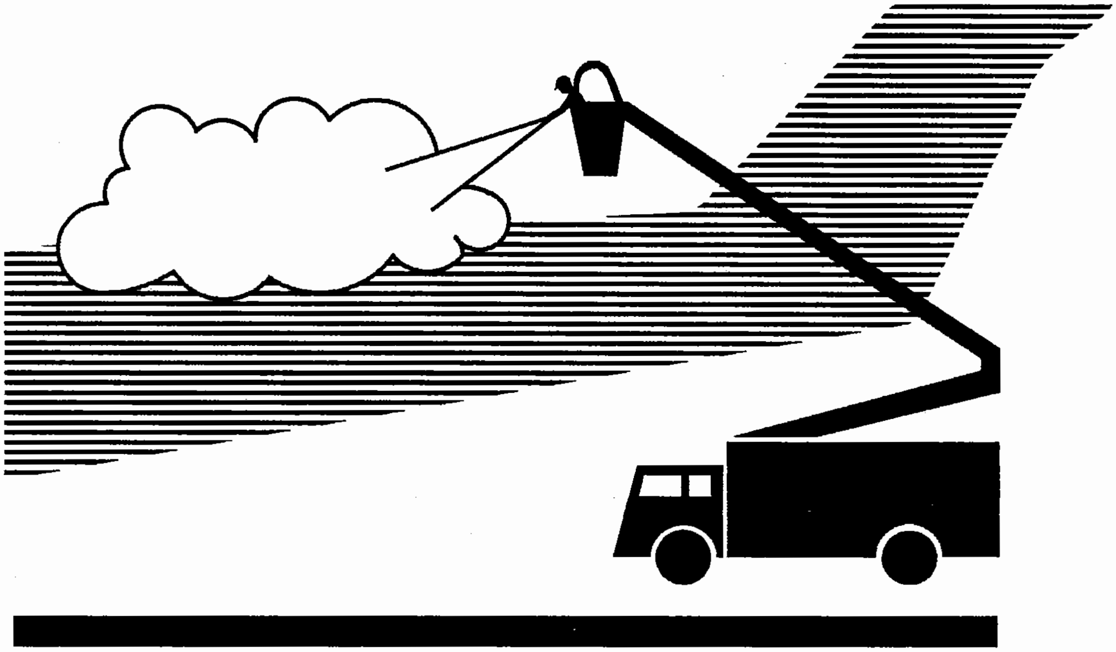
TP 12678E

Methodology for Simulating a Cold-Soaked Wing



Prepared for

Dryden Commission Implementation Project
Transport Canada

by

APS AVIATION INC.

December 1995

TP 12678E
CM1222.001

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The contents of this report reflect the views of APS Aviation Inc. and not necessarily the official view or opinions of the Dryden Commission Implementation Project of Transport Canada.

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Un sommaire en français de ce rapport est inclus.

PREFACE

At the request of the Dryden Commission Implementation Program of Transport Canada, APS Aviation Inc. has undertaken a research program to further advance aircraft ground de-icing/anti-icing technology. Specific objectives of the overall program were:

- Substantiation of SAE/ISO Holdover Time Tables that define a de-icing fluid's ability to delay ice formation by conducting tests on flat plates under conditions of natural snow, simulated freezing drizzle, simulated light freezing rain, and simulated freezing fog for a range of fluid dilutions and temperature conditions;
- Development of data for "cold-soaked" wing conditions using cooled flat plates to simulate the conditions;
- Correlation of flat plate test data with the performance of various fluids on service aircraft by concurrent testing;
- Evaluation of the suitability of hot blown air equipment to remove frost at extreme low temperatures;
- Evaluation of the suitability of equipment which blows air to remove snow;
- Determination of the environmental limits for use of hot water as a de-icing fluid;
- Evaluation of a remote sensor to detect contamination on wing surfaces;
- Determination of the pattern of fluid run-off from the wing during take-off; and
- Determination of wing temperature profiles during and after the de-icing operation.

The research activities of the program conducted on behalf of Transport Canada during the 1994/95 winter season are documented in four separate reports. The titles of these reports are as follows:

- TP 12595E Aircraft Full-Scale Test Program for the 1994/95 Winter;
- TP 12653E Hot Water De-Icing Trials for the 1994/95 Winter;
- TP 12654E Aircraft Ground De/Anti-icing Fluid Holdover Time Field Testing Program for the 1994/95 Winter; and
- TP 12655E Forced Air De-Icing Trials for the 1994/95 Winter.

Three additional reports were produced as a part of this research program. The titles of these reports are as follows:

- TP 12676E Consolidated Fluid Holdover Time Test Data;
- TP 12677E Consolidated Research and Development Report; and
- TP 12678E Methodology for Simulating a Cold-Soaked Wing.

This report TP 12678E addresses the development of a methodology for simulating a cold-soaked wing. Report reference TP 12654E provides the data for the substantiation of existing SAE/ISO Holdover Time Tables by the conduct of tests on cooled flat plates simulating a cold-soaked wing.

The completion of this program could not have occurred without the assistance of many individuals and organizations. APS would therefore like to thank the Dryden Commission Implementation Project, Transportation Development Centre, the Federal Aviation Administration, the National Research Council, Atmospheric Environment Services, Transport Canada and the fluid manufacturers for their contribution and assistance in the project. Special thanks are extended to Aeromag 2000, Aerotech International Incorporated, Air Atlantic, Air Canada, Calm Air, CanAir Cargo, Canadian Airlines International, and United Airlines for their cooperation, personnel and facilities.

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Research reports produced on behalf of Transport Canada for testing during previous winters are available as follows: TP 11206E 1990/91; TP 11454E 1991/92; TP 11836E 1992/93; and 1993/94 Summary Report submitted to DCIP. Seven reports (including this report) were produced as part of this winter's research program: TP 12595E Full-Scale Tests; TP 12653E Hot Water; TP 12655E Forced Air; TP 12654E Holdover Time Substantiation; TP 12676E Consolidated Holdover Time Data; TP 12678E Methodology for Simulating a Cold-Soaked Wing; and TP 12677E Consolidated Research and Development.

16. Abstract

The objective of this study was to develop a methodology to simulate a cold-soaked wing. Using this method, tests were conducted to substantiate the ranges of times for rain on cold-soaked wing cells in the SAE/ISO holdover time tables.

The development of the methodology and experimental approach for simulating a cold-soaked wing was based upon standard heat transfer theory, and is applicable for any form of precipitation. The theory was based on the concept of a conservative "time constant" approach which can be calculated for a box of given dimensions, insulation and filled with a liquid of given initial temperature. The time constant for a wing can similarly be calculated.

The sealed boxes can represent a cold-soaked wing condition given that the thermal time constants of the two surfaces are matched. The results for a wing can also be derived by interpolation provided the time constant of the wing falls between that of two boxes.

Further cold-soaked tests should also be carried out with new 2.5 cm deep boxes to further substantiate the SAE/ISO HOTs and set new values for the Type IV fluids.

17. Key Words

Aircraft, anti-icing, fluid, holdover time, precipitation, wing, plate, de-icing, cold-soaked, snow, rain, test, data, ice, sensor, box

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

Transports Canada a fait produire les rapports de recherche suivants sur les essais menés durant les hivers précédents : TP 11206E 1990-1991; TP 11454E 1991-1992; TP 11836E 1992-1993 et le rapport sommaire pour l'année 1993-1994 présenté au Comité de mise en oeuvre de la Commission Dryden. Concernant le programme de recherche mené durant l'hiver de 1994-1995, les sept rapports suivants (y compris le présent) ont été produits : TP 12595E Full-Scale Tests; TP 12653E Hot Water; TP 12655E Forced Air; TP 12654E Holdover Time Substantiation; TP 12676E Consolidated Holdover Time Data; TP 12678E Methodology for Simulating a Cold-Soaked Wing et, enfin, TP 12677E Consolidated Research and Development.

16. Résumé

Description de la démarche visant à mettre au point une méthode permettant de simuler une aile d'aéronef sur-refroidie, et grâce à laquelle des expérimentations ont pu être menées pour confirmer les tables de durée d'efficacité SAE/ISO concernant une partie d'aile sur-refroidie dans des conditions de pluie.

La méthodologie et la démarche expérimentale sous-tendant cette simulation sont fondées sur la théorie classique des transferts thermiques et peuvent être utilisées avec n'importe quelle forme de précipitation. La démarche, prudente, est fondée sur la détermination d'une constante de temps, que l'on peut calculer pour une boîte de dimensions données, calorifugée et remplie d'un liquide dont la température initiale est connue. Il est possible aussi de calculer la constante de temps d'une aile d'aéronef.

Une aile sur-refroidie peut être représentée par des boîtes scellées en supposant que les constantes de temps des deux surfaces correspondent. Il est possible aussi de déterminer par interpolation les valeurs correspondantes pour une aile d'aéronef, à condition que la constante de temps de celle-ci s'intercale entre celles de deux boîtes soumises à des conditions identiques.

Des expérimentations plus poussées devraient être menées avec des nouvelles boîtes de 2,5 cm de profondeur afin d'apporter une nouvelle confirmation des durées d'efficacité SAE/ISO et d'en établir de nouvelles pour celles des liquides de type IV.

17. Mots clés	Aéronefs, anti-givrage, liquide, durée d'efficacité, précipitation, aile, plaque, dégivrage, sur-refroidissement, neige, pluie, essai, données, glace, capteur, boîte
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EXECUTIVE SUMMARY

At the request of the Dryden Commission Implementation Program (DCIP) of Transport Canada (TC), APS Aviation Inc. (APS) undertook a research program to further advance aircraft ground de/anti-icing technology. While a number of objectives of the test program are covered by other related reports, this report addresses the topic relating to the development of a methodology for simulating a "cold-soaked" wing. Using this method, tests were conducted to substantiate the ranges of times for rain on cold-soaked wing cells in the SAE/ISO holdover time tables.

The development of the methodology and the experimental approach for simulating a cold-soaked wing was based upon standard heat transfer theory. The theory was based on the concept of a conservative "time constant" approach which can be calculated for a box of given dimensions, insulation and filled with a liquid of given initial temperature. The time constant for a wing can similarly be calculated. This method could also be used to evaluate holdover times on cold-soaked wings under snow conditions.

It was confirmed that sealed boxes completely filled with a fluid can represent a cold-soaked wing condition as long as the temperature decay profiles of the two surfaces are matched. The results for a wing can also be derived by interpolation provided the thermal profile of the wing falls between that of two boxes subject to the same external conditions.

Preliminary test results (see related Report TP 12654E) have shown that the SAE/ISO HOT ranges may be adequate for Neat Type II and Type II 75/25. For Type II 50/50 and diluted Type I fluids, the SAE/ISO holdover time table ranges may require a reduction, subject to further testing.

The scope of future tests should focus on the use of the new Type II (Type IV) fluids for a range of precipitation rates under all dilutions (50/50, 75/25, and Neat) and for a variety of skin temperatures. New cold-soaked tests should also be carried out with 2.5 cm boxes to further substantiate the SAE/ISO HOTs and set new values for the Type IV fluids.

SOMMAIRE

À la demande du Comité de mise en oeuvre de la Commission Dryden mis sur pied par Transports Canada, APS Aviation Inc. a lancé un programme de recherches visant à faire progresser la technologie de dégivrage/antigivrage des avions au sol. Certains des objectifs fixés à ce programme sont décrits dans plusieurs rapports connexes. Le présent rapport traite plus particulièrement de la simulation d'une aile «sur-refroidie». Grâce à cette méthode, des expérimentations ont pu être menées pour confirmer les tables de durée d'efficacité SAE/ISO concernant une partie d'aile sur-refroidie dans des conditions de pluie.

La méthodologie et la démarche expérimentale sous-tendant cette simulation sont fondées sur la théorie classique des transferts thermiques. La démarche, prudente, est fondée sur la détermination d'une constante de temps, que l'on peut calculer pour une boîte de dimensions données, calorifugée et remplie d'un liquide dont la température initiale est connue. Il est possible aussi de calculer la constante de temps d'une aile d'aéronef. Cette même méthode permet d'évaluer les durées d'efficacité sur ailes sur-refroidies dans des conditions d'enneigement.

La recherche a confirmé le bien-fondé d'une simulation d'une aile sur-refroidie pour des boîtes scellées, complètement remplies de fluide, à condition que les profils de décroissance du gradient thermique de chacune correspondent. Il est possible aussi de déterminer par interpolation les valeurs correspondantes pour une aile d'aéronef, à condition que le profil thermique de celle-ci s'intercale entre ceux de deux boîtes soumises à des conditions externes identiques.

Les premiers résultats des expérimentations (voir le rapport connexe TP 12654E) montrent que les durées d'efficacité normalisées par la SAE (Society of Automotive Engineers) et l'ISO (Organisation internationale de normalisation) sont valables pour les liquides de type II purs ou dilués 75/25. Pour ce qui est des liquides de type II dilués 50/50 et les liquides de type I dilués, il faudra probablement réviser à la baisse les valeurs extrêmes des plages de durée d'efficacité indiquées dans les tables SAE/ISO, sous réserve d'expérimentations plus poussées.

Il est recommandé que les essais à venir portent sur les nouveaux liquides de type II (type IV) en faisant varier les taux de précipitation, la concentration (50/50, 75/25 et pur) et la température superficielle des surfaces. On recommande également de mener de nouvelles expérimentations avec des boîtes de 2,5 cm de profondeur afin d'apporter une nouvelle confirmation des durées d'efficacité SAE/ISO et d'en établir de nouvelles pour celles des liquides de type IV.

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LIST OF ACRONYMS

APS	APS Aviation Inc.
CEF	Climatic Engineering Facility, National Research Council of Canada
HOT	Holdover Time
MD-80	McDonnell Douglas MD-80 Series Aircraft
NRC	National Research Council of Canada
OAT	Outside Air Temperature
RJ	Canadair Regional Jet Aircraft
SAE	Society of Automotive Engineers
ISO	International Standards Organization
UCAR	Union Carbide
YUL	Dorval International Airport, Montreal

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1. INTRODUCTION

1.1 Background

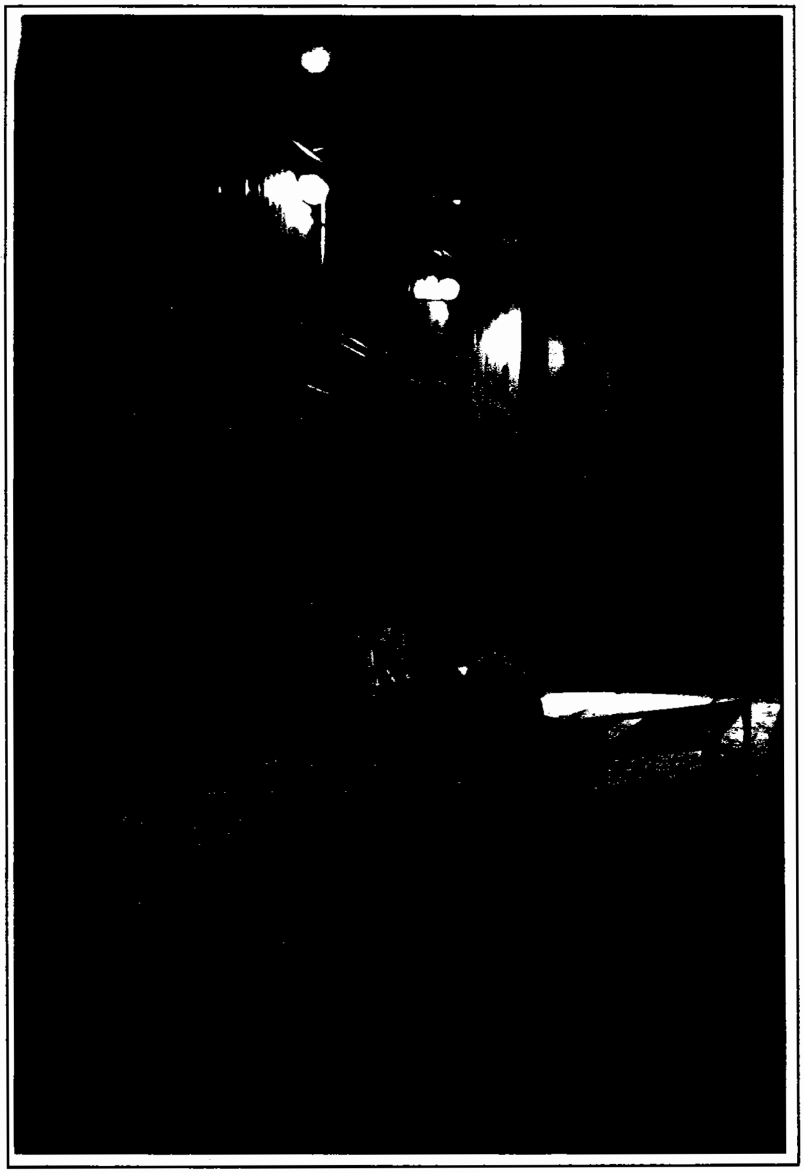
1. INTRODUCTION

Aircraft ground de-icing has been the subject of concentrated industry attention over the past decade as a result of a number of fatal aircraft accidents. Much of this attention has been given to the abilities of de-icing fluids to provide an extended duration of protection against further snow or ice build up following initial de-icing. This has led to the development of fluid holdover time tables for use by aircraft operators, and accepted by regulatory authorities. As well, new improved fluids have been developed with the specific objective of extending holdover times without adversely impacting upon aerodynamic characteristics of the airfoil.

The problem of cold-soaked wings could apply to any aircraft during precipitation. For example, when precipitation is falling in the form of wet snow and the outside air temperature is 0°C, snow may melt on a pavement but could freeze if the wing is cold-soaked and the surface temperature on the wing is -1°C. Most of the attention relating to rain on cold-soaked wings has been given to McDonnell Douglas MD-80 Series aircraft. The fuel in the wing of this aircraft, unlike many other aircraft, touches the upper surface of the wing, when the wing is filled with fuel. Another aircraft with this type of "wet wing" design is the Canadair RJ aircraft. One other aircraft design characteristic which has led to industry discussion is rear-mounted engines. The MD-80 and the Canadair RJ as well as other aircraft types have such engines. Rear-mounted engine aircraft are susceptible to engine failure caused by ingestion of ice from the wings.

This report addresses the development of a method to simulate a cold-soaked wing, with the subsequent objective of substantiating the "rain on cold-soaked wing" column in the SAE/ISO holdover time tables.

PHOTO 1
INSIDE VIEW OF NRC's CEF IN OTTAWA



1.1 Background

Testing of rain on cold-soaked surfaces is carried out at NRC's indoor Climatic Engineering Facility. Photo 1 was taken inside the Climatic Engineering Facility and provides a general indication of the size of the facility. The chamber size is 30 m long by 5.4 m wide by 8 m high, and the minimum achievable temperature in the chamber is -46°C.

Rain on cold-soaked wing conditions cannot be tested using the conventional fluid test frosticator plate set-up. The effect of "cold" fuel in the fuel tanks of an aircraft needs to be simulated to ensure that test results are representative of actual cold-soaked situations. The approach adopted to simulate cold wing effects was to use a sealed rectangular aluminum box, 100% filled with a cold fluid (Photo 2 shows the cooling unit) and insulated on all sides except for the upper surface. The top of the box consists of a welded aluminum flat plate identical to a conventional frosticator plate used for fluid testing. The sealed boxes (15 cm and 7.5 cm deep) which were used for simulating a cold-soaked wing are shown in Figure 1.1. The test procedure is similar to that used for conventional de/anti-icing fluid flat plate tests (see Transport Canada Report TP 12654E).

PHOTO 2

FLUID COOLING UNIT USING LIQUID NITROGEN

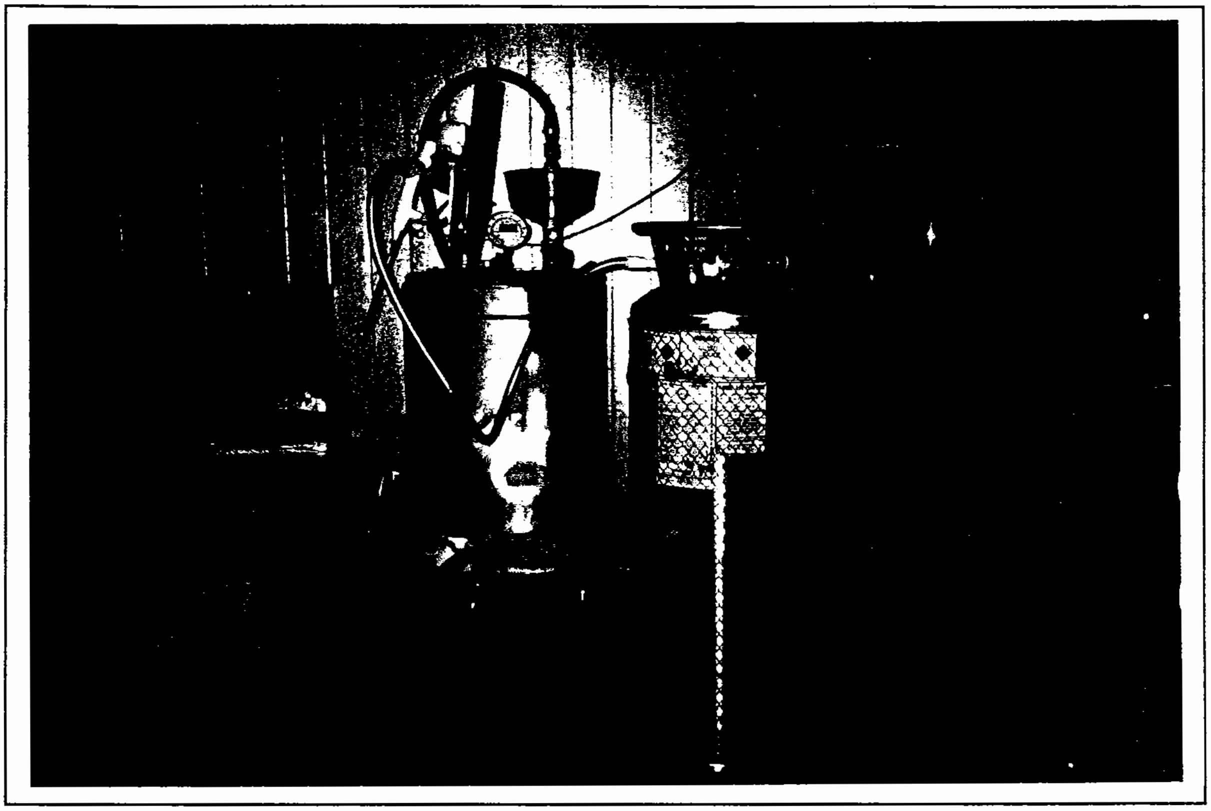
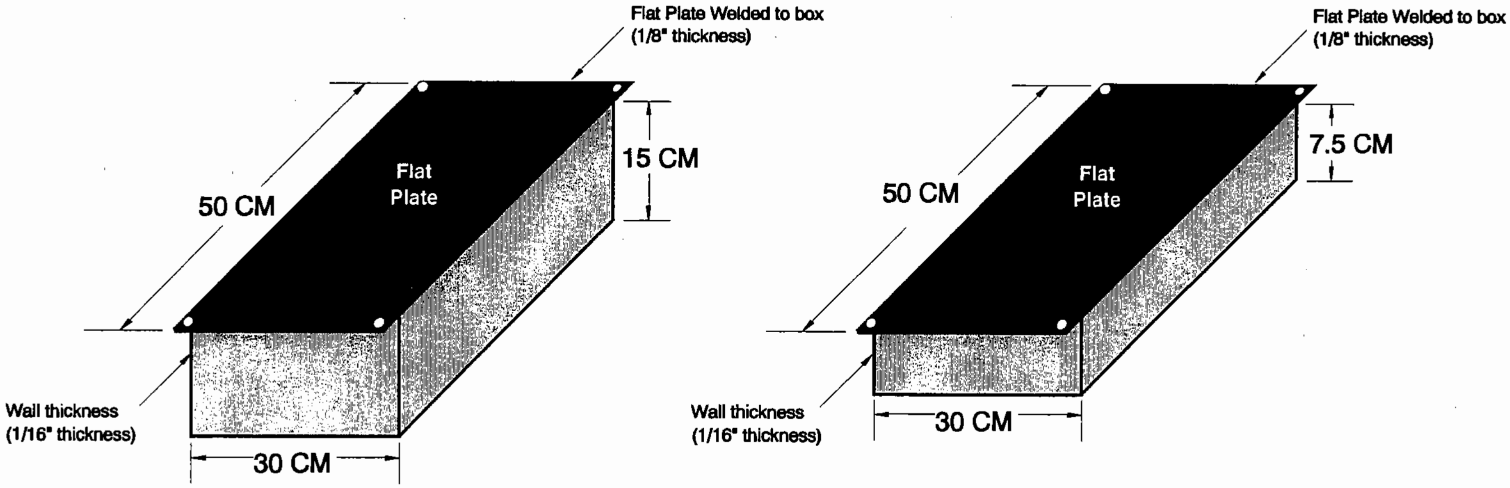


Figure 1.1

SKETCH OF BOXES USED FOR SIMULATING A COLD-SOAKED WING

- Boxes were 100% filled with glycol which was cooled with a liquid nitrogen cooling unit. An insulating jacket was attached on all sides except the top to maintain its cold temperature. Test fluids were poured on the cold-soaked boxes to start the test. Plate temperatures on the top were recorded throughout the test.

Two Cold-Soak Box Sizes Used



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2. THEORETICAL HEAT TRANSFER ANALYSIS

2. THEORETICAL HEAT TRANSFER ANALYSIS

The objective of this analysis is to relate the two boxes, used in the experiments, to a representative aircraft wing surface. The similarity between the box and a "wet" wing is that the heat transfer mode to the atmosphere is by free convection. To quantify the relationship between the wing and the box, a heat transfer analysis for both of the surfaces was performed. For this analysis, it was assumed that the temperature gradients within the fuel tank were negligible. This is a valid assumption in that it would provide the most conservative results. The following will provide the theoretical equations that were used in the heat transfer analysis of the two surfaces to compute the time constants.

In the transient mode, the energy balance of the wing, based on standard heat transfer analysis, can be represented by this expression:

$$-\dot{E}_{out}=\dot{E}_{st}$$

Where $-E_{out}$ *=rate of the heat loss at the wing surface by convection*

$\dot{E}_{st}$ *= rate of change of wing's internal energy by conduction*

Standard convection and conduction theory provides the equations listed below for

$\dot{E}_{out}$ and $\dot{E}_{st}$

$$\dot{E}_{st} = \rho \forall C_p \frac{dT}{dt}$$

$$\dot{E}_{out} = -hAw(T-T\infty)$$

Where T_∞ : ambient temperature (°K)
T : wing skin temperature (°K)
h : convection heat transfer coefficient (w/m^2 °K)
C_p : specific heat coefficient at constant pressure of the wing/fuel combination (J/Kg °K)
$\forall$: volume of the wing (m^3)
ρ : density of the wing/fuel combination (Kg/m^3)
t : time (sec.)

It is worth noting that this analysis is only valid in the fuel tank vicinity ("wet" wing condition) and all the wing dimensions of concern can be replaced by the fuel tank dimensions. All wing/fuel combination properties can be reasonably replaced by fuel properties.

Let $\Theta = T - T_\infty =$ the temperature difference

$$\Rightarrow \quad \frac{d\Theta}{dt} = \frac{dT}{dt}$$

since T_∞ is constant over time

Integrating over temperature and time we get,

$$\frac{\rho \forall C_p}{h\,Aw} \ln \frac{\Theta}{\Theta_0} = -t$$

$$\frac{\Theta}{\Theta_0} = \exp\left[-\frac{t}{\frac{\rho \forall C_p}{h\,Aw}}\right]$$

$$\frac{\Theta}{\Theta_0} = \exp\left[-\frac{t}{\tau_t}\right]$$

$$where\ \tau_t = thermal\ time\ constant = \frac{\rho \forall C_p}{h A_w}$$

The above expression can be used to determine the time constant of a wing by using its dimensions and fuel properties. Conversely, when a surface temperature profile is available, one can calculate the corresponding time constant by selecting two points on the temperature curve and following this procedure:

$$\frac{\Theta_1}{\Theta_0} = \exp\left[-\frac{t_1}{\tau_t}\right]$$

point 1 coordinates: (t_1, Θ_1)

$$\frac{\Theta_2}{\Theta_0} = \exp\left[-\frac{t_2}{\tau_t}\right]$$

point 2 coordinates: (t_2, Θ_2)

$$dividing\ \frac{\Theta_1}{\Theta_2} = \exp \frac{\left[-\frac{t_1}{\tau_t}\right]}{\left[-\frac{t_2}{\tau_t}\right]}$$

$$\frac{\Theta_1}{\Theta_2} = \exp\left[\frac{(t_2 - t_1)}{\tau_t}\right]$$

$$\ln\left[\frac{\Theta_1}{\Theta_2}\right] = \frac{(t_2 - t_1)}{\tau_t}$$

$$\tau_t = \frac{(t_2 - t_1)}{\ln\left[\frac{\Theta_1}{\Theta_2}\right]}$$

For a better understanding of τ_t, one can set: $t = \tau_t$

$$\frac{\Theta}{\Theta_0} = \exp[-1] = 0.37$$

$$\Theta = 0.37\ \Theta_0$$

The time constant (τ_t) is therefore defined as the time taken for the temperature gradient of a surface to be reduced by 63% (see Appendix B for explanation). Physically, the time constant (τ_t) has the dimension of time and is expressed in seconds, minutes or hours. It is generally accepted that a temperature gradient will stabilize after about 4 to 5 times the value of the time constant. Thus, the time constant is a direct indication of the ability of a body (e.g. a wing) to sustain its temperature, and can serve as a "cold-soak index". The higher the time constant, the more susceptible a wing is to cold-soak problems since once it is cooled to below OAT at ground level, it will stay in this temperature range for a time directly proportional to the time constant.

3. COMPUTATION OF THERMAL TIME CONSTANT

3.1 Determination of the Theoretical Time Constant

3.2 Determination of the Experimental Time Constant

3.3 Commentary on Time Constant Method

3. COMPUTATION OF THERMAL TIME CONSTANT

3.1 Determination of the Theoretical Time Constant

From the equations in Section 2, an analytic expression of the thermal time constant has been defined and is:

$$\tau_t = \frac{\rho \forall C_p}{h A_w}$$

This expression depends on the fuel properties and the fuel tank dimensions as well as the atmospheric conditions. The thermal time constant was analytically calculated for two sizes of cold-soaked boxes (7.5 cm and 15 cm deep) filled with a 65% propylene glycol solution and covered with a de/anti-icing fluid (propylene glycol) layer, and was found to be:

τ_t = 8000 seconds (2.2 hours) for the 7.5 cm box
τ_t = 16000 seconds (4.4 hours) for the 15 cm box

The same calculation was repeated for a Canadair Regional Jet wing fuel tank using fuel tank dimensions as provided by Canadair and typical fuel properties. The result was $\tau_t \approx 6000$ seconds (1.7 hours) for the Canadair RJ wing fuel tank. The details of a general analytical thermal time constant calculation are presented in Appendix A1.

3.2 Determination of the Experimental Time Constant

The time constant can also be obtained from an experimental surface temperature profile. The procedure is to choose two points (1 and 2) on the temperature profile of each box with coordinates (t_1, Θ_1) and (t_2, Θ_2) respectively. The derivation shown in Section 2 provided the following expression for the time constant:

$$\tau_t = \frac{(t_2 - t_1)}{\ln\left[\frac{\Theta_1}{\Theta_2}\right]}$$

This method was applied to obtain experimental expressions of the time constants of the cold-soaked boxes mentioned in Section 3.1. The temperature profiles of the boxes resulted in values of

$$\tau_t = 10{,}000 \textit{ seconds } (2.8 \textit{ hours}) \textit{ for the } 7.5 \textit{ cm box}$$

$$\tau_t = 16{,}000 \textit{ seconds } (4.4 \textit{ hours}) \textit{ for the } 15 \textit{ cm box}$$

These values are in good agreement with the theoretical values. No experimental temperature profiles for cold-soaked Canadair RJ wings were available. It would be advantageous to conduct tests to obtain such data.

3.3 Commentary on Time Constant Method

The cold-soak problem mainly concerns the regions of the fuel tank where fuel is touching the upper surface. The wing time constant may therefore need to be computed only at the regions of the fuel tank where fuel is touching the upper surface. Should the time constants of such areas be higher than the complete fuel tank time constant, a worst case scenario corresponding to the fuel load with the highest time constant would need to be defined. Collection of cold-soak data corresponding to different fuel levels would allow such a possibility to be investigated.

The only modes of heat transfer accounted for in the time constant method are natural convection from the atmosphere and transient conduction within the fuel tank. Radiation is not accounted for. However, in a typical cold-soaked wing situation, the OAT is above zero and the wing temperature below zero. Radiation would consist of additional heat transfer into the wing resulting in a faster increase in its temperature over time and higher surface temperatures than assumed in the time constant method. The time constant method is therefore a conservative approach since it neglects the radiation effects that might be significant in some cases.

Moreover, the method does not account for wind which represents a forced convection mode. Accounting for wind and forced convection results in high values of the convection heat transfer coefficient, h, which in turn results in faster surface temperature rise of the wing. Therefore, neglecting wind effects and using solely natural convection is the worst case scenario and a condition which can occur in practice.

Traditionally, the time constant method has been used to simulate the temperature variation of a body in a convection environment. The temperature distribution inside the body is assumed to be uniform and the accuracy of the method depends on the validity of this assumption. Such validity can be verified by calculating the Biot number, Bi, of the body in question (see Appendix A2). The Biot number is a dimensionless number that is equivalent to the ratio of the temperature gradient inside the body to the temperature difference between the surface of the body and the environment. The time constant method provides sufficient accuracy to be applicable for body temperature simulation if $Bi \leq 0.1$ [1]*, meaning that the temperature difference within the body is negligible with respect to the difference between the body surface and the environment. In our case, Bi = 6.6, 13.3, 15.1 for the 7.5 cm box, 15 cm box and the Canadair RJ wing respectively, which means that the time constant method cannot be used to simulate the temperature variation within the boxes and the wing. However, our real interest lies in simulating the temperature variation at the surface of the wing and in ultimately providing a representative HOT. At this point, the Biot number becomes secondary since it reflects the method's validity within the whole wing and not exclusively at the surface.

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* Number in brackets denote references given at the end of the report

The time constant method should then be compared to an estimate of the surface temperature variation with time. Such an estimate can be obtained from an infinite plate 1-D analysis. The infinite plate 1-D analysis was carried out for a section of the rectangular uninsulated box shown in Figure 3.1. The box has the dimensions of a typical wing fuel tank, an initial temperature of -15°C and the properties of the same 65% propylene glycol solution used to fill the cold-soaked boxes. The OAT is +2°C.

The 1-D solution is of the form [2]

$$\frac{\Theta}{\Theta_0} = \sum_{n=1}^{\infty} C_n \exp\left(-\zeta_n^2 Fo_i\right) \cos\left(\zeta_n \frac{X}{L}\right) = \sum_{n=1}^{\infty} \Theta_n$$

$$\text{where } C_n = \frac{4 \sin \zeta_n}{(2 \zeta_n + \sin 2 \zeta_n)}$$

The discrete values ζ_n are the positive roots of the transcendental equation

$$\zeta_n \tan \zeta_n = B_i$$

$$Fo_i = \frac{\alpha t_i}{L^2} \text{ is the Fourier modulus or dimensionless time}$$

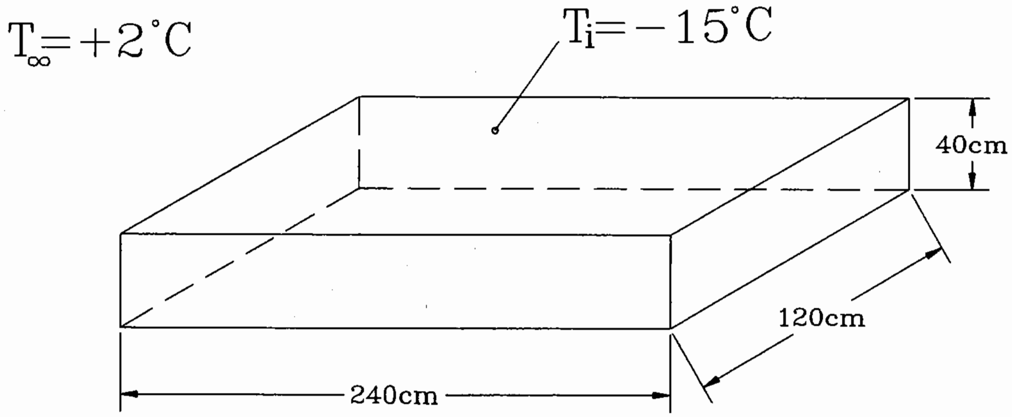
α is the surface thermal diffusivity (m^2/s)

t_i is the real time in seconds varying in k time step from 0 to t_{final} when the two methods converge to equal temperature values at the surface.

L is the half thickness of the box.

The sum of terms was carried out until a residual $L_2 = 3.0 \times 10^{-7}$ was reached. The L_2 residual is a norm expressed as

Figure 3.1
General Problem Layout for Comparison of
Time Constant Method and Infinite Plate 1-D Method



g:\cm1283\analysis\coldsoak\1D_PLATE.DWG

$$L_2 = [\sum_{i=1}^{k} \frac{(\Theta_n - \Theta_{n-1})^2}{n})]^{1/2}$$

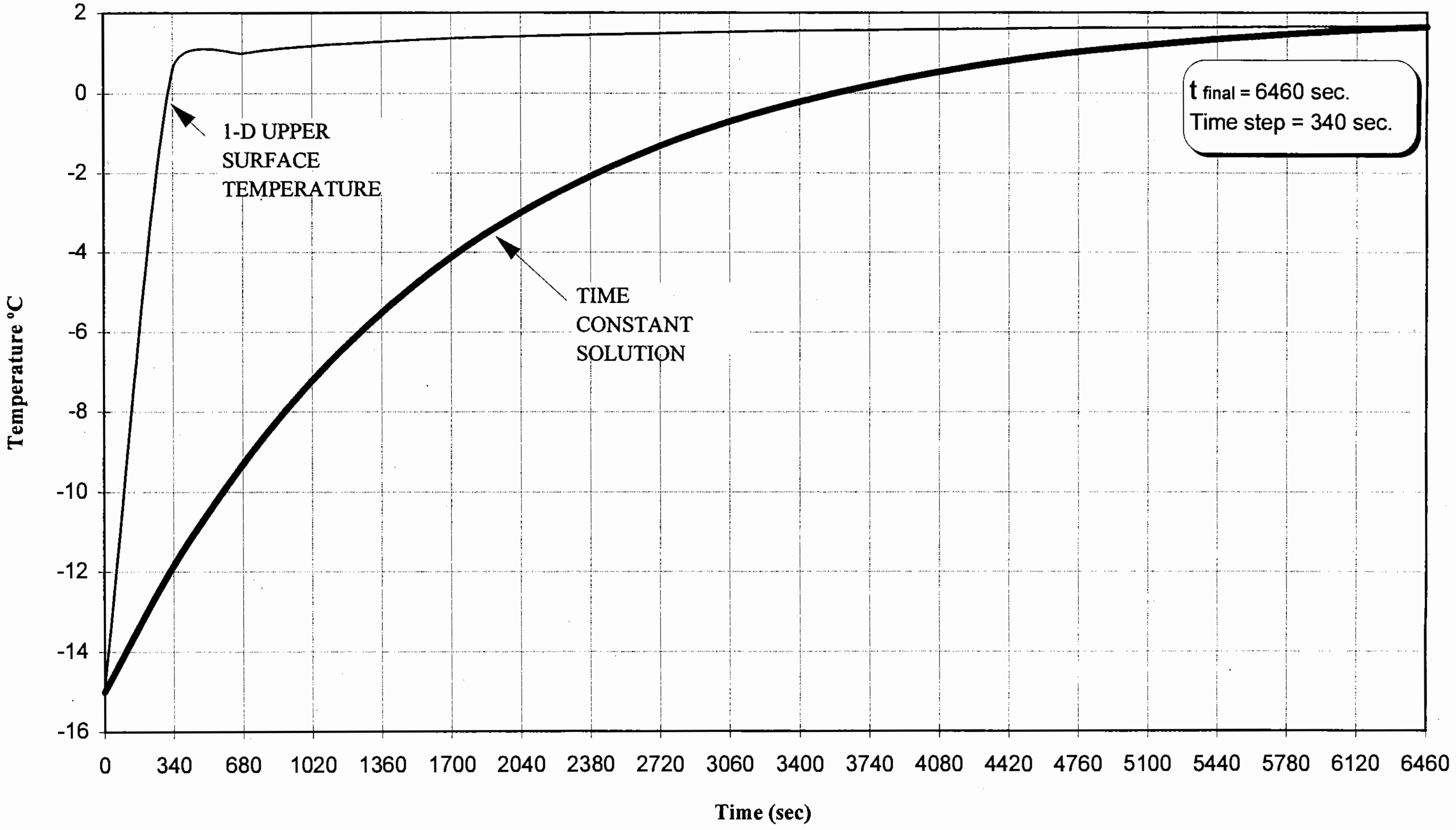
where k is the total number of time steps and n the number of terms used in the infinite series. Θ_n and Θ_{n-1} are the last two consecutive terms in the infinite sum. The L_2 residual is an indication of whether satisfactory overall convergence has been reached at all the time steps. An L_2 residual of 3.0×10^{-7} means that the solution is accurate at least to the 10^{-6} or the 6th decimal place.

Figure 3.2 shows the infinite plate 1-D upper surface temperature solution and the thermal time constant solution from 0 to ≈ 7000 seconds in 20 time steps of 340 seconds each. The time constant solution clearly indicates a slower rising temperature than the infinite 1-D solution at the surface. The average difference between the two is -3.2°C over ≈ 7000 seconds. This means that when interpolating over time constants for HOTs, a temperature buffer will be present, resulting in slightly conservative HOTs.

FIGURE 3.2

SURFACE TEMPERATURE COMPARISON OF TIME CONSTANT SOLUTION AND 1-D INFINITE PLATE SOLUTION

L_2 = 2.8E-07



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4. COMPARISON OF COLD-SOAKED BOX AND AIRCRAFT WINGS

4. COMPARISON OF COLD-SOAKED BOX AND AIRCRAFT WINGS

It was shown in Section 3.3 that a time constant approximation of the surface temperature of a body comparable in dimensions to a fuel tank resulted in somewhat conservative HOTs. Therefore, when testing with a cold-soaked box, any obtained HOT would be applicable to a wing with a similar time constant with an inherent temperature buffer in the HOT. It remains to determine the value of a typical wing time constant.

A time constant value was calculated for the Regional Jet wing fuel tank with a layer of propylene glycol on top. The theoretical time constant expression of Section 3.1 was used and the obtained value was 6000 seconds (1.7 hours), well below the theoretical time constant of the 7.5 cm box of ≈ 8000 seconds (2.2 hours). While it is clear that most wings will have different time constants, it is suggested that a smaller box of 2.5 cm depth be used for testing with the larger ones. The 2.5 cm box is expected to have a theoretical time constant of ≈ 2700 seconds (0.75 hours), therefore bracketing the Regional Jet wing time constant with the 7.5 cm box time constant. This is a better approach than using one box with a time constant equal to the theoretical Regional Jet wing since we can interpolate for the HOT of any other wing with the time constant falling between the time constants of the two boxes. Within the range of HOT values that will exist for all aircraft, those that are of interest for published HOT tables are the shortest ones.

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5. OBSERVATIONS AND CONCLUSIONS

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- A cold-soak sealed box can provide a conservative representation of a cold-soak wing condition given that the thermal time constants of the two surfaces are matched. Boxes of different sizes can be tested to simulate different wings. The results for the wing of interest can be derived by interpolation, provided the time constant of the wing falls between that of the two boxes.

- The use of a cold box shallower than the 7.5 cm deep box tested, may provide a more accurate simulation of a real wing.

- Thermistors should be placed above the aircraft fuel tanks in future temperature measurements, to compute thermal time constants more precisely.

- Thermal time constants for partial fuel loads need to be computed to determine the worst case scenario.

- The availability of an experimental time constant for a Canadair RJ or another aircraft wing would confirm data.

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6. RECOMMENDATIONS ON FUTURE TESTING

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Recommendations were made to:

- Provide more data with the 7.5 cm box and test with a new 2.5 cm sealed box for conventional Type II and Type I fluids to improve the quality of the prediction. This data should include simulation of rain at higher rates of precipitation.
- Conduct tests on sealed boxes with new Type II (Type IV) fluids.
- Conduct full-scale cold-soak aircraft field tests in order to verify the analytical HOTs and to verify the time constant assumptions.

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REFERENCES

[1] Incropera, Frank P., De Witt, David P., *Fundamentals of Heat and Mass Transfer*, John Wiley & Sons, 1985, Page 179

[2] Incropera, Frank P., De Witt, David P., Page 184

[3] Incropera, Frank P., De Witt, David P., Pages 430-433

APPENDIX A

DETAILED EQUATIONS USED FOR COLD-SOAKED BOX AND WING COMPARISON

DETAILED EQUATIONS USED FOR COLD-SOAKED BOX AND WING COMPARISON

A.1 Computation of Theoretical Time Constants

The theoretical time constants are calculated using the following set of equations:

$$\tau = \frac{\rho\ C_p\ \forall}{h\ A}$$

ρ, Cp, ∀ and A are given. h is obtained using

$$h = \frac{Nu\ K}{L}$$

where Nu is the Nusselt number in effect at the body surface. The Nusselt number is a dimensionless number that is equal to the dimensionless temperature gradient at the surface of the body and it provides a measure of the convection heat transfer occurring at the surface.

The Nusselt number can be obtained from the following empirical correlations for free convection over a cooled surface [3]

$$Nu = 0.27\ Ra_L^{1/4} \quad \text{for a top horizontal surface} \tag{1}$$

$$Nu = 0.15\ Ra_L^{1/3} \quad \text{for a bottom horizontal surface} \tag{2}$$

$$Nu = 0.68 + \frac{0.670\ Ra^{1/4}}{[1 + (\frac{0.492}{Pr})^{9/16}]^{4/9}} \quad \text{for a vertical surface} \tag{3}$$

Ra_L is the Rayleigh dimensionless number. Ra_L is a measure of the degree of free convection present at the surface with respect to forced convection and is given by

$$Ra_L = \frac{g\,\beta\,\Theta\,L^3}{\nu\,\alpha}$$

where, g = earth gravitational acceleration (m/s^2)

β = environment expansion coefficient ($°K^{-1}$)

Θ = $T_\infty - T^{surface}$ (°K)

L = <u>Area</u>/Perimeter, specific length (m)

ν = kinematic viscosity of surrounding fluid (m^2/s)

α = thermal diffusivity of surface (m^2/s)

h = surface convection heat transfer coefficient ($W/m^2°K$)

K = environment conduction heat transfer coefficient (W/m°K)

ρ = box coolant density (Kg/m^3)

C_p = box coolant specific heat value (J/Kg/°K)

$\forall$ = box volume (m^3)

A = box heat transfer area (m^2)

A.1.1 Boxes Theoretical Time Constants

The boxes dimensions are

A = 0.15 m^2 (top surface area)

L = Area/Perimeter = 0.15/(2 x (0.3+0.5)) = 0.094 m

$\forall$ = 0.15 x 0.075 = 1.125×10^{-2} m^3 for the 7.5 cm box

= 0.15 x 0.15 = 2.250×10^{-2} m^3 for the 15 cm box

The coolant inside the boxes is a 65% propylene glycol solution at -15°C with the following properties,

ρ = 1065 Kg/m^3
Cp = 3300 J/kg K
T_∞ = +2°C

The box surface temperature is taken to be -10°C and the top surface fluid layer is a propylene glycol solution taken at -9°C. The reason for this fluid temperature choice is that the fluid is applied at room temperature and will typically cool down to a temperature very close to the surface temperature in a matter of minutes after pouring. The fluid will also have to transfer heat from the atmosphere to the box surface so its temperature will likely be slightly higher than the surface temperature. The top surface fluid layer properties are,

ρ = 1063 Kg/m^3
β = 0.548 x 10^{-3} °K^{-1}
ν = 54.01 x 10^{-6} m^2/s
K = 0.374 W/m°K
Cp = 3320 J/Kg °K
α = 10.6 x 10^{-7} m^2/s

The resulting Rayleigh number is

$$Ra_L = 701562$$

$$Nu = 0.27\ Ra_L^{1/4} = 7.8$$

$$h = \frac{Nu\ K}{L} = 33.1\ W/m^2K$$

$$\tau = \frac{\rho\ C_p\ \forall}{h\ A} = 8003\ \textit{for the } 7.5\,cm\ \textit{box}$$

$$\tau = \frac{\rho\ C_p\ \forall}{h\ A} = 16005\ \textit{for the } 15\,cm\ \textit{box}$$

A.1.2 Canadair RJ Wing Theoretical Time Constant

The Canadair RJ wing fuel tank total volume is 2.84 m^3 and its total surface area is 23.14 m^2 broken up as follows in four sets,

top surface area	= 9.85 m^2
bottom surface area	= 9.85 m^2
total front and rear spars surface area	= 3.28 m^2
total root and tip rib area	= 0.64 m^2

The convection heat transfer coefficient will need to be calculated for each independent set since each corresponds to a different condition.

The top surface is treated just like the box with the propylene glycol layer on top and corresponds to equation (1). The bottom surface is horizontal and exposed to air and corresponds to equation (2). The spar and rib areas are also exposed to air but are vertical surfaces and correspond to equation (3).

The average dimensions of the fuel tank are:

chord	= 1.39 m
thickness	= 0.23 m
length	= 7.11 m

The specific lengths of the different surfaces are:

$L_{top} = L_{bottom}$ = Area/Perimeter = 0.71 m

$L_{LE\ spar} = L_{TE\ spar}$ = Area/Perimeter = 0.15 m

$L_{root\ rib} = L_{tip\ rib}$ = Area/Perimeter = 0.14 m

The fuel tank surface temperature is taken to be -10°C and the air temperature +2°C so the properties of air are taken at a film temperature of $T_{fa} = \frac{-10+2}{2} = -4°C$

and are the following,

β	=	$3.7 \times 10^{-3}\ K^{-1}$
Pr	=	0.7148
α	=	$18.54 \times 10^{-6}\ m^2/s$
K	=	23.9×10^{-3} W/mK
ν	=	$13.22 \times 10^{-6}\ m^2/s$

The de-icing fluid is typically applied hot on the top wing surface and hits it around a temperature of 25°C. The fluid properties will be taken at a film temperature of $T_{ff} = \frac{25 + 10}{2} = 17.5°C$

One cannot take a lower temperature as done for the boxes because previous tests at YUL have shown that the fluid temperature will be several degrees higher than the wing temperature for at least 10 minutes. So the fluid properties are best taken at $T_{ff} = 17.5°C$ and are

ρ = 1056 Kg/m^3

β = 0.6005×10^{-3} K^{-1}

α = 17.97×10^{-6} m^2/s

K = 0.369 W/m K

Pr = 192.49

Cp = 3380 J/Kg K

ν = 1.03×10^{-7} m^2/s

The h calculations for the different surfaces are as follows,

Top surface: propylene glycol layer at 25°C, $T_{ff} = 17.5°C$, $\Delta\theta = 35°K$

$$Ra = \frac{g \beta \Delta\Theta L^3}{\nu \alpha} = 4.0 \times 10^{10}$$

$$Nu = 0.27 Ra_L^{1/4} = 120.6$$

$$h = \frac{Nu K}{L} = 62.7 W/m^2C$$

Bottom surface: air at +2°C, T_{fa} = -4°C, $\Delta\theta = 12°K$

$$Ra = \frac{g\ \beta\ \Delta\Theta\ L^3}{\nu\ \alpha} = 4.0 \times 10^{10}$$

$$Nu = 0.15\ Ra_L^{1/4} = 128.1$$

$$h = \frac{Nu\ K}{L} = 4.3\ W/m^2K$$

LE and TE spars: air at +2°C, T_{fa} = -4°C, $\Delta\theta = 12°K$

$$Ra = \frac{g\ \beta\ \Delta\Theta\ L^3}{\nu\ \alpha} = 6.4 \times 10^{6}$$

$$Nu = 0.68 + \frac{0.67\ Ra_L^{1/4}}{[1 + (\frac{0.492}{Pr})^{9/16}]^{4/9}} = 26.6$$

$$h = \frac{Nu\ K}{L} = 4.1\ W/m^2K$$

Root and tip ribs: air at +2°C, T_{fa} = -4°C, $\Delta\theta$ = 12°K

$$Ra = \frac{g\,\beta\,\Delta\Theta\,L^3}{\nu\,\alpha} = 4.9 \times 10^6$$

$$Nu = 0.68 + \frac{0.67\,Ra_L^{1/4}}{[1 + (\frac{0.492}{Pr})^{9/16}]^{4/9}} = 24.9$$

$$h = \frac{Nu\,K}{L} = 4.2\ W/m^2K$$

In order to calculate the Canadair RJ wing time constant, one needs to obtain the overall heat transfer convection coefficient for the whole fuel tank. This can be done by calculating surface by surface the overall heat transfer per °K for the whole fuel tank and then by normalizing by the total fuel tank surface area.

Overall heat transfer /°K = $h_{overall}\ A_{overall}$

$$= hA_{upper} + hA_{lower} + hA_{LE + TE\ spars} + hA_{root + tip\ ribs}$$

$$= 62.7 \times 9.85 + 4.3 \times 9.85 + 4.1 \times 3.28 + 4.2 \times 0.64 = 676.1\ W/°K$$

$$\Rightarrow h_{overall} = 676.1/A_{overall} = 676.1/23.14$$

$$= 29.2\ W/m^2\ °K$$

The theoretical time constant for the Canadair RJ wing becomes,

$$\tau = \frac{\rho_{fuel}\,\forall_{fuel}\,C_{p(fuel)}}{h_{overall}\,A_{overall}} = \tau = \frac{800 \times 2.84 \times 1660}{29.2 \times 23.14} = 5578 \approx 6000\ seconds$$

A.2 Computation of Biot Number

$$B_i = h_\infty \frac{L_c}{K_s}$$

where h_∞ is the heat transfer convection coefficient at the surface of the body and is calculated as outlined in A.1.

It can be seen that the Biot number has the same expression as the Nusselt number. The only difference is that the Nusselt number uses the heat transfer conduction coefficient of the environment as opposed to the Biot number using K_s the conduction heat transfer coefficient of the body in question. This similarity is reflected also in the physical meaning of Nu and Bi since Nu represents the dimensionless temperature gradient at the surface of the body and Bi the ratio of the temperature difference within the body to the temperature difference between the body and the atmosphere.

$L_c = \forall/A$ is the body specific length

h_∞ was calculated in A.1 for both the boxes and the Canadair RJ wing and found to be 33.1 W/m^2K for the boxes and 29.2 W/m^2K for the Canadair RJ wing. K_s is taken to be the coolant conduction heat transfer coefficient. The conduction heat transfer in the skin is completely neglected since its thickness is very small (≈ 2 minutes) and the temperature difference across it is negligible.

$K_s = 0.374$ W/mK, the propylene glycol value for the boxes

$K_s = 0.238$ W/mK, the fuel value for the Canadair RJ wing

$L_c = \forall/A \quad = 0.075$ m for the 7.5 cm box

$= 0.15$ m for the 15 cm box

$L_c = 2.84/23.14 = 0.123$ m for the Canadair RJ wing

$$B_i = h_\infty \frac{L_c}{K_s} = \frac{33.1 \times 0.075}{0.374} = 6.6 \textit{ for the } 7.5\,cm \textit{ box}$$

$$B_i = h_\infty \frac{L_c}{K_s} = \frac{33.1 \times 0.15}{0.374} = 13.3 \textit{ for the } 15\,cm \textit{ box}$$

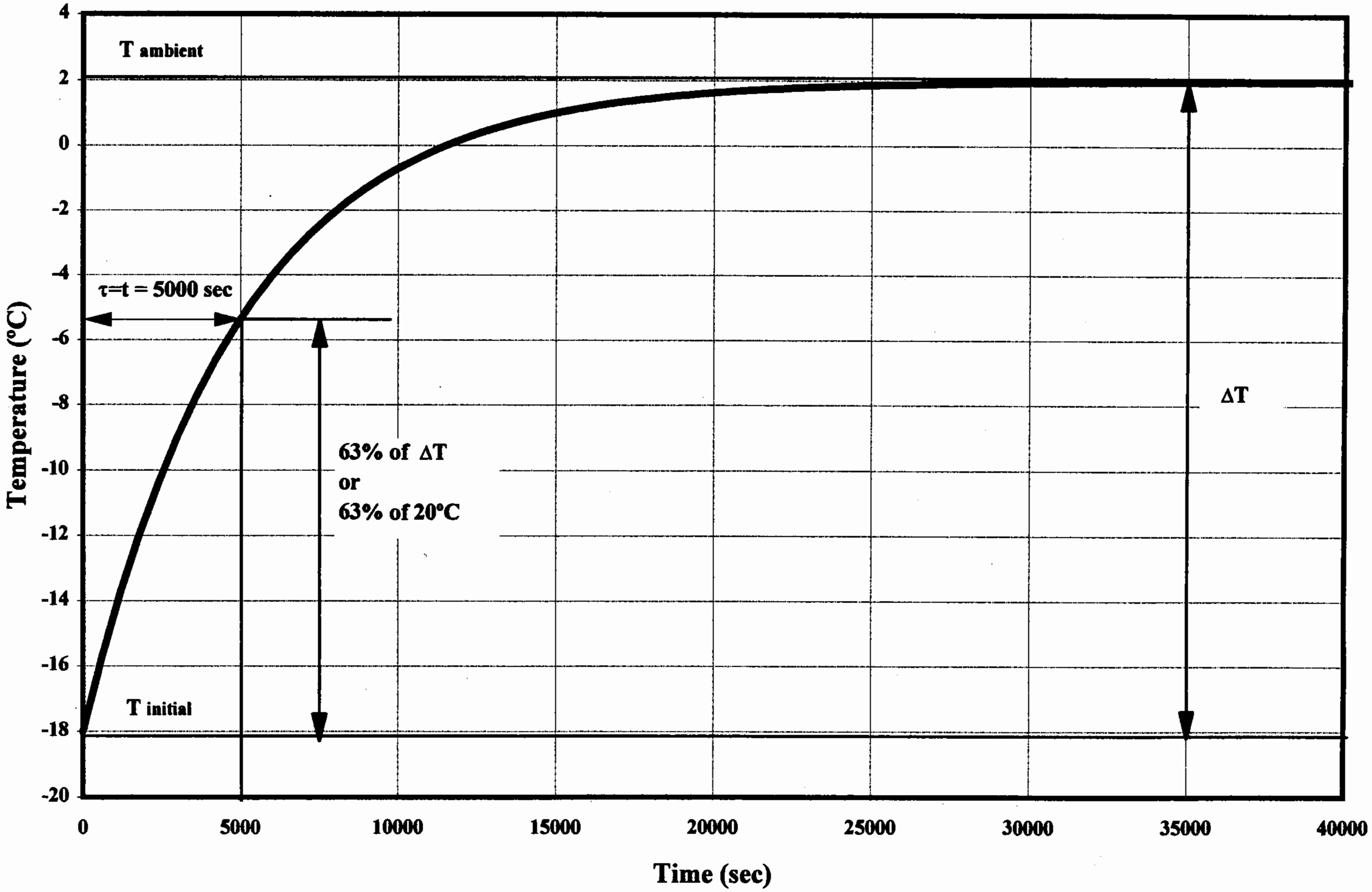
$$B_i = h_\infty \frac{L_c}{K_s} = \frac{29.2 \times 0.12}{0.238} = 15.1 \textit{ for the RJ wing}$$

APPENDIX B

EXPLANATION OF TIME CONSTANT CONCEPT

APPENDIX B

EXPLANATION OF TIME CONSTANT CONCEPT



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