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RTO-TR-038

NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION

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RTO TECHNICAL REPORT 38

Ice Accretion Simulation Evaluation Test

(Essai d’évaluation de la simulation de l’accumulation de glace)

Report of the Applied Vehicle Technology Panel (AVT) Task Group AVT-006.

Published November 2001

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Edited by R.J. Kind

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The Research and Technology Organization (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also coordinates RTO's cooperation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of initial cooperation.

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• AVT	Applied Vehicle Technology Panel
• HFM	Human Factors and Medicine Panel
• IST	Information Systems Technology Panel
• NMSG	NATO Modelling and Simulation Group
• SAS	Studies, Analysis and Simulation Panel
• SCI	Systems Concepts and Integration Panel
• SET	Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier cooperation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Ice Accretion Simulation Evaluation Test

(RTO TR-038 / AVT-006)

Executive Summary

In-flight ice accretion continues to be an important flight safety issue. Computational simulation of ice accretion is a key tool in the design, development and qualification or certification of aircraft for flight into known icing conditions. The ability of the computational codes to accurately predict ice accretion shapes is pivotal to improving costs and scheduling currently required to certificate/qualify aircraft for in-flight icing operations. The North Atlantic Treaty Organization Research and Technology Organization has sponsored an international task group to provide an assessment of how reliably computer codes can predict ice accretion shapes for conditions representative of in-flight icing. A key objective was to provide aviation regulatory authorities with an improved basis for judging the degree of reliance that can be placed on computational ice-accretion simulation methods in the aircraft certification/qualification process. The work, which was complementary to other related activities sponsored by the SAE and FAA, is documented in this report.

The assessment was based on computation of ice-accretion-shape predictions by developers and users of icing codes for selected aerodynamic shapes and icing conditions, and comparison of the predictions with the experimental ice shapes for those cases. The experimental data cases were selected by the Task Group. A high level of confidence in the accuracy of the data was an important selection criterion; data from a range of facilities was also considered desirable. Participants in the code assessment activity first computed predictions of ice accretion shapes for the various data cases without having access to the measured ice-shape data (i.e. ‘blind’ predictions). The experimental ice-shape data was then provided to participants and they were asked to prepare oral presentations discussing their results, to be given at a workshop held on December 6-7 at the CIRA facility near Capua, Italy. A CD-ROM containing all the experimental and predicted ice shapes was made and distributed, at the start of the Workshop, to all attendees. The contents of this CD-ROM are included in the present report.

In addition to presentations on the code/experiment comparisons, the workshop included presentations giving the views of regulatory authorities and manufacturers regarding icing codes, as well as a panel discussion on in-flight icing measurements for research purposes.

Conclusions and recommendations arising out of the assessment activity and workshop include the following:

- There is still room for improvement in the quality of ice-accretion-shape predictions yielded by current icing codes. Large differences between predicted shapes and between predicted and experimental shapes were often encountered. None of the assessed codes stood out as being distinctly consistent and reliable relative to the experimental ice shapes.
- The experimental data cases used in this workshop were mainly glaze or mixed icing cases, the most difficult to predict. Results would have been more favourable on average if a substantial number of rime icing cases had been included.
- Although they have their shortcomings, current icing codes are very useful to both aircraft manufacturers and certification/qualification authorities. It is thus important to continue efforts to improve robustness, accuracy and range of applicability of icing-code predictions.
- The capabilities of ice-accretion codes need to be documented and validated over their full range of intended application. Version control of codes is essential for maintaining confidence in their use.
- Additional ‘benchmark’ validation data sets need to be collected and validation processes and acceptability criteria need to be developed.
- There is a need for in-flight data in natural icing conditions, suitable for validation of icing codes and of icing test facilities and techniques. A dedicated research aircraft is needed for this purpose.
- The consistency of ice shapes produced in icing wind tunnels needs to be investigated.
- Development of a reliable method to quantitatively judge similarity between ice shapes is needed. The method should consider the similarity between the aerodynamic effects of the ice shapes as well as the geometric similarities.

Essai d’évaluation de la simulation de l’accumulation de glace

(RTO TR-038 / AVT-006)

Synthèse

L’accumulation de glace en vol demeure un problème majeur pour la sécurité des vols. La simulation par ordinateur de l’accumulation de glace est un outil clé pour la conception, le développement, la qualification et la certification des aéronefs en conditions givrantes connues. La diminution des coûts et la révision des programmes actuels de certification/qualification des aéronefs en conditions givrantes passent par la prévision précise, à l’aide de codes de calcul des formes créées par l’accumulation de glace. L’Organisation pour la recherche et la technologie de l’OTAN a créé un groupe de travail international pour évaluer la fiabilité des codes de calcul en ce qui concerne la prévision des formes créées par l’accumulation de glace dans des conditions représentatives de l’accumulation de glace en vol. L’un des principaux objectifs de ce groupe a été de fournir aux autorités de l’aéronautique chargées de la certification/qualification des aéronefs un meilleur modèle pour l’évaluation du degré de confiance qui peut être accordée aux méthodes de simulation de l’accumulation de glace. Le travail, qui était complémentaire à d’autres activités connexes organisées par le SAE et le FAA, est présenté dans ce rapport.

L’évaluation a été basée sur des prévisions établies par ordinateur de la forme des accumulations de glace, effectuées par des concepteurs et des utilisateurs de codes de givrage pour des formes aérodynamiques et des conditions de givrage bien déterminées, ainsi que sur la comparaison des prévisions avec les formes expérimentales de glace pour ces mêmes cas. Les cas de données expérimentales ont été choisies par les membres du groupe de travail. Un degré de confiance élevé en la précision des données a été un critère de sélection important; la disponibilité de données fournies par un certain nombre d’installations différentes a été également considérée comme souhaitable. Les participants à l’activité d’évaluation des codes ont d’abord réalisé des prévisions des formes des accumulations de glace pour les différents cas de données sans avoir accès aux données sur les formes de glace obtenues par mesure (c’est-à-dire des prévisions “aveugles”). Ensuite les données expérimentales sur les formes de glace ont été fournies aux participants, auxquels il a été demandé de préparer des présentations orales sur leurs résultats et de les présenter lors d’un atelier organisé les 6 et 7 décembre au CIRA près de Capua, en Italie. Un CD-ROM contenant l’ensemble des formes de glace expérimentales et calculées a été réalisé et distribué à l’ensemble des participants lors de l’ouverture de l’atelier. Le contenu de ce CD-ROM est inclus au présent rapport.

En plus des présentations sur les comparaisons entre les codes et les expérimentations, l’atelier a proposé des présentations résumant les opinions des administrations et des fabricants concernant les codes de givrage, ainsi qu’une discussion sur des mesures du givrage en vol aux fins de recherche.

Les principales conclusions et recommandations résultant de l’activité d’évaluation et de l’atelier sont les suivantes :

- La qualité des prévisions des formes d’accumulation de glace données par les codes de givrage actuels peut encore être améliorée. Des différences importantes entre les formes calculées et les formes expérimentales ont été trouvées à plusieurs reprises. Aucun des codes évalués ne s’est révélé tout à fait sûr et fiable en ce qui concerne les formes de glace expérimentales.
- Les cas de données expérimentales examinés lors de cet atelier étaient pour la plupart des cas de glaçure ou des cas de givrage mixte, c’est-à-dire les cas les plus difficiles à prévoir. Les résultats auraient été plus favorables en moyenne si un nombre substantiel de cas de givre blanc avait été inclus.
- Malgré leurs lacunes, les codes de givrage actuels sont d’une grande utilité pour les avionneurs et pour les autorités de certification/qualification. Il est, par conséquent, très important de poursuivre les initiatives destinées à améliorer la robustesse, la précision et l’étendue de l’applicabilité des prévisions des codes de givrage.
- Il est important d’enregistrer les capacités des codes d’accumulation de glace et de les valider pour toutes les applications envisagées. Le contrôle de la version des codes est indispensable au maintien de la confiance de la part des utilisateurs.
- Des ensembles de données de validation supplémentaires de référence doivent être recueillis et des procédés de validation et des critères d’acceptabilité développés.
- Il y a lieu de collecter des données sur les conditions naturelles de givrage en vol, aux fins de la validation des codes de givrage et des installations et techniques d’essais de givrage. Cela suppose la mise à disposition d’un aéronef affecté à la recherche.
- Il y a lieu également d’examiner la régularité des formes de glace produites par les souffleries de givrage.
- Une méthode fiable d’évaluation quantitative de la similitude entre différentes formes de glace est demandée. La méthode doit prendre en considération la similitude entre les effets aérodynamiques des formes de glace ainsi que les similitudes géométriques.

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The following Appendices make reference to files contained elsewhere on this CD-Rom, information about which can be found by clicking on the appropriate Appendix below:

	FileName	Subject
Appendix A	**TR-038-APP-A-ReadMe.pdf**	**Workshop Presentations**
Appendix B	**TR-038-APP-B-ReadMe.pdf**	**Code Predictions versus Experiment**
Appendix C	**TR-038-APP-C-ReadMe.pdf**	**Numerical Indices for Experimental and Predicted Ice Shapes**

Preface

In-flight ice accretion continues to be an important flight safety issue. The North Atlantic Treaty Organization (NATO) Research and Technology Organization (RTO) has sponsored an international effort to provide an assessment of how well and reliably computer codes can predict ice accretion shapes for conditions representative of in-flight icing. The work is documented in this report.

The work was undertaken by the Task Group (TG) entitled “Ice Accretion Simulation Evaluation Test” which was established by the NATO-RTO Advanced Vehicle Technology Panel. This task group was a follow-on to the earlier AGARD-FDP-WG 20 on Ice Accretion Simulation, established by AGARD, the predecessor of RTO. In its final report, published in 1997*, AGARD-FDP-WG 20 documented experimental and computational methods available for simulation of in-flight ice accretion. In the course of their work, members of AGARD-FDP-WG 20 recognised the need for a thorough assessment of the capabilities of existing simulation tools, especially current computational methods for ice accretion simulation. That recognition led to creation of the follow-on task group which came into being in 1998.

Key objectives of the Task Group on Ice Accretion Simulation Evaluation Test were:

- Identify the current state of the art in computational ice accretion simulation.
- Provide a forum for code developers to identify shortcomings in their codes and to learn from other code developers how to improve their individual codes.
- Provide regulatory authorities with an improved basis for judging the degree of reliance that can be placed on ice accretion computational methods in the certification/qualification process.
- Promote the concept of quantitative assessment of ice shape comparison methods
- Provide a forum for identification of critical research needs in computational ice accretion simulation.

At about the same time, two other closely related activities were also getting underway: the Ice Accretion Code Panel of the SAE AC-9C sub-committee on Aircraft Icing Technology and, originating from the FAA Aircraft Inflight Icing Plan introduced in April 1997, the FAA Task 11A Task Group. There was a considerable amount of membership overlap on the RTO, SAE and Task 11A Task Groups. The SAE panel and Task 11A TG Icing Codes Subcommittee combined their activities to work on the development of validation criteria, information, and data for evaluation of simulation methods used to determine ice shapes on aircraft. These simulation methods included icing tunnels, ice accretion computer codes, and icing spray tankers. SAE Aerospace Recommended Practices will be produced for the simulation methods, to provide guidance in the design and use of the various icing simulation methods. Care was taken to ensure that the work of the three groups was complementary, that is to avoid overlap of work, and the RTO Task Group was confined to assessment of computational methods. Another related activity was an SAE workshop on Ice Shape Measurement and Comparison Techniques held at Boeing Engineering Center, Renton, Washington, USA in April 1999.

The RTO Task Group held its first meeting in September 1998 at Fokker Services in Amsterdam. At that meeting it was decided in somewhat specific terms what the Task Group should do and how it should be done, with due recognition of the aforementioned parallel activities. It was clear that computer predictions would have to be assessed by comparisons with data. The criteria for selection of data cases and possible sources of data were identified. Following the first meeting, invitations were issued to icing-code developers and users to participate in the assessment activity. The second meeting of the task group was held in October 1999 in Fort Walton Beach, Florida. At that meeting the approach to be used was defined in detail, a detailed schedule was established and specific data cases were selected. These decisions are reflected in the content of the main chapters of this report.

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* Ice Accretion Simulation, Report of the AGARD Fluid Dynamics Panel AGARD-FDP-WG 20, AGARD Advisory Report 344, December 1997 (ISBN 92-836-1067-9).

The work reported herein relied for its success on many substantial contributions. It would have been impossible without the experimental data for comparison, provided by BAe, Boeing, DERA, INTA, NASA and ONERA. The work of those who computed ice-shape predictions for the selected data cases was of course crucial; their names and affiliations appear in the Introduction. Also particularly important was the work of Rosemarie McDowall who served as Data Coordinator and Processor; she prepared the excellent graphical presentations of the experimental and computed ice shapes, which are the central feature of this report. Particular thanks are due to the FAA which supported Rosemarie McDowall’s participation in the work. Thanks are also due to Fokker Services which hosted the first meeting of the Task Group and to CIRA which hosted the December 6 and 7, 2000, workshop at which the results were presented and discussed. There were numerous other contributions in addition to those explicitly mentioned and the Task Group gratefully acknowledges them all.

It is noted with sadness that Prof. Dr. Bernhard Wagner passed away in April 1999. Up to that point in time he was a key member of the Task Group. He was the Chair of the earlier TG 20 and was one of the proposers of the present Task Group. As a colleague and friend he is much missed.

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1. Introduction

In-flight ice accretion continues to be an important flight safety issue. Computational and experimental simulation of ice accretion is one of the key tools used in the design, development and qualification or certification of aircraft for flight into known icing conditions. This report documents a recently completed international effort to assess the capabilities of computational methods for predicting ice-accretion shapes on aircraft. As outlined in the Preface, this effort was undertaken by a NATO Research and Technology Organization (RTO)Working Group and was complementary to other related activities sponsored by the SAE and FAA.

The primary goal of the work was to provide an assessment of the accuracy, reliability and range of application of computational methods for predicting ice accretion shapes on aircraft. A secondary goal was to collect experimental 'benchmark' test cases suitable for future code verification and validation work. The assessment of computational methods was based on computation of ice-accretion-shape predictions by developers and users of icing codes for selected aerodynamic shapes and icing conditions, and comparison of the predictions with the experimental ice shapes for those cases. A key objective was to provide aviation regulatory authorities with an improved basis for judging the degree of reliance that can be placed on computational ice-accretion simulation methods in the aircraft certification/qualification process. Another key objective was to provide a forum for code developers to assess capabilities of their codes and to identify research required for improving their accuracy and reliability.

Chapter 2 outlines how the assessment process was carried out, while Chapter 3 summarizes the presentations and discussions that occurred at a workshop which was the culmination of the process. Chapter 4 presents some conclusions drawn by the Working Group and offers recommendations for future work.

2. Description of the Assessment Process

As outlined in the Preface, the Working Group held two meetings at which the main decisions were made. An early decision was that the Working Group would achieve its goals by inviting icing code developers and users (*participants)* to compare predicted ice-accretion shapes with selected experimental shapes. The plan involved two stages. In the first stage the comparisons were 'blind'; that is only airflow, cloud, model geometry and test-facility data were provided to participants, who were requested to send their predicted results to a coordinator. In the second stage, the experimental ice-shape data was provided to participants. At this stage participants were free to carry out additional computations which could be included in the oral presentation of their results. In their oral presentations participants were requested to emphasise trends and to offer reasons for successes and shortcomings and suggestions for improvements to computational simulation methods. The oral presentations were delivered at a Workshop held on December 6-7, 2000 at CIRA, the Italian Aerospace Research Centre near Capua, Italy.

The experimental data cases were selected by the Working Group in a two-step process. At its first meeting it was decided to focus on glaze and mixed icing cases as these are much more difficult to predict than rime icing. Potentially suitable data sets were tentatively identified and members of the Working Group were tasked with gathering more detailed information on these for distribution prior to the second meeting. A high level of confidence in the accuracy of the data was an important selection criterion; data from a range of facilities was also considered desirable. At the second meeting 31 data cases were selected. These were sub-divided into two groups, 18 ‘core’ cases and 13 ‘optional’ cases. Participants were required to compute all the core cases and were encouraged, but not required, to compute optional cases. After the second meeting members of the working group assembled detailed flow condition, cloud condition, body geometry and facility data in a standard format for each of the selected data cases. The standard format was defined in terms of a Microsoft EXCEL spreadsheet; all of the cases used are available in this format in Appendix B. Tables 2.1 and 2.2 list the core and the optional cases, respectively. Unfortunately, it eventually proved impossible to assemble suitable detailed data for Cases C-1 to C-3 and O-2 to O-4, so these cases were not actually used in the assessment process.

Table 2.1 Core Data Cases

Case No.	Title	Provider	Description
C-1.	NASA Twin-Otter data	NASA, Potapczuk	In-flight icing (not available)
C-2.	NASA Twin-Otter data	NASA, Potapczuk	In-flight icing (not available)
C-3.	NASA Twin-Otter data	NASA, Potapczuk	In-flight icing (not available)
C-4.	DERA data (Artington icing tunnel)	DERA, Gent	NACA-0012, FAR Appx. C conds.
C-5.	DERA data (Artington icing tunnel)	DERA, Gent	NACA-0012, SLD
C-6.	LEWICE2 Validation data (IRT)	NASA, Potapczuk	GLC305 airfoil
C-7.	LEWICE2 Validation data (IRT)	NASA, Potapczuk	GLC305 airfoil; longer exposure.
C-8.	LEWICE2 Validation data (IRT)	NASA, Potapczuk	NLF0414 airfoil
C-9.	LEWICE2 Validation data (IRT)	NASA, Potapczuk	NLF0414 airfoil; longer exposure
C-10.	LEWICE2 Validation data (IRT)	NASA, Potapczuk	NLF0414 airfoil; higher alpha
C-11.	Multi-element Airfoil data (IRT)	NASA, Potapczuk	3-element airfoil; alpha = 8 deg.
C-12.	Multi-element Airfoil data (IRT)	NASA, Potapczuk	3-element airfoil; alpha = 4 deg.
C-13.	INTA/NASA Scaling Tests (IRT)	INTA, Feo	NACA-0012, 533mm (reference)
C-14.	INTA/NASA Scaling Tests (IRT)	INTA, Feo	NACA-0012, 267 mm (half-scale)
C-15.	Super Puma Run 8 (CEPr tunnel)	ONERA, Guffond	Blade section, high alpha
C-16.	Super Puma Run 19 (CEPr tunnel)	ONERA, Guffond	Blade section, high Mach no.
C-17	Boeing, BRAIT facility	Boeing, Shah	NACA-0012; MVD= 25µm
C-18	Boeing, BRAIT facility	Boeing, Shah	NACA-0012; MVD=39µm

Table 2.2 Optional Data Cases

Case No.	Title	Provider	Description
O-1	Jetstream 41	BAe, Hammond	In-flight icing
O-2	NASA Twin-Otter data	NASA, Potapczuk	In-flight icing (not available)
O-3	NASA Twin-Otter data	NASA, Potapczuk	In-flight icing (not available)
O-4	NASA Twin-Otter data	NASA, Potapczuk	In-flight icing (not available)
O-5	DERA data (Artington icing tunnel)	DERA, Gent	small cylinder
O-6	DERA data (Artington icing tunnel)	DERA, Gent	small cylinder, SLD
O-7	DERA data (Artington icing tunnel)	DERA, Gent	large cylinder
O-8	DERA data (Artington icing tunnel)	DERA, Gent	large cylinder, SLD
O-9	LEWICE2 Validation data (IRT)	NASA, Potapczuk	NACA-0012
O-10	LEWICE2 Validation data (IRT)	NASA, Potapczuk	NACA-23014(mod) airfoil
O-11	LEWICE2 Validation data (IRT)	NASA, Potapczuk	LTHS airfoil (round nosed)
O-12	LEWICE2 Validation data (IRT)	NASA, Potapczuk	NLF-0414 airfoil, 6 min.
O-13	LEWICE2 Validation data (IRT)	NASA, Potapczuk	NLF-0414 airfoil, 22 min.

Beginning in mid-1999 all known icing-code developers and various code users were invited to become participants in the code assessment activity. Open invitations to participate were also issued at various technical meetings. The initial response was excellent with all known production and developmental icing codes from Europe and North America represented by their developers and in many cases also by several users. Table 2.3 lists those who eventually did participate in the code assessment activity and whose results were presented at the workshop.

Table 2.3 Participants in the Code-Assessment Activity

Participant	Affiliation	Code Used
S. Aschettino	Eurocopter	ONERA 2000
N. Boer, F. Spek, I. de Bruyn	ADSE	TRAJICE 2
C. Dima, V. Brandi	CIRA	CIRA Multi-Ice, HELICE
G. Duprat	EADS Airbus SA	ONERA 2000
R. Gent	DERA	TRAJICE 2
D. Guffond, R. Henry	ONERA	ONERA 2000
D. Hammond	BAe	ICECREMO 3.1
I. Paraschivoiu	École Polytechnique de Mtl.	CANICE 3.0-beta
F.J. Simon-Calero	CASA	ONERA 1990
W. Wright; M. Potapczuk	OSS, Inc.; NASA	LEWICE 2.0

On March 21, 2000 about half of the data cases listed in Tables 2.1 and 2.2 were sent to all those who had indicated an interest in participating in the icing code assessment activity; the remainder of the available cases were sent some weeks later. All cases were sent by electronic mail in the standard MS-EXCEL spreadsheet format mentioned earlier; the experimental ice shape data were not included. Participants were instructed to compute ice accretion shape predictions and to enter their results as sets of x/c, y/c coordinates into a standard template provided by the Working Group in the form of an MS-EXCEL spreadsheet. These results were to be sent to the Data Coordinator by September15, 2000. Most participants met this deadline although a few results arrived within about two weeks after the deadline. The experimental ice-shape data was sent to participants either on September 15th or in the case of late submission of predictions, as soon as the predictions were received. This completed Stage 1 of the assessment activity, namely computation of blind predictions for the selected data cases.

Stage 2 was centred around the aforementioned workshop held December 6-7, 2000. Prior to the workshop the Data Coordinator prepared a compact disc (CD) containing the EXCEL data files, including the experimental ice shape data, and all the predicted ice-shape results in both spreadsheet and graphical form for all the data cases. This CD was distributed to all 28 workshop attendees; all of the material on this CD is included in this final report, in Appendix B. The workshop comprised oral presentations, typically of 30 minutes duration, by most of the persons listed in Table2.3 (in some cases where more than one participant used a particular code the oral presentations were consolidated). Open discussion sessions followed the presentations pertaining to each particular code. The workshop also included presentations outlining the perspectives of an aircraft manufacturer and of certification authorities regarding use of icing codes in their activities, as well as a short panel discussion on the place of in-flight icing data in icing research. Synopses of the presentations and discussions at the workshop are available in Chapter 3. These have been prepared by the Working Group with the help of synopses and copies of oral presentation slides provided by all presenters.

It was hoped that the participants would compare, in some quantitative fashion, their computed ice shapes with the experimental shapes. However, a robust computational tool for generating a numerical index giving some measure of quality of agreement for each case is not currently available. Additionally, no standard approach for performing such comparisons has been agreed upon within the icing community. The SAE, NASA, and FAA Working Groups are working at present to identify an acceptable method for comparison of ice accretion shapes. Unfortunately, no one useful method emerged from the SAE workshop on Ice Shape Measurement and Comparison Techniques. As a result only one organization, NASA, performed any such quantitative evaluation of their predictions. Following the Workshop, numerical indices were computed by the FAA for all of the experimental and predicted ice shapes, using the NASA methodology. These indices are tabulated in Appendix C.

Immediately after the workshop the Working Group held its third meeting to plan preparation of this report.

3. Icing Workshop

3.1 Description

The NATO/RTO Icing workshop was held at Centro Italiano Ricerche Aerospaziali(CIRA), Capua, Italy on December 6-7, 2000. The workshop was well attended by many members of the Working Group, code developers and users, and members from aviation regulation agencies. Approximately 30 participants took part in the two-day workshop. As outlined in the Introduction, the workshop was the culminating event in an activity undertaken to assess ice accretion code prediction capabilities and to establish a set of ‘benchmark’ experimental data cases suitable for code verification/validation purposes.

Presenters at the workshop included six code developers, two code users, and two representatives of certification authorities. Table 2.3 of the previous chapter lists the codes considered in the presentations. The code developers and users presented the results of their ‘blind’ predictions for the core and optional cases listed in Tables 2.1 and 2.2 and provided their perspectives on use of their codes. It had been hoped that each participant would compute at least all of the core cases; however only one participant presented predictions for all of the core cases. A representative of the FAA and another of the JAA presented their views on use of icing codes for aircraft certification and rule making. A manufacturers’ point of view was also presented. The workshop included extensive open discussion as well as a brief panel discussion on in-flight icing data. The slides used in the presentations are included in their entirety in Appendix A of this document. The sessions were very productive.

The workshop began with a brief overview of the data cases, presented by R.W. Gent. As mentioned earlier, the experimental ice shape data and all the predicted ice-shape results had been distributed to workshop attendees prior to the workshop in both tabular and graphical form and this material is available in Appendix B. As outlined in Chapter 2, the data cases were selected by the Working Group to further its objectives of assessing icing code prediction capabilities and to establish a set of ‘benchmark’ experimental data cases. Potential test cases were carefully examined for a high level of confidence in the accuracy of the data. The Working Group collected data cases for a wide range of conditions, 18 core cases and 13 optional cases, listed in Tables 2.1 and 2.2 . Flight test data are prone to doubts about accuracy of ice shapes and uncertainty in test conditions and this was a factor in the unavailability of the hoped-for in-flight icing data for core cases C-1 to C-3 and optional cases O-2 to O-4.

R. Gent’s overview was followed by presentations on the various codes. Short summaries of these presentations appear in the following sub-sections. The summaries include brief descriptions of the codes. Complete presentation slides are included in Appendix A.

3.2 Synopses of Presentations on Code/Experiment Comparisons

3.2.1 ONERA and Eurocopter Results (ONERA -2000 code)

The results computed at ONERA were presented by D. Guffond. They were obtained using the ONERA-2000 code. This is the most recent version of the ONERA 2-D icing code. Relative to earlier versions, it improves stagnation line ice thickness for high speed and total temperature cases. Two other organizations, Eurocopter and EADS Airbus SA also computed predictions using the ONERA-2000 code; in addition, CASA used the ONERA-1990 version of the code. All predictions were computed independently without any information exchange. EADS Airbus SA and CASA made separate presentations. Guffond’s presentation included comments on the Eurocopter results which were not presented separately.

The ONERA code uses a finite element method with a C grid to solve the velocity potential equation to determine the airflow field and it uses Lagrangian tracking to determine droplet trajectories and impingement locations. The Messinger model is used for ice accretion thermodynamics and correlations are used for convective and evaporative heat transfer. The Makkonen correlations enable a representation of roughness effects. The ice shape is first estimated for a given icing time in one step. Then the flowfield, the trajectories and the heat transfer coefficient are calculated for this ‘estimated shape’. Assuming that the values of the local collection efficiency and heat transfer coefficients vary linearly from their values on the clean airfoil to their values on the profile covered by the estimated shape, the thermodynamic balance is made and the final ice shape is calculated.

A few selected cases were presented. Guffond remarked that the ONERA code does not model cylinder cases well.

Three of Guffond’s slides (see Appendix A) compared the results obtained by ONERA and Eurocopter. One can see that the results are very close. This provides some indication of the negligible influence of the user on the final results produced by the ONERA-2000 code, at least in these examples.

Guffond believes that the test angle of attack for case C-15 was reported incorrectly. For this case (Super Puma blade, Mach 0.3, $\alpha = 10$ deg.) the ice accretion predicted by the ONERA code is not at the same position as the experimental accretion. The slides show predictions computed for angles of attack ranging from 2 to 10 degrees, with the best correspondence at 5 degrees. Guffond believes that the effective aerodynamic angle of attack was actually about 5 degrees, even though the quoted experimental (geometric) value is 10 degrees.

In one of Guffond's slides, a correction in the icing duration was given at the last moment and the calculation was made in great haste. A NACA0012 profile (in red) was erroneously used to calculate the ice deposit on a cylinder. This result should thus be ignored.

3.2.2 EADS Airbus SA Results (ONERA-2000 code)

The results computed at EADS Airbus SA for the core cases were presented by G. Duprat. They were obtained using the ONERA-2000 code, which is briefly described in sub-section 3.2.1

Duprat felt that in most of the cases the predicted ice shape agrees quite well with experimental data especially for cold temperature and low LWC conditions. Nevertheless, the ONERA code has difficulties in accurately predicting ice shapes in warm temperature and high LWC conditions. This suggests a need for improving the thermodynamic and mass balance modelling.

In spite of the modifications implemented in the ONERA-2000 code, the prediction of ice shape for supercooled large droplets (SLD) conditions reveals that ice thickness is still underestimated. Duprat believes that this indicates a need for efforts on modelling of droplet break up and splashing, development of a water run-back model that includes shedding of excess water, improvement of models for development of roughness, and for heat transfer associated with rough surfaces. However, the modifications implemented in the ONERA-2000 code have improved the prediction of the ice accretion extent on upper and lower surfaces.

Duprat observed the following trends, with input variations made within the accuracy range of the data: 1) good results are obtained for low temperature and low liquid water content, 2) ice thickness and shape are still underestimated, 3) the ice thickness in general was underestimated in SLD conditions, and 4) it is difficult to predict ice shapes in warm temperature and high liquid water content conditions.

Duprat observed that the attempt to predict ice accretion on the multi-element airfoil provided quite good results on the slat leading edge. A specific methodology was used, based on using an envelope profile to create a single element that enables predicting the ice shape on the leading edge. This method used varying incidence angle to match required lift.

Capabilities of the ONERA code to predict ice shapes for the optional cases were not assessed.

The following observations were made on the results for specific cases (changes are within accuracy range of the data):

C-4: improved results with temperature variation, but still not good.
C-5: changed temperatures again.
C-6 to C-9: predicted ice shapes agree reasonably well with the experimental data.
C-10: not good. Change temperatures and incidence to improve agreement. AOA changed. Best combination is T+5°C and AOA -4°.
C-11 & C-12: (multi-element): Used envelope method; leading-edge ice shapes agree quite well with the experimental data.
C-13 & C-14: changed temperature and LWC to change agreement. Improvement obtained by increasing temperature and decreasing LWC for C-13 and *vice versa* for C-14.
C-15: poor agreement – improved by changing AOA -5° and LWC by +20% increment.
C-17 & C-18: temperature changes do not help.

Duprat pointed out that his comparisons have shown the great influence of aero-icing conditions on ice predictions. In fact, within the typical accuracy range of parameters such as temperature and LWC, the predicted ice shape could vary significantly. Thus he recommended efforts to improve measurement quality (LWC, temperature, and droplet temperature) and to extend the experimental database in order to provide code developers with enough validated data for future developments.

3.2.3 CASA Results (ONERA-1990 code)

CASA used an early version of the ONERA code for computing ice shapes for the Core test cases. The results were presented by F.J. Simon. For high temperature cases, this version of the code underestimates ice thickness in the stagnation region. The essential features of this code are the same as those outlined in sub-section 3.2.1 for the ONERA-2000 code.

The mesh generation of the ONERA-1990 code failed for the cylinders. The cylinder geometry had to be streamlined in order to run the code. This was done by adding a tangent to the cylinder at the 100° geometrical angle from the stagnation point. Also, an ‘equivalent airfoil’ was used for simulating the multi-element cases since the code is not written for such an application. Best match of pressure coefficient, Cp, was used to select the modified geometry.

Simon observed that in general the ice shapes do not match well. Sensitivity analyses were conducted by changing roughness parameters, droplet size, LWC, density effects and exposure time.

3.2.4 CIRA Results (Multi-Ice and HELICE codes)

The results computed at CIRA were presented by V. Brandi and C. Dima. Two codes, Multi-Ice (2D) and HELICE (3D), were assessed. Multi-Ice is based on a panel method to calculate the aerodynamics, but can also be interfaced to different aerodynamic solvers. Multi-Ice can be used for both single- and multi-element cases. It uses the Messinger model for ice accretion thermodynamics. Either time stepping or a predictor-corrector method can be used to deal with ice accretion growth. Three time steps were usually used for the computations. Generally, this code works well for a single-element geometry. The multi-element calculations experienced some problems. Because of lack of time, viscous effects were not included in the aerodynamic calculations for the presented cases.

HELICE is intended for computation of ice accretion on 3-D components and can use a non-inertial reference frame, allowing computations for rotor or propeller blades. It can interface with various aerodynamic codes to determine the airflow field. It uses a Lagrangian approach for impingement and does boundary layer calculations with an integral method. At present the code performs only single time-step calculations. This code is in the development phase.

There were significant differences in the results for the two codes. A single droplet size, the MVD, was used in calculations for all cases except the multi-element airfoil cases where the actual droplet size spectrum was used.

The following observations were made in the presentation:

> For Case C-5, increased roughness helps; reducing the temperature between 2 and 3^{o}C is best. Changing the number and distribution of points makes significant changes in agreement.
>
> For Case C-9: multi-step works better. Agreement is better with fewer, rather than more, points.

3.2.5 DERA and ADSE Results (TRAJICE2 code)

The results computed at DERA and at ADSE were presented by R. Gent. They were computed using the TRAJICE2 code which was developed by DERA. The codes used by DERA and ADSE were essentially the same except that the DERA computations used the relative humidity value quoted for the experimental cases while the ADSE computations assumed 100% relative humidity in all cases. ADSE also used a fixed, constant, value of roughness for all runs, whereas DERA used a different value for each case, which was calculated by the code.

TRAJICE2 uses an aerodynamic panel method to solve for the potential airflow field and it uses Lagrangian tracking to determine droplet trajectories, impingement locations and catch efficiency distribution. A modified Messinger model is employed for calculating the ice accretion thermodynamics. This has been developed by DERA to allow for the effects of compressible-flow conditions on the convective and evaporative cooling heat transfer terms. Either roughened cylinder correlations or an integral boundary layer solution may be used to evaluate the convective heat transfer coefficient. The heat transfer coefficients are calculated using either a user specified value of ice roughness, or with a value of roughness generated by a correlation embedded within the code. The ice accretion can be re-panelled and the air flow field re-computed at a number of time steps to recognize the growth of the ice accretion as time proceeds. In TRAJICE2, this ‘multi-step’ approach to ice accretion prediction has to be completed manually by the user. A typical trajectory and ice accretion calculation on a Pentium class IBM Compatible PC requires less than 1 minute CPU time and is therefore very efficient for use in aircraft icing analyses.

DERA predicted results for 22 of the test cases. All results were for a single droplet size, the MVD. The ADSE runs, which used 100 % relative humidity, tend to have runback.

Gent also presented a personal qualitative assessment of the quality of the predictions of all of the codes presented at the Workshop. His evaluation appears in Table 3.6.1, in sub-section 3.6.

3.2.6 CANICE Results

The CANICE code has been developed at École Polytechnique de Montréal, in collaboration with Bombardier Aerospace Inc. Predictions made using the CANICE 3.0-beta version of the code were presented by I. Paraschivoiu, of École Polytechnique, leader of the CANICE development effort.

CANICE uses an aerodynamic panel method to solve for the potential airflow field which is then corrected for compressibility effects. The code uses Lagrangian tracking to determine droplet trajectories and impingement locations. The modified Messinger model is used for ice accretion thermodynamics, in conjunction with an integral boundary-layer solution for heat and mass transfer rates. The ice accretion is re-panelled and the airflow field is re-computed at each time step to determine the growth of the ice accretion as time proceeds. The time-step is user specified; it is recommended that it be between 30-50 seconds. CANICE 3.0-beta incorporates smoothing of the ice shape between each time step. The smoothing is based on three criteria: a minimum and a maximum allowable panel length and a maximum allowable angle between adjacent panels.

Results were presented for the core test cases only. The presented results were obtained using runs with 10 time steps. The presentation included the following observations on the results:

C-4 & C-5: too much runback.
C-6: colder temperature produced more satisfactory runback.
C-7: too much smoothing of the ice shape.
C-8: Relative humidity needs to be considered.
C-9 & C-10: Time step too large.
C-16: problem in the stagnation region.

It was noted that this exercise pointed out some areas that need to be improved. These include: the water-runback model, a better integration of roughness effects, models for physical properties and flow field prediction; also compressibility effects, suppression of ice accretion rate smoothing and correction of multiple stagnation points.

Trial modifications to the CANICE code based on 2-D wind-tunnel experiments resulted in a better matching with the NATO/RTO core test cases but validation against many other cases is still needed.

3.2.7 LEWICE 2.0 Results

Predictions using the LEWICE 2.0 code, developed by the NASA Glenn Research Center Icing Branch, were presented by W. Wright of OSS, Inc. (a contractor to NASA Glenn). The 15 Core cases and 9 optional cases were computed. Fourteen of the cases were 'blind' test cases and were not part of the LEWICE validation database.

LEWICE 2.0 uses a panel method to solve for the potential airflow field and it uses Lagrangian tracking to determine droplet trajectories and impingement locations. A modified Messinger model, which accounts for compressibility of the air and conduction into the airfoil, is used for ice accretion thermodynamics. An integral boundary layer technique is used to evaluate convective heat transfer rates. A correlation based upon the convective heat transfer rate is used to find the evaporation rate. The technique includes a correlation that accounts for roughness effects. The ice accretion is re-panelled and the airflow field is re-computed at a number of time steps to recognize the growth of the ice accretion as time proceeds.

A single drop size was used for computation of all the presented predictions except for the multi-element airfoil cases. The relative humidity was set at 100% if not specified. An average run-time for the code is approximately 161 seconds on a 400MHz PC.

The results and comparisons were presented using a quantitative analysis of ice shapes. Two methods were used. Eight geometric parameters were used in both methods for the quantitative analyses; these included icing limits, ice thickness, ice area, and horn angles. The quantitative analysis provides a more in-depth and objective assessment of code prediction capabilities than qualitative comparisons. Numerical indices corresponding to the eight geometric parameters were computed for the experimental and predicted ice shapes using a NASA in-house utility code. As mentioned in Chapter 2, after the Workshop the same numerical indices were computed by the FAA for all of the experimental and predicted ice shapes considered in the NATO/RTO assessment activity, using the NASA methodology; these indices are tabulated in Appendix C.

Wright observed that his quantitative analyses showed that LEWICE tends to under-predict the amount of ice for the NATO/RTO test cases. He found that LEWICE results were significantly poorer for conditions outside the previous NASA validation matrix than for cases inside that matrix, indicating that continued research is necessary to expand its capabilities in those areas.

The following observations were made on the results for specific test cases:

> C-15: High angle of attack is likely to cause separation. LEWICE showed a large increase in error for $\alpha = 6^o$ and greater.
>
> C-16: At high Mach number, there is extremely high evaporation; this may be a 'bug' in the program.

3.2.8 ICECREMO Results

D. Hammond of BAe Systems presented predictions obtained using the ICECREMO, Version 3.1, code.

The ICECREMO code has been under development by a collaborative research partnership in the United Kingdom during the last four years. It strives to use physics-based methods, free of empiricism, to the maximum extent possible. It is a fully 3-D method though currently restricted to a single block structured icing mesh. The airflow solution can be obtained from a range of computational fluid dynamics packages. The coupling of the flow solution to the icing code is currently done manually. The ICECREMO code consists of a Lagrangian droplet tracking module, a splash and bounce module, a water-film thickness and motion module, a heat transfer module and a freezing module. The heat balance and freezing is treated as a Stefan problem, allowing thermal conduction to be included in the heat balance (the Messinger model is a limiting case).

The BAE Systems RANSMB Navier-Stokes solver was used to provide the air flow field solutions for the presented cases. The present manual coupling between the flow solver and the ICECREMO code makes the use of the code involved and time consuming hence only two cases were analyzed, cases C-17 and C-18.

The predictions used a total of 6 time steps. Each step involves complex iterations to determine the water film motion, the heat transfer (conduction and convection) and the freezing. Hammond observed that the predictions appear to give good agreement on the position and amount of ice but the horn development is somewhat under predicted. He stated that an important factor is the current inability of the code to fully retain the history of water-film and ice thickness from one time step to the next. This gives the predictions a more rime like appearance than should be the case.

3.3 Regulatory Authority Views

3.3.1 JAA Perspective

E. Duvivier, of the JAA Icing Certification Branch, presented an overview of how artificial ice shapes are used in certification of aircraft. The prime goals are to reduce the number of flight tests required in natural icing conditions and to conduct in-flight evaluation of the aircraft handling and performance degradation due to ice accretion on the critical control surfaces.

To meet these goals, it is important to improve simulation tools' prediction capabilities to better match the observed conditions. Simulation tools such as computer codes and icing wind tunnels are accepted standards. The capabilities of these tools need to be documented, verified, and validated.

3.3.2 FAA Perspective

E. Hill, FAA National Resource Specialist for Environmental Icing, outlined FAA in-flight icing certification regulatory requirements and commented on the use and validation of ice accretion computer codes used during the certification process. In-flight icing certification regulations under development by the FAA and JAA will require recognition of aircraft performance degradations resulting from ice accretion beyond limited tolerances. Avoidance of these performance penalties is expected to place greater emphasis on the accuracy of icing computer codes. Also, the anticipated regulations will require recognition, as part of the aircraft's scheduled performance, of the performance degradation resulting from ice accreted prior to when the ice protection system becomes effective. Consequently increased use of primary automatic ice detection systems is foreseen.

FAA finds the following issues relating to ice-accretion simulation tools:

- To reduce the cost and flow-time of aircraft certification, industry would like the certification authorities to accept greater reliance on use of icing simulation tools.
- Certification authorities must ensure the acceptability of the icing simulators that are used for demonstrating compliance with in-flight icing regulations.
- There is limited documentation on validation and quality assurance programs for icing simulation tools.
- Criteria for acceptable tools for regulatory compliance are not clearly defined. How good is “good enough”?
- Limitations of icing simulation methods are not clearly understood.
- How universal is the validation?
- Questions remain relative to use of icing-wind-tunnel simulation methods:
  - Scale effects
  - Wind tunnel effects and limitations
  - Variations between simulation capabilities and natural icing conditions for droplet size spectra.
  - Steady-state simulated icing conditions *versus* unsteady natural icing conditions.
- Methodology for comparing ice accretions is obscure.

FAA believes that ice-accretion codes need to be validated and placed under version control to ensure continued confidence and acceptance of the codes as a tool to support regulatory compliance. Meeting these requirements, in turn, will reduce the need for flight testing of aircraft in natural icing conditions.

To accomplish the above, FAA recommends the following:

- Collection of ‘benchmark’ validation data sets from icing tunnel testing.
- Development of validation criteria.
- Development of validation processes and tolerances.
- Development of scaling laws.

3.4 Views of an Aircraft Manufacturer

This presentation was given by G. Duprat of EADS Airbus SA; not all members of the Working Group share some of the views that he expressed.

Aircraft manufacturers use ice-accretion codes as integrated design tools. At an early design stage this tool is necessary to identify the most critical aero-icing conditions. Icing constraints are taken into account for the definition of aerodynamic shape. One objective is to reduce the sensitivity and performance degradation due to ice and to optimise aircraft performance in an icing environment. Also, during the design stage, improvement of aircraft performance leads to consideration of the need for anti/de-icing systems. Accurate tools are also necessary to determine the proper area to protect (wing leading edge, engine intake,….) and to define the extent of the ice protection. Impingement limits of droplet diameters within the FAR Appendix C envelope must be considered. Finally, ice accretion codes are used for the definition of simulated ice shapes used for the assessment of aircraft performance in wind tunnel tests and in flight tests. The use of ice accretion simulation is necessary because of safety considerations, because the whole icing envelope defined by FAR Appendix C for natural icing conditions is difficult to cover in flight tests and the most critical icing conditions are difficult to find in nature. Economic considerations are also important, because flight tests in natural icing conditions are costly and time consuming. The computed ice shapes are reproduced and applied to the real aircraft or to wind tunnel models in order to justify the absence of protection and/or assess the aircraft behaviour when flying in icing conditions.

Duprat suggested that existing ice accretion codes are globally satisfactory for predicting ice shapes and that their limitations in use are well identified. He also suggested that the existing ice accretion codes are very accurate for use in the domain where extensive validation against comprehensive experimental data has been done. Duprat indicated that for other conditions such as SLD, multi-element airfoils, etc. there is a need for further development. The concerns are first how to clear the limitations within the Appendix C envelope and second how to further extend the capability of the codes to run for more severe conditions such as SLD. A major validation effort is necessary to enhance confidence of aircraft manufacturers and regulatory authorities.

3.5 Panel Discussion: In-flight Data

During pre-workshop activities, difficulties were encountered in attempting to collect reliable and accurate in-flight icing data. It was decided to have a panel discussion on this issue during the workshop. Panellists were T. Bond (NASA), R. Gent (DERA), D. Guffond (ONERA) and M. Potapczuk (NASA).

In-flight measurements of aerodynamic and cloud-condition parameters tend to be subject to large uncertainties; also cloud conditions tend to be very unsteady. Potapczuk presented tracings of flight test data for discussion purposes. He concluded that it was difficult to find 2 to 3 minutes of stable in-flight data which would resemble the steadiness of conditions prevailing in icing tunnel tests or assumed in computations. Reviewing the data, the panel agreed that the confidence levels in the accuracy of in-flight condition measurements are difficult to assess.

The panel discussed in-flight icing data requirements and what will be necessary to provide a form of data suitable for evaluation and validation of computational methods. It was felt that a dedicated research aircraft is needed for providing data suitable for such purposes. Discussion continued on the purpose of collecting icing data from flight tests. If the intent is to validate simulation tools, that is computer codes or icing tunnels, the task is enormously difficult. It was pointed out that there are differences between natural icing conditions and conditions in icing wind tunnels. The latter are, in effect, Appendix C icing-condition simulators; they are not natural icing simulators.

Because of the lack of suitable in-flight data, the panel concluded that code evaluation should, at least for the present, be conducted using only the empirical database ensemble from icing tunnel tests. Verification and validation of ice accretion codes will have to rely upon the extent to which current state-of-the-art test facilities can simulate in-flight icing conditions. Qualitative verification of the ability of codes to predict in-flight ice accretion shapes can be provided by comparisons with in-flight photographs showing ice accretion orientation and shape.

3.6 Concluding Remarks

3.6.1 Code Performance

The objective of this workshop was to examine the state of the art for ice prediction codes. As such, the experimental data cases selected for comparison were for the most part for warm temperature and high LWC conditions. These glaze and mixed ice shapes are the more difficult cases to predict due to the complex thermodynamic, fluid motion and heat transfer processes involved in ice growth under these conditions. The simple rime ice cases were not included and thus the overall performance of all the codes appears to be worse than if these cases had been included. The reader should keep this in mind when assessing the performance of these tools in general.

Readers may make their own assessment of code performance by viewing the plots of predicted and experimental ice shapes for the various cases. These plots are available in Appendix B in both PDF and TECPLOT format. The ‘composite’ plots are particularly useful for this purpose as each of these plots includes all of the predicted ice shapes submitted for a particular case as well as the experimental ice shape. To see an example, open the file \CoreCases\Core 10\Adobe Reader Files\C-10 Comp.pdf .

In his overview of the data cases, R.Gent presented a table showing his personal assessment of the quality of many of the predictions for the data cases. This table appears below as Table 3.1. Although this is an assessment by one individual only, it is helpful in giving a sense of the overall predictive capability of current icing codes. Clearly there is much room for improvement as in only relatively few cases is the quality of prediction rated as Good.

Table 3.1
Computed Ice Shape Predictions Assessed by DERA (R. Gent) for Blind Predictions

Case ID	Icing Code								
	Trajice (DERA)	Trajice (ADSE)	ONÉRA Duprat	ONÉRA Simon	ONÉRA Guffond	CIRA	CANICE	LEWICE	ICECREMO
C4	P	P	P	P	**	P	F/P	PU	X
C5	F	P	P	P	**	P	P	P/F	X
C6	P	X	G	G	**	F	G	F/G	X
C7	PS	X	G	F	**	F/P	F	PS	X
C8	F/G	F/G	F/G	F	G	G/F	F/G	F/G	X
C9	F/P	F/P	F/P	F/P	**	F	F/P	F/P	X
C10	P	P	P	P	**	PU	P	P	X
C11	X	X	P/F	P/F	**	PS	**	F	X
C12	X	X	F	F	PS	PS	**	F	X
C13	F	F/P	F/P	F/G	**	P	F/G	F/P	X
C14	F/G	F/G	F	F	**	P	F	P	X
C15	P	X	P	P	P	PS	P	P	X
C16	F	X	F	F/G	F	F/G	PS	PU	X
C17	F/G	X	PS	FS	**	F/G	FS	F/G	FS
C18	F/G	X	PS	F	PS	F/G	PS	F/G	FP
O1	X	F/G	X	PU	P	P/F	X	X	X
O5	F	X	X	PU	P	P	X	P	X
O6	F/G	X	X	PU	P*	P	X	PS	X
O7	F/P	X	X	PU	P	P	X	PU	X
O8	F	X	X	PU	P	P	X	FS	X
O9	F/G	X	X	F/G	F/G	F/G	X	FS	X
O10	F	X	X		**	F/G	X	G/F	X
O11	Deleted								
O12	FS	X	X	FS	F	F/G	X	PS	X
O13	P	X	X	PS	F	PU	X	PS	X

LEGEND:
G = Good
G/F = Good/Fair
F = Fair
F/G = Fair/Good
FS = Fair/Safe
P = Poor
PS = Poor/Safe
PU = Poor/Unsafe
P* = Poor due to user error, not code error
** = Result Unknown/Not Presented
X = Not Evaluated

Another assessment of the quality of the code predictions is presented in Appendix C where the eight NASA ice-shape indices, mentioned in Chapter 2 and in sub-section 3.2.7, are tabulated for the experimental and all the predicted ice accretions. This quantitative comparison also indicates that there is much room for improvement. The comparison plots in Appendix B enable the most direct appraisal of the quality of code predictions. It is evident from these plots that there are often large differences between predicted and experimental ice-accretion shapes. One noticeable trend is that most codes tend to under-predict the amount of ice build up. Not surprisingly, predictions tend to be poorer at relatively warm temperatures and high LWC, that is when freezing fraction is relatively low. None of the codes stands out as being distinctly superior.

Not all of the discrepancies between predicted and experimental ice shapes are necessarily due to deficiencies of the codes. As some of the presenters demonstrated, predictions can be quite sensitive to variation of aerodynamic and cloud parameters input to the code and variations within the uncertainty limits of the data produced substantial changes in predicted ice shapes. This illustrates the desirability of improving accuracy of measurements.

The ONERA-2000 code was used by three participants (ONERA, EADS Airbus SA and Eurocopter) who computed their predictions independently of each other. Except for the circular cylinder cases, where the ONERA code experienced difficulties with meshing, and for case O-9, the results of the different participants were quite similar, though not identical. Thus, at least for this code the results do not appear to be particularly sensitive to user judgements. On the other hand, when comparing results obtained by DERA and ADSE, who used slightly different versions of TRAJICE2, significantly different predicted ice shapes are seen for a number of cases. This is also seen when comparing predictions of the ONERA-1990 code, used by CASA, with those of the ONERA-2000 code. This suggests that predictions can be sensitive to modest changes in codes or to selection of options if codes make options available to users.

3.6.2 Code Usage

Although they have their shortcomings, current icing codes are clearly very useful to both aircraft manufacturers and certification/qualification authorities. A key use is to define simulated ice shapes to be used in wind tunnel and flight tests to assess aircraft performance and handling qualities degradation in icing conditions. Icing codes are also an important tool in the early stages of aircraft design; in this role they are used to identify the most critical aero-icing conditions and for the definition of aerodynamic shape of lifting surfaces etc., with one objective being to reduce the sensitivity of performance and handling to ice accretion. They are also used in the design of ice protection systems.

A strong incentive to improve icing codes is the desire to reduce the amount of test flying in natural icing conditions required for certification or qualification of the aircraft and its components.

3.6.3 Desirable Developments

Efforts to improve the accuracy and reliability of icing-code predictions, and to extend their range of applicability (e.g. to SLD conditions and multi-element airfoils), should of course continue. As part of these efforts, improved modelling of the physical processes (e.g. roughness development, heat and mass transfer, runback, splashing, droplet breakup, etc.) should be incorporated into codes. Icing tunnel experiments will be needed to provide information about these processes.

The capabilities of ice-accretion codes need to be documented and validated. To accomplish this, more ‘benchmark’ validation data sets need to be collected. In the near term these should come from icing-tunnel testing. Validation processes and criteria need to be developed. Validation needs to extend over the full range of intended application of the codes. In particular, validation is needed for both FAR Appendix C and SLD conditions and for multi-element airfoils.

Icing tunnel facilities and test techniques themselves need to be validated. Until suitable flight-test data become available, results from different facilities should be compared. Scaling laws should be further developed to expand the scope of icing tunnel testing. Effort to develop more accurate tools for measurement of aero-icing conditions is also necessary due to the sensitivity of ice shape predictions to parameter values.

The ultimate purpose of both icing codes and icing tunnels is to enable cost-effective design and certification of aircraft for flight in natural icing conditions. This implies a need for in-flight data in natural icing conditions, suitable for validation of the simulation tools. It was concluded that although obtaining such data presents great challenges, it is a highly desirable objective and a dedicated research aircraft is needed for the purpose.

4. Conclusions and Recommendations

There is still room for improvement in the quality of ice-accretion-shape predictions yielded by current icing codes. Large differences between predicted and experimental shapes are often encountered. None of the assessed codes stood out as being distinctly consistent and reliable relative to the experimental ice shapes. The experimental data cases used in this workshop were mainly glaze or mixed icing cases, the most difficult to predict. Results would have been more favourable on average if a substantial number of rime icing cases had been included.

Although they have their shortcomings, current icing codes are very useful to both aircraft manufacturers and certification/qualification authorities.

It is important to continue efforts to improve robustness and accuracy of icing-code predictions. To this end, improved modelling of the relevant physical processes should be incorporated into codes. Icing tunnel experiments will be needed to support these efforts. Code applicability should include SLD conditions and multi-element airfoils.

The capabilities of ice-accretion codes need to be documented and validated over their full range of intended application. Version control of codes is essential for maintaining confidence in their use. Additional ‘benchmark’ validation data sets need to be collected and validation processes and acceptability criteria need to be developed. Improvements in measurement accuracy are desirable for validation purposes.

There is a need for in-flight data in natural icing conditions, suitable for validation of icing codes and of icing test facilities and techniques. A dedicated research aircraft is needed for this purpose.

The consistency of ice shapes produced in icing wind tunnels needs to be investigated.

Development of a reliable method to quantitatively judge similarity between ice shapes is needed. The method should consider the similarity between the aerodynamic effects of the ice shapes as well as the geometric similarities.

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Research management
Requirements

14. Abstract

The NATO-RTO Task Group assessed computer codes for the prediction of ice accretion on aeroplanes which is an important flight safety issue. The following topics were treated:

- state of the art
- review codes in use or being developed
- provide reliability data for regulation and certification
- ice shape comparison methods
- critical research needs.

In order to compare the detail of codes a workshop was held involving experts from various institutions and companies.

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