COST Action 727 WG2 – Review of Results

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***Abstract*— The European Cooperation in the Field of Scientific and Technical Research, COST, established an Action on measuring and forecasting of atmospheric icing on structures in 2004 [1]. Phase 1 was completed in 2006 with a report describing the state of the art, mainly concerning WG2 "Measurements and data collection of icing" activities on available data and devices for measuring and observing icing on structures. A substantial part of Phase 1 was to establish an inventory of National activities and test sites within all participating countries in Europe, as well as an overview of available devices and instruments for measuring ice accretions and ice loads.**

I. Introduction

THE COST Action 727 was earlier presented to IWAIS 2005 [1] and IWAIS 2007 [2]. Several governmental and private institutions participated from initially 12 European countries: Austria, Bulgaria, Czech Republic, Finland, Germany, Hungary, Norway, Slovakia, Spain, Sweden, Switzerland and United Kingdom. During the course of the Action Spain became inactive, and Iceland joined the Action in 2008. Collaboration with Romania did unfortunately not succeed in full membership. In addition, the Kanagawa Institute of Technology in Japan has taken a very valuable part throughout the Action due to its icing wind tunnel facilities for instrument testing.

The Action consisted originally of 3 working groups: WG1 "Icing modeling" (chairman: Dr. Lasse Makkonen, Finland), WG2 "Measurements and data collection of icing" (chairman: Svein M. Fikke, Norway) and WG3 "Mapping and forecasting of atmospheric icing" (chairman: Dr. Hartwig Dobesch, Austria). The chairman of the Action was Dr. Bengt Tammelin, Finland from the start in 2004 until December 2007 when he handed over the Chairmanship to Dr Alain Heimo, Switzerland. From 2006 WG1 and WG3 merged, and the new combined WG1 is chaired by Dr. Lasse Makkonen.

The preparatory phase (Phase 1) terminated in 2006 with a report mainly based of the work of WG2 [3] (can be downloaded from http://www.cost727.org/). This phase focused on state-of-art, mainly to present the status of present and current activities in Europe and other countries concerning ice measurements and data collection of icing. The main content of that report was then to overview such activities in Europe over the last 50 – 60 years, provide links where to find further details on icing data, review available ice detectors in the market, contribute to the set up of icing measurements in Europe to compare and validate various ice detectors, and develop the scientific and technical base of specifications for ice sensors.

The main scope of Phase 2, from 2006 until the official end of the Action in April 2009, was to establish a number of test sites in Europe where selected instruments were tested and developed, with the purpose of finding appropriate instruments to be recommended for measurements and monitoring of atmospheric icing events on infrastructure such as wind turbines, electric overhead power lines, ski lifts, telecommunication towers, etc. Also, a major objective was to collect relevant icing data to be implemented by WG 1 in their developments of icing models, where existing physical models of icing were incorporated in numerical weather forecasting models of the atmosphere. The common goal was then to provide tools for monitoring and forecasting of icing as requested by the industry.

The Action 727 followed earlier activities within the field of atmospheric icing mainly pursued by bodies like the World Meteorological Organization (WMO/CIMO) [4] and the network of European Meteorological services (EUMETNET/SWS I&II) [5], [6]. These studies were supported mainly by France, Switzerland and Finland. Also other studies had been performed under wind energy related projects partly supported by European Union: "Wind Energy Production in Cold Climates" (WECO) and "Wind Turbines in Icing Environment: Improvement of Tools for Siting, Certification and Operations" (NEW ICETOOLS") [7], [8], as well as the International Energy Agency (IEA) R&D Wind Annex XIX "Wind Energy in Cold Climates" [9], [10].

Furthermore, WG2 has links to the Conseil International de Grands Réseaux Electriques", Cigré (www.cigre.org) [11], the International Electrotechnical Commission, IEC, (www.iec.ch) and its European counterpart CENELEC [12], [13] as well as the International Standardization Organization, ISO [14].

Additionally, WG2 refers to the broad spectrum of papers on atmospheric icing that have been presented to IWAIS since its beginning in 1982.

II. Phase 1

A. Definitions and terminology

Due to the lack of stringent terminology in practical communication it was decided to adopt and emphasize globally the terminology and definitions as specified by the ISO Standard 12494 "Atmospheric icing on structures" [14]. Here *ice accretion* is defined as "*any process of ice build up and snow accretion on the surface of an object exposed to the* *atmosphere*". Atmospheric icing is then classified according to two physically different formation processes:

- Precipitation icing, and
- In-cloud icing

Precipitation icing is then subdivided in freezing rain and wet snow. In-cloud icing is also named as "rime icing". Furthermore it must be noted that both freezing rain and in-cloud icing may have "dry growth" or "wet growth" according to variability in environmental parameters.

In order to advance the specifications and requirements for meteorological instruments and icing sensors of various kinds it is found necessary and practical to introduce two new definitions: 1) Meteorological icing and 2) Instrument 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, and d) the average and maximum accretion rate.

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

Instrument icing is then 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. Accreted ice which does not influence on the measurements is therefore not considered.

A **Performance Index**, **PI**, can then be defined as *"the ratio of the Instrument icing to the Meteorological icing"*:

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

By means of a "Site icing index" defined in [5] and [6], it is then possible to establish an *"Instrument Class Index"*, ICI, in order to classify a meteorological instrument with the respect to its performance for different icing locations.

Further definitions, details and discussions concerning these terms can be found in [3].

B. Requirements for Ice Detectors

Many sensors that are designed and labeled 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. 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 the generic descriptions given in the report.

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

Furthermore, the end user of the icing data has different requirements to the measurements and output parameters. Table I indicates this variability that has to be met by different sensors and other measuring devices [3].

TABLE I
ICE PARAMETERS REQUIRED [3].

	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	
Telecom masts		X		X
Suspension bridges		X		X
Transport (roads, railways)	X		X	
Meteorology and climatology	X	X	X	X

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.

C. Review of available ice detectors

There were few available instruments on the market during Phase 1 of the Action. However, there were some prototype instruments which seemed promising and might 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.

Table II displays the available and prototype instruments, to the best knowledge of the COST-727 / WG2 participants during Phase 1. These are classified according to working principles a) – h) above.

TABLE II
LIST OF AVAILABLE AND PROTOTYPES OF ICE DETECTORS ON THE MARKET DURING PHASE 1 OF THE ACTION

Type	Instrument	Manufacturer
a	Rosemount 0872J / 0871LH1	Goodrich (USA)
	Rosemount 872C2 (ASOS)	Goodrich (USA)
	SYGIVRE (Icing Rate Meter)	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 had been built in one version in Sweden ("IceMonitor" by then company Combitech, currently SAAB Security: automatic weighting, free rotation) and two in Finland (Digita: automatic weighing, forced rotation and FMI: manual weighting, forced rotation). A further development was 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. 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.).

D. National experiences

The experiences with automatic instruments for ice measurements within member countries of the Action are summarized in the Phase 1 report [3]. In short, these experiences are that most of the instruments do not perform satisfactorily over the season. Some of the prototypes were technically insufficient and/or not feasible for "plug-and-play" use. By the end of Phase 1 it seemed that the Rosemount/Goodrich ice detector and the IceMonitor had the best potential for field application. However, the availability for service of the Rosemount/Goodrich was not as good as was expected, and the IceMonitor had to be improved on some details.

Despite these restrictions it was decided by the Action 727 to base the ice measuring program in Phase 2 on these two instruments. The Rosemount/Goodrich is basically an on/off indicator for icing events and duration, while IceMonitor measures the development of accumulated loads.

E. Available data and information in Europe

The Phase 1 Report [3] summarizes the activities on collecting icing data from all member countries of the Action over the last 6-7 decades. This information is given in one Annex for each country. Iceland is however not included as it was not a member during this phase.

The need for long term measurements or monitoring was strongly emphasized based upon the measurements at Mount Studnice in the Czech Republic, where continuous data was collected since 1940. The time series of annual maxima is shown in Fig. 1.

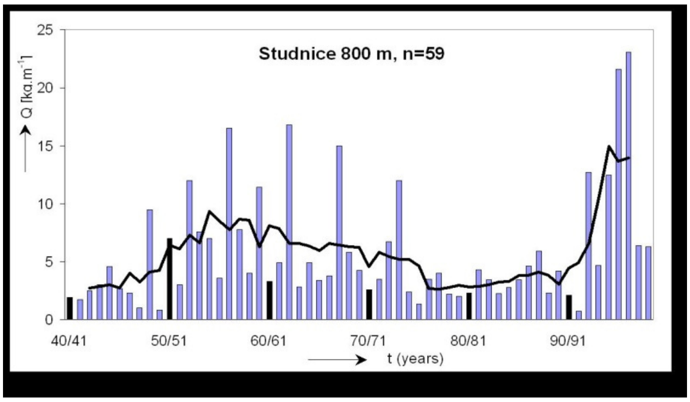

Fig 1. Time series of annual extremes of ice loads measured since 1940. Blue columns: annual maximum ice load in kg/m. Black line: 5 years averages plotted in central point of each moving interval [3].

Fig. 1 shows that there were quite dramatic changes in the frequency of high ice loads over these decades. The most important conclusion from this figure is that it may be dangerous for planning of infrastructure in mountainous areas to base the design and operation plans on to short time series of monitoring icing events. Icing studies must therefore be combined with climatological studies of related parameters.

F. Permanent forum for monitoring of icing in Europe

In the conclusion of Phase I WG 2 recommended working for a permanent forum for monitoring atmospheric icing in Europe. Such a network should cover regions of different icing environment noting the different climatic aspects, such as:

- 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)

Such a network must be established in collaboration with those public and private bodies that may have economic interest in icing aspects. One very important benefit from such a network is that it will provide a network of sites where new instruments can be tested out under natural conditions. There are certainly needs for a small number of sites where both icing instruments and conventional meteorological instruments could be tested out under natural conditions.

It was decided by the COST Action 727 to pursue such discussions with both the industry (especially for wind power) and the WMO/CIMO.

III. Phase II

The main objectives of Phase II were to:
- Select a number of existing measuring sites in Europe for parallel testing of potential reference instruments for atmospheric icing
- Collect data from the selected measuring sites to be used for modeling purposes by WG1
- Select two instruments (if possible) to be recommended as international reference instruments to be used for providing homogeneous data and global comparisons of icing conditions

A. *Measuring Sites*

6 different test sites were selected among the member countries. These were:
- Luosto, Finland
- Sveg, Sweden
- Deadwater Fell, UK
- Zinnwald, Germany
- Studnice, Czech Republic
- Gütsch, Switzerland.

These stations were selected because they already had a good infrastructure with monitoring systems, a variety of different meteorological sensors and instruments, data storage and transfer, good routines for inspections, etc.

As these stations and their equipment, instrumentation and data collection are presented separately in numerous papers and posters of this COST 727 Final Workshop (see final conference program for references), they will not be described further in the present paper.

From the practical point of view, all Station Managers met several times in order coordinate their work and to resolve common challenges. Also, it was provided opportunities for the WG2 members to visit as many of the test sites as possible.

A significant result from these sites is that WG1 got several sets of relatively homogeneous and standardized data from many icing events in Europe during the winters from 2007/2008 and 2008/2009. These events were then analyzed by the high resolution numerical "Weather Research Forecasting" model (WRF) and presented in [15].

B. *Reference Instruments*

The only known instrument which is able to measure correctly the liquid water content and median volume diameter of droplets in super-cooled clouds is the rotating multicylinder (RMC) [16]. This instrument depends however on manual operation and does not provide direct information on accumulated mass on a reference object. If automated, this instrument could be excellent for identifying icing events and their intensities. Also it would provide proper data for calculations of accreted ice on reference objects with the use of accretion models for rime icing.

Unfortunately the RMC cannot be used for standard measurements of icing since it is not automatic.

The RMC would not be feasible for wet snow or freezing rain.

Two different automatic instruments were selected as a basis for standard instruments for atmospheric icing. They also represent two different measuring techniques:
- *IceMonitor* manufactured by SAAB Security AB (former Combitech AB), Sweden. This is an instrument based in the recommendation in ISO 12494 [14]. It measures the weight of accreted ice on a 0,5 m long rod with diameter of 30 mm. It rotates freely and allows the ice to build up cylindrically. The bearings and electronics are kept ice-free by a thermostat controlled heater. This instrument monitors the accumulated ice during an icing event.
- *Rosemount (Goodrich) 0872J Ice detector (prototype)* and *Rosemount (Goodrich) Aerospace 0871LH1 Freezing Rain Sensor* manufactured by Campbell Scientific Corp., Canada. These detect icing on a vertical probe which vibrates vertically when the vibrating frequency drops due to extra weight on the probe. These instruments monitor the "on/off" condition of icing and the duration of an icing event.

These instruments were all generously provided by the manufacturers for the purpose of these tests. In particular, SAAB Security AB took part as active member of WG2 and made several efforts to improve their instrument during the course of these tests.

See reports from the six test sites for further details and experiences with these instruments. Some of these stations were also equipped with additional icing sensors that were provided by various manufacturers for testing.

Unfortunately, despite all efforts, in particular from SAAB Security AB, it was not possible for WG2 after these two winter seasons to conclude that any of these instruments was ready to be recommended to the market at this stage of their development. The main reasons for these are:

1) IceMonitor

The major shortcoming with this instrument was the stability of output signals. In several cases the output signal was destroyed by a noise signal (oscillations) with greater amplitudes than the measuring signal. Therefore it was in many cases not possible to deduce any appropriate level of accreted load. However, it seemed to identify the onset of an icing event relatively good, and also the shedding of ice after influence of warmer air.

This signal noise was identified to be related to the built-in heater and the thermostat regulation. A revised version was delivered by SAAB Security late autumn 2008 and was tested for a short time at some of the stations. The performance of this revised version was significantly improved, but it was not possible to conclude finally on this revision before the end of the Action.

A new version with forced rotation was under preparation by the end of the Action.

2) Rosemount (Goodrich)/Campbell Ice detectors

According to the field experiences from the test site Luosto in Finland the prototype 0872J provided fairly good results. It worked correctly most of the time and the heating power of the sensor was sufficient to keep the device free of ice and operational even in heavy icing situations [17]. In soft icing situations the accreted ice on the probe was not sufficient to trigger the onset function. Due to this effect the starting point of an icing event could be somewhat delayed.

The commercial version 0871LH1 worked correctly only during few icing events. After this it produced correct-looking data, but did not react to accreted ice on the probe. The reason for this is still not yet found. Also, it seemed that the de-icing heating system was not powerful enough and therefore the instrument was sheltered by lumps of ice around it, preventing any ice detection and operation.

Despite some positive reactions from Campbell Scientific Corp. it was too late to analyze this behavior in more details before the end of the Action.

3) Wind Tunnel Tests

Icing wind tunnel tests of several ice detectors were performed in two icing wind tunnels in Japan, one at the Japanese National Research Institute of Earth Science, and the other at the Disaster Prevention and Kanagawa Institute of Technology [18].

Since there are no standard specifications or requirements for ice detectors, with respect to droplet sizes, wind speeds, onset values, sensitivity, resolution, measuring range, etc., such tests procedures must be designed according to available infrastructure of the available icing wind tunnel, as well as the intrinsic properties of each available instrument. The wind tunnel tests would then provide information on the performance of different ice detectors. As long as an instrument shows stable and reproducible results, it should then be considered feasible for the use according to its own specifications.

Four different instruments were tested:

- IceMonitor, SAAB Security AB (former: Combitech AB), Sweden
- Rosemount/BF Goodrich 0871LH1, Campbell Scientific Corp., Canada
- SYGIVRE, Hydro-Québec, Canada (same detection mechanism as the previous)
- HoloOptics T26 Icing Rate Sensor (prototype), HoloOptics AB, Sweden

The general conclusion was that neither of these instruments was feasible for practical use under severe icing conditions without further revisions and developments. The output signals of IceMonitor had too large fluctuations due to noise, and freeze-up of rod connections prevented the free rotation of the rod in unidirectional wind (no turbulence). For the others it seemed that the heating capacity was too low to prevent ice build-up on the casing that disturbed the measurements.

These results were in line with the field experiences from the six test sites in Europe.

IV. Concluding Remarks

Unfortunately it was not possible during the course of the Action 727 to develop instruments with a sufficient degree of reliability and stability with the purposes of 1) clearly identify the onset and duration of an icing event, and 2) measure accumulated mass (weight) of ice during an icing event.

However, it must be stated that the chosen principles for such instruments, 1) frequency shifts of a vibrating rod and 2) weighing of a vertical rotating cylinder, are probably better than any other measuring principle that were available for the purpose of the Action.

Through the efforts by SAAB Security AB during this Action it seems very clear that, unless there is an abundance of research and development (R&D) funds available, it is of basic importance to have a powerful company as partner which is willing to allocate the necessary funding for such development. Consequently, such development can only take place when there is a sufficient market to pay back such investments.

At the end of the Action is the clear impression that, on a general basis, such markets are still too small in Europe. For the time being the wind energy industry seemingly cannot absorb more projects than today's market in European lowlands, and possibly at sea, where in-cloud icing or sea spray is not a problem. The electric overhead power line industry has at some occasions, in particular in Iceland requested monitoring systems for power line icing. Following smaller margins for reliable operation of European grids, this market may increase in coming years.

One exception from this pattern seems to be Sweden where a substantial wind power development is starting up, including wind turbines on hilltops of 300 m above sea level or more. In such cases in-cloud icing can be of great importance for the design and operation of wind turbines. A collaboration was therefore about to start up between SAAB Security AB and

Swedish wind companies at the time when the COST Action 727 was about to stop. For more information see [19].

It is also a conclusion from the test sites that it is not always sufficient to test icing instruments in laboratories. The complexity of adverse weather during icing events causes generally much more variability in environmental conditions than can be reproduced in a laboratory. Therefore wind tunnel tests of such instruments must always be accompanied with field studies of practical performance of the device.

It seems difficult to combine sensors which can operate reliable for all different icing types. The Rosemount/Campbell principle seems to work well for rime icing and freezing rain. In both cases it works probably only for dry growth. The IceMonitor is probably better for rime icing than for any other type, although it may have a potential for wet snow accretions as well, as long as the snow is not too wet and the wind is not too strong. These restrictions are however not controlled or quantified.

For future developments in this field it is important, as the experiences from e.g. Luosto and Gütsch show, to combine field measurements with video cameras and near on-line image transmissions in order to monitor the instruments on almost a continuous basis.

Future research should also be organized in collaboration with WMO/CIMO with the goal to recognize fully atmospheric icing as an important weather element under the concern and attention of WMO. Only with such collaboration a limited network of international field test sites for various types of instruments, conventional or non-conventional. Standard laboratory tests are not always sufficient to demonstrate the complete behavior and reliability of such instruments in harsh environments.

The most outstanding result of our activities is in collaboration with WG1 and our common efforts to combine measurements with the WRF simulations, showing that atmospheric icing can be measured and modeled as an independent meteorological element with credible results for both measurements and models. This is probably the most promising area of development in future research.

V. ACKNOWLEDGMENT

The author wants to thank all members of WG2 “Measurements and data collection of icing” for their enthusiastic and encouraging participation and efforts during the 5 years of inspiring activities in the COST Action 727. No one is mentioned, no one is forgotten. Indeed also the National institutions supporting each member have been important for the progress, achievements and knowledge we all now share. On behalf of WG2 the author is grateful to the first Chair of the Action, Dr Bengt Tammelin, for his and his colleagues’ original initiative and efforts to get this Action established and formed the basis for its success. Also the second Chair of the Action, Dr. Alain Heimo has been a driving force during the Phase II and inspired us all.

On behalf of WG2 the author will thank the industrial collaborators for their efforts and willingness to contribute to the challenging development of icing sensors, with the “dream-like” intention to work automatically under probably one of the most extreme environmental conditions the atmospheric boundary layer of the Earth can provide.

MeteoSchweiz provided generously their services by printing and publishing our Phase I Report within their series of publications, for which we are indeed very grateful.

Last, but not least, the Author is sincerely grateful to the European COST collaboration. This Action has provided excellent opportunities for a large group of young and more experienced researchers first of all to meet and to exchange experiences and knowledge, but also to develop international relations that future research will indeed benefit from.

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