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BOUNDARY LAYER EVALUATION OF ANTI-ICING FLUIDS FOR COMMUTER AIRCRAFT

Prepared for

Transportation Development Centre
Policy and Coordination
Transport Canada

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Groupe de Recherche en Ingénierie de
l'Environnement Atmosphérique (GRIEA)
Université du Québec à Chicoutimi (UQAC)

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Un sommaire en français de ce rapport est inclus avant la table des matières.

Transport Canada Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No. TP 11811E	2. Project No. 8109	3. Recipient's Catalogue No.
4. Title and Subtitle Boundary Layer Evaluation of Anti-icing Fluids for Commuter Aircraft		5. Publication Date December 1994
		6. Performing Organization Document No.
7. Author(s) P.R. Louchez, J.L. Laforte, G. Bouchard		8. Transport Canada File No. ZCD1455-241
9. Performing Organization Name and Address Groupe de recherche en ingénierie de l'environnement atmosphérique Université du Québec à Chicoutimi 555, boulevard de l'Université Chicoutimi, Quebec, G7H 2B1		10. PWGSC File No. XSD92-00169-(673)
		11. PWGSC or Transport Canada Contract No. T8200-2-2543/01-XSD
12. Sponsoring Agency Name and Address Transportation Development Centre (TDC) 800 René Lévesque Blvd. West Suite 600 Montreal, Quebec H3B 1X9		13. Type of Publication and Period Covered Final
		14. Project Officer Barry B. Myers

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

Cosponsored by the Dryden Commission Implementation Project

16. Abstract

The use of anti-icing fluid to prevent ice formation on aircraft requires adequate demonstration that fluid residues do not perturb the take-off operation. For large aircraft, a standard testing method is already in place. This work documents the evaluation procedure for commuter aircraft. The method is implemented in a cold wind tunnel where the BLDT over a flat plate covered with the candidate fluid is measured after 20 seconds of a 2.1 m/s^2 air acceleration and a 35 m/s maximum air velocity. A maximum acceptable value of 10.6 mm is derived for the BLDT according to a lift study on a 2D model. One candidate Type III fluid tested in this study exhibits acceptable behaviour down to about -25°C.

17. Key Words Aircraft take-off, Anti-icing, Boundary Layer, Commuter, Fluid, Wind tunnel	18. Distribution Statement Limited number of copies available from the Transportation Development Centre

19. Security Classification (of this publication) Unclassified	20. Security Classification (of this page) Unclassified	21. Declassification (date) —	22. No. of Pages xi, 35	23. Price Shipping/ Handling

CDT/TDC 79-005
Rev. 88

Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada TP 11811E	2. N° de l'étude 8109	3. N° de catalogue du destinataire
4. Titre et sous-titre Boundary Layer Evaluation of Anti-icing Fluids for Commuter Aircraft		5. Date de la publication Décembre 2004
		6. N° de document de l'organisme exécutant
7. Auteur(s) P.R. Louchez, J.L. Laforte, G. Bouchard		8. N° de dossier - Transports Canada ZCD1455-241
9. Nom et adresse de l'organisme exécutant Groupe de recherche en ingénierie de l'environnement atmosphérique Université du Québec à Chicoutimi 555, boulevard de l'Université Chicoutimi (Québec) G7H 2B1		10. N° de dossier - TPSGC XSD92-00169-(673)
		11. N° de contrat - TPSGC ou Transports Canada T8200-2-2543/01/XSD
12. Nom et adresse de l'organisme parrain Centre de développement des transports (CDT) 800, boul. René-Lévesque Ouest Bureau 600 Montréal (Québec) H3B 1X9		13. Genre de publication et période visée Final
		14. Agent de projet Barry B. Myers

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

Recherche coparrainée au titre du Programme de mise en oeuvre de la Commission Dryden.

16. Résumé

Il doit être prouvé que les résidus d'un agent antigivre ont un effet négligeable sur les performances d'un aéronef au moment du décollage. Une méthode d'essai normalisée est déjà adoptée dans le cas des gros porteurs. Le présent rapport décrit une procédure d'évaluation applicable aux aéronefs de taille allant de petite à moyenne. Cette méthode a été essayée dans une soufflerie réfrigérée, mettant en œuvre une plaque plane recouverte de l'agent antigivre visé et dont on a ensuite mesuré l'épaisseur de déplacement de la couche limite (EDCL) à la vitesse maximale de 35 m/s, après une accélération de 2,1 m/s^2 pendant 20 secondes. Une valeur maximale acceptable de 10,6 mm a été obtenue pour l'EDCL d'après une étude de portance effectuée sur une maquette à deux dimensions. Un agent de type III testé dans le cadre de cette recherche s'est révélé acceptable jusqu'à environ -25 °C.

17. Mots clés Décollage, antigivre, couche limite, petits avions, agent, soufflerie	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication) Non classifiée	20. Classification de sécurité (de cette page) Non classifiée	21. Déclassification (date) —	22. Nombre de pages xi, 35	23. Prix Port et manutention

ACKNOWLEDGMENTS

The work presented in this text has been funded by Transport Canada; the guidance of Mr. B. Myers of the Transportation Development Centre, Policy and Coordination Group is gratefully acknowledged.

The study performed by Boeing Canada de Havilland Division is a cornerstone of this work and Dr. N. Ellis is to be particularly thanked for the significance of the information presented. The preliminary research performed at Von Karman Institute by Dr. M. Carbonaro is also greatly appreciated.

All fluid manufacturers were also very helpful in providing us with the fluids in this study.

Finally the authors are greatly indebted to the technical staff, Mr. C. Grenon, Mr. C. Gauthier, Mr. L. Maltais, for their skillful and thorough work in the wind tunnel and to Mr. M. Tremblay in the chemical laboratory.

SUMMARY

The requirement for a clean aircraft wing surface at the time of take-off has been amended for cases where anti-icing fluids are used. However, the negligible effect of fluid residues must be adequately demonstrated. For large aircraft (with a rotation velocity above 100 KT), a standard testing procedure has been designed and implemented at the Université du Québec à Chicoutimi (UQAC) by the Groupe de recherche en ingénierie de l'environnement atmosphérique (GRIEA).

The present work defines and illustrates a testing procedure related to the use of anti-icing fluids on commuter aircraft. The purpose of the procedure is to evaluate the interference caused by residual anti-icing fluid during the take-off of an aircraft with a rotation velocity and time to rotation significantly smaller than those of a large aircraft (such as the B737).

The testing method, similar to that for large aircraft, determines the boundary layer displacement thickness (BLDT) induced by a film of anti-icing fluid, applied on a flat horizontal plate and subjected to a linear acceleration of 2.1 m/s^2, during 17 s, up to 35 m/s. The method is shown to be repeatable and accurate. The maximum acceptable BLDT value, for aircraft with a rotation velocity between 55 KT and 100 KT, was found to be 10.6 mm, according to a correlation with a 2D model study performed at NASA Lewis Research Center by Boeing Canada dc-Havilland Division.

One existing fluid was found to be acceptable down to about -25ºC. Other fluids are acceptable in a limited temperature range. In this study, no Type II fluid was found acceptable. The writing of a corresponding SAE document is recommended.

SOMMAIRE

La propreté de l'aile d'un aéronef au moment du décollage est une exigence fondamentale qui a dû être assouplie pour tenir compte des situations où un agent antigivre doit être utilisé. Il reste cependant à prouver que les résidus d'un tel fluide ont un effet négligeable. Dans le cas des gros porteurs (dont la vitesse de cabrage dépasse les 100 nœuds), une procédure d'essai normalisée a été conçue et mise en œuvre à l'Université du Québec à Chicoutimi par le Groupe de recherche en ingénierie de l'environnement atmosphérique.

Le présent rapport décrit la procédure d'essai relative à l'utilisation d'agents antigivre sur la voilure d'aéronefs de taille allant de petite à moyenne. L'objectif de cette procédure a été d'analyser les perturbations que peuvent causer les résidus au moment du décollage dans le cas d'un aéronef dont la vitesse de cabrage ainsi que le temps mis à atteindre cette vitesse sont nettement inférieurs à ceux d'un avion plus gros (comme le B-737).

La méthode d'essai, semblable à celle appliquée aux gros porteurs, détermine l'épaisseur de déplacement de la couche limite (EDCL) induite lorsqu'une couche d'agent antigivre versé sur une plaque plane horizontale est soumise à une accélération de 2,1 m/s^2 pendant 17 s pour atteindre la vitesse de 35 m/s. Cette méthode s'est révélée à la fois fiable et reproductible. La valeur maximale acceptable de l'EDCL s'est révélée être de 10,6 mm pour un aéronef dont la vitesse au moment du cabrage se situe entre 55 et 100 nœuds, valeur fixée après corrélation avec les résultats d'une étude sur une maquette à deux dimensions effectuée au centre de recherche Lewis de la NASA par la division de Havilland de Boeing Canada.

Un agent antigivre offert sur le marché a été jugé acceptable jusqu'à -25 ºC environ, alors que d'autres l'ont également été mais dans une gamme de températures plus étroite. Cette étude n'a trouvé acceptable aucun des agents de type II. Il est recommandé de procéder à la rédaction d'un document SAE relatif à cette procédure.

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GLOSSARY

a	linear acceleration during test (m/s^2)
t_{f_0}	initial fluid thickness (mm)
t_m	period of linear acceleration during test (s)
t_r	period of ground acceleration to be simulated (s)
C_l	2D lift coefficient (-)
C_{lmax}	2D equivalent of aircraft C_{Lmax} (-)
$\Delta C_l/C_l$	2D lift loss (%)
V_r	rotation velocity (m/s or KT)
V_m	maximum velocity (m/s or KT)
T_a	air temperature (°C)
T_f	fluid temperature (°C)
T_2	air temperature at cross section 2 (°C)
T_3	air temperature at cross section 3 (°C)
α	angle of attack (°)
$\dot{\alpha}$	rotation rate (°/s)
δ_d^*	BLDT with no fluid (mm)
δ_f^*	BLDT with fluid (mm)

1 Introduction

1.1 Ground aircraft anti-icing

A clean surface (wings and body) is a standard operational requirement during take-off of any commercial aircraft [1]. In winter, when climatic conditions result in ice formation and deposition on the aircraft, mere ice removal (de-icing) may not be enough to ensure a safe condition at take-off, since new deposits may appear during queuing or taxi time. Anti-icing fluids, which prevent ice formation for 3 minutes (Type I) to 30 minutes (Type II), have therefore been used for several years now in most ice sensitive airports in North America.

The anti-icing fluid, left on the aircraft at the time of take-off, constitutes an exception to the clean surface policy mentioned before, but must not significantly alter the aerodynamic and control performance of the aircraft. To ensure the aerodynamic acceptability of the fluid residues, a standard procedure has been established for large aircraft (rotation velocity above 100 knots) [2], and is routinely performed at the Université du Québec à Chicoutimi (UQAC), whose facilities are certified by the Aerospace Industries of America (AIA) and the Association Européenne des Constructeurs de Matériel Aérospatial (AECMA).

1.2 The case of commuter aircraft

The fluid elimination from the aircraft wing during the period of ground acceleration depends on the duration of this period and on the velocity at rotation. So does the amount of interference caused by the fluid residues. With Type II fluids, various flight test experiments have been performed, such as those on LE BARON and CESSNA aircraft [3]. Although no lift data were produced, a general assessment was that the lift capability could be significantly affected by residues of Type II fluids.

A quantitative investigation was designed by BOEING-CANADA DE HAVILLAND DIVISION (BCDD) and was run at the NASA Lewis Research Center (LeRC) in 1991. The study pursued the measurement of lift (drag and pitching moment) on a 2D wing model covered with anti-icing fluid (the list of fluids was extensive and is reported in Table 1). The wing geometry and the velocity schedule were selected to represent the ground acceleration of DHC-6 and DHC-8 aircraft. The results of the investigation [4] exhibited, for certain fluids and temperatures, an unacceptable lift loss of about 20%, at C_{lmax} (see Figure 1). These results clearly indicated, as expected, that the standard for large aircraft was not applicable to commuter aircraft.

1.3 Objectives

In order to adapt the evaluation method of anti-icing fluids to the case of commuter aircraft, a study of the effect of reduced acceleration time and maximum velocity in the standard testing method was performed at the Von Karman Institute [5]. In September 1992, the European Regional Aircraft association (ERA) met in Amsterdam to identify the actions needed to develop recommendations for the use of anti-icing fluids on commuter aircraft. Based on the VKI study, and a preliminary UQAC investigation [6], a general evaluation procedure was outlined. This procedure, which includes a low speed ramp to simulate commuter aircraft take-off, is detailed in section 2.2. The Groupe de Recherche en Ingénierie de l'Environnement Atmosphérique (GRIEA), which operates the UQAC facility, was mandated by Transport Canada's Transportation Development Centre (TDC) to implement the procedure, assess its merits and evaluate all existing fluids which are considered by their manufacturers as potential candidates for commuter aircraft use. These are the objectives of the present document. It should be noted that most experimental fluids for commuter aircraft provide a significantly higher degree of protection than Type I fluids, but do not exhibit the level of protection required for Type II fluids [7], and, therefore, are now referred to as Type III fluids.

2 Description of the Evaluation Method

2.1 Testing procedure

The wind tunnel testing method, for large aircraft, is performed on a flat horizontal plate. The flat horizontal plate provides a simple reference for BLDT development since a common curvature cannot be defined for the various commercial aircraft wings. The boundary layer displacement thickness (BLDT) of the air boundary layer, developed on a 1.5 m long flat horizontal plate covered with a 2 mm thick layer of candidate fluid, is measured during a 30 s wind acceleration, at temperatures ranging from 0°C to -30°C. The more fluid interference left after 30 s, the higher the BLDT value at the end of the plate. Using a Boeing 737 200-ADV as reference, the BLDT value thus obtained has been shown to be well correlated to lift loss during rotation [8]. The same procedure is used for commuter aircraft testing. A 2 mm thick layer is applied on a horizontal plate of length L; linear acceleration is maintained during a time t_m up to a maximum velocity V_m and, then, the wind velocity is kept constant during 30 seconds before shut down. The reported BLDT value is measured, at the end of the plate, and averaged during a 6 second period after time t_m. Experiments are performed at -30°C, -20°C, -10°C and 0°C and repeated three times at each temperature. Dry runs (without fluid) and a reference run (with a well documented reference fluid) are performed at each temperature for calibration purposes. For large aircraft, the reference fluid is an 88% monopropylene glycol defined in the military specification MIL A-8243D (coded MIL in this study). In order to have a reference within the acceptability range for commuter aircraft, the reference fluid used in this study is a 75/25 water dilution of the MIL A-8243D fluid (coded MIL 75/25 in this study).

A general sketch of the GRIEA refrigerated, closed circuit wind tunnel is given in Figure 2. The flat plate is the bottom plane of a rectangular test duct inserted in the test section of the wind tunnel. A sketch of the test duct is given in Figure 3. BLDT value at the end of the plate (cross-section 3) is obtained from differential static pressure measurement between cross-section 2 and 3. Measurement and calculation methods are presented in reference [2], and detailed discussion can be found in reference [9].

2.2 Test parameter identification

According to the previous section, the test parameters to be selected are t_m, V_m, and L. These parameters have to be defined in relation to the characteristics of the aircraft take-off to be represented.

In the case of large transport aircraft, the velocity schedule parameters (t_m and V_m) were chosen to relate to a ground acceleration, a, of 2.6 m/s² (5 KT/s) and a small rotation velocity, V_r, of 52 m/s (100 KT). According to equation 1 below, the time to rotation , t_r, is thus 20 s:

$$t_r = \frac{V_r}{a} \qquad (1)$$

The time to reach the climb out speed at about 10 m (35 ft), was considered the critical moment where adequate maximum lift must be ensured in case of one engine operative. Consequently, it is the value retained for V_m. Denoting Δt_u the time increment between rotation and unstick, and Δt_c the time increment between unstick and 10 m aft clearance, and furthermore, considering that acceleration is kept about constant, the relationships for t_m and V_m are given in equations (2) and (3).

$$t_m = t_r + \Delta t_u + \Delta t_c \qquad (2)$$

$$V_m = at_m \qquad (3)$$

Considering typical take-off conditions, $\dot{\alpha}$ = 3°/s and α = 7°, for large aircraft, Δt_u and Δt_2 are between 2 and 3 seconds, therefore t_m was chosen as 25s and, consequently, V_m = 65 m/s (126 KT). The corresponding velocity schedule is shown in Figure 4a.

The situation for small commercial aircraft is more difficult since there is a large range in performance to cover. Ideally, considering the objective of the testing method, we should take the worst case scenario for fluid elimination, i.e. short rotation time and low rotation velocity. An extreme case, mentioned by Tyrolean Airways (Austria) at the ERA meeting, was $t_r \cong 12$s and $V_2 \cong 30$ m/s. However, the potential market for Type III fluids would rather reside in the high part of the performance scale (for example, the FOKKER 100). A preliminary UQAC study was performed, using two kinds of wind schedule (Figures 4a and 4c) and representative fluids (Table 3). The results, exhibited in Figure 5 for high ramp and Figure 6 for low ramp, showed that the BLDT values increased dramatically as V_m decreased. Consequently, a fluid exhibiting an elimination performance acceptable in the worst case scenario would not exhibit an ice protection significantly better than that of Type I fluids, i.e. far from the ice holdover of about 20 minutes expected for Type III fluids (for the present day fluid technology). Consequently, a fair compromise was to select a middle range performance aircraft excluding from the recommended use of anti-icing fluids all aircraft with take-off characteristics lower than the one selected.

Following the directives of the ERA meeting, and acknowledging the only available model study [4], the reference case chosen is the DHC-6 in the following take-off conditions: V_r = 31 m/s (60 KT) and $a = 2.1$ m/s² (4 KT/s), which leads to t_r = 15 s according to equation (1). Now, considering the "mitigating circumstances for multi-engined propeller driver aircraft " [4], the acceptable lift loss in C_{lmax} can be increased from 5.25% for large aircraft to 8% for commuter aircraft. This means that between lift-off and climb out, the propeller slipstream is expected to help fluid flow off and thus bring down the loss in C_{lmax} to less than 5.25%. Consequently, the critical moment to be considered is taken as the lift-off time (unstick): a more severe constraint than for large aircraft which compensates for the higher lift loss acceptability. Thus, in equation (2), we have $\Delta t_u = 0$ and considering typical values, $\dot{\alpha}$ = 4°/s and α = 8°, we obtain t_m = 17 s, and from equation (3), V_m = 35 m/s (70 KT). The corresponding velocity schedule is given in Figure 4c. Consequently, this proposed testing method does not apply to small aircraft rotating under 60 KT or before 15 s of ground acceleration. As a remainder, the large aircraft limitation on V_r is 100 KT; the limitation on rotation time is about 20 seconds (not specified in reference [2]).

The 2D model study used for comparison with the present work was based on a cut at the 45 % semi-span station of DHC-8 series 100 wing. The chord length was then about 2.3 m, which is a good representative value to select L if we want to compare flat plate results with model results. Since 2.3 m is not far from the reference value used for large aircraft (60 % span of B737-200ADV), it is therefore sensible to keep L at the same value as in the large aircraft test. Furthermore, Carbonaro's comparison of BLDT data between half and full plate length [5] indicated that the procedure was more reliable at the maximum available plate length, i.e. L = 1.5 m.

2.3 Acceptance criteria

The acceptance criteria for large aircraft were derived from a limit of 5.25 % of acceptable lift loss on reference lift data which was then converted into a maximum acceptable value for BLDT at -20°C and below. A somewhat empirical reduction of the limit is required from -20° to 0°C. Definition of the maximum BLDT line was a function of dry run data and reference fluid data. Details of the calculation are given in various documents: [2], [7], [8] or [9]. The rationale behind these formulas can be found in reference [8].

For commuter aircraft, the definition of an acceptance level follows essentially the same steps. First, a limit lift loss must be selected (at -20° C). This strongly depends on the reference aircraft chosen; also, the favorable propeller effect should be taken into account. Then, a lift loss vs. flat plate BLDT correlation must be drawn from 2D model results of the reference aircraft. Thus, the limit value (at -20°C) for flat plate BLDT can be derived. The significance of reducing the limit in the -20°C to 0°C range (as done for large aircraft) may be questioned for commuter aircraft, and a straight constant line could be used. Presently, the BCDD study is the only existing quantitative work on 2D models of commuter aircraft. A correlation from the BCDD and UQAC data is presented in Figure 12, with the resulting tentative acceptance line.

3 Fluid Evaluation

3.1 Fluids and experiments

The aerodynamic performance evaluation using the flat plate method was first performed in August 1992 with a 2.6 m/s² ramp ($V_m = 45$ m/s) and a 2.1 m/s² ramp ($V_m = 35$ m/s) at 0°C, - 10°C and -20°C, each test being duplicated. The fluids used in this preliminary work are listed in Table 3a. In this study, some inaccuracies exist due to large deviation in velocity ramp value.

The main study (December to March 1993) corresponds to the work performed according to the procedure specified in section 2.2. The fluids are listed in Table 3b. Control of the ramp was not entirely satisfactory in the preliminary study; therefore, only the results pertaining to the main study are considered quantitatively. The fluids, mostly experimental, are considered by the various manufacturers as candidates for commuter aircraft use. These fluids are now labeled as Type III fluids. However, there is not yet an AMS available for these products. At this time, the suggested holdover time on Water Spray Endurance Test is about 20 minutes, but it is possible that the fluid manufacturers will be able to raise the holdover time to 30 minutes, the same as Type II's. A companion study, sponsored by the FAA, provides the holdover time assessment of the candidate fluids used in this study [10].

3.2 Calibration results

The dry BLDT value is first used as a calibration of the calculation procedure. At 65 m/s, the measured BLDT value is, on average, equal to 2.75 mm. With the help of an integral numerical model [9], this was found to correspond to a transition at 23.5 cm from the entrance, and therefore to a critical Reynolds number $Re_C \cong 1.5\times10^6$. This value, used to compute the transition distance at 35 m/s (43.6 cm), provides the means to predict the measured BLDT value in dry conditions with a 35 m/s free stream velocity. The prediction value obtained in this fashion is 2.69 mm.

Typical dry test curves are shown in Figure 7a, and corresponding data are listed in Table 4. Dry BLDT values at all temperatures are listed in Table 5. According to Table 5, experimental values range from 2.64 mm up to 2.85 mm, which is in fair agreement with the numerical prediction.

The reference fluid used here is a 75/25 dilution of the MIL 8243D de-icing fluid. For large aircraft, the military fluid is used neat as a reference. The dilution is meant to lower the reference BLDT value close to the acceptable range. Typical reference fluid test curves are shown in Figure 7b, with corresponding data listed in Table 6. Overall BLDT calibration data are exhibited in Figure 8. The variation of BLDT at a given temperature is shown to be small. The variation is close to the ± 0.15 mm accuracy evaluated for the overall procedure in reference [9]. The accuracy was expected to be lower, since, at 20 s, the BLDT is still significantly decreasing (see Figure 8 for example), which was not the case in the large aircraft test (measurement at 30 s). It should be noted that, at -30°C, the reference fluid is freezing in certain cases.

3.3 Fluid BLDT values

The BLDT value of the boundary layer developed on the 1.5 m long flat horizontal plate, initially covered with a 2 mm of a candidate anti-icing fluid, after 17 s of a linear wind acceleration of 2.1 m/s^2 (averaged over six consecutive seconds) is reported as the standard value for evaluation of the aerodynamic effect of the fluid left on the aircraft at the time of take off.

Examples of typical output data are presented in Figure 9 for a Type II (A447) and a Type III (A392) fluid. It should be noted that, unlike those in the large aircraft schedule, the BLDT value is quite sensitive to the acceleration. Using A392 at -10°C as a guide (Figure 10), it can be seen that a reduction of 0.1 m/s^2 in ramp increases the BLDT by 0.4 mm.

The main BLDT results are presented in Figure 11 for cold temperatures ranging from 0°C down to -30°C. The repeated values provide a good estimation of the stability of the overall procedure variation and BLDT values can thus be estimated at about ± 0.2 mm at a given temperature.

All fluids present a decreasing value of their BLDT with increase of temperature, which is due to the decrease of viscosity. An exception to this rule is the A447 fluid, which is about constant, indicating how much the non-Newtonian behavior of the fluid may sometimes interfere with common sense expectations. Also, we note that the temperature dependence of the BLDT is generally linear with the exception of the A428 fluid.

4 Results and discussion

To select the acceptance criteria, we have to establish a linear correlation between the 2D maximum lift loss in the BCDD study with the flat plate BLDT values. For high BLDT values, the blockage method saturates, becoming less sensitive to boundary layer increase, a phenomenon also noted in VKI facilities [5]. Consequently, only BLDT values less than 14 mm and lift loss less than 13 % are considered for the correlation.

As in the Boeing work for large aircraft [8], a single curve fitting is performed at all temperatures to derive the desired correlation. This means that the data for the same fluid at two different temperatures are treated as the data for different fluids. This is acceptable since the procedure is performed at constant temperature. Furthermore, the restrictions on aerodynamic performance regarding the temperature effect is only related to the freezing point. Safety in this matter is ensured by consideration of temperature buffer requirements as described in reference [7]. Consequently, the BLDT requirement, as an independent requirement, does not have to be temperature dependent.

In comparing the BCDD and UQAC studies, the common points are: A318 (-10°C, 0°C), A392 (-20°C, -10°C, 0°C), A415 (-20°C, 0°C), A447 (-20°C, 0°C), A457 (-20°C, 0°C), and A458 (0°C). The resulting data are plotted in Figure 12. A linear regression fits reasonably well , $R^2 = 93\ \%$, and is given in equation (4) below:

$$\frac{\Delta C_{l\,\max}}{C_{l\,\max}} = -6.92 + 1.41\left(\frac{\delta_f^*}{t_{f_0}}\right) \qquad (4)$$

where t_{f_0} is the initial fluid thickness (2 mm).

It should be noted that the dry BLDT value is not incorporated in the calculation of the correlation coefficient since the Plexiglas surface does not have a roughness comparable to that of the aluminium surface of an aircraft wing. The BLDT value corresponding to a 0 % lift loss is 4.91 mm which agrees well with the 4.9 mm value obtained at VKI with a 1.5 mm thick 3M antislip adhesive material at $V_m = 42$ m/s [5]. To define the acceptance level, a maximum lift loss must be set. In reference [4], a maximum level of 8 % is suggested. It is higher than the 5.25 % margin allowed for large aircraft, but this takes into account the beneficial effect of the propeller in clearing the fluid. An 8 % loss corresponds to a limit of 10.6 mm in BLDT. As explained previously, this value can be used at all temperatures. Again it should be stressed here that this applies to commuter aircraft with a rotation velocity between 60 and 100 KT (and ground time above 15 s).

Using the information in Figure 11, we can attempt to provide a reasonable diagnostic on the aerodynamic performance of the various fluids in this study. The A392 is acceptable down to about -25°C. The fluid A458 is acceptable down to about -20°C. The fluid A428 is acceptable down to about -15°C. Fluids A418 and A318 are acceptable down to about -10°C. Fluid A483 may be an excellent candidate; it was only tested at -10°C and was well within the acceptance domain. All other fluids, in particular all Type II fluids, are not acceptable. It should be noted that the preceding numbers are only indicative of the range of acceptability of the fluids. Taking into account the available protection time of the fluid (not reported here), the only fluid emerging as an “all purpose” commuter aircraft anti-icing fluid is the A392.

The range of relative humidity during the tests (Figure 13) was from 50 % to 80 %. The corresponding water change in the fluid, by water diffusion in the boundary layer, is shown in Figure 14 to be negligible (below ± 2%). Finally, thickness measurements, at the end of the tests, allow an estimation of the volume elimination (see Figure 15). The percentage of fluid cleared during the acceleration increases from about 60 % at -30°C, up to about 80 %, at 0°C (average values).

5 Conclusions

Up to now there has been no evaluation of the potential aerodynamic penalties in using anti-icing fluids for protecting grounded commuter aircraft subjected to ice formation and deposition. The GRIEA at UQAC has designed and implemented a testing method, which establishes whether a given fluid can be used without significantly altering the aerodynamic performance during take-off.

The method, similar to that for large aircraft, measures the effect of fluid film on the air boundary layer developed on a horizontal flat plate during a wind acceleration typical of small commuter aircraft (DHC-6). Based on the 2D model study performed in 1991 by BCDD, a correlation has been established between the BLDT thus measured and the maximum lift loss. This correlation, using an acceptable lift loss of 8 %, sets at 10.6 mm the maximum value of BLDT for acceptable behavior.

A significant number of candidate fluids for commuter aircraft were tested. According to the proposed testing method, which is valid for aircraft of rotation velocity between 60 KT and 100 KT (and a minimum ground time of 15 s), one fluid (A392) was found acceptable down to about -25°C; other fluids (A458, A428, A418, A318, A483) may be used with restrictions on temperature value. All Type II fluids used in this study were found unacceptable.

The procedure is considered pessimistic, since most commuter aircraft that are likely to be provided with anti-icing facilities have take-off performances which are less stringent, in relation to fluid flow-off, than the DHC-6. However, since a reasonable compromise enters in the design of the procedure, the writing of the corresponding AMS and ASTM specifications is recommended.

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Tables

Table 1: Fluids in BCDD[*] Study.

BCDD code	Type[**]
1	I
2.2	II
2.4	III
3.2	II
3.3	III
4	III
4.3	II
4.5	I
4.6	II
5.1	II
5.3	III
6	I
6.1	II
6.2	I
7.1	II
7.2	II
8.1	II
9.1	I
10	I

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[*] Boeing Canada De Havilland Division

[**] Tentative Classification

Table 2: Lift Loss at 8° in BCDD Study.

	$T_f \cong 0$°C			$T_f \cong -10$°C			$T_f \cong -20$°C			$T_f \cong -30$°C		
Fluid	V_r (KT)	T_f (°C)	$\Delta C_l / C_l$ (%)	V_r (KT)	T_f (°C)	$\Delta C_l / C_l$ (%)	V_r (KT)	T_f (°C)	$\Delta C_l / C_l$ (%)	V_r (KT)	T_f (°C)	$\Delta C_l / C_l$ (%)
1	66	1.5	-2.4	—	—	—	—	—	—	66	-28.4	-16.4
2.2	67	1.7	-7.5	—	—	—	66	-18.9	- 8.2	—	—	—
2.4	70	-0.3	-6.3	—	—	—	66	-20.1	-15.6	—	—	—
3.2	69	0.3	-9.7	62	-10.3	-16.3	64	-19.8	-16.8	—	—	—
3.3	67	-0.9	-4.5	64	-8.6	-9.2	68	-20.0	-11.1	—	—	—
4	69	-0.5	-2.1	64	-8.9	-6.0	65	-19.5	- 6.3	—	—	—
4.3	69	-0.5	-4.6	—	—	—	63	-19.1	-17.3	—	—	—
4.5	64	2.1	-5.1	—	—	—	—	—	—	66	-27.8	- 8.6
4.6	68	-0.4	1.0	64	-8.3	-5.8	65	-19.7	- 5.6	—	—	—
5.1	64	-0.3	-9.7	—	—	—	—	—	—	—	—	—
5.3	65	-0.7	-7.4	—	—	—	65	-19.2	-11.6	—	—	—
6	68	1.2	-2.6	—	—	—	—	—	—	66	-27.6	-20.2
6.1	64	-0.9	-12.5	—	—	—	64	-18.8	-15.3	—	—	—
6.2	64	-0.1	-7.5	64	-8.0	-9.9	66	-19.3	-12.0	—	—	—
7.1	67	1.5	-8.3	—	—	—	—	—	—	—	—	—
7.2	67	1.5	-8.7	—	—	—	—	—	—	—	—	—
8.1	66	0.0	-2.6	—	—	—	65	-18.5	- 9.9	—	—	—
9.1	67	0.8	-0.2	—	—	—	—	—	—	69	-28.5	- 8.6
10	—	—	—	—	—	—	—	—	—	69	-28.1	-17.2

Table 3: Fluids in UQAC Studies

(a) Preliminary Study

GRIEA Code	BCDD Code	Type*
MIL	10	I
MIL75/25	—	I
A341	2.2	II
A203	3.2	II
A392	4	III

(b) Main study

GRIEA Code	BCDD Code	Type *
A318	6.2	I
A428	—	I
MIL	10	I
MIL75/25	—	I
A458	9.1	I
A418	—	II
A447	2.2	II
A457	5.3	II
A483	—	III
A392	4	III
A415	3.3	III
A398	—	III

* Tentative classification

Table 4: Typical Dry BLDT Results

Time (s)	**T_a (°C)**	**RH (%)**	**P_1-P_2 ("H_2O)**	**V_m (m/s)**	**P_2-P_3 ("H_2O)**	**BLDT (mm)**
17.04	-0.2	66.0	3.18	35.2	-0.15	2.81
18.00	-0.2	66.0	3.18	35.2	-0.16	2.76
18.96	-0.2	66.0	3.17	35.1	-0.16	2.71
20.00	-0.2	66.0	3.13	34.9	-0.17	2.65
21.05	-0.2	66.0	3.16	35.1	-0.16	2.74
22.01	-0.2	66.0	3.21	35.4	-0.16	2.78
22.96	-0.2	66.0	3.22	35.4	-0.16	2.77
Averages	-0.2	66.0	3.18	35.2	-0.16	2.74

Table 5: Dry BLDT values

Test Label	T_a (°C)	RH (%)	V_m (m/s)	BLDT (mm)
236	-1.5	62.3	34.7	2.76
237	-2.2	61.3	35.3	2.80
238	-0.4	64.2	34.5	2.75
239	-0.2	66.0	34.9	2.74
240	-0.7	53.5	35.2	2.77
241	-0.5	56.1	34.7	2.80
244	-12.1	77.8	35.9	2.74
245	-11.0	79.1	35.4	2.75
246	-11.6	79.1	34.7	2.75
247	-12.1	79.8	35.5	2.64
248	-11.8	81.9	34.8	2.71
250	-10.2	71.2	35.7	2.74
251	-21.6	70.9	35.3	2.74
252	-20.7	63.3	35.6	2.74
253	-21.8	70.1	34.5	2.77
254	-20.7	59.5	34.9	2.83
255	-21.4	69.5	36.0	2.85
257	-20.8	58.2	36.2	2.85
258	-30.8	56.7	34.9	2.77
259	-30.0	57.4	35.3	2.82
260	-33.2	54.1	35.4	2.81
261	-26.6	66.2	35.2	2.77

Table 6: Typical Reference Fluid BLDT Results

Time (s)	**T_a** (°C)	**T_f** (°C)	**RH** (%)	**P_1-P_2** ("H_2O)	**V_m** (m/s)	**P_2-P_3** ("H_2O)	**BLDT** (mm)
16.98	-10.1	-8.0	76.2	3.30	35.9	0.26	9.10
17.97	-9.9	-7.9	76.2	3.48	36.8	0.22	8.35
19.00	-9.8	-7.9	76.2	3.52	37.0	0.19	7.92
20.05	-9.8	-7.9	76.3	3.36	36.2	0.14	7.37
21.00	-9.8	-7.9	76.3	3.49	36.9	0.12	7.05
21.92	-9.8	-7.9	76.3	3.42	36.5	0.11	6.88
22.95	-9.7	-7.9	76.3	3.34	36.0	0.08	6.54
Average	-9.8	-7.9	76.3	3.41	36.4	0.16	7.58

Table 7: Reference BLDT values

Fluid	T_a (°C)	T_f (°C)	RH (%)	V_m (m/s)	BLDT (mm)
MIL	-2.4	-1.9	62.7	37.2	9.30
MIL75/25	-1.3	-1.2	62.3	36.5	6.31
MIL75/25	-2.4	-1.8	63.1	36.8	6.16
MIL75/25	-1.5	-1.8	65.5	36.5	6.32
MIL	-10.6	-9.6	78.6	35.8	11.23
MIL75/25	-10.7	-8.6	74.9	36.2	7.57
MIL75/25	-10.5	-8.3	76.4	35.8	7.75
MIL75/25	-9.8	-8.1	76.3	36.5	7.58
MIL	-21.1	-19.9	63.1	34.1	13.03
MIL75/25	-20.6	-19.5	63.3	36.2	10.68
MIL75/25	-19.2	-19.1	58.6	36.5	10.33
MIL75/25	-20.7	-20.1	63.5	36.0	10.68
MIL	-29.2	-28.2	51.9	35.0	13.65
MIL75/25	-28.6	-27.0	51.8	35.3	13.02
MIL75/25	-30.6	-29.4	57.6	35.4	13.12
MIL75/25	-28.6	-27.6	60.7	35.0	13.03

Figures

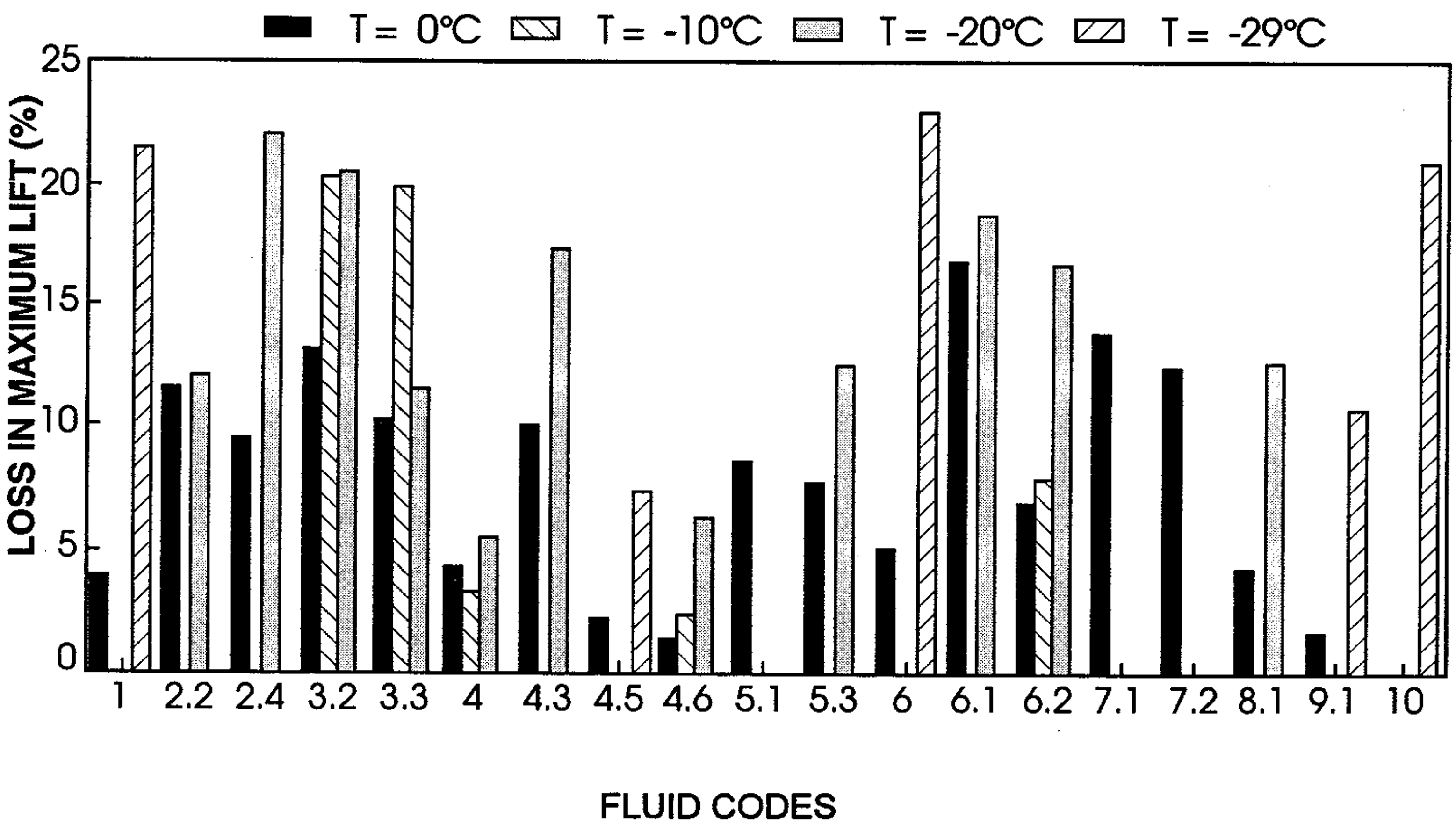
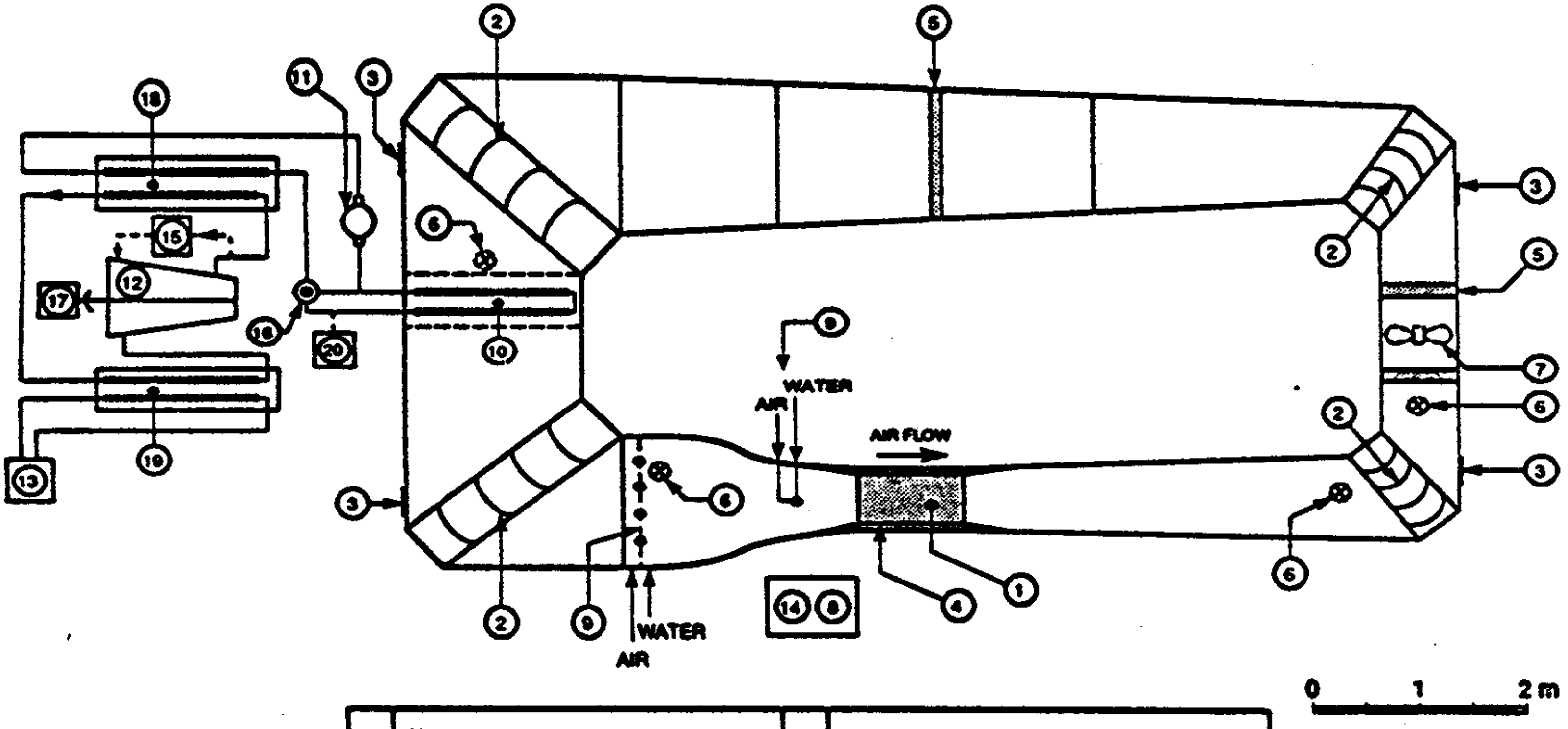


Figure 1: Lift Losses in 2D Model
(BCDD, Vr - 60 KT, CLmax)



1	TEST SECTION	11	GLYCOL PUMP
2	CORNER DEFLECTORS	12	COMPRESSOR (75 TONS)
3	SIDE OPENING	13	WATER MAIN
4	SIDE PANELS	14	PANEL CONTROL
5	FLEXIBLE JUNCTION	15	ON/OFF CONTROLLER
6	DRAIN	16	BY PASS 3-WAY VALVE
7	FAN AND MOTOR	17	MOTOR DRIVE
8	MOTOR CONTROL	18	FREON/GLYCOL HEAT EXCHANGER
9	SPRINKLERS	19	FREON/WATER HEAT EXCHANGER
10	AIR/GLYCOL HEAT EXCHANGER	20	TEMPERATURE CONTROLLER

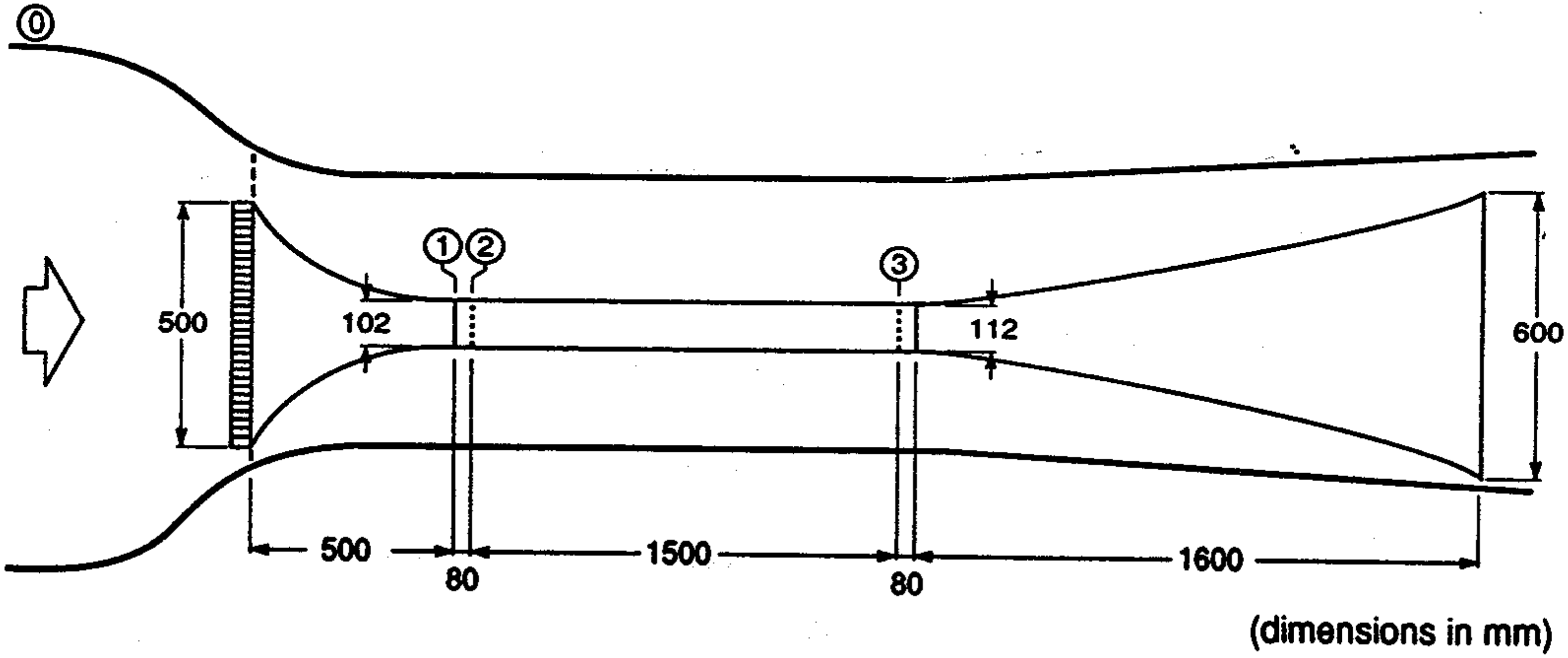
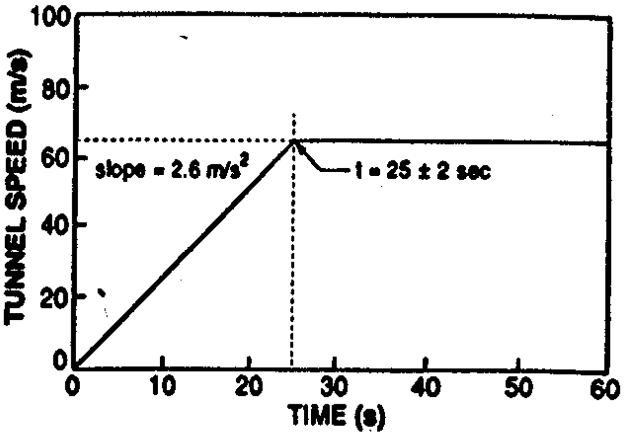
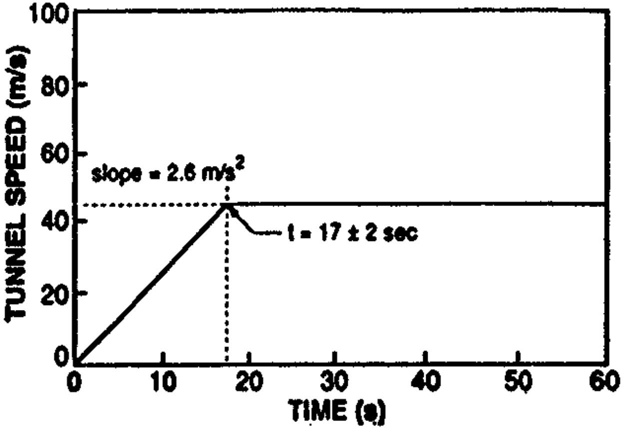


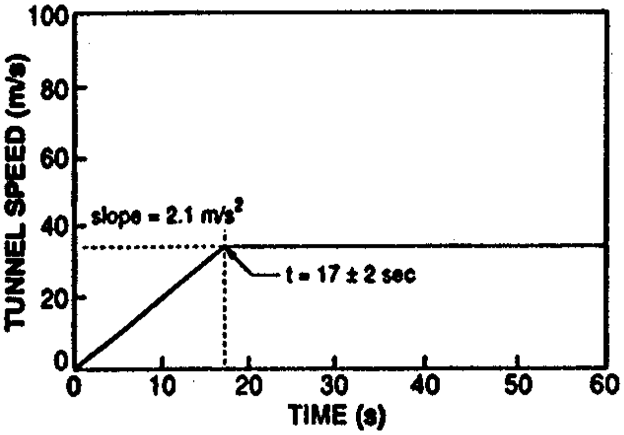
Figure 3: Test Duct Geometry



a) Large Aircraft



b) Commuter, High Ramp



c) Commuter, Low Ramp

Figure 4: Take-Off Ground Acceleration Simulations

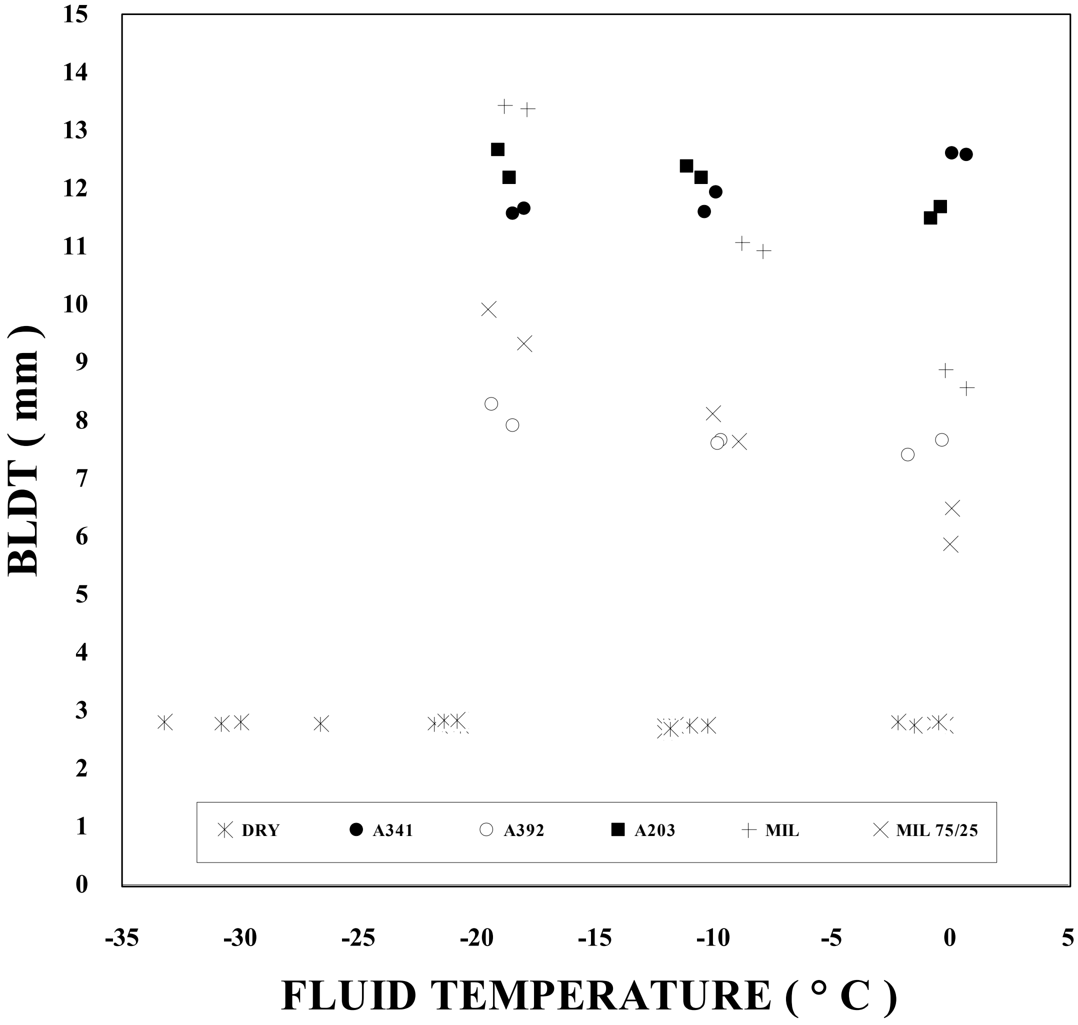


Figure 5: BLDT Results in Preliminary Study (High Velocity Ramp)

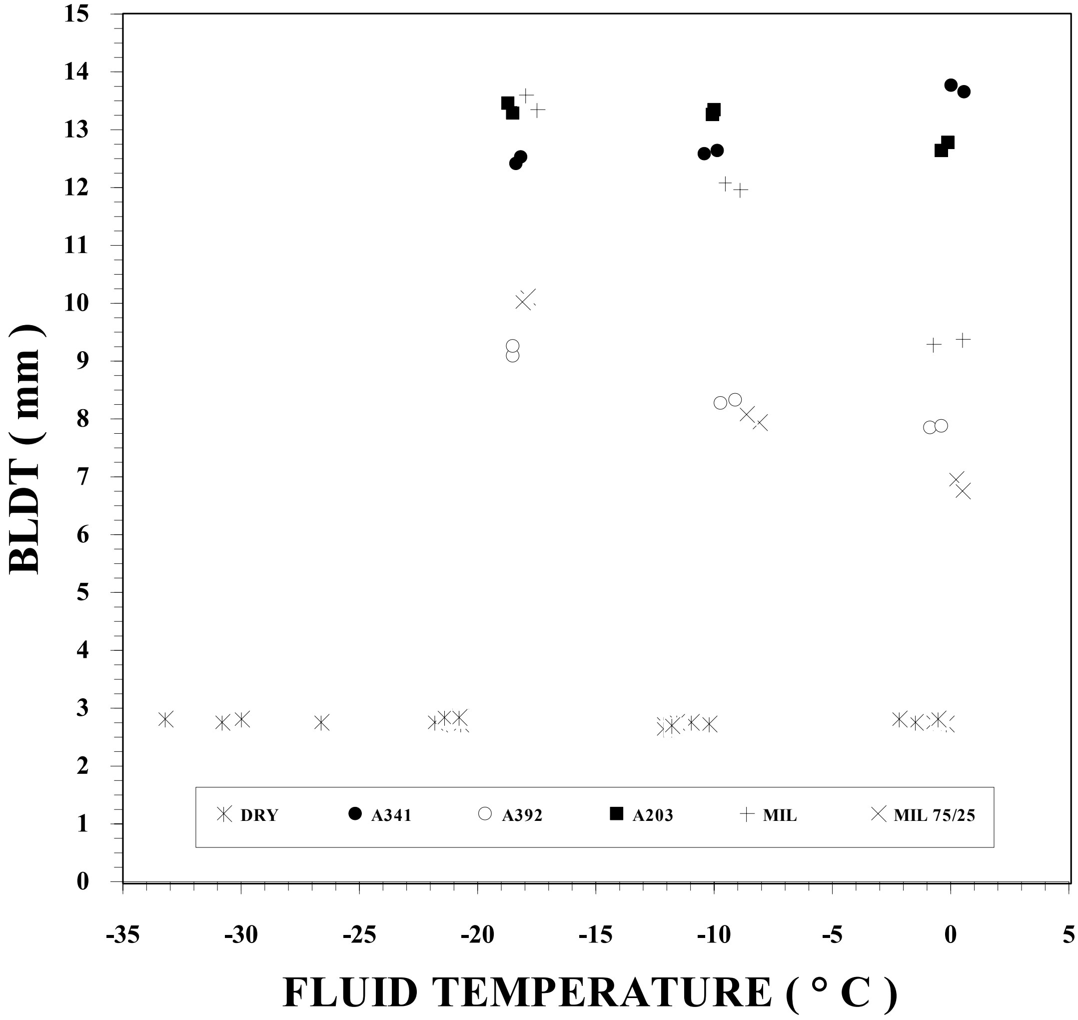
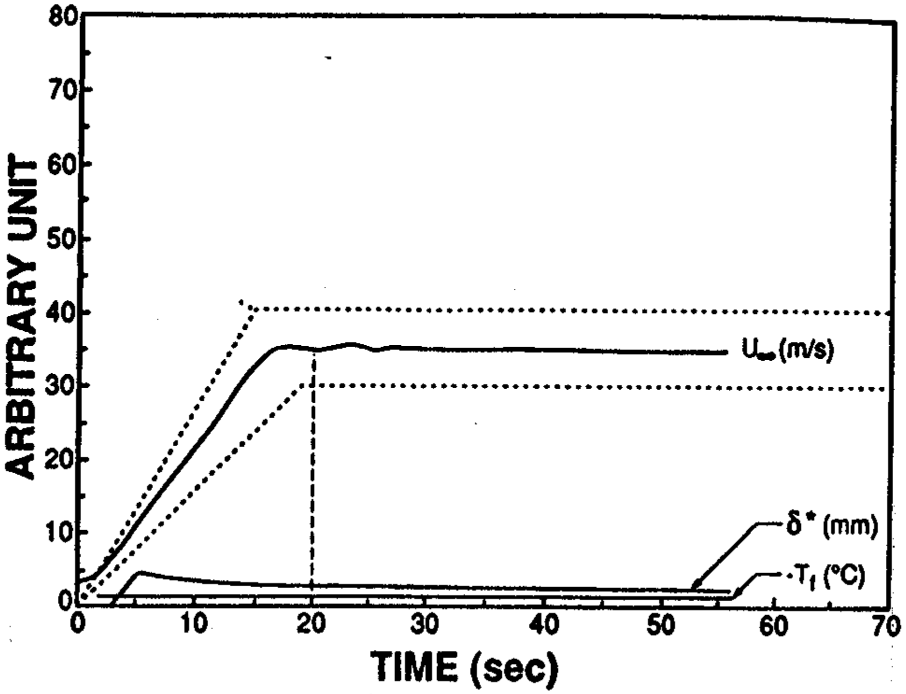
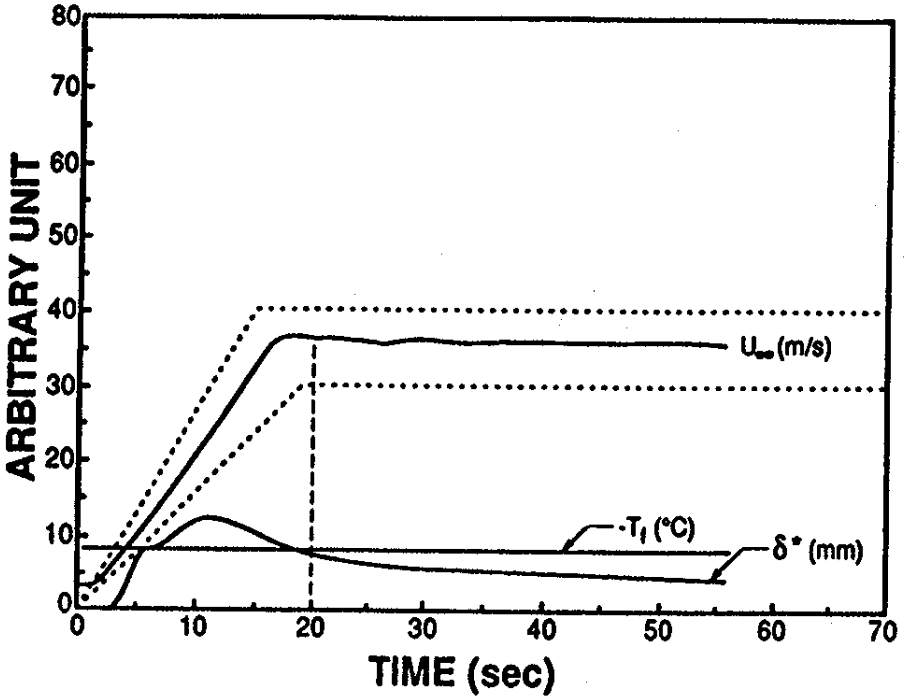


Figure 6: BLDT Results in Preliminary Study (Low Velocity Ramp)



a) Dry Test



b) MIL 75/25 Test

Figure 7: Typical Calibration Test Data

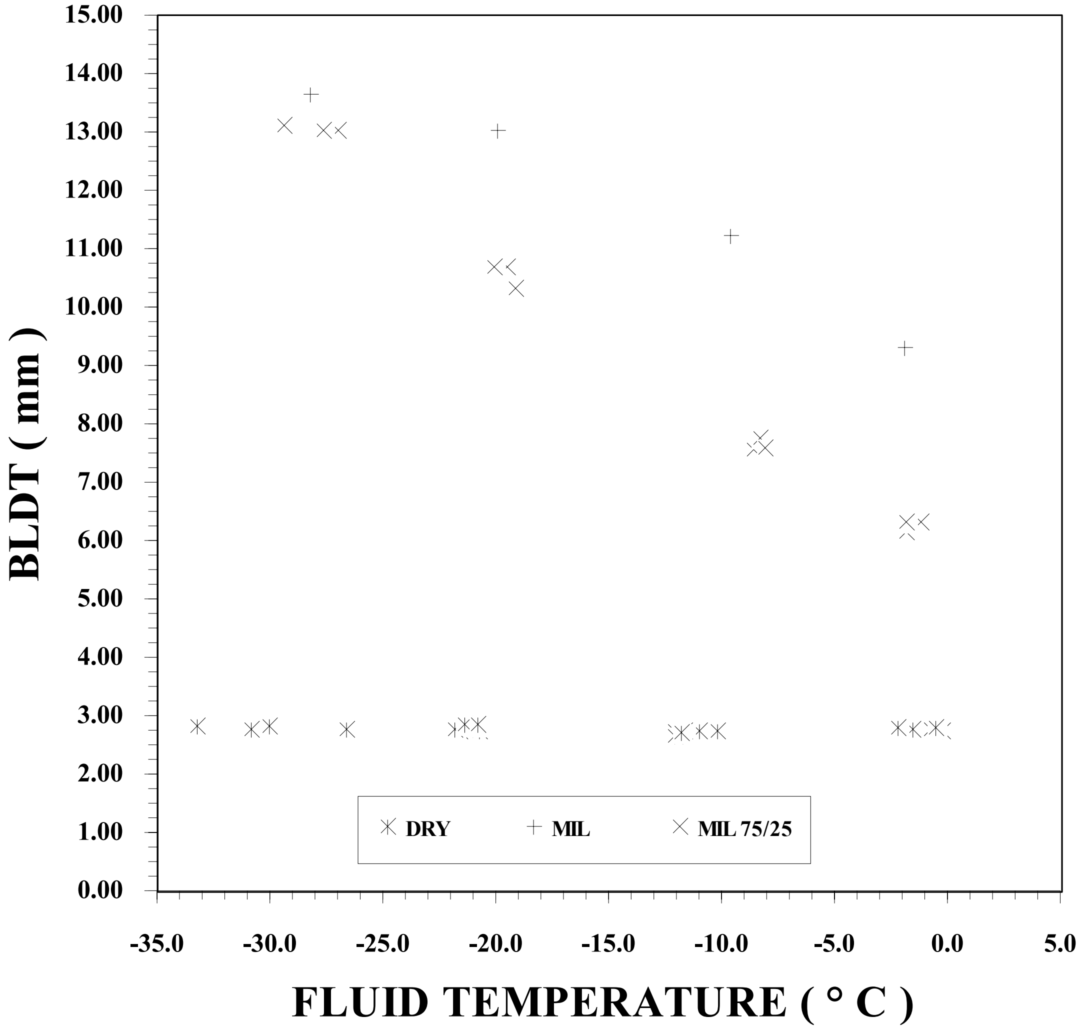
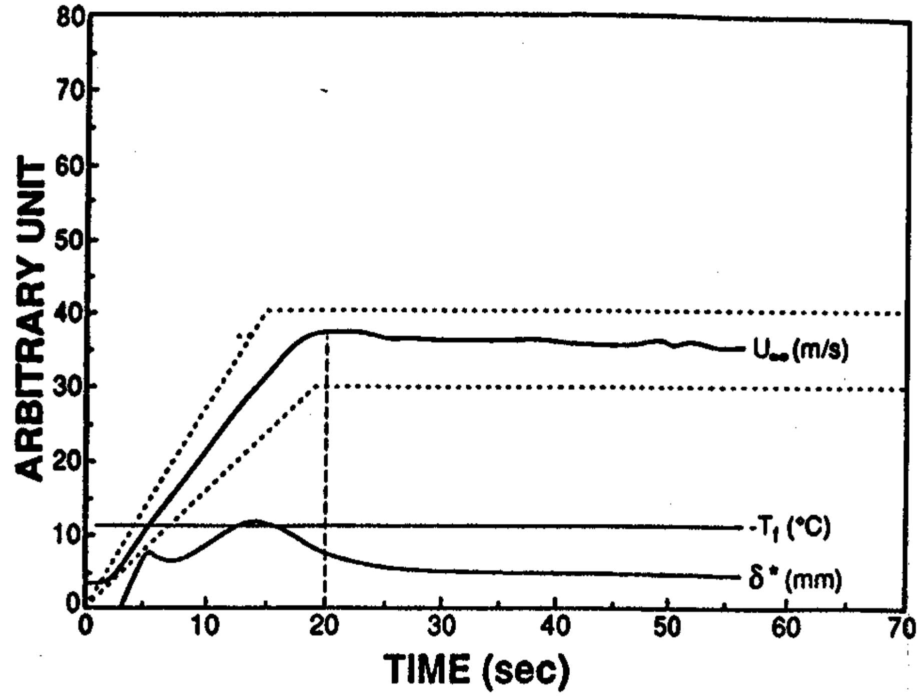
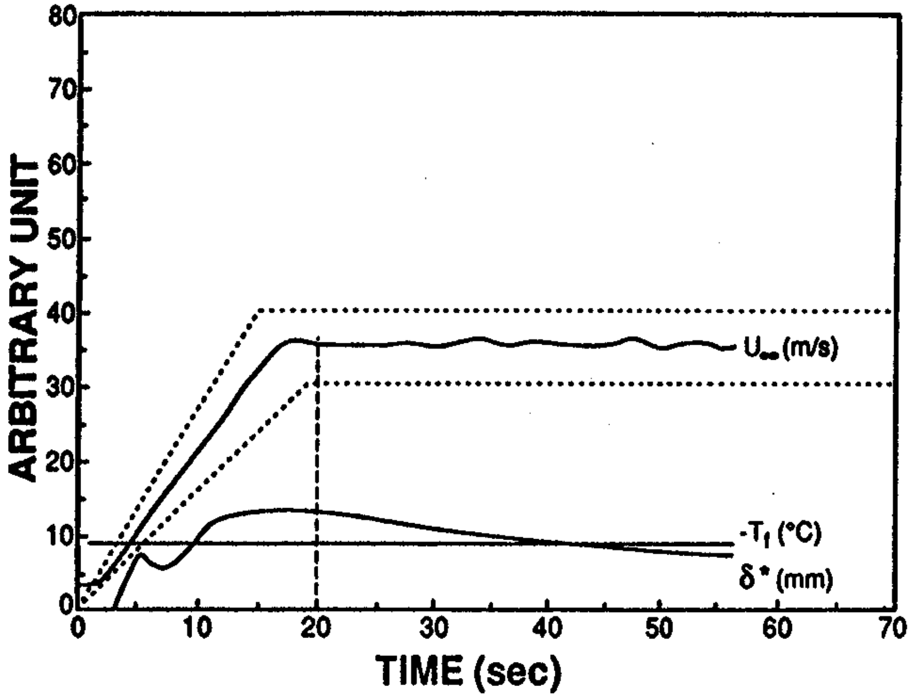


Figure 8: BLDT Calibration Results



a) A392



b) A447

Figure 9: Typical Fluid Test Data

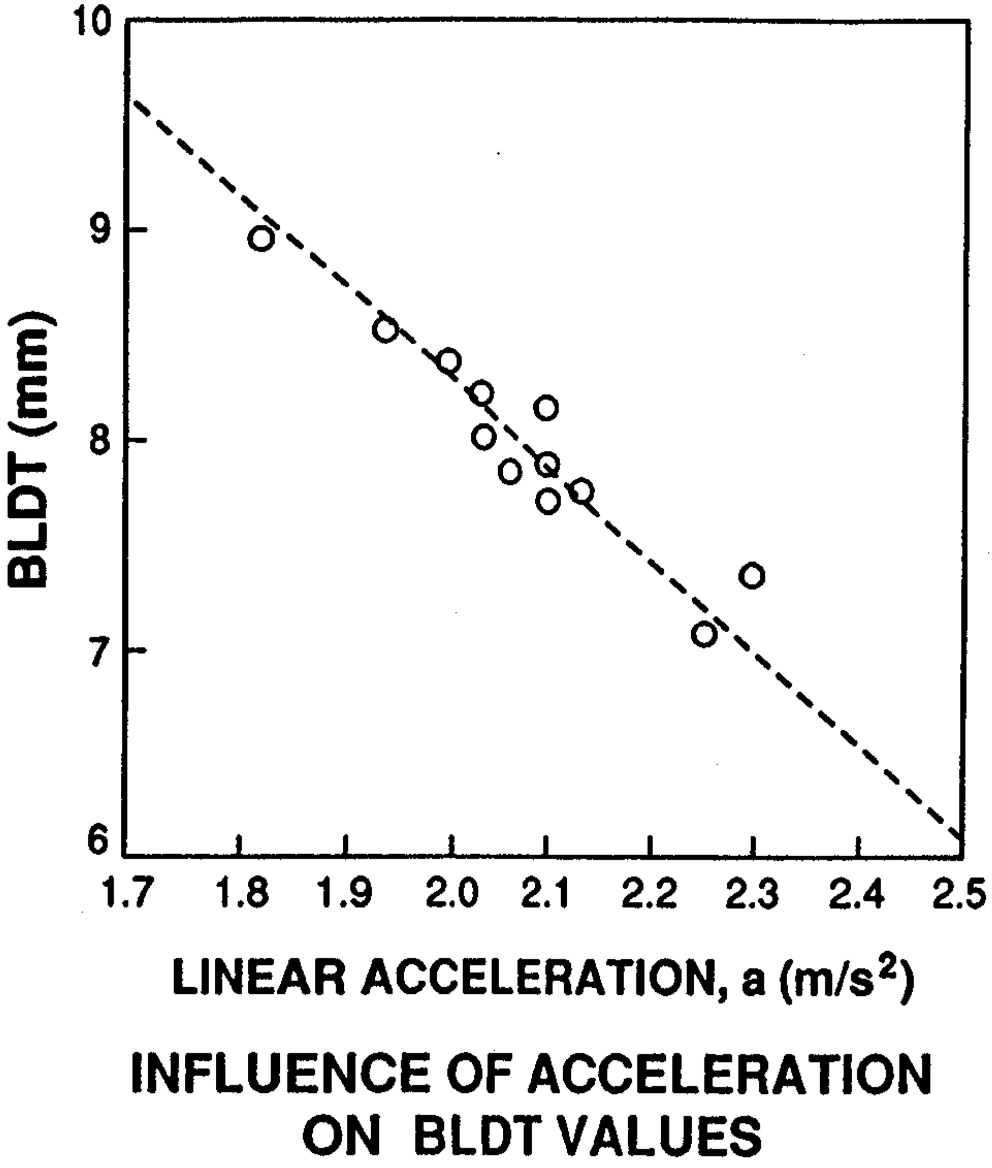


Figure 10: Influence of Acceleration on BLDT Values
(A392 at -10°C)

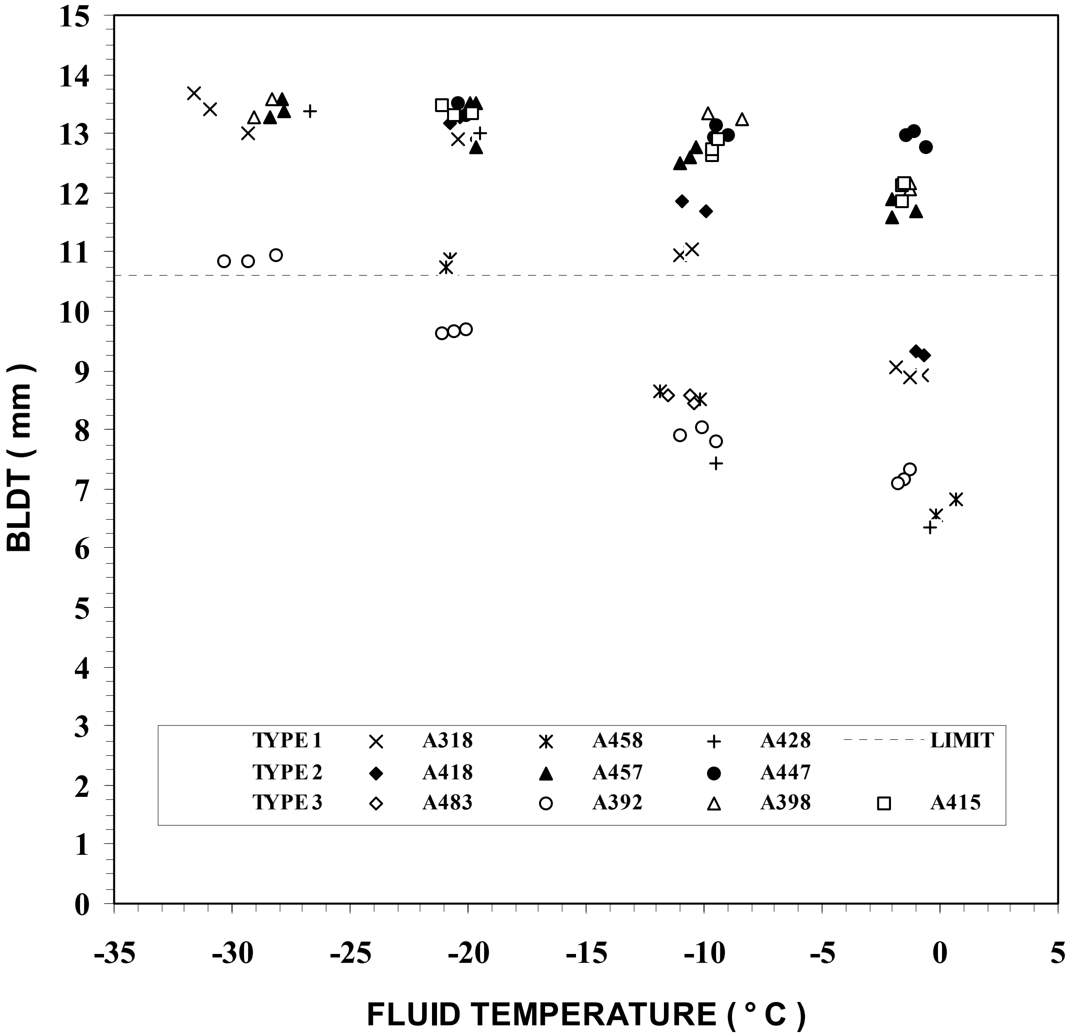


Figure 11: BLDT Results

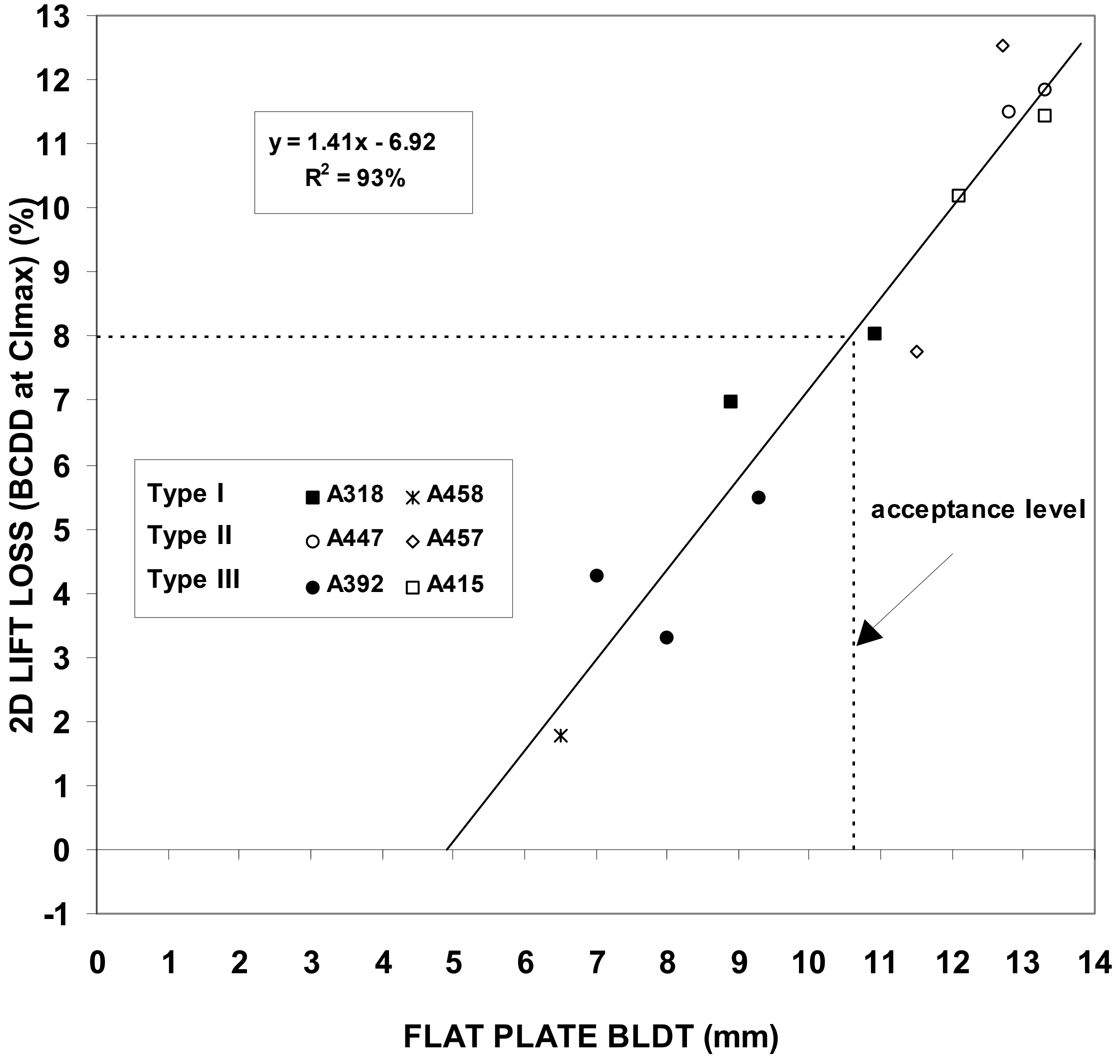


Figure 12: Correlation between 2D Lift Loss and Flat Plate BLDT

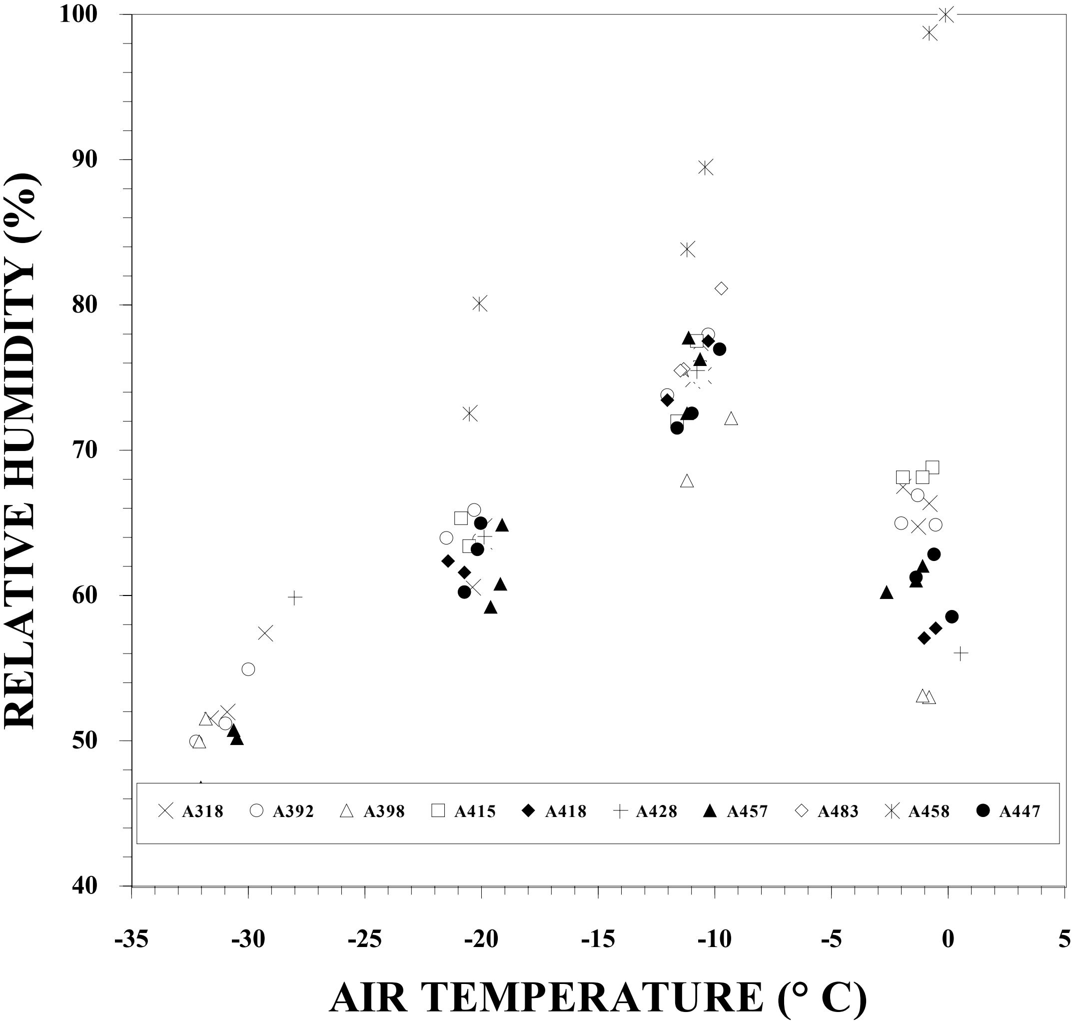


Figure 13: Relative Humidity

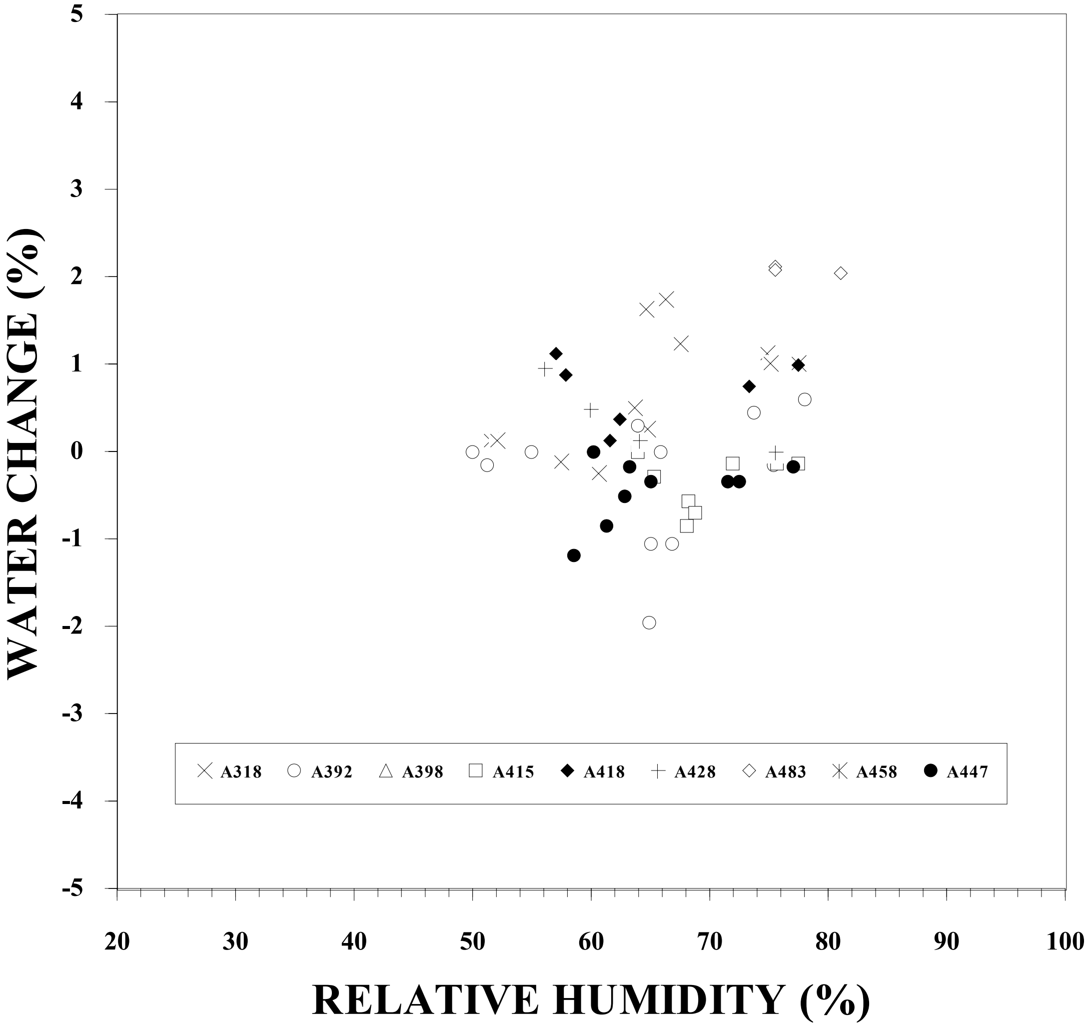


Figure 14: Water Change in Fluids

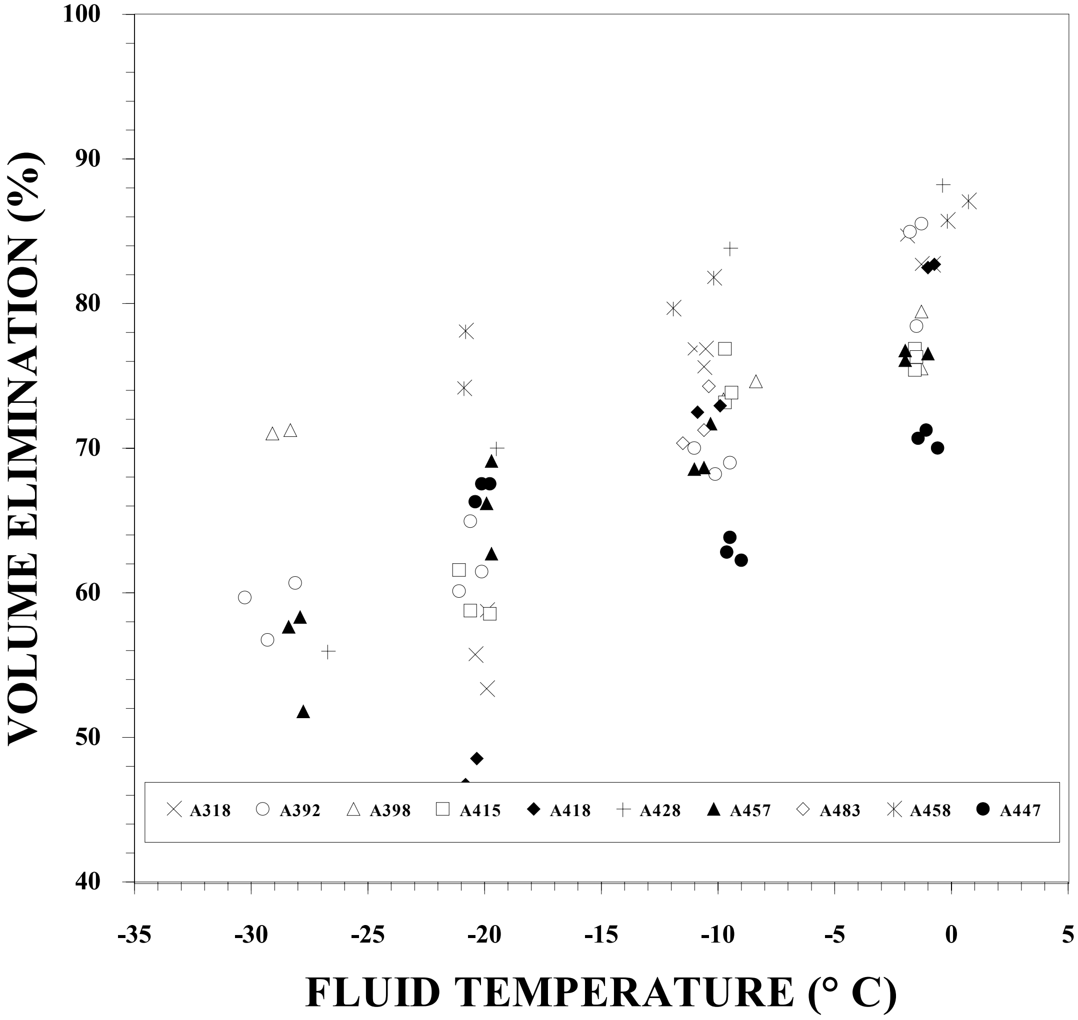


Figure 15: Fluid Elimination