NASA Technical Memorandum 107538

Scaling Methods for Simulating Aircraft In-Flight Icing Encounters

David N. Anderson
Lewis Research Center, Cleveland, Ohio

and

Gary A. Ruff
Drexel University, Philadelphia, Pennsylvania

National Aeronautics and
Space Administration

Lewis Research Center

October 1997

Available from

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David N. Anderson
NASA Lewis Research Center
Cleveland OH 44135
and
Gary A. Ruff*
Mechanical Engineering and Mechanics Department
Drexel University
Philadelphia PA 19104

ABSTRACT

This paper discusses scaling methods which permit the use of subscale models in icing wind tunnels to simulate natural flight in icing. Natural icing conditions exist when air temperatures are below freezing but cloud water droplets are super-cooled liquid. Aircraft flying through such clouds are susceptible to the accretion of ice on the leading edges of unprotected components such as wings, tailplane and engine inlets. To establish the aerodynamic penalties of such ice accretion and to determine what parts need to be protected from ice accretion (by heating, for example), extensive flight and wind-tunnel testing is necessary for new aircraft and components. Testing in icing tunnels is less expensive than flight testing, is safer, and permits better control of the test conditions. However, because of limitations on both model size and operating conditions in wind tunnels, it is often necessary to perform tests with either size or test conditions scaled. This paper describes the theoretical background to the development of icing scaling methods, discusses four methods, and presents results of tests to validate them.

NOMENCLATURE

A_c	Accumulation parameter, dimensionless
b	Relative heat factor, dimensionless
c	Characteristic model length, cm
$c_{p,w}$	Specific heat of water, cal/g K
d	Water droplet median volume diameter, μm
K_0	Modified droplet inertia parameter of Langmuir and Blodgett, dimensionless
LWC	Liquid-water content of cloud, g/m^3
M	Mach number, dimensionless
n	Freezing fraction of impinging water, dimensionless
p	Ambient static pressure, nt/m^2

*Summer Faculty Fellow at Lewis Research Center.

Re	Reynolds number, dimensionless
t	Ambient static temperature, °C
V	Free-stream airspeed, m/s
We	Weber number, dimensionless
ϕ	Water-energy transfer term, °C
Λ_f	Latent heat of freezing for water, cal/g
θ	Air-energy transfer term, °C
ρ_i	Density of ice, g/m³

Subscripts

| R | Reference or full size |
| S | Scale |

INTRODUCTION

Aircraft are susceptible to ice formations on engine inlets, tail planes and wings whenever flight through clouds at below-freezing temperatures occurs. Suspended water droplets in clouds are frequently super cooled; that is, the water exists as a liquid at a temperature below freezing. Supercooled water striking aircraft surfaces freezes, and the resulting ice accretions can have a significant and dangerous effect on the aerodynamic performance of an aircraft. In particular, ice formations decrease the lift and increase the drag. Large transport aircraft are protected against ice on critical components by directing hot air bled from the engine compressor to keep those surfaces warm enough to vaporize water. Some less critical surfaces may not be protected, and smaller aircraft often use intermittent impulse methods to remove small amounts of ice repeatedly.

Aircraft and component manufacturers must thoroughly test new products to determine the effect of icing on their performance. This testing is performed both during the design process and for certification purposes. Flight testing is ultimately required but is expensive and can only be done when atmospheric icing conditions exist. Icing wind tunnels can simulate natural icing with water-spray and refrigeration systems and provide control of cloud conditions, temperature and airspeed to permit safe, convenient and relatively inexpensive testing. Some measurement of lift and drag changes can be made in the icing tunnel, and ice shapes are often recorded. More precise aerodynamic-penalty studies can be made in flight or in an aerodynamic tunnel by attaching a wood or styrofoam reproduction of the ice shape to the leading edge of the airfoil.

Because of size limitations some components cannot be tested full size in an icing wind tunnel; furthermore, every tunnel has some bounds on the ranges of test conditions available for testing. For these reasons, it is desirable to establish reliable methods to scale either model size or test conditions. Efforts to establish scaling methods for icing tests began in the 1950's and continue to the present. In general, to test scaling methods an ice shape is recorded for a reference, or full-size, condition, the scaling equations are applied to find the appropriate scaled condition, and the scaled ice shape is recorded. The

two ice shapes are then compared. If size has been scaled, the comparison is facilitated by multiplying the coordinates of the scaled shape by the appropriate scaling factor. Whether the two shapes are in agreement is frequently dependent on subjective judgment, and the quality of agreement when the match isn't perfect has always been difficult to define. In this paper, in addition to the conventional subjective ice-shape comparisons, we also present a new approach to quantifying the ice shapes which permits more objective comparisons. We give an overview of the theoretical basis for traditional scaling methods, discuss briefly a Buckingham-π analysis, describe four scaling methods and present results from a series of tests of these scaling methods.

DERIVATION OF SCALING EQUATIONS

The traditional approach to the development of scaling methods has been to attempt similitude in the geometry, the flowfield, the trajectories of the water droplets, the water catch, and the energy balance at the surface. Various scaling "laws" have been derived [1,2,3,4,5] which provide similitude in some or all of these factors which affect ice accretion. When ice accretes in the rime form, in which impinging water freezes on impact, simple scaling methods which ignore the surface energy balance have been shown to work successfully [6]. On the other hand, glaze-ice accretion, for which water does not freeze immediately on impact, can only be scaled by methods which include the energy balance. Recently, attempts to understand more about the physics of ice accretion have shown that for glaze ice, surface phenomena can also have a significant effect on the final ice shape [7,8]. In this section, we will address each of the similitude requirements which have been satisfied by traditional methods.

Geometry The scaled and reference models must be geometrically similar over their entire surfaces. It is assumed that as ice accretes, the scale ice shape will continue to be a scaled representation of the reference ice shape. An alternate approach is currently being studied for airfoils in which the leading-edge-region geometry is full-size while the remainder of the scale airfoil is truncated [9, 10]. The design of the truncated airfoil is such that the flowfield around it matches that of the reference airfoil. This method will not be discussed in this paper.

Flowfield The flowfield over the scale model must simulate that of the reference case. This requirement is implicitly satisfied in the scaling equations by assuming that velocity, pressure and temperature distributions over at least the leading-edge region of the scale model match those for the reference.

Droplet Trajectory To insure that the mass of water reaching each part of the scaled model is relatively the same as that reaching the same part of the reference model, both the droplet trajectories and the local water catch have to be similar. The water catch will be discussed in the next section.

A complete analysis of droplet trajectory similarity has been published in Ref. [5] and [11]. These analyses show that the scale water droplet size, d_S, must relate to the reference size, d_R, according to Eq. (1):

$$\frac{d_S}{d_R} = \left(\frac{c_S}{c_R}\right)^{.62} \left(\frac{p_S}{p_R}\right)^{.24} \left(\frac{V_S}{V_R}\right)^{-.38}$$

(1)

This expression is convenient to use and is generally accurate for the range of droplet sizes of interest to aircraft icing (10 - 50 μm). It was derived by approximating the Re effect on the drag of a moving spherical water droplet by a linear expression. A somewhat more accurate approach was used by Ruff [5]; he determined the scale droplet size which satisfied equality of the modified inertia parameters, $K_{0,S} = K_{0,R}$. Langmuir and Blodgett [12] defined the modified inertia parameter to include effects of both Re and inertia of a spherical droplet. Either Eq. (1) or Ruff's method can be easily programmed for computer calculation of the required scale droplet size.

Water Catch The total amount of water which impacts the model surface is assumed to freeze eventually. The quantity of ice accretion can then be described by the non-dimensional accumulation parameter, $A_c = LWC\, V\, \tau\, /\, c\, \rho_i$. To insure that the scale test will accrete the same relative quantity of ice, the scale accumulation parameter is matched to the reference. Thus,

$$\frac{\tau_S}{\tau_R} = \left(\frac{c_S}{c_R}\right)\left(\frac{LWC_R}{LWC_S}\right)\left(\frac{V_R}{V_S}\right)$$

(2)

For rime ice conditions, because water freezes immediately on impact, it is only necessary to satisfy Eqs. (1) and (2), with LWC_S chosen for convenience. For glaze ice, however, similitude in energy balance is also required; this will be discussed next.

Energy Balance The energy analysis on an unheated surface with water impingement and freezing was performed by Messinger [13] and has been the basis of most scaling methods since that time. Messinger's heat balance included the loss of heat from the surface due to convection, ice sublimation, water evaporation, radiation, and sensible heat required to warm impinging water to the freezing temperature. The gain of heat at the surface is due to release of latent heat on freezing and the kinetic energy of incoming water droplets. Ruff [5] added terms for the conduction of heat through the model surface and for heat carried from the surface by runback water.

Messinger [13] and Tribus [14] defined two non-dimensional parameters in the energy balance: the freezing fraction, n, is the fraction of water which freezes within an impingement region; the relative heat factor, b, is the ratio of the total heat capacity of the impinging water to the ability of the airflow to convect heat from the surface. Two other parameters used are ϕ, which is a grouping of the terms associated with droplet energy transfer, and θ, which groups the air-energy transfer terms. When the energy balance is written using these parameters, it becomes

$$n = \frac{c_{p,w}}{\Lambda_f} \left(\phi + \frac{\theta}{b} \right)$$ (3)

Various scaling methods have selected one or more of the parameters n, ϕ, θ, and b to match between scale and reference values.

BUCKINGHAM-Π ANALYSIS

The scaling parameters discussed in the preceding section result from a phenomenological approach in that they are derived from a set of equations that describe our current understanding of the ice-accretion process. Classical scaling by dimensional analysis and application of the Buckingham-π methodology has also been applied to icing scaling. The premise behind this approach is that if the proper dimensionless parameters, or π terms, can be identified, any one of the π terms can be written as a function of the remaining π terms. Only the parameters relevant to physical phenomena and their dimensions must be specified. This approach is very attractive because it requires minimal knowledge about the physics of icing, and we presently lack a full understanding of all the physical processes involved in ice accretion.

This methodology was applied to icing scaling by Bilanin [7] who identified 23 variables that play a role in the ice-accretion process. With 23 variables and 4 dimensions (length, mass, time and temperature), there are 19 possible dimensionless parameters. Three of the parameters are easily recognizable as the Mach, Reynolds and Weber numbers. Others are related to the drop size, inter-droplet spacing and free-stream temperature. Still others are ratios of the physical properties of water and ice which will, of course, be matched automatically between scale and reference situations. It's possible to show that all of the traditional icing similitude parameters discussed previously can be expressed as functions of some of the π parameters. If all 19 of the π parameters for the scale test were simultaneously matched to their respective reference, or full-size, values the ice accretion should be rigorously scaled.

Unfortunately, not all π parameters can be simultaneously matched from scale to reference conditions. For example, a constant M requires approximately that $V_S = V_R$, a constant Re requires that $c_S/c_R = V_R/V_S$ and a constant We requires that $c_S/c_R = (V_R/V_S)^2$. Except for the special case when $c_S = c_R$, these are inconsistent restrictions. Fortunately, it may not be necessary to match all π parameters to scale successfully; the methods described in Refs. [1] - [6] were based on the traditional icing similitude parameters which ignored many of the π parameters, yet scaled the geometry of ice accretions fairly accurately for some conditions. Although Bilanin's Buckingham-π analysis has not proved to be practical as a scaling method by itself, it has served to identify parameters which may have been overlooked by the traditional methods. One such parameter is the We which has now been incorporated into a new scaling method discussed below.

SCALING METHODS

Icing scaling methods have matched the scale and reference values of a variety of the terms discussed above to find the scale test conditions. The scaling methods will be described next in terms of the parameters matched. A summary of the 4 scaling methods and the similitude parameters which they satisfy is given in Table 1. This list of scaling

Table 1. Similitude Terms Satisfied by Four Scaling Methods.

Method	Drop Traj	Drop Catch	Rel. Heat Fact	Freez. Fract.	Drop Engy Trans	Air Engy Trans	M	Re	We
LWC x time	x	x			x	x	x	x	x
Olsen	x	x		x			x	x	x
Ruff (mod)	x	x		x	x				
Const-We	x	x		x	x				x

methods is not complete; in particular, the French method [3] will not be discussed here. It was evaluated in Ref. [6] and has been used extensively in the ONERA icing tunnel at Modane.

"LWC x time = constant"   This is the simplest and oldest scaling "law." It applies when the model size is not scaled and all parameters except the liquid-water content can be matched to the desired test conditions. In this situation, the law states that the amount of accreted ice for the scaled LWC will be the same as for the desired LWC if the product of accretion time and LWC for the scaled test equals that for the desired, or reference, encounter being simulated. This expression is derived from Eq. (2) with $c_S = c_R$ and $V_S = V_R$. In addition, with $p_S = p_R$, Eq. (1) gives $d_S = d_R$. This method requires that the static temperatures also match; i.e., $t_S = t_R$. As a result, and because of the other matched parameters, $\phi_S = \phi_R$, $\theta_S = \theta_R$, $We_S = We_R$, $Re_S = Re_R$ and $M_S = M_R$ as well.

Olsen   A variation on "LWC x time = constant" is the Olsen method [6, 14] in which, again, only the LWC is to be scaled. As in the case of the "LWC x time = constant" approach, matching the model size and test conditions other than LWC results in a match of the We, Re and M as well. In this method, however, the scale static temperature does not equal the reference temperature, but is found by matching the scale and reference freezing fraction, n.

Ruff The last two methods to be discussed are used when the scale model size is different from the reference. The Ruff method was developed at the AEDC by Ruff [5] and is sometimes known as the AEDC method. It was intended originally for use in wind tunnels with altitude capability. The user first selects a scale model size and test velocity. The static temperature for the scale test can then be found by matching the water-energy transport term, ϕ. The scale droplet size is determined by matching the modified inertia parameter, K_0, which insures that the scale droplet trajectories will be the same as the reference case. The scale static pressure is found by matching the air-energy transport terms, θ. For tunnels which cannot control the static pressure independently of velocity, a modified Ruff method has been used in which the θ terms are not matched. Next, the freezing fraction is matched to establish the scale liquid-water content, and, finally, the icing encounter time is found from matching the scale and reference accumulation parameters.

Constant-*We* The Buckingham-π analysis of Bilanin [7] showed that the Weber number may be a significant icing scaling parameter. This method assumes that *We* is of greater importance than either *Re* or *M*, as no attempt is made to match these two parameters to the reference values. The user chooses the model size; all other scale parameters are determined by similitude requirements. The 3 equations formed by matching the Weber number, the modified inertia parameter, and the water-energy transfer term are solved simultaneously to give the scale velocity, droplet size and static temperature. The scale liquid-water content and icing time are then found from matching the freezing fraction and accumulation parameter, respectively.

EXPERIMENTAL METHODS

Test Facility and Models Tests to validate scaling methods were performed in the NASA Lewis Icing Research Tunnel (IRT) shown in Fig. 1. It is a closed-loop tunnel with a test section 1.8 m high by 2.7 m wide. Temperature can be controlled from -30°C to 4°C. 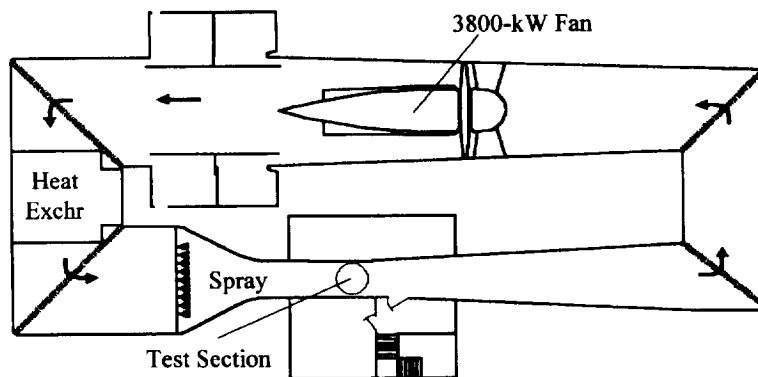The water spray system gives a range of liquid-water content and water droplet size which covers a significant portion of the FAA Part 25 Appendix C icing envelope. Velocities of up to 160 m/s are possible.

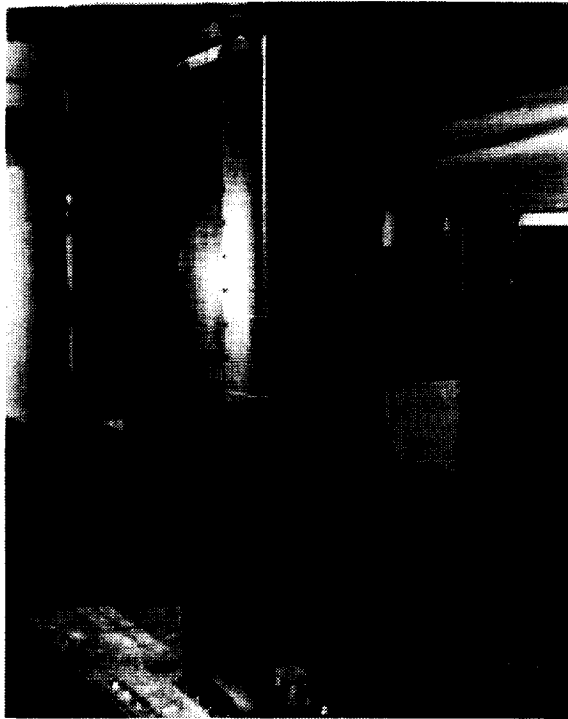Fig. 2 is a photo of a 53.3-cm-chord, 1.8-m-span NACA 0012 airfoil mounted vertically

Figure 1. NASA Lewis Icing Research Tunnel (IRT).

Figure 2. 53.3-cm-Chord NACA 0012 Airfoil installed in IRT.

in the IRT test section for tests to be reported here. This model had a uniform chord over the full span and was unswept. Test conditions were selected to represent reference cases, and the various scaling methods applied to determine the corresponding scale test conditions. When the scale tests involved a size change, an NACA 0012 model with 26.7-cm chord was used. Tests were run at both reference and scale conditions, two-dimensional cuts through the resulting ice accretions were made at the center of the tunnel test section, and ice shapes were recorded by tracing the ice outline onto a cardboard template. These tracings were then digitized for computer storage. From these computer files, the shapes were analyzed and compared.

Quantitative Analysis of Ice-Shape Features   In general, evaluations of icing scaling methods have relied on qualitative comparisons of the scale and reference ice shapes. With this approach, the experience, judgement and objectivity of the researcher determine to some extent whether a scaling method is acceptable. In practice, what constitutes an acceptably scaled ice accretion actually depends on the purpose of the test. In aerodynamic tests, it is most critical that the sub-scale accretion have the same lift and drag coefficients as the full-scale. In other applications, geometric parameters such as the width or mass of the accretion is most important. In still others, the critical parameter may be the mass of ice shed. For general evaluation of scaling m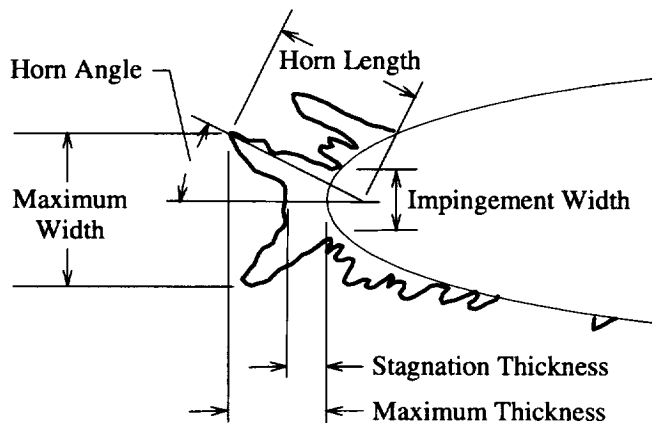ethods, however, a comparison of ice shapes is most appropriate. In this study, both qualitative and quantitative comparisons of ice shapes will be made.

Several characteristic dimensions representative of the overall shape of a typical glaze ice accretion were identified. As shown in Fig. 3, these dimensions included the thickness of the ice accretion at the stagnation

Figure 3. Ice-Shape Characteristic Dimensions.

point, the maximum thickness, the maximum width of the ice accretion, the impingement width, horn length and horn angle. These characteristics were all measured on the main ice shape. Downstream of the primary glaze ice shape is a region in which rime feathers form. The features of these feathers vary considerably from test to test and from one location to another on the model. Because of this variability, the feather region is ignored in comparing ice shapes. Measurements of the characteristic dimensions were made by hand for this study.

Ice-Shape Repeatability To be judged acceptable, scaling methods must produce ice shapes that are similar to the reference shape within the typical shape variability from run to run. To establish this variability, several test conditions were repeated and the shapes compared. In Fig. 4 (a) are shown results for tests made in October, 1995, December, 1995 and June, 1996 at the same tunnel conditions. In
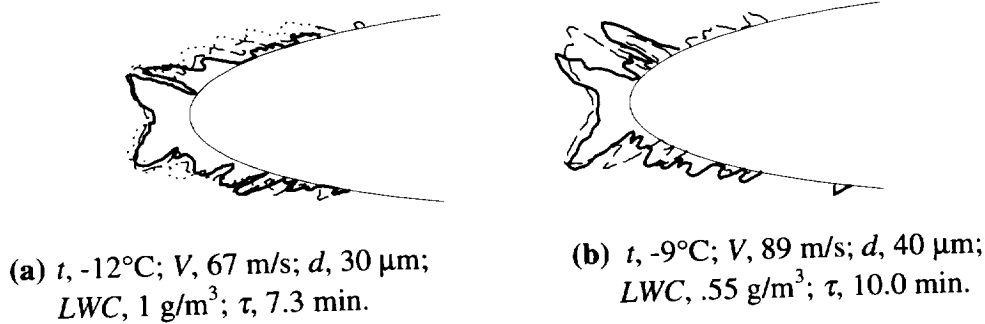

(a) t, -12°C; V, 67 m/s; d, 30 μm; LWC, 1 g/m³; τ, 7.3 min.

(b) t, -9°C; V, 89 m/s; d, 40 μm; LWC, .55 g/m³; τ, 10.0 min.

Figure 4. Repeatability of Ice Shapes. 53.3-cm-Chord NACA 0012 Airfoil.

Fig. 4 (b) are results from tests in October, 1995 and December, 1995 at another set of conditions. The reference shape (October, 1995 test) is shown with a solid line in both parts of the figure. Although small differences in ice shape are apparent from this qualitative comparison, the IRT generally gives fairly repeatable ice shapes.

In addition to this subjective evaluation, a quantitative assessment of ice-shape repeatability was also made. The six characteristic dimensions of the ice-shapes in Fig. 4 were measured and averages for each dimension obtained separately for Fig. 4 (a) and Fig. 4 (b). The difference between each dimension and the average value of that dimension was then obtained. Finally, the absolute values of these differences were averaged and

Table 2. Variability of Six Characteristic Ice-Shape Dimensions.

Ice Feature	Average Percent Difference from Mean Dimension	
	Fig. 4 (a)	Fig. 4 (b)
Stag. Thickness	8.7	11.4
Max. Thickness	2.8	5.2
Max. Width	10.4	6.6
Horn Length	0.4	4.2
Horn Angle	7.7	23.1
Impinge. Width	9.4	13.7

reported as a percent of the mean dimension in Table 2. For these two icing conditions, the maximum thickness and horn length had the best repeatability, while the stagnation-zone thickness, maximum ice-shape width, horn angle and impingement width were less repeatable. Unfortunately, some judgement is still required to determine some of these measurements. The impingement width, which is dependent on the droplet trajectory, is often particularly difficult to define, and this uncertainty was reflected in the relatively poor repeatability of this dimension. Fortunately, scaling of droplet trajectories and impingement limits has been verified both computationally and experimentally using temperatures above freezing [11,17].

It's reasonable to expect that the characteristic dimensions of an ice shape can be defined better as more repeat data are available. In Table 2, for most dimensions, the average deviation from the mean dimension was less when based on three ice shapes (data from shapes in Fig. 4 (a)) than when only two ice shapes were used (results for Fig. 4 (b)). Table 2 also indicates that most ice-shape characteristic dimensions are repeatable to about ±10%, with horn angle somewhat more difficult to repeat. Ability to reconstruct most ice dimensions to within ±10% is thus a reasonable goal for scaling methods with somewhat more relaxed expectations to reproduce horn angle.

EVALUATION OF THE SCALING METHODS

Scaling Liquid-Water Content   Reference and scale ice shapes are compared in Fig. 5 for the "*LWC* x time = constant" rule (Fig. 5 (a)) and for the Olsen scaling
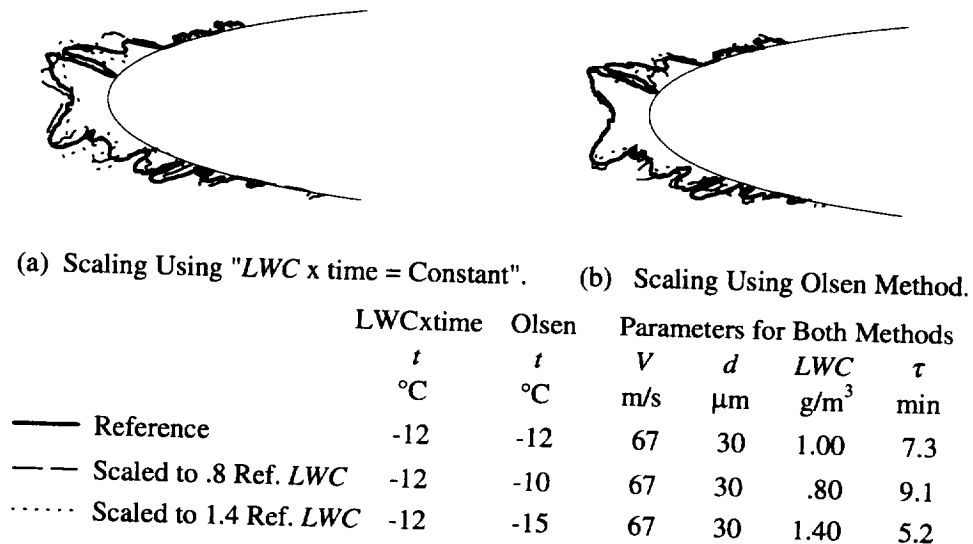

(a) Scaling Using "*LWC* x time = Constant".   (b) Scaling Using Olsen Method.

	LWCxtime	Olsen	Parameters for Both Methods			
	t	t	V	d	LWC	τ
	°C	°C	m/s	μm	g/m^3	min
—— Reference	-12	-12	67	30	1.00	7.3
— — Scaled to .8 Ref. *LWC*	-12	-10	67	30	.80	9.1
······ Scaled to 1.4 Ref. *LWC*	-12	-15	67	30	1.40	5.2

Figure 5. Scaling Liquid-Water Content. 53.3-cm-Chord NACA 0012 Airfoil.

method (Fig. 5 (b)). In each case, the reference test (solid line) was performed with a liquid-water content of 1 g/m^3, and scale tests were made with *LWC*'s of .8 and 1.4

Table 3. Quantitative Evaluation of "*LWC* x time = Constant" and Olsen Scaling Methods. Reference *LWC*, 1.0 g/m³; Scale *LWC*, .8 and 1.4 g/m³.

| Ice Feature | Percent Difference from Reference | | | |
| | *LWC* x Time | | Olsen | |
	.8 g/m³	1.4 g/m³	.8 g/m³	1.4 g/m³
Stag. Thickness	10.0	-20.0	0.0	5.0
Max. Thickness	5.7	-17.1	0.0	-4.3
Max. Width	-17.0	30.1	11.3	-1.9
Horn Length	0.0	4.6	-2.8	-0.9
Horn Angle	-43.5	39.1	-4.4	0.0

g/m³. In this test series, both methods of scaling produced an ice shape which simulated the reference shape fairly well when the liquid-water content was reduced to .8 g/m³, but the Olsen method gave a superior match when the scale *LWC* was increased to 1.4 g/m³.

The ice shapes shown in Fig. 5 were analyzed quantitatively, and the results are reported in Table 3. Because of the difficulty in defining the impingement width, this dimension will not be included. With the exception of the horn angle, the scaled dimensions resulting from using the "*LWC* x time = constant" method were close to being within the acceptable limit of ±10% of the reference dimensions when the liquid-water content was scaled from 1 to .8 g/m³. However, for the 1.4-g/m³ scaling case, this method produced an ice shape with dimensions significantly different from the reference.

The Olsen method provided scaled shapes whose dimensions closely matched the reference for both scaling cases. The match of the horn angle produced by the Olsen method is particularly notable. The formation of horns depends on the dynamics of liquid water on the surface of the ice accretion. The success of the Olsen method over the "*LWC* x time = constant" method indicates that the freezing fraction, matched to the reference value by the Olsen method, is of greater importance in determining final ice shape than the air-energy or water-energy transport terms, which are matched by the "*LWC* x time = constant" method.

Scaling Size Results of tests with size scaled to ½ the reference value are shown in Fig. 6. The solid line in each part of the figure represents the reference ice shape which was the same for each scaled test. The dotted-line shape is the scaled result. Both the Ruff and the constant-*We* methods gave liquid-water contents for the ½-scale conditions which were outside the range of the operating map for the IRT; consequently, the *LWC* for the scale tests was selected to be 0.8 g/m³, and Olsen scaling was applied to maintain the same freezing fraction as the reference test. Thus, both size scaling and *LWC* scaling were combined for this evaluation.

Because the IRT does not provide control over the test-section pressure, the modified form of the Ruff method was used. The results in Fig. 6 (a) show that the scale ice shape was of similar size to the reference although, qualitatively, the stagnation thickness and horn location were slightly different. The ice tracings shown in Fig. 6 (b) for the constant-*We* scaling conditions appear to match the

(a) Scaling Using Ruff (Mod) Method.   (b) Scaling Using Constant-*We* Method.

	c cm	t °C	V m/s	d μm	LWC g/m^3	τ min
—— Reference	53.3	-12	67	30	1.00	7.3
⋯⋯ Ruff Method	26.7	-8	67	20	.80	4.6
⋯⋯ Constant-*We* Method	26.7	-10	88	18	.80	3.5

Figure 6. Model Size Scaled to ½ Original Chord. NACA 0012 Airfoils.

Table 4. Quantitative Evaluation of Modified Ruff and Constant-*We* Methods for ½-Size Scaling. Test Conditions Given in Fig. 6.

Ice Feature	Percent Difference from Reference	
	Ruff (Mod)	Const-*We*
Stag. Thickness	25.0	25.0
Max. Thickness	-17.1	-5.7
Max. Width	-22.6	-18.9
Horn Length	-14.8	-13.0
Horn Angle	52.2	39.1

reference shape slightly better. The quantitative comparison of the dimensions shown in Table 4 show that the constant-*We* method provided agreement with the reference shape which was only slightly better than that for the modified Ruff method for this case. Because the constant-*We* method places more restrictions on the scaling conditions, it's not surprising that it was fairly successful; however, the fact that the Ruff method, which ignores *We*, was relatively successful suggests that *We* may not be of major importance to icing physics. Clearly, there is opportunity for additional improvement in icing scaling by better understanding the phenomena involved in the ice-accretion process.

CONCLUDING REMARKS

This paper described the theoretical background leading to the development of four icing scaling methods. The phenomenological basis for current scaling technology was presented and compared to the classical approach using the Buckingham-π

methodology. Tests to evaluate these scaling methods were conducted in the Icing Research Tunnel at NASA Lewis Research Center, and results were presented. The "*LWC* x time = constant" and Olsen methods can be used to scale test conditions while the constant-*We* and modified Ruff methods scale test article size. A method to quantify the goodness of the scale ice shapes based on measuring six characteristic dimensions was proposed. Results from this quantitative approach supplemented visual comparisons performed by overlaying two-dimensional tracings of the ice accretion. The conclusions from this study are summarized below:

1. Quantitative verification of icing scaling methods is helpful in defining their accuracy and increasing confidence in their use.

2. When comparing the characteristic ice-shape dimensions from repeat conditions, differences on the order of ±10% can result if only two tests are compared. Characteristics such as horn angle and impingement width are sometimes difficult to define, resulting in large run-to-run deviations in these dimensions. Improved definition of dimensions resulted from a greater number of samples.

3. When liquid-water content was scaled using a full-size model, the Olsen method produced better results than the "*LWC* x time = constant" method. The former maintains the freezing fraction constant between reference and scaled conditions, while the latter matches the water-energy-transfer and the air-energy-transfer terms. This result suggests that the freezing fraction has a greater effect on ice shape than the water- or air-energy-transfer terms.

4. For scaling to ½ size at the conditions tested, the constant-*We* method produced a slightly better match of ice shape than the modified Ruff method. Either of these methods appeared to provide at least approximate scaling for ½-size models. However, the relative success of the less-restrictive Ruff method suggests that *We* may not be as important to ice-accretion physics as once thought. Additional study of the parameters of most importance to the development of ice shapes is needed to improve scaling methods further.

Several directions for future work are evident from these results. The quantitative evaluation of ice accretion shapes appears to be a promising tool, but the observed variation between any two repeat conditions showed that a large number of repeated tests providing better statistics are required to perform more detailed evaluations of icing scaling methods. Characteristics of the ice shape other than those discussed here may also need to be considered for future quantitative evaluations. To improve scaling methods, other parameters, such as *Re*, need to be examined to determine their importance relative to *We*. Finally, parameters relevant to the dynamics of liquid water on the surface of an ice accretion during the freezing process should be identified and included in icing scaling methods.

REFERENCES

[1]   E.J. Sibley and R.E. Smith, Model Testing in an Icing Wind Tunnel, *Report LR10981*, Lockheed Aircraft Corporation, California Division, (1955).

[2]   E.D. Dodson, Scale Model Analogy for Icing Tunnel Testing, *Document no. D6-7976*, Boeing Airplane Company, Transport Division, (1962).

[3]   F. Charpin and G. Fasso, Icing Testing in the Large Modane Wind Tunnel on Full Scale and Reduced Scale Models, *L'Aeronautique et l'Astronautique*, no 38, (1972); English translation: *NASA TM-75373*.

[4]   M. Ingelman-Sundberg, O.K. Trunov, and A. Ivaniko, Methods for Prediction of the Influence of Ice on Aircraft Flying Characteristics, *Report No. JR-1*, Swedish-Soviet Working Group on Flight Safety, 6th Meeting, (1977).

[5]   G.A. Ruff, Analysis and Verification of the Icing Scaling Equations, *AEDC-TR-85-30*, Arnold Engineering Development Center, Tullahoma TN (1986).

[6]   D.N. Anderson, Rime, Mixed- and Glaze-Ice Evaluations of Three Scaling Laws, *AIAA 94-0718*, American Institute of Aeronautics and Astronautics, Washington DC, and *NASA TM 106461*, NASA Lewis Research Center, Cleveland OH, (1994).

[7]   A.J. Bilanin, Proposed Modifications to the Ice Accretion/Icing Scaling Theory, *AIAA-88-0203*, American Institute of Aeronautics and Astronautics, Washington DC, (1988).

[8]   A.J. Bilanin and D.N. Anderson, Ice Accretion with Varying Surface Tension, *AIAA-95-0538*, American Institute of Aeronautics and Astronautics, Washington DC, (1995).

[9]   F. Saeed, M.S. Selig and M.B. Bragg, A Design Procedure for Subscale Airfoils with Full-Scale Leading Edges for Ice Accretion Testing, *AIAA-96-0635*, American Institute of Aeronautics and Astronautics, Washington DC, (1996).

[10]   F. Saeed, M.S. Selig and M.B. Bragg, A Hybrid Airfoil Design Method to Simulate Full-Scale Ice Accretion Throughout a Given C_l Range, *AIAA-96-0635*, American Institute of Aeronautics and Astronautics, Washington DC, (1996).

[11]   M.B. Bragg, G.M. Gregorek and R.J. Shaw, An Analytical Approach to Airfoil Icing, *AIAA-81-0403*, American Institute of Aeronautics and Astronautics, Washington DC, (1981).

[12]   I. Langmuir and K.B. Blodgett, A Mathematical Investigation of Water Droplet Trajectories, *Technical Report No. 5418*, Army Air Forces, (1946).

[13]   B.L. Messinger, Equilibrium Temperature of an Unheated Icing Surface as a Function of Airspeed, *J. Aeron. Sci.*, 20: 29 (1953).

[14]   M. Tribus, G.B.W. Young and L.M.K. Boelter, Analysis of Heat Transfer Over a Small Cylinder in Icing Conditions on Mount Washington, *Trans ASME*, 70: 971, (1948).

[15]   W.A. Olsen, Jr., unpublished notes, NASA Lewis Research Center, (1989).

[16]   D.N. Anderson, Evaluation of Constant-Weber-Number Scaling for Icing Tests, *AIAA-96-0636*, American Institute of Aeronautics and Astronautics, Washington DC, and *NASA TM 107141*, NASA Lewis Research Center, Cleveland OH, (1996).

[17]   M.B. Bragg, A Similarity Analysis of the Droplet Trajectory Equations, *AIAA J.*, 20:12 (1982).

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1997	Technical Memorandum

4. TITLE AND SUBTITLE

Scaling Methods for Simulating Aircraft In-Flight Icing Encounters

5. FUNDING NUMBERS

WU-548-20-23-00

6. AUTHOR(S)

David N. Anderson and Gary A. Ruff

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E-10861

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM-107538

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category: 02   Distribution: Nonstandard

This publication is available from the NASA Center for AeroSpace Information, (301) 621-0390.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This paper discusses scaling methods which permit the use of subscale models in icing wind tunnels to simulate natural flight in icing. Natural icing conditions exist when air temperatures are below freezing but cloud water droplets are supercooled liquid. Aircraft flying through such clouds are susceptible to the accretion of ice on the leading edges of unprotected components such as wings, tailplane and engine inlets. To establish the aerodynamic penalties of such ice accretion and to determine what parts need to be protected from ice accretion (by heating, for example), extensive flight and wind-tunnel testing is necessary for new aircraft and components. Testing in icing tunnels is less expensive than flight testing, is safer, and permits better control of the test conditions. However, because of limitations on both model size and operating conditions in wind tunnels, it is often necessary to perform tests with either size or test conditions scaled. This paper describes the theoretical background to the development of icing scaling methods, discusses four methods, and presents results of tests to validate them.

14. SUBJECT TERMS

Icing; Scaling; Aircraft safety

15. NUMBER OF PAGES

20

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	