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Veröffentlichung MeteoSchweiz Nr. 75

COST 727: Atmospheric Icing on Structures Measurements and data collection on icing: State of the Art

S. Fikke, G. Ronsten, A. Heimo, S. Kunz, M. Ostrozlik, P.-E. Persson, J. Sabata, B. Wareing, B. Wichura, J. Chum, T. Laakso, K. Säntti, L. Makkonen

COST is supported by the EU RTD Framework Programme

ESF provides the COST Office through an EC contract

Veröffentlichung MeteoSchweiz Nr. 75

ISSN: 1422-1381

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Fikke S., G. Ronsten, A. Heimo, S. Kunz, M. Ostrozlik, P.-E. Persson, J. Sabata, B. Wareing, B. Wichura, J. Chum, T. Laakso, K. Säntti, L. Makkonen: 2006, COST-727 - Atmospheric Icing on Structures, Measurements and data collection on icing: State of the Art, *Publication of MeteoSwiss*, **75**, 110 pp.

Herausgeber

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Foreword

COST Action 727 "Measuring and forecasting atmospheric icing on structures" was established in April 2004 and comprises 12 signatory countries: Austria, Bulgaria, the Czech Republic, Finland, Germany, Hungary, Norway, Slovakia, Spain, Sweden, Switzerland and the United Kingdom. Following the "Memorandum of Understanding" (MoU), three working groups were established, WG1 "Icing modelling", WG2 "Measurements and data collection on icing" and WG3 "Mapping and forecasting of atmospheric icing".

The present report covers the work of WG2 during Phase 1 of the Action. The main scope of this phase was to create an inventory of earlier and current activities on icing measurements, data resources and instrument testing. The emphasis is on activities within the signatory countries, however some additional information from other countries like Russia and Canada is included as well.

It is important to notice that COST does not support project activities. Therefore all contributions concerning individual countries are provided according to available time and engagements of the participants. Hence the structure and details of each contribution will vary, and the reader will not necessarily find the same information for all countries. A lot of references are given, however, and the reader will find links to institutions where further information can be retrieved.

It is the intention of Phase 2 to structure and update information from existing test sites and open data sources in a more systematic way than was possible in this report. Phase 2 will also include instrument comparisons from test sites, and also elaborate recommendations for WMO observations and permanent data bases for icing in Europe.

COST Action 727 acknowledges Dr Wiel M. F. Wauben, the Royal Netherlands Meteorological Institute (KNMI) for reviewing this report and MeteoSwiss for their generous offer to print the report as part of their series of internal reports.

Svein M. Fikke
Chairman of Working Group 2

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Annexes

1 Management summary

The COST-727 Action ”Measuring and forecasting atmospheric icing on structures” was established in April 2004. It is divided in 3 working groups dealing with modelling, measurements and forecasting of icing.

Phase 1 of the action is dedicated to gathering available information for comprehensive state-of-the-art reports with the following deliverables:

- Reports on the state-of-the-art
- Inventory of users' needs based on analyses
- Working plan for the Second Phase of the Action

Phase 2 of the Action is dedicated to R&D and will concentrate on research on in-cloud icing, measurement on atmospheric icing, modelling of icing processes, improved forecasting systems, verification of existing icing sensors and mapping of icing occurrences and potentials in Europe. The following deliverables will be expected:

- Scientific and technical publications on measurements and predictions of in-cloud icing
- Publications on verification of icing forecasts
- European icing map
- Recommendations for WMO observations and further work

.

The present paper deals with the result of WG2 concerning measurements of icing as well as measurements performed under icing conditions. It contains information on:

Definition of icing: WG 2 recommends adopting the ISO12949 standard.

Past and present activities: International projects such as WMO/CIMO Instrument Intercomparison, EUMETNET SWS I and II projects, EU/WECO and NEW ICETOOLS projects as well as entities such IEC/CENELEC, ISO, IWAIS are shortly presented.

Standards: Prevailing standards in use (ISO, IEC and WMO) dedicated to icing on structures and icing measurements are shortly presented.

Measurements under icing conditions: As the WMO has presently no specific recommendations for measurements performed in harsh conditions, e.g. icing, a set of recommendations is presented concerning classification of sites and classification of sensors depending on severity of icing and the site climatic environment.

Requirements and availability of ice detectors: It is shown that requirements on ice detectors are dependent of the user’s requirement (wind energy, power lines, meteorology etc.) and on the application. Installation procedures are presented, depending on users requirements together with validation and verification processes.

Examples of existing data and experiences with existing ice detectors: A number of available long term experiments are presented concerning icing measurements and characterization of icing sensors. These activities have taken place in numerous countries like Finland, Germany, Slovak Rep., Norway, Czech Rep., UK, and indirectly from France, Switzerland, Sweden, Bulgaria, Russia, Canada, etc.

Recommendations for future activities: The establishment of test centres within the COST-727 Action (Phase 2) have a temporary character. It is recommended that long-term international calibration stations are established with a sufficient financial support for continuous operation. These calibration centres are to be recognized for delivering approved certificates for icing detectors and ice-free sensors.

2 Introduction

2.1 Memorandum of Understanding

COST Action 727 "MEASURING AND FORECASTING ATMOSPHERIC ICING ON STRUCTURES" was established in April 2004 according to a Memorandum of Understanding (MoU) [1]. The present report was prepared by Working Group 2 WG2 “MEASUREMENTS AND DATA COLLECTION ON ICING” and was given the following objectives:

“Measurements over a specific period of time on ice accretion and testing of icing sensors will be based on existing test sites in the far north (Luosto/Finland) and in the Alpine region (Guetsch/Switzerland). Additional experimental data from other ongoing activities will be used for this Action.

WG2's activities will be dedicated to the following activities:

a) create an inventory and collect available experimental data on icing as well as ancillary data
b) review and assess existing ice detectors and their performance
c) review and assess existing verification data from different sources
d) contribute to the set up of icing measurements at different locations in Europe and to the development of existing test sites
e) set up a data quality control scheme for measured icing data
f) establish a basic data set for icing modeling and verification
g) provide recommendations to set up a long-term icing measuring network and data base (to be submitted to WMO)
h) establish an icing monitoring core group for collecting and maintaining data on icing during and especially after the course of the Action
i) develop the scientific and technical bases of specifications of ice detectors
j) set up recommendations for testing/approving ice detectors and ice/free sensors.”

The present report summarizes the information and material WG2 has collected for the Preparatory Phase (Phase 1) of the Action, where the focus is to establish the “state of the art” in the field of icing and to indicate the data available for icing in Europe. Some information from Japan, Canada and Russia is also presented. The MoU focuses mainly on in-cloud icing, but wet snow and freezing rain are included when appropriate.

This report is based on input from WG members according to their current activities and related references. Furthermore it includes information on measuring activities in Europe related to both wind turbines and electric overhead power lines.

2.2 Interface with WG1 and WG3

During Phase 1 the Action WG2 had a close collaboration with WG1 and WG3 which were entitled:

- WG1 “ICING MODELLING”,
- WG3 “MAPPING AND FORECASTING OF ATMOSPHERIC ICING”.

These WGs are merged for Phase 2 and renamed WG1.

In particular, WG1 requires knowledge of what kind of icing data are available and can be provided for the purpose of validating and calibrating icing models as well as meteorological data that are unaffected by icing. WG3 needs similar data for mapping icing climates in Europe, as well as information on measurement networks that can be incorporated in forecasting routines by National Weather Services.

2.3 Past and present activities

This chapter is based on the input from different countries and covers both experimental work and administrative activities.

2.3.1 WMO/CIMO Wind Instrument Intercomparison

Mt. Aigoual, France: 1992-1993
A documented experiment has been conducted at the Mt. Aigoual station, France (within a joint venture between France and Switzerland) in order to analyze the performances of a number of ice-free anemometers under extreme meteorological conditions. [2]. See section 6.10 for more details regarding the available data.

2.3.2 EUMETNET / SWS I&II

SWS I: 1997-1998
The EUMETNET launched a study of severe weather sensors (SWS) to summarize the experiences concerning icing effect on sensors, knowledge in handling the ice affected data by the meteorological services, requirements of ice free sensors and direct measurements of icing, to make a market survey in ice free gauges available, and to give a proposal of specification of improved measurements under cold climate and ice affected sites. [3]

SWS II: 2000-2002
A documented experiment [4] has been conducted at three sites in Finland, France and Switzerland in the period 2000-2002 in order to analyze the performances of ice-free instruments under extreme meteorological conditions.
See section 6.11 for more details regarding the available data of the SWS projects.

2.3.3 WECO: Wind Energy in cold climates

"**W**ind **E**nergy Production in **CO**ld climates" **WECO** (JOR3-CT95-0014) 1996-1998, which was partially supported by the European Commission DG XII Non Nuclear Energy Programme aims at the investigation of wind turbines under cold climate operation.

It is shown experimentally and by numerical simulations that icing of rotor blades or other components lead to decreased production due to ice accretion or safety demands. The icing effect is directly related to the climate of the site of the wind turbine, and varies strongly from region to region in Europe. Extreme low air temperature again set new demands for design parameters. Icing of anemometers and other wind gauges typically lead to wrong estimation of wind power potential and operational problems of wind turbines [5].

2.3.4 NEW ICETOOLS

"Wind Turbines in Icing Environment: Improvement of Tools for Siting, Certification and Operation" NEW ICETOOLS NNE5-2001-259, 2002-2004, was partially supported by the European Commission Energy, Environment and Sustainable Development Programme. The aim was to produce tools and information to improve safety, availability and reliability of wind turbines and their components and thus improve the economics of wind power production in icing environments [6].

2.3.5 IEA WIND R&D Annex XIX

IEA R&D Wind is an agreement between 19 countries and the European Commission to follow international development on wind energy deployment and to stimulate co-operative research and development of wind technology. In 2001, International Energy Agency (IEA) R&D Wind started Annex XIX; "Wind Energy in Cold Climates". Since the start-up, the participants of Annex XIX have been collecting operational experiences from selected sites that experience frequent atmospheric icing or low temperatures. Collected data include information on performance of standard wind turbines as well as performance of adapted wind turbine technology specifically developed for cold climate sites. The aim of the work is to reduce the risk that originate from cold climate and thereby reduce the cost of wind electricity produced in cold climates [7, 8]. A second 3-year period of Annex XIX started late 2005 with Italy and Germany as additional members.

2.3.6 CIGRE

The „Conseil International de Grands Réseaux Electriques“ is a non-profit NGO dealing with all types of electrical component: production, transmission, distribution of electric energy. It is research oriented and organized in study committees. Study Committee B2 „Overhead lines“ deals also with meteorological aspects such as icing on overhead lines (WGB2.16 „Meteorology for overhead lines“) (www.cigre.org).

2.3.7 IEC/CENELEC

The International Electrotechnical Commission is the standardization body for all electrical components in parallel to ISO (see below). IEC prepares standards for the design of overhead lines taking into account meteorological parameters such as icing. CENELEC is the European counterpart of IEC (www.iec.ch).

2.3.8 ISO

The International Standard Organization has issued the ISO-12494 [9] recommendation which represents today the most widely used reference for icing on structures in general, but not for overhead lines. The standard describes the ISO standard instrument to measure icing (see Section 4.1).

2.3.9 IWAIS

The International Workshop on Atmospheric Icing of Structures is an informal institution supported by research institutions and utilities. IWAIS Workshops that have been organized every 2-3 years since 1982 are meant to be the main international gathering of researchers in icing and icing related problems and assess the state of the art in icing research [10]. The eleven published proceeding volumes of IWAIS contain approximately 5000 pages of information on icing related issues.

3 Definitions and meteorological conditions

3.1 Generic definition

According to the ISO-12494 standard [9], ice accretion can be defined as any process of ice build up and snow accretion on the surface of an object exposed to the atmosphere.

WG2 recommends adopting as standard the ISO-12494 and in particular the definitions presented in the following section.

3.2 Icing types (extracts from ISO-12494)

Atmospheric icing is traditionally classified according to two different formation processes:

a) Precipitation icing (including freezing precipitation and wet snow).
b) In-cloud icing (also called rime/glaze, including fog)
c) Hoar forst (not considered here?).

However, a classification may be based on other parameters, see table 1 and 2.

The physical properties and the appearance of the accreted ice will vary widely according to the variations of the meteorological conditions during the ice growth.

Besides the properties mentioned in table 1, other parameters, such as compressive strength (yield and crushing), shear strength, etc., may be used to describe the nature of accreted ice.

The maximum amount of accreted ice will depend on several factors, the most important being humidity, temperature and the duration of the ice accretion.

A main precondition for significant ice accretion is the dimensions of the object exposed and its orientation to the direction of the icing wind. This is explained in more detail in chapter 7 of the ISO document.

Table 2 gives a schematic outline of the major meteorological parameters controlling ice accretion.

A cloud or fog consists of small water droplets or ice crystals. Even if the temperature is below the freezing point of water, the droplets may remain in the liquid state. Such super cooled droplets freeze immediately on impact with objects in the airflow.

When the flux of water droplets towards the object is less than the freezing rate, each droplet freezes before the next droplet impinges on the same spot, and the ice growth is said to be dry. When the water flux increases, the ice growth will tend to be wet, because the droplets do not have the necessary time to freeze, before the next one impinges.

In general, dry icing results in different types of rime (containing air bubbles), while wet icing always forms glaze (solid and clear).

Figure 1 gives an indication of the parameters controlling the major types of ice formation. The density of accreted ice varies widely from low (soft rime) over medium (hard rime) to high (glaze).

Table 1: Typical properties of accreted atmospheric ice[1]

Type of ice	Density [kg/m^3]	Adhesion & Cohesion	General Appearance	
			Colour	Shape
Glaze	900	strong	transparent	evenly distributed/ icicles
Wet snow	300-600	weak (forming) strong (frozen)	white	evenly distributed/ eccen-tric
Hard rime	600-900	strong	opaque	eccentric, pointing wind-ward
Soft rime	200-600	low to medium	white	eccentric pointing wind-ward

Table 2: Meteorological parameters, controlling atmospheric ice accretion

Type of ice	Air tempe-rature [°C]	Wind speed [m/s]	Droplet size	Water content in air	Typical event duration
Precipitation icing					
Glaze (freez-ing rain or drizzle)	$-10 < t_a < 0$	any	large	medium	hours
Wet snow	$0 < t_a < +3$	any	flakes	very high	hours
In-cloud icing					
Glaze	see fig. 1	see fig. 1	medium	high	hours
Hard rime	see fig. 1	see fig. 1	medium	medium	days
Soft rime	see fig. 1	see fig. 1	small	low	days

[1] In practice, accretions formed of layers of different types of ice (mentioned in table 1) may also occur, but from an engineering point of view, the types of ice do not need to be described in more detail.

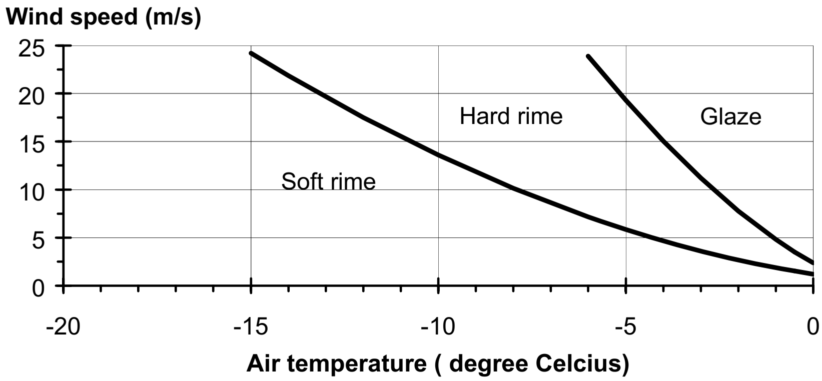


Figure 1: Type of accreted ice as a function of wind speed and air temperature[2].

3.2.1 Glaze

Glaze is the type of precipitation ice having the highest density. Glaze is caused by freezing rain, freezing drizzle or wet in-cloud icing and normally causes smooth evenly distributed ice accretion.

Glaze may result also in formation of icicles, and in this case the resulting shape can be rather asymmetric.

Glaze can be accreted on objects anywhere, when rain or drizzle occurs at temperatures below freezing point[3].

The surface temperature of accreting ice is near freezing point, and therefore liquid water, due to wind and gravity, may flow around the object and freeze also on the leeward side.

The accretion rate for glaze mainly varies with:

- Rate of precipitation
- Wind speed
- Air temperature

3.2.2 Wet snow

Wet snow is, because of the occurrence of free water in the partly melted snow crystals able to adhere to the surface of an object. Wet snow accretion therefore occurs when the air temperature is just above the freezing point.

---

2 The curves In figure 1 shift to the left with increasing liquid water content and with decreasing object size

3 Freezing rain or drizzle occurs when warm air aloft melts snow crystals and forms rain drops, which afterwards fall through a freezing air layer near the ground. Such temperature inversions may occur in connection with warm fronts or in valleys, where cold air may be trapped below warmer air aloft.

The snow will freeze when wet snow accretion is followed by a temperature decrease. The density and adhesive strength vary widely with, among other things, the fraction of melted water and the wind speed.

3.2.3 Rime

Rime is the most common type of in-cloud icing and often forms vanes on the windward side of linear, non-rotary objects, i.e. objects which will not rotate around the longitudinal axis due to eccentrically loading by ice.

During significant icing on small, linear objects the cross section of the rime vane is nearby triangular with the top angle pointing windward, but as the width (diameter) of the object increases, the ice vane changes its form, see chapter 7 of the ISO document.

Evenly distributed ice may also be formed by in-cloud icing when the object is a (near) horizontal "string" (linear shape) which is rotary around its axis. The accreted ice on the windward side of the "string" will force it to rotate when the weight of ice is sufficient. This mechanism may continue as long as the ice accretion is going on[4]. It results in an ice accretion more or less cylindrical around the string.

The most severe rime icing occurs at freely exposed mountains (coastal or inland), or where mountain valleys force moist air through passes, and consequently both lifts the air and increases wind speed over the pass.

The accretion rate for rime mainly varies with:

- Dimensions of the object exposed
- Wind speed
- Liquid water content in the air
- Drop size distribution
- Air temperature

3.2.4 Other types of ice

Hoarfrost, which is due to direct phase transition from water vapour into ice, is common at low temperatures. Hoarfrost is of low density and strength, and normally does not result in significant load on structures[5].

[4] The liquid water content of the air becomes so small at temperatures below about -20°C that practically no in-cloud icing occurs.

[5] Comments to ISO definitions: Icing types on wind turbine blades depend on the velocity i.e. the radial position. Glaze ice may occur on the tip while rime occurs near the root. Figure 1 should be extended to 80 m/s.

4 Ice measurements as described in standards

Atmospheric icing affects all kinds of installations in susceptible areas. The following standards have been found depending on the field of application.

4.1 International Standardization Organization (ISO)

The ISO issued in 2001 a standard [9] for ice accretion on all kinds of structures, except for electric overhead line conductors. In this recommendation, a standard ice-measuring device is described as:

- A smooth cylinder with a diameter of 30 mm placed with the axis vertical and rotating around the axis. The cylinder length should be a minimum length of 0.5 m, but, if heavy ice accretion is expected, the length should be 1 m.
- The cylinder is placed 10 m above terrain[6].
- Recordings of ice weight may be performed automatically.

However, it is important to be aware of the different properties of various icing types, especially the wet and dry growth of freezing rain, but also the possibly weaker adhesion of wet snow. If the cylinder cannot rotate freely due to wind drag, it may be provided with a motor to force the rotation. The speed of rotation of the vertical collector is not critical.

The vertical cylinder is not fully appropriate for freezing rain in the wet growth stage[7]. For this purpose it is preferred to use sets of horizontal collectors (rods) which are oriented orthogonal, like the Soviet standard ice collector [11] or the Canadian Passive Ice Meter (PIM) as described in [12].

4.2 International Electrotechnical Commission (IEC)

4.2.1 Overhead lines

For electric overhead power lines, icing is often the most significant design parameter in economic terms.

The IEC 60826 [12] gives rules for design of overhead lines in order to make them function reliably under icing conditions. However, IEC does not give numeric values for ice loads which are to be taken into account in various countries, as this aspect is considered to be the responsibility of each country. The only requirement used in [12] is that the “reference ice load” should be related to a “horizontal, circular conductor of 30 mm in diameter”.

[6] Consideration must be given to the maximum snow depth during the winter. The cylinder should preferably be placed in an area, where snow is blown away. For practical reasons, different erection heights above terrain are accepted, as long as the results correspond to those for 10-m height.

[7] For this purpose it is preferred to use sets of horizontal collectors (rods) which are oriented orthogonal, like the Soviet standard ice collector [11] or the Canadian Passive Ice Meter (PIM) as described in [12].

IEC has also issued a Technical Report on measurement of ice loadings for overhead lines [13]. It includes a description of historical test spans in Europe as well as in countries outside Europe.

4.2.2 Wind turbines

Extracts from IEC 61400-1, ed 2 [14]:

”*Environmental (climatic) conditions other than wind can affect the integrity and safety of the Wind Turbine Generator Systems WTGS, by thermal, photochemical, corrosive, mechanical, electrical or other physical action. Moreover, combinations of the climatic parameters given may increase their effect. The following other environmental conditions shall be at least taken into account and the action taken stated in the design documentation:*

- *temperature;*
- *humidity;*
- *air density;*
- *solar radiation;*
- *rain, hail, snow and ice*

Other extreme environmental conditions that shall be considered for WTGS design are wind speed, lightning and earthquakes. No minimum ice requirements are given for the standard WTGS classes.

Other loads such as wave loads, wake loads, impact loads, ice loads, etc. may occur and shall be included where appropriate.

During installation, environmental limits specified by the manufacturer shall be observed. Items such as the following should be considered:

- *wind speed, and*
- *snow and ice”*

The standards issued by CENELEC include for Europe the same principles of overhead line design as described in [12].

Furthermore, the international standard IEC 61774 [13] covers meteorological data with respect to icing observation and measurement concerning electric overhead lines. This standard has been designed on the basis of previous experiences of icing observation and has been adopted in such a way that the information acquired is unified. These procedures are useful because data conversion from different systems is very difficult.

4.3 World Meteorological Organization (WMO)

There are presently limited standards defined by the WMO and its Commission for Instruments and Methods of Observation (CIMO) either for measurements performed under harsh conditions (e.g. icing) or for the measurements of icing itself at Automatic Weather Stations (AWS).

However, taking into account the recommendations of the final report of the recent EUMETNET (Network of European Meteorological Services) / Severe Weather Sensor experiment SWS II [15], the WMO/CIMO Expert Team of Surface Measurements has recently decided to include in the next version of the CIMO Guide – or in a later version - a chapter concerning meteorological measurements performed under harsh conditions such as artic/mountain climate (icing), desert, urban, tropical, ocean, etc.. This topic should be further handled during the CIMO XIV session.

4.4 Icing and wind turbines

Icing of wind turbines is briefly described in the standards [14, 16]. However, the results from the EU-project NEW ICETOOLS [6] indicate that these standards seem to underestimate:

- the actual amount of ice,
- the influence on fatigue loads from extended periods of frost and
- the time period of ice accretion.

In the following, extracts concerning icing from present wind turbine design standards are presented.

Extract from GLRP3.0-1998 [16]:

For non-rotating parts an ice formation with a thickness of 30 mm on all sides is to be assumed on all exposed surfaces. The ice density is to be taken as 700 kg/m³. For the Wind Energy Converter (WECs) at standstill also the rotor-blades have to be analyzed with this ice cover.

For the rotating machine the situations "all blades are iced over" and "all but one blade iced over" have to be analyzed. The mass distribution (mass per unit length) is to be assumed on the leading edge. The mass distribution increases linearly from zero in the rotating axis to the value μ_E *at half radius and stays constant to the blade tip. The value* μ_E *is given by:*

$$\mu_E = \rho_E k c_{\min} (c_{\max} - c_{\min})$$

where

ρ_E = density of the ice : 700kg/m^3

$k = 0.00675 + 0.3\exp(-0.32R/R_1)$

R = rotor radius

$R_1 = 1\text{m}$

$c_{\max}$ = maximum chord lenght

$c_{\min}$ = chord lenght at the tip

5 Meteorological measurements under icing conditions

5.1 Introduction

The accuracy of the surface measurements of various meteorological variables is essential for meteorological services, researchers in climatology (e.g. climate change[8]), aeronautical meteorology, etc. It is therefore essential to characterize the effects of ice accretion on the sensors and, when possible, to prevent it.

The WMO Guide for meteorological measurements [17] does not define the temporal reliability of sensors, e.g. the required availability of data per year or per month, so that most meteorological services have specified their own targets for availability of data. Similar targets are defined also for other applications. Furthermore, the WMO Guide does not separately consider severe weather conditions like icing, even if low temperature is specified in the requirements. In the same way, the manufacturers typically specify their instruments' performance for severe weather conditions by taking into account low temperature (for instance operating range: -40°C… + 50°C), but not icing. Presently, icing events are defined as periods of time where the temperature is below 0°C and the relative humidity is above 95%, a very simplified approach. Usually low air temperature is not a major problem for meteorological observations: for many sensors, this is taken into account e.g. by using shaft heating for anemometers with rotating parts (at small and/or mobile automatic stations, the power supply may not be sufficient even for shaft heating).

5.2 WMO/CIMO Recommendations

The following recommendations are stated by WMO/CIMO:

- Improve the quality of meteorological measurements under cold climate conditions,
- Provide manufacturers data for design of ice- free sensors,
- Provide users and providers of meteorological information better bases for selection of suitable sensors for their purposes.

To improve the general knowledge on icing and icing climatology, the following recommendations for further activities are given:

- Improve the design of the instrument (mechanical) and heating system to optimize the required heating power
- Promote the development of icing observation instruments
- Promote the results of past, present and future experiments
- Promote national " icing maps"
- Promote a classification for "meteorological" sensors taking into account accuracy, climatic conditions and reliability of data required for different applications

[8] The anticipated increase in air temperature will inherently lead to higher contents of water (vapour) in the lower atmosphere. In mountains, and especially in northern latitudes, there is therefore an increased frequency of temperatures near freezing, and together with more water available this could lead to higher frequencies of icing as well as higher icing intensities and ice loads on structures. An anticipated increase in extreme wind speeds will contribute likewise and indeed lead to significantly higher static and dynamic loads on exposed infrastructure. [Svein Fikke, private communication]

- Promote the improvement of the WMO/CIMO Guide 8 for measurements in severe icing conditions
- Promote WMO-approved test sites for ice- free sensors, preferably combined with the use of icing wind tunnels for testing of sensors, including anemometers.

It must be noted that most activities on developing requirements for instruments in harsh climatic environments focus on icing conditions only (*i.e.* in extremely cold mountainous/Arctic climates). Therefore, equipment for dusty and dry deserts, humid and hot tropics and oceans with a harsh climate need further investigation. For these climates only very limited guidance material is available on the implementation and maintenance of automatic observing systems and, therefore, further studies are necessary. Moreover, not only the performance and maintenance issues of a system are a point of concern but also destruction of instruments caused by extreme weather should be considered (*e.g.* tropical cyclones reaching 300 km/h or more.)

In line with past developments and published material on this matter, documentation on the requirements for instruments for observations in harsh climatic conditions has to be generated. In particular the IOM report, as announced at CIMO XIII should be finalized and published. Moreover, as stated in the recommendations in the SWS II report (see above) more attention to this topic should be given in a future revision of the CIMO Guide [17].

Taking these recommendations into account, and in line with CIMO XIII, the CIMO management group has decided to continue the work on the provision of guidance material on implementation of instruments in harsh climatic environments as requested by Congress and Technical Commissions. To realize this, further study on already existing test reports should be carried out. Moreover the already announced IOM report has to be finalized and published. A decision should be made on how to implement requirements on the instruments capable of measurements in a harsh environment in a new revision of the CIMO Guide and it should be considered to carry out inter-comparisons of dedicated sensors in such environments. Preceding such inter-comparison an inquiry should be carried out among the Members facing shortcomings of today's equipment due to harsh and extreme weather.

5.3 Definitions

5.3.1 Meteorological icing M_{icing}

Meteorological icing M_{icing} is defined as the duration of a meteorological event or perturbation which causes icing [unit: time].

Meteorological icing can be characterized by:

a) the duration of the icing event, and/or
b) the meteorological conditions,

and possibly with additional information such as:

c) the total amount of ice accreted on a standard (reference) object during the icing event,
d) the average and maximum accretion rate.

Automatic certified reference sensors are lacking for the determination of items a) and d), whilst the items b) and c) can be more or less achieved with presently available technology.

However, it must be noted that meteorological icing is not easy to define. It is today widely accepted that it depends on the following factors:

a) the shape of the object,
b) the wind speed,
c) the air temperature,
d) the liquid water content LWC,
e) the droplet size distribution,

the latter two being difficult to measure in operational mode. Tentative developments have been achieved, such as the Rotating Multicylinder RMC. Unfortunately, these cannot be operated in an automatic way and cannot therefore be implemented at automatic stations. New developments may improve this situation [18].

Today, ice accretion can be measured directly by instruments measuring:

a) changes of a vibrating frequency (Rosemount, Vibrometer, Wavin-Labko),
b) changes in electrical properties (Instrumar, Labko)
c) the load of ice (ISO 12494)
d) the growth rate of ice by yielding a yes/no output (at regular intervals) by a heating cycle
e) optically (obstruction of light path, IR or reflection technologies: Infralytics, HoloOptics).

In addition, icing can be measured indirectly by measuring the variables that cause icing (see Chapter 4.2) or variables that correlate with the occurrence of icing, such as cloud height and visibility.

5.3.2 Instrument icing I_{icing}

Instrument icing I_{icing} is defined as the duration of the technical perturbation of the instrument due to icing [unit: time].

Instrument icing is the effect of icing on the quality (e.g. degradation) of the measurements, depending on icing conditions as well as the design of the instrument. It can be today only recorded by analyses of video recordings, and/or regular visual observation, or by comparison of the measurements with a reference that is kept ice free.

This definition is valid for all objects or structures. It can be easily generalized to “structural icing”.

5.4 Site effects

In the preceding section meteorological icing has been shown to be different from instrumental icing, the latter being the consequence of the former, but with different effects depending on the characteristics of the meteorological conditions and of the instrument design.

Instruments (or structures) will behave differently depending on the location of their installation. A sensor operated in northern countries may get frozen at the beginning of the winter and remain as such due to the low temperatures and the lack of sunshine. On the contrary, this instrument may be installed further south and work more or less undisturbed under milder, sunnier conditions. Therefore, the instruments characteristics must be evaluated as a function of the site of installation in terms of local icing conditions.

5.5 Site Icing Index

To be able to express the maximum expected amount of accreted ice at a certain site, the term ICE CLASS (IC) is introduced in the ISO 12494 standards, for design purposes. For the purpose of meteorological instruments a **site icing index, Sn**, is introduced by using icing frequency, duration and intensity:

Sn is the parameter to be used by the meteorological community to determine how severe ice accretion is expected at a particular site, in regard to meteorological instruments. Maximum loads are not included in this definition.

The climatologists may provide information about Sn, which (in general terms) tells how much icing can be expected at a given location. Measurements and/or model studies are necessary to obtain the information needed for a specific site, unless experience can supply the same information.

The station class may vary within rather short distances of a specific area. Measurements should be carried out either where ice accretion is expected to be most severe, or at the precise station site, or both.

Therefore, it is recommended that a classification of sites, e.g. Automatic Weather Station (AWS) is introduced indicating the degree of severity of local icing conditions. The following table was set up during the EUMETNET/SWS II experiment and describes tentatively the framework of such a classification.

Table 3: *Classification of sites according to the severity of icing* (from EUMETNET/SWS II Report).

Site icing index	Days with meteorological icing / year	Duration of meteorological icing %/year	Intensity of icing g/100 cm^2/h (typical)	Icing severity
S5	> 60	> 20	> 50	Heavy
S4	31-60	10-20	25	Strong
S3	11-30	5-10	10	Moderate
S2	3-10	< 5	5	Light
S1	0-2	0-0.5	0-5	Occasional

5.6 Measurements under icing conditions

In the preceding section, it was possible to set up definitions which are used to describe the behaviour of meteorological instruments under harsh conditions and to select new adequate sites, or specify existing ones for Automatic Weather Stations (AWS). In the following, these definitions are used to classify sensors accordingly.

5.6.1 Ice-free meteorological sensors

Icing environments set special requirements for sensors. Accurate meteorological measurements under cold and icing conditions are required for various applications such as aviation, transportation, emergency services, tourism industry, meteorological observations, wind energy production, agriculture, etc. Instruments performing measurements (such as humidity, temperature, wind speed, wind direction, precipitation, radiation, etc.) in cold climate environments have to be properly heated to maintain their accuracy under icing conditions. Today, there are several types of ice-free sensors available on the market. Some of them will not fulfil the requirements of the World Meteorological Organization (WMO) for accuracy and availability when operated under icing conditions, especially at mountainous sites, but also at sites like airports, road stations e.g. in northern Europe. The practical requirements on accurate operation of sensors are even more demanding for many applications other than for meteorological synoptic purposes.

During the EUMETNET/SWS II project, a simple classification for instrument icing characteristics was introduced for analyzing the behaviour of the different available - defined as ice-free - sensors under icing conditions. This classification made it possible to study statistically the effects of different amounts of ice upon sensors, and the magnitude of the resulting errors. The state of the instruments was classified at all stations with a value between 0 and 3:

- Class 0: totally free of ice
- Class 1: light ice accretion, without obvious effect on the sensitive part but which could influence the wind field.
- Class 2: medium ice accretion, probably disturbing the measurements – Sensitive elements seem free of ice and wind field is obviously disturbed.
- Class 3: totally covered with ice – sensitive elements are covered with ice.

A tentative classification of reliability of different types of sensors under icing conditions was performed in such a way. The results were summarized with respect to general requirements for a meteorological synoptic station. The sensor got one star when not adequate to provide reliable data at the climatic conditions met at sites with more than 60 icing days per year, but could be used reliably at some other less demanding sites. Three stars indicate that the sensor is close to 100 % ice-free but has other significant errors, and sensors with five stars can be strongly recommended for measurements at sites with harshest icing conditions.

It must be kept in mind that for practical measurements the requirements and the choice of sensor depend significantly on the goals of the application and on the location of weather station (icing climate). This leads to the following classification proposal.

5.6.2 Performance Index

During a meteorological icing event, the relationship between meteorological and instrument icing can be expressed in the following way:

An instrument which remains free of ice during a meteorological icing period (good heating, good coating, etc.) may be considered as well adapted for the station's climatology. On the other side, an instrument that becomes frozen during a meteorological icing period and remains in that state after the meteorological icing period must be classified as poorly adapted to the site's environmental conditions. This leads to the following definition:

The Performance Index (PI) is the ratio of the instrument icing to the meteorological icing, both expressed in the same time unit.

$$PI = I_{icing} / M_{icing}$$

The PI can be used for the selection of the instrument as function of some station's classification. A value of PI near 0 reflects a good performance of the instrument in terms of icing (e.g. good heating). Values of PI between 0 and 1 may be acceptable as long as ice detector information is available to "flag" dubious periods of measurements. Values of PI higher than 1 indicate a sensor which is sensitive to icing (e.g. poor heating) for a time period (much) longer than the meteorological icing.

Further useful definitions:

Incubation time: delay between the beginning of the meteorological icing and of the instrumental icing.

Recovery time: delay between the end of the meteorological icing and the full recovery of the performance of the instrument

Instrument icing can be smaller, equal or longer than meteorological icing. The incubation time indicates how quickly the instrument responds to icing while the recovery time may be much longer that the meteorological icing, especially in northern countries with low solar irradiance in winter.

In summary, the following definitions are needed to characterize the properties of an instrument under icing conditions:

The meteorological icing $\mathbf{M_{icing}}$ is the duration of the icing event (see §5.3.1)
The instrument icing $\mathbf{I_{icing}}$ describes the effect of $\mathbf{M_{icing}}$ the on the instrument (see § 5.3.2).
The Performance Index PI characterizes the behaviour of the instrument under icing conditions.

5.6.3 Instrument Class Index

It is evident that a classification for meteorological sensors will be difficult to achieve taking into account accuracy and required reliability of data combined with climatic conditions. Therefore, the goal is now to build a common indicator by combining PI and Sn (see § 5.5).

A potential indicator may be given by ICIn (n=1..5), the Instrument Class Index, which corresponds to PI values ranging from 0 **->** ∞ depending on the different site icing indices S1 to S5 as indicated in Table 4. The range of this classification extends from ICI5 (PI = 0; availability = 100 % → perfect icing non-sensitive instruments) to ICI1 (PI = very high values; availability ≤40 % → instruments which could remain frozen for a very long period after the meteorological icing period, e.g. long recovery time for high latitude stations without sun during whole seasons).

Table 4: *Classification of instruments in terms of mean performance depending on the station's site icing index (the availability values displayed in italic are purely hypothetical and will have to be specified in future).*

Instrument Class Index	PI for S1 … S5	Mean availability in % for S1 … S5	Remarks
ICI5	0	*100 %*	Excellent instrument not sensitive to icing
ICI4	0 …1	*99 ... 90 %*	Good instrument, little sensitivity to icing
ICI3	1 ... 5	*89 ... 70 %*	Instrument moderately sensitive to icing.
ICI2	5 ... 20	*69 ... 40 %*	Instrument to be used only with separate icing detection
ICI1	20 ... ∞	*39 ... 0 %*	Instrument not recommended for such applications

The interpretation of the ICIn index is strongly linked to the station's site icing index (Sn, n=1-5) and the effect of icing on the results' quality as described by the PI defined above. This leads to the following graphical representation (Figure 2) where the user could select the class of instruments needed to fulfil his requirements depending on the location (e.g. classification) of his station and requirement.

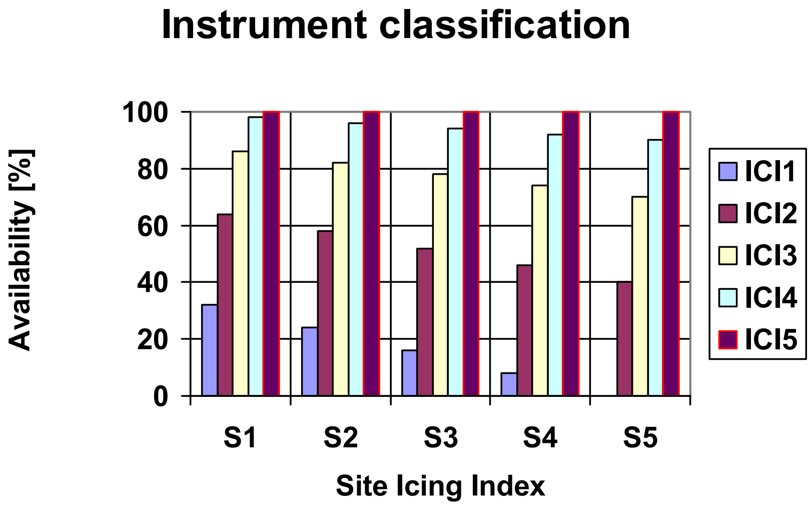


Figure 2: *Graphical display of the instruments' classification presented in Table 4 (hypothetical sensors) reflecting the availability of an ICIn sensor installed at a Sn site. In reality, the ICI will have to be determined for each Sn. The availability will then be computed considering the severity and duration of icing periods.*

6 Examples of existing icing data

Numerous activities in the field of measurement of icing have already taken place in different countries. The following gives an overview of what has been achieved to date. More details may be found in the Annexes, as indicated.

The contributions in this chapter are based on information provided by members of the COST Action 727. Other data may be available in some countries.

6.1 Finland

VTT and Digita (former Finnish Broadcasting Co., Distribution Dept.) have made measurements of icing on tower structures and measurements of drop size and liquid water content of clouds and comparisons of meteorological instruments on hilltops in severe icing conditions in Finland since 1986. An operating 128m tall TV tower and a 7.5 m test tower at Ylläs (700 m asl) have both been equipped with load cells, so that the ice load on them could be continuously measured [19,20]. Ice detectors were also tested [21], and VTT has also later performed ice detector tests in four locations during the period 1998 – 2005.

The Luosto test station (500 m asl) in northern Finland was set up during the winter 2000/2001 by Finnish Meteorological Institute. The main purpose of the Luosto test station is to measure icing as well as the behaviour of meteorological instruments.

More details are given in Annex 1.

6.2 Germany

Icing measurements were carried out at altogether 40 locations in the eastern part of Germany during 1965 – 1990, up to 35 locations were operated simultaneously. Since 1991 five stations are still in operation. A standard observation pole has been used for all stations. On the Deutscher Wetterdienst's meteorological observatory Lindenberg, ice measurements are currently made at 10, 50 and 90 m above ground.

More details can be found in Annex 2

6.3 Slovak Republic

The Slovak Hydrometeorological Institute has data on icing from 13 stations, ranging from 115 to 2 634 m asl. The measurements are both visual and by instruments. The oldest data are from 1957.

More details can be found in Annex 3.

6.4 Norway

A measuring station for ice monitoring has been operated at a coastal mountain of about 800 m asl in central western Norway with the support of the Norwegian Research Council and two Norwegian energy companies. The station was equipped with ice-free wind sensors, temperature sensors and a web-camera. Ice accumulation was derived from web-camera pictures of wires. Measurements took place during two winters. The monitoring results have been compared with an ice model and the results are reported in Harstveit [22] and Harstveit et al. [23]. Accumulated ice at 10 m up to a maximum value of 20-25 kg/m where reported. As a part of the development of wind farms in the costal mountains of Norway new ice monitoring programs have recently been set up. Different ice detection equipment, such as rotating multi-cylinder, ice indicators and web-cameras are utilized. Unfortunately, no data are yet available, but hopefully useful information will become available from these programs in the future.

During the period 1978-2000 the Norwegian Power Grid Company, Statnett SF, has operated more than 20 sets of racks for ice measurements in 16 locations in mountainous areas for power line design purposes. Each set consists mainly of two perpendicular racks, where one leg is perpendicular to the main icing wind direction. Some sets were established to study the effect of local topography. Most of these racks are in coastal mountains in the range of 600 – 1 200 m asl.

More details can be found in Annex 4.

6.5 Czech Republic

Two institutes have performed icing studies in Czech Republic, EGU Brno and Institute of Atmospheric Physics (IPA, Prague). EGU Brno has operated a test site on Studnice (800 m asl) continuously since 1940. Ice loads were measured on a rack with orthogonal rods 2 m above ground. The annual maxima of loads on this rack for the period 1940/41 – 1998/99 are presented in Figure 3. This unique time series is outstanding, since it is the only series of this kind in the world covering such a long time period.

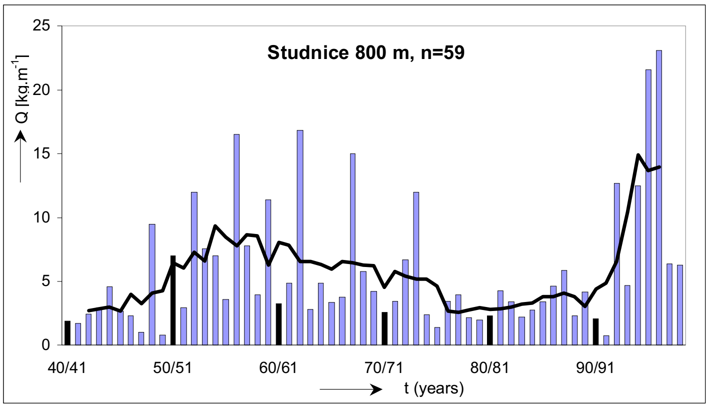


Figure 3. The Studnice site has also a test installation for power lines consisting of a central observation tower and 2 spans of about 250 m length on each side.

Furthermore, EGU Brno has developed the instrument "METEO" which is installed at 14 locations in the country. The measuring probe is a vertical rod of 30 mm diameter.

The IPA has a similar instrument, IceMeter, installed in two locations, Milesovka (837 m asl) and Nová Ves.

More details can be found in Annex 5.

6.6 UK

Test data on icing has been available on rotating rigs and test spans since 1988. Many of these sites lasted only a few years before being closed down for financial reasons. The longest running site, at Deadwater Fell in Northern England, was established in 1991 and is still currently open, although it has been 'mothballed' occasionally so there is no continuous ice measurement over this period. It currently monitors wind speed and direction, temperature, ice loads (by time lapse video cameras and also load cells), precipitation and relative humidity. It has operated the Gerber instruments on loan from the UK Meteorological Office. Measurements have been made on conductors from $16mm^2$ to $800mm^2$ of the copper, aluminium and covered variety as well as fiber optic systems such as Optical Pipe Ground Wire (OPGW), fiber-wrap and All Dielectric Self-Supporting (ADSS).

More details can be found in Annex 6.

6.7 Sweden

Three different sensors (IceMonitor, HoloOptics and Segerstrom) are currently being tested under field conditions in Sweden and Norway. Meteorological parameters are measured, along with icing data, in Ritsem, Åre and Drammen (Norway).

More details can be found in Annex 7.

6.8 Bulgaria

More details can be found in Annex 8.

6.9 Hungary

More details can be found in Annex 9.

6.10 Russia

Some information on measurements in Russia is found in Annex 10.

6.11 Canada

Some information on measurements in Canada is found in Annex 11.

6.12 WMO/CIMO inter-comparisons of wind instruments under harsh conditions

The WMO Wind Instrument inter-comparison was organized following the recommendation of the Commission for Instruments and Methods of Observation CIMO [2]. It was carried out under the aegis of the WMO by both Meteo-France and the Swiss Meteorological Institute (presently MeteoSwiss) at the Mt. Aigoual (France) from July 1992 to October 1993.

The objectives of the inter-comparison were the following:

- To derive performance characteristics on the operational use of wind sensors based on the detailed record of their measurement values and a record of the prevailing atmospheric conditions.
- To determine the suitability of these instruments for long-term unattended operation especially in a mountainous environment
- To make proposals for further improvements to the WMO regulatory materials concerning the measurements of wind
- To evaluate and publish the results of this analysis in a WMO publication

Icing phenomena have been studied from visual sensor control by the observer and by studying the data. It was noted that:

- The importance of the icing phenomenon could not be characterized from the ice detectors.
- The formation of ice made almost all the calculated parameters incoherent.

In the conclusions of the report, the difficulties of performing measurements under harsh icing conditions are reported in the following way:

- The only sensors having supported severe icing events without noticeable measurement errors are the Pitot sensors and one vertical axis anemometer. These sensors require a high amount of energy for heating (300 to 500W). The meteorological performance of these sensors is not perfect and does not meet the WMO accuracy recommendations. It appears difficult to be both “accurate” and rugged for severe icing.
- Manufacturers commercializing measurement instruments should put at the users’ disposal a detailed and complete documentation including a detailed installation and maintenance book and the exact metrological specifications of the sensors.

6.13 EUMETNET/SWS II project

The EUMETNET "Severe Weather Sensors II" project (SWS II) tested 15 wind sensors, 6 temperature and humidity measurement systems with different types of shields and 4 solar radiation sensors equipped with heating. During the project also different methods of measurement of atmospheric icing were used and tested. The three test sites were located in northern Finland, in the Swiss Alps and close to the Mediterranean in the French mountains, all with more than 60 days/year of atmospheric icing.

From the results presented here, it can be seen that heating power is required especially for wind measurements, but the power consumption can be relatively low if the sensors are properly designed. The tests and verifications showed that wind speed, wind direction and air temperature could be measured with high accuracy and high reliability at cold climate sites under most severe icing conditions even at automatic weather stations. For temperature and humidity sensors, some of the shields provide significant improvement in comparison with measurements performed with other systems in use at different national meteorological services. However, under harsh conditions, the reliability of temperature and humidity measurements does not yet reach the level available for wind measurements. Concerning test measurements on the heating/ventilation systems for solar radiation measurements, results show that strong icing conditions may dramatically disturb the measurements. None of the tested systems were able to fully withstand the harsh climatic conditions prevailing at such sites.

It was not possible to study the performance of the various sensors versus intensity of ice accretion due to the lack of dedicated sensors to measure icing [4].

7 Requirements for ice detectors

7.1 Concepts

7.1.1 Purposes of measurements

At the present time, many sensors that are designed and labelled as ice detectors are available. Some of the instruments measure icing rate, some measure the weight of ice (persistence and maximum loads) and some indicate if an icing event is ongoing. Therefore, the purpose for using ice detectors needs to be defined. Some detectors are clearly designed to indicate incipient icing only whereas others have been designed to measure the total mass of ice accumulation.

Requirements regarding time resolution, measuring range, threshold values as well as response time of sensors depend on the purpose of individual measurements, and are therefore not further specified in these generic descriptions.

7.1.2 Range of use

The range of use varies between different ice detectors. For example, some sensors have been designed for aviation purposes and perform well on airplanes, but may not be very well adapted for meteorological purposes due to different environmental conditions as indicated below.

The parameters that have an effect on the operation of an ice detector are air velocity, size of water droplets, amount of liquid water present and the physical size of the probe i.e. all the parameters that have an effect on the amount of water ending up on a detection surface. The range of use should be defined by means of these parameters and should be validated in controlled circumstances (see below). Furthermore, it must be kept in mind that in certain circumstances the operation of the ice detector may be affected by other phenomena, such as ice sublimation due to dynamic heating in high velocity airflows and Ludlam's limit, which sets the upper LWC limit of use for some ice detectors [24].

Heated sensors may be iced up during non-icing periods due to melting of dry snow.

7.1.3 Icing types

All icing types that adhere on static or moving structures can be harmful and need to be identified.

7.1.4 Verification of performance

Considerable deviations between the results of ice detectors of the same type and even similar ice detectors can be found [25,26].

Definition of the range of use and some calibration scheme might improve the current situation. Range of use and data verification could possibly be carried out in icing wind tunnels, where the icing condition can be regulated and monitored. Kanagawa Institute of Technology (KAIT) has conducted wind tunnel test for investigation of icing events on airfoil models and anemometers as described in Annex 21. Wind tunnel tests include various kinds of testing carried out in an atmosphere of low and moderate temperatures. The primary objectives were to quantitatively find out the effect of icing on wind speed measurements and to evaluate the effectiveness of measures to prevent ice or snow accretion on specific objects.

A further possibility lies in the development and long term operation of "icing test centres" similar to (or included in) the Regional Instruments Centres (RICs) of the WMO where market available and future instruments could be tested under different climatic conditions (e.g. Scandinavia, Alps, Pyrenees, etc.).

7.2 Siting of icing sensors

7.2.1 Micrositing

Ice sensors should be placed so that the detection surface of the device faces up wind and free air flow is granted. In addition all ice detection devices should be placed above tree tops and other possible obstacles. Appropriate locations for ice detectors are support structures of overhead power lines, wind turbines, link masts of mobile phone networks and in general high structures that provide free air flow around the ice detector. ISO 12949 [9] recommends 10m measurement height above ground. However, as icing measurements are dependent on the different application types, ice sensors can be installed at different heights. Automated weather stations are not generally appropriate as they are located close to ground level and seldom provide a correct representation of those icing conditions that prevail at a higher level e.g. wind turbine rotors.

Details such as the mounting orientation and height detectors will have to be analysed directly at the test centre sites.

7.2.2 Standard Reference and procedures

Ice accretion on structures is not only a function of environmental parameters, but is also dependent on the properties of the accreting object itself, e.g.:

a) size (diameter, width etc.)
b) shape (flat, sharp edges, cylindrical, spherical etc.)
c) flexibility (rigid/flexible member in bending/torsion etc.)
d) orientation relative to wind direction (angle of incidence)

and to some extent:

a) surface structure (paint, steel, concrete etc.)
b) material (wood, steel, plastics etc.)

Measurements of ice accretions therefore have to be specified with respect to devices, procedures, arrangements on site etc. The set-up must be designed in a way that causes the lowest possible influence on the accretion process itself:

A **standard reference** device should always be part of the measurements, giving the traceability to standard measurements of ice accretion. Other parts of the set-up may help to establish the connections between "standard accretions" and the most important structural parameters as described above (size, shape, etc.). These extended measurements should only be executed at special selected sites, and collected data should be analysed and used, generally together with the standard measurements. Frequency of observations may be adjusted to the local conditions.

On sites where melting or shedding are likely to occur shortly after the accretion period, observations must be carried out before this happens for example by making use of camera systems.

When automatic recordings are performed, it is important to add also visual observations during and/or after the accretion period, because only these types of observation can give sufficient information on such complex load situations. These visual observations have to be logged, and documented with appropriate digital camera pictures. Remote reading (including camera observations) makes it possible to get online information about an icing event so that the site may be visited in proper time.

7.2.3 Macrositing

The following table 5 describes the information needed concerning ice types that are requested for the different fields of application.

Table 6 displays the density of meteorological networks equipped with ice detection systems for the different fields of application. For example a developer of a wind energy project would need relatively dense measurement network due to the considerable influence of local landscape to the icing conditions.

Table 5: *Ice parameters required*

	Requested information			
Application	**Icing rate**	**Ice load**	**Icing time**	**Persistency**
Wind turbine operation	x	x	x	x
Wind project planning		x	x	x
Power line design		x		
Power line operation	x	x	x	x
Aviation	x		x	
Telecommunication masts		x		x
Suspension bridges		x		x
Transport (roads, railways)	x		x	
Meteorology and climatology	x	x	x	x

Table 6: *Location of ice detection needed by the different users.*

	Minimum distance to closest ice detection point		
Application	**On the site of interest**	**Less than 50km from the site of interest**	**More than 50 km from the site of interest**
Wind turbine operation	x		
Wind project planning	x	x	
Power line design	x		
Power line operation	x		
Aviation	x		
Telecommunication masts	x		
Suspension bridges	x		
Transport (roads, railways)	x	x	
Meteorology and climatology		x	x

7.3 Guidance for selecting ice detectors

7.3.1 General

Appropriate ice detectors should be chosen with respect to the purpose of their use. There are presently two systems of ice detectors:

- with status icing / no icing
- with recording of the whole icing cycle (ice mass, ice accretion rate).

The size of the detector probe has a significant effect on performance of an ice detector. When icing detectors shall be selected, the purpose of the measurements has to be considered carefully. For example, smaller droplets in low speed airflow pass large objects more efficiently due to their low inertia and the fact that large objects deflect the airflow upstream from the object (collision efficiency). Therefore, no single ice detector can provide data that are directly applicable to all types of structures and conditions [27].

Ice detectors should be used only in conditions for which the devices were designed. For example, in order to design overhead lines, it is necessary to know the ice mass during an icing cycle. Measurement systems recording the whole icing cycle must be used in such a case without ice shedding or heating of a sensor during an icing cycle.

7.3.2 Applications

Wind turbines

Ice detectors are needed for planning and operation of wind turbines. Results from the planning phase will influence the selection of type of turbine and equipment. During operation, ice detectors are needed to detect incipient icing as quickly as possible for controlling heating systems, turbines and to give a warning about possible ice shedding in populated environments. Another type of ice detector is needed to indicate whether there is ice on some surface or not. The primary output would be the duration of the period that accumulated ice adheres on a detection surface without any heating or external forces. The most important parameter is time in both applications.

Icing is closely related to the speed of air flow and so the ice detector for wind turbine applications should preferably be attached to the outer part of the turbine blade.

Power lines

Power line companies are mainly interested in local wind and ice loads and wind-on-ice factors. Ice detection is needed to determine whether the power supply is likely to be secure or whether an emergency response may be required. It could also enable pro-active measures. In terms of line design the use of ice sensors to provide historical data for probability purposes is important.

Because power line conductors have low torsional rigidity and thus rotate along the span during icing events, the instrument that measures icing rate or ice load for this application should be elongated horizontally and free to rotate [11].

Road safety

Mountain roads and bridges are commonly provided with wind and ice sensors for traffic safety information, for combination with weather forecasts for pro-active road treatment (gritting etc) as well as falling ice from bridges. Incorrect timing due to poor or badly interpreted data can mean that road treatment is less effective and can lead to increased accident rate.

Airports

Preventive treatment of runways as well as de-icing of airplanes before take-off may represent a important security problem as well as a heavy financial load for airport authorities. Early ice accretion warnings should represent a safety increase, pollution decrease and financial savings. As airports are usually located at low terrain, the emphasis is to detect freezing precipitation. Icing may be a hazard on an aeroplane wing even at temperatures above freezing due to cold fuel stored in the wing tanks.

Transport facilities

Railways, cable cars, ski lifts, etc. require icing information so as to allow pro-active measures to be put in place (e.g. heating of switches) and also to enable staff/de-icing trains to be on standby to combat icing. The ice can occur on power (3^{rd} rail) and overhead power lines causing pantograph damage. It is also serious when accumulations on traction rails reduce the adhesion of train wheels.

Telecommunications

Telecommunication masts and towers are subject to icing on structures, antennas and/or guy wires, with potential effects on the quality of the transmissions and on the structural loads. At least 150 telecommunication towers have collapsed due to ice loads in the last 40 years. Wind loads are an important contributing factor, so that a combined ice and wind load needs to be estimated for the design.

8 Availability, verification and requirements of ice detectors

8.1 Available ice detectors

There are presently few available instruments on the market. However, there are some prototype instruments which seem very promising and may lead to interesting products after thorough testing and certification. These instruments are based on different working principles:

a) Vibrating rods: the vibrating frequency depends on the state of the rod (yes/no information)
b) Direct infrared beam backscatter: light is reflected as soon as the sensor's surface is covered with a film of ice.
c) Infrared beam reflected on surface: the reflection characteristics change when the „mirror" is covered with ice.
d) Measurement of the weight of ice.
e) Measurements of LWC and droplet size distribution.
f) Detection of the attenuation of ultrasonic signal on ice detector structure due to ice.
g) Detection of changes in the electrical impedance on the surface of the probe.
h) Obstruction of light path.

The following table displays the available and prototype instruments, to the best knowledge of the COST-727 / WG2 participants.

Table 7: List of available and prototypes of ice detectors on the market

Item	Instrument	Manufacturer
a	Rosemount 0872J / 0871LH1	Goodrich (USA)
	Rosemount 872C2 (ASOS-USA)	Goodrich (USA)
	SYGIVRE (Icing Rate Meter (IRM))	Hydro Quebec – Transénergie (CA)
	Vibrometer (Prototype)	Boschung (CH)
b	Infralytic IR detector (Prototype)	Infralytic (D), MeteoSwiss (CH)
c	T21, T23 and T26	HoloOptics (SE)
d	ICEmeter	IAP (CZ)
	METEO device	EGU (CZ)
	IceMonitor	Combitech (SE)
	ICECylinder (Prototype)	FMI (FI)
	EAG 200	*(D) No longer manufactured*
e	Rotating Multicylinder (Prototype)	VTT (FI), STATNETT (NO)
	Gerber	Gerber Scientific Inc. (USA)
f	Labko LID-3210C	Wavin-Labko (FIN)
g	Instrumar IM101 V2.4	Instrumar Inc. (CA)
h	Jokkmokk	Segerström (SE)
i	IceMeister	www.newavionics.com

The ISO 12494 standard ice collector mentioned in the preceding chapters has been built in one version in Sweden (Combitech: automatic weighting, free rotation) and two in Finland (Digita: automatic weighing, forced rotation [28], FMI: manual weighting, forced rotation). A further development is presently being designed in Switzerland to yield ISO compatible sensors with automatic weighting and forced rotation (Markasub) within the framework of a national project linked to the COST-727 Action. Devices similar to the ISO ice collector have been used at some locations in the past as well [29].

For the detection of the meteorological icing (see definition above) M_{icing}, there are a few systems which are either available on the market (Rosemount Goodrich), or available as prototypes (HoloOptics, Infralytic, Vibrometer/Boschung, etc.)

8.2 Data requirements for icing models

Icing models can be run for sites where no specific in-situ icing data is available, but where basic meteorological information is provided by Automatic Weather Stations. The following list summarizes the parameters which must be provided in order to characterize the start/end of all types of icing events as well as the total mass of ice accreted:

- Wind
- Temperature
- Humidity
- Precipitation
- Visibility
- Cloud base
- Radiation
- Present weather (precipitation type)

Ideally, icing models require information concerning LWC and median volume diameter (MVD) of the droplet size distribution. Unfortunately, these parameters are measured only at research test centres, if at all. However, it may be possible to use small-grid weather forecast models to perform an approximation of these values (see WG1 report). Such models also include information about vertical air stability which influences the LWC and MVD.

8.3 Verification of data

Assessment and verification of existing data is scarce, unless visual observations or camera information or both are available at the station. Unfortunately, measurements of atmospheric icing are presently not included in the existing meteorological WMO standard observations. Some information may be found in the annexes related to section 6.

9 Experiences with automatic instruments for ice measurements

A number of instruments and resulting data are presented in the following and references are made to more detailed descriptions in the annexes.

9.1 ICEmeter

Manufacturer: Institute of Atmospheric Physics, Prague, CZ.

Experiences made with the automatic measurement of the mass of icing accumulated on the collector of icing sensor developed in the Institute of Atmospheric Physics, Prague, Czech Republic. First, the measuring device and its basic specifications are briefly described. Then a short description of sites where the measurements were performed is given and the selected data presented. Next the results of the measurements and experience with the sensor are discussed along with outlines for its possible improvement.

See Annex 12 for detailed explanations.

9.2 Labko ice detectors

Wavin-Labko Oy has one ice detector model LID-3210C to offer, LID (Labko Ice Detector). Ice detection of Labko ice detectors is based on longitudinal wire waves [30]. Usability of the device has been found to be good. It is also reasonably easy to get acquainted with the device and to adjust the parameters of the device to correspond with different icing climates. However, Labko's different versions have suffered from snow-induced icing indications and inability to melt all the ice. It seems to have a lower correlation with ice detections by humidity data than the Instrumar sensor [21].

See Annex 13 for detailed explanations

9.3 Rosemount/BFGoodrich, model 0872J

The Rosemount 0872J Ice Detector[9] (prototype) is designed for various applications from meteorological measurements to radio tower de-icing programs [31]. The Rosemount ice detector uses an ultrasonically axially vibrating probe to detect the presence of icing conditions. The sensing probe is a nickel alloy tube mounted in the strut at its midpoint with one inch exposed to the air-stream. As the ice detector enters an icing environment, ice collects on the sensing probe. The added mass of accreted ice causes the frequency of the sensing probe to decrease in accordance with laws of classical mechanics. Ice detector software monitors probe frequency and detect this decrease. The ice signal activates at 0.52 mm ice accretion. At the same point the internal probe heater power is applied until the frequency rises to a predetermined set point. The probe is then heated to melt the ice. Once de-iced, the sensing probe

[9] This instrument is different from the Rosemount Model 872C3 Sensor, known as a freezing rain sensor and used in the ASOS network in the USA [31].

cools within a few seconds and is ready to sense ice formation again. The ice detector outputs include ice detection indication and fault status indication.

See Annex 14 for detailed explanations

9.4 EAG 200

The ice load sensor EAG 200 is the automatic icing measurement device that is used at DWD‘s measuring sites at present (see Annex 2, Figure A.2). It measures the weight of ice accumulated on a vertical pole by the use of an electro-mechanical scale system. The comparison of EAG 200 results with those of manually operated poles show the reliability of EAG200‘s data. Experiences from continuous long term measurements show, that the system operates well even for short icing periods and for small amounts of ice accretion.

See Annex 15 for detailed explanations.

9.5 Gerber

The UK Meteorological Office sourced two instruments (Gerbers) capable of measuring the LWC of the air. Two Gerber PVM-100 instruments were installed at the EA Technology severe weather test site at Deadwater Fell test site on the English/Scottish border in the UK. The instruments are laser devices which monitor the scatter and transmission of a laser beam over a distance of around 450 mm. They are particulate volume monitors and have a 0 – 10 VDC output which give a measurement range 0.002 – 10 g/m3. One PVM-100 was mounted and aligned north/south and the other aligned east/west as shown in Annex 16.

See Annex 16 for detailed explanations.

9.6 METEO device

EGU Brno has developed an instrument for the measurement of temperature, ice mass and the velocity and direction of wind
The measuring device METEO is made of stainless steel and it has no moving parts requiring frequent maintenance. It consists of a body with sensors and of a measuring rod fixed vertically downwards.

See Annex 17 for detailed explanations.

9.7 IceMonitor

The IceMonitor is an instrument aimed for automatic weighing ice deposit on a vertical steel pipe, and it has been designed according to the recommendations in ISO 12494. The steel pipe has 30 mm diameter, it is 0.5 m long, and it can rotate freely to allow ice build-up to form cylindrically.

The instrument has been installed in two sites in Norway - the first in 2003 close to Drammen (west of Oslo) and the second in the far north (in Finmark 2005) - and in two sites in Sweden 2005. The Åre site is located in the middle of Sweden at a height of 1300 m above see level, and at this site both weather - air temperature, relative humidity and wind speed/direction -

and ice load data is measured. Measuring data from the Swedish site in Åre includes a number of heavy icing events during winter 2005-2006.

Manufacturer: SAAB Technologies, Sweden

See Annex 18 for detailed explanations.

9.8 T20-series Ice Detectors

All T20-series ice detectors are based on a patented digital optronic ice-indicator that indicates the presence of any type of atmospheric ice including clear ice. It comprises a head with an IR emitter and a photo detector and a probe.

The T20-series indicators:
• come in single-direction (±45° upwind) or omni-direction versions
• indicating either all icing types including clear ice or rime ice/wet snow growth only.

An indication of ice is made if more than 95 % of the probe is covered with a 50 µm thick layer of clear ice or a 90 µm thick layer of other types of ice. Testing of T20-series sensors have been carried out at locations noted in Annex 19.

Manufacturer: HoloOptics, Sweden

See Annex 19 for detailed explanations.

9.9 Instrumar IM101

Instrumar IM101, V.2.4 is an ice detector based on measuring the electrical impedance and surface temperature [32]. Its long-term use has shown it to be quite durable and it seems to detect icing in reasonable agreement with humidity indications and video recordings.

10 Long term recommendations for ice measurements in Europe

10.1 Regional variability

As icing conditions and icing climate vary significantly within Europe it is important to perform the measurements at different parts of Europe, noting the different climatic aspects:

- Northern European mountains with long icing periods under wide temperature and humidity range and lack of solar radiation (typically rime ice)
- Alpine regions with icing strongly depending on the altitude (typically rime ice and wet snow)
- Central and Southern European mountainous areas with icing and strong sunshine periods causing numerous melting and freezing consecutive events (typically glaze and rime ice)
- Maritime regions in Western Europe (typically wet snow)

As discussed above, meteorological instruments will respond differently depending on the location of their installation. At cold climate sites or at sites with temperatures below 0 ºC, meteorological sensors are subject to different types, durations and formation of icing. As no measurement data on atmospheric icing are available at the European Meteorological Services only a rough estimation of classification on severity of icing can be implemented at this stage. On the basis on the previous work on the classification of icing climates made mainly for wind energy purposes and the recordings made within the EUMETNET project the classification shown in § 5.6 was proposed. For example, it is typical that the duration of ice loads upon structures in class S5 is longer than duration of meteorological icing events.

10.2 Requirements for measuring sites

Consequently, a number of test centres should be established and operated in Europe (and in the world). There are however two points of view which will have to be combined in order to fulfil the requirements of the different communities.

10.2.1 Specifications of users

There are a number of potential users either for ice detectors or for icing data in different fields. Ice measuring centres will have to fulfil the requirements regarding:

- Modelling
- Electrical power lines
- Wind turbines
- Towers and masts
- Road/railway safety networks
- Cable cars and others equipments for tourism purposes
- Airport safety
- Weather forecasters: development and control procedures for models
- Climatologists: maps, long-term representativity and climate change
- Others

10.2.2 Specification of purpose

Ideally, instrumentation at all weather stations located in cold climates should be extended with icing recording systems, which is presently not the case. Therefore, the goal of establishing icing test centres is to provide an adequate infrastructure to fulfil the requirements of the above-mentioned potential users. In a general way, the following aspects will have to be dealt with:

- 3-6 test sites in Europe covering the different climatic environments (e.g. Luosto, Finland; Guetsch, Switzerland; Mt Aigoual, France; Studnice, Czech Republic; Spain; Germany; UK; etc.)
- 2-3 „reference“ instruments common to all sites: standardized testing and certification procedures and standardized data format
- Flexible infrastructures for the installation of different test beds (e.g. for wind turbine and power line testing)
- Common monitoring and quality control procedures (for future certification)
- Complete high quality data sets for forecasting and climatology

10.3 Permanent forum for monitoring icing in Europe

In relationship with the establishment of icing test centres, a permanent forum for monitoring icing in Europe needs to be established. The proposed way to achieve this goal is to establish projects on the European level.

Appropriate task specifications will be handled within Phase 2 of the present COST-727 Action in relationship with the establishment of the test centres. There are two complimentary activities which will have to be further analyzed:

- Launching of a new EUMETNET and/or EU project for the establishment of long-term icing test and observation sites in Europe
- Integration of icing measurements in meteorological networks under the umbrella of WMO/CIMO

Annex 1 Measurements in Finland

Technical Research Centre of Finland
Ice detector data of Technical Research Centre of Finland (VTT) is presented in Table A. 1. Data consists of status parameter, which tells whether ice was accumulating or not. Data was collected at 1Hz. Ten-minute averages, min, max and standard deviations were calculated and stored. Amplitude levels of wire wave signals (see §6) have also been recorded because all the performed icing measurements have been closely connected to development of the used ice detectors. The development of ice detectors has been driven by the need for development of blade heating systems for wind turbines.

Table A. 1 Ice detector data of Technical Research Centre of Finland.

Site	LAT	LON	Ice detector	Start	End	Parameters
Olostunturi	67.55	23.48	Labko Ice detector 3200	12/1999	-	Status (icing/no icing)
Pori	61.37	21.30	Labko Ice detector 3500	9/1999	-	Status (icing/no icing)
Lammasoaivi	68.47	21.20	Labko Ice detector 3500	2/1999	10/1999	Status (icing/no icing)
Pyhätunturi	67.01	27.13	Labko Ice detector 3500	11/1998	7/2000	Status (icing/no icing)
Ylläs	67.4	24.15	Instrumar IM101	10/1991	-	Status (icing rate)

VTT has within the COST 727 Action also studied humidity measurements in icing conditions. These studies [33] showed that

- The conventional humidity instruments measure incorrectly in icing conditions
- A heated Vaisala HMP243 (and HMT337) measures correctly in icing conditions
- It seems to be possible to detect rime icing by correct humidity measurements

FMI test station: Luosto
The Luosto test station is located in northern Finland, on the top of Luosto fell (500 m asl, N 67 08', E 26 54'). The station is operated by Finnish Meteorological Institute (FMI). The test station was established for the EUMETNET SWSII project, which studied the effect of icing on meteorological instruments and produced specifications for ice-free sensors. The platform for the instruments at Luosto was set up in the winter 2000/01. Since then icing measurements and meteorological measurements with ice-free sensors have been made at the site. Experience from the first winter was used to develop the measurement systems and the infrastructure. Performance of the instruments is monitored continuously with video cameras.

The icing climate of the site has been characterized as site class A (see §5): an elevated site inland in northern Europe with harsh and frequent icing climate.

The Labko LID-3503 and the Rosemount 0872J were installed at the site in the winter 2001/02. Both ice detectors indicate the presence of icing conditions. According to the measurements performed with the LID-3503 ice detector in winter 2001/2002, it was noted that the sensor is inadequate for icing measurements in extreme conditions. Measurements with this sensor were not continued.

Four video cameras are monitoring operation of the instruments. The cameras also give information on visibility (fog and clouds). Digital pictures are sent every 10 minutes to the FMI via the network.

The Vaisala's FD12P weather sensor is used for visibility observations. The FD12P measures meteorological optical range (MOR) from 10 m to 50 km.

Also temperature, dew point temperature and relative humidity measurements are analysed to get more accurate data on events and duration of icing.

The ICEcylinder has been built by FMI according to the International Standard ISO 12494. The cylinder with a diameter of 30 mm and length of 0.5 m is installed with the axis vertical and forced rotating around the axis. Accumulated ice load is weigh manually.

A device used for icing rate measurements is manufactured by Institute of Atmospheric Physics, Academy of Science of the Czech Republic. The ICEMETER measures the mass of ice accumulated on the sensor surface.

Table A. 2 List of instruments installed for icing measurements at the Luosto fell. Technical availability: the sensors are in operation and data (erroneous or correct) are received by the data acquisition system.

Instrument	Technical data availability	Parameter
LID-3503 ice detector	01.10.01-30.4.02	Icing occurrence
Rosemount 0872J ice detector	01.10.01 ->	Icing occurrence
ICEMETER CZ - IAP	09.03.06 ->	Icing rate
ICEcylinder	01.10.01 ->	Icing rate
2-4 video cameras	01.10.01 ->	Icing occurrence
FD12P weather sensor	01.10.01 ->	Visibility and rain

Figure A. 1 The test platform at Luosto with installed severe weather sensors.

DIGITA / VTT CAMPAIGN

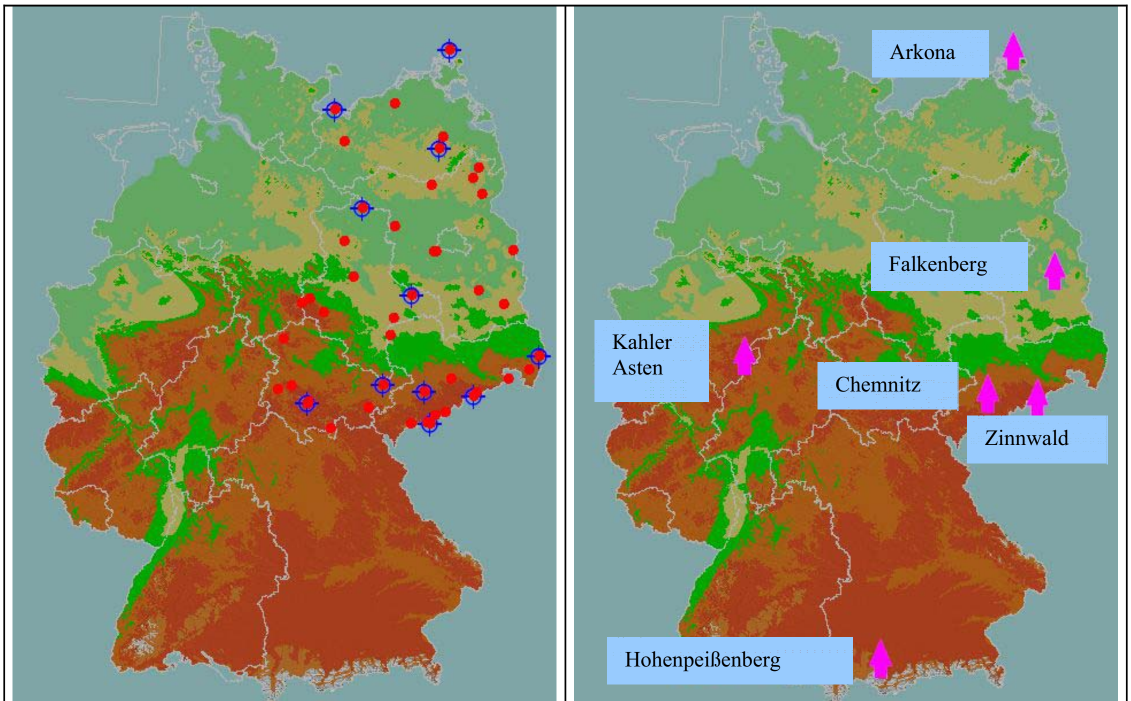
Digita Oy (former Finnish Broadcasting Co., Distribution Dept.) and Technical Research Centre of Finland (VTT) made measurements of icing on tower structures, tests on ice detectors, measurements of drop size and liquid water content of clouds and comparisons of meteorological instruments on hilltops in severe icing conditions in Finland in a four year national project in 1986-1990 and later. In this project both an operating 128 m tall TV tower and a 7.5 m test tower were equipped with load cells, so that the ice load on them could be continuously measured. The rotating multi-cylinder method was developed to a stage that would allow further development to automatic measurements of drop size and liquid water content during icing. The results of these activities have been reported in a number of publications [19,20,34,18,35,21,33].

Annex 2 Measurements in Germany

German Meteorological Service (DWD)

Icing measurements were carried out at altogether 40 locations in the eastern part of Germany during 1965-1990 [36,37], see red points in the left part of Figure A. 2). The number of locations has changed slightly during the years. However, up to 35 locations were operated simultaneously.

The measurements were performed at all locations by the use of manually operated vertical icing poles with a diameter of 35 mm. A standard measurement procedure defined an exposition period of 24 hours: The pole was exposed every day at 8:30 a.m. at a height of 2 m a.g.l.. In the case of ice accumulation the pole was exchanged after 24 hours. The icing mass was determined and additional information (e.g. icing diameter and direction, ice vane dimension, icing type(s)) was compiled. By using the standard measurement procedure the ice accretion was interrupted at least every 24 hours. For ice accretion periods exceeding 24 hours or on occasions of multiple icing events the standard procedure underestimated the maximum ice masses.



Time Period: 1965-1990, Red points: 24-hour measurements, Blue circles: Icing cycle measurements.	Time Period: 1990 (partly) - Present, Continuous icing measurements at all locations.

Figure A. 2 Locations of Icing Measurements in Germany, depicted in topographic maps for different time periods and resolutions of measurements.

Therefore the measurement procedure was modified at 11 locations in 1978 (blue circles in the left part of Figure A. 2) so that a second icing pole was exposed at those locations. In the event of ice accumulation all the measurements of the standard procedure (ice mass, additional information) were carried out after 24 hours. Afterwards the pole was re-exposed for another 24 hour period. By the application of this procedure it was possible to improve the knowledge about whole icing cycles (accumulation and loss of ice), so they were called icing cycle measurements. One of the main results of icing cycle measurements was ‘real’ (in distinction to the standard procedure) maximum ice mass.

The number of locations with icing measurements has been reduced to a total of five since 1991. The icing sensors are implemented at 5 locations (for details see the right part of Figure A. 2 and Table A. 3. They are operated continuously at a single height level. Furthermore, at 3 locations the icing measurements are still carried out by the use of manually operated icing poles. The latest advancement during the ongoing winter period are icing measurements at three heights (10 m, 50 m and 90 m above ground) at DWD’s Meteorological Observatory Lindenberg.

Table A. 3 Overview of present locations with icing measurements in Germany

Location	Height above sea level (m)	Measurement height (m)	Measurement device
Arkona	42	2, 5	EAG 200 (Annex 15), continuous, accumulation and Icing pole, intermittent, manual
Chemnitz	418	2, 5	
Zinnwald	877	2, 5	
Kahler Asten	839	10	EAG 200 (Annex 15), continuous, accumulation
Hohenpeißenberg	977	10	
Lindenberg	73	5, 50, 90	

Annex 3 Measurements in Slovak Republic

Extensive experimental data from the measurements of atmospheric icing can be obtained from the Slovak Hydrometeorological Institute (SHMI). This Institute is an administrator of the meteorological networks in Slovak territory. There are both visual observations and measurements of the amount of atmospheric icing. Visual observations of atmospheric icing enable an analysis of the lengths and annual occurrences of atmospheric icing events to be made in individual seasons. There are a large number of regular weather stations where atmospheric icing *observations* are carried out. Measurements are performed on a horizontal pair of orthogonal (N-S and E-W) wooden rods. The diameter of the rods is 32 mm and length is 1 m. Data are acquired 3 times a day at 7, 14, 21 hrs. The sites where the atmospheric icing *measurements* are made are fewer and are given in Table A. 4. [38]

Table A. 4 List of sites in the Slovak territory, where the parameters atmospheric icing are measured.

Location	Latitude	Longitude	Altitude	Recording	Since
Bratislava-Koliba	48° 10’ N	17° 06’ E	289 m asl	Climat. term	Dec. 1974
Hurbanovo	47° 52’ N	18° 12’ E	115 m asl	Climat. term	Dec. 1971
Chopok	48° 56’ N	19° 35’ E	2004 m asl	Climat. term	Jan. 1957
Jaslovské Bohunice	48° 30’ N	17° 50’ E	177 m asl	Climat. term	Dec. 1971
Kamenica nad Cirochou	48° 56’ N	22° 00’ E	178 m asl	Climat. term	Jan. 1972
Košice	48° 42’ N	21° 16’ E	206 m asl	Climat. term	Dec. 1972
Lomnický štít	49° 12’ N	20° 13’ E	2634 m asl	Climat. term	Jan. 1957
Lučenec	48° 20’ N	19° 40’ E	187 m asl	Climat. term	Dec. 1971
Nitra	48° 19’ N	18° 05’ E	145 m asl	Climat. term	Jan. 1973
Poprad	49° 04’ N	20° 15’ E	703 m asl	Climat. term	Jan. 1973
Sliač	48° 38’ N	19° 09’ E	312 m asl	Climat. term	Dec. 1976
Stropkov	49° 12’ N	21° 39’ E	209 m asl	Climat. term	Dec. 1971
Telgárt	48° 51’ N	20° 11’ E	901 m asl	Climat. term	Jan. 1972

Annex 4 Measurements in Norway

Icing on overhead lines varies strongly with height above sea level, exposure to air of maritime origin and local topography [39]. Therefore lines of 100 – 200 km length have a variety of local exposures in mountainous terrains. In Norway 100% of the electricity production is from hydropower. As the bulk production is on the western coast of the country, where the precipitation rates are highest, and the main consumption is in the south-eastern region around Oslo, there are many high voltage lines crossing the mountains and thereby also exposed to severe ice loads, as indicated in Figure A. 3 and Figure A. 4.

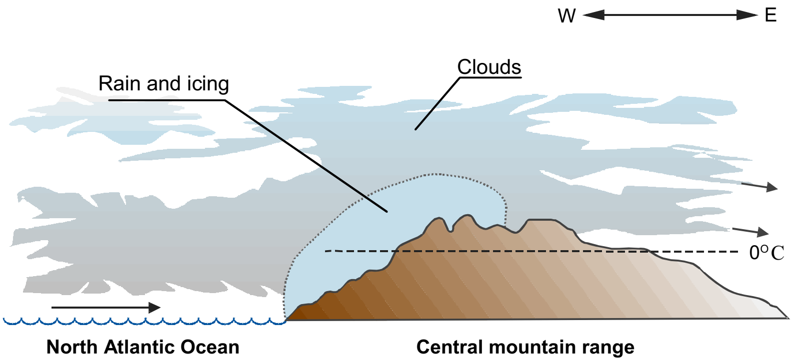


Figure A. 3 A cross section of southern Norway

Figure A. 4 420 kV line crossing the mountain divide (1 100 m asl) between western and eastern Norway (Photo: S.M. Fikke)

Probably the world's largest ice load on an electric power line was observed in Norway in 1961. Figure A. 5 shows an example of the accretion that measured 1,4 m x 0,95 m and weighed 305 kg/m. This is probably the clearest example on how topography and exposure influence the icing conditions on a power line. This line was feeding a radio and TV transmitter 1 412 m above sea level. It appeared to be impossible to maintain this line no matter how short the spans would be, how strong the (wood) poles were made and how strong the steel conductors were. It was built on the top of a mountain ridge more or less parallel to the coast, and therefore maximum exposed to the humid south-westerly winds from the Atlantic Ocean. Only when a new line was built up from the leeward side of the mountains the power supply to this radio and TV transmitter became stable.

Figure A. 5 In-cloud icing on a 22 kV line feeding a TV tower 1 400 m above sea level in south-western Norway. (Photo: O. Wist)

The topography influences the icing differently depending icing type. Freezing rain occurs mainly in basins and depressions where cold air can be trapped while warm air with precipitation may intrude the air aloft (temperature inversion). In-could icing occur only above cloud base, but the cloud base varies significantly with topography. A mountain (ridge) only 50 – 100 m higher in the upwind direction may be sufficient to reduce this icing to a minimum. Wet snow however may occur in all altitudes and also on the leeward side of mountains and ridges.

The great dependence on topography may result in a likewise great variety of expected ice loads along a line passing through zones with different exposure and climatic conditions from one sub-station to another. As a result of this variability all transmission lines belonging to the main grid of Norway are designed span by span according to the expected ice and wind loads for the particular span. For lower voltage lines in the distribution system the loads are given regionally according to the National code.

Since the late 1970s the Norwegian Power Grid Company, Statnett, has operated more than 20 ice racks of the type shown in Figure A. 6 and Figure A. 7 in remote and exposed locations in mountainous terrain in Norway. Figure A. 8 shows the distribution of the locations of the measuring stations and Figure A. 9 shows an example on extreme value calculations.

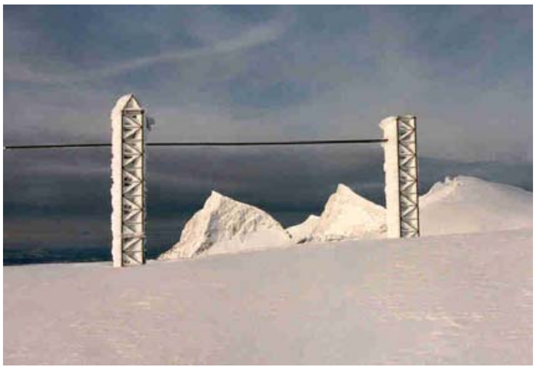
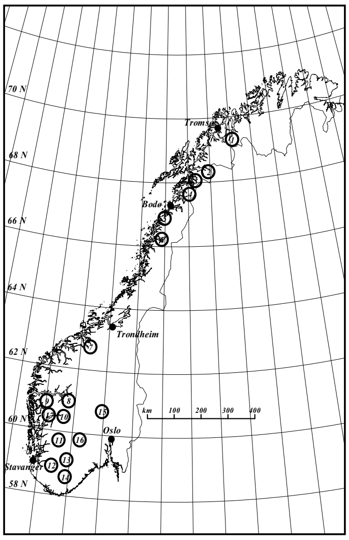


Figure A. 6 Norwegian rack for measuring ice loadings in remote areas

Figure A. 7 Details of dynamometer suspension in the rack



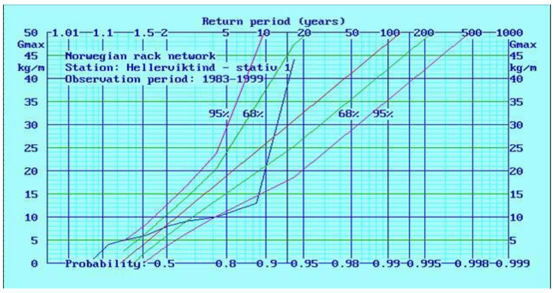


Figure A. 8 Location of the 16 ice measuring sites in Norway

Figure A. 9 Example of extreme value calculations of ice loadings from the ice racks

Annex 5 Measurements in the Czech Republic

EGU Brno carries out measuring of icing on racks at test site Studnice thus continuing the long time-series of icing data [40]. It is located about 60 km northwest from Brno at 800 m above see level. The whole site was built in the late 70's and has been in operation since 1980. There are 2 spans (ca 250 m each).

Table A. 5 Location of racks at Studnice

Location	Latitude	Longitude	Altitude
Studnice	49°36'27" N	16°05'7" E	800 m asl

Figure A. 10 Test site at Studnice (Photo: J. Sabata)

Various measurements are performed here:

- Ice measurement on conductors and measuring rods of various diameters
- The measurements on samples of stranded isolated conductors

- Observation of icing with respect to altitude gradient.

For measurement of ice accumulation we use different instruments with horizontally and vertically oriented rods (with diameter of 30 mm).

Table A. 6 Location of measurement devices on racks at Studnice

Measuring device	Measurement height (m)	Output	Since
Vertical rods (length of 0.5 m)	5, 10, 20, 30, 40, 50	Digital	1997
Horizontal rods (length of 1 m)	10, 30	Digital	1997
Temperature	5, 10, 20, 30, 40, 50	Digital	1997
Meteo device (length of 0.5 m)	10	Digital	2001

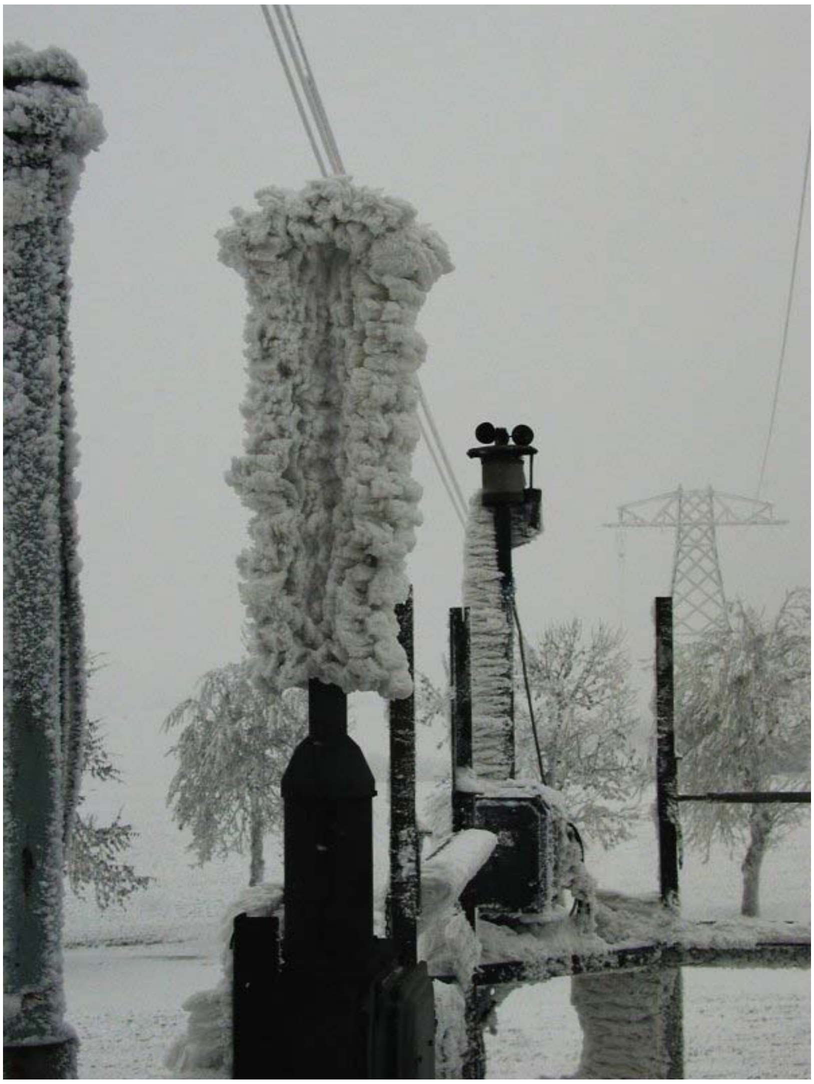


Figure A. 11 Vertical, freely rotating rod with sensor, at test site Studnice, 17.12.2004 (Photo: J.Sabata)

In addition to measurement at Studnice station fourteen Meteo devices are installed at locations supplied by two regional utilities. Two devices are located in the area of the regional utility VCE and the others in the area of regional utility JME. The Meteo device locations on the territory of JME cover the whole area susceptible to regular icing.

Table A. 7 Location of Meteo devices

Location	Latitude	Longitude	Altitude	Output	Parameters*	Since
Cotkytle				Digital	IM, T, WS, WD	1999
Novy Hradek				Digital	IM, T, WS, WD	2003
Beranov	49˚24' N	15˚39' E	554 m asl	Digital	IM, T, WS, WD	2001
Buchlov	49˚06' N	17˚18' E	477 m asl	Digital	IM, T, WS, WD	2001
Hlína	49˚06' N	16˚25' E	441 m asl	Digital	IM, T, WS, WD	2001
Kasarna	48˚53' N	16˚00' E	379 m asl	Digital	IM, T, WS, WD	2001
Klucov	49˚10' N	15˚55' E	570 m asl	Digital	IM, T, WS, WD	2001
Kralovec	49˚08' N	18˚02' E	634 m asl	Digital	IM, T, WS, WD	2001
Nyklovice	49˚36' N	16˚20' E	722 m asl	Digital	IM, T, WS, WD	2001
Kralovec	49˚08' N	18˚02' E	634 m asl	Digital	IM, T, WS, WD	2001
Protivanov	49˚28' N	16˚50' E	685 m asl	Digital	IM, T, WS, WD	2001
Predin	49˚12' N	15˚40' E	640 m asl	Digital	IM, T, WS, WD	2001
Ruda	49˚19' N	16˚07' E	580 m asl	Digital	IM, T, WS, WD	2001
Vyskovec	48˚56' N	17˚49' E	761 m asl	Digital	IM, T, WS, WD	2001

*) Measured values: IM (Ice mass), T (temperature), WS (wind speed), WD (wind direction).

Icemeter sites (for results see section 6)

Milesovka: Most of the measurements were carried out at the top of "Milešovka" mountain, which is the highest peak of the tertiary volcanic range of "České Středohoří". A synoptic meteorological station, now belonging to our Institute, was built on Milesovka's summit (837m asl). Milesovka has a shape of isolated forested cone, which exceeds the surrounding terrain by approximately 300 m. The steepness of slopes ranges from 20° to 30°. Concerning temperature, the long time average is 5.1 °C, absolute minimum was -28.3 °C and absolute maximum reached 34.7 °C. The average of annual precipitation is 564 mm. The mean wind speed is 7.7 m/s with most frequent winds from northwest, west and southwest. From the winter 2003/2004 two Icemeters, situated at different height above the ground (see Figure A. 12), have been operated.

Nová Ves: Since 2005, one Icemeter has been situated close to the wind turbine in Krušné hory (Ore mountains), near to the village of Nová Ves. Krušné hory is the region most suitable for wind energy production in the Czech Republic. Unfortunately that region is also affected by severe icing. It is probably most exposed region in the whole country, concerning the severe ice episodes.

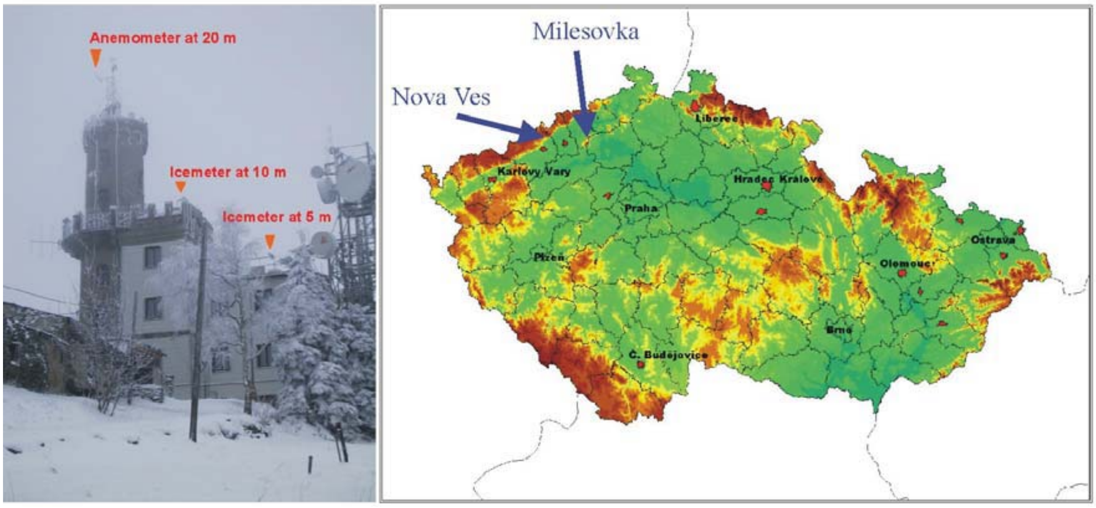


Figure A. 12 left – Observatory at the Milesovka peak with marked position of Icemeters; right – location of Milesovka mountain and Nova Ves in the Czech Republic

Other sites:
Two Icemeters have been in operation in Austria (Obersthralbach, Sternstein), both of them situated close to wind power station. One piece was tested in Luosto, Finland during the winter 2004/2005. The Icemeter was also located temporarily in other sites in the Czech Republic. Due to the short time of location at these sites, results are not available.

Annex 6 Measurements in UK

Deadwater Fell

Deadwater Fell is one of EA Technology's field stations at sites located to encompass a full range of weather conditions: wet and dry snow, hard and soft rime ice and glaze icing (freezing rain). The sites are situated in exposed locations at heights between 550m and 750m and range from hilltop to open moorland. Overhead line conductors are erected in test spans of between 90m and 200m. The data presented here comes from this and two other sites located on Susseter Hill in Shetland (an island off the north coast of Scotland) and south west Scotland (Green Lowther). These two sites have since been closed down and all work is now concentrated on the Deadwater Fell site on the English/Scottish border.

The site consists of a 200m test span with terminal H-poles supported by 14 stay wires each. The test spans are orientated North-South and suffer from severe winds as well as ice incidents and blizzards. Figure A. 13 shows the full 200 m span viewed from below the summit ridge and Figure A. 14 shows the rotating rig. Provision is made for shorter span lengths when appropriate. The site has the capacity to provide full meteorological measurements on-site. Load cells are used to measure loads on the conductors.

Figure A. 13 The full 200m span at Deadwater Fell

All the data is collected and stored at the site. It is downloaded automatically every 24 hours via a mobile telephone, for analysis at EA Technology at Capenhurst, near Chester, UK. Provision can be made for close up video coverage to identify ice shape. Conductors of different sizes and of different span lengths can also be installed to provide direct measurement of the total force on the conductors at their connection point to the supports. This force is made up of:

a) Conductor weight
b) Ice load
c) Wind-on-ice load.

Item a) is known and items b) and c) are measured together. This system can be used to evaluate the ice load by calculation of the wind load. The latter can be calibrated in above 0°C incidents with no ice present. However, the main concern with overhead lines is the total wind and ice load, so from a practical point of view it may not be necessary to separate these components. The site also has a rotating rig to test conductor samples (Figure A.14). This rig is designed so that the samples are always facing normal to the prevailing wind.

Test Spans

The H-poles are designed to withstand impulsive forces from the galloping of large conductors and at the same time, to withstand blizzard conditions. Intermediate poles are installed as required for shorter spans. In the test spans, each conductor is fitted with a load cell and, if required, a vibration monitor. Video surveillance can detect any galloping, rotation or general conductor movement under wind and ice loads. The spans are monitored 24 hours a day throughout the year by time lapse video cameras with low light level sensitivities down to 0.1 lux. The surveillance also allows short periods of real time coverage every 30 minutes. The cameras are mounted within specially adapted housings with insulation, internal heating and externally wound heating tape to reduce ice growth and are used to give close-up and long distance views using, if required, barely visible, environmentally friendly infra red floodlighting.

Figure A. 14 The rotating rig with snow accretion.

Conductor Data

Ice densities
Data from the test spans at Deadwater Fell was investigated for direct comparison of two bare conductors at a span length of 200 m. A series of load comparisons between Upas (diameter 24.7 mm) and Lynx (19.5 mm) conductors was extracted at various ice loads, but at wind speeds around 20 knots. The load cells will, of course, measure the total wind and ice load. The measured ice loads measured were between 1.6 and 8.8 kg/m. Ice load density was measured on occasions when the normally un-manned site was visited. The accretion density for rime ice gave an average value of 570 kg/m³ and for wet snow 825 kg/m³. This is in line with field data published for Iceland [41].

Ice loads
Shackleton et al [42], under an EATL contract, calculated the rime ice and wet snow loads for a range of conductors. The **initial** wet snow accretion rate (Model 1) is:

$$\text{Mass} = [\, A + B.D + C.D^2 \,] \,.\, 10^{-3} \quad \text{kg/m}$$

where $A = 0.449$
$B = 1.794$
$C = -0.0003$
and D = Conductor Diameter (mm)

The **longer time** version is called the Large Relaxation Time (LRT) Model, which gives ice loads according to:

Mass = $[0.243 + 1.792.D + 0.0034.D^2] . 10^{-3}$ kg/m

The factors A, B and C vary with time with A reducing and C increasing.

The EATL field data is given in Figure A.15 with a trend line polynomial in which:

where A = 0.013
B = 0.097
C = 0.1409

The formulae imply that over time the conductor diameter has an increasing effect on the modeled snow load.

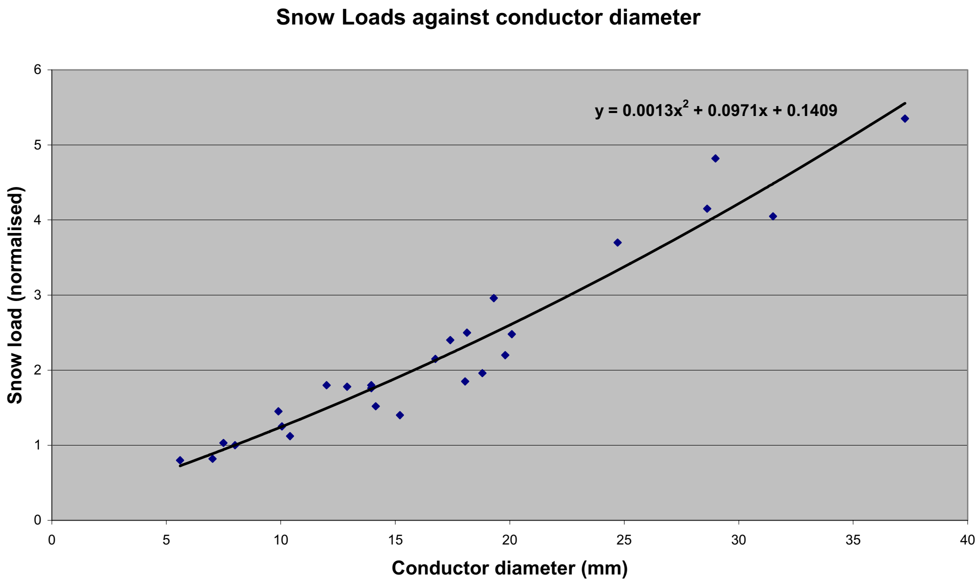


Figure A. 15 Field data with polynomial trend line

Sufficient information has been extracted from the database to give comparative values for 28 conductors. In order to eliminate the different field conditions, all the data is related back to the original 'control' conductor, 32 mm² Hard Drawn Copper (8.0mm diameter). This was used as the 'control' at the Green Lowther and Shetland sites. At Deadwater, the control conductor was changed to the Hazel conductor (9.9mm diameter), which is a bare AAAC 60 mm² conductor. Hazel was used extensively at Green Lowther to establish a relationship between this and the 32 mm² Copper conductor and so maintain the validity of the data from each site.

It can be seen in Figure A. 16 that assuming a constant accretion thickness for any conductor size (as used in current UK wind/ice maps in ET111) gives a reasonable fit for conductors up to Oak (14 mm diameter AAAC). For larger conductors up to 40 mm in diameter, the constant thickness assumption underestimates loads as compared with the EATL field data.

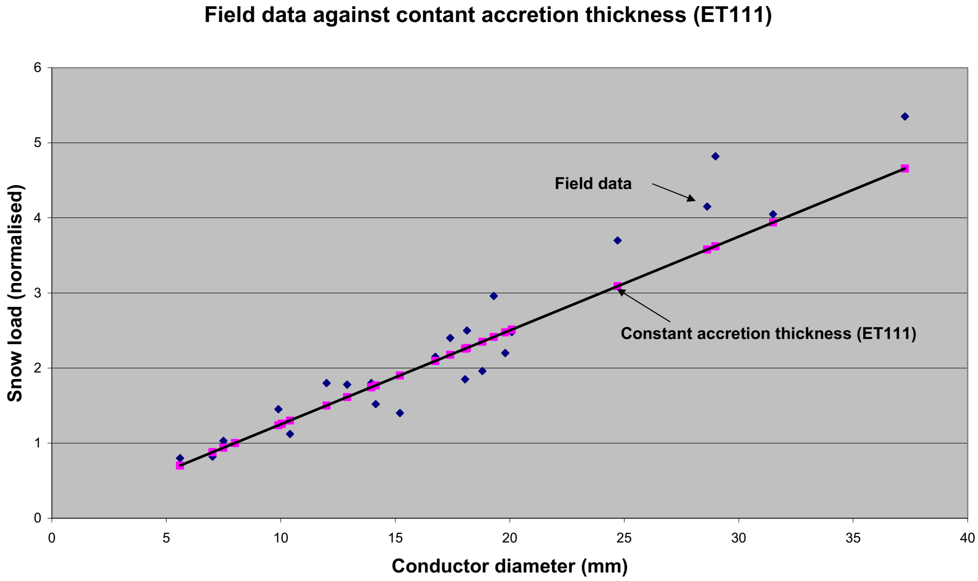


Figure A. 16 Snow load field data plotted against constant accretion thickness scenario for the same conductors.

Figure A. 17 Typical accreted ice loads on different conductors after a blizzard at Deadwater Fell

Annex 7 Measurements in Sweden

Three different sensors (IceMonitor, HoloOptics and Jokkmokk) are currently being tested under field conditions in Sweden and Norway.

The **IceMonitor** sensor is presently connected to monitoring stations located in

- Åre (SE)
- Ritsem (SE)
- Drammen (NO)

At these stations measurements of weather parameters, such as air temperature, relative humidity, wind speed and direction, and in some cases also precipitation, are being carried out. Measurements are normally made once every half hour (in Drammen once every 10 minutes). Data is retrieved to a server in Östersund via radio/radiolink or in some case via telephone modem.

A camera is monitoring the IceMonitor sensor at the site in Åre. Icing of this camera has been a problem during the winter 2005/2006 – and the installation and de-icing of the camera will be modified before the next icing season. The monitoring equipment was originally designed for use in road weather information systems and it is capable of handling a number of different sensors, including camera – which stores files in jpg format.

At the site in Åre, several icing events occurred during the winter 2005 /2006. A couple of the icing events have been severe with ice loads of more than 40 kg. (see figure below.) During the same period, no significant icing occurred at the site in Ritsem (Sweden) or at the test site in Drammen (Norway).

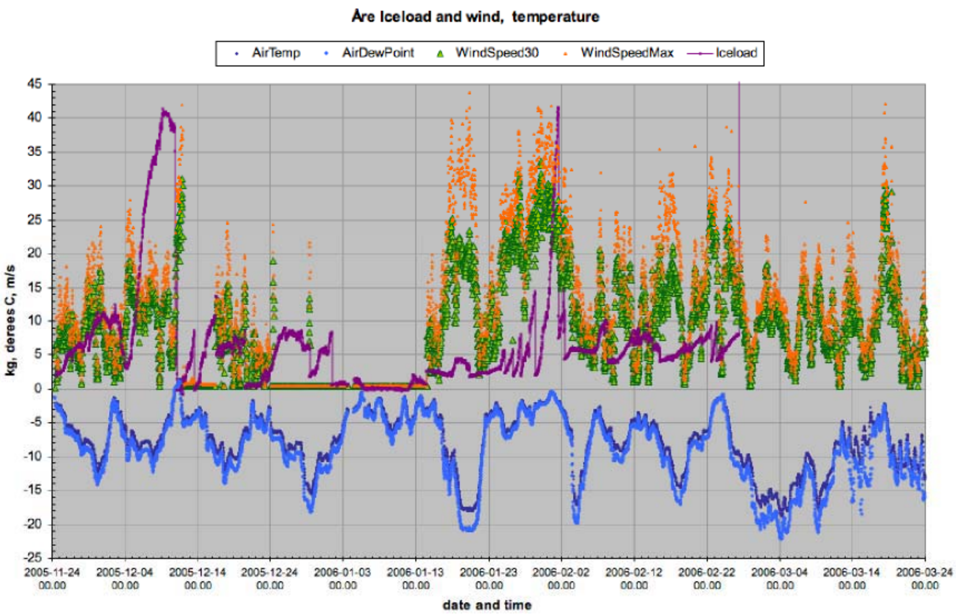


Figure A. 18 Icing measured at Åre during winter of 2005/2006 (Ice load signal error occurred by end of Feb.

The **HoloOptics** T23 Clear-Ice Indicator and the T26 Icing-Rate Sensor beta versions have in periods been tested at the following locations during 2003-2006:

- The Suorva wind power plant, Sweden. 150 km north of the polar circle. In co-operation with FOI (The Swedish Defence Research Agency), see figure A.19.
- KTH (The Royal Institute of Technology), Stockholm, Sweden
- Bromma Airport, Stockholm, Sweden. In co-operation with the airport authorities
- Åre Ski Resort, ski lift protection. Cooperation with Combitech

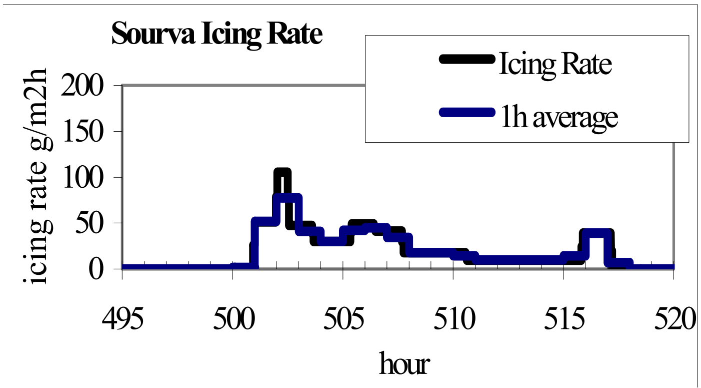


Figure A. 19 Icing rate measured at Suorva, Northern Sweden

Annex 8 Measurements in Bulgaria

The initial icing observations in Bulgaria were started in the late 50-s and in the beginning of the 60-s of the 20th century in some stations of the meteorological institute. The stations were chosen to cover the territory of the whole country. The ice measurement device was a couple of perpendicular conductors with diameter of 5mm located in the directions N-S and E-W. Data about the meteorological conditions during icing events and the final ice depositions have been collected. A list of all stations with initiated icing observations is presented in the table below.

The collected icing data in some of the stations are very short and/or not reliable due to the bad organization of observations, non motivated work as well simply to the fact that icing had been observed rarely in these regions for the whole period of measurements. However, other stations have collected long time series of icing events or short but very detailed measurements. These stations are highlighted with yellow in the table bellow (some of them still report icing data). They represent the regions where icing occurs most often and usually is very severe.

We have also additional information from the National Electric Company with data about icing depositions in cases of damages of the power lines in the period 1962 –1990. All these data have been used to characterize the typical icing conditions of the territory of the country. As example of these conditions the change of the number of icing events in the mountain regions of Bulgaria is depicted on the figure.

Our intention now is to continue with icing measurements on the places with good historical data using further visual observations as well as some ISO12494 icing sensors (rotated and non rotated).

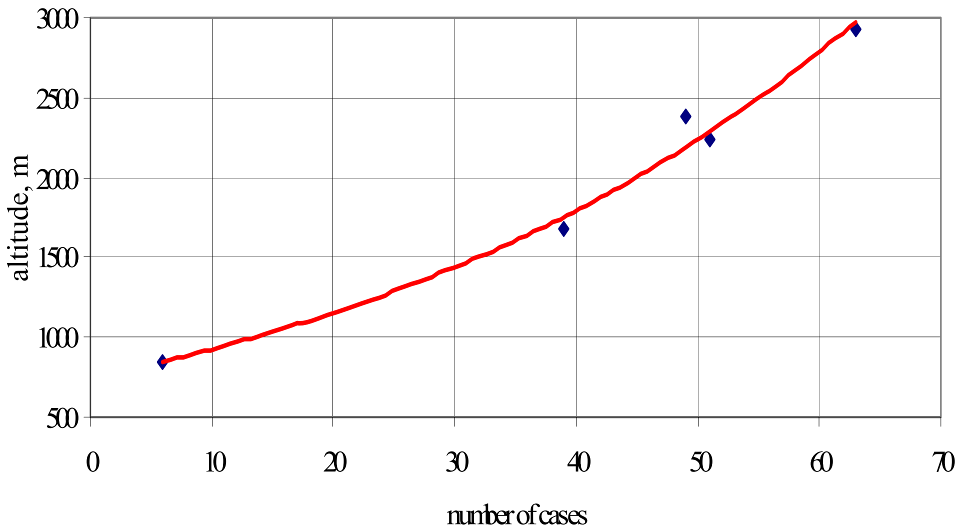


Figure A. 20. The change of the mean number of cases with the altitude in the mountain regions

Table A. 8: Meteorological stations with icing observation

Station	Altitude, m	Latitude	Longitude	Part of country, mountain	Start/End of icing observation	Data quality
Kozloduy	34	43.47	23.44	NW	1969-1970	not good
Vidin	31	43.59	22.51	NW	1992-1993	relatively good
Orjahovo	29	43.43	23.58	NW	1955-1964	relatively good
Gramada	257	43.50	22.40	NW, Stara planina	1955-1986	very good
Petrohan	1400	43.25	23.14	NW, Stara planina	1968-1983	good
Peak Murgash	1678	42.50	23.40	NW, Stara planina	1980-1994	very good
Vakerel	851	42.55	23.17	W, Lozenska planina	1959-1989	very good
BAC station, Vitosha	1485	42.41	23.10	W, Vitosha	1968-1974	not good
Borovec	1244	42.15	23.36	SW, Rila	1960-1975	relatively good
Smoljan	1180	41.34	24.12	SW, The Rhodopes	1968-1978	relatively good
Pamporovo	1599	41.39	24.41	SW, The Rhodopes	1976	not good
peak Snejanka	1925	41.40	24.41	SW, The Rhodopes	1974-1999	very good
peak Rozen	1750	41.53	24.44	SW, The Rhodopes	1999-2006	
Elhovo	136	42.11	26.35	SE	1959-1969	not good
Krumovgrad	235	41.28	25.39	S	1956-1975	relatively good
peak Botev	2376	42.43	24.55	Central Stara planina	1966-1994	very good
Chirpan	178	42.18	25.17	Central Bulgaria	1971	not good
Ljuljakovo	217	42.53	27.05	E	1957-1974	not good
Kaliakra	63	43.21	28.27	NE	1969-2006	very good
Gen. Toshevo	236	43.39	28.01	NE	1956-1986	very good
Dobrich	200	43.35	27.50	NE	1987-2006	very good

Razgrad	346	43.33	26.30	NE	1978-2006	very good
Gara Samuil	474	43.30	26.44	NE	1955-1979	very good

Annex 9 Measurements in Hungary

Visual observations of atmospheric icing enable from 1970 till nowadays. The measuring instrument system was established by the Hungarian meteorologist Mihaly Csomor. Icing measurements were carried out by Hungarian Meteorological Service (HMS) and Hungarian Defence Forces (HDF). The number of stations were 34 (1970-1992), but now we have only 16 (2005). The sites with the atmospheric icing measurements are given in Table A. 9. For measurement of ice accumulation we use horizontally oriented wires (diameter 31 mm).

Table A. 9 Record of the sites in Hungary, where the parameters of atmospheric icing are measured

Location	Latitude	Longitude	Altitude	Monitoring	Output
Bekescsaba	46.41	17.09	156	HMS	Manual
Budapest/Lorinc	47.26	19.11	138	HMS	Manual
Debrecen	47.29	21.36	108	HMS	Manual
Eger	47.54	20.23	220	HMS	Manual
Gyor	47.43	17.41	116	HMS	Manual
Kecskemet	46.54	19.44	113	HDF	Manual
Kekesteto	47.52	20.01	1010	HMS	Manual
Miskolc	48.05	20.46	233	HMS	Manual
Mosonmagyarovar	47.53	17.16	121	HMS	Manual
Nagykanizsa	46.27	16.58	139	HMS	Manual
Paks	46.37	18.5	97	HMS	Manual
Papa	47.21	17.29	146	HDF	Manual
Pecs	46	18.13	202	HMS	Manual
Siofok	46.55	18.02	108	HMS	Manual
Szeged	46.15	20.06	82	HMS	Manual
Szolnok	47.07	20.12	89	HDF	Manual

The observers determine the types of accretion (soft rime, hard rime, icy-hard rime, freezing rain, frozen dew, wet snow) and the duration. In addition the observers measure the thickness and water content of ice from the last 24 hours, and also the accumulated ice thickness at 06 UTC every day.

Figure A. 21 Hungarian instrument for manual icing measurement on samples of bare conductors.

Annex 10 RUSSIA

During the Soviet era, icing observations were included as part of routine meteorological observations beginning 1931 [43,44]. By 1970's the number of weather stations in the European part of the USSR that made regular manual icing observations was 220 [45]. In 1984 measurement based estimates of the design ice loads were reported to have been made for 700 weather stations in the USSR [46]. The current situation in Russia is unknown.

The ice collector device used in the Russian measurement network is a stand consisting of two rigidly clamped horizontal wires with a diameter of 5 mm. The wires are oriented at South to North and West to East and are at 2 m height from the ground. The measurement is done manually by weighing on a daily basis.

The main application of the Russian data has been in mapping the design ice loads on power lines. Because of that, considerable attention was paid in the USSR to determine the relationship between the ice load measured on the ice collector device and that on a real overhead power line conductor [47]. To that end, special measurement campaigns have been run at selected sites using wires with different diameter, torsional rigidity and height above terrain [48, 49]. Based on these studies, a measurement stand better suitable for the purpose of power line icing has also been developed and tested at many mountainous sites [50]. This device includes wires of both 5 mm and 10 mm diameter which are free to rotate around their axes. Another proposed ice collector includes a vane which adjusts the wires so that they are perpendicular to the wind direction [51].

Annex 11 CANADA AND USA

Hydro Québec has run a measurement network for glaze ice caused by freezing rain in the St. Lawrence Valley since 1974 [52, 53, 54]. Initially there were 35 observation sites and later observations have been made at 180 sites altogether. The present observation network includes 150 stations and has a grid dimension of about 50 km.

The ice collector used in the Hydro Québec observation network is the Passive Ice Meter (PIM). It includes four vertical flat faces, a 25 cm x 25 cm horizontal surface and two groups of horizontally oriented fixed cylinders with diameters of 1 and 2.5 cm [52]. The observations are made manually twice a day or, at synoptic weather stations, every three hours during freezing precipitation.

Other Canadian power utilities, e.g. Ontario Hydro, Newfoundland and Labrador Hydro and B.C. Hydro have also made icing tests, but only at some sites. Mount Washington Laboratory in USA continuously observes icing and was the first to make rotating multicylinder measurements.

The automatic weather observing system AWOS/ASOS (www.weather.gov/asos) covers almost 1000 sites in North America. The sites are mostly airports and the data are aimed at operational use. The AWOS/ASOS sites include an automated detection of freezing precipitation by the Rosemount 872/C3 ice detector (*Figure A. 22*). At these sites this is called “Freezing rain sensor”. The system reports on freezing precipitation based on an algorithm which takes into account the change in the resonant frequency of the Rosemount probe, the measured ambient temperature and precipitation.

Figure A. 22 The Rosemount freezing rain sensor mounted at an AWOS site

Annex 12 Icemeter (Czech Republic)

Description of the instrument

The icing sensor (or "Icemeter") developed in our Institute of Atmospheric Physics, Prague, Czech Republic measures the mass of icing accumulated on the surface of its collector. The first prototype was described in [55], together with a short review of previous methods of ice measurements that were applied in the Czech Republic. Primarily, it was considered for the investigation of the most favourable meteorological conditions for in cloud icing growth and the investigation of accumulation of in-cloud icing and its chemical analysis. The cylinder is orientated vertically in order to eliminate the detection of wet snow as much as possible. Nevertheless, the "Icemeter" can find its application also in the monitoring system of power lines, wind power station, and traffic roads; the vertical orientation of the collector can be changed to a horizontal one, if required.

The mass of accumulated ice is measured by means of a tensometric bridge (strain gauge load sensor), the output of which is tied to the precise AD converter. The digital signal is preprocessed by a micro-controller, which assigns the time and stores the data into the device memory.

In order to prevent the freezing of the horizontal rod, which couples the cylindrical collector to the tensometer, which is located together with the electronics in the housing. The passage through the housing may be heated depending on the passage temperature. A test electromechanical impulse is applied each hour to verify the free force transition to the tensometer, and thus to check whether the acquired data are reliable or not.

The „Icemeter" can operate autonomously as data logger (it has sufficient memory for approximately 50 days of operation with 10 min sampling intervals) or can pass the data on request to the PC. In the case of power supply failure, the Real Time Clock circuit is powered from the backup rechargeable battery, so the information is not lost. The basic technical specification of the instrument is summarized in Table A. 10.

Table A. 10 Basic technical specification of Icemeter

Measuring range	0...10 kg
Resolution	1 g
Accuracy	±5 g
Surface area of the sensor	0,05 m^2
Mass of the device	4,25 kg
Interface	RS232 (optionally RS485, RS422)
Capacity of the memory	~7500 data points incl. date and time
Voltage Supply	12-15 V
Electricity consumption	~50 … 230 mA depending on heating
Operating temperature range	-30°C …50 °C

A description of the sites is given in §6. Results of the measurements with details of the experience with the Icemeter operation are given below:

Examples of measurement

The Icemeter has been operated on the Milesovka peak from 2000. The maximum icing load was detected in the end of 2002, when more than 2.5kg accumulated on the collector of length 48 cm with surface area 0.05 m^2 (see Figure A. 23), thus the accumulated icing was about 1.26 kg/m^2. At that time several masts were broken due to heavy icing in the Czech Republic.

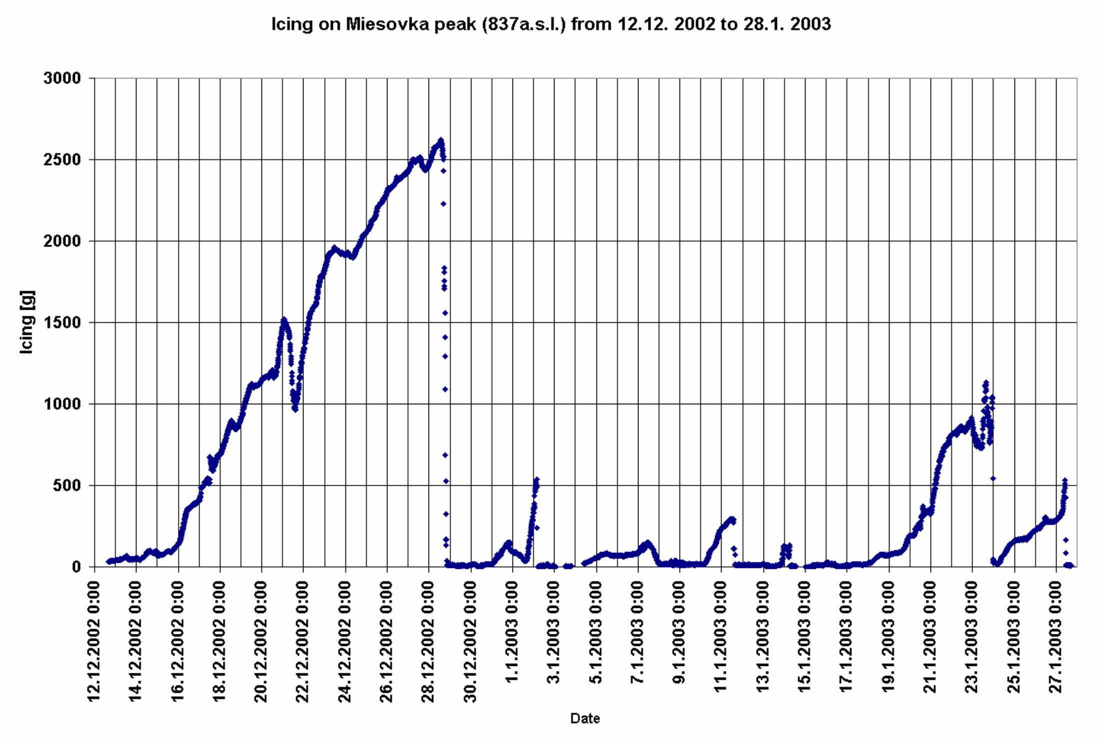


Figure A. 23 The severe icing recorded at Milesovka peak in the end of 2002

Figure A. 24 presents the example of measurements from different heights above the ground at the Milesovka observatory. We can see that significantly higher mass of icing accumulates at the higher position. The shape of the curve – record is similar, but not exactly the same during the presented period (January/February 2005). Interesting is the comparison with the measurement in Nova Ves, which is situated ~30km west from Milesovka at about the same altitude. Here, the icing lasted quite longer. At Milesovka the icing lasted just about two days from the evening 16.2.2005 to 18.2005, whereas in Nova Ves it lasted more than one week up to 1.3.2005 (see Figure A. 25). The accumulated mass was however comparable. Note that the records are not from the same time period. They overlap only partially.

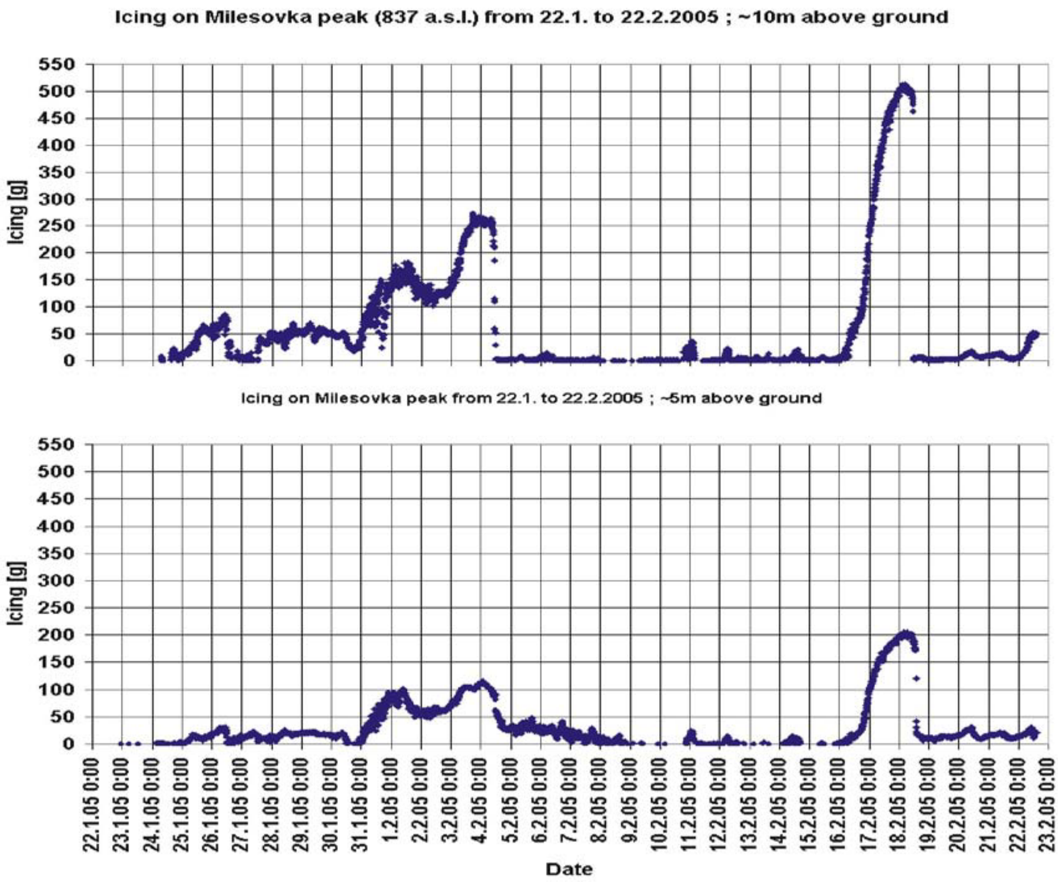


Figure A. 24 Example of icing measurement at different heights on Milesovka peak.

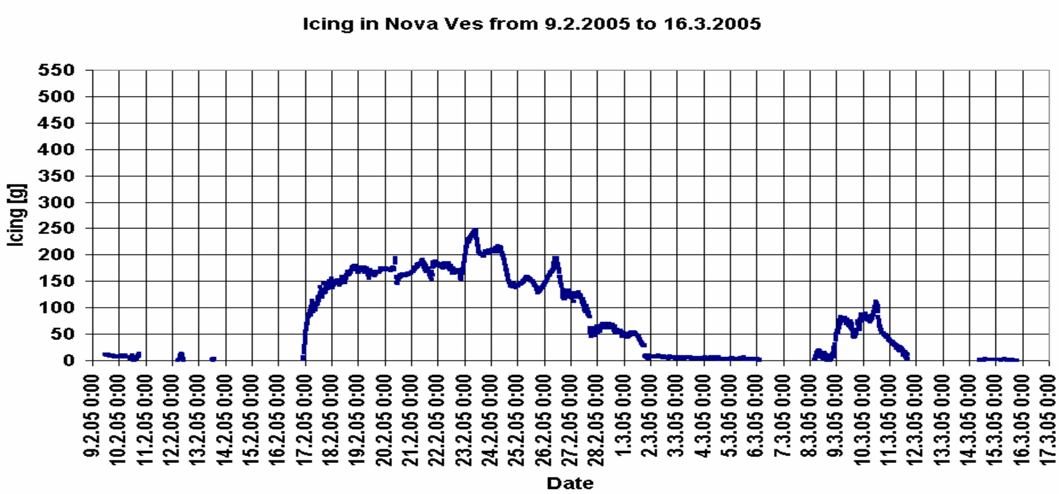


Figure A. 25 Example of recently (February 2005) installed icing measurement in Nova Ves.

Problems of operation

Although the Icemeters installed in the Czech Republic measured correctly most of the time, there were also time periods, when the instruments gave obviously wrong negative values. These times can usually be associated with the periods when the horizontal rod coupling the tensometer with the vertical collector became icebound to the instrument housing. Thus there was no free force transition. We could identify that from the fact that we didn't see the proper electromechanical pulse (see section 2) in the technological data. These periods of freezing – malfunctioning can be seen in Figure A. 25 as data gaps. The instrument gave the wrong negative values. Note that the location in Nova Ves has more severe cold and windy conditions than Milesovka. This freezing problem has been very rare on Milesovka.

Discussion, conclusions, future plans

Although we have reasonably good data from most of the time of operation in the Czech Republic, it seems that we should enhance the available heating power in order that the Icemeter can operate in cold climate conditions. We consider it should be no problem, provided there is no limitation to power consumption. Additionally, improvements are needed to the wind shielding of the passage of the coupling rod through the housing. Currently, the heating power is only ~ 2 W maximum. Since we haven't had many problems with freezing on Milesovka, where we have got most of our experience, we have maintained the heating power as low as possible to be sure that the heat doesn't prevent the ice growth.

Except for the enhancement of available heating power, we will try to follow future recommendation for ice sensors that may occur. For example, we will consider the possibility to build an instrument with a rotating collector. Probably we will mainly continue in focusing on sensors that measure accumulated icing. We had preliminary talks about the possible placement of the Icemeter in the test site in Switzerland, and in a site in Bulgaria.

Regarding the investigation of conditions favourable for icing growth in the Czech Republic, we will make the comparison of icing measurement with the measurement of liquid water content on Milešovka peak. Such comparison should be possible at Milesovka beginning from the winter 2005/2006. We believe that such measurements could improve our knowledge of icing. The recent attempts to simulate icing measurements by using temperature, wind and humidity records haven't shown sufficiently good results.

Annex 13 Labko Ice Detector (Finland)

Technical features of LID3210C

The main functional hardware parts of the ice detection system are a sensor probe and a control unit. The sensor probe consists of a 350 mm long electrical heating element fastened to a protective cylindrical housing. The ice sensing wire, which is an ultra sonic sensor, is helically wound around the cylinder as near as. When ice accretion has been detected, the cylinder is heated to make the sensor wire ice free again. Heating power, cut off temperature and ice alarm amplitude can be controlled. So, the ice alarm level and restart delays can be well set to correspond to changing conditions and purposes.

Operational experiences

Mechanically the Labko 3200-ice detector that has been developed for wind turbine use has been good. The older model 3500, which was originally developed for meteorological purposes, has been found to indicate ice more accurately compared to the LID 3200 series but it has also been more fragile to vibrations due to its physical shape [25].

Performances of ice detectors have been monitored with video cameras in order to solve the noted problems with delayed ice detection. Delayed ice detection is harmful because quick and reliable indication of the beginning of icing is especially important in wind turbine applications. This is due to the fact that ice detectors are used to control anti- and de-icing systems as well as to control operation of turbines in populated environment where ice throw may pose a safety risk [31].

One such case where an ice detector was not able to detect incipient icing is presented in Figure A. 26.

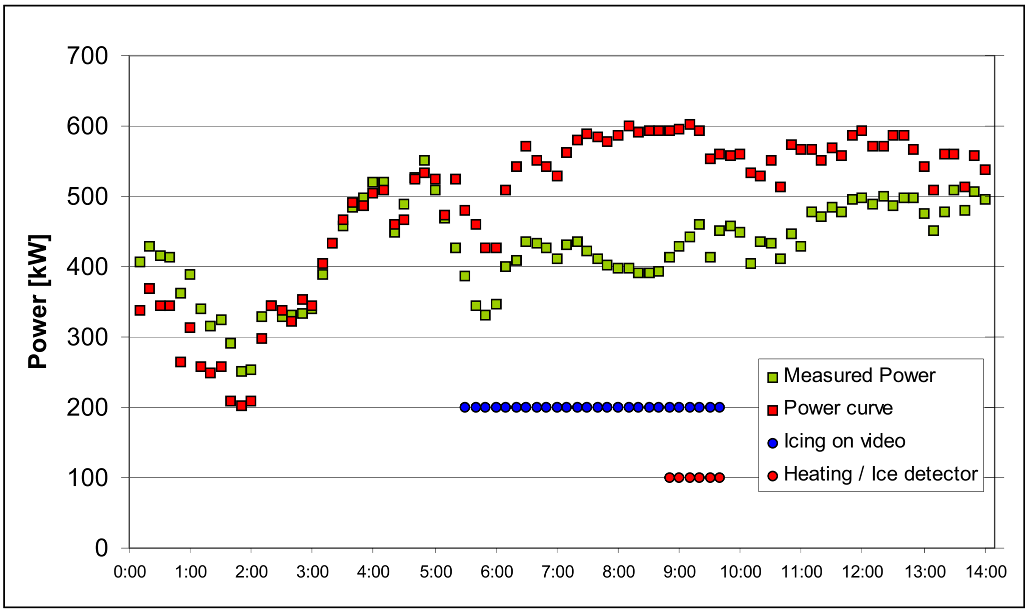


Figure A. 26 Wind turbine's performance during icing event 22.2.2002 in northern Finland.

The performance of the wind turbine deteriorated due to delayed ice detection. Delayed ice detection also increases the heating power demand of anti-icing systems due to the increased heat transfer as a consequence of non-laminar (=turbulent) airflow over a rough iced blade surface.

Annex 14 Rosemount, BFGoodrich, 0872J (Finland)

Finnish Meteorological Institute (FMI) has performed field tests to verify the performance of ice detectors on an arctic mountain. Measurements on icing events and duration of icing were carried out during three winter using Rosemount model 0872J (prototype), at the FMI's test site. The test station is located in northern Finland on the top of Luosto fell (500 m asl, N 67 08', E 26 54'). The Luosto test sites represent an elevated site inland with harsh and frequent icing climate. Information and documented experimental data on meteorological conditions during icing events and performance of ice detectors was collected.

The performance of the two ice detectors was monitored with two video cameras Also, data measured with present weather sensors (visibility/fog), temperature, humidity, dew point and wind sensors was evaluated.

According to the results, the two automatic instruments used for ice detection were not entirely reliable and differences were found between the performances of ice detectors. The ice detectors are to some extent insensitive to icing under heavy icing conditions. It was possible to record more or less accurately the start and ending of icing periods but not the accretion rate or type of the icing.

The Rosemount sensor has yielded fairly good measurements at Luosto and detected the presence of icing conditions. In soft icing conditions (snow-like formation composed mainly of thin ice needles or flakes of ice), ice accretion may exist on the sensor probe during short periods of time especially in the beginning of the icing event but the sensor does not detect ice. This sensor is fairly adequate for icing measurements and it operated better than the other tested instruments. Nevertheless, it cannot guarantee accurate measurements in all icing conditions especially in soft icing conditions.

Annex 15 EAG 200 (Germany)

Figure A. 27 shows an example of the ice load sensor EAG 200. The measurement pole of the ice load sensor EAG 200 has diameter of 0.032 m, a length of 0.5 m and consists of PVC. The measurements are carried out by an electro-mechanical sensor in the lower part of the instrument. It scales the mass of ice that is accumulated at the pole. The measured mass is converted to a frequency signal in a range from 100 Hz to 10 kHz.

The EAG 200 has a measurement range from 0 g to 4000 g (note: type EAG 210 has a capacity of 10kg) and a resolution of 1 g. The measurement error at 0°C is ≤±0,5% of the measured value with an accuracy ≤±10 g. The measurements of the ice load sensor EAG 200 show a slight dependency on temperature with a temperature coefficient of ≤±15 g/10 K [56].

	
Icing pole	Ice load sensor EAG 200

Figure A. 27 Icing measurement instruments used by German Weather Service ([37], pictures were taken at Zinnwald, February 2005)

Before 1991 the icing measurements were performed by the use of manually operated icing poles at all locations the eastern part of Germany (see chapter 4 for a detailed description). The icing poles have a diameter of 0.035 m, a length of 1 m and consist of PVC. Figure A. 27 shows an example of icing measurement poles, operated at the station Zinnwald of the German Weather Service.

The icing poles are still used for measurements at three locations at present (see 6.2) in order to compare their results with simultaneous automatic icing measurements by the use of EAG 200. The measurement results of both instruments were evaluated for the maximum ice masses that were measured during whole icing cycles (accumulation and loss of ice). The findings are displayed in Figure A. 28.

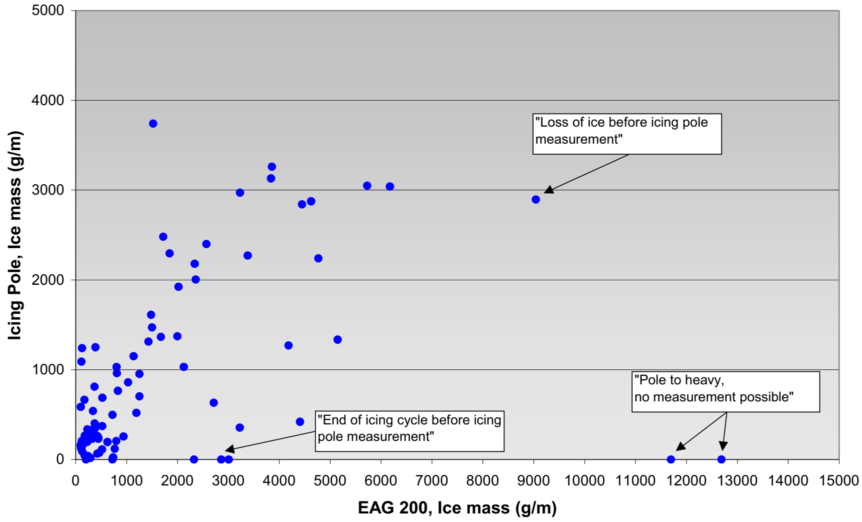


Figure A. 28 Comparison of maximum ice masses, that were measured in icing cycles by the use of a manually operated icing pole and automatic icing measurements (EAG 200) during the period 1996-2004 at the station Zinnwald of the German Weather Service (remarks are from the measurement protocol of icing pole measurements).

Figure A. 28 illustrates the limitations of manually operated icing pole measurements: For very large ice masses either no measurements are carried out, because the impossibility of pole-handling, or the measurements are erroneous. Furthermore the icing cycle may have been finished before the measurement was carried out.

Regression analysis of both measurement techniques shows acceptable results if the unreliable data points are excluded (see Figure A. 29). This illustrates that reliable results can be achieved by the use of an automatic instrument. Nevertheless, additional information about the icing types or about the icing geometry (e.g. icing diameter, icing vanes) are missed.

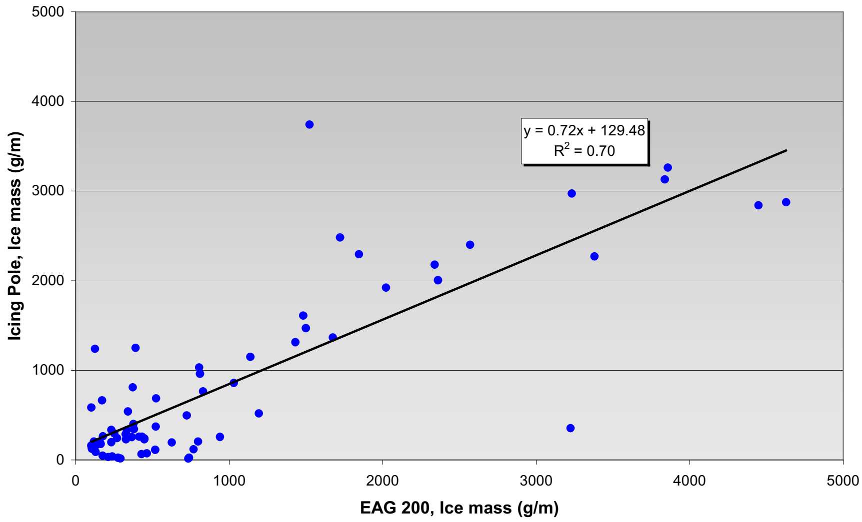


Figure A. 29 As Figure A. 28, but without confirmed unreliable data points

For the illustration of the EAG 200 system operation and performance a selected result of an icing event is presented in Figure A. 30. It was measured at the 100 m mast of the Falkenberg measurement site of DWD's Meteorological Observatory Lindenberg. Icing measurements at three heights (see Table "Overview of present locations with icing measurements in Germany") have been carried out at this location since winter 2004/2005. The example shows, that the system operates well even for short icing periods and for small amounts of ice accretion. Furthermore, it shows a minor zero offset for all ice load sensors as well as a zero offset drift, at least for the instrument in 5 m height. These offsets and their drift for the measurement system at the Falkenberg measurement site are mainly due to a temperature dependence of a signal converter, that had to be used to adapt the ice load sensors frequency data output to the acquisition system of the tower. It will be reduced by appropriate temperature compensation in the future.

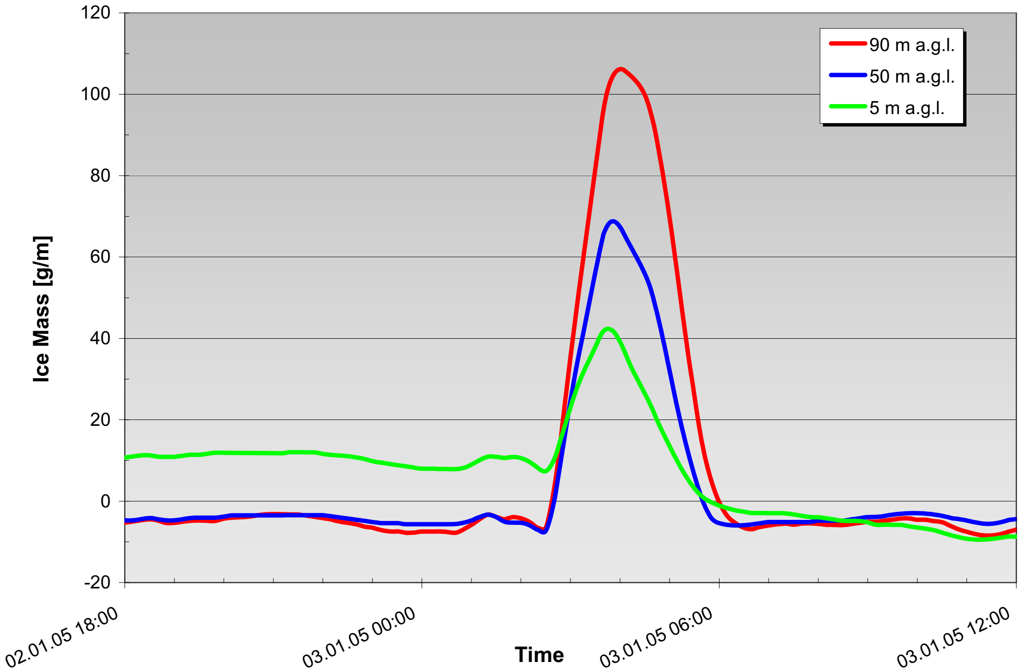


Figure A. 30 Vertical profile of ice masses for an icing event, measured at the 100 m high tower of DWD's Meteorological Observatory Lindenberg

Annex 16 Gerber (USA)

Gerber Instruments

The UK meteorological office sourced two instruments (Gerbers) capable of measuring LWC of the air. Two Gerber PVM-100 instruments were provided by the UK Meteorological office and were installed at the EA Technology severe weather test site at Deadwater Fell test site on the English/Scottish border in the UK. Data was collected over the winter period December 2003 to April 2004. The aim was to see whether output from these instruments could be related to the conditions under which overhead line conductors suffer ice loads.

Test Spans

The test span is 200m long and orientated North-South. H-pole supports are used, the southern H-pole having a platform attached for working and sensor attachment. The Gerbers are mounted on this southern H-pole platform (Figure A. 32 and Figure A. 33).

Figure A. 31 The site on a clear day after winter snowfall.

Monitoring of the Gerbers started on 11th December 2003. The site is fitted with load cells and turnbuckles to adjust the conductor tensions. Figure A. 32 shows the southern dead end platform and rotating rig.

Figure A. 32 The Southern dead end platform and rotating rig at Deadwater Fell.

Figure A. 33 Gerber instruments on southern dead end platform.

Performance

The Gerber particulate volume monitors have a 0 - 10VDC output which give a measurement range 0.002 – 10g/m3. Figure A. 34 to Figure A. 36 show some typical weeks data from the test site.

One PVM-100 was mounted and aligned north/south on the southern platform and the other aligned east/west as shown in Figure A. 33.

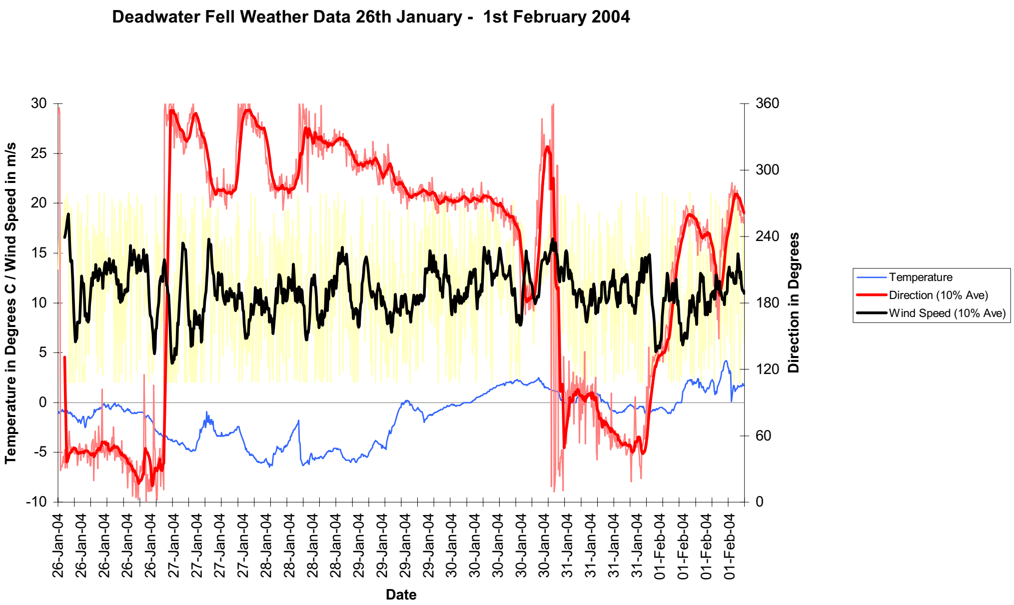


Figure A. 34 Weather data 26 January – 1 February 2004

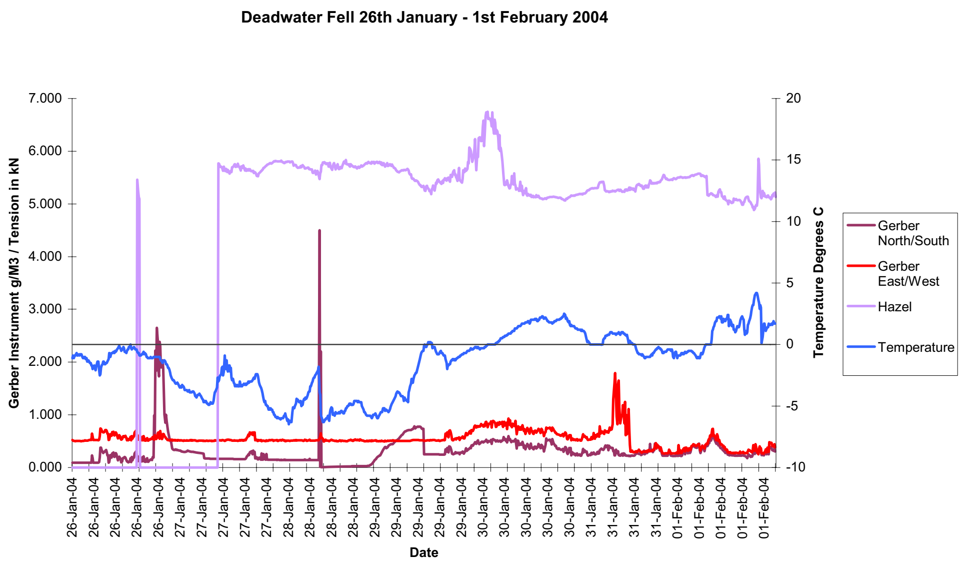


Figure A. 35 Load cell and Gerber data for conditions in Figure A.34

The site span is orientated north-south so winds around 0° or 180° should cause very little ice load accretion on the conductors according to the meteorological models even if icing conditions are met. Winds around 90° and 270° will be normal to the span and icing on the conductor should occur if the meteorological conditions are right. However, sub-zero temperatures and appropriate winds should not cause icing if there is no liquid water content i.e. the Gerbers do not indicate the presence of water particles. In Figure A. 34 and Figure A. 35, there are sub-zero temperatures up to 29 January with occasional winds normal to the span. However, the Gerbers do not indicate the presence of moisture and there is also no indication of ice load on the Hazel conductor. Late on 29 January, the temperatures are rising slightly but still sub-zero and both Gerbers are starting to indicate the presence of moisture. The wind direction is normal to the span and ice accretes on the Hazel as indicated by the increasing load in a steady wind speed. Later on 30 January the temperature rises above zero and there is no icing even though the Gerbers indicate moisture. So this week indicates correct performance.

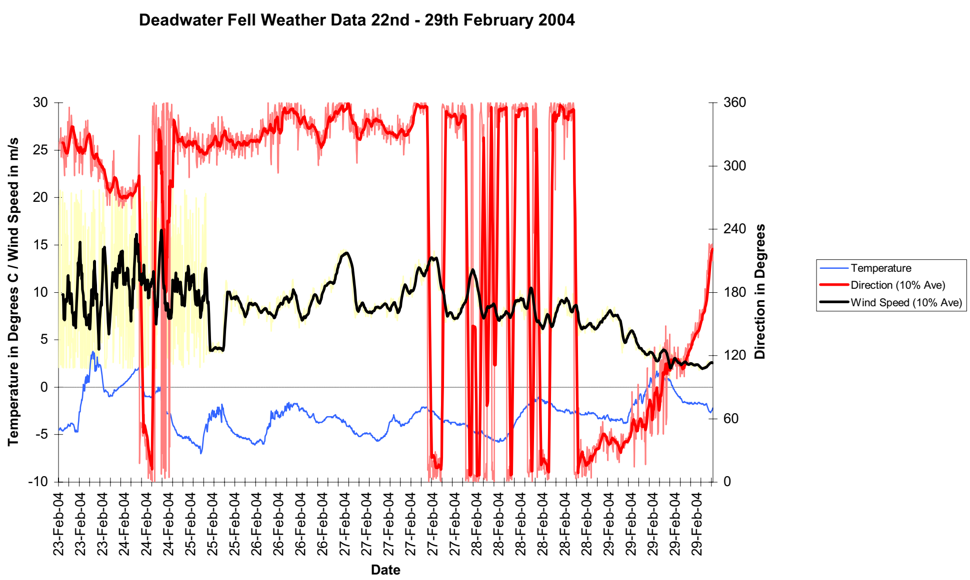


Figure A. 36 Weather data from Deadwater Fell 23-29 February

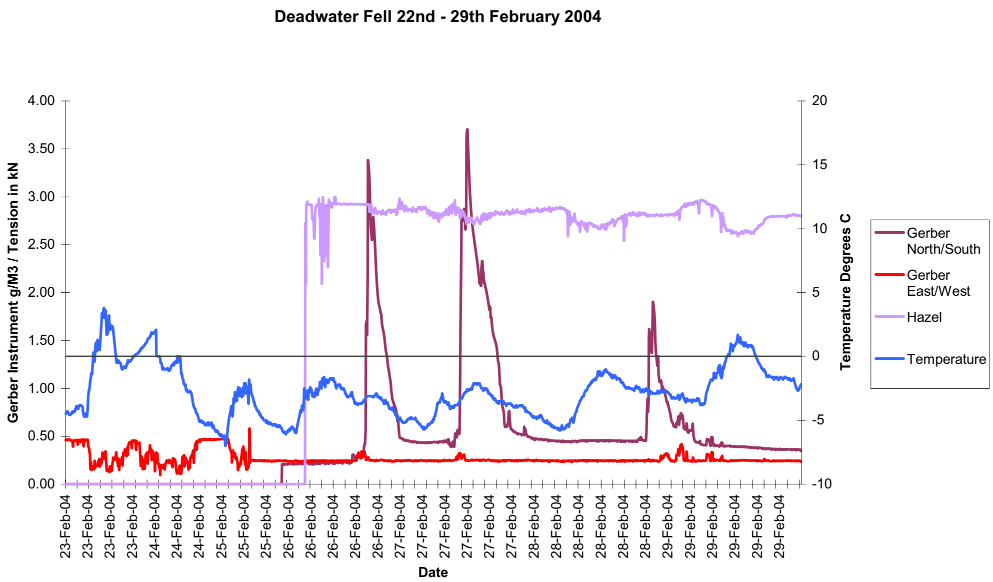


Figure A. 37 Data output from Gerbers and Hazel load cell for period of Figure A. 34

Figure A. 36 and Figure A. 37 show a period in late February. Sub-zero temperatures were present for almost the whole period and there were indications of moisture but no ice loads as the winds were always along the span. Figure A. 38 and Figure A. 39 show a week in March when the winds were almost always in a direction giving a major component across the span. These were associated with sub-zero temperatures for most of the period.

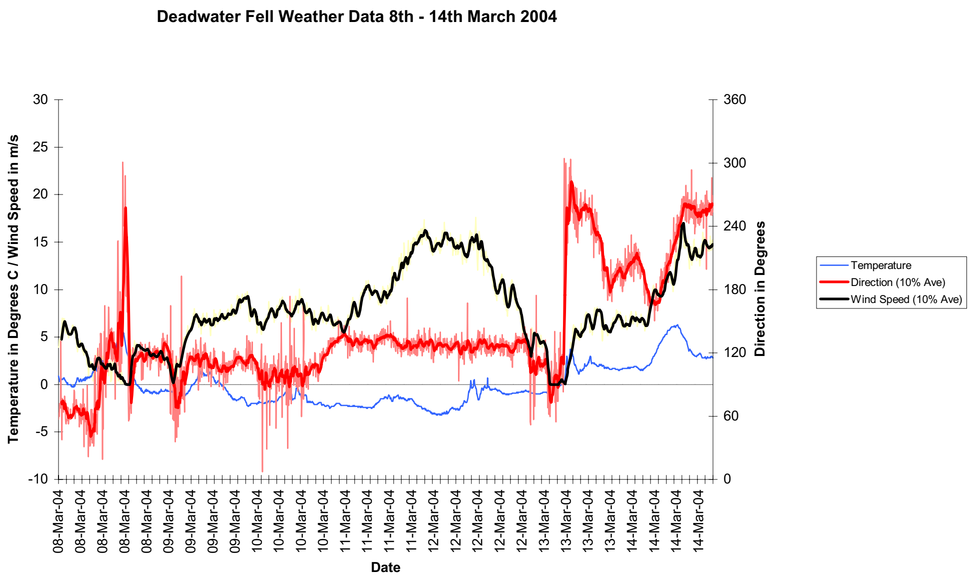


Figure A. 38 Weather data for 8-14 March

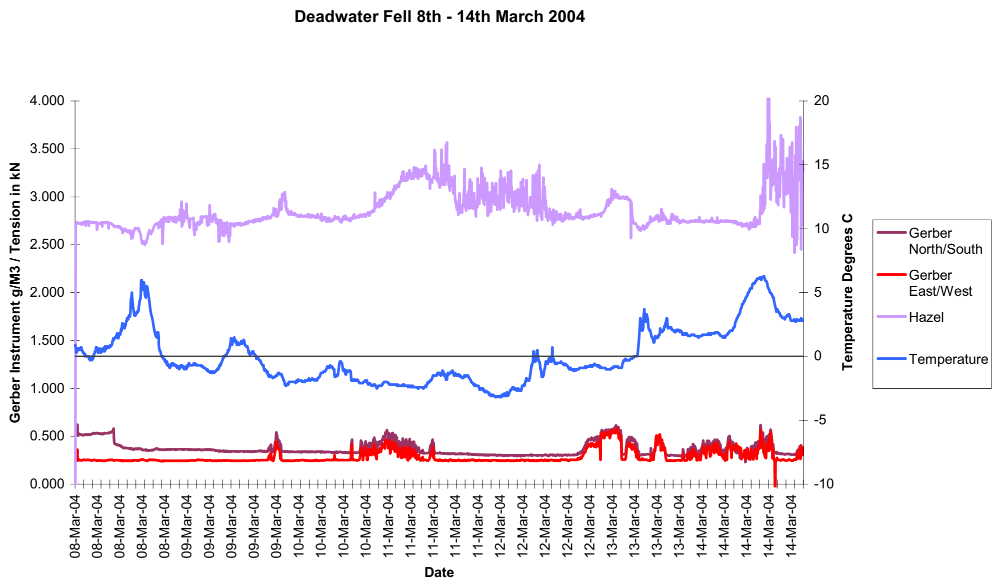


Figure A. 39 Gerber and load cell data for period covered in Figure A. 38

On 9 March a minor indication of moisture from the Gerbers combined with a wind normal to the span and sub-zero temperatures indicated icing conditions which was confirmed by a minor load increase on the Hazel. Late on 10 March the Gerbers indicated more severe icing conditions with a wind at an angle of 30° to the span. The Hazel suffered a significant increase in ice load which stopped when the Gerbers indicated no further liquid water content in the air. The ice load stayed for a while as the temperatures were still below zero. A less significant incident occurred on 12/13 March when icing conditions showed up with a further ice load on the Hazel. Gerber indications of moisture but at above-zero temperatures on 13/14 March did not indicate icing conditions and no ice-load was measured. In the final day of the period load variations measured were due to an increase in wind speed and violent conductor movement.

A full 17 weeks data has been supplied to the UK Meteorological office. This includes logged tension data from the bare Hazel conductor strung over the 200m span with an intermediate pole at 100m. A camera was also set up to monitor the ice load characteristics near the H-pole. This would identify rime and wet snow icing events.

Annex 17 METEO device (Czech Republic)

During long-term development at the stand at Studnice, EGU Brno designed a new automated monitoring equipment METEO which, in connection with communication means, enables a continuous measurement of ice mass built up by an automated system including, wind velocity and direction and temperature without the requirement for the presence of attending personnel [57,58,59,60].

Device Meteo measures following quantities:

- ice mass up to 20 kg with accuracy 0.01 kg on the measuring rod with length of 0.5 m and diameter of 30 mm. The value must be multiplied by two in order to obtain the value corresponding to 1 m
- temperature with accuracy 0.1°C
- range of wind velocity from 0 to 10 m/s with accuracy ± 2 m/s, range from 10 to 40 m/s with accuracy ± 1 m/s
- wind direction – angle from 0 to 355 degrees in steps of 5 degrees.

Measured values are stored in the flash memory, velocity and direction of wind are recorded every minute and temperature and ice mass every ten minutes. The size of the daily file is 6 192 B and the capacity of the disc is sufficient for 40 or 80 days (depending on size of the memory used). When the flash memory is filled up the oldest daily file will be overwritten by the latest one. For eliminating the growing together of the icing on the measuring rod with the body of the Meteo device heating can be activated (heating is set up in dependence on temperature and on ice mass) [61,62].

Figure A. 40 Device Meteo on a concrete pole of LV power line, location Predin (Photo: J.Sabata)

The concept of its solution assumes to build up a network of monitoring equipments by which the measurement will be performed and the data on air temperature, ice mass and wind velocity and direction processed.
Means such as radio networks or GPRS may be used for data transmission and for communication between the centre and individual monitoring equipments.

The operation itself of the automated icing monitoring system is realized in two regimes:

A. Standard regime

The monitoring equipment measures the current quantities, processes the measured values and downloads them into the local database for each equipment. By the command of the server from the centre or on demand of the dispatcher the newly measured data will be transmitted and downloaded into the central data base.

B. Warning regime

Each monitoring equipment may be set up with regard to the expected local conditions in such a way so that it may, by itself, send a warning message into the centre when the set up values have been exceeded or when another abnormal event arised.
The warning messages may indicate:

- exceeding the set up ice mass,
- exceeding the set up steepness of ice growing,
- exceeding the value of wind velocity,
- outage of supply and its restoration,
- foreign intervention into the monitoring equipment.

Actual state
At present 14 devices are in the operation, two of them on the territory of regional utility VCE, 12 on the territory of regional utility JME. The first one was put into operation in 1999, the others in 2001.

The automated monitoring equipment are installed on the towers of LV, MV a HV overhead lines.

Data transmission

The data and alarms sent by each monitoring device to the central dispatch office are transmitted by the radio network via retransmission points.

Each hour current data from each METEO device are sent into the dispatch system and are displayed in the dispatch office. The dispatcher can also make query any time to get immediate values.

Daily files with measured values, recorded in the flash memory, are sent into SCADA system at the time of low radio network load (usually at the night). All data are archived in this system [63].

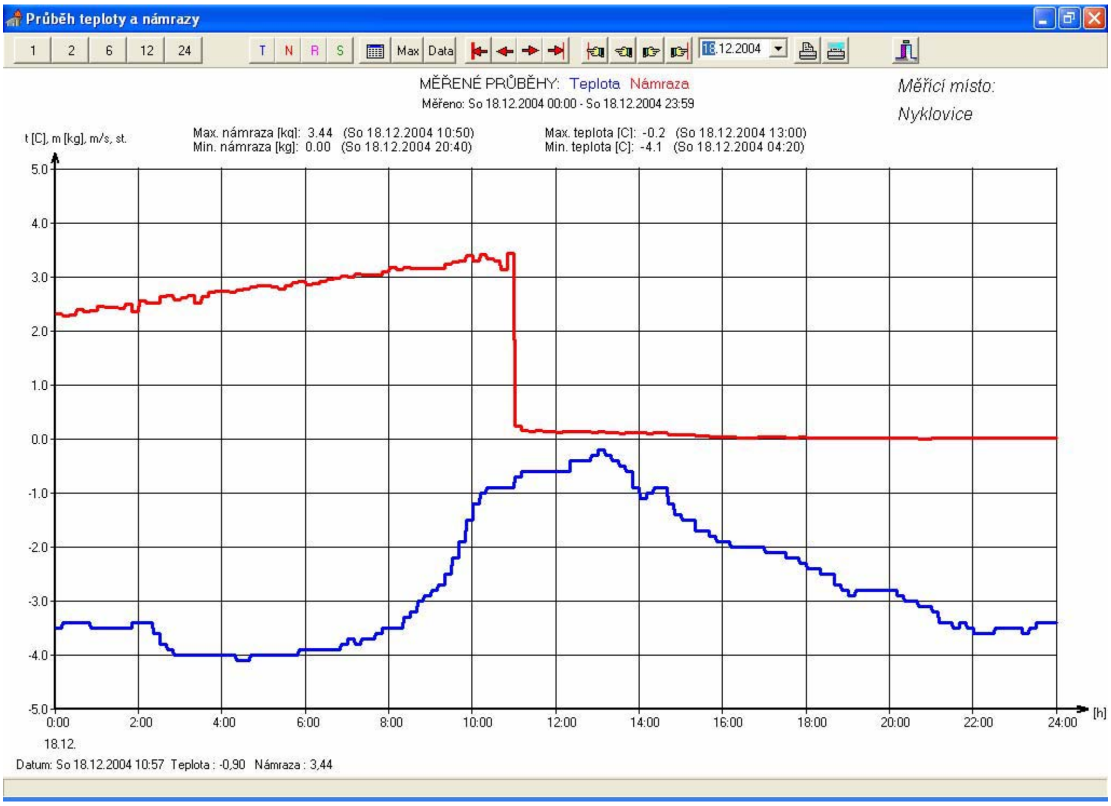


Figure A. 41 Daily record of temperature and ice mass, 18th December 2004 – location Nyklovice; the end if icing event

Annex 18 IceMonitor (Sweden)

The IceMonitor was originally developed for the use in a power line surveillance system installed in Norway 2003, for the Norwegian Power Grid Company, Statnett, and their research test site in the mountains west of Oslo. The prototype was designed for a maximum ice load of 100 kg, and later it was modified for lower maximum loads (10, 25 or 50 kg). The ice that accretes on the vertical, freely rotating sensor (steel pipe with a surface area of 5 dm^2) is weighed by a load cell, as the pipe is supported by a rod which is resting on the load cell. To avoid ice in the area for the bearing of the rod there is electrical heating of the bearing that is controlled with a thermostat. The output of the load cell is connected to a precision amplifier and converted into a standardized output current loop – 4 to 20 mA. To be able to perform testing of the instrument remotely there is a test relay included that will activate an electrical unbalancing of the load cell – at which the output signal will increase with 8 mA to indicate that acquired data are reliable.

To log data any kind of data logger with standardized current input (4 – 20 mA) can be used. At the first site in Norway (Drammen) and at the Swedish sites: in Åre and in the far north (Ritsem) the IceMonitor is connected to a monitoring station designed by SAAB Technologies (previously AerotechTelub). These stations also perform measurements of weather parameters, such as air temperature, relative humidity, wind speed and direction, and in some cases also precipitation is detected – type and intensity. Measurements are made once every half hour normally, but in Drammen once every 10 minutes. Data is retrieved to a server in Östersund via radio/radiolink or in some case via telephone modem. A camera is monitoring the IceMonitor sensor at the site in Åre. Icing of this camera has been a problem during the winter 2005/2006 – and the installation and de-icing of the camera will be modified before the next icing season. The monitoring equipment was originally designed for use in road weather information systems and it is capable to handle a number of different sensors, including camera – which stores files in jpg format.

At the site in Åre, several icing events occurred during the winter 2005 /2006. A couple of the icing events have been severe with ice loads of more than 40 kg. (see figures below.) During the same period, no significant icing occurred at the site in site in Ritsem (Sweden) at the test site in Drammen (Norway).

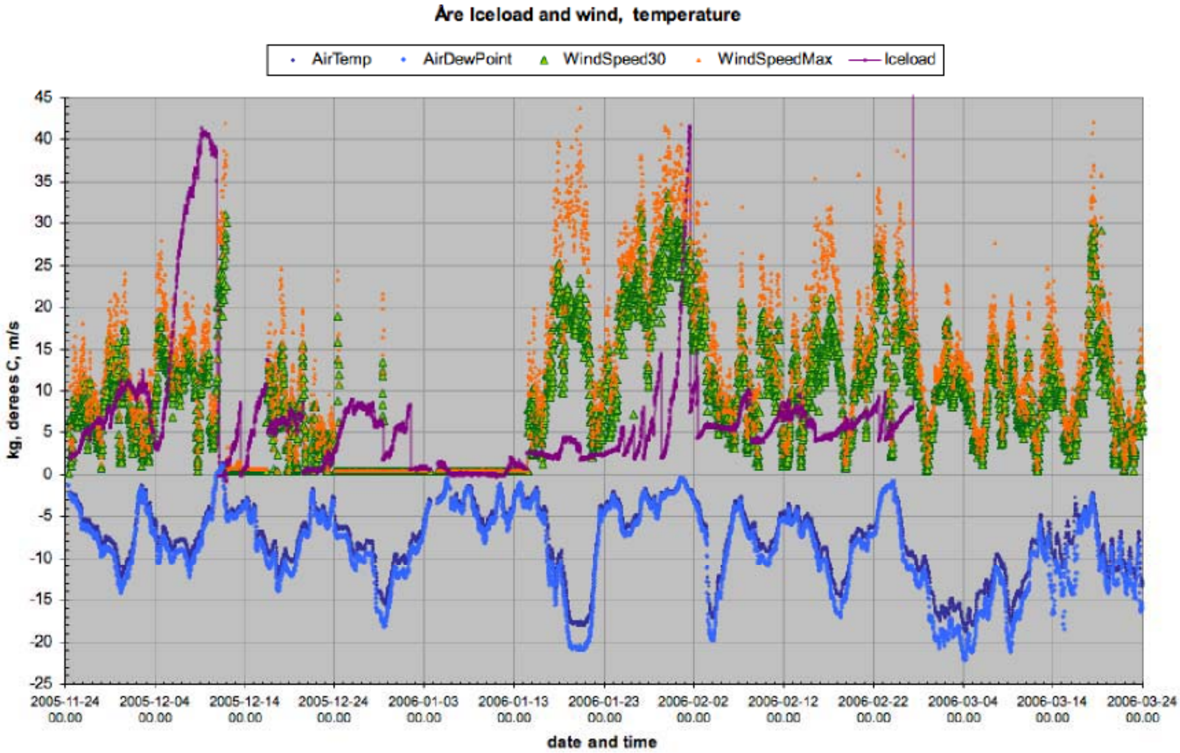


Figure A. 42 Ice build-up developed during the two severe icing events during 2005/2006. Details are shown in the figures below.

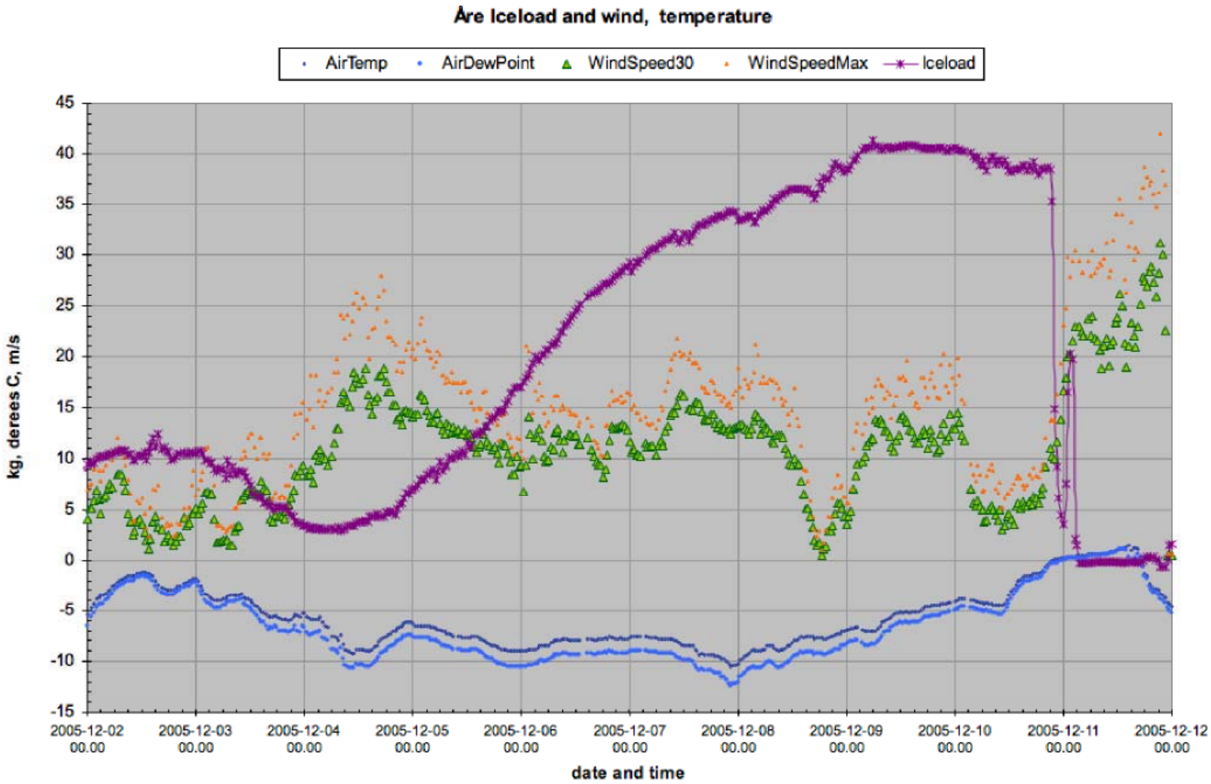


Figure A. 43 First significant icing event at Åre during winter of 2005/2006

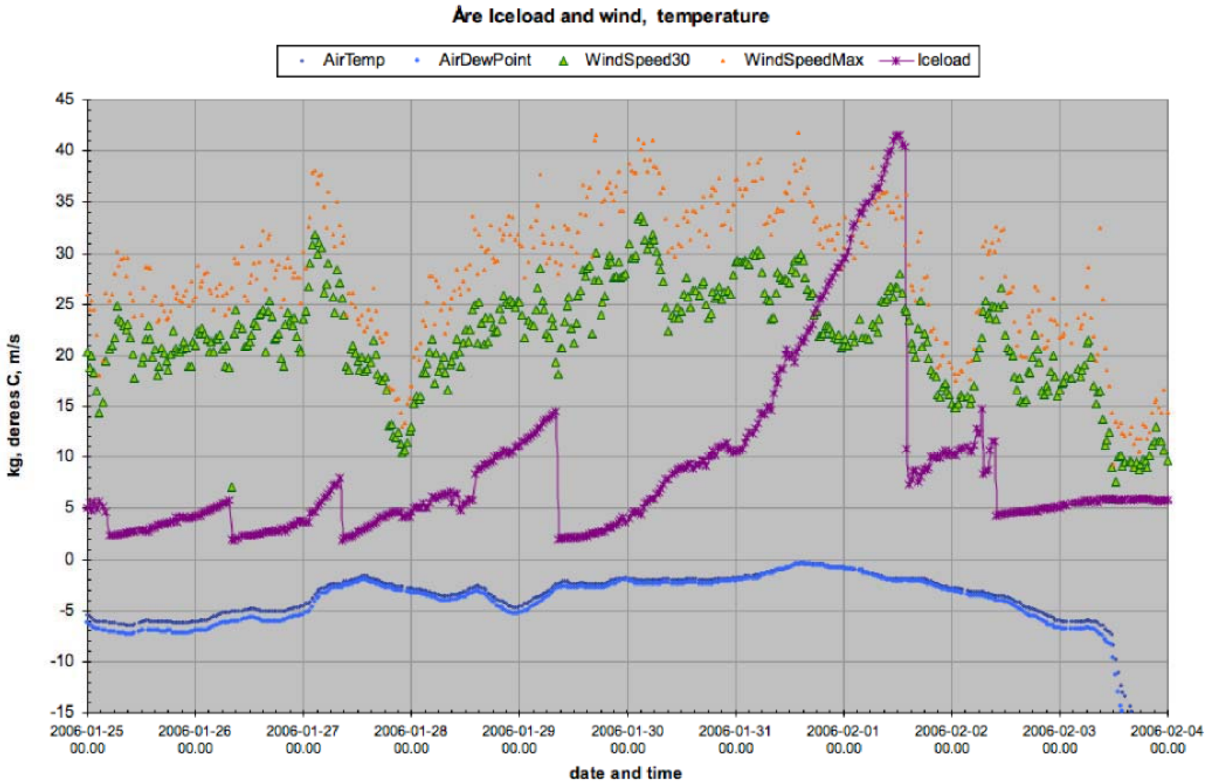


Figure A. 44 Second significant icing event at Åre, winter 2005/2006

Figure A. 45 Pictures of the site installation in Åre on top of the roof of a ski lift house, with a camera mounted on the wind sensor support. The site is also prepared for remotely controlled de-icing of the sensor using

Annex 19 HoloOptics T20-series Ice Detectors (Sweden)

• The T21 Ice-Duration Indicator™ and Ice-Guard™ indicate the duration of ice on non-heated structures and can be used for controlling anti-icing or defroster equipment. T21 has no probe heating so if used as controller the probe is to be heated by the anti-icing or defroster system. The sensitivity is 50 g/m^2

• The T23 Clear-Ice Indicator™ indicates the presence of atmospheric icing. The probe heating is internally controlled and the sensitivity is ≥ 50 g/m^2.

• The T26 Icing-Rate Sensor™ measures the atmospheric icing rate using internally controlled high power probe heating. The sensitivity range is 50 g/m^2h – 18 kg/m^2h

Common features of the T20-series ice detectors
The T20-series indicators

- single-direction (±45° upwind) or omni-direction versions
- indicates either all icing types including clear ice or rime ice/wet snow growth only.

The probe is mounted on a cylinder θ=30 mm L=500 mm. A single-direction T20-series indicator is sufficient if there is only one wind direction of interest and it is known (e.g. on a wind turbine nacelle). In all other cases the T20-series omni version is recommended. The sensors are equipped with a health-test which provides an early warning if the performance of a sensor is degraded.

All T20-series ice detectors are based on a patented digital optronic ice-indicator that indicates the presence of any type of atmospheric ice including clear ice. It comprises of a head with an IR emitter and a photo detector and a probe. If not indicated otherwise, reference in this Annex is made to the indicator sensitive to any type of ice including clear ice.

Figure A. 46 T26 Icing Rate Sensor™ Single and omni direction versions

Description of operation – T26

Icing is detected if more than 95 % of the probe is covered with a 50 µm thick layer of clear ice or 90 µm thick layer of other types of ice. As ice is detected, the internally controlled probe heating[10] is turned on without time delay. After a short period of time the ice has melted and the water has fallen off the probe. The indication of icing will stop when the probe heating is turned off. The time interval between two indications may be as short as ten seconds.

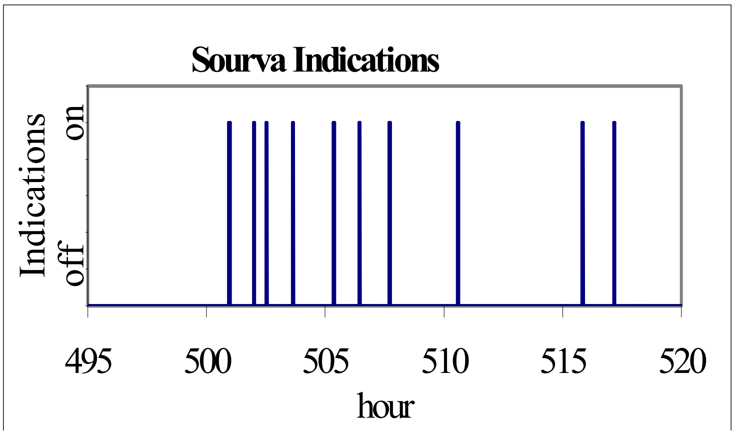


Figure A. 47 Typical icing indications measured at Suorva, Northern Sweden

The time it takes to melt the ice is dependent on many factors (e.g. icing rate, air and surface temperature, melting power, wind speed and type of ice). Ice may start to build up on the probe again as the probe cools down. This cycle is repeated for as long as ice is created on the probe surface. If sufficient heating is applied, the time it takes for the probe to be covered with ice after it has been de-iced, is mainly dependent of the icing rate. The time between icing indications is used to calculate the icing rate using the T26 Icing-Rate Sensor™.

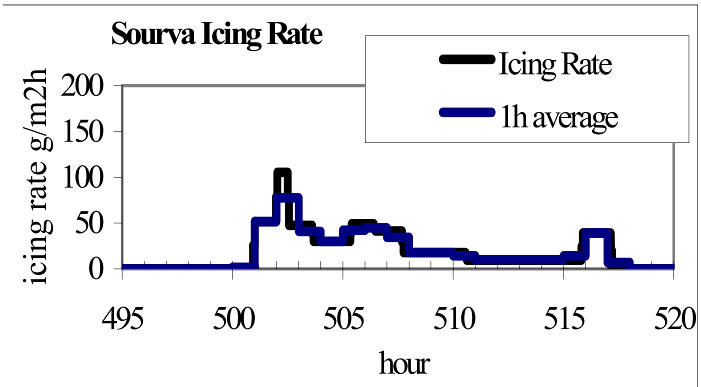


Figure A. 48 Icing rate measured at Suorva, Northern Sweden

[10] External control of the probe heating is available

Measurement campaigns 2003-2006

The 23 Clear-Ice Indicator and the T26 Icing-Rate Sensor beta versions have been tested at the following locations:

- The Suorva wind power plant, Sweden. 150 km north of the polar circle. In co-operation with FOI (The Swedish Defence Research Agency)
- KTH (The Royal Institute of Technology), Stockholm, Sweden
- Bromma Airport, Stockholm, Sweden. In co-operation with the airport authorities
- Greenville Wind power plant, Sc, USA. In cooperation with General Electric
- Sandhaugen test felt, Tromsö, Norway, 400 km North of the polar circle. Cooperation with Norsk Miljøkraft
- University of Narvik, Norway. 300 km North of the polar circle. Cooperation with the University of Narvik.
- Keller test field, Norway. Power line protection. In close cooperation with Norsk Hydro
- Åre Ski Resort, ski lift protection. Cooperation with Combitech.
- The T21 Ice-Guard is, in cooperation with KTH (The Royal Institute of Technology), tested as a defroster controller for freezers

Annex 20 Instrumar IM101

Instrumar IM101, V.2.4 is an ice detector based on measuring the electrical impedance and surface temperature [29]. Its long-term use has shown it to be quite durable and it seems to detect icing in reasonable agreement with humidity indications and video recordings [21]. No further information is available on this instrument.

Annex 21 Wind tunnel calibration

This annex refers to Kanagawa Institute of Technology, Japan, as a collaborating member of COST Action 727. No references are made to wind tunnel studies in other countries in this report.

Verification of an ice detector

To know the duration of an icing event exactly pointing out its beginning and end is essential in taking efficient countermeasures for the prevention of icing. Note that the terms of *beginning* and *end* mean the onset and completion of an icing event, not of icing conditions. For that purpose an ice detector is usually employed. The Finnish Meteorological Institute has been carrying out the field tests to verify the performance of ice detectors in the arctic region. KAIT conducted the icing wind tunnel test for the German ice detector Infralytic developed for wind turbines, The principle of ice detection is based on the reflection of infrared light within an ice deposit emitted from the tip of the optical fibre connected to the sensor. It turned out that the ice detector can detect ice on the test model. At that moment, the thickness of ice could not be measured. [64]

Icing on anemometer

In the first place, KAIT has conducted the icing wind tunnel test using a cup anemometer to know the manner how ice accretes on a cup anemometer and the effect of ice accretion on measurements. Icing wind tunnel test was done according to the ordinary test scheme as depicted in Figure A. 49. The most important parameters of LWC and MVD were obtained by the rotating multi-cylinder method through some calculation. [65,66,67]

Figure A. 50 shows the growth of ice accretion on a cup anemometer at the different temperatures. *Dry-icing* and *Wet-icing* mean the conditions in which rime and glaze grow respectively. As can be seen in the figure, rime affects significantly the performance of the cup anemometer. As ice grows, the measured wind speed dramatically decreases. The reduction rate in the figure was defined by the following equation:

$$RR = \frac{V_{clean} - V^*}{V_{clean}} \qquad (1)$$

where V_{clean} and V^* denote the wind speed measured by a clean anemometer and by one with iced cups respectively.

The additional wind tunnel test (shown in Figure A. 51) for the acquisition of the aerodynamic characteristics of an iced cup-shaped body was carried out to infer the aforementioned reduction of measured wind speed by the iced cup anemometer. As shown in Figure A. 52, ice grown under the conditions of rime formation exerts the significant influences on the aerodynamic properties of the cup particularly in the range of the angle of incident higher than 90 degrees. Ordinarily in this range, there is a negative thrust force generated which reduces the cup revolution. The greater the negative thrust becomes, the weaker the torque around the shaft tends to be. After all, it can be implied, as easily expected, that the decrease of the measured wind speed by an iced cup anemometer is attributed to a decline of driving force of cups with an ice deposit. With using the acquired data, the numerical approach was taken to evaluate the effect of icing on a cup anemometer. The behaviour of cups was calculated by solving the equation of motion with respect to a cup part of a cup anemometer considering the force acting on each cup and stem, and at bearings supporting a rotating part. The results are shown in Figure A. 53

Snow accumulation of anemometers

How snow accumulates on an anemometer and how a snow deposit affects measurements have been examined by the wind tunnel test where snow flakes of dendritic shape were fed into the wind tunnel test section by a snow fall device as shown in Figure A. 54. The consequence revealed that wet snow accretes dramatically only on a cup anemometer and the surface of the snow deposit is asymmetric with respect to the axis through the centre of a cup (Figure A. 55). The most intriguing feature is that the snow deposit grows no further beyond some certain height, which was approximately 50% in the centre in those tests. These findings led us to undertake additional tests using cup anemometers with cups covered by a thin membrane in the cup open face, and with cups with snow deposit having the leveled surface in order to quantitatively evaluate the effect of change of the shape of snow accumulation inside a cup in terms of measured wind speed as well. All the results are shown in Figure A. 56. This indicates that snow accumulation inside cups reduces the measured wind speed by a maximum of 13% and the reduction of the measured wind speed by the cup anemometer is merely 20%, even if the cup open face is covered completely. [68,69]

Based on the test results mentioned earlier, the wind tunnel test (Figure A. 57) was conducted in order to investigate the aerodynamic effect of the cup covering of a cup anemometer. The results show that the skilfully fabricated covering exerts negative influences on the aerodynamic characteristics of a cup-shaped body only when the air stream flows into the covered side of a cup (Figure A. 58). Figure A. 59 shows the linear relation between the measured wind speed and the cup revolutions of the covered cup anemometer slightly changing the coefficients of the linear transfer function provided by the manufacturer.

Field measurements using a heated covered-cup anemometer and a heated ultra-sonic anemometer were implemented for verification of the effectiveness of cup-covering in icing-endangered mountains in Japan. Wind speed, together with temperature, humidity, solar radiation and precipitation was successively measured for 186 days starting from November. During the period of campaign, precipitation over a period of 754 hours was identified. The covered cup anemometer stopped its measurement for only 1 hour, whilst the ultra-sonic anemometer transmitted meaningless signals for 56 hours, probably due to ice or snow accretion on the emitter/receiver(s). The correlation between the covered and ultra-sonic anemometer was depicted in Figure A. 60 where the wind speed measured by the covered cup anemometer was calibrated by using the transfer function that can be seen in the figure. It turned out that the correlation is so satisfactory that the cup covering of a cup anemometer would be effective when used in icing prone areas.

Coatings to reduce the adhesive strength of ice

In order to seek the possibilities of coating as de- and/or anti-icing measures, the performance of commercially available coatings was examined by load test. An ice deposit accreted on specimens was created in two different manners: dynamic and static ice formation. The former was the formation of ice in an icing wind tunnel test letting super-cooled minute water droplets collide onto an airfoil model with a specific velocity where the complicated thermodynamic process always takes place. The latter was actualized in the low temperature chamber where water was poured into a steel ring placed on a specimen and then frozen at rest. In those tests, the force was applied parallel to the adhesion surface until ice was removed. The typical results are shown in Figure A. 63 and Figure A. 63. Although there may be a problem that has to be solved in terms of durability, the test results shows that one type of coating can significantly reduce the ice adhesion regardless of the manner of formation of ice [70,71].

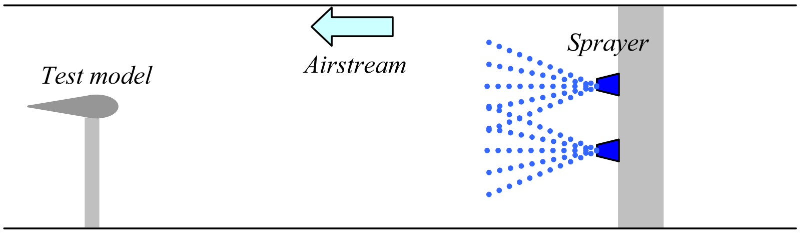


Figure A. 49 Schematic view of icing wind tunnel

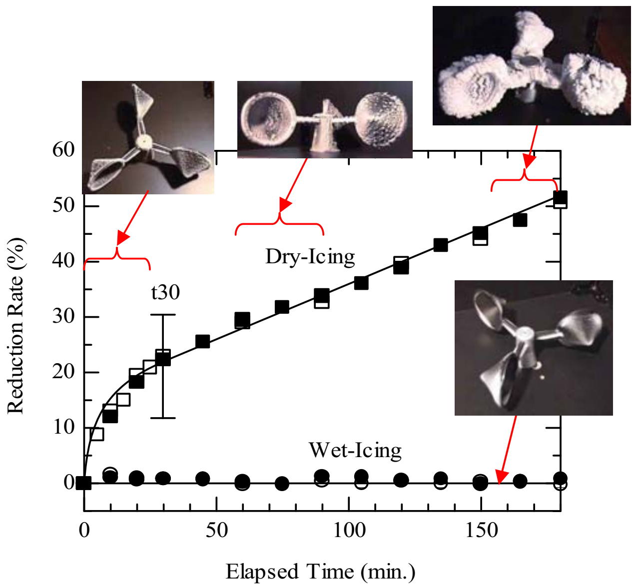
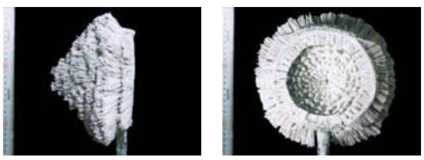


Figure A. 50 Effect of ice accretion on measurements by a cup

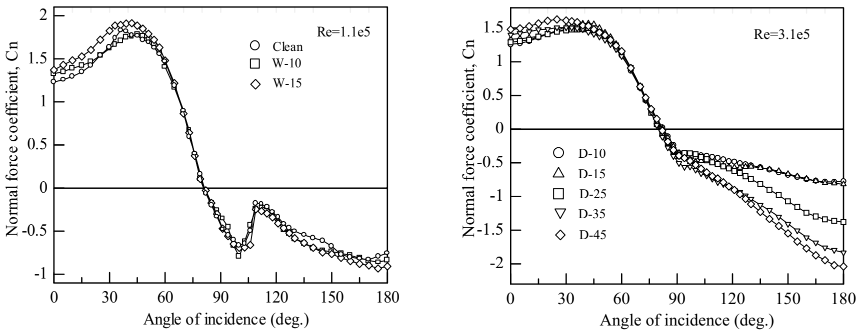
(a). Test model in the test sec-



(b). Imitated model

(c). Actually iced cup

Figure A. 51 Wind tunnel test for acquisition of aerodynamic characteristics



(a). Wet-Icing *(b). Dry-icing*

Figure A. 52 Aerodynamic characteristics of an iced cup-shaped body

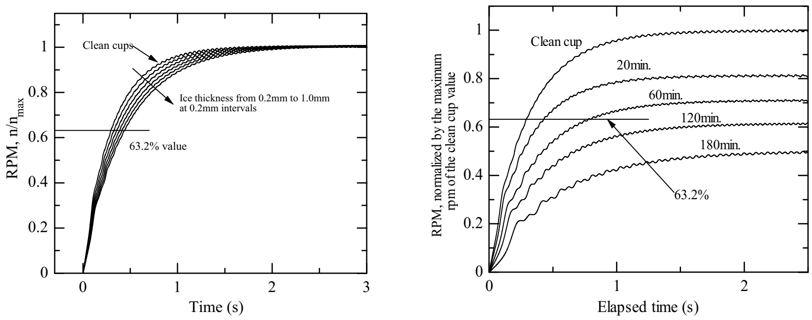


Figure A. 53 Calculations for cup behaviour

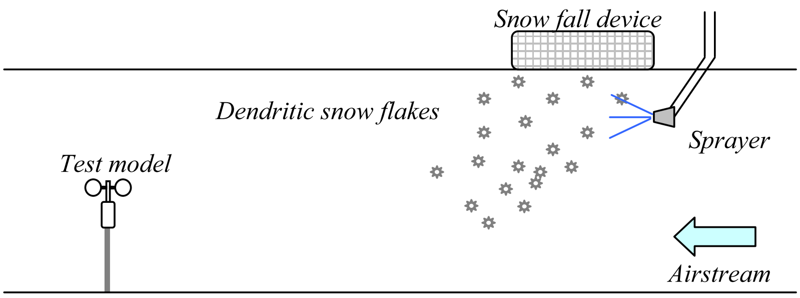


Figure A. 54 Schematic view of the wind tunnel test for snow accumulation on anemometer

Figure A. 55 Comparison of snow deposit between wind tunnel test and field test

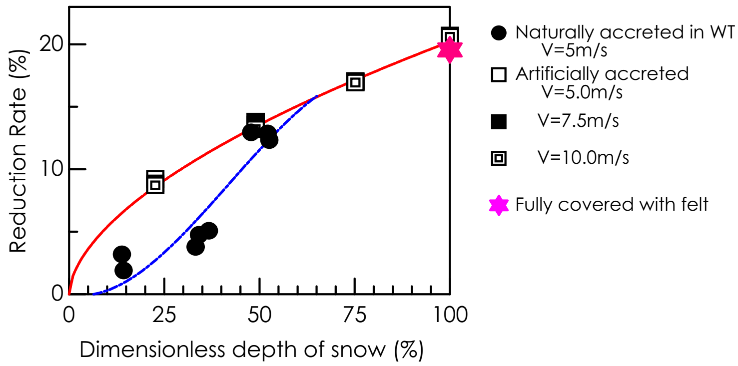
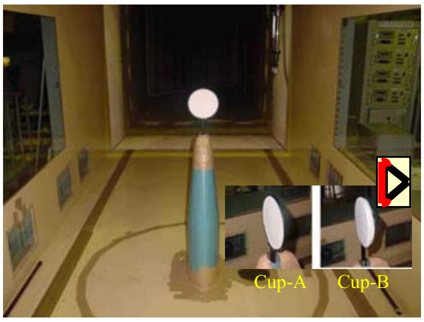


Figure A. 56 Effect of snow accumulation and cop-covering on measurements



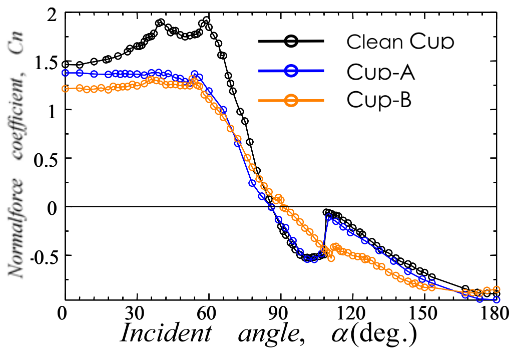
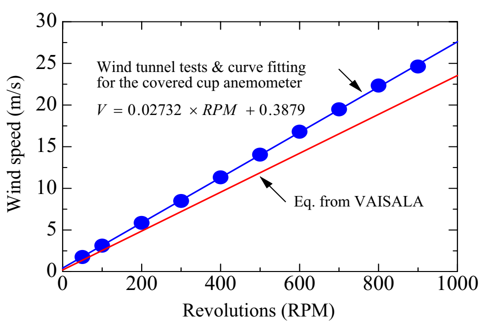


Figure A. 57 Test model in wind tunnel

Figure A. 58 Aerodynamic characteristics of a covered cup



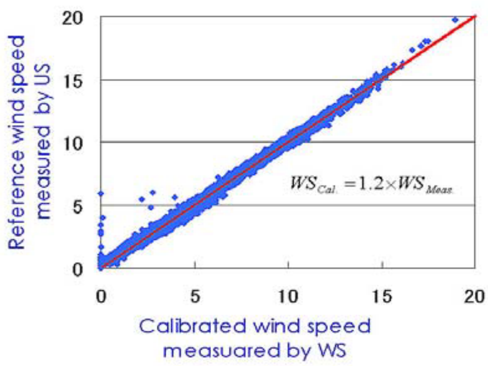


Figure A. 59 Transfer function of a covered cup anemometer

Figure A. 60 Field measurements by a covered cup anemometer and an ultra-sonic anemometer

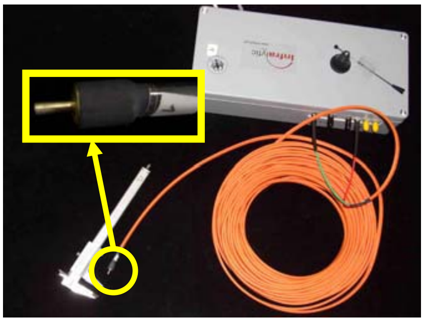


Figure A. 61 Ice detector tested

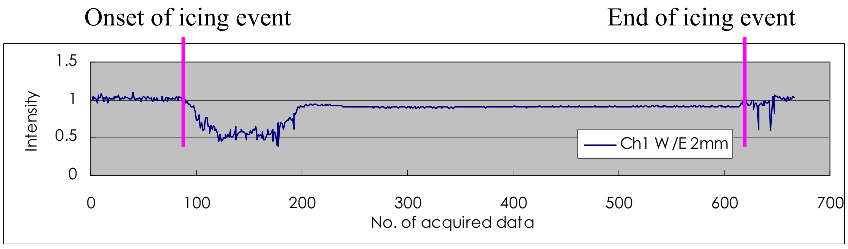


Figure A. 62 Signals from the ice detector in ice detection

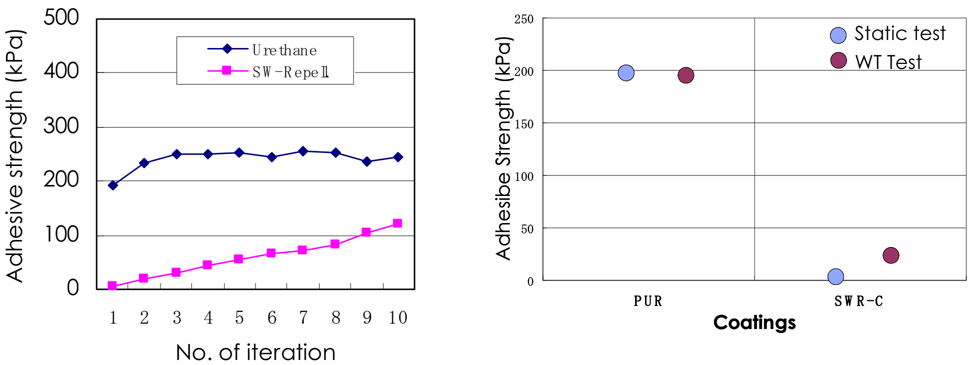


Figure A. 63 Comparison of the adhesive strength of ice formed in the wind tunnel test and in a chamber

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