AEROSPACE INFORMATION REPORT	AIR5666™	REV. A
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Icing Wind Tunnel Interfacility Comparison Tests

RATIONALE

This document represents a snap shot of the ice accretion capabilities of various icing test facilities. While accurate and current at the time of publication, the information contained in the AIR may or may not be current for those facilities today.

STABILIZED NOTICE

This document has been declared "Stabilized" by the SAE AC-9C Aircraft Icing Technology Committee and will no longer be subjected to periodic reviews for currency. Users are responsible for verifying references and continued suitability of technical requirements. Newer technology may exist.

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1. SCOPE

This SAE Aerospace Information Report (AIR) presents and discusses the results of tests of three models in six icing wind tunnels in North America and Europe. This testing activity was initiated by the Facility Standardization Panel of the SAE AC-9C Aircraft Icing Technology Subcommittee. The objective of the testing activity was to establish a benchmark that compared ice shapes produced by icing wind tunnels available for use by the aviation industry and to use that benchmark as a basis for dialogue between facility owners to improve the state-of-the-art of icing wind tunnel technology.

1.1 Purpose

The purpose of this AIR is to discuss the results of these tests. It documents that for any particular test-condition specifications the ice accretions produced in all of the participating facilities bore a broad resemblance to one another, but there were substantial facility-to-facility differences in ice shape and volume of accreted ice. Possible causes of the differences are discussed.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AIR4906 Droplet Sizing Instrumentation Used in Icing Facilities

AIR5320 Summary of Icing Simulation Test Facilities

ARP5624 Aircraft Inflight Icing Terminology

ARP5905 Calibration and Acceptance of Icing Wind Tunnels

2.1.2 U.S. Department of Transportation, Federal Aviation Administration (FAA) Publications

Available from FAA, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov. The FAA Icing Handbook is available through National Technical Information Service Springfield, Virginia 22161 (800)-553-6847 or (703)-605-6000.

Title 14 of the US Code of Federal Regulations, Federal Aviation Regulation Part 25 Airworthiness Standards: Transport Category Airplanes (14 CFR Part 25)

Title 14 of the US Code of Federal Regulations, Federal Aviation Regulation Part 29 Airworthiness Standards: Transport Category Rotorcraft (14 CFR Part 29)

DOT/FAA/CT-88/8-l, "Aircraft Icing Handbook, Volume 1 of 3" March 1991

2.1.3 NATO Advisory Group for Aerospace Research and Development (AGARD) Publications

Available from the North Atlantic Treaty Organization (NATO) office, at 7 Rue Ancelle, Neuilly-sur-Seine, France.

AGARD Advisory Report AR-304, Quality Assessment for Wind Tunnel Testing

2.1.4 Other Applicable Documents

Bragg, M. B., “A Similarity Analysis of the Droplet Trajectory Equation,” AIAA Journal, Vol. 20, no. 12, pp. 1681-1686, Dec. 1982.

Chigier, N., “Spray Science and Technology,” FED-Vol.178/HTD-Vol. 270, Fluid Mechanics and Heat Transfer in Sprays, ASME, 1993.

Chintamani, S., Delcarpio, D., and Langmeyer, G., “Development of Boeing Research Aerodynamic Icing Tunnel Circuit,” proc. AGARD Symposium on Aerodynamics of Wind Tunnel Circuits and Their Components, Moscow, Oct. 1996, AGARD CP-585, pp. 8.1- 8.27.

Gonsalez, J.C., Arrington, E.A., and Curry, R.M., “Aero-Thermal Calibration of the NASA Glenn Icing Research Tunnel (2000 Tests),” AIAA-2001-0233, Reno NV, Jan. 2001.

Ide, R. F. and Oldenburg, J. R., "Icing Cloud Calibration of the NASA Glenn Icing Research Tunnel," AIAA-2001-0234, Reno NV, Jan. 2001.

Kind, R.J., Potapczuk, M.G., Feo, A., Golia, C., and Shah, A.D., “Experimental and Computational Simulation of In-Flight Icing Phenomena,” Progress in Aerospace Sciences, Vol. 34, pp. 257-345, 1998.

Knezevici, D., Kind, R.J., and Oleskiw, M.M., “Determination of Median Volume Diameter (MVD) and Liquid Water Content (LWC) by Multiple Rotating Cylinders,” AIAA Paper 2005-0861, Reno NV, Jan. 2005.

Kreith, F., Principles of Heat Transfer, 2nd ed., International Textbook Co., Scranton, PA, 1965, ch. 9, 13.

Marek, C. J. and Bartlett, C. S.; “Stability Relationship for Water Droplet Crystallization with the NASA Lewis Icing Spray Nozzle,” AIAA-88-289, Reno, NV, Jan. 1988.

Miller, D.R., Potapczuk, M.P. and Langhals, T.J., “Preliminary Investigation of Ice Shape Sensitivity to Parameter Variations,” AIAA-2005-0073, Reno, NV, Jan. 2005.

Oleskiw, M.M., Hyde, F.H., and Penna, P.J., “In-Flight Icing Simulation Capabilities of NRC’s Altitude Icing Wind Tunnel,” AIAA-2001-0094, Reno NV, Jan. 2001.

Olsen, W., Takeuchi, D., and Adams, K., “Experimental Comparison of Icing Cloud Instruments,” AIAA Paper 83-0026, Reno NV, Jan. 1983. White, F.M., Viscous Fluid Flow, 2nd ed., McGraw-Hill Inc., 1991.

Schick, R.J., “An Engineer's Practical Guide to Drop Size,” Spraying Systems Co. (www.spray.com/lit/g_dropguid.asp).

Smolik, J., Dzumbovia, L., Schwartz, J., and Kulmala, M., “Evaporation of Ventilated Water Droplet: Connection Between Heat and Mass Transfer,” Journal of Aerosol Science, Vol. 32, pp. 739-748, 2001.

Strapp, J.W., Oldenburg, J., Ide, R., Lilie, L., Bacic, S., Vokovic, Z., Oleskiw, M., Miller, D., Emery, E. and Leone, G., “Wind Tunnel Measurements of the Response of Hot-Wire Liquid Water Content Instruments to Large Droplets,” Journal of Atmospheric and Oceanic Technology, Vol. 20., No. 6, pp. 791-806, 2003.

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Aerospace Technical Report.

Wright, W.B., “User Manual for the NASA Glenn Ice Accretion Code LEWICE (Version 2.2),” Ch. 13.

2.3 Abbreviations and Symbols

A_c	Accumulation parameter
ASSP	Axial scattering spectrometer probe
CIRA	Centro Italiano Ricerche Aerospaziali
CD	Compact Disc containing a complete set of all test data (see Section 5)
CR	Contraction ratio
FAA	Federal Aviation Administration
FSSP	Forward scattering spectrometer probe
FSTL	Approximate freestream turbulence intensity in test section with atomizing air on
H	Test section dimension in the direction perpendicular to the model span
L	Approximate distance from spray nozzles to model mid-chord
LWC	Liquid water content
MPSA	Malvern particle size analyzer
MVD	Median volumetric diameter
PDPA	Phase Doppler particle analyser
S1	Upper horn height (in)
S2	Upper horn angle (deg)
S3	Lower horn height (in)
S4	Lower horn angle (deg)
S5	Ice area (sq. in)
S6	Leading edge minimum thickness (in)
S7	Upper icing limit (in)
S8	Lower icing limit (in)
α	Angle of attack
β	Collection efficiency
τ	Test-run duration

3. INTRODUCTION

Partly in response to the United States Federal Aviation Administration (FAA) Inflight Aircraft Icing Plan, the Facility Standardization Panel of the SAE AC-9C Aircraft Icing Technology Subcommittee initiated an activity involving tests of three models in various icing wind tunnels and comparison of the ice shapes produced on the models. The test results were discussed by test participants at a workshop held in August 2003 at Galaxy Scientific Corp. in New Jersey and again at a meeting of the Facility Standardization Panel held at the Italian Aerospace Research Center (CIRA) in Capua, Italy, in October 2003. This report presents an outline of the test results and a discussion of possible reasons for some features of the results. Included in Appendix C and Appendix D are reports which were prepared for that workshop and meeting, and which support the discussion contained in the main body of this AIR.

4. BACKGROUND

Each of the major icing wind tunnel facilities in North America and Western Europe were invited to participate in the Facility Standardization activity, with a deadline of March 31, 2003, for submission of initial test results. It was agreed at early meetings of the Facility Standardization Panel that test results would be kept anonymous so that the facility that produced any particular set of results could not be identified. Each participating facility would be identified only by a randomly assigned letter. However, once testing was completed and an initial review conducted, it was agreed that the facilities could be identified in the final report and the identifying letters are included in Table 1.

Six facilities (designated by the randomly assigned letters A, E, F, H, M, and P) performed tests. Table 1 lists these facilities and includes icing wind tunnel parameters and information regarding instrumentation used for the tests.

Three models were tested: a 36 in chord NACA 0012 airfoil at angle of attack α = 3 degrees, a 12 in chord NACA 0012 airfoil at α = 3 degrees, and a 1.5 in diameter circular cylinder. The same three models were shipped from facility to facility for use in each test. Nominal test condition parameters were specified as follows:

- freestream air static temperature: -7, -23 and -30 °C
- liquid water content (LWC): 0.5 and 1.0 g/m^3
- drop diameter (MVD): 20 and 40 μm
- freestream airspeed: 67 and 90 m/s

TABLE 1 - PARTICIPATING FACILITIES DATA

Tunnel Letter	H	P	F	A	E	M
Facility	AIWT, NRC (Oleskiw, et al [2001])	GKN ATS (formerly ACT), UK*	BRAIT, Boeing (Chintamani, et al [1996])	COX	Goodrich	IRT, NASA (Gonsalez, et al [2001])
H	22.5 in (57.2 cm)	30 in wide (76.2 cm)	72 in (182.9 cm)	46 in (116.8 cm)	44 in (111.8 cm)	108 in (274.3 cm)
L	13 ft (3.96 m)	16 ft (4.9 m)	20 ft (6.1 m)	19 ft (5.8 m)	21 ft (6.4 m)	44 ft (13.4 m)
CR	5.8	15.5	7.2	9.6	11.0	14.1
FSTL (%)	1.5	No details available at present	Less than 2%	1 to 1.25	3	<1.5
Instrumentation for LWC	Single Rotating Cylinder confirmed by Icing Blade.Multiple rotating cylinders and King Probe have also been used for some conditions.	Icing blade.	Icing Blade	Icing Blade	Rotating Cylinders	Icing Blade
Instrumentation for MVD	Malvern Spraytec (borrowed from Cox & Co.) and PDPA (borrowed from AEDC). Multiple rotating cylinders have been used for some conditions.	Malvern Insitec (Spraytec) Model No. OHD-EPCS-4.0	PDPA	Malvern Spraytec RTS 5214 (mainly), and FSSP+OAP	*TSI* PDPA	FSSP & OAP
Calibration Standards for LWC	Single Rotating Cylinder and Icing Blade.	LWC calibrated at 1 in or 2 in grid spacing (depending on test component size) for each new test installation / configuration or variation of airspeed and/or cloud drop MVD	Icing Blade	ARP5905	ARP5905	
Calibration Standards for MVD	Field calibration Reticule for Malvern (borrowed from Cox & Co.)	Malvern Insitec calibrated (verification) annually by manufacturer using standard reticule	Boeing Procedure utilizing mono-dispersed drop generator	Malvern Reticule	ARP5905	Glass beads (FSSP) Rotating Reticule (OAP) (Ide, et al [2001])
Test Date	7/02 & 7/04	2/03 & 5/04	11/98	9/02	10/02 & 10/03	11/98 & 9/00

* When required the Malvern instrument is used to confirm the cloud drop MVD just before the start of test. The measurements are made "in situ" just downstream of the tunnel contraction - immediately before entering the tunnel working section.

H = test section dimension in the direction perpendicular to the model span
L = approximate distance from spray nozzles to model mid-chord
CR = contraction ratio
FSTL = approximate freestream turbulence intensity in test section with atomizing air on

Up to three repeat runs were carried out for some cases and centerline and off-centerline ice-shape tracings were made by most of the facilities. The specified test matrix is shown in Table 2.

TABLE 2 - SPECIFIED TEST MATRIX

					Icing Time (min)				
Test Cond.	Static Temp °C/°F	LWC g/m^3	Drop Size µm	Speed m/s/mph	36 in NACA 0012	12 in NACA 0012	1.5 in Cylinder	Icing Type	Repeat Cond.
1	-7/20	0.5	20	67/150	25	20	15	Glaze	3
2	-7/20	0.5	20	90/200	20	15	10	Glaze	3
3	-7/20	1.0	20	67/150	20	15	10	Glaze	3
4	-7/20	1.0	20	90/200	15	10	10	Glaze	3
5	-7/20	1.0	40	67/150	20	15	10	Glaze	3
6	-7/20	1.0	40	90/200	15	10	10	Glaze	3
7	-30/-22	0.5	20	67/150	25	20	15	Rime	2
8	-30/-22	0.5	20	90/200	20	15	10	Rime	2
9	-23/-10	0.5	20	67/150	25	20	15	Rime	2
10	-23/-10	0.5	20	90/200	20	15	15	Rime	2
11	-30/-22	1.0	20	67/150	15	10	10	Rime	3

No standard was available to gauge which ice shapes were closest to the “truth.” The test results consist primarily of ice-shape tracings. Tracings obtained in the different facilities are compared to provide an indication of facility-to-facility variations.

In the original test plan (Appendix A), 12 test condition cases were proposed. Test condition 12 was nominally the same as test condition 2 except that the test facilities would adjust the air temperature to get a model temperature that was recorded when the first facility (NASA) ran the test. The intent was to evaluate any facility-to-facility differences in measured air temperature. Because of an inadequate explanation in the test plan of how to run test condition 12 and a confusion of the intent behind condition 12, that condition was not run consistently or widely at all. Therefore, condition 12 results are not included in this report.

The test matrix in Table 2 would involve 29 test runs for each model, for a total of 87 runs, if the specified number of repeats were carried out. Some of the facilities carried out a substantially smaller number of test runs, mainly by reducing the number of repeat runs. Note that glaze icing is expected for about half of the specified test conditions and rime icing for the remainder. The results were collected in the form of ice-shape tracings on cardboard templates, prepared using the techniques in normal use at each facility. Facility operators were encouraged to collect three tracings from each ice accretion, one at the centerline (i.e., mid-span), one some distance to the left and another some distance to the right. The spanwise distances between tracings were chosen by the operators.

The tracings are designated as *centerline, left,* and *right.* However, only one tunnel provided tracings with these designations. In order to facilitate comparison of the data, the designations provided by tunnel operators were mapped onto *centerline, left, and right*. Table 3 shows the designations provided by the tunnel operators and their mapping onto *left* and *right*. All centerline tracings were designated centerline by the tunnel operators, except for one which only provided one tracing for each test. These were assumed to be centerline.

TABLE 3 - LEFT/RIGHT MAPPINGS

LEFT	RIGHT
West	East
Starboard	Port
Outside	Inside
-	+
Below	Above

5. PROCESSING AND PRESENTATION OF RESULTS

All ice-shape tracings were digitized using a Calcomp digitizing tablet controlled by Didger 3® software created by Golden Software, Inc. The initial digitization typically yielded files containing several thousand coordinates for each tracing. The number of coordinates was reduced to about 200, using a process called *decimation,* and these coordinates were entered into an MS-Excel® spreadsheet. Checks showed that the number of coordinates retained was more than adequate to represent the tracings in detail.

A Cartesian coordinate system was used for the clean models and digitized ice-shape tracings. The origin is at the leading edge of the clean model and the x axis is coincident with the model's chordline. The x-axis points to the right which is the downstream direction in the plots. Coordinates of the model were entered sequentially, proceeding counterclockwise, starting at the trailing edge (x/c, y/c = 1.0, 0) of the model. However, coordinates of the ice shapes were entered in either clockwise or counterclockwise direction, depending on the complexity of the plot. Plots of the tracings and clean models were prepared in Excel®. The plots are in terms of non-dimensional coordinates, (x/c, y/c), where c is the chord length. Only selected results will be presented in the hard-copy version of this document, to illustrate the discussion. The complete results are stored on a CD-ROM (CD), which is available by request from the Flight Safety Branch, FAA William J. Hughes Technical Center. This CD contains directories for each participating facility, A, E, F, H, M, and P, as well as *Composites* directory and a directory using the THICK computer program written by W. Wright for NASA Glenn Research Center. Table 4, and also the file *Overview Matrix* on the CD, shows which test runs were done by each facility. The facility directories contain Excel® spreadsheets, including plots of all tracings, for every test condition provided by that facility. The *Composites* directory contains Excel® files with composite plots, i.e., overlaid plots of the centerline tracings from the various facilities for each test condition of Table 2. The plots in the *Composites* directory enable easy comparison of the results from the different facilities. See the *Read Me* file on the CD for details.

After the August and October 2003 workshop and meeting, several of the participating facilities carried out additional test runs. These were runs specified in the test matrix, Table 2, that the facility had either not done in its initial tests, or wished to repeat, because tunnel settings or icing times in the initial test runs had not corresponded with the specifications of Table 2. In cases where initial tests were re-run, only the results of the re-runs are included on the CD-ROM; that is the results of the corresponding earlier runs have been discarded. The final results comprise tracings from 340 runs, with 930 ice-shape tracings.

The following identification convention was adopted for the test runs:

first field [*model*]	*N36*, *N12* or *C15* for 36 in NACA 0012, 12 in NACA 0012 or 1.5 in Cylinder, respectively
second field [*test condition*]	*01* to *11* per left hand column of Table 2
third field [*repeat #*]	*R1, R2, or R3* corresponding to first, second or third run for the particular test condition; this field is omitted if reference is to more than one repeat run
final field [*facility*]	*A, E ,F, H, M*, or *P*