cold soaked wing and form ice. The ice formed is usually clear ice, and because the entire surface of the wing, icy and non icy areas alike, is often wet and shiny, the ice is very difficult to see.

If the ice is not detected and removed prior to departure, then the flexing of the wing during the taxi for take-off may loosen some of the ice which can be ingested by the engines during take-off causing ice foreign object damage. This damage often manifests itself as a buzz or vibration in the aft cabin, and in extreme cases may cause compressor stalls/ surges, significant power losses or even flame-outs.

So, why did the problem only manifest itself on the later model DC-9-51 and MD-80 aircraft?

The earlier aircraft had smaller fuel tanks and generally flew sectors too short to cold-soak the wing fuel. On longer sectors where cold-soaking was possible, much of the wing fuel was consumed and the wing fuel on landing was low enough for the airspace above the fuel to tend to insulate the wing skin from the cold soaked fuel.

In comparison to the 3000 kg centre tank of the DC9, the MD 80 has a 1 0,000 kg centre tank, making a three hour flight possible before wing fuel is used. Tankering flights of two to three hours duration therefore, become particularly vulnerable to this type of icing. For flights longer than four hours sufficient wing fuel is generally burned to eliminate the risk of ice somewhat but not entirely.

Variables involved in this type of icing appear to be :

- Flight duration.
- En-route and ground ambient temperatures.
- The timing and extent of refuelling.
- The presence of humidity, fog, drizzle or rain.
- The cooling effect of a series of flights may be cumulative.
- Overnighting with full wing tanks on a cold night.
- Adding sub-freezing fuel which has been stored outside in sub-zero temperatures.

IN-FLIGHT ICING

DC8, MARCH 1989 (EDMONTON, CANADA)

The aircraft made a night ILS approach in fog and freezing drizzle. Airframe icing became apparent almost immediately after entering cloud at 2800 feet AGL. When the First Officer asked the Captain if wing anti-ice should be switched on he was told that it was not necessary as they would be landing soon. The aircraft landed within ten minutes of entering cloud. Due, possibly to visual illusions, the aircraft landed hard in a right bank with the left main gear off the runway, scraping the Nr. 4 engine on the runway.

Three hours later accident investigators found rime ice build ups on all aerofoil leading edges, gear struts and engine bullets. The wing had a sharp, jagged, 25 mm build up of rime ice. The investigators believe that had a go-around been attempted the wing would have stalled due to the ice build up.

MITSUBISHI MU-2s

MU-2s have had at least 15 icing related accidents and 46 incidents, mainly involving heavy aircraft above FL150. The most frequent type of incident involved a rapid speed loss caused by icing. However, many of the incidents and all of the accidents involved a rapid speed loss due to icing followed by a stall and loss of control. A typical example was an MU-2 cruising-at FL210 at night. The pilot gave ATC a routine position report one minute before radioing, *"Mike Uniform Alpha's out of control, going down".* Thirty seconds later, apparently under high physical stress the pilot made his last call: *"we are in ice and spinning down through 8000 feet"* :

No Recovery, No Survivors !

The following pilot report made investigators aware of a previously unknown problem in that the heavy high altitude cruise required a nose-up attitude which allowed clear ice to form on the lower side of the fuselage. *"The aircraft was cruising at FL150 at night, It entered a line of Cumulus-type cloud and immediately started to accumulate ice.*

I watched the leading edge for a suitable amount of ice to form before activating the de-ice boots but noticed that the autopilot was trimming the nose up. I noticed that the airspeed had decreased to 120 knots and activated the boots immediately and descended.
As the aircraft passed FL130 I felt a great sheet of ice slide off the airframe from underneath and the airspeed increased to normal."

Although the MU-2 has largely unknown spin characteristics, it is known that a high rate of descent is experienced along with possible violent and unstable oscillations. One of the problems affecting possible recovery is the fact that just prior to the departure from stable flight the autopilot has been trimming nose-up to maintain altitude as the speed rapidly reduces.
The pilot will probably be unable to overcome the high stick forces needed to effect a recovery from the spin unless he quickly moves the trim forwards towards the neutral position.

A few months after the introduction of higher experience levels and tougher training standards, an MU pilot who met the new requirements and was confident that he was aware of the icing problems relating to the aircraft reported the following incident while cruising at FL180.

"With little or no turbulence and no more than one to two minutes since last inspecting the wing, airframe vibrations began (autopilot engaged). I was doing the flight log at the time and looked up to see the IAS at 125 knots, 600 bank to the left, IAS decreasing at about 2 knots per second.
I disconnected the autopilot and had the feeling that the tail was trying to overtake me. Wings were levelled and I pushed forward until 160 knots, eased back gently and stalled.
All anti-ice, de-ice and igniters were selected as per the flight manual. I unstalled at 170 knots and 1000 feet low. Total reaction time available to me was about five seconds. Beyond this I would have been inverted and stalled, judging by the roll and IAS reduction rates."

TAILPLANE STALL VARIABLES

Ice-induced tailplane stall accidents have occurred with reported ice accretion on the leading edge of the tailplane varying from 5 to 25 mm thick. In other cases pilots successfully landed the same model of aircraft with ice 75 to 160 mm thick on the leading edge of the tailplane. The primary factors affecting whether an aircraft landed safely or was involved in an accident appear to be :

- the shape, texture and location of the ice
- the approach speed
- the degree of gustiness
- the pilots pitch control inputs

COLLECTION EFFICIENCY

Collection Efficiency is a measure of how much ice an aerofoil collects compared to the moisture content of the air, droplet size and airspeed. Pilots have reported finding ice accretion on the tailplane three to six times thicker than ice on the wing, and about two to three times thicker than on the windshield wiper arm.

Small leading edge super-critical wings, or those with a relatively narrow leading edge, and most horizontal stabilizers were thought to be less susceptible to ice accumulation, especially if a relatively high airspeed was maintained. In reality the opposite is true for the following reasons :

A relatively large radius aerofoil, flying at slow or moderate airspeed creates a large pressure wave ahead of the leading edge. This forces the air around the aerofoil 's contour, carrying most of the moisture with it. Some droplets are, however, too heavy to make the turn and impact the leading edge. Collection efficiencies are in the order of 45 percent. Conversely, a narrow radius leading edge does not generate a large pressure wave and consequently, the ice collection efficiency can be as high as 95 percent.

On any aircraft the leading edge of the horizontal stabilizer is smaller than that of the wing, therefore the stabilizer has a higher collection efficiency than the wing. *The stabilizer may, therefore, have a significant ice build-up while there is little or no ice build-up on the wing.* Even if ice accumulated at the same rate on the tail as on the wing, the effect of the same thickness of ice on the shorter chord of the tail would be more adverse than it is on the wing. Pilots are generally unable to see the stabilizer from the cockpit and may be totally unaware of the build-up. This may be critical for aircraft equipped with de-icing equipment which has to be activated once a certain amount of ice has built up.

PROPWASH COOLING EFFECT

Limited ground testing shows that the local airflow associated with certain wing/tail geometry, temperature and moisture may be favorable for ice accretion on the tailplane, without visible ice on the wing due to propwash cooling effect. This condition results from the propeller accelerating the air which causes locally reduced pressures and thus lower temperatures in the near-adiabatic process.

At zero airspeed with take-off power, a temperature depression of -2.5°C has been measured in dry air, and - 5°C in the presence of moisture. At Mach 0.4 (257 knots at 0°C) the expected temperature depression would be about -1°C.

This phenomenon can be observed on humid days when vapor clouds appear behind a propeller where the air temperature is temporarily reduced to the dew point. While -1°C does not sound like a significant ..window", the FAA has received a number of reports of in-flight power loss on a current turboprop engines which resulted from engines ingesting ice that formed when the temperature depression was only -1°C.

IN-FLIGHT ENGINE ICING

A BAe 146 cruising at FL310 flamed out all four engines due to icing. Fortunately they were able to relight them at 10,000 feet and diverted to the nearest airport.

A Falcon 20 bored through the tops of some developing CUs and emerged coated in clear ice. The Captain instinctively switched on the anti-ice but both engines flamed out after ingesting clear ice. Even though both engines, fortunately, relit. Both had, however, suffered substantial damage.

A B767 was descending through 17,000 feet in moderate to heavy rain with the OAT less than +10°C and anti-ice off when both generator warning lights came on. It was only when the crew attempted to apply power to level off at 14,000 feet that they realized that both engines had flamed out. Fortunately they both relit.

On the B737-300/400 aircraft the CFM-56-3 fitted has had to be modified after numerous flame-outs due to moderate to heavy rain at idle power. All turbine engines are vulnerable to rain and icing causing roll-back, surging or possible flame-out.

The use of engine anti-ice coupled with continuous ignition prior to entering visible moisture at temperatures below +10°C or moderate to heavy rain at idle power provides better protection.

PITOT ICING

Possibly the most well known example was the B727 that took off without the pitot heats switched on and during initial part of the climb the pitot tubes iced up. As the aircraft climbed further the reducing static pressure caused the IAS to increase. In an attempt to maintain the selected airspeed the nose of the aircraft was raised to the point where stall and departure from controlled flight occurred.

IN-FLIGHT CONTROL ICING

Besides the conventional type of control icing, there have recently been a number of incidents involving jet aircraft including B747s and DC9s where water has leaked onto control cables and then frozen during high altitude flight disabling those controls (generally ailerons).

FUEL FREEZING

There have been a number of reported multiple engine flame-outs on jet transport aircraft in cruise flight due to lower than standard temperatures that caused fuel freezing. The problem has mainly been associated with Jet A fuel, which is predominantly used in the USA, and Static Air Temperature (SAT) of -70°C. Jet A, with a specification freezing point of - 40°C, is more vulnerable to freezing than Jet Al which has a specification freezing point of -47°C .

Well below standard temperatures are most often encountered in winter months, particularly over the North Atlantic. If a flight lasts long enough, fuel will eventually cool to the Total Air Temperature (TAT) which can be below the freezing point of the fuel. This could occur hours before top of descent. SAT awareness during planning and TAT awareness during flight is always important.

In planning flights, dispatchers and captains ensure that fuel temperatures can be maintained at least 3°C above the freezing point of the fuel. When forecast temperatures dictate, contingency fuel should be added to cater for either a higher cruise speed, a lower cruising level or a different track to keep the TAT at least 3°C above the fuel's freezing point.

Although present computer flight plans do not generally show SAT, unusually cold SATs can be detected by comparing Mach number and TAS. For example: on a standard day at FL370 (-56°C), 0.84 Mach gives a TAS of 482 knots. On a –10°C day (66°C) the TAS drops 11 knots to 471. (A rule of thumb is that each knot of TAS below standard for the Mach number equals one degree C below the standard temperature of –56°C.) As can be seen, lower than normal TAS for a given Mach number indicate lower than normal SAT.

ANTI-ICE INDUCED CLEAR ICE

At temperatures below –40°C ice particles are supercooled and generally will not stick to aircraft. Using airframe anti-ice in these circumstances has been known to warm the particles sufficiently to form clear ice on the airframe.

CONCLUSION

The FAA/ NASA International Workshop noted that critical icing conditions occur infrequently, which may lead flight crew members to be complacent about the potential for critical ice accretion in certain operating areas or conditions. I hope that this information will help us to be realistically aware of the hazards icing poses to the safety of our operations.