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FAKULTA DOPRAVNÍ

ÚSTAV LETECKÉ DOPRAVY

Rizika námrazy v letovém provozu

Safety risks arising from icing in flight operations

(diplomová práce)

Studijní program: Technika a technologie v dopravě a spojích

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MASTER'S THESIS ASSIGNMENT

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- Introduction
- Types of icing
- Identification of icing
- Influence of icing on the flight operations
- Safety analysis of icing in flight
- Areas representing the highest risk for flight operations
- Recommendations to increase the level of safety
- Conclusion

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I confirm assumption of master's thesis assignment.

Bc. Slavomír Filo
Student's name and signature

Prague .... July 31, 2014

Prohlášení

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V Praze dne 20.5.2015

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Abstrakt

Diplomová práca pojednáva o hrozbe námrazy v letovej prevádzke. V prvej časti práce sa nachádza popis námrazy z meteorologického hľadiska. V úvode je zadefinovaný jav námrazy, doplnený opisom vzniku námrazy. Práca pokračuje uvedením rôznych druhov námrazy. V tejto časti práce sú opísané typy námrazy podľa jej intenzity a podľa definícií v leteckých predpisoch. Následne je priblížený princíp identifikácie námrazy odborníkmi z oblasti meteorológie a z oblasti letectva. Práca opisuje nástroje a vybavenie používané pre rozpoznanie námrazy. V ďalšej časti práce je analyzovaný vplyv námrazy na letovú prevádzku, na lietadlo a na jeho systémy. Kapitola 4 sa venuje nebezpečným meteorologickým javom, ktoré naznačujú prítomnosť námrazy. Zvyšok práce je zameraný na bezpečnostnú analýzu námrazy za letu. Kapitola 6 obsahuje návrhy na zlepšenie úrovne bezpečnosti a elimináciu rizika námrazy v letovej prevádzke. Záver práce obsahuje náhľad na metódy, ktoré budú v budúcnosti používané pri predpovediach námrazy.

Kľúčové slova:

ľad, námraza, inovať, mrznúci dážď, mrznúca hmla, ľadové kryštály, podchladená voda, veľké podchladené dažďové kvapky, odmrazovanie

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Abstract

The thesis treats a hazard of the icing in the flight operations. In the first part of the work, a description of the meteorological aspect of the icing can be found. At the beginning, the phenomenon of icing is defined and completed by a description of icing formation. The work continues by defining the types of icing. It contains a description of the intensity classification and an overview on the regulatory classification of icing. Subsequently the process of icing identification is described by the meteorologists on the one hand and by the pilots on the other hand. It provides the definition of the products and the equipment used for the icing identification. In the next part of the work, an influence of icing on the flight operations (on the airframe, on the instruments, on the propulsion system and on the windscreen) is analyzed. Chapter 4 identifies the areas representing the highest risk for the flight operations. The rest of the work elaborates on the safety risk analysis of the icing in flight. In Chapter 6 an attempt to find out the ways how to increase the safety level and how to decrease the hazard of icing related occurrences is proposed. Finally, the new methods of icing forecasts are described in the thesis.

Keywords:

Icing, Ice, Frost, Freezing rain, Freezing drizzle, Freezing fog, Ice crystals, Supercooled water, Supercooled Large Droplets, anti/de-icing

Contents

Units

Quantity name	*Unit name*
Mass	Pound (*lb*, 1 *lb* = 0,45 *kg*)
Speed	Knot (*kt*, 1 *kt* = 1,852 *km/hour)*
Altitude	Foot (*ft*, 1 *ft* = 0,3048 *m)*
Temperature	Celsius (*°C*)

Abbreviations

Abbreviation name	*Abbreviation meaning (SK)*	*Abbreviation meaning (EN)*
AAL	Nad úrovňou letiska	Above Aerodrome Level
ACARS	Lietadlový komunikačný a oznamovací systém	Aircraft Communication Addressing and Reporting System
AEA	Asociácia Európskych Aerolínií	Association of European Airlines
Ac	Altocumulus	Altocumulus
Cu	Cumulus	Cumulus
Cb	Cumulonimbus	Cumulonimbus
Ns	Nimbostratus	Nimbostratus
Sc	Stratocumulus	Stratocumulus
St	Stratus	Stratus
CS 25	Požiadavky pre certifikáciu lietadiel	Certification Specifications for aircraft
CS - E	Požiadavky pre certifikáciu lietadlových motorov	Certification Specifications For Engines
EASA	Európska agentúra pre bezpečnosť letectva	European Aviation Safety Agency
ICAO	Medzinárodná organizácia pre civilné letectvo	International Civil Aviation Organization

IFR	Pravidlá pre let podľa prístrojov	Instrument Flight Rules
ISO	Medzinárodná organizácia pro normalizáciu	International Standards Organization
LWC	Obsah tekutej vody	Liquid Water Content
PIREP	Správa o počasí z letu	Pilot report
SIGMET	Meteorologická správa o významnom počasí	Significant Meteorological Information
RPM	Otáčky za minútu	Revolutions Per Minute
SAE	Odborná spoločnosť pre automobilový priemysel	Society of Automotive Engineers
TAMDAR	Správa z leteckého meteorologického prieskumu troposféry	Tropospheric Airborne Meteorological Data Report
HOT		Hold-over time
MMEL	Hlavný súpis minimálneho vybavenia lietadla	Minimum Master Equipment List
FAR	Letecký úrad Spojených štátov amerických	Federal Aviation Regulation
FIR	Letová Informačná Oblasť	Flight Information Region
HF	Vysoké Frekvencie	High Frequency

Introduction

The aviation industry is dependent on the several sources of information to maintain current level of safety. One of the most important sources is a meteorological service. It supplies aviation personnel with the most accurate forecasts, reports, charts and other available information about the weather conditions. Icing is one of them. It plays an important role in aviation weather.

Planes used in the commercial aviation nowadays are able to fly IFR inside some types of clouds. During one flight they can fly through many different air masses that don´t have the same characteristics (temperature, humidity …). This may represent a real risk for the aircraft.

Icing is one of the most significant hazards for the safe and efficient operation of aircraft in these conditions. The highest risk of icing exists in the lower parts of the troposphere where humidity is present at the higher concentration. Jet aircraft normally fly in these altitudes only during climbing to the cruising level and during approaching for landing. But turbo-propeller planes and piston aircraft very often don´t have a possibility to overfly complicated weather conditions. Their cruising level is sometimes still affected by hazardous weather phenomena as icing is.

The icing reduces aircraft performance in a number of ways. Unfortunately, it´s proven by a fact that 30 % of accidents in commercial aviation are caused by icing. (Labyt, 2008) One of the latest accidents caused by icing took place near Tyumen in Western Siberia on 2 April 2012 and ended by death of 33 persons on board. ATR 72 of UTair airlines performing domestic flight from Tyumen to Surgut crashed after take-off in a field located just a few miles from a runway in use. A final report from the investigation committee states that the aircraft took off with ice deposit on the airframe and stalled during the initial climb at 688 feet AAL.[1] (GUTTERMAN, 2012)

In the United States of America the airframe icing resulted in 583 accidents and more than 800 fatalities between years 1982 and 2000. (PETTY, 2000) The number of accidents caused by icing slightly decreased in comparison with the documented icing related accidents from year 1975 to 1988. During these 13 years more than 803 accidents happened that were caused by icing.

But is this decreasing rate satisfactory? Recently a lot of studies have been made to better understand the conditions associated with the icing. One of them was a research of

[1] http://www.reuters.com/article/2012/04/03/uk-russia-crash-idUSLNE83202D20120403

supercooled large droplets influence on the flight safety. It was performed as a reaction on the accident of American Eagle Flight 4184 when ATR 72 crashed after flying into unknown icing conditions. Another comprehensive investigation started after the disappearance of A330 of Air France airline during the flight from Rio de Janeiro to Paris. It was inconceivable that one of the most modern airliners with an excellent safety record and the latest technology could simply disappear. (PALMER, 2013) One of the main causes of the accident was again the icing.

It is difficult to forecast icing. As it´s written in a book of Aeronautical Meteorology from ENAC (Ecole Nationale de l'Aviation Civile) the biggest problem of icing is that it´s not as obvious as other meteorological phenomena (visibility, precipitations, strong wind…) If you are not prepared, trained or you forget to think about the risk of icing, it can surprise you violently and quite often very late to recover it.

Apart from the meteorological icing, pilots also need to plan for the carburetor icing. I will not write about this type of icing in this work. The aim of the thesis is to study the icing mainly in the area of commercial aviation. There is a minor use of a piston engine aircraft that are influenced by the carburetor icing in the commercial aviation. Nevertheless it´s another icing phenomena that can be dangerous for the air safety in some specific conditions.

The thesis is organized as follows. At the end of the Introduction part, you can find a definition of icing, completed by a description of icing formation.

Chapter 1 characterizes types of icing as it is classified in aviation meteorology. It contains a description of the intensity classification. An overview on the regulatory classification of icing is described at the end of the first chapter.

Chapter 2 consists of a process description of icing identification by the meteorologists on the one hand and by the pilots on the other hand. It also provides the description of the products and the equipment used for the icing identification.

Chapter 3 analyzes an influence of icing on the flight operations. It discusses the problems of ice accretion on the airframe, on the instruments, on the propulsion system and on the windscreen.

Chapter 4 identifies the areas representing the highest risk for flight operations. It warns about a danger of flying in weather patterns that could have a big icing potential. For each hazardous area, the reason of icing presence is examined and it is completed by icing severity and by the type of icing that can be anticipated.

Chapter 5 reviews the major safety occurrences caused by icing that happened in the last 20 years in a commercial aviation. It is based on the official investigation reports published by local authorities. The goal of each occurrence analysis is to reveal meteorological conditions which led to icing formation and to find an effect of icing on the flight safety.

Chapter 6 expands on the Chapter 5 safety analysis and it tries to find out the ways how to increase the safety level and how to decrease the hazard of icing related occurrences. It figures out what precautions should be made to avoid situations studied in Chapter 5.

The conclusion part summarizes the important findings of this thesis and briefly describes the new methods of icing forecasts.

Definition of icing

Icing is a specific form of contamination that consists of a deposit or coating of ice on an object such as an aircraft or part of it. Contamination means any deposit of lithometeors (dry particles suspended in the atmosphere such as dust, haze, smoke, and sand) or hydrometeors (any of various forms of water in liquid or solid form) on a surface. (Labyt, 2008)

Icing formation

In the atmosphere, there are existing three processes that lead to the formation of an ice deposit on a surface at the negative temperature:

1. (Re)sublimation also known as “deposition”, which consists of water changing directly from vapor form to ice form.
2. The freezing of residual water.
3. It´s well known that below the temperature of 0 °C the water exists in form of ice. Very often this is not true. In this case, we speak about supercooled water. The supercooled water starts to freeze in presence of freezing nucleus. Another way how it can be transformed to ice is by hitting an airframe. It mainly occurs in a cloudy or rainy atmosphere.

The amount of supercooled water present in the atmosphere decreases proportionally to a decreasing static air temperature. It´s rare to find some water in liquid form below -40°C, however in well-developed Cumulonimbus clouds it can happen. The size of supercooled water droplets changes with increasing altitude and decreasing temperature as it is presented in the Table 1.

Table 1 - Size of supercooled water droplets (Oxford: Oxford Aviation Academy, 2008)

Temperature	***Size of droplets (diameter)***
0 °C to -20 °C	Large (≥ 50 μm) and small
-20 °C to -40 °C	Only small (10 μm ≤ droplet ≤ 50 μm)
Below -40 °C	Only very small (≤ 10 μm). Freezing will occur without the aid of nuclei.

The result of the supercooled droplet impact is uncertain due to the fact that freezing a small quantity of water can release sufficient latent heat to increase its temperature to 0 °C. Freezing can´t therefore really occur unless all the latent heat released is removed.

At very low temperatures (lower than -20 °C) and for very small droplets (with a diameter less than 10 μm) freezing occurs very quickly via a whole series of heat propagation modes, such as conduction, convection and evaporation. Freezing can therefore occurs almost instantaneously, since the latent heat released is used very quickly. At negative temperatures close to 0 °C, the freezing process can occur much more slowly. This is especially the case of large droplets that have enough time to spread over a surface, while remaining in liquid state before freezing.

The droplet needs a special particle known as nucleus to be transformed into ice. The number of active nuclei is inversely proportional to the temperature. Very few droplets are active until the temperature decreases to -15 °C. Their activity quickly increases below this temperature. The freezing temperature depends on the diameter of the droplets too. The drops that have the diameter of over 1 mm generally freeze at temperature between -15 °C and -20 °C. Smaller droplets with a mean diameter of 20 μm freeze at about -30 °C. The smallest droplets can transform to the ice at temperatures as low as -40 °C. (Labyt, 2008)

1 Types of icing

It exists more kinds of icing classification. The first one is based on the three processes that were previously described, which leads to icing formation. Depending on the weather conditions we can define the basic types of airframe icing as hoar frost, rime ice (soft ice), clear ice (hard ice, glaze ice) and several specific types of icing as mixed ice, rain ice (glazed frost) and pack snow.

1.1 Basic icing types

1.1.1 Hoar frost

Formation:

Hoar frost appears in the conditions when the air temperature reaches the saturation point and a surface of the aircraft is cooled to the freezing temperature. It is the only type of icing that can occur in clear air if we don´t speak about the ice crystals icing (described in the chapter 1.2.3). The water vapor that touches the airframe is directly transformed to ice crystals. This phenomena is known as desublimation or more precisely gas-to-solid condensation. It requires the presence of the desublimation nucleus that has often an inorganic composition (volcanic dust, clay, soil particles). Hoar frost appears both on the ground and in flight. On the ground it usually builds up on the airframe of the aircraft parked outside overnight. It is very similar to the frost that forms on a car windscreen.

Figure 1 – Hoar frost deposit on a wing

In flight, hoar frost appears in case of rapid descent from a very cold air to a warm moist air layer. This icing type is often observed when the plane enters into the inversion layer from a region where air temperature was below 0 °C. The hoar frost icing is not severe in intensity. It can be overcome by flying in a region where the temperature has positive value or by increasing air speed to intensify kinetic heating. (Oxford: Oxford Aviation Academy, 2008)

Appearance:

Hoar frost is a white crystal deposit in a form of needles, scales or feathers which make it quite brittle. It is very similar to the frost on the ground. (Labyt, 2008)

1.1.2 Rime ice

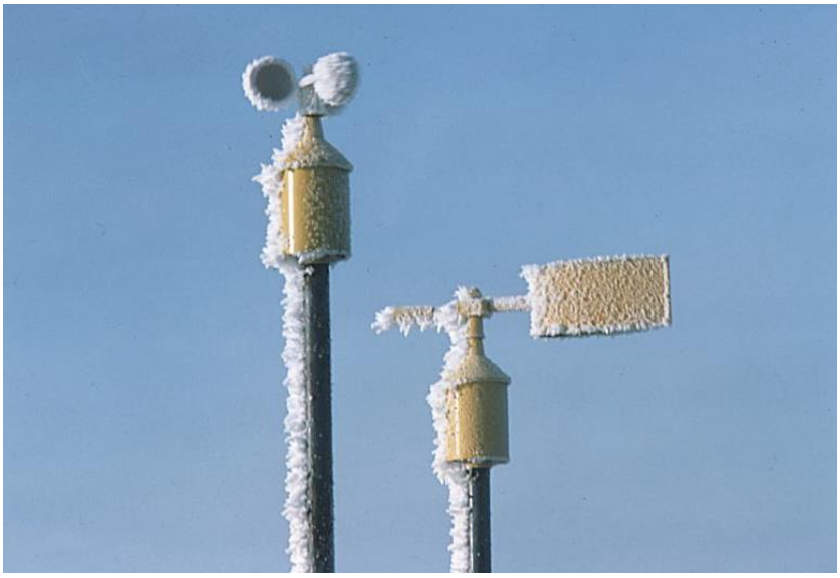
Formation:

Inside the clouds, the rime ice is formed by rapid freezing of the supercooled drops or by very small cloud droplets in contact with a surface at negative temperature. A fast freezing of small water droplets causes that air bubbles contained in the water are trapped in the ice. The ice accretion occurs on the surfaces exposed to the relative airflow and it develops against the airflow direction. Ice doesn´t spread over aft wing surface because of the quick freezing process. Small airfoil shape changes can occur and air intakes can be affected. Rime ice is very often present in Ns, As, Ac, Sc, St and some Cumulus type clouds. (Labyt, 2008)

Appearance:

The rime ice has an opaque, white appearance that is making it fragile and brittle due to trapped air bubbles.

Figure 2 – Rime ice accretion on the meteorological measuring equipment



© (LABYT, 2008)

1.1.3 Clear ice

Formation:

Opposite to the rime ice, the clear ice formation is connected with a slow freezing process of supercooled water droplets. As it is a slow process, ice has enough time to spread over airframe surface, to create homogeneous layer without the air inclusion. The slow freezing process is mainly caused because of the release of latent heat, but the whole process involved is very complex. Only one droplet out of eighty droplets hitting the aircraft surface freezes immediately for each degree below freezing temperature. Clear ice is very dangerous for the flight safety point of view because of uneven build up on the aircraft that often causes problems with controls. The contamination of clear ice is frequently observed on the propellers where it can cause vibrations or skin damage when it is braked off. Typical clouds where a clear ice occurs are Ns, Cu and Cb at temperature between 0 °C and -20 °C. (Oxford: Oxford Aviation Academy, 2008)

Appearance:

Clear ice forms a transparent layer of ice without air inclusion. It can be characterized as homogeneous, smooth, clear, compact and very solid. (Labyt, 2008) It can spread over big airframe surface.

Figure 3 – Clear ice on a leading edge

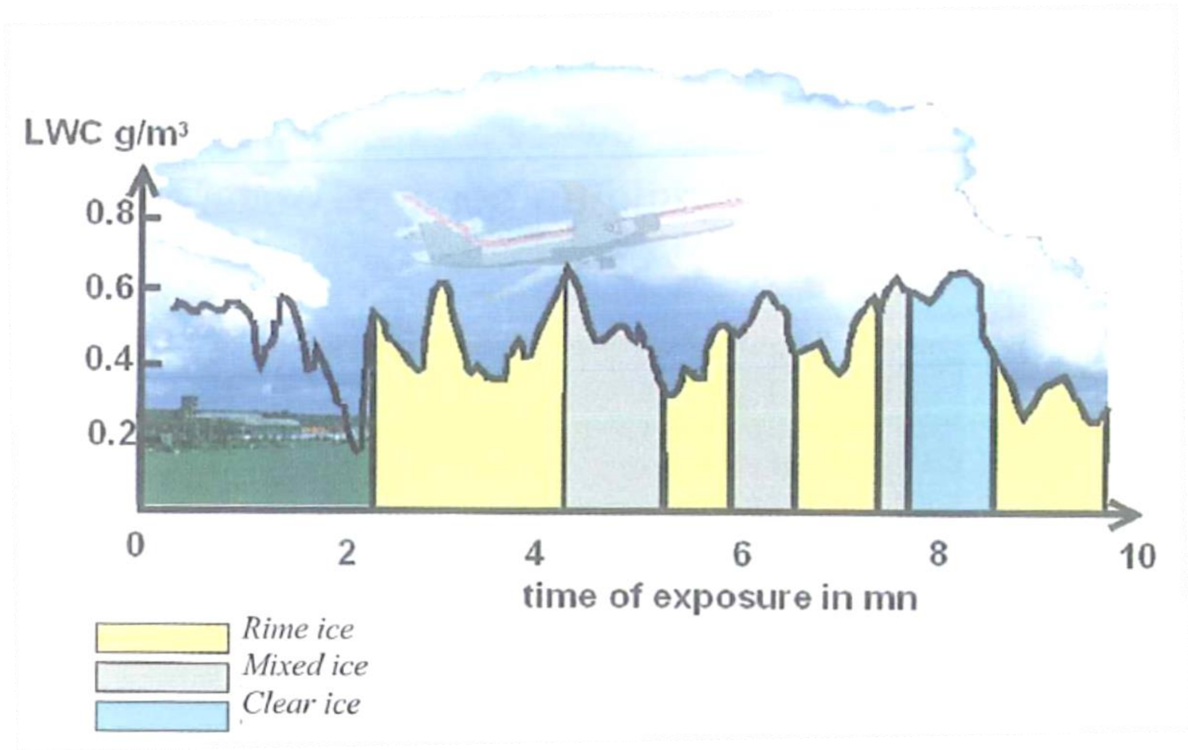
© (LABYT, 2008)

1.2 Specific icing types

1.2.1 Mixed ice

We speak about the mixed ice when clear ice and rime ice are formed simultaneously or in rapid alternations. This occurs in a cloudy atmosphere with a great variety of droplet sizes. The mixed ice formation depends on the variability of phenomena leading to the water freezing.

Figure 4 – Type of icing accreted according to LWC and time exposure



© (LABYT, 2008)

1.2.2 Rain ice (glazed frost)

One of the most dangerous types of icing is the rain ice. It is mainly formed in presence of fronts that separates air masses with different temperatures. The rain formed in a warmer air falls through the layer of colder air with temperature below 0 °C and it becomes supercooled. Clear ice is formed when it hits an airframe. Rain ice builds up very quickly. Pilot has to take immediate action to overcome it. Rain ice is particularly associated with the moderate continuous rain which often falls from Ns clouds. (Oxford: Oxford Aviation Academy, 2008)

1.2.3 Pack snow (graupel), ice crystals

Pack snow is formed when snow is combined by supercooled water droplets. In some cases, it can block probes and engine intakes, but normally it doesn´t have any dangerous consequences.

Ice crystals lead to similar problems, but their formation process is slightly different. A hazard of ice crystals icing exists in high altitudes where a strong convection activity lifts an important quantity of the water. The warm moist air, which contains high water quantity, cools while it climbs. The water condenses and freezes subsequently while it is forming small ice particles – the ice crystals. In high altitudes, in the tropopause layer, strong winds (jet-streams) move ice crystals far away from the clouds where they are formed. That´s why ice crystals are very difficult to detect. In case of Air France flight 447 from Rio de Janeiro to Paris ice crystals were one of the mains causes of the accident (described in chapter 5.1.8). They blocked the pitot tubes of the aircraft and disorientated the crew. Ice crystals don´t form a deposit on a smooth and clean airframe. Ice crystals can be trapped by the droplets freezing on the contaminated surfaces in clouds. When warm surface is hit by ice crystals, they can melt and stick aft of the warm surfaces. If a big amount of ice crystals is present, it can result in probes blockage or engines problems. (Duvivier, 2010)

1.3 Intensity classification

The other type of icing classification is defined in the ICAO documents. Three main types of the icing severity exist in Europe: light, moderate and severe. They are more precisely defined in the Table 2. In the USA, one more level of the lowest icing intensity is defined as "trace". The Intensity level expresses the state of the icing environment, the aircraft's response, and the pilot's assessment of the response. (Politovich, 2003) The classification shown in the Table 2 is used by the pilots. The symbols shown in the Table 2 are visualized on the significant weather charts (SIGWX) where the areas representing the potential risk of icing for the flight can be found.

Table 2 – Atmospheric Icing Potential (Labyt, 2008)

Icing intensity	***Light***	***Moderate***	***Severe***
Icing symbol			
Average quantity of supercooled water	0,6 g/m^3 and less	0,6 – 1,2 g/m^3	1,2 g/m^3 and more
Average diameter of droplets	50 µm and less		50 µm and more
Nature of clouds and hydrometeors	Stable	Unstable	Very unstable Freezing rain and drizzle
Types of icing	Hoar frost Rime ice	Rime ice Mixed ice Clear ice	Mixed ice Clear ice Glazed frost

Table 3 - Effects of the icing in flight (M K Politovich, National Center for Atmospheric Research, 2003)

Icing intensity	***Description***
Trace	Ice becomes perceptible. Rate of accumulation is slightly greater than rate of sublimation. It is not hazardous even though de-icing/anti-icing equipment is not utilized, unless encountered for an extended period of time (over 1 hour).
Light	The rate of accretion may create a problem if flight is prolonged in the environment (over 1 hour). Occasional use of de-icing/anti-icing equipment removes/prevents accretion. It does not present a problem if the de-icing/anti-icing equipment is used. In this case, change of heading or altitude is not necessary.

Icing intensity	*Description*
Moderate	The rate of accretion is such that short encounters become potentially hazardous and use of de-icing/anti-icing equipment, or diversion, is necessary. The change of heading or altitude may be considered.
Severe	The rate of accretion is such that de-icing/anti-icing equipment fails to reduce or control the hazard. Immediate diversion, change of heading or altitude is necessary.

The classification shown in the Table 3 is based on the effect of icing on the aircraft. The meteorologists use another way how to classify the icing severity as it´s presented in the Table 4. Of course, the meteorologists use also other weather information as LWC to identify the icing (e.g. temperature, movement of the air, information about cloud cover)

Table 4 - Icing intensity classification in meteorology (Giuseppe Mingione (CIRA), 2000)

Icing intensity	***LWC[i] [g/m3]***
Trace	0,1 and less
Light	0,11 – 0,6
Moderate	0,61 – 1,2
Severe	1,2 and more

An estimated quantity of the water content inside the clouds is visible in the Table 5.

[i] LWC Liquid Water Content

Table 5 – LWC in clouds (Giuseppe Mingione (CIRA), 2000)

Cloud type / weather phenomena	***LWC [g/m3]***
Mist and fog	0,1 – 2
Stable clouds	0,2 – 0,5
Unstable clouds	0,5 – 5
Unstable clouds in tropical regions	up to 16

1.4 Regulatory classification

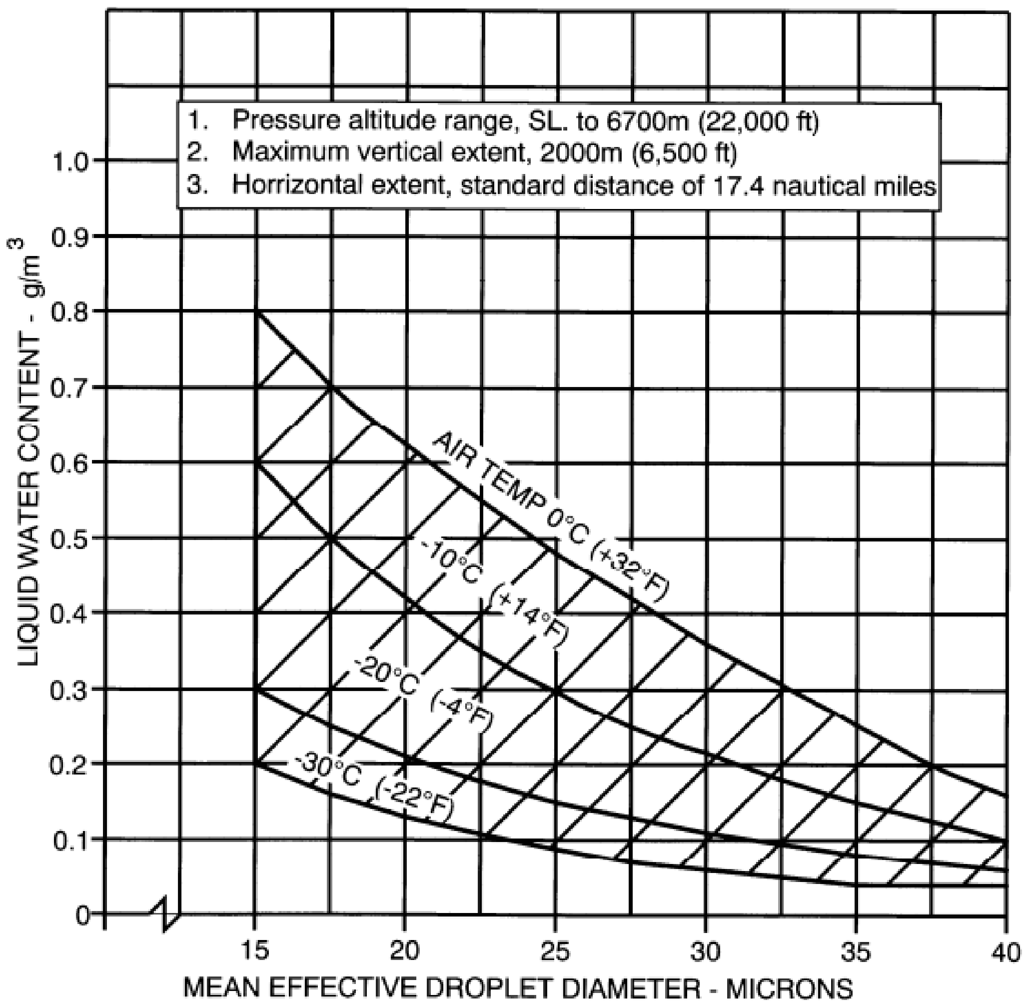
1.4.1 Aircraft certification

In Europe, the requirements for heavy aircraft certification (over 5,7 tons of MTOW) are specified in CS 25 document. This regulation contains a specification of the atmospheric icing conditions and defines airframe ice accretion for the certification needs as it is shown in appendix C.

Icing conditions are divided to 3 limiting types:

1. Continuous maximum icing (stratiform clouds)
2. Intermittent maximum icing (cumuliform clouds)
3. Takeoff maximum icing

Figure 5 – Continuous maximum (stratiform clouds) atmospheric icing conditions Liquid water content VS mean effective drop diameter (CS-25, 2012)



Each type of icing conditions is defined by multiple figures or values as variables of the cloud liquid water content, the mean effective diameter of the cloud droplets, the ambient air temperature. The interrelationship of these three variables is given as it´s shown in the figure below. The limiting icing envelope is defined in terms of altitude and temperature. Continuous maximum icing differs from Intermittent maximum icing mainly by the horizontal extent that is defined in the regulation.

For example the takeoff maximum icing is defined by the cloud liquid water content of 0.35 g/m3, the mean effective diameter of the cloud droplets of 20μm, and the ambient air temperature at ground level of minus 9 °C. CS 25 defines that the takeoff maximum icing conditions can extend from ground level to a height of 457 m (1500 ft) above the level of the takeoff surface.

In order to pass certification tests, an aircraft must show the ability of safe flight with the most critical ice accretion in terms of airplane performance and handling qualities. Ice accretion are defined in the following categories based on a phase of the flight:

a) Take-off Ice (from ground to 400 ft AAL)
b) Final Take-off Ice (from 400 to 1500 ft AAL)
c) En-route Ice
d) Holding Ice
e) Approach ice
f) Landing ice

The problem of CS 25 requirements specified in appendix C is that they don´t cover all types of icing. CS 25 doesn´t ensure a safe operation in presence of freezing precipitations with supercooled large droplets (droplets with diameter 50 μm or more), in case of ice crystals and mixed phased icing.

1.4.2 Engine certification

Requirements for engines certified to operate in icing conditions are specified in CS-E. CS-E 780 says: "It must be established by tests, unless alternative appropriate evidence is available, that the Engine will function satisfactorily when operated in the atmospheric icing conditions of CS-Definitions without unacceptable:

(1) Immediate or ultimate reduction of Engine performance,

(2) Increase of Engine operating temperatures,

(3) Deterioration of Engine handling characteristics, and

(4) Mechanical damage." (CS-E, 2015)

The capability of the engine to work in icing environment has to be proven in the most critical engine settings. The certification tests should take into account all the parts/equipment of the engine that could affect the air intake. Table below specifies the conditions of engine icing tests cycles.

Table 6 - Engine icing tests cycles (CS-E, 2015)

Ambient air temperature	Altitude		Liquid water content (g/m^3)		Mean effective droplet diameter
(°C)	(ft)	(m)	(a)	(b)	(µm)
–10	17 000	5 200	0·6	2·2	20
–20	20 000	6 100	0·3	1·7	
–30	25 000	7 600	0·2	1·0	

2 Identification of icing

2.1 Identification by meteorologists

Meteorologists identify the icing by evaluating an ice potential of the atmosphere. The ice potential is directly proportional to the total quantity of supercooled water, to the size and to the distribution of the water drops or of the droplets. It depends on the temperature and on the vertical movements of the air. It is not easy to forecast icing conditions because precise meteorological forecasting model doesn´t exist. The droplet size is not observed during meteorological observations. The quantity of the liquid water in the atmosphere is not forecasted. We don´t have information about vertical movements of the air in all the troposphere. We are able to identify and forecast the ice potential just based on a good knowledge of the physics of icing, radar data, satellite imagery and thanks to the numerical forecasts. An operational knowledge of the humidity, temperature and vertical movements are used in the ice potential evaluation. To determine the humidity, analysis of the cloudy saturated atmosphere is required. Big probability to find some supercooled water droplets or the precipitations exists in clouds. The temperature is another important factor when considering supercooled water droplets. A maximum density of supercooled water droplets is present near the temperature of 0 °C. That is the reason why the ice potential is maximal close to 0 °C isotherm. It is really rare to find present some liquid water below -40 °C. Generally we can say that ice potential decreases with increasing altitude. Vertical movements play a very important role too. Their task is to distribute the humidity from the lower parts of the troposphere to the upper parts. That´s why an unstable cloud with strong vertical movements has a bigger content of water than a stable cloud with much weaker vertical movements. When comparing a stable cloud and an unstable cloud with the same dimensions and the same temperature at the base of clouds, the unstable cloud contents five to ten times more condensed water than a stable cloud on average. The ice crystals naturally exist only below the temperature of -15 °C. The presence of ice crystals causes that the liquid water content decreases in a cloud. It means that as ice crystals develop, the water droplets disappear and ice potential is decreasing. That´s why recently developed Cumulus, which hasn´t reached an altitude where the temperature is -15 °C yet, has a higher ice potential than a well-developed Congestus in an altitude of 10 km.

In meteorology a few specific terms describing clouds and their content are used.

Mixed cloud

The mixed cloud contains both the supercooled water droplets as well as the ice crystals.

Ice cloud

Ice crystals dominate inside the ice cloud.

Warm cloud

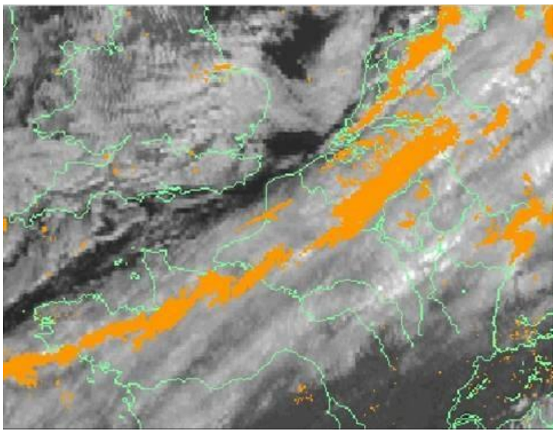
A cloud where the temperature doesn´t drop below 0 °C is called a warm cloud. (Labyt, 2008)

2.2 Weather products used in icing identification

2.2.1 Satellite and radar images

Satellite and radar images can provide valuable help in identification of the icing areas. However, it is not possible to observe the icing while using the satellites and the radar data only. Even if the most modern radars can provide us with the information about the temperature of precipitation, it´s still complicated to forecast icing. The combination of various data about weather conditions (temperature, vertical movement of the air, humidity, forecasts…) are needed very often to be able to forecast icing potential. For example Swiss company specialized in short-term weather forecasts combines data from ground measurements of the temperature, humidity, precipitation with the satellite and the radar data to forecast the danger of freezing rain.[2]

Figure 6 – Superposition of radar echoes with the satellite image

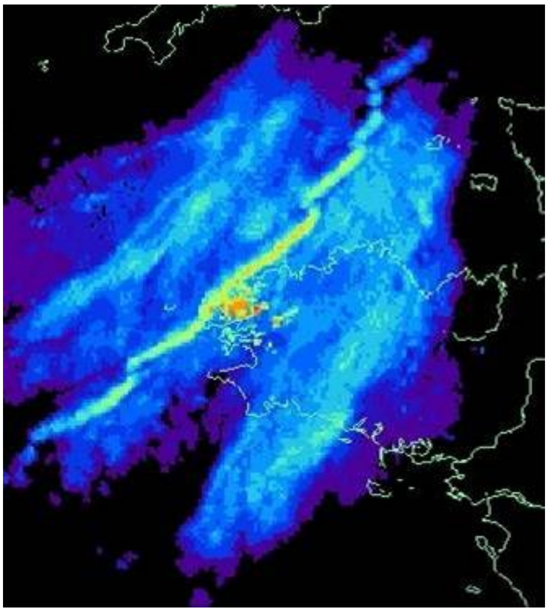


© (LABYT, 2008)

[2] http://www.meteoradar.ch/pdf/181_abf_e_Schmid.pdf

Icing can be sometimes identified thanks to the rain bands that are displayed on the rainfall radar screens. We can see the superposition of radar echoes with the satellite image taken when the front was passing over the Northwest part of France in the Figure 6. It shows the areas of icing in long bands.
In the other radar picture (Figure 7), it´s possible to identify the structures known as “scaled structures”. In these areas it´s very probable to find a maximum icing intensity.

Figure 7 – “Scaled structures” in the radar picture



2.2.2 Forecasts, charts and reports

The pilots use several types of meteorological products to stay informed about the weather conditions. A lot of them also contain the information about icing. For example AIRMETs reports are issued to inform about moderate icing and SIGMETs reports are published for the areas of severe ice formation outside of thunderstorms. The figure 8 below shows an example of SIGMET report with a warning that occasional severe icing can be encountered above expected freezing level.

Figure 8 - Example of SIGMET report

DFWA UWS 051710

SIGMET ALFA 1 VALID UNTIL 052110

AR LA MS

FROM MEM TO JAN

OCNL SVR ICING ABV FRZLVL EXPCD.

FRZLVL 080 E TO 120 W.

CONDS CONTIG BYD 2100Z.

PIREPs issued by pilots in flight are used to confirm information about icing or to warn the other pilots about the icing conditions. When the PIREP exists, we can speak about “known icing”. It is always required from pilots to make a PIREP in case they observe the icing during a flight due to safety reasons. An example of PIREP report below warns about the light rime icing between 2 000 ft (610 m) and 4 000 ft (1 219 m) and about the light freezing rain in clouds.

Figure 9 - Example of PIREP report

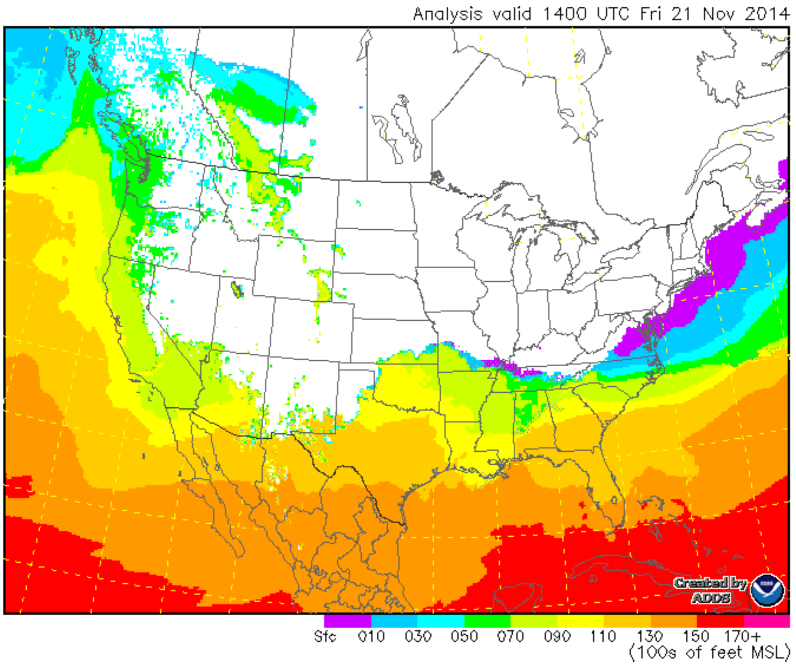
UACN10 CYQT 192128

YZ WG

UA /OV YSP 090025 /TM 2120 /FL050 /TP BE99 /SK 020BKN040 110OVC /TA -14 /WV 030045 /TB MDT CAT 060-080 /IC LGT RIME 020-040 /RM LGT FZRA INC

The observed freezing level charts are provided to determine the altitude of 0 °C isotherm. The traditional way of measuring air data needed to publish these types of chart was a radiosonde. Nowadays an additional instruments such as measuring devices attached to the aircraft, satellites and weather radars are used to determine the actual freezing level.

Figure 10 - Freezing level chart



© Aviation Digital Data Service (ADDS) [3]

2.2.3 ACARS data usage

Commercial airplanes provide over 130 000 meteorological observations per day nowadays, including measurements of the temperature, winds and in some cases the planes observe of the icing, humidity, vertical wind gusts or eddy dissipation rate (turbulence). (Moninger, 2003) During the experiment called TAMDAR special sensors were installed on 63 Mesaba Airlines Saab 340 aircraft flying over the central and eastern United States and Canada. Real time weather data were collected during a climb, cruise flight and descent. Meteorologists on the ground tried to forecast icing in areas where pilot reports (PIREPS) were missing. (Mamrosh, 2003)

ACARS is also used in the opposite direction of communication for sending the messages or data from the ground to the air. For example Air France dispatchers monitor the flights from the ground. In case of need, they can inform a crew about icing conditions expected on the route or they can directly re-plan their flight if it is necessary.

[3] http://www.aviationweather.gov/adds/icing/frzgnav

2.3 Identification by pilots

Before a flight, pilot must study the meteorological conditions that will affect his flight. If there is a probability of icing conditions, he uses all the materials available from the paragraph above to plan the flight safely.

2.3.1 Weather radar

Weather radar is a big help for the pilots up in the air. Pilot needs some skills and the experience to well interpret what the radar shows. When operating the radar, pilot has the options to adjust the sensitivity of the receiver, the tilt of the radar beam, the range and the brightness of the display. Radar screen shows the colors and the shapes that have to be interpret.

The main reason of radar presence on board is to enable the navigation of the pilots around the thunderstorms, to avoid dangerous turbulences and the icing as well. However, it is not in the capabilities of the radar to directly identify the icing. Radars work on a principle of sending out the pulses of radio waves and then listening for those waves to bound back off the water droplets about the size of a raindrop.

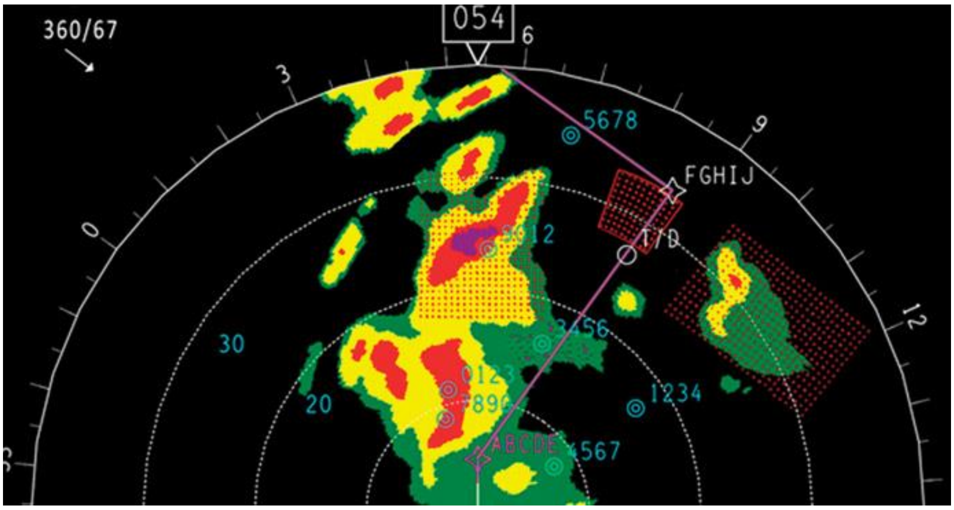
A hazard of overflying the storm is proportional to the concentration of water droplets. The correlation with a turbulent parts of storm is quite good. In addition, on some radar sets, it is possible to use Doppler signal processing to measure the movement of different areas of the water droplets within a storm for an additional indication of the turbulence. This option is generally available at short range (40 miles) only.

The problem of radar is that it reflects poorly when liquid water is not present. It´s not able to reflect off the water vapor, the micro sized droplets that form majority of clouds and it reflects poorly ice crystals, ranging from the snowflakes to the hail stones. In the most cases the icing is caused by supercooled liquid water but in some special conditions the micro sized droplets or ice crystals can create really dangerous icing environment.

Pilots have to consider many aspects when interpreting a weather radar, e.g. the intensity of the return (shown in colors), the gradient and shapes of the different intensities, blocking of returns by a complicated weather or the curvature of the earth and they have to differentiate between radar returns reflecting off the ground and the actual weather.

There is no need to avoid all areas displayed on the radar screen. Sometimes it is even not possible. The pilots look at the intensity and the gradient of radar returns as well as at the shape of those returns in order to make a good decision about the state of the weather. At the cruising phase of flight, when thunderstorms are suspected, pilots must adjust the tilt of the radar antenna beam down to look for the more reflective parts of the storm that may cause problem at their altitude. (PALMER, 2013)

Figure 11 – On-board weather radar screen



© Rockwell Collins[4]

2.3.2 Ice detectors

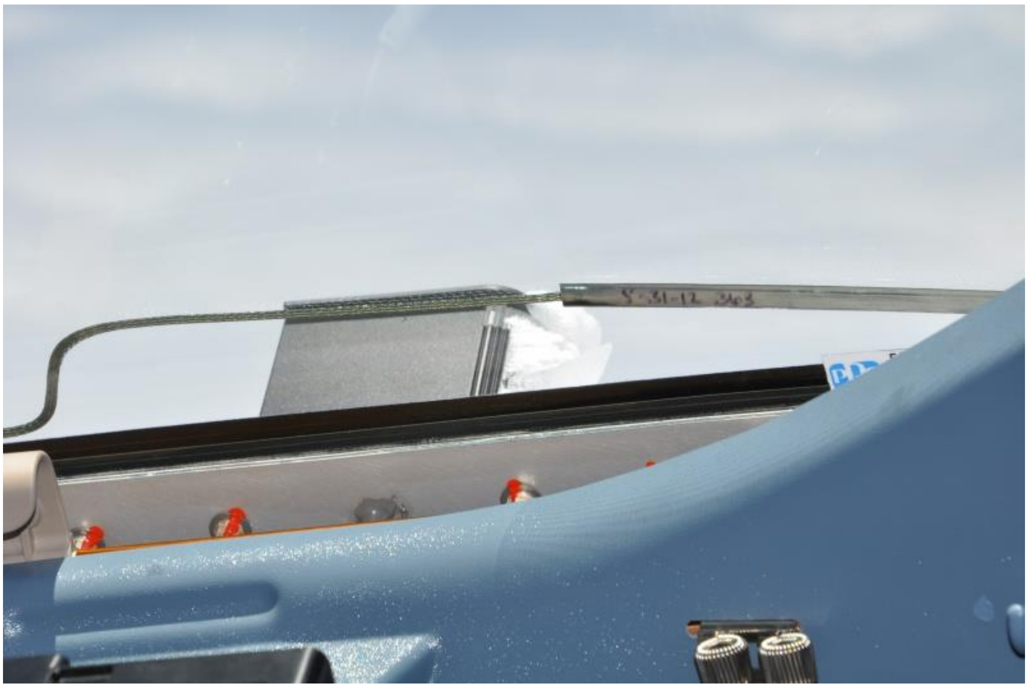
Visual inspection is a basic way how to check if there is no ice accretion on the airframe. Many airplanes used for the night flights are equipped with the ice formation spot lights mounted on an each side of the fuselage to light up the leading edges of the wings allowing visual examination for an ice formation. Sometimes it´s hard to see any other part of the airframe from the cockpit. For this case, there are the ice detectors that are used to verify that the ice accretion on the most vulnerable parts of the aircraft is acceptable. Otherwise use of de-icing/anti-icing equipment or escape from icing conditions are necessary. Several types of icing detectors exist and are used on board of the aircraft.

2.3.2.1 Visual ice detectors

Some systems make it easier to detect icing conditions by simply showing ice accretion on a special device in shape of an airfoil that is visible from the cockpit. When ice starts to adhere to the surface of the airfoil, heater can be switched on to de-ice the surface.

4 https://www.rockwellcollins.com/sitecore/content/Data/Products/Radar_and_Surveillance/Weather_Radar/WXR-2100_Weather_Radar_System.aspx

Figure 12 – Ice detector used on the ATR aircraft



© Jan Tutaj[5]

2.3.2.2 Smiths ice detector

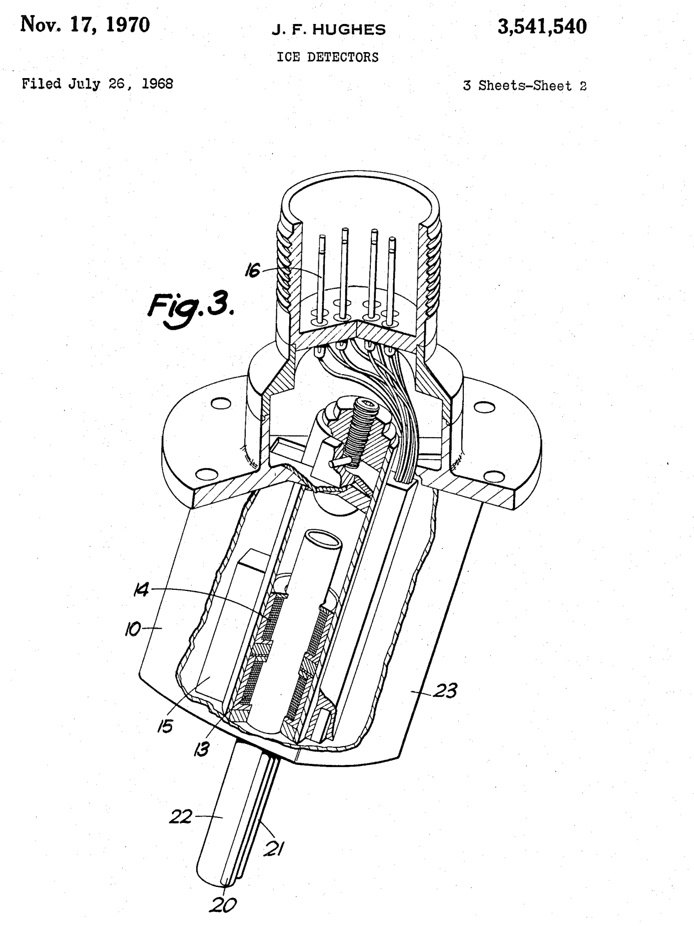
The other ice detectors can actively warn the flight crew about the icing conditions. Smiths ice detector is one of them. It is a tube attached to the aircraft, with holes in the leading and trailing edges. Pressure sensor is placed inside the tube. Flying in icing conditions causes that holes at the leading edge become blocked by ice and a negative pressure is created in the tube. This activates a relay unit and gives a warning to the crew. Accumulated ice can be dissipated using a heater element.

2.3.2.3 Vibrating ice detector

Some sensors use the variation of vibration frequency of the probe where ice built up to determine ice accretion. It´s a case of Rosemount ice detector. A mass of ice that builds up on the probe reduces its resonant frequency. When it falls below a predetermined value a warning is given.

[5] http://www.pilotes-prives.fr/viewtopic.php?f=2&t=17099&start=30

Figure 13 – Patent schema of the vibration type detector - Hughes concept



© Hughes John Francis [6]

2.3.2.4 Napier ice detector

Napier ice detector works on the principle of rotating shaft and knife edge cutter. When icing occurs, ice accumulates on the shaft that is flexibly mounted on the aircraft fuselage. The knife cutting the ice on the shaft causes a small rotation movement of the shaft in its mounting which activates the icing detectors. Depending on the system design this can directly initiate the anti-icing sequence.

2.3.2.5 Sangamo Weston ice detector

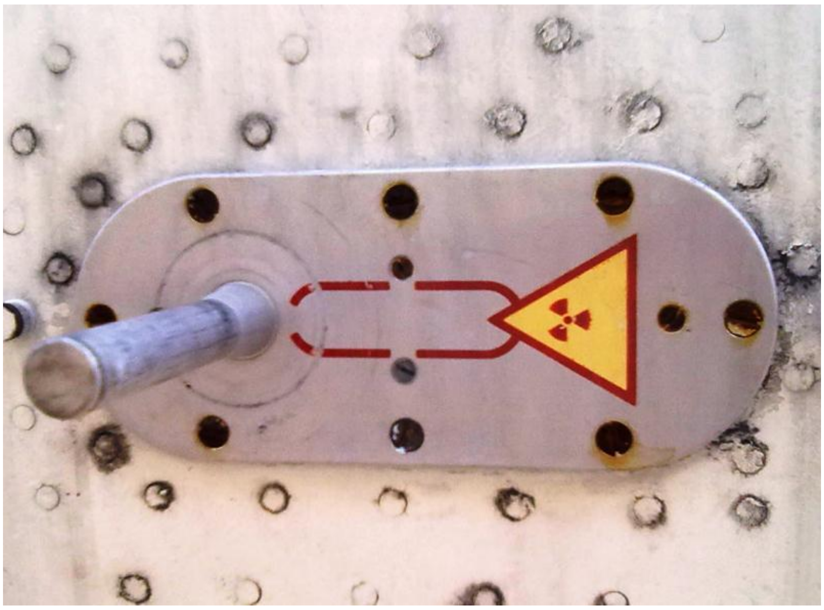
Ice can be detected by measuring a combination of the humidity and the temperature too. Sangamo Weston ice detector measures the humidity present in the air. When it determines a sufficient amount of water and freezing temperature, it activates an icing warning. In this case, icing conditions are detected rather than actual ice formation.

[6] http://www.google.com/patents/US3541540?hl=en

2.3.2.6 Ice detectors using radiation

Other types of detectors use an emission of small quantity of radioactive beta particles. If ice builds up on the detector, beta particles are absorbed by ice. A known difference between the amount of emitted and detected particles is proportional to the level of icing. (Oxford: Oxford Aviation Academy, 2001)

Figure 14 – Ice detection probes emitting beta particles



© Wikimedia Common[7]

[7]https://commons.wikimedia.org/wiki/File:%D0%94%D0%B0%D1%82%D1%87%D0%B8%D0%BA_%D0%BE%D0%B1%D0%BB%D0%B5%D0%B4%D0%B5%D0%BD%D0%B5%D0%BD%D0%B8%D1%8F.jpg?uselang=ru

3 Influence of icing on flight operations

Until now, we have looked on icing as on the meteorological issue mainly. But icing is influenced significantly by the aircraft, flight and aerodynamic characteristics of flight as well.

A speed of the aircraft and its aerodynamic shape are very important factors in aircraft icing. They have important influence on the surface temperature of the airframe through aerodynamic heating. When we look at the wing section, the temperature of surface varies a lot as we move backwards from leading edge to trailing edge. It reaches the highest value at the impact point where a relative airflow speed is zero. As the airflow reaches the point of maximum thickness, the temperature of surface decreases to the minimal value. From that point, it restarts to increase until reaching the trailing edge. The difference of surface temperatures caused by aerodynamic heating can reach 27°C at 450 knots airspeed. For example, an aircraft flying at FL100, where standard air temperature is -5°C, cruising at Mach 0,6 will have the temperature of 12,8°C at the point of impact and the average temperature of the wing surface section will be 11°C.

Another factor that determines the ice accretion is a trajectory of water droplets. The movement of the water particles is slightly different from the trajectory of relative airflow. The difference in trajectory depends mainly on the inertia of water droplets, on their speed and on the shape of the airfoil.

Some parts of the airframe are more sensitive to the icing than the other parts. The most sensitive parts to the icing are the sharp components such as the leading edges of the wing, the empennage, the engine intakes, the propellers, the spinners, the antennas, probes, the windscreen wipers. The icing occurs easily on these components because boundary layers give only a little insulation between sharp skin and ice.[8] It´s important to monitor these parts of the airframe as the ice accretion on these parts could be critical for all the aircraft. (Labyt, 2008)

3.1 Airframe icing

3.1.1 Mass increase

The quantity of an ice accretion depends on the type of icing. It ranges from less than 1centimeter per hour, up to several centimeters in a few minutes in case of well-developed Cumulus type clouds, containing supercooled water droplets or freezing precipitations. This

[8] http://www.caa.govt.nz/safety_info/gaps/aircraft_icing_handbook.pdf

can lead to an increase of several tons in aircraft mass during a short period of time. Variation of the mass caused by icing will have more significant effect on a light aircraft that has generally less excess of power then on a heavy aircraft type. Unexpected weight increment from the icing can have serious consequences on the aircraft flying close to maximum take-off weight after departure. (Labyt, 2008)

3.1.2 Modification of balance

Ice deposits will not often be uniformly repartitioned across the airframe. This will modify a distribution of mass, CG position will be modified and finally it may cause a loss of stability. (Oxford: Oxford Aviation Academy, 2008)

3.1.3 Aerodynamic effects

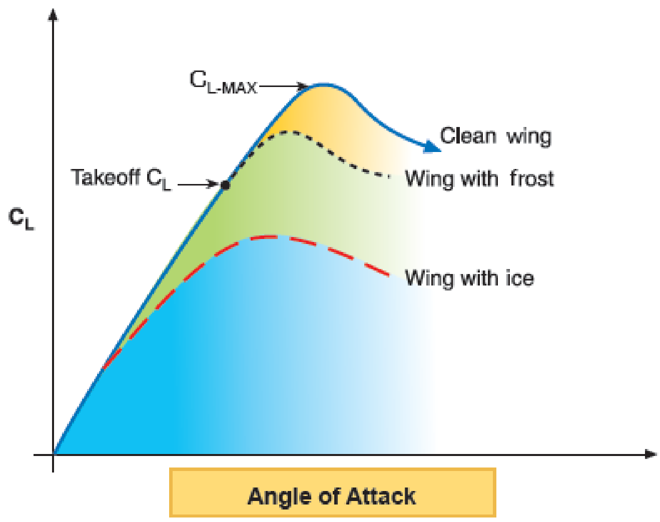
The ice accumulates firstly on the leading edges of an airfoil. It disrupts the laminar air flow on the wing and significantly reduces a lift. This causes an increase of drag and reduction of the stall angle. Ice modifies the handling characteristics and the aircraft performance. Turbulent air flow can also cause small effectiveness of the control surfaces. In some special cases, when de-iced water re-freezes on the movable surfaces, mechanical jamming of the control surfaces, especially blockage of the slots, is possible. (Labyt, 2008)

3.1.4 Problems with controls

3.1.4.1.1 Wing stall

Ice deposit on a wing affects the lift negatively. It decreases the critical angle of attack while drag and weight increase.

Figure 15 – Lift curve showing the effect of the icing (U.S.Federal Aviation Administration, 2008)



1mm thick layer of the ice on the wing is sufficient to change the wing lift-angle of attack curve. This leads to a smaller value of maximum lift coefficient and to a smaller stall angle value. The maximum value of the lift (on the lift coefficient/angle of attack curve) can be reduced by a half because of the ice accretion depending on the airfoil type. The controllability of the aircraft becomes worst at low speeds, close to the stall speed, when plane flies at high angle of attack.

3.1.4.1.2 Roll upset

One type of the problems with the controls caused by severe inflight icing are known as roll upset. It is an uncommanded and uncontrolled roll phenomena. Every pilot should be aware that severe icing is a condition that is out of the airplane's certification icing envelope, even if pilot is flying with an aircraft certified for flight in known icing conditions.

Ice ridge, which builds up on an unprotected surface of the wing, disrupts laminar flow of the air. Airflow separation on the wing induces self-deflection of the ailerons and degraded roll handling characteristics. The problems with the controls can start unexpectedly without the usual symptoms of ice accumulation.

3.1.4.1.3 Empennage stall

The second problem with the controls caused by icing is the empennage stall. As the tail plane accumulates ice faster than the wing and as it is outside the view of the pilot, the crew is unaware of the situation until the stall occurs. When the ice deposit on the tail plane becomes excessive and the horizontal stabilizer reaches critical value of angle of attack the tail plane stall occurs. Natural nose down tendency produced by the center of lift of the main wing will not be compensated by tail plane any more. The plane will react by pitching down uncontrollably. The biggest problem of the tail plane stall is a relatively high airspeed at the onset. Unfortunately, it is favorable to happen in low altitudes before landing. In this phase of the flight, the flaps are in extended position what increases pitching moment of the aircraft.[9] (CIVIL AVIATION AUTHORITY OF NEW ZEALAND , 2000)

[9] http://www.caa.govt.nz/safety_info/gaps/aircraft_icing_handbook.pdf

3.2 Instruments icing

3.2.1 Probes icing

Following the accident of Air France Flight 272 in July 1961, caused by the Pitot tube icing, the pressure probes on the passenger aircraft are now heated during all the flight. Without the heating, the pitot tubes can be very easily blocked by the ice, even in light icing conditions. In this case, they will not show a real airspeed of the aircraft and all pressure measuring instruments of the aircraft will not work properly. It can be very confusing for the crew. It is proven by the fatal accident of A330 in 2009. A lot of planes are equipped with de-icing of static pressure probes as well.

In jet engines, pressure probes are used to determine Engine Pressure Ratio that corresponds to the engine thrust settings. These probes are situated in the compressor inlet where they can become blocked by the ice. The pilots, who do not know that engine inlet pressure probes are blocked by the ice, will reduce the thrust and they can approach the stall speed because of an incorrect instrument data reading. Very similar situation happens with the Engine Inlet Temperature sensors which can be also blocked by the icing. These problems could cause operation difficulties and sometimes they lead to inappropriate power settings.

3.2.2 Antennas icing

A sharp shape and the position of the antennas makes them very vulnerable to the ice formation. Antennas must be equipped with anti-icing protection to do not disturb the radio communication. Antenna can starts to vibrate in case of ice accretion on it. Sometimes it leads to breaking up the antenna. The communication is impossible without the antenna and there exists a danger of damage of some other aircraft parts by hitting when it breaks.

3.2.3 Angle of attack indicators icing

Some commercial aircraft types, as for example late models of Boeing 737, 767 or 777, are equipped with the angle of attack indicators. They provide the indication of a green approach band which represents the normal range of the angle of attack for approach. (PALMER, 2013) As the indicators protrudes from the nose of the aircraft, the ice can easily builds on them. Without any electric heating, the indications of the angle of attack indicators would not be reliable.

3.3 Propulsion system icing

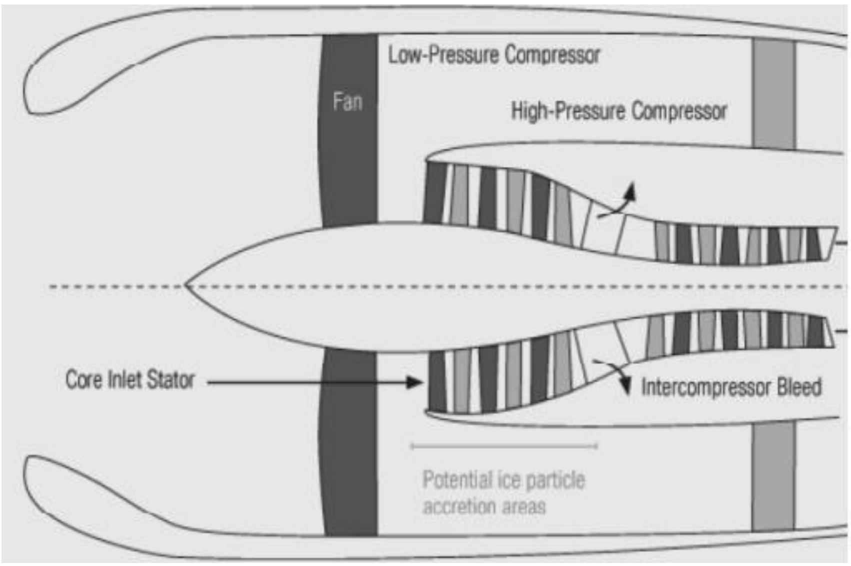
3.3.1 Engine icing

The ice can accrete on the engine intakes and on the fan blades following the same principle as on the wing. The ice deposits on the engine intakes disrupt an airstream and degrade the thrust. When the ice formation is excessive or if the de-icing of the engine inlet is operated improperly, big ice blocks can be ingested by the engine. This can damage the blades of the compressor or it could lead to the engine flame-out and sometimes to the explosion of the engine.

It happens that the ice builds up on the fan blades after start-up of the engine, whilst it is running at low thrust for a longer period of time. In this case the prescribed engine handling procedures may be used to remove the ice from the blades.

Ice crystals often present a high risk for a safe run of the jet engine. The principle of the ice crystals accretion in the engine is not completely understood. It seems that the ice crystals which enter the engine start to melt on the surfaces of the compressor. The melted ice creates a liquid film that captures other ice crystals. Heat is removed from the compressor until the liquid film starts to freeze inside the engine. The ice layer can easily shed from the compressor parts. It results in the engine instability such as a surge, a flameout, or an engine damage. (Duvivier, 2010)

Figure 16 – Cross-section of the turbo-fan jet engine and the potential icing accretion area



[10]

[10]© (Duvivier, 2010) https://easa.europa.eu/conferences/iascc/doc/Workshop%201%20Presentations/Workshop1_DAY%202/1_Duvivier_EASA/IASCC_E%20Duvivier.pdf

3.3.2 Propeller icing

The propellers are the parts of the aircraft, which are significantly exposed to the effects of the icing. They have to be protected in case of flying into the icing conditions. With a fixed blade propeller, a drop in the RPM is often a sign that the ice starts to build up. When using a constant speed propeller, the presence of the icing is revealed by observing the manifold pressure reduction. The propeller will start to vibrate because of the ice sometimes. The severe icing can cause a destruction of the propeller. To overcome it, the anti-icing systems are mounted on the propeller. Some of them are electric but a chemical principle is used very often. The tips of the blades are normally not protected against ice. Ice shades naturally from there because of the centrifugal force. A first sign of the ice accumulation on the propeller is observed on the propeller spinner that must be de/anti-iced too.

3.4 Windscreen icing

In case of an IFR flight in a cruising level, you don´t need to watch out through the window frequently. When landing, it can be necessary to have a visual reference with the ground and the obstacles. The ice formation on the windscreen is nothing uncommon during the winter operations in Europe. The airliners are prepared for it. Their windscreen are composed from the multiple layers. One of the layers contains electrically heated metal, used to de-ice the windows. The advantage of this type of anti-ice equipment is that it keeps all the windscreen without the ice. The pilots of smaller planes that are not equipped with this type of windscreens, must watch out from the cockpit through a small rectangle that is de-iced by electricity, hot air or by other means.

Figure 17 – Anti-icing plate on the Cessna´s windshield


[11]

[11] Kevin G. Mackenzie © 2002-2005, http://www.337skymaster.com/arlington2004/dirkp337/index.htm

4 Areas representing the highest risk for flight operations

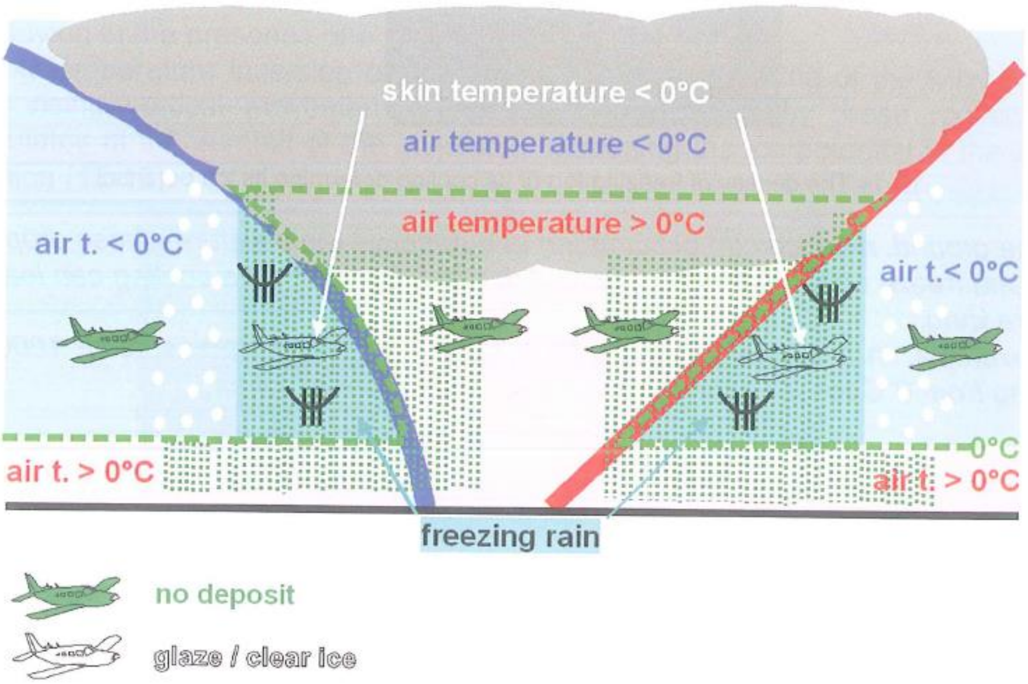
4.1 Areas under influence of front passage

The dangerous phenomena for the flight appears in a presence of the cold front but the warm front complicates the weather situation even more.

4.1.1 Influence of Cold front

Cold front is a barrier that separates two different air masses. The warmer air is being replaced by the colder air. The colder air has bigger density than the warmer air and it pushes up the warmer air to the higher altitudes. Two different air masses exist one over the other, separated by the front line. This state is perfect for the icing formation. Precipitations that are formed in the warmer air, in form of the rain, fall to the colder air. If the colder air has a temperature below 0 °C, freezing rain occurs. Rain drop that condenses in the warm sector, falls to the cold air. Freezing air cools the water droplet. When it falls on the ground or on an aircraft in flight, it breaks, spreads out and forms clear ice. In these conditions severe icing is very probable. Ice accumulates so quickly that almost every aviation industry manufacturer advises that none of its products, even those certified for known icing, are design to fly in the freezing rain.

Figure 18 – Icing conditions near fronts



© (LABYT, 2008)

4.1.2 Influence of Warm front

Similar situation as we have seen at the cold front area happens with the warm front passage. In this case the warmer air is replacing the colder air. It means that the warmer air will climb above the colder one that has bigger air density. A 0 °C isotherm increases its altitude. The air temperature increases first at higher altitudes as the front passes. If a temperature of the colder air is negative, the freezing rain forms again. In case of the warm fronts, the areas under the influence of the freezing rain is much wider in comparison with the cold front. The freezing rain forms only in case that rain drops are falling on a short distance threw the colder air (with the negative temperatures). Otherwise, water is transformed into ice and drops become ice pellets. It is a night mare of every pilot to cross this type of weather during the flight.

4.2 Flight into supercooled precipitations

In the winter, mainly in some mountainous regions, it happens that the warm air arrives in the upper parts of the troposphere but the cold freezing air is blocked in the valleys (because of the orographic blocking). There exists a big probability of glazed frost formation on an aircraft flying in a valley when the precipitations form in this area. Glazed frost represents a severe icing conditions with a serious hazard for the aviation activity.

4.3 Inversion in an altitude

Strong temperature inversion in the altitude of a few thousand feet or the wind shear can block all the updrafts in the air. The water lifted up from the ground to the inversion layer starts to accumulate near the top parts of the inversion. If this phenomena takes places in a higher altitude, where the temperature drops under 0 °C, the probability of the icing is quite high. Statocumulus clouds imply the presence of the temperature inversion very often. Closer to the top of Stratocumulus we are flying, higher icing severity is possible.

4.4 Orographic lifting

The glider pilots could speak about the power of wave flying. The wind is deflected to the high altitudes thanks to the mountains. In the mountains, an air mass contains a big amount of the humidity. This humidity is transported to a high troposphere by an orographic lifting. It results in the formation of the clouds above the mountains. These clouds contain supercooled water. It represents the potential icing conditions in combination with the cold air.

4.5 Influence of the seasons

In the winter, the weather can be characterized by more active disturbances, lower temperatures and higher thermal contrasts. All these factors increase the ice potential. In Western Europe an influence of the air masses, situated above the ocean that are different from a continental air mass, plays an important role. The circulation of the water is affected by a presence of these two different air masses. The consequences are most visible in the autumn. In this season, the sun has much less power to warm the ground and consequently the air above the continent. The ocean and the water inside has higher thermal capacity than the air. The water becomes warmer than the air coming from the continent. This leads to the water evaporation, humidity increase in the air and it indicates that icing can occur. (Labyt, 2008)

4.6 Foggy areas

The fog is quite often a problematic issue because of the poor visibility in aviation. In the winter, a temperature of the air in the fog sometimes drops under 0 °C. In this case, we speak about the freezing fog.

As the land cools under the clear skies overnight, it easily loses its temperature. When the air temperature decreases, the ability of the land to preserve humidity decreases as well. That´s why the fog is created. In the winter, the land can radiate as much heat that it starts to freeze. Water exists in the state of supercooled water droplets until it hits some surface or the ground. Rime ice with light to moderate intensity can be expected. Very low freezing temperatures can sometimes lead to severe icing conditions.

4.7 Cold high pressure areas

The presence of clouds is not always necessary for the icing formation. The high pressure situation in presence of the cold air is very similar to the freezing fog described in the previous paragraph. There is only one important difference. In this case, the air doesn´t contain enough moisture to create the fog. It makes the icing conditions less obvious than in the case of freezing fog. That´s why a strict pre-flight check is important in this case. The severity of icing is lower in comparison with the freezing fog. During a clear sky night, with no wind, the hoar frost forms on the airframe of the aircraft. Generally it has an influence on the aircraft parked on the ground only. Although the hoar frost forms on the planes in flight, in slightly different conditions too. For example, an aircraft performing fast climb from the areas with freezing air temperatures to the areas with warmer but moister air, can often encounter hoar frost formation on the frozen airframe surfaces. It works the same way when descending from the freezing air to a lower altitude where the warmer air contains more moisture again.

4.8 Inter-Tropical Convergence Zone

Inter-Tropical Convergence Zone is an area of a significant weather that circles the globe near the equator. An exact position varies with the longitude and the season. It moves slightly south of the equator in the southern-latitude summer, and slightly north in the northern-latitude summer. This zone is well known for pilots because of massive thunderstorm development. The biggest difference between Inter-Tropical Convergence Zone thunderstorms and conventional land-mass thunderstorms is in a principal of formation. Usually the thunderstorms are created by frontal actions or by convection. The Inter-Tropical Convergence Zone thunderstorms are formed differently. They are driven by the global circulation patterns with warm moist air coming from the equatorial region. Easterly trade winds (steady, persistent winds blowing on the Equatorial side of the subtropical high pressure systems in both hemispheres[12]) of the Northern and Southern hemispheres converge near the equator, providing the lifting action required to create a storm. This leads to the cloud formation. The strongest thunderstorms formed in this zone occur above the land areas in the afternoon. In equatorial region, the air temperature is high. A tropopause, the atmospheric layer separating the troposphere and the stratosphere, will be therefore located in much higher altitudes (15 km – 18 km) than in polar or mid-latitude regions (9 km – 12 km). Only one thing can stop the vertical development of Inter-Tropical Convergence Zone thunderstorms. It is a change of lapse rate of the temperature in tropopause. Tropopause creates the ceiling where an anvil head appears on many thunderstorms, as they can´t grow any higher. Cumulonimbus tops at the Inter-Tropical Convergence Zone reach sometimes more than 15 000 m altitude. It´s impossible to overfly them in common commercial aircraft. Finally, a problem with Inter-Tropical Convergence Zone for pilots is that the thunderstorm clouds formed in this zone show up poorly on weather radar. At night, thunderstorms are very easily recognizable by lightning but Cumulonimbus clouds produce less lightning in this area than in other regions, what masks their activity. (PALMER, 2013)

[12] http://www.skybrary.aero/index.php/Trade_Winds

4.9 Icing conditions at high altitudes

Although the previous parts of the thesis state that icing has the biggest probability to occur in the lower altitudes, near 0 °C isotherm, there exists the possibility of ice crystals icing in the upper troposphere. This type of icing was not seen as a real hazard for aircraft until the accidents happened. Air France flight 447 from Rio de Janeiro to Paris is an example. The most vulnerable parts of the plane threatened by the ice crystals are the engines and the probes. A certain number of thrust fluctuations and probe blockages in high convection zones have been noted in service, pointing the finger at the ice crystals. Unlike classic icing, detectable by the crew, the ice crystals icing is untraceable. There exists the reserves in understanding physical and accretion phenomena in high altitudes and at low temperatures. (Duvivier, 2011)

It is a serious hazard for the flight safety to lose thrust of the engine because of an ingestion of the ice crystals. During the flight, the airplanes can often cross the clouds where the ice crystals concentration is over 2 g/m^3. As it can´t be predicted by radar use, it is complicated to avoid this weather hazard. More than 100 events were classified as ice ingestion incidents or accidents between years 1990 and 2004 . A BAe 146 flying through severe ice crystals icing totally lost the engine thrust in 1990s. Honeywell, the manufacturer of the engines of BAe 146, was forced to change the construction of the engine. Crystals icing effect on the engines is more complex than the effect on the probes. Ice formation on the parts of the compressor can alter thrust. The engine can stall when ice passes into the combustion chamber.

Even if the radars are not able to identify small ice particles, there exists other signs that could help to reveal their presence:

- Inaccurate indication of temperature caused by ice melting and refreezing in probes
- Traces of water (melted ice crystals) on the windscreen
- Noise of ice crystals hitting the airframe

The problem with ice crystal icing is that our knowledge about it is not sufficient. We don´t have enough precise data about the volume of ice crystals in the upper troposphere. The researches that were made in the 1950s tell about values of up to 8 g/m^3. More recent measurements found the smaller values of 3 g/m^3. In addition, it is a big difference between convective activity over oceans and continents. The quantity of ice crystals depends a lot on the strength of vertical movements that is a result of the convection.

That´s why the new tests were carried out by Airbus in Darwin in February 2010 and in Cayenne in May 2010. Results showed a big variation of ice water content in high altitudes that reached the maximum value of 6 – 7 g/m^3. Other tests organized by FAA, NASA, and Boeing were planned in Darwin in 2013. New information discovered during these campaigns should be included in crew training by fastest possible way. The development of space technology gives the possibility to improve detection capability in the future. (Strapp, 2011)

5 Safety analysis of icing in flight

The first part of this chapter will summarize the last major safety events which happened during the flights of commercial aircraft and that have something in common with the icing. The information contained in this part of the work will be based on the investigation reports published by the official investigative authorities. Each accident/incident report will be completed by a table summarizing effect of the icing on the occurrence. In this table, I will try to define related hazards, trace the consequences of these hazards and evaluate the existing barriers. To assess a risk of the hazard related consequences, the safety risk index will be assigned to each occurrence, as it is defined in ICAO Doc 9859 - Safety Management Manual. This index is an alphanumeric designator, which contains information about the probability and the severity of the consequence related to the hazard. In each case, the most suitable value from the Table 7 will be chosen to approximate the likelihood or the estimated frequency of the safety occurrence.

Table 7 - Safety risk probability
(Safety Management Manual (SMM), 2013)

Likelihood	*Meaning*	*Value*
Frequent	Likely to occur many times (has occurred frequently)	5
Occasional	Likely to occur sometimes (has occurred infrequently)	4
Remote	Unlikely to occur, but possible (has occurred rarely)	3
Improbable	Very unlikely to occur (not known to have occurred)	2
Extremely improbable	Almost inconceivable that the event will occur	1

The values/characters form the Table 8 will be used to characterize the severity of each occurrence. The severity index will be assigned upon the correlation between the description of the severity index (column “Meaning” in the Table8) and the outcome of an analyzed hazard.

In the next chapter I will try to make a summary of all the occurrences presented in this chapter. The aim of the safety analysis will be to propose further actions to enhance the safety level.

Table 8 - Safety risk severity
(Safety Management Manual (SMM), 2013)

Severity	*Meaning*	*Value*
Catastrophic	— Equipment destroyed — Multiple deaths	A
Hazardous	— A large reduction in safety margins, physical distress or a workload such that the operators cannot be relied upon to perform their tasks accurately or completely — Serious injury — Major equipment damage	B
Major	— A significant reduction in safety margins, a reduction in the ability of the operators to cope with adverse operating conditions as a result of an increase in workload or as a result of conditions impairing their efficiency — Serious incident — Injury to persons	C
Minor	— Nuisance — Operating limitations — Use of emergency procedures — Minor incident	D
Negligible	— Few consequences	E

5.1 Major accidents/incidents caused by icing in flight

5.1.1 Clear ice accretion, ATR 72 (AIRCRAFT ACCIDENT REPORT, 1996)

- Date: 31 October 1994
- Operator: American Eagle
- Registration: N401AM
- Location: near Roselawn, Indiana (United States of America)
- Type of occurrence: Fatal accident

On Monday, October 31, 1994 in the afternoon an ATR 72-212 operated by Simmons Airlines on behalf of American Eagle began a descent to Chicago O'Hare International Airport. There were two pilots, two flight attendants, one made its first flight and 64 passengers on board.

Shortly after the take-off, when the aircraft passed 1,800 feet, the pilot engaged the autopilot and continued climb to the cruising flight level FL160. On the frequency, several pilots were reporting moderate icing in the lower flight levels.

The aircraft was cleared to descend to FL 100 and then the crew started holding procedure. While descending, the pilots turned on de-icing on maximum and increased NP to 86% to fulfil the criteria for flight in icing conditions. When the plane reached FL 100, the pilots reduced de-icing to level 1 and they set the throttle to 77%. After 10 minutes, the captain was not satisfied with a big pitch angle in the holding pattern turns. The FO set the flaps to 15 degrees to lower the angle of attack. In this moment the plane was flying through the areas of large supercooled drizzle/rain drops. Approximately 7 minutes after that, de-icing was reset to level 3 and the throttle was increased to 86% again.[13]

After a few minutes, the ATR was cleared to descend to 8 000 ft in holding, and pilots were informed that they can expect approach in 10 minutes. It was the last radio contact between the ATC and the plane.

The pilots retracted the flaps during the descent but the autopilot was still engaged. This fact was very important because while descending, aerodynamic performance of the aircraft got significantly worse. If the pilots had been flying manually, they would have had bigger chance to realise the problems. Increase in the angle of attack and excessive flight control deflections reflected the autopilot´s effort to stabilize the plane. Suddenly, the autopilot reached its limits and it disengaged. In this moment the crew started a fight with the flight controls. The ATR got into unusual flight positions and the pilots were not able to get the plane under control any more. The ATR crashed into field located about 60 NM from their destination.[14]

The critical reason of the accident was an ice accretion aft of the deice boots on the wings. This caused an inconvenient airflow around the ailerons and subsequent aileron hinge moment reversals. The ailerons abruptly deflected to a right-wing-down position due to this reason. The pilots tried to stabilize the flight. Unfortunately they didn´t find the way how to overcome the repeating rolling effect of the flight controls.

[13] http://www.ntsb.gov/doclib/reports/1996/AAR9601.pdf
[14] http://www.ntsb.gov/doclib/reports/1996/AAR9602.pdf

The ATR 72 encountered a mixture of rime and clear airframe icing in supercooled cloud and drizzle/rain drops. Some drops were estimated to be bigger than 100 μm in diameter, and some were as large as 2,000 μm.[15]

The accident near Roselawn resulted in big research in influence of supercooled large droplets on the flight safety and on the aircraft certification requirements concerning icing conditions.

The problems with the control of the ATR aircraft repeated also in 1998. The ATR 42 flying from Dresden to Posen (Poland) had nearly the same problems as the crew of the ATR 72 near Roselawn. The aircraft was climbing to the cruise level FL 190 through the layer of stratiform clouds with a presence of the precipitations. They encountered moderate to severe icing (the crew identified the level of icing as light to moderate). The pilots turned on anti-icing and de-icing equipment. As they were climbing, the rate of climb decreased first to 500 ft/min and subsequently to 200-300 ft/min. At this moment, the pilots decided to level off at FL135 to increase an airspeed which dropped from 160 kt (in the beginning of the climb) to 155 kt. Suddenly the stall warning was activated, an autopilot disengaged and the aircraft uncontrollably rolled to the left and to the right several times. Pilots had the problems to stabilize the aircraft and they declared an emergency to the ATC[ii]. Fortunately, in contrast with the accident near Roselawn, this flight could be classified as an incident and it finished by precautionary landing at Berlin-Schönefeld airport.[16]

[ii] ATC Air Traffic Control

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[15] http://www.ntsb.gov/doclib/reconsiderations/AAR9601r.pdf
[16]http://www.bfu-web.de/EN/Publications/Investigation%20Report/1998/Report_98_5X011-0_Cottbus_ATR42.pdf?__blob=publicationFile

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Table 9 - Clear ice accretion, ATR 72

Type of operation or activity	*Generic hazard*	*Specific components of the hazard*	*Hazard-related consequences*	*Existing defenses to control safety risk(s)*	*Safety risk index*
Flight in significant weather	Approach /holding in an area of supercooled precipitations	Severe rime and clear airframe icing	Degraded aerodynamic performance – roll upset, stall	De-icing boots	4A

5.1.2 Wing stall, Cessna Citation V Ultra C560 U (Muller, 1997)

- Date: 2 January 1996
- Operator: Contrails Ltd.
- Registration: VP - BQB
- Location: near Augsburg, Bavaria (Germany)
- Type of occurrence: Accident

The Cessna C560 with two flight crew members and three businessmen on board took-off from Lugano airport to Augsburg at 17:00. The aircraft was established on the ILS of a runway at Augsburg airport and it was prepared for the precision approach landing with autopilot engaged at 17:30.

The weather conditions in Augsburg were not ideal. The area was covered by high fog. The wind was calm. The visibility was about 2 000 m. The cloud base had the altitude of 500 ft AGL[iii] only. There was a big probability of icing from the ground up to a height of 5 000 ft. Pilots that landed at the airport 2 hours later after the accident reported unusual heavy icing during the approach. The crew of the C560 evaluated the icing level as light using an ice detection equipment. A passenger who was watching the leading edge of the aircraft witnessed that there was a layer of ice approximately 1 cm thick on the wing. Investigators of the accident found an ice deposit about 2 mm thick which spread 30 cm back along the lower surface of the wing.

The approach speed of 105 kt was calculated before the flight and it was maintained during the approach. At an approximate altitude of 330 ft the pilots got visual reference with the ground, they disengaged the autopilot and controlled the aircraft manually. The airplane flew slightly under the correct approach path because the pilots wanted to touch –down right at the beginning of the runway which was 1 250 m long. Suddenly, when the aircraft passed the height of 50 m it stalled on the right wing. The pilot flying reacted by setting a full thrust. The aircraft than banked to the left side and hit the ground with the wing. The first contact of the airplane with the ground was at the distance of about 130 m in front of the threshold of runway. The C560 stopped after approximately 230 m of run, between the runway and a taxiway. One of the passengers suffered minor injuries. The aircraft was seriously damaged.

The crew members were appropriately qualified and certified for flying with the C560. Both of them had more than 2 000 flight hours. They were well rested and prepared to perform the flight.

The Cessna 560 had only 200 hours of total flight time. It was registered at the Bermuda Islands. Position of CG was within the prescribed limits during the flight.

The investigation discovered that even if the aircraft was flown as prescribed in the flight manual, with anti-icing and de-icing devices on, it stalled at higher than expected stall speed. It means that the wing icing modified the aircraft normal characteristics and made it more susceptible to stall without any warning.

Cessna Company carried out the tests of this aircraft to examine the flight parameters during the flight at minimum airspeed in icing conditions because several similar occurrences had happened in flight with C560. These tests proved unstable flight characteristics in icing well above published stalling speeds. The AD[iv]was issued as a reaction on the findings of Cessna Company. The manuals of the aircraft were changed to prevent the danger situations.[17]

[iii]AGL About Ground Level

[iv] AD Airworthiness Directive

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[17]http://www.bfu-web.de/EN/Publications/Investigation%20Report/1996/Report_96_CX001-0.pdf?__blob=publicationFile

5.1.2.1 Safety risk assessment

Table 10 - Wing stall, Cessna Citation V Ultra C560 U

Type of operation or activity	***Generic hazard***	***Specific components of the hazard***	***Hazard-related consequences***	***Existing defenses to control safety risk(s)***	***Safety risk index***
Flight in significant weather	Precision approach in freezing fog	Wing icing - clear ice	Stall	Operational procedures	3B

5.1.3 Stall caused by icing, Embraer 120RT Brasilia (AIRCRAFT ACCIDENT REPORT, 1998)

- Date: 9 January 1997
- Operator: COMAIR Airlines
- Registration: N265CA
- Location: near Monroe, Michigan (United States of America)
- Type of occurrence: Fatal Accident

Flight 3272 was a regular domestic flight from Cincinnati/Northern Kentucky International Airport to Detroit Metropolitan/Wayne County Airport operated by COMAIR Airlines. 2 flight crew members, 1 flight attendant, and 26 passengers were on board. The Embraer 120 took-off from Convington at 15:09. Departure was in delay of about 30 minutes, because the plane required servicing and the weather conditions (light snow) required airframe deicing before takeoff.

The flight continued without any significant problems until the approach phase. At 15:38, captain advised the flight attendant that the flight from Covington to Detroit would take “only forty minutes today.” That time, the crew got permission from ATC to descend for approach to Detroit. The pilots listened to Detroit’s ATIS which informed about visibility of 1 mile in light snow and it warned off the poor braking action. During the descent the Embraer was vectored for spacing. As the plane was descending, the pilots completed the descent checklist that included an ice protection prompt. Although the crew didn´t notice any signs of icing, they activated the windshield heating and the propeller de-ice system as it is recommended in the aircraft operational manual. The pilot didn´t use leading edge deicing boots. At 15:52, the pilots were cleared to descend to 4 000 ft. As there was another faster airplane (A320) approaching Detroit, the Embraer was requested to reduce speed. The A320 got the warning about wind shear, tailwinds aloft from ATC and the crew reported "slick runways and low visibility." At 15: 53 the Embraer was vectored to intercept the localizer by making a left turn to heading 090°. At this moment aircraft started to bank uncontrollably and when the bank angle exceeded the value of 45° the autopilot disconnected. The speed was slowly reducing when the bank angle increased to 140° and the pitch attitude decreased from nearly 2° nose up to about 17° nose down. At 15:54 the ground proximity warning system (GPWS) was activated and it announced "bank angle" aural warning. A few seconds after that, the aircraft hit the ground in a steep nose-down attitude in a field located about 19 nm southwest of Detroit airport.

The crew consisted of experienced airline transport pilot rated captain. He had accumulated 5 329 total flight hours, including about 1 097 hours as pilot-in-command in the Embraer 120. First officer held a commercial pilot license. The day of accident, his total flight time was 2 582 flight hours, including 1 494 hours as first officer in the Embraer 120. Both pilots obtained all necessary ratings to fly with the Embraer 120. The crew was well rested before the flight and all the members of the crew were properly certified for the flight.

The problems of the Embraer 120 coping with the icing had been known even before the flight. After the ATR accident near Roselawn, the FAA[v] conducted a review of in-service accidents and incidents involving roll axis control events in icing conditions and identified about 50 events, including the 6 Embraer 120 events.

Flight 3272 took place in winter season. The temperature at cruising altitude of 21 000 ft MSL [vi]was far below 0 °C during all the cruising phase of the flight. That´s why the probability of icing formation in these conditions was minor and the aircraft started to descend without any ice deposit on the airframe. As the plane was approaching Detroit, meteorological conditions started to deteriorate. Data from meteorological center and radar images show the evidence of icing conditions in the clouds along the accident airplane's descent path below 11,000 feet MSL with the highest intensity between 4,100 feet MSL and 3,900 feet MSL. The pilots that were overflying the same region at the time of the accident reported varying no-ice to severe rime icing conditions. It means that the icing conditions near the accident site were very variable. There was a probability of formation of rime or mixed ice at various altitudes and in various amounts, rates, and types of accumulation. If supercooled large droplet icing conditions were present, the droplet sizes probably did not exceed 400 microns and most likely existed near 4,000 feet MSL.

It seems that as the Embraer was descending through the layer of clouds, it accumulated a thin, rough glaze/mixed ice coverage on the leading edge deicing boot surfaces, possibly with ice ridge formation on the leading edge upper surface. This thin layer of ice was unidentified by the pilots and the de-icing boots were not activated. As the ice accreted asymmetrically on the wings, the aircraft gained a left roll tendency. The crew didn´t identify it, until the autopilot disengaged. The flight characteristics, the critical angle of attack and the stall speed changed because of the ice deposit on the wings. The pilots unaware about this, were not able to recognize the dangerous situation and they did not succeeded to recover from unusual aircraft attitude. [18]

[v] FAA Federal Aviation Administration

[vi] MSL Mean Sea Level

5.1.3.1 Safety risk assessment

Table 11 - Stall caused by icing, Embraer 120RT Brasilia

Type of operation or activity	*Generic hazard*	*Specific components of the hazard*	*Hazard-related consequences*	*Existing defenses to control safety risk(s)*	*Safety risk index*
Flight in significant weather	Descent through the layer of clouds	Wing icing - glaze/mixed ice	Degraded aerodynamic performance – roll upset	De-icing boots	4A

5.1.4 Frost accumulation, Cessna 208 Caravan Amphibian (Aviation Investigation Report A99P0181, 2001)

- Date: 28 December 1999
- Operator: Seair
- Registration: C-FGGG

[18] http://www.ntsb.gov/doclib/reports/1998/AAR9804_body.pdf

- Location: near Abbotsford Airport, British Columbia (Canada)
- Type of occurrence: Accident

Cessna 208 was involved in 26 icing related accidents or incidents between years 1987 and 2003. In 15 of 26 occurrences, the ice accumulated in-flight, in 10 cases it accumulated during approach and landing phases. The other 10 accidents happened because the ice was not removed from the airframe before the take-off.[19]

The flight of the Seair Cessna 208 was a private flight from Abbotsford Airport to the Bahamas. It was a single pilot flight and five passengers were on board.

The morning when accident happened, Abbotsford Airport was under influence of high pressure area, that leaded to the formation of fog and low visibility in stratus clouds. Vancouver International Airport, about 34 miles west of Abbotsford, was reporting freezing fog throughout the morning.[20] The morning METAR[vii] issued for Abbotsford Airport contained warning about frost indication in the remarks.

The pilot had accumulated over 12 000 hours of flying time, with experience on float-equipped aircraft, such as the DHC-2 Beaver and DHC-2T Turbo Beaver until the accident. He had recently completed type rating on the Cessna 208 and he had about 85 hours of experience on this type of aircraft. However there is no evidence that he passed some training to get the qualification for the aircraft in the amphibious configuration. [16]

The Cessna 208 was parked outside overnight before the flight and a layer of frost had accumulated on the airframe. In the morning, the pilot used tap water to remove frost from the windshield in order to see out of the aircraft. It´s obvious he knew that the airframe was covered by the frost but he assessed that it couldn´t influence the safety of the flight. He believed that the sun would melt the ice. But as the temperature was below 0 °C until the take-off, it did not happen.

The pilot studied the meteorological situation, he filed a VFR flight plan and he was ready for take-off at 9:16. He took-off using 20° flaps settings. He retracted the flaps in two steps during the climb. First from 20° to 10° and then from 10° to 0°. When the flaps were fully retracted, the pilot started to have the problems with control. The aircraft rolled to the left and descended rapidly. The pilot first succeed to stabilize the flight by pushing the controls and by applying the full throttle. The effect of this maneuver was that the aircraft started to

[19] https://www.ntsb.gov/doclib/speeches/weener/weener_020111.pdf
[20] http://www.tsb.gc.ca/eng/rapports-reports/aviation/1999/a99p0181/a99p0181.asp

descend. However the plane didn´t have enough altitude and it hit the ground about one minute after the take-off. As the aircraft was equipped with the floats, they absorbed an important portion of energy accumulated during the impact and there were no fatalities.

The final report of the accident investigation states that the main reason of the accident was the frost that wasn´t removed from the surface of aircraft before the flight. That day, many pilots cancelled or postponed their flights because of the weather. Some airplanes on the ramp were covered by ice until late that morning. The Cessna stalled at lower than normal stall speed because of the ice deposit on the wings. Another factor that negatively affected the stall speed was that the Maximum Take-off Weight of the aircraft was exceeded by more than 230 kg. The reduction of the lift caused by flaps retraction leaded to the stall and to the destruction of the plane.

[vii] METAR Meteorological Aerodrome Report

5.1.4.1 Safety risk assessment

Table 12 - Frost accumulation, Cessna 208 Caravan Amphibian

Type of operation or activity	*Generic hazard*	*Specific components of the hazard*	*Hazard-related consequences*	*Existing defenses to control safety risk(s)*	*Safety risk index*
Preflight-check	Condition of the surface of an aircraft	Frost deposit on the airframe	Degraded aerodynamic performance – MTOW exceeded, stall	Ground de-icing	4B

5.1.5 Engine flame-out, Shorts SD3-60 (Final Report of the Investigation Committee of the Libyan Civil Aviation Authorities, 2001)

- Date: 13 January 2000
- Operator: Avisto Ltd. (operating for Sirte Oil Company)
- Registration: HB-AAM
- Location: near Marsa el-Brega (Libya)
- Type of occurrence: Fatal accident

The accident happened on the flight from Tripoli to Marse el-Brega, while approaching Marsa el-Brega airport. The Shorts SD3-60 was used by Sirte Oil Company, a state-owned Lybian oil and gas Company, to transport workers and their families. Oil Company had several factories and the aircraft was providing a fast connection between them. That day, the plane had completed already five flights without any technical problem. The last flight, back to the home base of the aircraft, ended by fatal accident.

A crew consisted of three persons in total. Two flight crew members arrived with the empty Shorts SD3-60 to Tripoli. A cabin crew joined the crew and 38 passengers got on board of the aircraft in Tripoli. There were two pilots of Libyan nationality in the cockpit. Both of them held ATP license issued by Swiss authorities and they were properly qualified to fly the Shorts SD3-60. Until the accident, the captain had accumulated the total flight time of 8814 hours with 3840 hours on the Shorts SD3-60. First-officer was quite experienced pilot, with total flight time of 10422 hours, as well. He was flying for Sirte Oil Company as the captain on the Fokker 28.

The Shorts SD3-60 (also Shorts 360) is a commuter turbopropeller aircraft that was built by British manufacturer Short Brothers during the 1980s.[21] It is powered by two Pratt & Whitney PT6A engines. The plane involved in the accident was fully airworthy. The position of CG calculated before the flight, was within prescribed limits. The amount of fuel on board fully satisfied the requirements for the flight.

The plane was refueled and ready for take-off from Tripoli International Airport at 9:29. The distance from Tripoli to Marsa el-Brega is about 650 km. The cruise level of the flight was FL70. Normally, the Shorts SD3-60 were not used on flight from Tripoli to Marsa el-Brega. The aircraft has a small range to fly to Marsa el-Brega without refueling. As it is not a pressurized aircraft, it has a low cruise level to overfly the sea becasue the Libyan regulations don´t permit lower flight level than FL130. As the flight with refueling is not very comfortable, for a final leg of the flight, pilots used to request air traffic control to fly directly to Marsa el-Brega in maximum distance of 10 miles from a cost at low flight level. On 13 January 2000, the Shorts SD3-60 got the permission to overfly the sea as approaching Marsa el-Brega airport. At 11:25, when the aircraft was 40 miles from Marsa el-Brega, the pilots started to descend from the cruising flight level 70. At 11:36 left engine stopped to work. One and half a minute after, right engine flamed out. The pilots declared an emergency but

[21] http://en.wikipedia.org/wiki/Short_360

only on the company frequency 131.5 where nobody responded. After a minute of gliding, without any thrust of the engines, the airplane ditched to the sea at 10° nose up attitude and with flaps in retracted position. During the impact with the water surface, the airframe was destroyed and many people drown because they didn´t know how to use or where to find an emergency equipment.

Some parts of the flight were flown under IMC.[viii] The air temperature at the cruising flight level was -2°C. The aircraft flight manual recommends to turn on engine anti-icing equipment when outside air temperature is 6°C or below. In case of flight in mist, fog, clouds (the areas of high relative humidity) or when flying in a distance of 500ft (or less) vertically from cloud base or in precipitations, engine anti-icing must be always turned-on. The crew observed that they were flying in icing conditions because of ice deposit which accreted on a windscreen. They activated the pitot-static ant-icing systems, ice detectors and windscreen anti-icing but they did not turn on the engine anti-icing system. Ice deposit that had built up on the engine inlets started to melt when the aircraft entered to the warmer air, during the descent. The pieces of ice entering to the engine leaded to the flame out of both engines. This could be avoided by turning on an ignition switch which provides re-ignition of the engine in case of flame out. However neither the igniters nor the engine anti-icing was turned on. The other hint that could help to reveal the engine inlet icing is an increase of the engine temperatures. But as the CVR[ix] record demonstrates, the pilots were not fully concentrated on the flight and they didn´t observed any suspicious variation of the engine temperatures.[22][23]

[viii] IMC Instrument Meteorological Conditions

[ix] CVR Cockpit Voice Recorder

[22] http://www.sust.admin.ch/pdfs/AV-berichte//1732.pdf
[23] http://aviation-safety.net/database/record.php?id=20000113-0

5.1.5.1 Safety risk assessment

Table 13 - Engine flame-out, Shorts SD3-60

Type of operation or activity	*Generic hazard*	*Specific components of the hazard*	*Hazard-related consequences*	*Existing defences to control safety risk(s)*	*Safety risk index*
Flight in significant weather	Descent from colder air to warmer air	Ice accretion on the engine inlets	Engine flame-out	De-icing	3A

5.1.6 Blocked elevator controls, BAe 146-300 (Investigation report, 2006)

- Date: 12 March 2005
- Operator: cargo company
- Registration: unknown
- Location: en-route, between Frankfurt and Stuttgart
- Type of occurrence: Serious incident

On 12 March 2005, the BAe 146-300 was transporting some cargo from Frankfurt to Stuttgart. The aircraft was climbing from FL80 to FL100 with autopilot engaged. Suddenly, the crew started to have the problems with slow pitch oscillations with increasing amplitude. It resulted in a variation of the angle of attack up to 18° altered by sink rate up to 4 500 ft/min. The aircraft had flew in IMC and in icing conditions until pilots regained the control by disengaging the autopilot and by using the elevator trim. They continued the flight at FL130 under VMC[x]. Even if there were no icing conditions at this flight level, the problems with the controls persisted. Pilots were forced to finish the flight in Stuttgart, where better meteorological conditions were expected, by using elevator trim to control the pitch. Immediately after the landing, the BAe 146-300 was examined. A layer of "frozen and swollen up de-icing fluid residues" were found in the gap between elevator and horizontal stabilizer and in the area of ailerons and rudder. Luckily, the residues hadn´t blocked the yaw and roll controls but it jammed elevator movements. As the BAe 146-300 is the aircraft with non-powered flight controls (the elevator is controlled by mechanically operated servo tabs), pilots were not able to develop sufficient force to overcome the blocked elevator.

The flight nearly resulted in catastrophe, because of the development of residues from de-icing and anti-icing liquids. Several types of de-icing and anti-icing fluids are used to treat an aircraft before a flight. Some of the liquids are thickened, for example SAE[xi] Type II (used on the BAe 146-300), Type III or Type IV. These types of anti-icing fluids contain small amount of polymers, which create a thick layer on the anti-iced surfaces. The polymers are used in anti-icing fluids to prolong hold-over time. When the fluid dries or it shears off the airframe, the polymers persist on the airframe. An excessive quantity of rehydrated polymers can influence aerodynamic performance of the aircraft or it can mechanically block the controls. The problem of the polymers is that it easily absorbs the humidity from the air. The polymers that accumulate high water content are very dangerous in the freezing temperatures. Even a small amount of them, which freezes in a small gap on the airframe, can block the controls as it had happened on the flight from Frankfurt to Stuttgart. (Figure 19)

Other 40 occurrences caused by anti-icing fluids happened in Europe apart from this serious incident during year 2004. That´s why the aircraft manufacturer BAe organized a meeting in May 2005 to discuss the problem. The results of the meeting were that it is necessary to amend some operational procedures connected with the usage of anti-acing liquids. The investigation of the incident of the BAe 146-300 confirms that there is a need to replace the thickened fluids with un-thickened de-icing fluids mainly on the airplanes with non-powered flight controls. In winter, the precautions should be taken to avoid the accumulation of the anti-icing fluids residues on an airframe.

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[x] VMC Visual Meteorological Conditions

[xi] SAE Society of Automotive Engineers standards

Figure 19 – Anti-icing fluid residues development

© Boeing, 2010[24]

5.1.6.1 Safety risk assessment

Table 14 - Blocked elevator controls, BAe 146-300

Type of operation or activity	***Generic hazard***	***Specific components of the hazard***	***Hazard-related consequences***	***Existing defenses to control safety risk(s)***	***Safety risk index***
Ground anti-icing	Application of thickened anti-icing liquid	Accumulation of anti-icing liquid residues on an airframe	Controls blockage	Pre-flight check, unthickened anti-icing liquids	5D

[24] http://www.boeing.com/commercial/aeromagazine/articles/2010_q4/2/#fig1

5.1.7 Airspeed indicator error, Airbus A320-200 (Investigation report, 2010)

- Date: 24 January 2007
- Operator: Air Berlin
- Registration: D-ABDI
- Location: in climb from Nuremberg to London
- Type of occurrence: Serious incident

The A320-200 of Air Berlin was performing scheduled flight from Nuremberg to London. The airplane departed from Nuremberg airport at 08:04 LT[xii]. It was passing FL120 when the crew heard a strange bang coming from below the windscreen parts of the fuselage. All the airspeed indicators in the cockpit started to show different values of actual airspeed at this moment. ECAM[xiii] informed the crew about ADR 1[xiv], ADR 2 and ADR 3 units fault. The A320-200 uses ADR unit to determine the airspeed of the aircraft. ADR 1 and ADR 2 units are backed up by ADR 3 unit. If all three units don´t work, the crew will not get the information about airspeed from pressure measuring equipment.

Autopilot disengaged and pilots controlled the aircraft manually. The pilot in-command complained about the tendency of the aircraft to drift to the right. They thought that the plane is damaged because of this controls problem and because of the sound pilots heard. They stopped the climb in FL130 and entered to a holding pattern. Pilots tried to solve the problem by resetting the FAC[xv]. As it didn´t help, they decided to divert to Frankfurt airport. The A320-200 safely landed at Frankfurt airport. The aircraft went directly to the maintenance center and the faulty ADR unit was replaced. No other visible damage was discovered on the aircraft.

There were three pilots in the cockpit during the flight. At the beginning of the flight, trainee co-pilot was seating on the right seat. When the aircraft started to have the problems, pilot in-command requested the other co-pilot to take the place of the trainee pilot. All of them were qualified and prepared for the flight.

The weather in Nuremberg was under influence of low pressure area. The snow had been falling (about 20 cm) during the night before the flight. Air temperature and dew point temperature had the same value of -5 °C. The cloud base was at approximately 600 ft. The visibility had a tendency to deteriorate because of the snowfall. During the climb, the snow continued to fall and the intensity of precipitations was increasing. The aircraft was flying through an inversion layer and the temperature increased up to 1 °C between FL100 and

FL120 when the crew heard the strange noise. The investigation says that a possible cause of the incident was that the ice accreted on the fuselage which wasn´t de-iced before the flight. It started to melt when the aircraft was passing through the inversion layer and it blocked the pressure probes. However this suspicion could not be confirmed because the aircraft wasn´t examined on the presence of the water inside the pressure probes when it landed in Frankfurt.

5.1.7.1 Safety risk assessment

Table 15 - Airspeed indicator error, Airbus A320-200

Type of operation or activity	***Generic hazard***	***Specific components of the hazard***	***Hazard-related consequences***	***Existing defences to control safety risk(s)***	***Safety risk index***
Flight in significant weather	Flight through an inversion layer in freezing temperature	Melting ice deposit	Pressure probes blockage	Pressure probes construction	3D

[xii] LT Local Time

[xiii]ECAM Electronic Centralized Aircraft Monitor

[xiv] ADR Air Data Reference

[xv] FAC Flight Augmentation Computers

5.1.8 High altitude stall, Airbus A330-200 (PALMER, 2013)

- Date: 1 June 2009
- Operator: Air France
- Registration: F-GZCP
- Location: the Atlantic Ocean, near Brazilian coast
- Type of occurrence: Fatal accident

Air France 447 took off from Rio de Janeiro Galeão airport outbound to Paris Charles de Gaulle airport at 22:29 UTC. It was prepared for a 12 hour flight across the Atlantic Ocean. A330-200 climbed to its cruising flight level FL350 after the departure. When it was passing the altitude of approximately 20 000 ft, First Officer Robert left the cockpit to have about three hours of rest break. As it was the transatlantic flight, the aircraft had to contact the ATC by HF[xvi] communication at defined point. On its route AF447 had to pass several oceanic FIRs[xvii] where only HF communication and ADS-C[xviii] was available. ADS-C is a special type of automatic ground-air communication used on transatlantic flights during which information about flight are transmitted via satellite or HF means. ADS logon has to be done by the crew and correct flight plan data must be uploaded to the ground ATC system communicating with the aircraft to start the ADS-C communication. Air France 447 made an attempt to start ADS-C communication with Dakar oceanic control. It was unsuccessful the first time because controller hadn´t uploaded the flight plan data into the system. Second and third attempts were not successful again because the controller didn´t input the correct data about the flight 447 into the system. That´s why the crew continued the flight using HF communication only. The aircraft approached the Inter Tropical Convergence Zone at 01:35 UTC. There were some active thunderstorms in that zone so the crew wanted to climb above it. Unfortunately, it was impossible as the A330-200 was too heavy and the performance of the aircraft didn´t allowed it. From 01:49 UTC the airplane was out of the ATC radar coverage. At 02:00 UTC First Officer Robert came back to the cockpit. The captain informed him about HF communication frequencies and he left the cockpit to take a rest. First Officer Robert took a left seat in the cockpit but First Officer Bonin, who was seating on the right seat, was the pilot flying and the pilot in command when captain was absent. First Officer Bonin got a short briefing about weather and flight status to First Officer Robert because captain hadn´t informed Robert about it. Only a few minutes after arrival of First Officer Robert from the rest, the aircraft encountered light and moderate turbulences. They had advised the cabin crew about the weather but they had expected that they would pass through it quickly. At 02:08 UTC they made a deviation in heading of 12° to the left because of the thunderstorms. A minute after that they experienced another turbulence during which a sound typical of ice crystals hitting the fuselage was heard. The pitot tubes clogged with ice crystals. The airspeed indicators started to show misleading data. As airspeed data are used by aircraft´s systems to recalculate the altitude and the vertical speed, the altitude indicator and the vertical speed indicator showed slightly incorrect values corresponding to the incorrect low airspeed indication. The autopilot disconnected and the airplane´s flight control law changed to Alternate 2B. It means that many of the built-in protections shut down and roll inputs sensitivity was increased. First Officer Bonin took the controls of the aircraft. He pulled up immediately as the vertical speed indicator was showing incorrectly the descent rate of 600 ft/min. The aircraft started to roll and Bonin used the lateral controls to stabilize the aircraft. He over-controlled the aircraft because Alternate 2B flight control law increased the sensitivity to roll inputs and it took him about 30 seconds to get the airplane back under control. Bonin was still pulling up and the vertical speed reached its maximum of 6 900 ft/min when Robert instructed Bonin to watch his vertical speed. Bonin reduced pitch but the aircraft continued to climb. Robert repeated his worries about the excessive rate of climb. Bonin progressively reduced the rate of climb to 4 000 ft/min and after that to 1 400 ft/min. At 02:10:50 UTC, the pilots made an attempt to call the captain back to the cockpit. As Bonin increased the pitch again, the aircraft started to stall and it encountered a series of alternating roll movements. The stall warning activated for about 45 seconds. Bonin reacted by roll inputs and he applied a full thrust while he was still pulling up. At 02:11:07 UTC the pitot tubes became clear of ice and the airspeed was indicated correctly from this moment. With the full power applied, the aircraft reached a maximum altitude of 37 924 ft. The stall warning activated again. Bonin was still pulling up but the airplane started to descend and roll to the right. The pilots tried to counteract the roll movement but they didn´t have control of the aircraft. The rate of descent increased to 10 000 ft/min and it was oscillating between 10 000 ft/min and 15 000 ft/min until the end of the flight. The aircraft had still positive pitch attitude and the angle of attack reached the value of 40°. Only the roll inputs and the automatic yaw damper function avoided the aircraft to enter the spin. At 02:11:42 UTC the captain returned back to the cockpit. The pilots explained him that they had loosed control of the aircraft and that they didn´t understand what had been happening. Till 02:13:18 UTC the A330-200 had loosed nearly 28 000 ft of altitude. When they were passing the altitude of 9 000 ft, Bonin declared that he was pulling up nearly all the time. Robert pushed his side stick forward but Bonin was still pulling up. In this case the A330-200 sum up the commands from both pilots. That´s why it resulted in no change in attitude. The captain instructed pilots to do not climb and Robert requested to have the controls. He decreased the pitch angle to 7° below the horizon. When the aircraft was passing 4 000 ft Bonin pulled up again. He switched on the takeover button to get a priority to his commands and he applied the full thrust. At altitude of 2 500 ft GPWS[xix] activated and warned about sink rate. At 02:14.28 UTC the aircraft crashed to the ocean at 16° nose up with forward and vertical speed of 107 kt (10 900 ft/min).

The flight crew was qualified for the flight. There were three pilots in the cockpit because of the long transatlantic flight. The captain was an experienced pilot with approximately 11 000 flight hours. First Officer Robert had accumulated over 6 500 hours of flight time and about 4 500 hours of which were in the A330. First Officer Bonin was the least experienced and the youngest pilot on board with total flight time of approximately 3 000 hours (800 hours on the A330).

Air France 447 was flying through Intertropical Convergence Zone on the route to Paris. The weather conditions were complicated in this area. The problem of the zone is that the thunderstorms have an enormous power there. In addition, it could be hard to estimate the dimensions of the clouds and the force of the updrafts because Inter Tropical Zone´s thunderstorms are poorly identifiable by radars and lightning intensity is much lower in comparison with the mid-latitudes thunderstorms. The A330-200 was overflying one of the well-developed Cumulonimbus when it encountered severe ice crystals icing. Even if the aircraft was equipped with de-iced pitot tubes, the quantity of ice crystals that was entering the pitot tube was bigger than the capability of de-icing equipment. It resulted in a blockage of the pitot tubes.

The final report from investigation of the accident says that the ice crystals icing "was known but misunderstood by the aviation community at the time of the accident." It summarizes that the misleading airspeed indication disorientated the pilots. The problems with handling the airplane in turbulent air and in high altitude leaded to destabilization of the flight. Despite the signs of stall (stall warning, strong buffet), "the crew never understood that they were stalling and consequently never applied a recovery maneuver." The report sums up that the initial misunderstanding of the situation did not allowed the pilots to find the solution to save the flight.

5.1.8.1 Safety risk assessment

Table 16 - High altitude stall, Airbus A330-200

Type of operation or activity	***Generic hazard***	***Specific components of the hazard***	***Hazard-related consequences***	***Existing defenses to control safety risk(s)***	***Safety risk index***
Flight operations in Intertropical Convergence Zone	Cruise flight in the upper troposphere	Ice crystal icing	Pitot tubes blockage	Pitot-tubes de-icing	3A

[xvi] HF High Frequency

[xvii] FIR Flight Information Region

[xviii] ADS-C Automatic Dependent Surveillance - Contract

[xix] GPWS Ground Proximity Warning System

6 Recommendations to increase the level of safety

Table 17 – Summary of all accidents from the chapter 5.1 regrouped by the type of operation or activity

Type of operation or activity	*Generic hazard*	*Specific components of the hazard*	*Hazard-related consequences*	*Existing defenses to control safety risk(s)*	*Safety risk index*
Flight in significant weather	Approach /holding in an area of supercooled precipitations	Severe rime and clear airframe icing	Degraded aerodynamic performance – roll upset, stall	De-icing boots	4A
	Precision approach in freezing fog	Wing icing - clear ice	Stall	Operational procedures	3B
	Descent through the layer of clouds	Wing icing - glaze/mixed ice	Degraded aerodynamic performance – roll upset	De-icing boots	4A
	Descent from colder air to warmer air	Ice accretion on the engine inlets	Engine flame-out	De-icing equipment	3A
	Flight through an inversion layer in freezing temperature	Melting ice deposit	Pressure probes blockage	Pressure probes location	3D
Preflight-check	Condition of the surface of an aircraft	Frost deposit on the airframe	Degraded aerodynamic performance – MTOW exceeded, stall	Ground de-icing	4B
Ground anti-icing	Application of thickened anti-icing liquid	Accumulation of anti-icing liquid residues on an airframe	Controls blockage	Pre-flight check, unthickened anti-icing liquids	5D
Flight operations in Intertropical Convergence Zone	Cruise flight in the upper troposphere	Ice crystal icing	Pitot tubes blockage	Pitot-tubes de-icing	3A

6.1 Safety analysis outcome

In order to identify the safety risk index of each occurrence, I tried to discover all other situations where the aircraft´s safety margins were reduced by the same hazard related consequences. After this analysis I was able to set down the probability index of the occurrences. When you study the Table 17, it can be inferred that the most frequently assigned probability index is the index 3. This index defines a "Remote" probability of an occurrence. It means "Unlikely to occur, but possible (has occurred rarely)", as it is defined in the ICAO Doc 9859. I tried to focus the safety analysis on the icing related occurrences, which happened during the last 20 years. If the occurrence has the severity index 3 assigned in the Table 17, it means that the occurrence was rare or it happened only once during the analysed period.

All the occurrences with the hazard related consequence of the degraded aerodynamic performance have the probability index 4 (Occasional) assigned. It´s caused by a high rate of repetition of the problem as it is also described in the paragraphs where the accidents are analysed. I hesitated to class the accident of Cessna Citation to the degraded aerodynamic performance group because the stall was caused by the ice accretion on the wings. Finally, I made a decision that I will define a separate hazard related consequence "stall" for this occurrence. The reason is that Cessna suggested to solve the problem encountered during this accident mainly by amending operational procedures (increasing the approach speed) for the flight in the icing condition. It is in contrast with the accidents from the "degraded aerodynamic performance" group where the ADs modifying the construction of the plane were issued.

The highest probability index 5 (Frequent) is assigned to the hazard related consequence of the controls blockage by the anti-icing liquid. This occurrence type repeated forty times in Europe within the year 2004.

A parallel can be deduced between the problems of A320 and A330 as both the occurrences were initiated by the pressure probes problems. The biggest difference is in the severity index assigned. The flight of A320 could be classified as an incident where the emergency procedures were in use by the index D (Minor - Moderate). The A330 accident with multiple fatalities must be classified by the severity index A (Catastrophic). All the other occurrences have the severity index assigned following the criteria from the Table 8. The severity index of the second occurrence of ATR 42 described in the paragraph 5.1.1 could be lower than A as it didn´t result in an accident. However, it is good to learn from the worst situation and thereafter be prepared for it.

To move the safety analysis forward, the safety risk assessment matrix must be defined. It contains all the combinations of the severity and the probability indexes.

Figure 20 - Safety risk assessment matrix
(Safety Management Manual (SMM), 2013)

Risk probability		Risk severity				
		Catastrophic A	Hazardous B	Major C	Minor D	Negligible E
Frequent	5	5A	5B	5C	5D	5E
Occasional	4	4A	4B	4C	4D	4E
Remote	3	3A	3B	3C	3D	3E
Improbable	2	2A	2B	2C	2D	2E
Extremely improbable	1	1A	1B	1C	1D	1E

The final task is to define the tolerability region of the risk in the matrix. For this purpose a new diagram showed in the Figure 21 - Safety risk tolerability matrix the Figure 21 is used.

Figure 21 - Safety risk tolerability matrix
(Safety Management Manual (SMM), 2013)

Tolerability description	Assessed risk index	Suggested criteria
Intolerable region	5A, 5B, 5C, 4A, 4B, 3A	Unacceptable under the existing circumstances
Tolerable region	5D, 5E, 4C, 4D, 4E, 3B, 3C, 3D, 2A, 2B, 2C, 1A	Acceptable based on risk mitigation. It may require management decision.
Acceptable region	3E, 2D, 2E, 1B, 1C, 1D, 1E	Acceptable

The tolerability regions defined in this diagram must fulfil the criteria defined by a person/an organization responsible for the safety risk analysis. In a case of the safety analysis of the icing in my work, I preserved the tolerability regions as they are defined in the ICAO Doc 9859. I think that it corresponds quite well with a required level of safety for the operations in the icing environment.

The ultimate task of the safety risk analysis is a safety risk management. The aim of the safety risk management is to evaluate the safety risk and to find the way how to decrease the risk to the minimal tolerable or acceptable region. As it is shown in the Figure 21, three main regions of the risk factor are basically distinguished in the safety risk tolerability matrix. The highest risk exists in the Intolerable region. The safety risk analysis of the icing in flight contains five occurrences classified in the Intolerable region. All the occurrences in the Intolerable region require immediate mitigation action. In case of the occurrences described, the mitigation actions have been already taken as the reaction on the safety investigation. However, there are still existing some issues where the safety level can be improved. Even in the Tolerable region where all the remaining three occurrences are contained. I try to describe these opportunities in the next paragraph. The safety risk of the occurrences from the Tolerable region is acceptable but a strategy to prevent the risk may be developed. We always need to mitigate the risk until it reaches the acceptable region. Several techniques can be used for that purpose. You can try to decrease the probability of an occurrence, the severity of an occurrence or finally you can prohibit the action if no mitigation strategy is effective.

6.2 Severe icing conditions

Important number of occurrences presented in the Chapter 5 have all the same main reason why they happened. It is a flight in severe icing conditions with intensity exceeding capability of the aircraft to cope with the icing. Flight crew has a complicated task to examine if the weather conditions in an area they have intentions to fly trough are flyable or they don´t provide a safe environment for the flight. Several products described in the chapter 2.2 are used by pilots to solve this problems. However, it seems that these products can´t always provide satisfactory information. The most complicated issue is to recognize the state when icing starts to critically influence the flight safety. In case of probable severe icing conditions, pilots used to turn off the autopilot and they control the aircraft manually to discover any abnormal flight characteristics caused by icing as soon as possible. If the de-icing equipment of the aircraft can´t eliminate icing accretion, emergency procedures must be applied. Emergency procedures depend on the type of aircraft and are always specified in the flying manual.

6.2.1 Supercooled Large Droplets

An example of the flight in meteorological conditions exceeding capabilities of the aircraft that was certified to fly in icing conditions is described in chapter 5.1.1 where ATR 72 accident near Roselawn is analysed. This occurrence brought attention to meteorological phenomenon of Supercooled Large Droplets (SLD) that can be very dangerous for air traffic. SLD are supercooled droplets with diameter exceeding 50 μm and sometimes reaching diameter of 5 000 μm (5 mm). The icing caused by Supercooled Large Droplets influences big surface of the aircraft. Unprotected airframe parts against icing are vulnerable to SLD icing. Large droplets with big inertia don´t freeze at the point of impact with the wing (at leading edge). Supercooled Large Droplets icing spreads aft of de-iced airframe regions. This type of ice accretions has the worse effect on the aircraft during configuration changes or when full power with enhanced performance is needed. If the icing builds up on aerodynamically important surfaces (wings, tail parts…) the safety of the flight is significantly reduced.

FAA issued airworthiness directives against many turbopropeller planes with warning after Roselawn accident: “Severe icing may result from environmental conditions outside of those for which the airplane is certificated. Flight in freezing rain, freezing drizzle, or mixed icing conditions (supercooled liquid water and ice crystals) may result in ice build-up on protected surfaces exceeding the capability of the ice protection system, or may result in ice forming aft of the protected surfaces. This ice may not be shed using the ice protection systems, and may seriously degrade the performance and controllability of the airplane.” (Administration, 1996) The National Transportation Safety Board (NTSB, USA) requested the FAA to prohibit the intentional operations of ATR aircraft in known and reported icing conditions until a reason of the accident will be investigated. ATR Company issued the bulletins about operating procedures in the icing conditions. Recommended plane configuration speeds for the operation in the icing conditions and MMEL[xx] (to verify if icing detection lights and ice detectors are operative) were updated. Special certification review of ATR 42/72 was done by the FAA. Flight tests in icing conditions artificially created by tanker aircraft KC135A were performed. The tanker plane sprayed the water on the ATR aircraft in flight at various airspeeds and configurations. Dangerous ice accretion was observed during the flight tests. As a reaction on the results of the investigation, the ATR manufacturer increased the chord wise coverage of the active portion of the upper surface of the outer wing de-icing boots. The FAA stressed an importance of soon identification of severe icing conditions by all possible meanings, e.g. visual cues (ice on unheated portion of forward side windows, excessive accumulation of ice on the propeller spinner, use of icing detection lights in night), disengaging autopilot… Following recommendations were published to exit the severe icing conditions:

- "Immediately request priority handling from Air Traffic Control to facilitate a route or an altitude change to exit the severe icing conditions in order to avoid extended exposure to flight conditions more severe than those for which the airplane has been certificated.
- Avoid abrupt and excessive manoeuvring that may exacerbate control difficulties.
- Do not engage the autopilot.
- If the autopilot is engaged, hold the control wheel firmly and disengage the autopilot.
- If an unusual roll response or uncommanded roll control movement is observed, reduce the angle-of-attack.
- Do not extend flaps during extended operation in icing conditions. Operation with flaps extended can result in a reduced wing angle-of-attack, with the possibility of ice forming on the upper surface further aft on the wing than normal, possibly aft of the protected area.
- If the flaps are extended, do not retract them until the airframe is clear of ice.
- Report these weather conditions to Air Traffic Control." (FAA, 1996)[25]

6.3 Training improvements

High frequency of accidents caused by icing leaded the FAA to expand the regulation in this area. The first step was an amendment of training procedures to better prepare pilots for flight in icing conditions. The FAA discovered that the regulation provided a little guidance to the operators and to the training organizations on how to well prepare pilots for the icing. New training rules focus on four main issues:

1. General icing and meteorological information
2. Ground de-icing

[25] http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgAD.nsf/0/7480cb41add5d29586256982007009 7b!OpenDocument&ExpandSection=-8#_Section8

3. Type-specific operations
4. Company operations and procedures

Each of the previous training part may include knowledge based training, flight training on a simulator or on the aircraft and some operational experience (demonstration of real situations and discussions about it).

6.4 Modification of operational requirements

Second step was an update of Part 121 requirements for operations in icing conditions. New rules state that after October 21, 2013 “no person may operate an airplane with a certificated maximum take-off weight less than 60,000 pounds in conditions conducive to airframe icing unless it complies with requirements defined in Part 121.” Conditions conducive to airframe icing are defined as meteorological conditions when visible moisture is present at or below a static air temperature of 5 °C or total air temperature of 10 °C unless the approved Airplane Flight Manual provides another definition. The requirements to operate in icing conditions under Part 121 are described in following paragraph:

Certificated primary airframe ice detection system must be installed on the aircraft. When this system detects that the icing accretion is affecting the flight safety, the airframe ice protection system must be activated automatically or manually by the flight crew. Possibility to visually inspect for the first sign of ice formation anywhere on the plane must be provided. The airplane must be equipped with advisory airframe ice detection system. If the ice is detected visually or by using airframe ice detection system, the ice protection system must be activated. Activation of ice protection system may be always completed by other procedures defined in the Airplane Flight Manual. If the aircraft is not equipped with the systems to identify icing conditions specified above, the airframe ice protection system must be activated before and operated during the following phases of flight:

- Takeoff climb after second segment,
- En-route climb,
- Go-around climb,
- Holding,
- Maneuvering for approach and landing, and
- Any other operation at approach or holding airspeeds

During any other phase of flight, the airframe ice protection system must be activated and operated at the first sign of ice formation anywhere on the airplane unless the Airplane Flight

Manual specifies that the airframe ice protection system should not be used or provides other operational instructions. All the procedures for operations in conditions conducive to icing must be specified in Airplane Flight Manual and procedures for operation of the airframe ice protection system must be defined.(14 CFR Part 121)

In Europe the operating procedures for icing conditions are mainly described in EASA[xxi] Part – CAT (Commercial Air Transport Operations) regulation. It contains ground de-icing/anti-icing procedures (CAT.OP.MPA.250) and procedures for flight in expected or actual icing conditions (CAT.OP.MPA.255).

6.5 Update of aircraft certification requirements

The latest update of regulations in the field of icing was done by the FAA at the end of the year 2014. In November 2014, new icing certifications standards were published in the FAR[xxii] Part 25 (transport category aircraft) and they are effective from January 2015 for all new-designed planes (no retroactive application) with Maximum Take-off weight under 60 000 pounds equipped with reversible flight controls. Certification standards in the Part 25 were completed by the requirements for flight in freezing drizzle and freezing rain conditions. The types of ice accretion caused by freezing precipitations and their characteristics (drop diameter, liquid water content, mass, temperature, dimensions of the icing areas…) are described in the Appendix O of the Part 25. Requirements for the certification of airspeed indicating systems and the angle of attack measuring systems covering the ice crystal environment were updated by additional details. They can be found in Appendix D to Part 33 which contains also precautions to prevent engine icing. EASA has an aim to follow the steps of the FAA. In the Explanatory Note to Decision 2015/008/R, EASA describes intensions to introduce the new certification standards for Supercooled Large Droplet icing conditions (in new Appendix O to CS-25) and for ice crystals or mixed phase icing (in new Appendix P to CS-25). This is planned and included in the Agency's Rulemaking Program for 2014-2017.

6.6 Complicated weather and other threats

The predominant number of occurrences presented in the Table 17 is classified as "Flight in significant weather" type of operation or activity. In this case, the significant weather means all the types of meteorological conditions presented in the chapter 4. Even if the Intertropical convergence zone is also the significant weather type, it is separately specified in the table due to its importance and particular characteristics. The other two activities in the table (Pre-flight check, Ground anti-icing) are the tasks that have to be finished on the ground before the take-off. However in case of improper handling of these operations the hazard appears also during flight. Insufficient pre-flight check, before the flight of the Cessna 208 presented in the chapter 0, that didn´t reveal frost deposit on the airframe leaded to the accident while the aircraft was taking-off. Anti-icing liquids, sprayed on the aircraft surface before the flight, blocked the controls of the BAe 146-300 (as described in the chapter 5.1.6) and the pilots had to face serious complications during the flight. These two accidents show an important role of ground de-icing/anti-icing.

6.6.1 Ground de-icing/anti-icing

Ground de-icing or anti-icing are two tasks which help the aircraft to stay airworthy in complicated meteorological conditions. Without it, flying in winter IMC (snow, high humidity…) would be very hard and dangerous.

De-icing is a process of ice, snow or frost (frozen or semi frozen moisture) removal from the aircraft surface and the engine intake. Every aircraft is inspected for clean and smooth airframe surface before flight. A thin layer of frost or any other contamination on the airframe, especially on the wings, controls surfaces and on the propeller could lead to unairworthy conditions of the aircraft. That´s why each contamination on the aircraft´s wings, propellers or control surfaces must be cleaned before the take-off. It is called clean aircraft concept.

A heated aircraft de-icing fluid is used to de-ice a plane. There exist four basic types of de-icing/anti-icing fluids. Their specifications can be found in the SAE[xxiii] (Society of Automotive Engineers) documents or in the AEA[xxiv] (Association of European Airlines) recommendations and they are defined by International Standards Organization (ISO 11075, ISO 11078). Type I fluid is mainly used for de-icing. It is an unthickened fluid. When it is used as anti-icing fluid, it provides short HOT[xxv] (Hold-over time). Type II – IV fluids are thickened fluids. They have higher viscosity and contain polymer particles that makes them more suitable for aircraft anti-icing. Nowadays, Type II fluid usage is diminishing and it is being replaced by Type IV fluid which has longer HOT time. Type III fluid, thanks to the smaller viscosity than Type II, IV fluid is applied mainly on the slower commuter airplanes with rotation speed under 100 kts. Type II fluid has the same flow-off standards as Type IV fluid. It is used on larger jet aircraft with rotation speed above 100 kts.

Every type of anti-icing fluids has the Hold-over time defined. It is a time period during which plane surface is protected by anti-icing fluid against ice formation. If the Hold-over time is exceeded and the aircraft is not taking-off, the airframe must be inspected for icing again or de-icing and anti-icing procedures must be repeated. That´s why de-icing/anti-icing in the shortest possible time before take-off is the most suitable and the safest option. At the end of Hold-over time anti-icing protective layer on the airframe is no longer effective. The Hold-over times are published by SAE/AEA/ISO in tables for each type of anti-icing fluid. These time values are always only guidelines which help to determine a real Hold-over time that varies with the meteorological conditions. The HOT is reduced by strong wind, jet blast, heavy precipitations, and direct sunlight. All anti-icing fluids have to flow off from critical airframe parts (wings, control surfaces) until the speed of rotation is reached. The reason is that the fluids may not disturb the airflow and the performance of the aircraft during take-off and flight.

Several techniques to de-ice the aircraft are used. Ground de-icing procedure depends also on the type of contamination and thickness of the layer covering the airframe. If the plane stays on an apron during snowy night, manual methods of snow removal (with brooms, brushes…) can be used first. In extremely low temperatures these methods are a single possibility how to remove snow/frost from the aircraft. In such meteorological conditions the effectiveness of de-icing (glycol based) fluids is very limited.[26]

Ground de-icing and anti-icing can be accomplished in one step or in two steps process. One step process is characterized by application of heated thickened fluid on the aircraft surface. Two steps procedure is preferred as it minimizes the possibility of polymer residues built-up on the airframe (read about problem with blocked elevator by polymer residues in chapter 5.1.6). First, heated aircraft de-icing fluid is applied. It is a mixture of water, glycol solution, corrosion inhibitors, wetting agents and dye. Sometimes, if it is allowed by operational procedures, only hot water is used. Unthickened fluid is always applied in first step of two step procedure. If some polymer residues from previous anti-icing procedures are present on the airframe, they are smashed off by application of the fluid. The procedure continues in second step by application of anti-icing fluid. This is a substance with very similar composition to de-icing fluid but it shall contains polymeric thickeners. The polymer particles greatly absorb the humidity from the precipitations. In second step, it is more

[26] http://www.skybrary.aero/bookshelf/books/449.pdf

effective to apply undiluted and unheated anti-icing fluid. All surfaces must be clean before application of anti-icing fluid.

The fluids used for anti-icing are based on ethylene glycol or propylene glycol. Ethylene glycol fluids are toxic. They have sweet taste. In the USA, bitter additives must be added to ethylene glycol based fluids to prevent ingestion by a child or an animal and subsequent intoxication. In the human metabolism ethylene glycol is oxidized to oxalic acid that is toxic too. Intoxication affects central nervous system, the heart and the kidneys. It causes abnormal development of animals (rodents are the most affected).[27]
Propylene glycol fluids are not toxic. They can be used in food processing to keep a moisture inside the food. Propylene glycol fluids have not so favourable taste to human as ethylene glycol. After the ingestion it is transformed by our body to lactic acid which is a natural product of metabolism. Undiluted propylene glycol can sometimes slightly irritate eyes and respiratory tract, mainly when it is used in form of spray.[28]

[xx] Minimum Master Equipment List

[xxi] European Aviation Safety Agency

[xxii] Federal Aviation Regulation

[xxiii] Society of Automotive Engineers

[xxiv] Association of European Airlines

[xxv] Hold-over time

An importance of anti-icing/de-icing can be inferred from an accident of Cessna Caravan described in the chapter 0. It was one of the 30 accidents of this type of aircraft caused by ice. That´s why the NTSB insisted on the FAA to prohibit the flights of Caravans in known ice conditions. This would cause a big problem for operators of this aircraft. A group of regional air cargo operators in the USA tried to solve the situation. They asked the engineers from Cessna and the specialists from the FAA for cooperation. Their work resulted in a few Airworthiness Directives.
The first change requires "tactile" inspection of the airframe (mainly upper surface of the wings), no more than 5 minutes before the take-off. Five minutes limit is required, inter alia, because Cessna Caravans are operated under FAR 135, where no de-icing/anti-icing

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[27] http://cs.wikipedia.org/wiki/Ethylenglykol
[28] http://en.wikipedia.org/wiki/Propylene_glycol

procedure with Type III fluid is defined. The use of the anti-icing fluid Type III could prolong Holdover times to more than 5 minutes.

The second amendment is that the de-ice boots on the wing struts and on the leading edge of the cargo rod are required. A new speed warning system was developed. It warns the flight crew about IAS[xxvi] below 110 kts when propeller heat is turned on. This warning may remind the pilot to check for ice accretion. During the session, new climb and descent performance charts for icing conditions were published. Training guidelines were updated too. They are more focused on flight in known ice. The flight in such conditions is now approved only with successfully completed Caravan Cold Weather Course.[29]

[xxvi] IAS Indicated Air Speed

[29] http://www.aviationsafetymagazine.com/airplane/Cessna-Caravan-Safety-in-Icing-Conditions.html

7 Conclusion

Even if the icing is a well-known meteorological phenomena and its hazardous influence on the aviation safety was discovered many years ago, it is still underestimated or sometimes overlooked in real operations. The accidents and the incidents caused by the icing prove this fact. The biggest hazard exists when a plane flies in a difficult meteorological conditions. Area of the warm front passing through the Central Europe in the winter, the freezing drizzle or the freezing fog are the conditions that test the decision making qualities of every pilot. Sometimes un-careful pre-flight inspection or unawareness of the threat of icing can lead to the problems described in the Chapter 5.

Better knowledge of meteorology can help to improve the safety of flight. That´s why the first part of the work is dedicated to the description of meteorological aspect of the icing. Of course, pilot does not need to know about all the scientific researches in icing. However it is crucial for him to be able to take a right decision if the icing starts to be dangerous for him and for the aircraft. Capability to differentiate between the moderate rime ice and severe clear ice is a task the pilots have to be trained for. That´s why the work contains chapter about identification of the icing.

In the field of icing identification, the meteorologists and the other specialists on the icing have still a lot of work. The most complicated issue is to forecast freezing drizzle or freezing rain. There are two World Area Forecasting Centres where the icing conditions are analysed and the forecasts are issued. One is in the USA and the second one is the Met Office (WAFC-London) in the United Kingdom. The Met Office is in charge of icing forecasts for Europe.

In the last 20 years many improvements in forecasts of Super Large Droplets presence have been done. In America, Current Icing Potential (CIP)/ Forecast Icing Potential (FIP) reports are published by The Aviation Weather Centre.[30] (BERNSTEIN, 2005) The Met Office in London provides similar information for the European region. The meteorologists from the Aviation Weather Centre use the numerical weather prediction models to create FIP reports. For CIP reports, numerical weather prediction is combined with sensor data (temperature, humidity, clouds…) to hourly publish 3D analysis of the icing. This analysis contains information about icing probability, icing severity, SLD potential. The probability of icing detection reaches normally 90 %. The problem is, that the output of the icing report depends

[30] http://www.aviationweather.gov/adds/icing/icingnav

a lot on the method used to analyse the weather situation. When the outputs of the products used to forecast icing in Europe are compared to those used in the USA, big differences are discovered. Many times over-predictive methods are used. It means that they forecast the icing in an area where it will not be present. Sometimes severe icing was forecasted in the clear sky area. It is caused mainly because of an improper data analysis in the numerical weather models. New algorithms combining the observation based icing analysis and the numerical predicting models are being developed to make icing forecasts more accurate. (Morcrette, 2014)

Thanks to the supercomputers, the numerical weather models can work with much denser grid of data inputs than before. It means that the probability of the forecast accuracy is increased and icing conditions can be discovered more easily. Precise information about icing will improve the quality of the flight planning and it will increase the flight safety level. The prevention of the safety occurrences in aviation is an ultimate goal of all this effort.

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Figures

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