NASA TECHNICAL **MEMORANDUM** NASA TM-75373

ICING TESTING IN THE LARGE MODANE WIND-TUNNEL ON FULL-SCALE AND REDUCED SCALE MODELS

F. Charpin, G. Fasso

(NASA-TM-75373) ICING TESTING IN THE LARGE MODANE WIND-TUNNEL ON FULL-SCALE AND REDUCED SCALE MODELS (National Aeronautics and Space Administration) 20 p HC A02/MF A01 CSCL 01C

N79-20102

Unclas

G3/05 17098

Translation of "Essais de givrage dans la grande soufflerie de Modane sur maquettes a echelle grandeur et echelle reduite," L'Aeronautique et l'Astronautique, no. 38, 1972, pp. 23-31

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 MARCH 1979

List of Symbols/Notations/Abbreviations

a	median diameter of droplets in cloud	μm
b	relative heat factor [7]	dimensionless
C_D	actual drag coefficient of droplet	dimensionless
k	scale of model	dimensionless
L.W.C.	liquid water content of clouds	$g \cdot m^{-3}$
n	freezing fraction [7]	dimensionless
Pa	ambient atmospheric pressure	Pa
P_∞	water vapor partial pressure in atmosphere	Pa
Rv	Reynolds number relative to droplet diameter and velocity V	dimensionless
ta, Ta	static air temperature upstream at infinity	°C, °K
V	relative droplet velocity with respect to air	$m \cdot sec^{-1}$
V_∞	air speed upstream at infinity	$m \cdot sec^{-1}$
τ	icing time	sec

Subscripts

m	model
G	aircraft or full scale model

ICING TESTING IN THE LARGE MODANE WIND-TUNNEL ON FULL-SCALE AND REDUCED SCALE MODELS

F. Charpin, G. Fasso

Report presented to Conference On Protection Against Icing, London, 10 May 1972. English text published by Lucas Co, London, 1972.

Introduction

There are different means which permit determination of /24*
the form and extent of ice accretion on aircraft airframes and of qualifying deicing and antiicing systems:

natural icing flight tests;

artificial icing flight tests;

of actual parts installed on a carrier aircraft behind a water atomizing grid;

of the aircraft itself, flying in an artificial cloud behind a tanker aircraft;

fixed point ground tests (helicopters);

wind tunnel tests;

actual parts or full scale parts;

complete models or reduced scale models.

These latter wind tunnel test techniques have been used by ONERA (National Office of Aerospace Studies and Research) since 1962, in the large, naturally cooled Modane S1 wind tunnel [1], during the severe winter months. The first test, carried out on a full scale part of the leading edge of a Vickers-Armstrong VC 10

---

1 Numbers in the margin indicate pagination in the foreign text.

wing, was followed in later years by other tests on full scale parts of various aircraft:

wing and stabilizer parts of a Nord 262 (now known as the Aerospatiale Fregate), of a Potez 840 and of a Breguet 941 S STOL;

radome of a C 160 cargo Transall.

To perform these tests, test section No. 1 of the large S1 wind tunnel was equipped with a grid, which permits production of a homogeneous ice fog on a 0.8 m x 2 m area.

This atomizing grid was supplied by Vickers-Armstrong Ltd., which previously used it on its Vanguard flight test bed. The 90 Napier and Sons, Ltd. injectors, supplied with warm water and compressed air, provide a cloud of supercooled water droplets, the median diameter of which can be regulated between 15 and 25 μm, and a liquid water content between 0.2 and 2.5 $g \cdot m^{-3}$, for speeds up to 100 $m \cdot sec^{-1}$ and, with some limitations, up to 120 $m \cdot sec^{-1}$.

The problem of icing in the wind tunnel has been considerably modified by the study of ice accretion on the Concorde supersonic transport in the holding, approach and landing flight envelopes under icing conditions. In fact, this aircraft has an ogive delta wing, the vortex type flow of the top surface of which is closely connected to the shape of the entire wing and the presence of the front portion of the fuselage. Therefore, in order to determine the areas, shapes and extent of icing, it is necessary to perform tests on a complete airframe. Given the dimensions of the aircraft, full scale tests are possible only in actual flight. Wind tunnel icing tests performed at NRC Ottawa on models or semimodels of flat delta wings [2, 3], have demonstrated large ice accretions on the top of the wing, and they permit the belief that there is a prohibitive accretion of weight for the aircraft, as well as perturbation of the longitudinal stability. A collecting study in the hydrodynamic tunnel, carried out at the University of Bristol from 1963 to 1967 [4], led to the same qualitative conclusions. However, these models were not representative of the Concorde aircraft, with its cambered and twisted ogive fuselage and wing section. Therefore, it was necessary to decide on a larger scale, in order to have a better determination of the shapes and extent of the ice and the risk of perturbations caused by the ice accretion, so as to intervene as quickly as possible, at the level of aircraft fabrication, in the situation, extent and power of deicing systems. The Official English and French Services, in liaison with the British Aircraft Corporation (BAC), which made a detailed study of the phenomenon, decided to perform 1/6 similitude icing tests on a half model of the supersonic transport, in wind tunnel S1 of the ONERA Center at Modane-Avrieux. ONERA was responsible for definition and production of the appropiate test installation.

The 1/6 similitude icing was extended later to 1/12 similitude, for application to other tests.

ORIGINAL PAGE IS
OF POOR QUALITY

Theoretical Study of Laws Governing Similitude Icing

Theoretical study of the laws governing similitude icing requires analysis of various physical phenomena. The first of these phenomena is the mechanical collection of water drops, which brings into play research on the trajectories of these drops in the aerodynamic field of the flow surrounding the obstacle being iced. A study of this problem was accomplished as early as 1946, by Irving Langmuir and Katherine B. Blodgett of the General Eleectric Company [5].

The second of these phenomena is the distribution of water and, then, ice onthe profiles. This brings into play the concentration of water of the clouds, the icing time and, also, the convective heat transfer coefficient, which was defined by Thomas F. Gelder and James P. Lewis in [6]. The third phenomenon and, probably, the most difficult to deal with, is thermal equilibrium of a wall under icing conditions. A very detailed study of this problem was performed by Bernard L. Messinger of the Lockheed Aircraft Corporation [7], in which he brought the concepts of /25 the relative heat factor b and the freezing fraction n.

These various studies were joined together, so as to learn the relations between the parameters which govern similitude icing in the wind tunnel, by Hauger, K. G. Englar and W. W. Reaser of Douglas Aircraft Company, Inc. [8].

For the similitude icing tests on the Concorde, as well as for the similitude icing tests on simple models intended to confirm theoretical calculations, the parameters of the icing clouds were calculated, beginning with the work done by R. Googan, E. T. Jackson and J. H. Hubbold of the British Aircraft Corporation [9, 10]. This work permitted selection of the wind tunnel in which the tests should be performed, and accomplishment of the transposition of the holding and approach flight envelopes of the aircraft to that being simulated in the wind tunnel, within the framework of limited icing similitude. This similitude is limited, because it is not possible to observe simultaneously the Mach number and Reynolds number conditions of the aerodynamic flow around the obstacle and the Reynolds number conditions for the droplets. However, it is found that, under flight conditions in which icing can be a hazard, the aerodynamic field in the collecting zones is not sensitive to these two parameters.

Analysis of the aerodynamic and inertial forces on the water droplets in the vicinity of the obstacle permits formula (1) to be obtained, which connects the various parameters of the similitude of the droplet trajectory

$$k = \frac{\left(\frac{a_m}{a_G}\right)^{2-x} \left(\frac{V_{\infty m}}{V_{\infty G}}\right)^{1-x}}{\left(\frac{P_{am}}{P_{aG}}\right)^{x} \left(\frac{T_{am}}{T_{aG}}\right)^{\frac{3-5x}{2}} \left(\frac{T_{am}+117}{T_{aG}+117}\right)^{x-1}} \tag{1}$$

In this formula, x is the exponent of the Reynolds number in the function which defines the ratio between the actual drag of a droplet and that given by Stokes law. Fig. 1 shows that, for a droplet Reynolds number area between 6 and 120, which also covers the area of flight of the aircraft, as well as 1/6 and 1/12 scale tests, the value of x represented by the slope of the best straight line through the points can be assumed to be 0.39. In most cases, ratio T_{am}/T_{aG} is about 1, and the practical forumla to use for the calculations becomes

$$k = \frac{\left(\frac{a_m}{a_G}\right)^{1,61} \left(\frac{V_{\infty m}}{V_{\infty G}}\right)^{0,61}}{\left(\frac{P_{am}}{P_{aG}}\right)^{0,39}} \qquad (2)$$

Analysis of the various parameters acting on the volume and distribution of icing on the profiles, as well as introduction of the concepts of the fraction of water changing to the ice state n and of the relative heat factor b [7] permits formulas (3) and (4) to be obtained. They define, respectively, the ratio of the liquid water content of the fog (LWC) and the icing time ratio (τ)

$$\frac{(L.W.C.)m}{(L.W.C.)G} = \frac{\left(\frac{P_{am}}{P_{aG}}\right)^{0,8}}{K^{0,2} \left(\frac{V_{\infty m}}{V_{\infty G}}\right)^{0,2} \left(\frac{T_{am}}{T_{aG}}\right)^{1,6}} \qquad (3)$$

$$\frac{\tau_m}{\tau_G} = \frac{K^{1,2} \left(\frac{T_{am}}{T_{aG}}\right)^{1,6}}{\left(\frac{V_{\infty m}}{V_{\infty G}}\right)^{0,8} \left(\frac{P_{am}}{V_{aG}}\right)^{0,8}} \qquad (4)$$

The hypotheses on which these equations are based, i.e., that the relative heat factors and the icing fractions are equal in flight and on the model (b_m=b_G and n_m=n_G), can be satisfied or not, according to the values of the flow variables. Therefore, it is advisible to determine the relationships between the variables which ensure equilibrium between the convective, evaporative

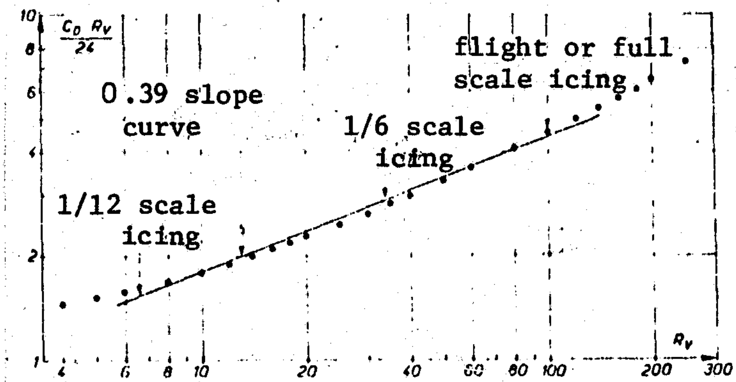

Fig. 1. Ratio between actual drag coefficient of droplet and that given by Stokes law.

and kinetic heat quantities. The formulas obtained in [7] give the equation which connects the air temperature, speed and pressure to the two parameters n and b, in the case of an unheated wall

$$\frac{10{,}58 \times 10^5}{Pa} = ta(1+b) + 1732\frac{P_\infty}{Pa} + 79{,}7\,nb + (3{,}6458 + b)\frac{V_\infty^2}{8373} \qquad (5)$$

If a point of the aircraft flight envelope is defined by P_{aG}, t_{aG}, $P_{\infty G}$ and $V_{\infty G}$, the relationship between n and b is defined. Then, mathematically, it is sufficient, with the wind tunnel /26
relationships known, which connect P_{am} and $V_{\infty m}$, as well as t_{am} and $P_{\infty m}$, to satisfy equation (5) so that the relationship between n and b is the same as that in the case of flight. Satisfaction of this relationship determines a pair of values of $V_{\infty m}$ and t_{am} which, substituted in equations (2), (3) and (4), permits determination of the homologous values of all the similitude icing parameters of the point of flight under consideration.

Test Resources

The specifications necessary to the British Aircraft Corporation to satisfy simulation of the holding and approach flight envelopes of the Concorde aircraft under icing conditions [10] required completely redoing the ice fog installation in test section No. 1 of wind tunnel S1. These are the limiting conditions of these specifications, which defined the performance of the installation.

The new atomizing grid can hold 444 air fractionation injectors, distributing a homogeneous cloud of droplets, the median diameter of which can be controlled between 10 and 20 μm on a 2 m x 2 m area (see Fig. 2). The liquid water content is

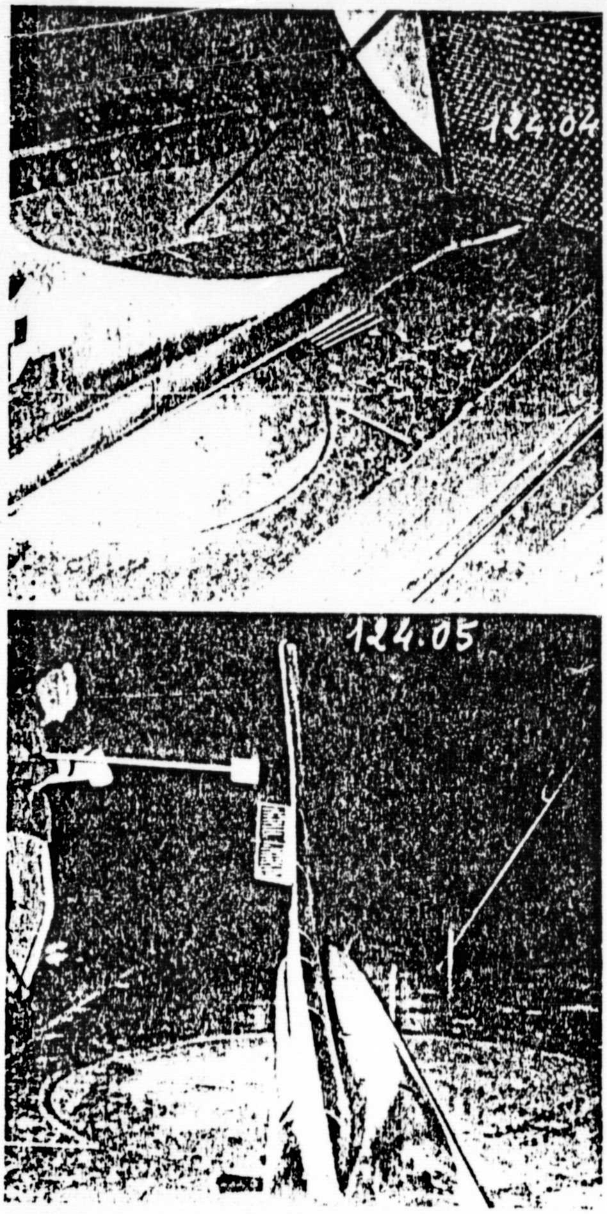

Fig. 2. Icing grid and G14 model of SST installed in wind tunnel S1 MA.

adjustable between 0.4 and 10 $g \cdot m^{-3}$, for speeds which can reach 100 $m \cdot sec^{-1}$.

The air and water supplies of this grid can be controlled automatically, to perform alternating icing (maximum discontinuity conditions and maximum continuous or clear sky conditions alternately, according to official specifications), while holding the droplet diameter practically constant, with periods of from 3 seconds to several tens of seconds. Study of the aerodynamic flow behind the grid was carried out at reduced scale by B.A.C., in Filton wind tunnel No. 4 and, then at full scale in wind tunnel S1 by ONERA. The loss of positive or negative charge, according to the atomizing air flow, was determined downstream of the grid.

The preliminary tests demonstrated that the water droplets of the fog evaporate if the air in the flow is not saturated. This evaporation changes the droplet diameter and the liquid water content of the ice fog, which then produces ice accretions which are not representative of the assigned conditions. To alleviate this disadvantage, wind tunnel S1 was equipped with a saturation unit, consisting of eight atomizing tubes, which can /27

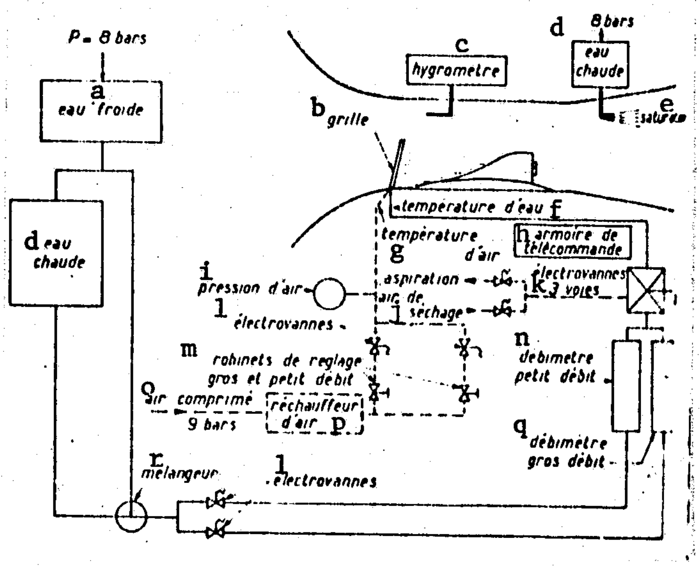

Fig. 3. Icing and saturation installation of return wind tunnel S1, Modane-Avrieux Center.

Key:
- a cold water
- b grid
- c hygrometer
- d warm water
- e saturated
- f water temperature
- g air temperature
- h telemetry cabinet
- i air pressure
- j drying air
- k three way electric valves
- l electric valves
- m coarse and fine flow regulators
- n fine flowmeter
- o compressed air
- p air reheater
- q coarse flowmeter
- r mixer

discharge 900 $\ell \cdot hour^{-1}$ each, thus permitting saturation in the test section by raising the relative humidity from 60 to nearly 100%. The relative humidity is monitored continuously, with an automatic continuous sampling dew point hygrometer in the test section.

The 8 m diameter test section of wind tunnel S1 permits the testing of large models with a small obstruction. Access to these models is very easy five minutes after icing is stopped. This easy access permits recording of the extent and shape of the ice, by photography at different distances and by direct measurement on the ice accretions. Interpretation of the photographs is facilitated by the use of cross ruled sights or by very distinct reference marks painted on the models, to mark the chord percentages or angles. The test section floor has a balance, which permits setting the angle of attack and measurement of the aerodynamic forces of the models before and after icing, as well as a compressed air inlet to supply the jet with primary air, which permits simulation of the air inlet flow coefficients of some models.

The test section walls can be equipped with projectors and high speed cameras (1200 images·sec^{-1}), required for study of the trajectories of ice fragments detached naturally or artificially from the upstream parts of the models.

Similitude Icing Tests

Still with no element of comparison between inflight icing and icing in the wind tunnel at reduced scale, it was necessary to support the similitude icing calculations by full scale and reduced scale comparative icing tests in the wind tunnel. Therefore, ONERA, in parallel with the manufacturer icing tests, carried out series of similitude icing tests, limiting the study, either to simple shapes such as cylinders, or to wing section shapes close to those used in the test for which these experiments were conducted. The tests first were conducted within the framework of 1/6 similitude and, then, extended to 1/12 similitude. In this case, the calculations were the same as for the similitude between flight and the wind tunnel, but conduct of the two tests in one wind tunnel, in which neither the pressure nor the temperature can be regulated, does not permit rigorous achievement of the theoretical thermodynamic similitude of icing.

Each similitude icing point involved two tests, one full scale (subscript G) and the other at scale k (subscript m). The mean droplet diameters used was a_G=20 μm (standard value given by the specifications) and a_m=10 μm (minimum certain value permitted by the installation), or a a_m/a_G ratio =1/2, similar to those used in the flight-wind tunnel similitude.

Here, for example, are the characteristics of two similitude icing points, one in 1/6 scale and the other, 1/12, carried out during the tests.

1/6 Similitude Icing Test

Full Scale Icing:

V_G=45 m·sec^{-1}, t_{aG}=-5.4° C, a_G=20 μm#, L.W.C.$_G$=4 g·m^{-3}, τ_G=10 min.

1/6 Scale Icing:

V_m=15 $m \cdot sec^{-1}$, t_{am}=-5° C, a_m=10 μm#, L.W.C.$_m$=7.2 $g \cdot m^{-3}$, τ_m=2.75 min.

1/12 Similitude Icing Test

Full Scale Icing:

V_G=76.2 $m \cdot sec^{-1}$, t_{aG}=-6.3° C, a_G=20 μm#, L.W.C.$_G$=2.4 $g \cdot m^{-3}$, τ_G= 10 min.

1/12 Scale Icing:

V_m=8 $m \cdot sec^{-1}$, t_{am}=-5° C, a_m=10 μm#, L.W.C.$_m$=6 $g \cdot m^{-3}$, τ_m=3 min.

It is very difficult to determine angles or dimensions on the models with a precision better than 10 to 15%. In the case of full scale icing, this is due to the branched forms of the deposits and, in the case of small scale icing, to the small actual thickness of the deposits.

In the case of icing where the similitude rules were not observed, very dissimilar ice deposits appear on the models, both from the point of view of extent and shape of this ice. Fig. 4 shows a set of photographs, in which the photographs on the left a. represent icing obtained on models associated with accurate clouds and those on the right b. icing obtained with models and clouds which do not observe the similitude rules. The icing on the cylinders of 4.1.a and .b exhibit very different icing angles (80 and 140°). As to the thickness of the ice reduced to the same scale (full scale), it differs very much (30 mm and 180 mm). On the delta wing sections of 4.2.a and .b, the icing on the leading edge, which develops in the case of a normal test, scarcely appears on the large model. In the case of icing on wing sections of thick cross section, in 4.3.a and .b, the differences are still greater; proper icing produces ice extending up to 2.5% of the chord, while the ice on the small model extends up to 15% of the chord, with very different accretion forms.

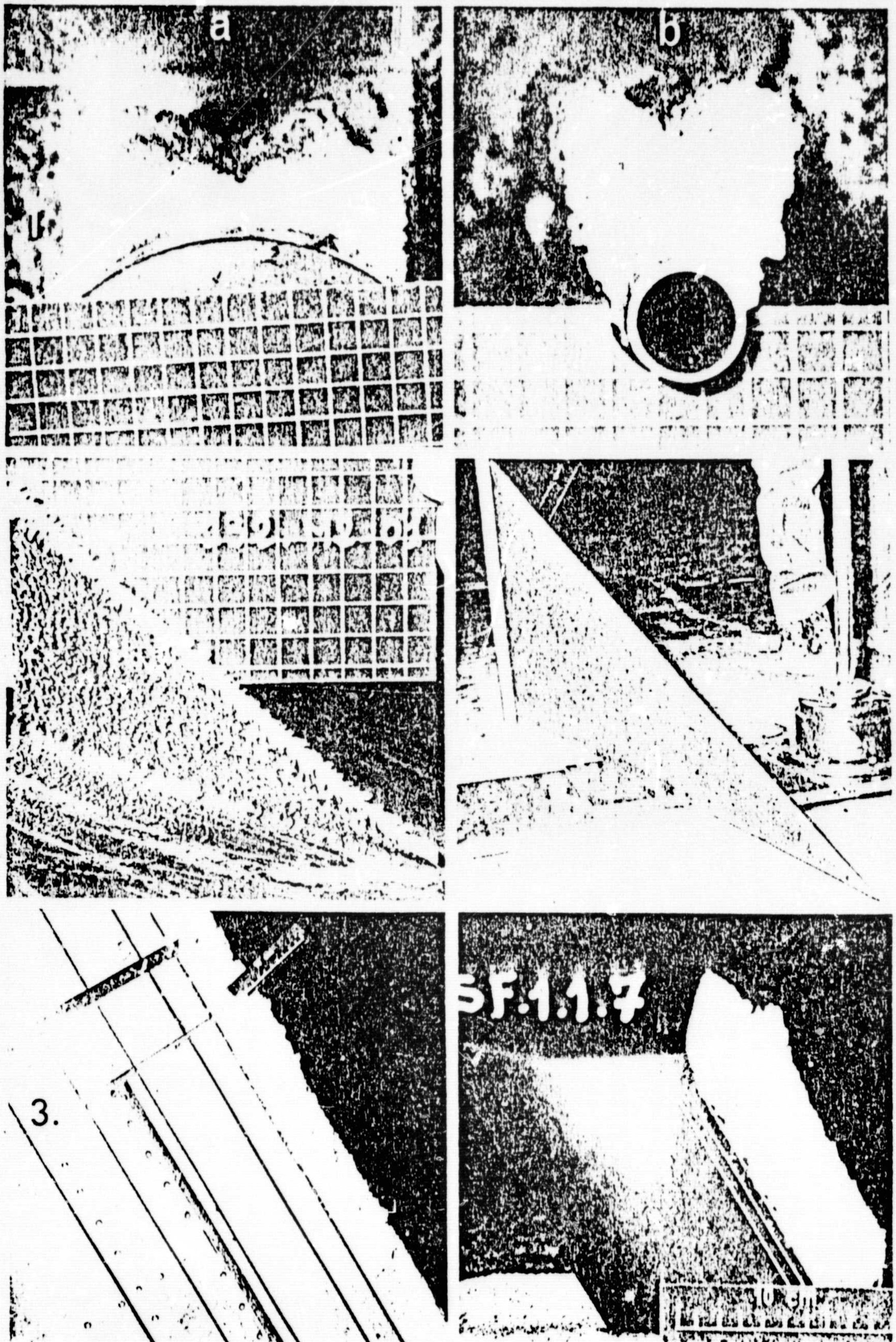

Fig. 4. Icing disregarding similitude rules.

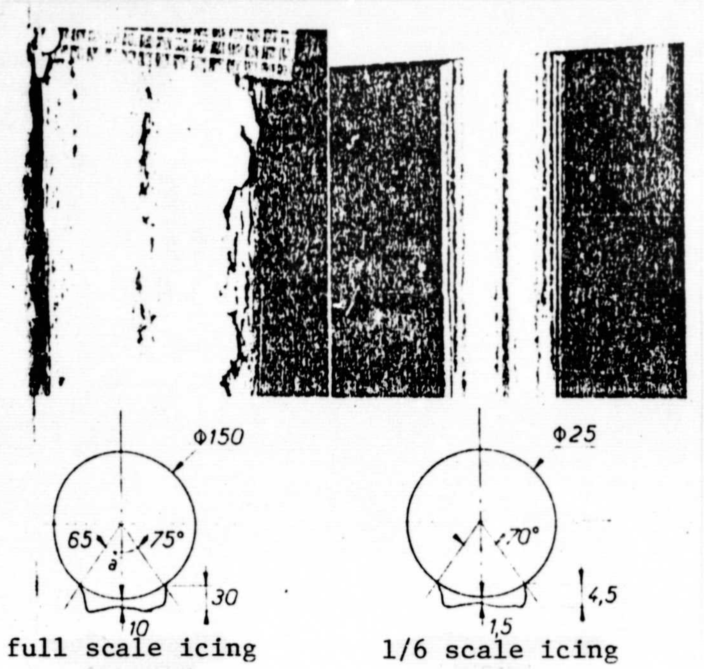

Fig. 5. 1/6 similitude icing on cylinders.

Figures 5 and 6 show the results of 1/6 and 1/12 similitude icing, in /29 the form of photographs and directional diagrams, obtained on cylindrical specimens.

The icing angles of the ice accretions are practically indentical: 65 to 75° for 70° in the case of 1/6 icing and 55 to 65° for 60° in the case of 1/12 icing. The ice thickness reduced to the same scale is similar:

ICE THICKNESS					
scale	location	e_G	e_m	e_m/k	relative error
1/6	center	10	1.5	9	10 %
	spars	30	4.5	27	10 %
1/12	center	15	1	12	15 %
	spars	40 - 45	3 - 3.5	36 - 42	10 %

The small scale icing is more regular than that at full /30 scale, where lateral projections appear. On the other hand, in all cases, the localized area around the stopping point of the flow is formed of transparent ice.

Figure 7 shows the shape and extent of ice obtained at 1/6 scale, on two 75° swept back delta half wings, set at a 15° angle of attack. Ice only develops on these wings on the bottom side

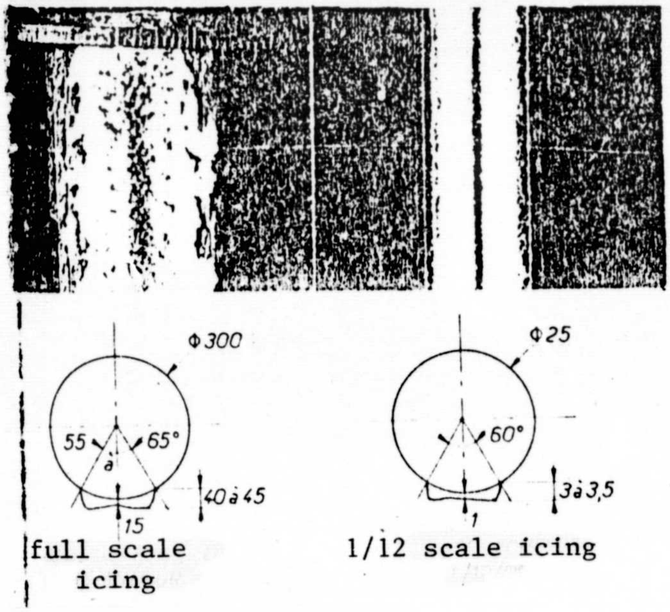

Fig. 6. 1/12 similitude icing on cylinders.

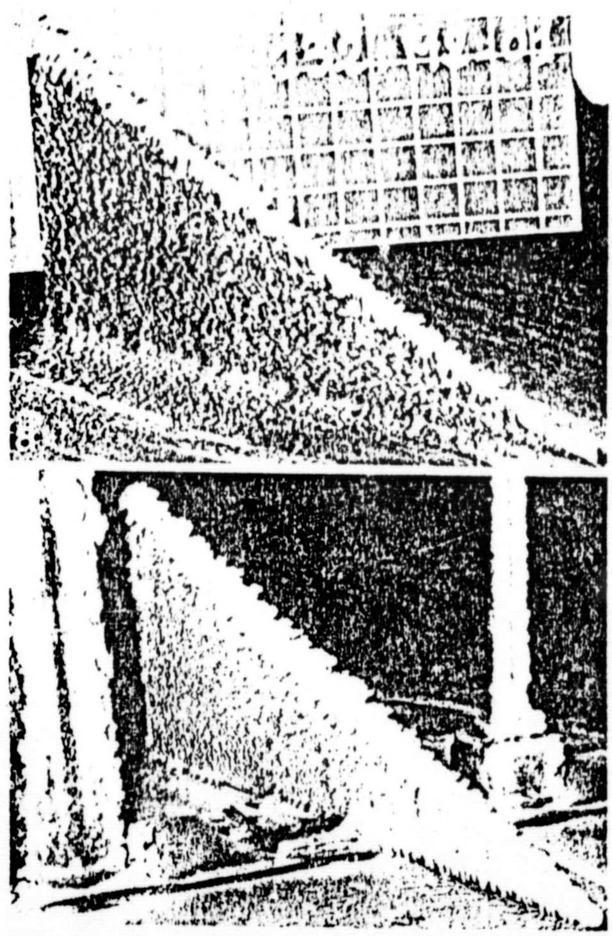

Fig. 7. 1/6 similitude icing of delta half wings.

of the leading edge, in the form of a laminar accretion, of which a section perpendicular to the leading edge has the shape of an isosceles triangle attached by one of its apexes. This accretion shape also has been observed at 1/6 scale, as well as at full scale.

The Figure 7 photographs show a relatively larger accretion on the full scale model, than on the 1/6 scale model. The ice thickness is 55 mm and 6.5 x 6=39 mm, respectively.

Figure 8 shows the mounting of two models of full scale and 1/12 scale thick cross section wing sections in the test section. The right portion of this figure shows a photographic montage, which has reduced the two models to the same size, guided by the spacing of the 20, 25, 10, 5 and 2.5 chord percentag markers. The similarity of the accretions is noteworthy, both as to thickness

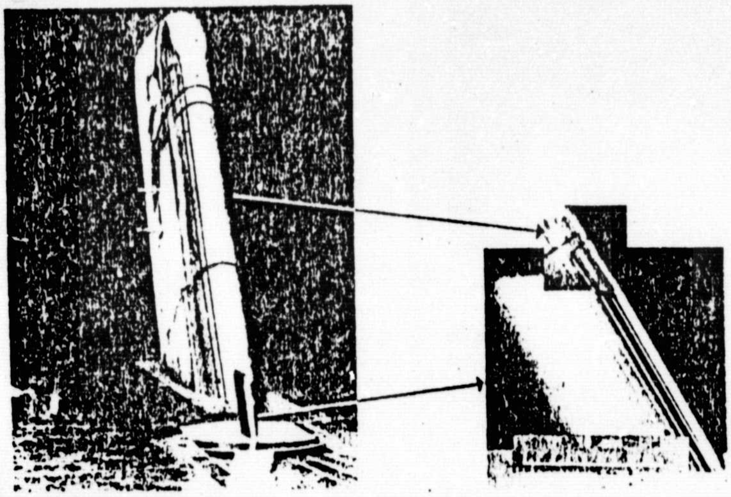

Fig. 8. 1/12 similitude icing on thick cross section wing sections at 0 angle of attack.

(23 mm and 1.7 x 12=20.4 mm), as well as for the extent of the ice (2.5% of chord). This test was performed at 0 angle of attack. The icing shown in Fig. 9 on the same models, was carried out at an 8° angle of attack. On the top views (left photos), no ice accretion appears downstream of the 2.5% chord. On the bottom views (right photos), small accretions appear far downstream of the leading edge, and they only become large on the two models between 5 and 2.5%. The two tests again demonstrate good consistency.

Altogether, these tests, performed under conditions observing the icing similitude rules, demonstrate the good agreement obtained, both as to the extent of the accretions and their shapes. Nevertheless, in general, a slight lack of ice must be noted in the case of small scale icing, which perhaps can be explained by the production of a certain percent of ice crystals, at the level of atomization of the water of the fog. This percentage of crystals is larger in small scale tests. This requires finer atomization and higher air pressure.

The tests also have shown that, in tests performed at constant temperature, it is not necessary to reproduce the internal structure of the aircraft, in order to obtain the same ice accretions, and that the material of which the models are made has no appreciable effect on the accretions (duralumin, steel, araldite, wood). This is very important, for it then is possible to perform reduced scale icing tests on the classical models used for aerodynamic tests. Most certainly, these tests do not involve the requirement of determination of the efficiency of equipment

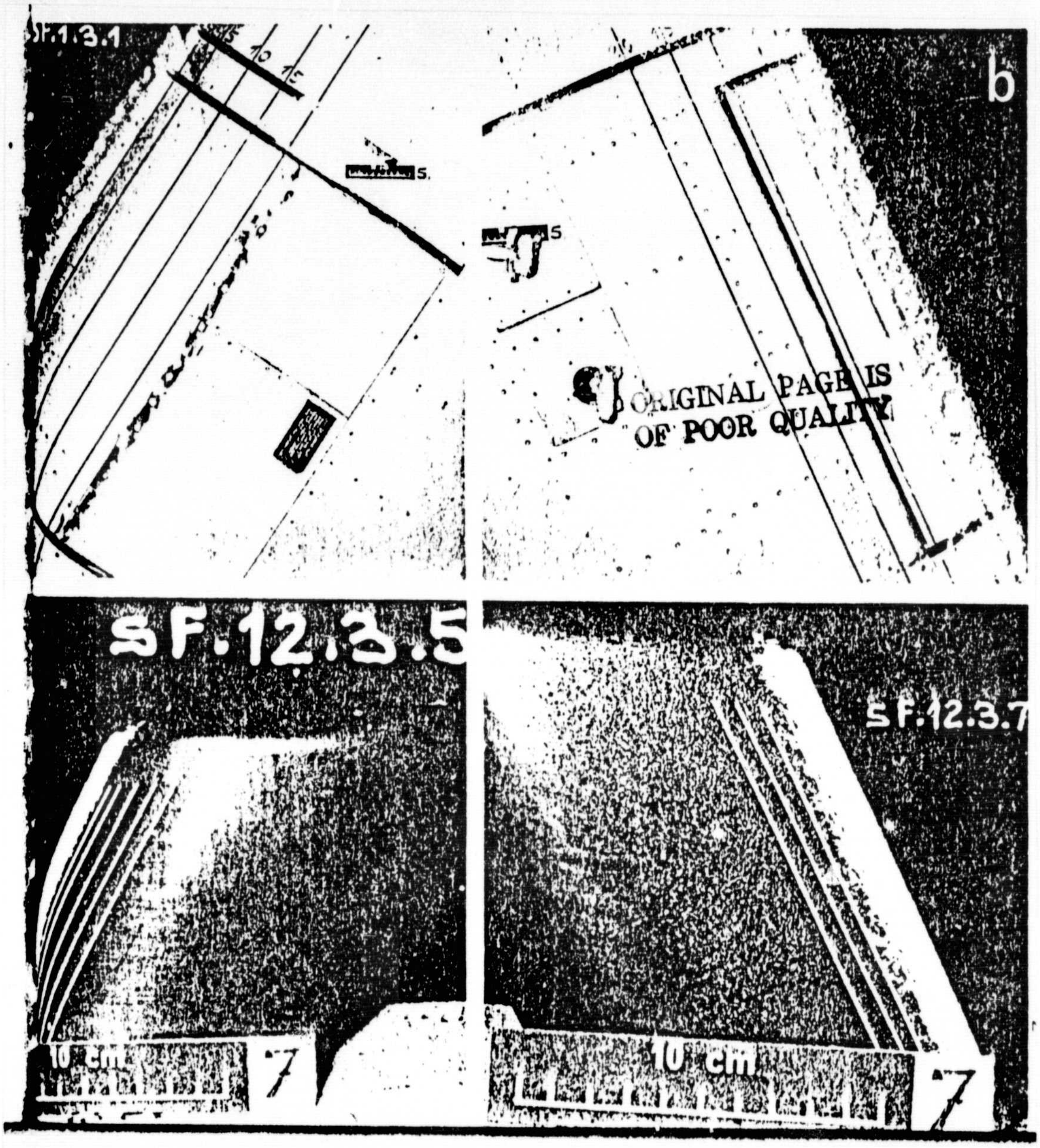

Fig. 9. 1/12 similitude icing on two thick cross section wing sections at 8^{o} angle of attack.

such as de-icers or antiicers, but, rather, of sticking to determination of the areas, extent and shapes of the ice.

The effectiveness of saturation of the test section has been verified, by performing icing tests with a variable distance between the atomizing grid and the models. There was no difference in the range of distances tested (from 4 to 10 m). These tests not only show that there is no evaporation of the water droplets, but also that the parameters of the ice fog are sufficiently accurate and constant, that no difference develops between tests performed under the same rated conditions.

Conclusions

The National Office of Aerospace Studies and Research has, in the large S1 wind tunnel of its Modane-Avrieux Center, equipped with its new ice fog producing installation, one means of investigation necessary to builders, to specify the icing hazard which can be encountered in flight and to define protection systems.

In recent years, ONERA, in close collaboration with the British Aircraft Corporation, the National Industrial Aerospace Company and the official services, has extended the field of use of the S1 wind tunnel to icing, by successfully studying and testing the similitude icing technique. Therefore, it is now possible to determine, long before producing the aircraft and on the models normally used for classical aerodynamic tests, the areas, shapes and thickness of ice, before it is formed on an aircraft in flight under icing conditions.

Some limitations, such as the annual useable cold period, /31
temperature minimums and limited similitude, means that this test resource cannot be completely substituted for all the others. Nevertheless, the flight test program of an aircraft can be considerahly eased, if the wind tunnel tests cut across typical points of this program. In particular, the most critical cases of icing, which are dangerous in actual flight, can be simulated in a wind tunnel without any risk, and their results can be extrapolated to flight, based on comparisons in less dangerous cases.

REFERENCES

1. Pierre, M. and G. Fasso, "The Modane-Avrieux aerothermodynamic test center," N.T. ONERA, No. 166, 1970.

2. Rush, C. K., "The Icing of Delta Wings of Unity Aspect Ratio Having Leading Edge Separation," N.R.C. Aeronautical Report L.R.268, January 1962.

3. Rush, C. K. "Icing Tests of a 10 ft. Delta Wing of Unity Aspect Ratio Having Leading Edge Separation," N.R.C. Aeronautical Report L.R.337, January 1962.

4. Avison, B., "The Determination of Icing Pattern on Slender Delta Wings," Volume 1: A Model Technique. University of Bristol, Department of Aernautical Engineering; A thesis submitted for the Degree of Doctor of Philosophy in the Faculty of Engineering of the University of Bristol.

5. Langmuir, I. and K. B. Blodgett,"A Mathematical Investigation of Water Droplet Trajectories," A.A.F. Technical Report 5418, February 1946.

6. Gelder, T. F., J. P. Lewis, "Comparison of Heat Transfer from Airfoil in Natural and Simulated Icing Conditions," NACA T.N. 2480, September 1951.

7. Messinger, B. L., "Equilibrium Temperature of an Unheated Icing Surface as a Function of Airspeed," I.A.S. Preprint No. 342, Presented at Annual Summer Meeting, June 1951.

8. Hauger, H. H., K. G. Englar, W. W. Reaser, "Analysis of Model Testing in an Icing Wind Tunnel," Douglas Aircraft Company Inc., Report No. SM 14993, May 1954.

9. Googan, R. and E. T. Jackson, Development Study "The Use of Scale Models in an Icing Tunnel to Determine the Ice Catch on a Prototype Aircraft, with Particular Reference to the Concorde," Issued by B.A.C. (Operating) Ltd. Filton Division, Aircraft Engineering Dept. SST/B75T/RMMoK/242, Issue 1, 24th July 1967.

10. Googan, R. and J. A. Hubbold, "Concorde De-Icing: Icing Tests on a 1/6th Scale Model (G14) at Modane," Preliminary Test/Program SST/B72T, 51/5927 Issue 1, 7th August 1968.