ADSYM: A FORTRAN MODEL OF AN AUTOMOBILE DEFOG/DEFROST SYSTEM

by

E.R. WELBOURNE

A.H. Hall
Structures and Materials Section

F.R. Thurston
Director

SUMMARY

This report describes the basis and use of the Fortran 4 program ADSYM (Automobile Defog/defrost SYstem Model). The scope and limitations of the model and the use of the program are illustrated by examples. Possibilities for future development are briefly discussed. A complete listing of the program is given in an appendix.

TABLE OF CONTENTS

ILLUSTRATIONS

TABLES

TABLES (Cont'd)

APPENDICES

ADSYM: A FORTRAN MODEL OF AN AUTOMOBILE DEFOG/DEFROST SYSTEM

INTRODUCTION

An adequate field of vision for the driver is evidently a basic necessity for the safe operation of an automobile. The problem of clearing and maintaining an adequate field of vision is one of particular importance in the rather severe weather conditions typical of a Canadian winter.

A series of tests on Canadian-built cars has recently been conducted for the Ministry of Transport by the Structures and Materials Laboratory of the National Aeronautical Establishment and the Low Temperature Laboratory of the Division of Mechanical Engineering. The purpose of these tests was to provide data related to CMVSS 103 on windshield defrosting and defogging and to possible future requirements in respect of rear windows. This work, and some related earlier experiments are described in References 1 to 3.

Cold chamber tests of this type, currently required by S.A.E. and U.S. Federal Government Specifications are, however, both expensive and time consuming. For the extensive parametric studies involved in the development of either new defrost and defog systems, or of new performance standards, faster and more economical techniques are needed to reduce the time required in the cold chamber. The value, in this context, of a mathematical model of an automobile defog/defrost system was recognized by Blatt and collaborators[4]. In their extensive study for a group of U.S. Federal Government agencies, they developed an analytical model which provides, in principle, a basis both for independent parametric studies and for correlating experimental results obtained under differing conditions.

The practical utility of the original model was rather severely limited by its analytical form; the present report therefore describes a version of the model programmed in Fortran and known as ADSYM (Automobile Defog/defrost SYstem Model). While the programmed version adheres closely to the basic equations of the original model, some improvements have been made by substituting or including numerical methods rather than analytical ones.

No attempt is made here to reproduce the extensive discussion and analysis given by Blatt et al. in developing the model. In general. the basic equations are merely restated with the major assumptions relating to their derivation and use. Where ADSYM differs in a major respect from the original model however, the additional or alternative derivation is fully stated.

SYSTEM MODEL

General Description

The complete system, comprising the environment, the vehicle and its occupants, is represented in the model as an assembly of five subsystems. These are:

(i) Vehicle exterior subsystem

(ii) Engine and heater subsystem
(iii) Vehicle interior subsystem
(iv) Interior boundary layer subsystem
(v) Windshield/backlight subsystem.

Ambient temperature and humidity are defined by the vehicle exterior subsystem. These parameters in turn define the occurrence and form of precipitation and hence the heat and mass transfer mechanism on the exterior surface of the windshield/backlight.

The parameters of the engine and heater subsystem define the transient temperature behaviour of the engine coolant and hence of the heater exit air.

The vehicle interior air temperature is related directly to the heater exit air temperature by the vehicle interior subsystem. The interior moisture concentration includes the effects of occupants' breathing and vapour generation, when appropriate, from wet clothing.

The interior boundary layer subsystem may be specified in either of two forms. The first represents the heat and mass transfer processes which occur when a hot defroster jet mixes with the cooler and wetter interior air. The second form represents free convection between the interior air and the surface of the windshield/backlight.

A windshield/backlight of either laminated or isotropic construction may be specified in the last subsystem. A uniform heating rate at a surface or interface may also be specified, to represent an electrical resistance element. The subsystem considers the heat flow through the windshield/backlight under the time-dependent boundary conditions determined by the first four subsystems. The surface temperatures at a specified location are determined and, with the surface moisture balances, lead to a prediction of the surface states at that location.

Vehicle Exterior Subsystem

The vehicle exterior subsystem defines the ambient temperature and moisture concentration throughout the temperature transient. In consequence, it also defines the initial surface condition and heat transfer mechanism for the exterior of the windshield/backlight. The table below shows the conditions which result, in the present model, from specifying the various possible combinations of temperature and humidity.

Ambient Temperature °F	Relative Humidity %	Initial Surface Condition	Heat Transfer Mechanism
All	<100	Dry	Forced convection
<25	100	.09 lb/ft^2 of ice	Forced convection
25-32	100	.09 lb/ft^2 of ice	Rainwater film cooling
>32	100	wet	Rainwater film cooling

For icing conditions, the surface loading assumed is that specified in SAE J902a for windshield defrosting performance. At ambient temperatures less than 25°F, the effect of precipitation on the heat transfer process is ignored. A precipitation rate of one inch per hour has been assumed in rainfall.

The heat transfer coefficient for forced convection is estimated from the expression for a uniformly heated flat plate with a turbulent boundary layer:

$$Nu = \frac{hx'}{k} = 0.0296\ Re^{8}\ Pr^{33} \qquad (1)$$

where
- Nu is the Nusselt number
- h is the local heat transfer coefficient
- x' is the distance from the leading edge of the plate
- k is the thermal conductivity of air
- Re is the local Reynolds number
- Pr is the Prandtl number for air.

Utilizing the approximate analogy between heat and mass transfer processes, the corresponding mass transfer coefficient is given by:

$$Sh = \frac{gx'}{D\rho} = 0.0296\ Re^{8}\ Sc^{33} \qquad (2)$$

where
- Sh is the Sherwood number
- g is the local mass transfer coefficient
- D is the diffusion coefficient for water in air
- ρ is the density of air
- Sc is the Schmidt number for air

Combining Equations 1 and 2 the relation

$$g = \frac{h}{c_p} \left(\frac{Pr}{Sc}\right)^{67} \qquad (3)$$

is obtained.

Considering the temperature dependence of the several properties of air involved in Equations 1 and 3, it appears that the heat and mass transfer coefficients may be assumed independent of temperature with little loss of accuracy over the ambient range of interest. Accordingly, the properties of dry air at 15°F, taken as

$k = 0.135 \times 10^{-1}$ Btu/ft hr °F

$\nu = 0.135 \times 10^{-3}$ ft²/sec

$Pr = 0.710$

$c_p = 0.240$ Btu/lb °F

$D = 0.234 \times 10^{-3}$ ft²/sec

have been used for computation.

In rain, the exterior surface of the windshield/backlight is assumed to be cooled by a rainwater film. The film heat transfer coefficient is:

$$h = \frac{k}{t} \qquad (4)$$

where k is the thermal conductivity of water and t is the film thickness.

In Appendix A a simple model of the flow over the windshield/backlight is developed which leads to an estimate of the film thickness t. The following properties of water at 32°F have been assumed in computation:

$k = 0.345$ Btu/ft hr °F

$\nu = 0.1925 \times 10^{-4}$ ft^2/sec

$\rho = 62.57$ lb/ft^3

The temperature-dependence of the properties of water has been ignored in the small temperature range of practical interest.

The details of the heat and mass transfer processes at the interface between the film and the ambient air have been ignored. The effects on the heat transfer coefficient that could reasonably be represented in the model are probably quite small; rainfall is the dominant mass transfer mechanism.

Engine and Heater Subsystem

Consideration of the heat balance for the engine and heater subsystem leads to a first order differential equation for the coolant temperature T_c at time t with solution:

$$(T_c - T_o) = T_{co} + (T_{c\infty} - T_{co})\,(1 - e^{-t/\tau}) \qquad (5)$$

where $T_{co} = (T_c - T_o)_{t=0}$

$T_{c\infty} = (T_c - T_o)_{t=\infty}$

T_o = ambient temperature

τ = characteristic time of subsystem

Operation of the thermostat imposes the limit:

$$T_c \not> T_{cmax}$$

where T_{cmax} is the coolant temperature at which the thermostat opens.

The temperature of the defroster jet as it enters the car is given by

$$T_{jet} - T_o = \epsilon_H (T_c - T_o) \qquad (6)$$

where ϵ_H is the heater effectiveness, assumed constant.

The parameters τ, $T_{c\infty}$ and ϵ_H are taken to be independent of ambient temperature. They are determined by fitting curves of the general form of Equation 5 to experimental measurements of the coolant and defroster jet temperatures. The values of τ, $T_{c\infty}$ and ϵ_H are dependent on other parameters, external to the model, such as engine idling speed and heater control valve position. Consequently they are defined only for specified sets of such external parameters.

The moisture concentration in the defroster jet is assumed to be the same as the ambient value, since no moisture is added to the air passing through the heater.

Vehicle Interior Subsystem

Consideration of the interior heat balance leads to an approximate expression for the interior temperature T_{car}:

$$T_{car} - T_o = w^*_{jet}(T_{jet} - T_o) \tag{7}$$

where w^*_{jet} is a dimensionless constant involving the heater mass flow, leakage flow into the vehicle and a thermal loss parameter. It is assumed independent of ambient temperature and may be determined for a particular vehicle from measurements of T_{car} and T_{jet} during a temperature transient.

Consideration of the moisture balance leads to an approximate expression for the interior moisture concentration m_{car}:

$$m_{car} - m_o = \frac{N_{occ}\left[0.16 + G_{occ}(m_{car,sat} - m_o)\right]}{w_{jm} + N_{occ}G_{occ}} \tag{8}$$

where m_o is the ambient moisture concentration

N_{occ} is the number of occupants

0.16 is the vapour generation rate in lb/hr due to one person's breathing

G_{occ} is the transfer coefficient for wet clothing

w_{jm} is a composite mass flow determined mainly by the heater mass flow.

Interior Boundary Layer Subsystem

The temperature and moisture concentration profiles in a defroster jet mixing with the vehicle interior air are assumed to be given by the empirical expression:

$$\frac{T_x - T_{car}}{T_{jet} - T_{car}} = \frac{m_x - m_{car}}{m_o - m_{car}} = \xi = \left(\frac{1.6}{1 + 0.15(x/z'_{jet})}\right)^{1/2} \tag{9}$$

where T_x is the maximum temperature in the jet at distance x from the exit slot

m_x is the corresponding maximum vapour mass fraction

ξ is the decay function

$z'_{jet} = rz_{jet}$

r = ratio of exit slot length to width of windshield

z_{jet} = width of exit slot (normal to windshield).

The local heat transfer coefficient h is obtained from the related empirical expression:

$$Nu = \frac{hx'}{k} = c\ Re^{.65}\ Pr^{.33} \qquad (10)$$

where Nu is the Nusselt number

$x' = x + z'_{jet}/0.15$

k is the thermal conductivity of air

$c = 0.405\ z'^{\ .325}_{jet}$

Re is the Reynolds number based on x' and the initial jet velocity v_{jet}

Pr is the Prandtl number for air.

The analogy between heat and mass transfer processes again leads to Equation 3 for the mass transfer coefficient:

$$g = \frac{h}{c_p}\left(\frac{Pr}{Sc}\right)^{.67}$$

where in this case h is given by Equation 10.

Considering the temperature dependence of the properties of air involved in Equation 10, it appears that the interior heat transfer coefficient is more nearly independent of temperature than the corresponding exterior coefficient given by Equation 1. However, while the ambient temperature remains constant, the defroster jet temperature varies markedly with time and over a greater range than that of interest in specifying ambient conditions. For this reason, the temperature dependence of the conductivity and kinematic viscosity of air has been retained in this part of the model. Applying Newton's interpolation formula to Eckert and Gross's Table A-4 of Reference 5, the following expressions are obtained for the temperature range -10 to +170°F:

$$\nu = 0.1218 + 0.00052\dot{2}\ (T+10) - 0.0000004938\ (T+10)\ (T-80) + \ldots$$

$$k = 0.1287 + 0.00025\dot{4}\ (T+10) - 0.00000006172\ (T+10)\ (T-80) + \ldots$$

where T is the air temperature in degrees Fahrenheit

ν is the kinematic viscosity in 10^{-3} ft²/sec units

k is the conductivity in 10^{-1} Btu/ft hr °F units.

The remaining relevant properties are assumed to be constants with values at 80°F:

$c_p = 0.240$ Btu/lb°F

Pr = 0.708

Sc = 0.577.

In the absence of an air jet blowing over the interior surface, heat and mass transfer between the surface and the vehicle interior are assumed to occur by free convection. For horizontal or vertical plates in turbulent free convective flow, the

ASHRAE Handbook of Fundamentals[6], gives the relation:

$$Nu = 0.13 \ (Gr\ Pr)^{1/3} \qquad (11)$$

where Nu is the Nusselt number

Gr is the Grashof number

Pr is the Prandtl number.

At temperatures within the range of interest, the simplified relations

$$h = 0.19 \ (T_o - T_s)^{1/3} \qquad \text{(vertical plate)}$$

$$h = 0.22 \ (T_o - T_s)^{1/3} \qquad \text{(horizontal plate)}$$

are given for air. For most angles of inclination of the windshield/backlight it is assumed to be sufficiently accurate to take:

$$h = 0.205 \ (T_{cor} - T_1)^{.33} \qquad (12)$$

where h is the average heat transfer coefficient

T_{cor} is the vehicle interior air temperature

T_1 is the windshield/backlight interior surface temperature.

The analogy between heat and mass transfer processes allows us to write:

$$Sh = 0.13 \ (Gr'\ Sc)^{1/3} \qquad (13)$$

where Sh is the Sherwood number

Gr' is a modified Grashof number based on density potential rather than temperature

Sc is the Schmidt number

Combining Equations 11 and 13 a relation between heat and mass transfer coefficients in free convection

$$g = \frac{h}{c_p} \left(\frac{Pr}{Sc}\right)^{.67} \left(\frac{Gr'}{Gr}\right)^{.33} \qquad (14)$$

can be obtained which is analogous to Equation 3 for forced convection. Now

$$\frac{Gr'}{Gr} = \frac{\rho_{cor}/\rho_1 - 1}{\beta(T_{cor} - T_1)} \qquad (15)$$

from the basic definitions of the two Grashof numbers[5], where the numerator is the density potential between the surface and the vehicle interior and β is the volumetric thermal expansion coefficient of the air. For small mass fractions of water vapour, the density potential may be expressed in terms of the mass fractions as:

$$\frac{\rho_{car}}{\rho_1} - 1 = 0.611 \ (m_1 - m_{car}) + 0(m^2) \tag{16}$$

where m_1 is the saturation mass fraction at the surface and m_{car} is the mass fraction of water vapour in the vehicle interior. A representative value of $\beta \simeq 0.00195°F^{-1}$ is consistent with the previous development of Equation 12. Taking values

c_p = .240 Btu/lb°F

Pr = .708

Sc = .577

and substituting also from Equations 15 and 16 into 14 we obtain finally:

$$g = 6.6 \ (m_1 - m_{car})^{.33} \tag{17}$$

Windshield/Backlight Subsystem

The heat balance for the windshield/backlight, neglecting in-plane conduction, is expressed by the one-dimensional heat conduction equation with time-dependent boundary conditions at the interior and exterior surfaces. In the original model, this equation was solved for the surface temperatures in a laminated windshield, using rather crude approximations to the temperature distribution and windshield properties. In the present model, which is not constrained by the need to produce analytical relations for the variables of interest, a laminated windshield/backlight may be represented as easily as one which is isotropic. Further, a uniform interlaminar heating rate, representative of an electrical resistance heating element, may readily be specified. In this section of the report, the basic equations are stated as concisely as possible. In Appendix B, the equivalent finite difference equations are given and the method of solution is described.

The equation governing heat conduction within a given lamina is:

$$\frac{\partial T}{\partial t} = \frac{k}{c\rho} \frac{\partial^2 T}{\partial z^2} \tag{18}$$

where
- T is the local temperature
- t is the time from initial thermal equilibrium
- k is the thermal conductivity of the lamina
- c is the specific heat of the lamina
- ρ is the density of the lamina
- z is the normal-to-plane co-ordinate

At the interface between adjacent laminae, continuity of heat flow requires that:

$$k_1 \frac{\partial T_1}{\partial z_1} = k_2 \frac{\partial T_2}{\partial z_2} + \dot{H}_{rh} \quad (19)$$

where $\dot{H}_{rh}$ is the interlaminar heating rate and the subscripts $_1$ and $_2$ indicate the particular laminae adjacent to the interface. Similarly, at the two surfaces, the boundary conditions are defined by:

$$\left.\begin{aligned} k_1 \frac{\partial T_1}{\partial z_1} &= h_i(T_1 - T_i) - \dot{H}_{s,i} \\ k_n \frac{\partial T_n}{\partial z_n} &= h_e(T_e - T_n) + \dot{H}_{s,e} \end{aligned}\right\} \quad (20)$$

where subscripts $_1$ and $_n$ indicate respectively the innermost and outermost laminae, h_i and h_e are the interior and exterior heat transfer coefficients, T_i and T_e the corresponding temperatures in the adjacent air, $\dot{H}_{s,i}$ and $\dot{H}_{s,e}$ the total superficial heating rates from all other sources.

In general:

$$\dot{H}_s = \dot{H}_{rh} + \dot{H}_{mt} - \dot{H}_{melt} \quad (21)$$

$\dot{H}_{rh}$ is the superficial heating rate due to an electrical resistance element, a known constant. H_{mt} is the superficial heating rate due to mass transfer to the surface:

$$\left.\begin{aligned} \dot{H}_{mt,i} &= g_i(m_i - m_{1,sat})\ h_v \\ \dot{H}_{mt,e} &= g_e(m_e - m_{n,sat})\ h_v \end{aligned}\right\} \quad (22)$$

where g_i and g_e are respectively the interior and exterior mass transfer coefficients, m_i and m_e the corresponding moisture concentrations in the adjacent air, $m_{1,sat}$ and $m_{n,sat}$ the saturation moisture concentrations corresponding with surface temperatures T_1 and T_n, and h_v is the latent heat of vaporization of water. According to Equation 22, H_{mt} may be positive or negative, as determined by the sign of the bracketed term. It thus represents either heating by condensation or cooling by evaporation. Evidently, evaporative cooling can only occur on a wet or icy surface, so we have the conditions on Equation 22:

$$\left.\begin{aligned} \dot{H}_{mt,i} &\nless 0 \quad \text{for} \quad w_{s,i} = 0 \\ \dot{H}_{mt,e} &\nless 0 \quad \text{for} \quad w_{s,e} = 0 \end{aligned}\right\} \quad (23)$$

where $w_{s,i}$ and $w_{s,e}$ are respectively the interior and exterior surface loadings of water or ice.

$\dot{H}_{melt}$ is zero except during melting of a surface ice layer. During melting, the surface temperature is assumed to remain constant at 32°F. The appropriate boundary condition is then chosen from

$$T_1 = 32; \quad T_n = 32 \tag{24}$$

to replace the standard boundary condition given by Equation 20. The requirement for continuity of heat flow across the boundary is then available for the determination of the unknown value of $\dot{H}_{melt}$. Substituting Equation 21 into 20 and transposing gives

$$\left.\begin{aligned} \dot{H}_{melt} &= k_1 \frac{\partial T_1}{\partial z_1} + h_i(T_i - 32) + \dot{H}_{rh,i} + \dot{H}_{mt,i} \\ \dot{H}_{melt} &= - k_n \frac{\partial T_n}{\partial z_n} + h_e(T_e - 32) + \dot{H}_{rh,e} + \dot{H}_{mt,e} \end{aligned}\right\} \tag{25}$$

for the inner and outer surfaces respectively.

The time required to melt a given surface ice loading is then determined from:

$$w_s h_f = \int_{t_{32}}^{t_{melt}} \dot{H}_{melt}\, dt \tag{26}$$

where w_s is the surface ice loading and h_f is the latent heat of fusion of water. The thermal resistance and capacity of the ice layer are neglected in comparison with those of the windshield/backlight.

The surface loadings of water or ice are determined from the integrals:

$$\left.\begin{aligned} w_{s,i} &= \int_0^t g_i(m_i - m_{1,sat})\,dt \not< 0 \\ w_{s,e} &= \int_0^t g_e(m_e - m_{n,sat})\,dt \not< 0 \end{aligned}\right\} \tag{27}$$

The condition $w_s \not< 0$ is an obvious physical limit.

Illustration of Model Characteristics

The general characteristics and some of the limitations of the model can be more fully understood by reference to two examples in which the behaviour of the major variables, namely temperature and moisture concentration, is followed. These same examples are also used in later sections of this report to illustrate the use of the program.

Example 1 - Defrosting of a Laminated Windshield

Figure 1 shows plots of temperature against time for the major points of interest in the system.

The ambient temperature, and initial temperature for all subsystems, is 20°F. The relative humidity is 100% so the windshield is assumed to be coated initially with 0.01 oz/in^2 of ice, other effects of precipitation being ignored. The external airflow over the vehicle has a velocity of one ft/sec.

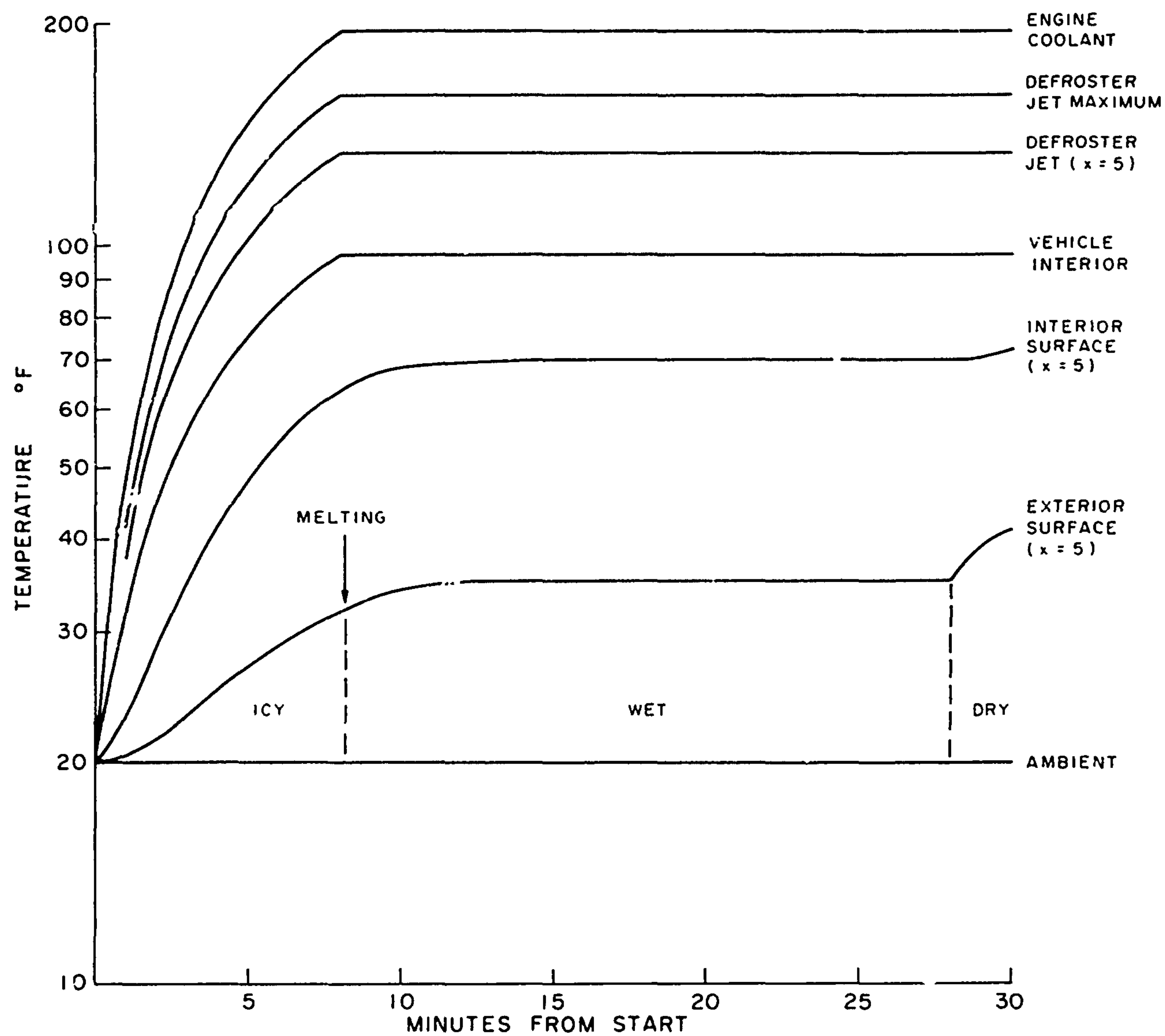


FIG. 1 : SYSTEM TEMPERATURES IN DEFROSTING OF WINDSHIELD FROM 20° F

The maximum engine coolant temperature is limited to 195°F by the thermostat. Other subsystem parameters are also assigned typical values. It can be seen in the figure that the maximum defroster jet temperature, the vehicle interior temperature and hence the local defroster jet temperature are directly related to the engine coolant temperature. In practice, while the coolant temperature rise is sharply cut-off by thermostat opening, some further rise in defroster jet temperature may occur. The vehicle interior temperature generally continues to increase, albeit more slowly than at first. The simplified model behaviour results mainly from ignoring the thermal capacities of the heater and of the vehicle interior.

The windshield surface temperatures are determined primarily by the local defroster jet temperature which is a function of distance along the jet axis. The plotted curves refer to a point five inches from the base of the windshield and the defroster jet slots. The effects of the thermal capacity and resistance of the laminated windshield which are represented in the model can be seen in the curves. Also of interest in the curve for the exterior surface are the small discontinuity at 32°F associated with melting of the ice layer and the sharp temperature rise following the completion of evaporation from the surface at 28 minutes.

In the present example, the corresponding curves of moisture concentration are of no special interest. Removal of exterior ice and water by sublimation and evaporation occurs throughout the first 28 minutes.

Example 2 - Defogging of an Electrically Heated Backlight

Figure 2 shows curves of temperature against time for the major points of interest in this case.

The ambient and initial temperature is 33°F with 100% relative humidity. The backlight is therefore cooled by a film of rainwater. The vehicle has six occupants with wet clothing. The engine and heater characteristics are the same as in the previous example. A constant heating rate of 160 Btu/ft^{2}hr is assumed at the interior surface of the backlight, which consists of a single $\frac{1}{4}$-inch glass.

Heat transfer between the vehicle interior and the backlight occurs only by free convection. The surface temperature rise is therefore determined primarily by the electrical heating. The curves refer to a point 12.5 inches up from the lower edge of the backlight but the actual defogging performance will not vary markedly with position in this case.

Figure 3 shows the relevant curves of moisture concentration against time. The mass fraction of water vapour in the vehicle interior rises above ambient owing to the vapour generated by the occupants' breath and clothing. While the interior vapour mass fraction exceeds the saturation value corresponding with the backlight interior surface temperature, fogging occurs. As the glass warms up, the surface saturation concentration rises above the vehicle interior value and the fog begins to evaporate, finally leaving the surface dry after about $2\frac{1}{2}$ minutes. The figure illustrates the rather critical dependence of the predicted defogging performance on the assumed characteristics of the vehicle interior subsystem.

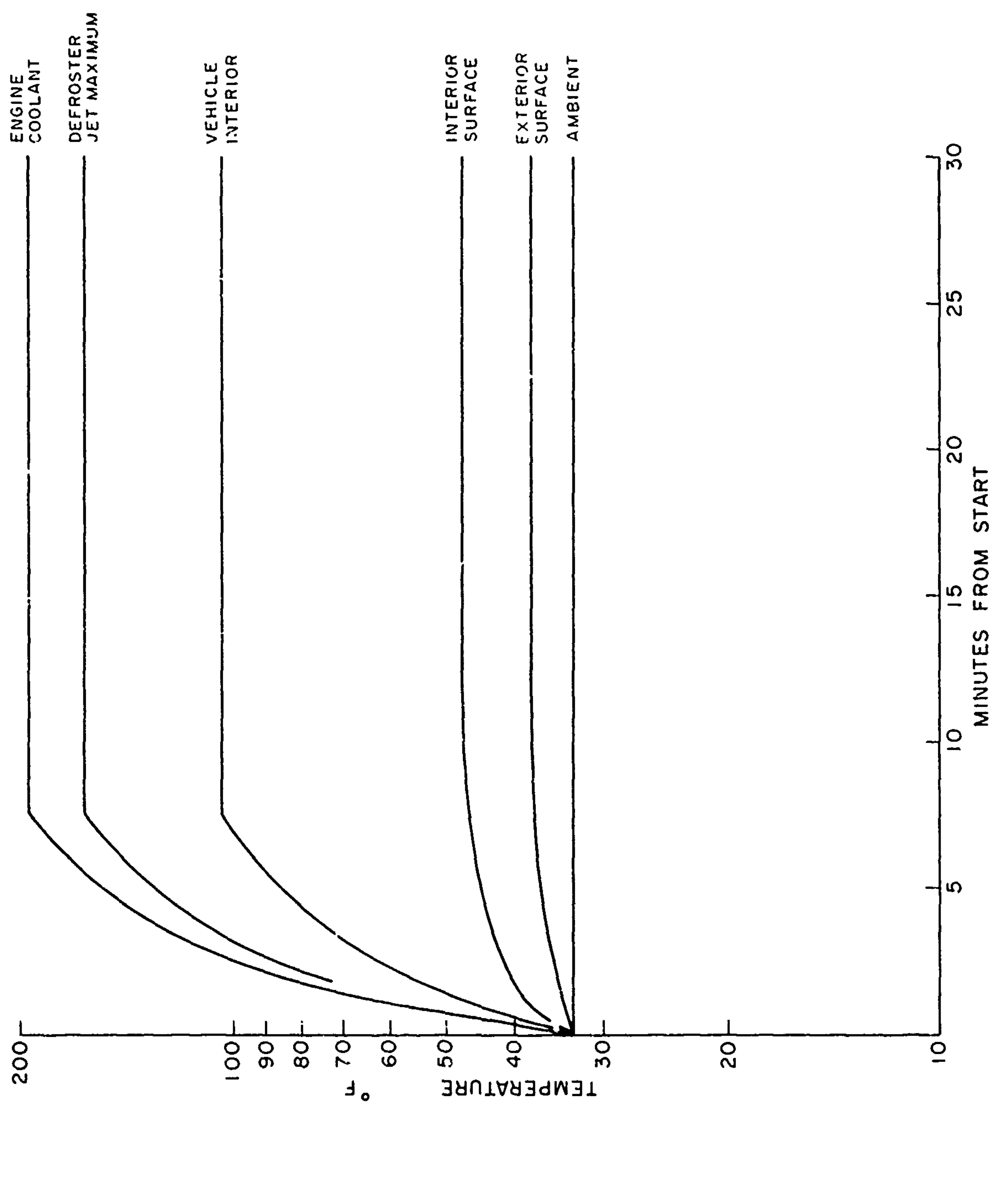


FIG. 2 : SYSTEM TEMPERATURES IN DEFOGGING BACKLIGHT IN RAINFALL AT 33°F

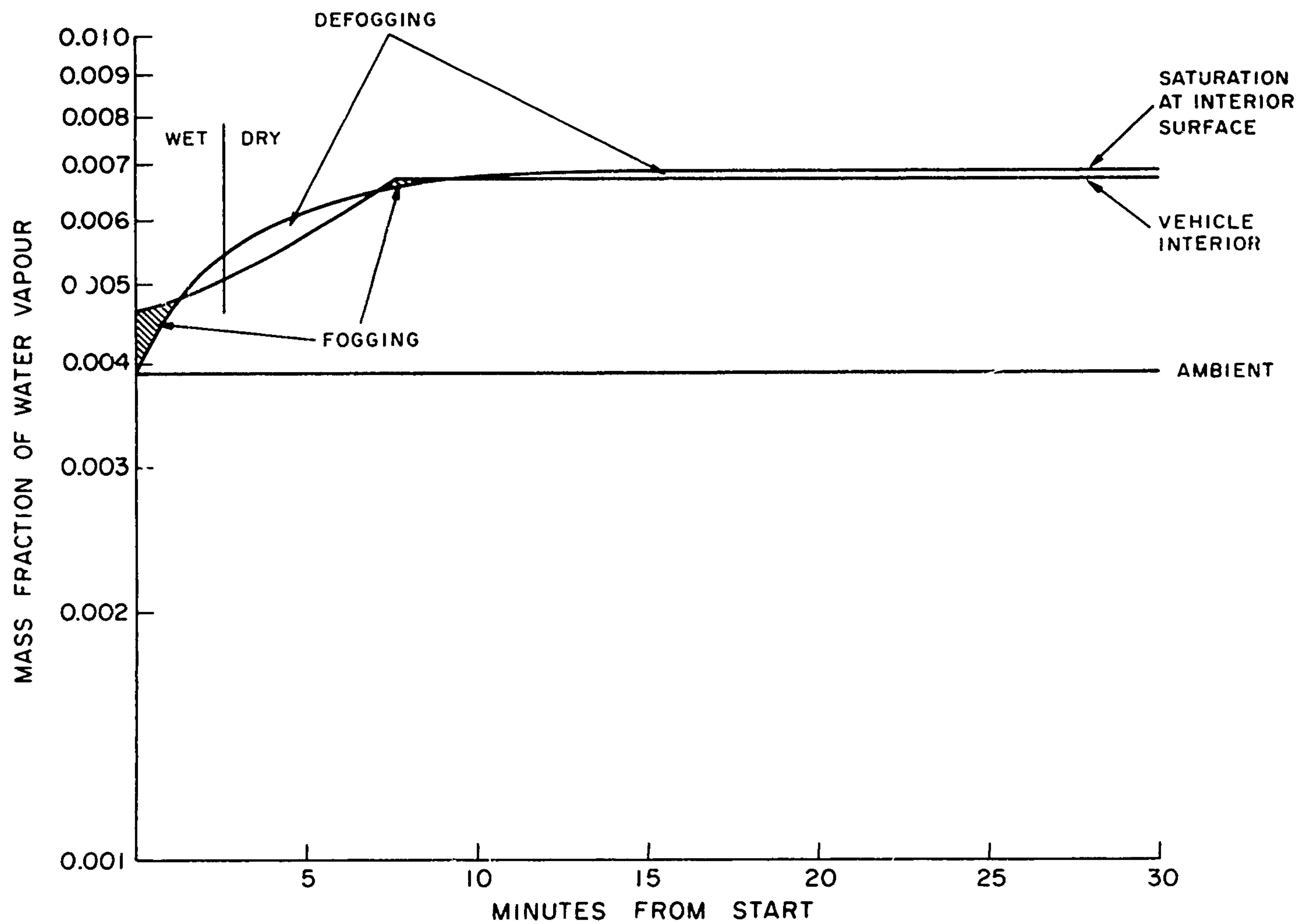


FIG. 3 . SYSTEM WATER VAPOUR CONCENTRATIONS IN DEFOGGING BACKLIGHT IN RAINFALL AT 33°F

Discussion of the Model

An ideal model of an automobile defog/defrost system would be capable of predicting defog/defrost contours on the windshield/backlight for a wide range of system designs and operating conditions. The present model clearly falls some way short of this ideal, primarily as a result of the inadequate level of detail in modelling the heat and mass transfer processes at the surfaces of the windshield/backlight. For all practical purposes, the requisite level of detail is unattainable, by reason of the very large range of geometrical and other parameters which determine the nature of the flow over the surfaces. It is further apparent that so long as the distribution of local heat and mass transfer rates can not be predicted with any confidence, possible refinements in other parts of the model may offer little return in overall accuracy or realism. Thus, for example, consideration of in-plane conduction effects in the windshield/backlight subsystem, which would significantly increase complexity and computing costs, could not be justified.

While detailed predictions of defog/defrost contours can not be made with the existing model or any practicable development of it, its value is nonetheless considerable. It may be expected to give good indications of the effects of the many available system parameters on the defog/defrost time for representative locations on the windshield/backlight. It will be recalled that these parameters define the major characteristics of both the operating conditions and the vehicle hardware. Thus, it may be used for preliminary studies of alternative performance criteria or of alternative system designs.

In this more limited context, there remain several parts of the model which could usefully be improved. The improvements might include the following:

(i) extension of engine and heater subsystem model to include engine rpm, engine load and coolant mass flow effects;

(ii) substitution of a differential model of the interior heat and mass balances for the existing equilibrium model;

(iii) development of a representative model of an unheated backlight defogger blower;

(iv) the facility to specify different start times for certain subsystems or subsystem components.

From a preliminary review of these items, it appears that: (i) could be represented by additional closed-form expressions derived from approximate theory; (ii) would involve the numerical solution of a simple first order equation and would slightly increase computing time; (iii) would probably require some experimental studies to develop a suitable correlation expression; (iv) seems only to involve program modifications.

USE OF THE PROGRAM

General Description

Figure 4 shows the major features of the program in flow chart form.

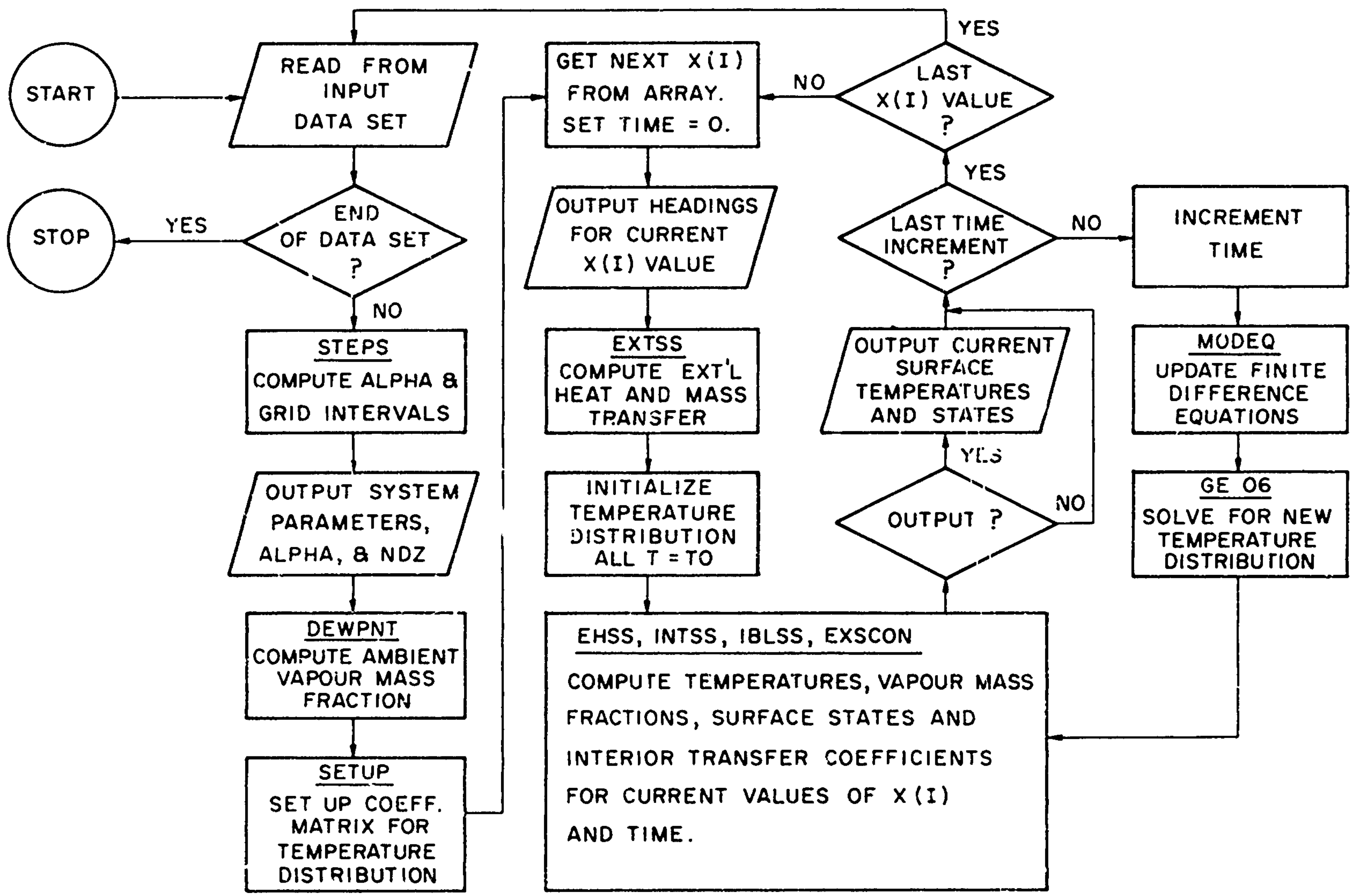


FIG. 4 : ADSYM FLOW CHART

Each input data set comprises one set of vehicle parameters and ambient conditions, a maximum of eight locations on the windshield/backlight to be considered, and a specification of the number and size of time increments to be used. The program has a simple nested loop structure in which the time history of the ice surface temperatures and states is evaluated for each specified location for each set of vehicle parameters and ambient conditions. The surface temperatures and states are written at some chosen multiple of the basic time increment.

Specifying the Input Data

Table I prescribes the structure of the input data set which is oriented to card format with a maximum record length of 80 bytes. The first field starts in card column 1 (or equivalent) and all fields are contiguous within one card (record).

The following notes relate to Table I:

(1) The value of IOPT(1) specifies the frequency of output from the program. A value of IOPT(1) = 1 will cause surface temperatures and states to be printed at every time increment, a value IOPT(1) = 2 at every other time increment, and so on.

The value of IOPT(2) specifies the nature of the interior heat transfer mechanism. A value IOPT(2) = 2 specifies free convection. Any other value of IOPT(2) specifies forced convection (the defroster jet).

The value of IOPT(3) specifies the presence or absence of interlaminar heating. A value IOPT(3) = 0 causes all HRH(I) to be taken as zero irrespective of the values read in. Any other value causes HRH(I) to be taken as read.

IOPT(4) and IOPT(5) are spare and should be left blank.

(2) If a windshield is being analyzed, XO is the distance from the front of the hood to the lower edge of the windshield. If a backlight is being analyzed, set XO equal to RFL.

(3) The value of NDZ must be specified for one lamina and one only. This value is used with the specified time increment to determine a 'master' value of the finite difference parameter α to which 'slave' values of α for the other laminae are matched as closely as possible, subject to other physical and program constraints.

(4) When IOPT(3) = 0, this record must be blank (but not omitted) for correct program functioning.

(5) The next record may be either a data set delimiter or the first record of a new data set.

Table II shows the input data set for the two illustrative examples used in the present report.

Output Format

The output format is fixed except in respect of the choice allowed in the value of IOPT(1). Table III shows the program output for the two examples.

The units of the system parameters are the same as specified in Table I for input. The surface state integer takes the values one, two and three for dry, wet and icy surfaces respectively.

Run Times and Stability

Actual run times in any particular case evidently depend on a number of factors some of which are under the control of the program user while others are program- and installation-dependent.

The development of the present program was carried out on an IBM 360/67 operating under TSS/360. The majority of examples extended over 180.0 increments of 10 seconds (30 minutes of real time). Typical CPU times for these conditions were found to be:

0.15 - 0.5 cpu sec to read data and set up problem;

1.0 - 3.0 cpu sec to compute surface temperatures and states at one location over a 30-minute period.

No evidence of oscillation or divergence due to rounding errors was observed in any of the examples used in program development.

REFERENCES

1. McCaffrey, G.F.W. — Automobile Defroster Performance During a Canadian Winter. NRC, NAE Mech. Eng. Report MS-119, National Research Council of Canada, June 1968.

2. Sillar, W. — Cold Chamber Tests on the Defrosting Equipment of a Mercedes Car. NRC, DME Lab. Tech. Report LTR-LT-25, National Research Council of Canada, January 1971.

3. Dunsby, J.A., Sillar, W., Walker, A.C. — Cold Chamber Defog/Defrost Tests on a Selection of 1972 Automobiles. NRC, NAE Lab. Tech. Report LTR-ST-523, National Research Council of Canada, March 1972.

4. Blatt, T.A. et al. — Defog and Defrost Systems. Northern Research and Engineering Corporation Report 1138-1, June 1969.

5. Eckert, E.R.G., Gross, J.F. — Introduction to Heat and Mass Transfer. McGraw-Hill, 1963.

6. Handbook of Fundamentals.
American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1967.

7. Carnahan, B. et al. Applied Numerical Methods.
Wiley, 1969.

TABLE I **Preceding page blank**

ADSYM INPUT DATA SET STRUCTURE

REC. NO.	FTN V'BLE	FIELD LENGTH	FTN FORMAT	DESCRIPTION	UNITS
1	-	56	56H	Problem title, preceded by 0 (zero)	-
2	DTIM	10	F10.5	Time increment in finite difference solution	sec
	NSTEP	5	I5	Number of time increments	-
	NX	5	I5	Number of locations considered (1 ≤ NX ≤ 8)	-
	IOPT	25	5I5	Program options[1]	-
3	TO	10	F10.5	Initial and ambient temperature	°F
	RHUM	10	F10.5	Relative humidity percent	-
	XO	10	F10.5	Characteristic length of car[2]	ft
	SLHT	10	F10.5	Slant height of windshield/backlight	in
	THETA	10	F10.5	Windshield/backlight angle to horizon	deg
	RFL	10	F10.5	Length of car roof	ft
	VCAR	10	F10.5	Speed of car (VCAR > 0)	ft/sec
4	TCO	10	F10.5	Initial coolant temperature	°F
	TCMAX	10	F10.5	Maximum coolant temperature	°F
	TCINF	10	F10.5	Asymptotic coolant temperature rise	°F
	TAU	10	F10.5	Characteristic time of engine + heater	sec
	HEFF	10	F10.5	Heater effectiveness (0 ≤ HEFF ≤ 1)	-
	WJT	10	F10.5	Mass flow parameter (0 ≤ WJT ≤ 1)	-
5	NOCC	5	I5	Number of occupants	-
	WJM	10	F10.5	Effective mass flow through car	lb/hr
6	ZJET	10	F10.5	Width of defroster jet slot (normal to windshield)	in
	VJET	10	F10.5	Initial jet velocity	ft/sec
	SPREAD	10	F10.5	Ratio of slot length to width of windshield	-
7	NLAM	5	I5	Number of laminae (1 ≤ NLAM ≤ 5)	-
8	AMAT	8	2A4	Material of first lamina	-
	THK	10	F10.5	Thickness of first lamina	in
	DENS	10	F10.5	Density of first lamina	lb/ft^3
	SPHT	10	F10.5	Specific heat of first lamina	Btu/lb°F
	COND	10	F10.5	Thermal conductivity of first lamina	Btu/hr ft °F
	NDZ	5	I5	Number of sublaminae[3]	-
9	AMAT	8	2A4	Material of second lamina	-
	THK	10	F10.5	Thickness of second lamina	
				etcetera	
NLAM +8	HRH	60	6F10.5	(NLAM + 1) values of interlaminar heating rates[4]	
NLAM +9	X	80	8F10.5	(NX) values of distance along reference axis[5]	

TABLE II

INPUT DATA SET FOR EXAMPLES

```
0REPORT EXAMPLE 1 - DEFROSTING OF LAMINATED WINDSHIELD
10.        180     3    6    1    0
20.        100.       5.         23.        35.        5.5        1.
20.        195.       300.       480.       .8         .55
    21200.
.5         50.        .40
    3
   GLASS.125       170.      .2         .44         3
   VINYL.03        78.       .4         .095
   GLASS.125       170.      .2         .44
0.         0.         0.        0.
5.         10.        15.
0REPORT EXAMPLE 2 - DEFOGGING OF ELECTRIC BACKLIGHT
10.        180     1    6    2    1
33.        100.       5.5        23.        35.        5.5        1.
33.        195.       300.       480.       .8         .55
    61200.
.5         50.        .4
    1
   GLASS.25        170.      .2         .44         5
160.       0.
12.5
%E
```

TABLE III

OUTPUT DATA SET FOR EXAMPLES

```
AUTOMOBILE DEFOG/DEFROST SYSTEM MODEL (ADSYM)

REPORT EXAMPLE 1 - DEFROSTING OF LAMINATED WINDSHIELD

EXTERIOR SUBSYSTEM PARAMETERS
    AMBIENT TEMPERATURE =  20.0     RELATIVE HUMIDITY = 100.0     CHARACTERISTIC LENGTH OF CAR =  5.0
    SLANT HEIGHT OF WINDSHIELD/BACKLIGHT = 23.0     SLOPE (DEG) = 35.0     LENGTH OF ROOF = 5.50     SPEED =   1.0

ENGINE AND HEATER SUBSYSTEM PARAMETERS
    INITIAL COOLANT TEMPERATURE =  20.0     MAXIMUM COOLANT TEMPERATURE = 195.0     ASYMPTOTIC COOLANT TEMPERATURE = 300.0
    CHARACTERISTIC TIME = 480.0     HEATER EFFECTIVENESS = 0.80     MASS FLOW PARAMETER = 0.55

INTERIOR SUBSYSTEM PARAMETERS
    NUMBER OF OCCUPANTS =  2     EFFECTIVE MASS FLOW = 1200.0

DEFROSTER JET SUBSYSTEM PARAMETERS
    SLOT WIDTH = 0.50     INITIAL JET VELOCITY =  50.0     SPREAD = 0.400
```

WINDSHIELD/BACKLIGHT SUBSYSTEM PARAMETERS

LAMINA	MATERIAL	THICKNESS	NUMBER OF SUBLAMINAE	DENSITY	SPECIFIC HEAT	CONDUCTIVITY	ALPHA	HEATING RATE
								0.00
1	GLASS	0.125	3	170.00	0.200	0.440	2.98	0.00
2	VINYL	0.030	2	78.00	0.400	0.095	5.41	0.00
3	GLASS	0.125	3	170.00	0.200	0.440	2.98	0.00

TABLE III (cont'd)

PREDICTED SURFACE CONDITIONS AT 5.0 INCHES FROM BASE OF WINDSHIELD/BACKLIGHT

TIME	INTERIOR SURFACE TEMPERATURE	INTERIOR SURFACE STATE	EXTERIOR SURFACE TEMPERATURE	EXTERIOR SURFACE STATE
0.0	20.0	1	20.0	3
60.0	23.0	3	20.3	3
120.0	28.8	1	21.4	3
180.0	35.3	1	23.1	3
240.0	41.8	1	25.0	3
300.0	48.0	1	27.0	3
360.0	53.8	1	28.7	3
420.0	59.0	1	30.4	3
480.0	63.7	1	31.8	3
540.0	66.5	1	33.4	2
600.0	68.1	1	34.2	2
660.0	69.0	1	34.7	2
720.0	69.5	1	34.9	2
780.0	69.8	1	35.1	2
840.0	70.0	1	35.1	2
900.0	70.1	1	35.2	2
960.0	70.1	1	35.2	2
1020.0	70.2	1	35.2	2
1080.0	70.2	1	35.2	2
1140.0	70.2	1	35.3	2
1200.0	70.2	1	35.3	2
1260.0	70.2	1	35.3	2
1320.0	70.2	1	35.3	2
1380.0	70.2	1	35.3	2
1440.0	70.2	1	35.3	2
1500.0	70.2	1	35.3	2
1560.0	70.2	1	35.3	2
1620.0	70.2	1	35.3	2
1680.0	70.2	1	35.3	2
1740.0	70.5	1	39.1	1
1800.0	72.1	1	41.1	1

TABLE III (cont'd)

PREDICTED SURFACE CONDITIONS AT 10.0 INCHES FROM BASE OF WINDSHIELD/BACKLIGHT

	INTERIOR SURFACE		EXTERIOR SURFACE	
TIME	TEMPERATURE	STATE	TEMPERATURE	STATE
0.0	20.0	1	20.0	3
60.0	21.8	3	20.1	3
120.0	25.0	1	20.8	3
180.0	28.8	1	21.8	3
240.0	32.8	1	23.0	3
300.0	36.7	1	24.2	3
360.0	40.4	1	25.4	3
420.0	43.9	1	26.5	3
480.0	47.0	1	27.5	3
540.0	48.9	1	28.3	3
600.0	50.1	1	28.9	3
660.0	50.8	1	29.2	3
720.0	51.3	1	29.4	3
780.0	51.6	1	29.5	3
840.0	51.7	1	29.6	3
900.0	51.8	1	29.7	3
960.0	51.9	1	29.7	3
1020.0	52.0	1	29.7	3
1080.0	52.0	1	29.7	3
1140.0	52.0	1	29.7	3
1200.0	52.0	1	29.7	3
1260.0	52.0	1	29.7	3
1320.0	52.0	1	29.7	3
1380.0	52.0	1	29.7	3
1440.0	52.0	1	29.7	3
1500.0	52.0	1	29.7	3
1560.0	52.0	1	29.7	3
1620.0	52.0	1	29.7	3
1680.0	52.0	1	29.7	3
1740.0	52.0	1	29.7	3
1800.0	52.0	1	29.7	3

TABLE III (cont'd)

PREDICTED SURFACE CONDITIONS AT 15.0 INCHES FROM BASE OF WINDSHIELD/BACKLIGHT

TIME	INTERIOR SURFACE TEMPERATURE	INTERIOR SURFACE STATE	EXTERIOR SURFACE TEMPERATURE	EXTERIOR SURFACE STATE
0.0	20.0	1	20.0	[illegible]
60.0	21.2	3	20.1	3
120.0	23.5	3	20.6	3
180.0	26.1	1	21.3	3
240.0	29.0	1	22.1	3
300.0	31.[illegible]	1	23.0	3
360.0	34.6	1	23.9	3
420.0	37.1	1	24.7	3
480.0	39.4	1	25.5	3
540.0	40.9	1	26.1	3
600.0	41.9	1	26.6	3
660.0	42.5	1	26.9	3
720.0	42.9	1	27.0	3
780.0	43.2	1	27.[illegible]	3
840.0	43.3	1	27.2	3
900.0	43.5	1	27.3	3
960.0	43.5	1	27.3	3
1020.0	43.6	1	27.3	3
1080.0	43.6	1	27.3	3
1140.0	43.6	1	27.4	3
1200.0	43.6	1	27.4	3
1260.0	43.6	1	27.4	3
1320.0	43.6	[illegible]	27.4	3
1380.0	43.6	1	27.4	3
1440.0	43.6	1	27.4	3
1500.0	43.6	1	27.4	3
1560.0	43.6	1	27.4	3
1620.0	43.6	1	27.4	3
1680.0	43.6	1	27.4	3
1740.0	43.6	1	27.4	3
18[illegible]0.0	43.6	1	27.4	3

TABLE III (cont'd)

AUTOMOBILE DEFOG/DEFROST SYSTEM MODEL (ADSYM)

REPORT EXAMPLE 2 - DEFOGGING OF ELECTRIC BACKLIGHT

EXTERIOR SUBSYSTEM PARAMETERS
    AMBIENT TEMPERATURE = 33.0   RELATIVE HUMIDITY = 100.0   CHARACTERISTIC LENGTH OF CAR = 5.5
    SLANT HEIGHT OF WINDSHIELD/BACKLIGHT = 23.0   SLOPE (DEG) = 35.0   LENGTH OF ROOF = 5.50   SPEED = 1.0

ENGINE AND HEATER SUBSYSTEM PARAMETERS
    INITIAL COOLANT TEMPERATURE = 33.0   MAXIMUM COOLANT TEMPERATURE = 195.0   ASYMPTOTIC COOLANT TEMPERATURE = 300.0
    CHARACTERISTIC TIME = 480.0   HEATER EFFECTIVENESS = 0.80   MASS FLOW PARAMETER = 0.55

INTERIOR SUBSYSTEM PARAMETERS
    NUMBER OF OCCUPANTS = 6   EFFECTIVE MASS FLOW = 1200.0

DEFROSTER JET SUBSYSTEM PARAMETERS
    SLOT WIDTH = 0.50   INITIAL JET VELOCITY = 50.0   SPREAD = 0.400

WINDSHIELD/BACKLIGHT SUBSYSTEM PARAMETERS

LAMINA	MATERIAL	THICKNESS	NUMBER OF SUBLAMINAE	DENSITY	SPECIFIC HEAT	CONDUCTIVITY	ALPHA	HEATING RATE 160.00
1	GLASS	0.250	5	170.00	0.200	0.440	2.07	0.00

TABLE III (cont'd)

PREDICTED SURFACE CONDITIONS AT 12.5 INCHES FROM BASE OF WINDSHIELD/BACKLIGHT

	INTERIOR SURFACE		EXTERIOR SURFACE	
TIME	TEMPERATURE	STATE	TEMPERATURE	STATE
0.0	33.0	1	33.0	2
60.0	38.2	2	34.0	2
120.0	40.7	2	35.0	2
180.0	42.5	1	35.8	2
240.0	43.8	1	36.3	2
300.0	44.7	1	36.7	2
360.0	45.5	1	37.0	2
420.0	46.2	1	37.3	2
480.0	46.7	1	37.5	2
540.0	47.0	1	37.6	2
600.0	47.2	1	37.7	2
660.0	47.3	1	37.7	2
720.0	47.4	1	37.8	2
780.0	47.4	1	37.8	2
840.0	47.5	1	37.8	2
900.0	47.5	1	37.8	2
960.0	47.5	1	37.8	2
1020.0	47.5	1	37.8	2
1080.0	47.5	1	37.8	2
1140.0	47.5	1	37.8	2
1200.0	47.5	1	37.8	2
1260.0	47.5	1	37.8	2
1320.0	47.5	1	37.8	2
1380.0	47.5	1	37.8	2
1440.0	47.5	1	37.8	2
1500.0	47.5	1	37.8	2
1560.0	47.5	1	37.8	2
1620.0	47.5	1	37.8	2
1680.0	47.5	1	37.8	2
1740.0	47.5	1	37.8	2
1800.0	47.5	1	37.8	2

APPENDIX A

RAINWATER FILM THICKNESS ON THE WINDSHIELD/BACKLIGHT

Basic Equations

Consider a rainwater film of local thickness y moving with local mean velocity v down the inclined surface of a windshield/backlight, as shown in Figure A-1. For unit width of the film, conservation of mass within the elementary length ds requires that:

$$d(\rho v y) - \dot{p} \cos\theta \, ds = 0 \qquad \text{(A.1)}$$

where ρ is the density of the water, $\dot{p}$ the precipitation rate and θ the inclination of the windshield/backlight to the horizon.

The second required condition for the determination of the unknown film thickness and mean velocity may be obtained by considering the equilibrium of the element under the forces acting in the s direction due to its inertia, weight, viscous drag and the momentum increment due to precipitation. Equilibrium (or conservation of momentum) requires that:

$$\frac{d}{dt}(\rho v y) ds - g\rho y \sin\theta \, ds + \tau_o ds - \dot{p} v_p \sin\theta \cos\theta \, ds = 0 \qquad \text{(A.2)}$$

where t is time, g is the acceleration due to gravity, τ_o is the viscous shear stress at the surface and v_p is the vertical velocity of the precipitation.

Shear Stress τ_o

The shear stress τ_o must be expressed in terms of the local film thickness and mean velocity before (A.2) can be used. It is assumed that the film flow is laminar and characterised by a simple parabolic velocity profile. Newton's expression states that:

$$\tau_o = \mu \left(\frac{dv'}{dy'}\right)_{y'=0}$$

where μ is the dynamic viscosity, v' is the velocity at distance y' from the surface. For the assumed velocity profile

$$\left(\frac{dv'}{dy'}\right)_{y'=0} = \frac{2v'_{max}}{y} = \frac{3v}{y}$$

whence

$$\tau_o = \frac{3\mu v}{y} \qquad \text{(A.3)}$$

Solution of Equations

Substituting for τ_o in Equation A.2, noting that $\frac{d}{dt} = v\frac{d}{ds}$ and that ρ is constant, Equation A.2 becomes

$$v\rho \frac{d}{ds}(vy) = g\rho y \sin\theta + \frac{3\mu v}{y} - \dot{p}v_p \sin\theta\cos\theta = 0$$

But from Equation A.1 we have

$$\rho \frac{d}{ds}(vy) = \dot{p}\cos\theta$$

so that

$$v\dot{p}\cos\theta - g\rho y \sin\theta + \frac{3\mu v}{y} - \dot{p}v_p \sin\theta\cos\theta = 0$$

Consideration of the relative magnitudes of the terms in this equation shows that the first and last are respectively three and two orders smaller than the remaining terms. For typical windshield/backlight angles we can therefore write

$$\frac{3\mu v}{y} - g\rho y \sin\theta \simeq 0$$

Multiplying by y^2, rearranging and noting $\nu = \mu/\rho$

$$vy = \frac{gy^3 \sin\theta}{3\nu} \qquad \text{(A.4)}$$

Equation A.1 can be integrated directly to give

$$vy = \frac{s\dot{p}}{\rho}\cos\theta + (vy)_{s=0} \qquad \text{(A.5)}$$

Equating the R.H.S. of Equation A.4 and A.5 we obtain

$$\frac{gy^3\sin\theta}{3\nu} = \frac{s\dot{p}}{\rho}\cos\theta + (vy)_{s=0}$$

whence

$$y = \left\{\frac{3\nu}{g\sin\theta}\left(\frac{s\dot{p}}{\rho}\cos\theta + (vy)_{s=0}\right)\right\}^{1/3} \qquad \text{(A.6)}$$

The value of $(vy)_{s=0}$ is determined by assuming that one-quarter of the precipitation falling on the roof flows over the windshield/backlight, that is:

$$(vy)_{s=0} \simeq \frac{\dot{p}L_{roof}}{4\rho}$$

where L_{roof} is the length of the roof.

The film thickness y can therefore be determined directly from the expression

$$y = \left\{ \frac{3\nu\dot{p}}{g\rho \sin\theta} \left(s \cos\theta + \frac{L_{roof}}{4} \right) \right\}^{1/3} \qquad (A.7)$$

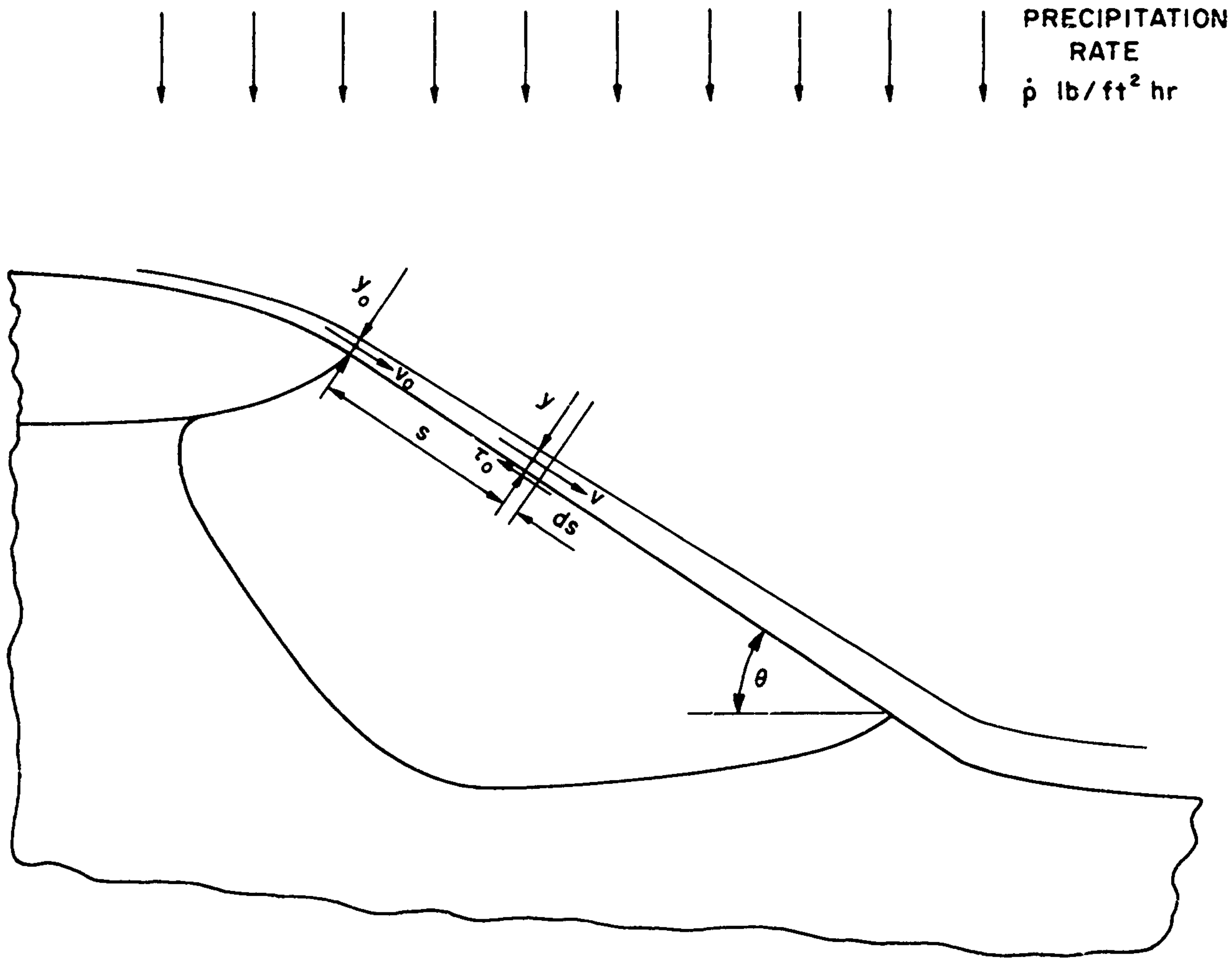


FIG. A-1 : RAINWATER FILM MODEL

APPENDIX B

FINITE DIFFERENCE SOLUTION OF WINDSHIELD/BACKLIGHT SUBSYSTEM EQUATIONS

Introduction

Finite difference approximations to the solution of partial differential equations are sufficiently familiar that no great elaboration on the basic approach is necessary here. Reference 7 provides an excellent source of such material. The following development concentrates on the special features of the present problem.

Basic Equation for Interior Temperatures

Figure B-1 shows a typical grid of points in (z, t) co-ordinates for the solution of a one-dimensional heat conduction problem in a laminated material. At any interior point of a given lamina, the heat conduction Equation 18 expressed in backward difference form is:

$$\frac{T_{i,j} - T_{i,j-1}}{\Delta t} = \frac{k}{c\rho} \left\{ \frac{T_{i-1,j} - 2T_{i,j} + T_{i+1,j}}{(\Delta z)^2} \right\} \qquad (B.1)$$

where $T_{i,j}$ is the temperature at the interior point. Letting $\alpha = k\Delta t/c\rho(\Delta z)^2$ and rearranging gives:

$$T_{i,j-1} = -\alpha T_{i-1,j} + (1 + 2\alpha)T_{i,j} - \alpha T_{i+1,j} \qquad (B.2)$$

where it will be noted that α is a parameter of the particular lamina considered.

Continuity Condition

At each interface between laminae, the continuity condition, Equation 19 may be used to determine a fictitious value of $T_{i+1,j}$ denoted $T^*_{i+1,j}$ for use in Equation B.2. In finite difference form, Equation 19 becomes:

$$k_1 \frac{(T^*_{i+1,j} - T_{i,j})}{\Delta z_1} = k_2 \frac{(T_{i+1,j} - T_{i,j})}{\Delta z_2} + (\dot{H}_{rh})_i$$

$$\text{whence,} \quad T^*_{i+1,j} = \left(1 - \frac{k_2}{k_1}\frac{\Delta z_1}{\Delta z_2}\right) T_{i,j} + \frac{k_2}{k_1}\frac{\Delta z_1}{\Delta z_2} \cdot T_{i+1,j} + (\dot{H}_{rh})_i \frac{\Delta z_1}{k_1} \qquad (B.3)$$

where the significance of the various terms is apparent from Figure B-1 and Equation 19. It will be noted that when the conductivity and grid spacing in adjacent laminae are the same and $(\dot{H}_{rh})_i = 0$, the required result for a homogeneous material, namely $T^*_{i+1,j} = T_{i+1,j}$ is obtained.

Substituting Equation B.3 into Equation B.2 gives the special form of the basic equation for points on an interface:

$$T_{i,j-1} + \alpha_1 \frac{\Delta z_1}{k_1} (\dot{H}_{th})_i = - \alpha_1 T_{i-1,j} + \left\{1 + \alpha_1 \left(1 + \frac{k_2}{k_1} \frac{\Delta z_1}{\Delta z_2}\right)\right\} T_{i,j}$$

$$- \alpha_1 \frac{k_2}{k_1} \frac{\Delta z_1}{\Delta z_2} T_{i+1,j} \qquad \text{(B.4)}$$

Boundary Conditions

The boundary conditions, Equation 20, may similarly be used to determine fictitious temperatures $T^*_{i-1,j}$ and $T^*_{i+1,j}$ outside the boundaries of the windshield/backlight for use in Equation B.2. In finite difference form, the boundary conditions become:

$$k_1 \frac{(T_{i,j} - T^*_{i-1,j})}{\Delta z_1} = h_{int}(T_{i,j} - T_{int}) - (\dot{H}_s)_{int}$$

$$k_n \frac{(T^*_{i+1,j} - T_{i,j})}{\Delta z_n} = h_{ext}(T_{ext} - T_{i,j}) + (\dot{H}_s)_{ext}$$

The significance of the various terms should again be clear from Equation 20 and previous development in this appendix.

Transposing the above equations, we obtain

$$\left.\begin{aligned} T^*_{i-1,j} &= \left(1 - \frac{h_{int}\Delta z_1}{k_1}\right) T_{i,j} + \frac{\Delta z_1}{k_1} \left\{h_{int} T_{int} + (\dot{H}_s)_{int}\right\} \\ T^*_{i+1,j} &= \left(1 - \frac{h_{ext}\Delta z_n}{k_n}\right) T_{i,j} + \frac{\Delta z_n}{k_n} \left\{h_{ext} T_{ext} + (\dot{H}_s)_{ext}\right\} \end{aligned}\right\} \qquad \text{(B.5)}$$

Substituting Equation B.5 into the basic equation gives the special forms associated respectively with the interior and exterior surfaces of the windshield/backlight:

$$T_{i,j-1} + \alpha_1 \frac{\Delta z_1}{k_1} \left\{h_{int} T_{int} + (\dot{H}_s)_{int}\right\} = \left\{1 + \alpha_1 \left(1 + h_{int} \frac{\Delta z_1}{k_1}\right)\right\} T_{i,j} + \alpha_1 T_{i+1,j}$$

$$\text{(B.6)}$$

$$T_{i,j-1} + \alpha_n \frac{\Delta z_n}{k_n} \left\{h_{ext} T_{ext} + (\dot{H}_s)_{ext}\right\} = - \alpha_n T_{i-1,j} + \left\{1 + \alpha_n \left(1 + h_{ext} \frac{\Delta z_n}{k_n}\right)\right\} T_{i,j}$$

Initial Condition

The basic Equation B.2 for interior points with the special forms, Equations B.4 and B.6, for points on interfaces and boundaries provides a sufficient number of equations for the determination of the current temperature distribution $T_{i,j}$ from the previous temperature distribution, $T_{i,j-1}$.

The initial condition:

$$T_{i,1} = T_o \quad \text{for all } i \tag{B.7}$$

completes the data required to determine the temperature distribution for any $j > 1$. T_o is a specified uniform initial temperature, equal to the ambient temperature in the present case.

Melting of Surface Ice

Equation B.6 for the surface temperatures is invalid during melting of surface ice films. However, owing to the backward difference formulation of the equations, it will not be apparent that one or other has become invalid until after it has been used to determine a surface temperature which exceeds the melting point of ice. To avoid the misapplication of Equation B.6 and the consequent necessity to recalculate temperature distributions following the occurrence of melting, an estimate of the final surface temperatures is required before Equation B.6 is applied.

Such an estimate is available through the use of the forward difference approximation to the governing equations. In forward difference form, we have instead of Equation B.1:

$$\frac{T_{i,j+1} - T_{i,j}}{\Delta t} = \frac{k}{c\rho}\left\{\frac{T_{i-1,j} - 2T_{i,j} + T_{i+1,j}}{(\Delta z)^2}\right\} \tag{B.8}$$

and instead of Equation B.2:

$$T_{i,j+1} = \alpha T_{i-1,j} + (1 - 2\alpha)T_{i,j} + \alpha T_{i+1,j} \tag{B.9}$$

The boundary conditions expressed in Equation B.5 are unchanged, so substituting these in turn into Equation B.9 leads to the following estimates of the surface temperatures based on the forward difference approximation:

$$\left.\begin{aligned} T_{i,j+1} &= \alpha \frac{\Delta z_1}{k_1}\left\{h_{int}T_{int} + (\dot{H}_s)_{int}\right\} + \left\{1 - \alpha\left(1 + h_{int}\frac{\Delta z_1}{k_1}\right)\right\} T_{i,j} + \alpha T_{i+1,j} \\ T_{i,j+1} &= \alpha \frac{\Delta z_n}{k_n}\left\{h_{ext}T_{ext} + (\dot{H}_s)_{ext}\right\} + \left\{1 - \alpha\left(1 + h_{ext}\frac{\Delta z_n}{k_n}\right)\right\} T_{i,j} + \alpha T_{i-1,j} \end{aligned}\right\} \tag{B.10}$$

In the event that one or other of these equations predicts that the temperature of an ice-covered surface will exceed 32°F during the next time increment, the alternative boundary condition:

$$T_{i,j} = 32 \qquad \text{(B.11)}$$

is applied to either or both of the first and last equations, reducing the number of unknown $T_{i,j}$ accordingly.

The finite difference form of Equation 25, namely

$$\left.\begin{aligned} \dot{H}_{melt,int} &= \frac{k_1}{\Delta z_1}(T_{i+1,j} - T_{i,j}) + h_{int}(T_{int} - T_{i,j}) + (H_{rh})_i + (H_{mt})_i \\ \dot{H}_{melt,ext} &= \frac{k_n}{\Delta z_n}(T_{i-1,j} - T_{i,j}) + h_{ext}(T_{ext} - T_{i,j}) + (H_{rh})_i + (H_{mt})_i \end{aligned}\right\} \qquad \text{(B.12)}$$

provides the basis for determining the heat available for melting the surface ice layer during the j^{th} time increment.

The time required to melt the surface ice layer is obtained from the finite difference form of Equation 26:

$$(w_s h_f)_j = \sum_1^j \dot{H}_{melt} \Delta t_{melt} \qquad \text{(B.13)}$$

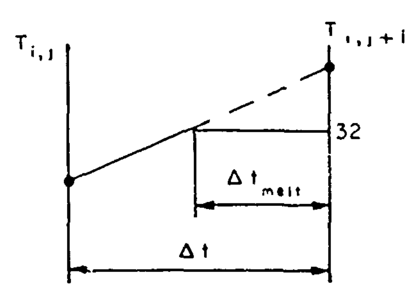
The surface loading w_s is determined from the finite difference form of Equation 27:

$$\left.\begin{aligned} w_{s\,int,j} &= \sum_1^j g_{int,j}\,(m_{int,j} - m_{1\,sat,j})\ \Delta t \not< 0 \\ w_{s\,ext,j} &= \sum_1^j g_{ext,j}\,(m_{ext,j} - m_{n\,sat,j})\ \Delta t \not< 0 \end{aligned}\right\} \qquad \text{(B.14)}$$

which apply quite generally to ice or water and irrespective of the occurrence of melting.

In general, Δt_{melt} in Equation B.13 is simply Δt. However in the first time increment in which melting occurs, Δt_{melt} is determined from:

$$\frac{\Delta t_{melt}}{\Delta t} = \frac{T_{i,j+1} - 32}{T_{i,j+1} - T_{i,j}}$$



where $T_{i,j+1}$ is the forward difference estimate of the surface temperature in the absence of melting. In the last increment in which melting occurs, Δt_{melt} is chosen to be just large enough to satisfy Equation B.13.

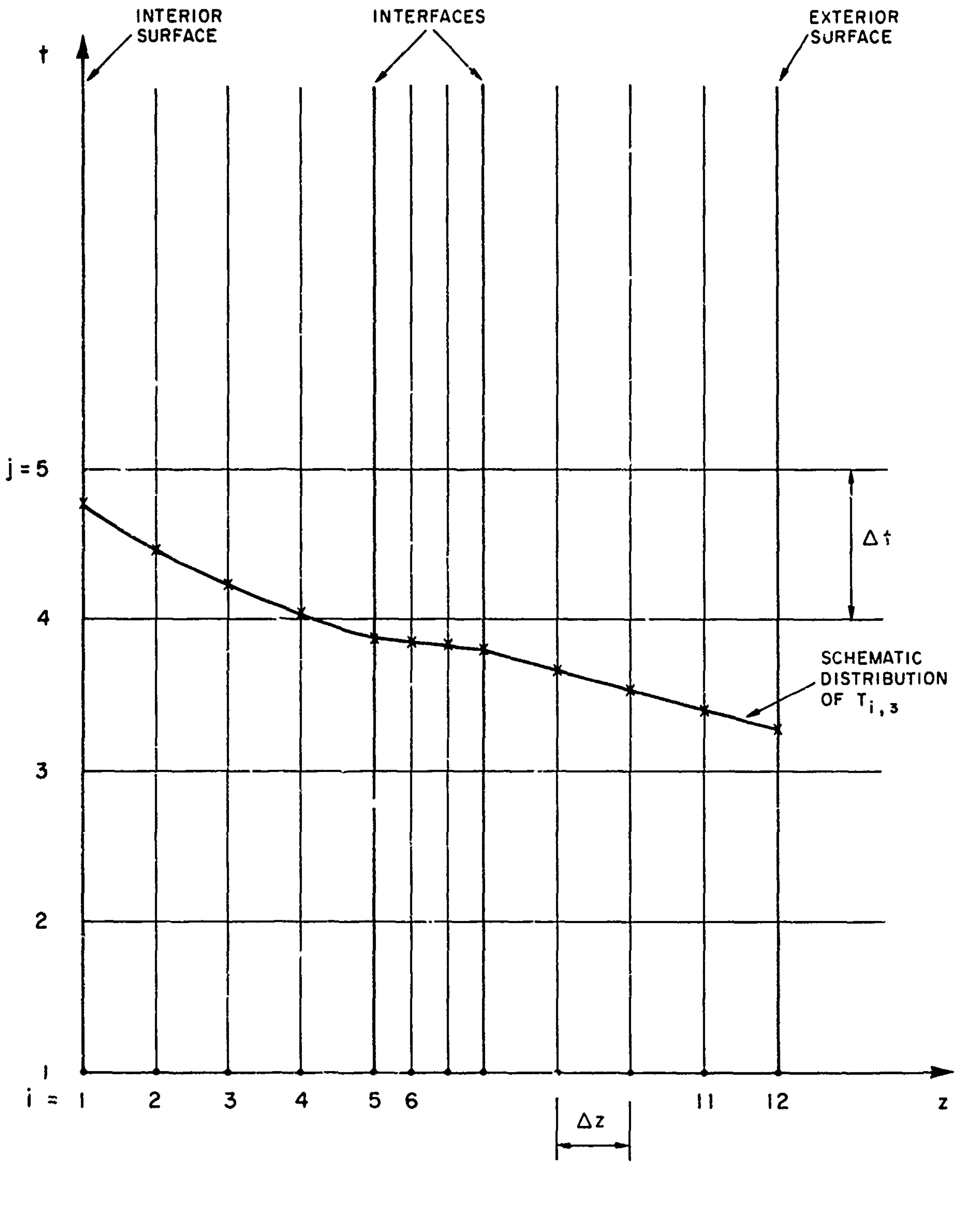


FIG. B-1 : TYPICAL GRID FOR FINITE DIFFERENCE APPROXIMATION TO WINDSHIELD/BACKLIGHT TEMPERATURE DISTRIBUTION

APPENDIX C

PROGRAM SOURCE LISTING

```
C   NRC/NAE AUTOMOBILE DEFOG/DEFROST SYSTEM STUDY
C   HEAT AND MASS TRANSFER MODEL
C   MAIN PROGRAM VERSION 1 LEVEL 2  DECEMBER 1971 ERW
C   MODULE NAME=ADSYM
       DIMENSION AMAT(2,5),X(8),IOPT(5)
       COMMON/ONE/TO,RHUM,XO,SLHT,THETA,RFL,VCAR,TCO,TCMAX,TCINF,TAU,
      &HEFF,WJT,WJM,ZJET,VJET,SPREAD,NOCC/TWO/THK(5),DENS(5),SPHT(5),
      &COND(5),ALPHA(5),DZ(5),HRH(6),NDZ(5),NLAM,NIF,NGP/THREE/A(3,51),
      &TOLD(51),TNEW(51)
     2 READ(1,999,END=100)
       READ(1,997)DTIM,NSTEP,NX,(IOPT(I),I=1,5)
       READ(1,995)TO,RHUM,XO,SLHT,THETA,RFL,VCAR
       READ(1,995)TCO,TCMAX,TCINF,TAU,HEFF,WJT
       READ(1,992)NOCC,WJM
       READ(1,995)ZJET,VJET,SPREAD
       READ(1,990)NLAM
       READ(1,987)((AMAT(J,I),J=1,2),THK(I),DENS(I),SPHT(I),COND(I),
      &NDZ(I),I=1,NLAM)
       NIF=NLAM+1
       READ(1,995)(HRH(I),I=1,NIF)
       READ(1,995)(X(I),I=1,NX)
       CALL STEPS(DTIM)
       WRITE(3,985)
       WRITE(3,999)
       WRITE(3,982)TO,RHUM,XO,SLHT,THETA,RFL,VCAR
       WRITE(3,980)TCO,TCMAX,TCINF,TAU,HEFF,WJT
       WRITE(3,977)NOCC,WJM
       WRITE(3,975)ZJET,VJET,SPREAD
       WRITE(3,972)
       DO 5 I=1,NLAM
       WRITE(3,970)HRH(I)
       THKP=12.*THK(I)
     5 WRITE(3,967)I,(AMAT(J,I),J=1,2),THKP,NDZ(I),DENS(I),SPHT(I),
      &COND(I),ALPHA(I)
       WRITE(3,970)HRH(NIF)
       CALL DEWPNT(TO,RHUM,TD2,VMF2)
       CALL SETUP
       DO 15 I=1,NX
       WRITE(3,965)X(I)
       CALL EXTSS(I,X(I),TF2,HTC2,TCM2)
       TIM=0
       ISTEP=0
       KPRNT=IOPT(1)-1
       DO 7 J=1,NGP
     7 TNEW(J)=TO
    10 CALL EHSS(TIM,TC,TJET)
       CALL INTSS(TIM,TJET,VMF2,TCAR,VMFCAR)
       CALL IBLSS(IOPT(2),I,X(I),TIM,TJET,VMF2,TCAR,VMFCAR,TF1,VMF1,HTC1,
      &TCM1)
       CALL INSCON(TIM,DTIM,TF1,VMF1,HTC1,TCM1,KS1,WS1,HS1,M1)
       CALL EXSCON(TIM,DTIM,TF2,VMF2,HTC2,TCM2,KS2,WS2,HS2,M2)
       KPRNT=KPRNT+1
       IF(KPRNT.NE.IOPT(1)) GO TO 12
       WRITE(3,962)TIM,TNEW(1),KS1,TNEW(NGP),KS2
```

```
      KPRNT=0
   12 ISTEP=ISTEP+1
      IF(ISTEP.GT.NSTEP) GO TO 15
      TIM=TIM+DTIM
      CALL MODEQ(IOPT(3),TF1,HTC1,HS1,M1,TF2,HTC2,HS2,M2,I1,I2)
      CALL GE06(I1,I2,A,TNEW,TOLD)
      GO TO 10
   15 CONTINUE
      GO TO 2
  100 STOP
  999 FORMAT('JOB TITLE NOT EXCEEDING 56 CHARACTERS                      ')
  997 FORMAT(F10.5,7I5)
  995 FORMAT(8F10.5)
  992 FORMAT(I5,F10.5)
  990 FORMAT(I5)
  987 FORMAT(2A4,4F10.5,I5)
  985 FORMAT('1AUTOMOBILE DEFOG/DEFROST SYSTEM MODEL (ADSYM)')
  982 FORMAT('0EXTERIOR SUBSYSTEM PARAMETERS'/ 5X,'AMBIENT TEMPERATURE =
     &',F6.1,5X,'RELATIVE HUMIDITY =',F6.1,5X,'CHARACTERISTIC LENGTH OF
     &CAR =',F5.1/5X,'SLANT HEIGHT OF WINDSHIELD/BACKLIGHT =',F5.1,5X,'S
     &LOPE (DEG) =',F5.1,5X,'LENGTH OF ROOF =',F5.2,5X,'SPEED =',F6.1)
  980 FORMAT('0ENGINE AND HEATER SUBSYSTEM PARAMETERS'/5X,'INITIAL COOLA
     &NT TEMPERATURE =',F6.1,5X,'MAXIMUM COOLANT TEMPERATURE =',F6.1,5X,
     &'ASYMPTOTIC COOLANT TEMPERATURE =',F6.1/5X,'CHARACTERISTIC TIME ='
     &,F6.1,5X,'HEATER EFFECTIVENESS =',F5.2,5X,'MASS FLOW PARAMETER =',
     &F5.2)
  977 FORMAT('0INTERIOR SUBSYSTEM PARAMETERS'/5X,'NUMBER OF OCCUPANTS ='
     &,I3,5X,'EFFECTIVE MASS FLOW =',F7.1)
  975 FORMAT('0DEFROSTER JET SUBSYSTEM PARAMETERS'/5X,'SLOT WIDTH =',F5.
     &2,5X,'INITIAL JET VELOCITY =',F6.1,5X,'SPREAD =',F6.3)
  972 FORMAT('0WINDSHIELD/BACKLIGHT SUBSYSTEM PARAMETERS'/8X,'LAMINA',6X
     &'MATERIAL',5X,'THICKNESS',5X,'NUMBER OF',7X,'DENSITY',6X,'SPECIFIC
     &',2X,'CONDUCTIVITY',9X,'ALPHA',7X,'HEATING'/46X,'SUBLAMINAE',24X,'
     &HEAT',38X,'RATE')
  970 FORMAT(112X,F14.2)
  967 FORMAT(I14,6X,2A4 ,F14.3,I14,F14.2,2F14.3,F14.2)
  965 FORMAT('1PREDICTED SURFACE CONDITIONS AT',F5.1,' INCHES FROM BASE
     &OF WINDSHIELD/BACKLIGHT'/26X,'INTERIOR SURFACE',12X,'EXTERIOR SURF
     &ACE'/10X,'TIME',8X,'TEMPERATURE',4X,'STATE',8X,'TEMPERATURE',4X,'S
     &TATE')
  962 FORMAT(8X,F6.1,14X,F5.1,8X,I1,14X,F5.1,8X,I1)
      END
```

```
      SUBROUTINE STEPS(DTIM)
C  DETERMINES ALPHA FOR FINITE DIFFERENCE EQUATIONS
C  AND COMPUTES NUMBER OF GRID INTERVALS
C  MODULE NAME= ADSM1
      COMMON/TWO/THK(5),DENS(5),SPHT(5),COND(5),ALPHA(5),DZ(5),HRH(6),
     &NDZ(5),NLAM,NIF,NGP
      DO 2 I=1,NLAM
      THK(I)=.08333333*THK(I)
      IF(NDZ(I).NE.0) IS=I
    2 CONTINUE
      DT=DTIM*.2777778E-03
      DZ(IS)=THK(IS)/FLOAT(NDZ(IS))
      ALPHA(IS)=COND(IS)*DT/(SPHT(IS)*DENS(IS)*DZ(IS)*DZ(IS))
      NGP=1
      DO 7 I=1,NLAM
      IF(I.EQ.IS) GO TO 5
      CONST=SPHT(I)*DENS(I)
      CONST=COND(I)/CONST
      DZ(I)=SQRT(CONST*DT/ALPHA(IS))
      NDZ(I)=INT(THK(I)/DZ(I))
      IF(NDZ(I).LT.2) NDZ(I)=2
      IF(NDZ(I).GT.10) NDZ(I)=10
      DZ(I)=THK(I)/FLOAT(NDZ(I))
      ALPHA(I)=CONST*DT/(DZ(I)*DZ(I))
    5 NGP=NGP+NDZ(I)
    7 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE DEWPNT(T,RH,TD,VMF)
C   COMPUTES DEW POINT AND MASS FRACTION OF WATER VAPOUR IN MOIST AIR
C   FROM THE MAGNUS FORMULA. REFERENCE: IHVE HANDBOOK
C   MODULE NAME=ADSM2
      TC=.5555555*(T-32.)
      IF(T.LT.32.) GO TO 2
      PLG=7.5*TC/(237.6+TC)+.78571
      GO TO 5
    2 PLG=9.5*TC/(265.5+TC)+.78571
    5 PVS=10.**PLG
      PV=RH*PVS*.01
      PLG=ALOG10(PV)-.78571
      TD=237.3*PLG/(7.5-PLG)
      IF(TD.LT.0.) TD=265.5*PLG/(9.5-PLG)
      TD=TD*1.8+32.
      PAIR=1013.25-PV
      VMF=18.*PV
      VMF=VMF/(29.*PAIR+VMF)
      RETURN
      END
```

```
      SUBROUTINE SETUP
C  FORMS MATRIX OF COEFFICIENTS IN FINITE DIFFERENCE EQUATIONS
C  FOR WINDSHIELD/BACKLIGHT TEMPERATURE DISTRIBUTIONS
C  MODULE NAME=ADSM3
      COMMON/TWO/THK(5),DENS(5),SPHT(5),COND(5),ALPHA(5),DZ(5),HRH(6),
     &NDZ(5),NLAM,NIF,NGP/THREE/A(3,51),TOLD(51),TNEW(51)
      A(1,1)=0.
      A(3,1)=-ALPHA(1)
      I2=1
      DO 5 IL=1,NLAM
      I1=I2+1
      I2=I1+NDZ(IL)-2
      FA=1.+2.*ALPHA(IL)
      DO 2 I=I1,I2
      A(1,I)=-ALPHA(IL)
      A(2,I)=FA
    2 A(3,I)=A(1,I)
      I2=I2+1
      IF(IL.GE.NLAM) GO TO 7
      DZK=DZ(IL+1)*COND(IL)/(DZ(IL)*COND(IL+1))
      A(1,I2)=-ALPHA(IL)
      A(2,I2)=1.+ALPHA(IL)*(1.+DZK)
    5 A(3,I2)=-ALPHA(IL)*DZK
    7 A(1,I2)=-ALPHA(NLAM)
      A(3,I2)=0.
      RETURN
      END
```

```
      SUBROUTINE EXTSS(I,X,TF,HTC,TCM)
C   EXTERIOR SUBSYSTEM MODEL
C   COMPUTES HEAT AND MASS TRANSFER COEFFICIENTS ON EXTERNAL SURFACE OF
C   WINDSHIELD/BACKLIGHT UNDER SPECIFIED AMBIENT CONDITIONS
C   MODULE NAME=ADSM4
      COMMON/ONE/TO,RHUM,XO,SLHT,THETA,RFL,VCAR,TCO,TCMAX,TCINF,TAU,
     &HEFF,WJT,WJM,ZJET,VJET,SPREAD,NOCC
      IF(I.GT.1) GO TO 5
      TF=TO
      IF(TO.GE.25..AND.RHUM.GE.100.) GO TO 2
C**ESTABLISH CONSTANTS FOR ZERO PRECIPITATION OR DRY SNOW**
      GNU=.135E-03
      COND=.135E-01
      PR=.710
      FPR=EXP(.33*ALOG(PR))
      GO TO 7
C**ESTABLISH CONSTANTS FOR HEAVY RAINFALL**
    2 PI=3.141593
      TH=THETA*PI/180.
      CTH=COS(TH)
      PDOT=5.205
      GNU=.6930E-01
      RHO=62.57
      G=32.18*3600.
      COND=.345
      CONST=3.*GNU*PDOT/(G*RHO*SIN(TH))
      GO TO 10
    5 IF(TO.GT.25..AND.RHUM.GE.100.) GO TO 10
C**COMPUTE LOCAL HEAT AND MASS TRANSFER COEFFICIENTS FOR DRY CONDITIONS*
    7 XL=XO+.08333333*X
      RE=VCAR*XL/GNU
      FRE=EXP(.8*ALOG(RE))
      HTC=.0296*FPR*FRE/XL
      TCM=4.8*HTC
      RETURN
C**COMPUTE LOCAL HEAT TRANSFER COEFFICIENT IN HEAVY RAINFALL**
   10 XL=.08333333*(SLHT-X)
      H=EXP(.3333333*ALOG(CONST*(XL*CTH+.25*RFL)))
      HTC=COND/H
      TCM=0.
      RETURN
      END
```

```
      SUBROUTINE EHSS(TIM,TC,TJET)
C   ENGINE AND HEATER SUBSYSTEM MODEL
C   COMPUTES COOLANT AND DEFROSTER JET TEMPERATURES AT SPECIFIED TIME
C   MODULE NAME=ADSM5
      COMMON/ONE/TO,RHUM,XO,SLHT,THETA,RFL,VCAR,TCO,TCMAX,TCINF,TAU,
     &HEFF,WJT,WJM,ZJET,VJET,SPREAD,NOCC
      IF(TIM.GT.0.) GO TO 2
      TCLAST=0.
    2 IF(TCLAST.GE.TCMAX) GO TO 5
      TC=TCO+(TCINF-TCO)*(1.-EXP(-TIM/TAU))
      IF(TC.GT.TCMAX) TC=TCMAX
      TJET=HEFF*(TC-TO)+TO
      TCLAST=TC
      TJLAST=TJET
      RETURN
    5 TC=TCLAST
      TJET=TJLAST
      RETURN
      END
```

```
      SUBROUTINE INTSS(TIM,TJET,VMF2,TCAR,VMFCAR)
C   VEHICLE INTERIOR SUBSYSTEM MODEL
C   COMPUTES INTERIOR AIR TEMPERATURE AND MOISTURE CONTFNT AT SPECIFIED T
C   MODULE NAME=ADSM6
      COMMON/ONE/TO,RHUM,XO,SLHT,THETA,RFL,VCAR,TCO,TCMAX,TCINF,TAU,
     &HEFF,WJT,WJM,ZJET,VJET,SPREAD,NOCC
      IF(TIM.GT.0.) GO TO 2
      GOCC=10.
      IF(RHUM.LT.100.) GOCC=0.
      ANO=FLOAT(NOCC)
    2 TCAR=TO+WJT*(TJET-TO)
      CALL DEWPNT(TCAR,100.,TD,VMFSAT)
      VMFCAR=VMF2+ANO*(.16+GOCC*(VMFSAT-VMF2))/(WJM+ANO*GOCC)
      RETURN
      END
```

```
      SUBROUTINE IBLSS(IOPT,I,X,TIM,TJET,VMF2,TCAR,VMFCAR,TF1,VMF1,HTC,
     &TCM)
C  INTERIOR BOUNDARY LAYER SUBSYSTEM MODEL
C  COMPUTES TEMPERATURE, MOISTURE CONTENT, LOCAL HEAT AND MASS
C  TRANSFER COEFFICIENTS FOR INTERIOR BOUNDARY LAYER
C  MODULE NAME=ADSM7
      COMMON/ONE/TO,RHUM,XO,SLHT,THETA,RFL,VCAR,TCO,TCMAX,TCINF,TAU,
     &HEFF,WJT,WJM,ZJET,VJET,SPREAD,NOCC/THREE/A(3,51),TOLD(51),TNEW(51)
      IF(IOPT.EQ.2) GO TO 7
C**ESTABLISH CONSTANTS FOR FORCED CONVECTION**
      IF(I.GT.1) GO TO 2
      A1=.5222E-06
      A2=-.4938E-09
      A2=-.71604E-09
      B1=.2544E-04
      B2=-.6172E-08
      ZEFF=ZJET*SPREAD*.08333333
      FZEFF=EXP(.325*ALOG(ZEFF))
    2 IF(TIM.GT.0.) GO TO 5
      XFT=.08333333*X
      XPRM=XFT+6.666667*ZEFF
      FXPRM=EXP(-ALOG(XPRM))
      DECF=SQRT(1.6/(1.+.15*XFT/ZEFF))
      IF(DECF.GT.1.) DECF=1.
C**COMPUTE HEAT AND MASS TRANSFER COEFFICIENTS FOR FORCED CONVECTION**
    5 FTJ1=TJET+10.
      FTJ2=FTJ1*(TJET-80.)
      GNU=.1288E-03+A1*FTJ1+A2*FTJ2
      COND=.1287E-01+B1*FTJ1+B2*FTJ2
      TF1=TCAR+DECF*(TJET-TCAR)
      VMF1=VMFCAR+DECF*(VMF2-VMFCAR)
      HTC=.36*COND*EXP(.65*ALOG(VJET/GNU))*FZEFF*FXPRM
      TCM=4.8*HTC
      RETURN
C**COMPUTE HEAT AND MASS TRANSFER COEFFICIENTS FOR FREE CONVECTION**
    7 TF1=TCAR
      VMF1=VMFCAR
      TDIFF=ABS(TCAR-TNEW(1))
      IF(TDIFF) 10,10,12
   10 HTC=0.
      GO TO 15
   12 HTC=.205*EXP(.33*ALOG(TDIFF))
   15 CALL DEWPNT(TNEW(1),100.,TD,VMFSAT)
      VDIFF=ABS(VMFCAB-VMFSAT)
      IF(VDIFF) 17,17,20
   17 TCM=0.
      RETURN
   20 TCM=6.6*EXP(.33*ALOG(VDIFF))
      RETURN
      END
```

```
      SUBROUTINE INSCON(TIM,DTIM,TF,VMF,HTC,TCM,KS,WS,HS,MELT)
C  DETERMINES INTERIOR SURFACE CONDITION OF WINDSHIELD/BACKLIGHT
C  AND COMPUTES TOTAL SURFACE HEATING RATE FOR NEXT STEP
C  MODULE NAME=ADSM8
      COMMON/ONE/TO,RHUM,XO,SLHT,THETA,RFL,VCAR,TCO,TCMAX,TCINF,TAU,
     &HEFF,WJT,WJM,ZJET,VJET,SPREAD,NOCC/TWO/THK(5),DENS(5),SPHT(5),
     &COND(5),ALPHA(5),DZ(5),HRH(6),NDZ(5),NLAM,NIF,NGP/THREE/A(3,51),
     &TOLD(51),TNEW(51)
      IF(TIM.GT.0.) GO TO 5
      DT=DTIM*.2777778E-03
      CDZ=COND(1)/DZ(1)
      ADC=ALPHA(1)/CDZ
C**INITIALIZE SURFACE CONDITION**
      MELT=0
      KS=1
      WS=0.
      GO TO 10
C**DETERMINE CURRENT SURFACE CONDITION**
    5 IF(WS.GT.0.) GO TO 7
      KS=1
      GO TO 10
    7 KS=2
      IF(TNEW(1).LE.32.) KS=3
C**COMPUTE TOTAL HEAT AND MASS TRANSFER DURING NEXT STEP**
   10 CALL DEWPNT(TNEW(1),100.,TDP,VMFSAT)
      DWS=TCM*(VMF-VMFSAT)
      IF(DWS)12,15,15
   12 IF(WS.LE.0.) DWS=0.
   15 WS=WS+DWS*DT
      IF(TNEW(1)-32.)17,17,20
   17 HS=HRH(1)+DWS*1204.1
      GO TO 22
   20 HS=HRH(1)+DWS*1060.61
   22 IF(KS.NE.3) RETURN
C**TEST FOR OCCURRENCE OF MELTING DURING NEXT STEP**
      IF(MELT.GT.0) GO TO 25
      TNEXT=ADC*(HTC*TF+HS)+(1.-ALPHA(1)-HTC*ADC)*TNEW(1)+ALPHA(1)*
     &TNEW(2)
      IF(TNEXT.LT.32.) RETURN
C**COMPUTE MELTING RATE AND TEST FOR COMPLETION**
      MELT=1
      HMSUM=0.
      DTM=DT*(TNEXT-32.)/(TNEXT-TNEW(1))
      GO TO 27
   25 DTM=DT
   27 HMSUM=HMSUM+DTM*(CDZ*(TNEW(2)-TNEW(1))+HTC*(TF-TNEW(1))+HS)
      HMREQ=143.49*WS
      DEF=HMREQ-HMSUM
      IF(DEF)30,30,32
   30 MELT=0
      HS=-DEF/DT
   32 RETURN
      END
```

```
      SUBROUTINE EXSCON(TIM,DTIM,TF,VMF,HTC,TCM,KS,WS,HS,MELT)
C  DETERMINES EXTERIOR SURFACE CONDITION OF WINDSHIELD/BACKLIGHT
C  AND COMPUTES TOTAL SURFACE HEATING RATE FOR NEXT STEP
C  MODULE NAME=ADSM9
      COMMON/ONE/TO,RHUM,XO,SLHT,THETA,RFL,VCAR,TCO,TCMAX,TCINF,TAU,
     &HEFF,WJT,WJM,ZJET,VJET,SPREAD,NOCC/TWO/THK(5),DENS(5),SPHT(5),
     &COND(5),ALPHA(5),DZ(5),HRH(6),NDZ(5),NLAM,NIF,NGP/THREE/A(3,51),
     &TOLD(51),TNEW(51)
      IF(TIM.GT.0.) GO TO 5
      DT=DTIM*.2777778E-03
      CDZ=COND(NLAM)/DZ(NLAM)
      ADC=ALPHA(NLAM)/CDZ
C**INITIALIZE SURFACE CONDITION**
      MELT=0
      IF(RHUM.GE.100.) GO TO 2
      KS=1
      WS=0.
      GO TO 10
    2 KS=2
      WS=.09
      IF(TO.LT.32.) KS=3
      GO TO 10
C**DETERMINE CURRENT SURFACE CONDITION**
    5 IF(WS.GT.0.) GO TO 7
      KS=1
      GO TO 10
    7 KS=2
      IF(TNEW(NGP).LE.32.) KS=3
C**COMPUTE TOTAL HEAT AND MASS TRANSFER DURING NEXT STEP**
   10 CALL DEWPNT(TNEW(NGP),100.,TDP,VMFSAT)
      DWS=TCM*(VMF-VMFSAT)
      IF(DWS) 12,15,15
   12 IF(WS.LE.0.) DWS=0.
   15 WS=WS+DWS*DT
      IF(TNEW(NGP)-32.)17,17,20
   17 HS=HRH(NIF)+DWS*1204.1
      GO TO 22
   20 HS=HRH(NIF)+DWS*1060.61
   22 IF(KS.NE.3) RETURN
C**TEST FOR OCCURRENCE OF MELTING DURING NEXT STEP**
      IF(MELT.GT.0) GO TO 25
      TNEXT=ADC*(HTC*TF+HS)+(1.-ALPHA(NLAM)-HTC*ADC)*TNEW(NGP)+
     &ALPHA(NLAM)*TNEW(NGP-1)
      IF(TNEXT.LT.32.) RETURN
C**COMPUTE MELTING RATE AND TEST FOR COMPLETION**
      MELT=1
      HMSUM=0.
      DTM=DT*(TNEXT-32.)/(TNEXT-TNEW(NGP))
      GO TO 27
   25 DTM=DT
   27 HMSUM=HMSUM+DTM*(CDZ*(TNEW(NGP-1)-TNEW(NGP))+HTC*(TF-TNEW(NGP))+
     &HS)
      HMREQ=143.49*WS
      DEF=HMREQ-HMSUM
```

```
      IF(DEF)30,30,32
   30 MELT=0
      HS=-DEF/DT
   32 RETURN
      END
```

```
      SUBROUTINE MODEQ(K,TF1,HTC1,HS1,M1,TF2,HTC2,HS2,M2,I1,I2)
C     MODIFIES FINITE DIFFERENCE EQUATIONS TO INCLUDE CURRENT VALUES
C     OF TIME DEPENDENT QUANTITIES
C     MODULE NAME=ADSM10
      COMMON/TWO/THK(5),DENS(5),SPHT(5),COND(5),ALPHA(5),DZ(5),HRH(6),
     &NDZ(5),NLAM,NIF,NGP/THREE/A(3,51),TOLD(51),TNEW(51)
      DO 2 I=1,NGP
    2 TOLD(I)=TNEW(I)
      IF(M1.GT.0) GO TO 5
      I1=1
      A(2,1)=1.+ALPHA(1)*(1.+HTC1*DZ(1)/COND(1))
      TOLD(1)=TOLD(1)+ALPHA(1)*DZ(1)/COND(1)*(HTC1*TF1+HS1)
      GO TO 7
    5 I1=2
      TNEW(1)=32.
      TOLD(I1)=TOLD(I1)-A(1,I1)*32.
    7 IF(K.EQ.0) GO TO 12
      II=1
      DO 10 I=1,NLAM
      II=II+NDZ(I)
      TOLD(II)=TOLD(II)+HRH(I+1)*ALPHA(I)*DZ(I)/COND(I)
   10 CONTINUE
   12 IF(M2.GT.0) GO TO 15
      I2=NGP
      A(2,NGP)=1.+ALPHA(NLAM)*(1.+HTC2*DZ(NLAM)/COND(NLAM))
      TOLD(NGP)=TOLD(NGP)+ALPHA(NLAM)*DZ(NLAM)/COND(NLAM)*(HTC2*TF2+HS2)
      RETURN
   15 I2=NGP-1
      TNEW(NGP)=32.
      TOLD(I2)=TOLD(I2)-A(3,I2)*32.
      RETURN
      END
```

```
      SUBROUTINE GE06(I1,I2,A,X,Y)
C   SOLVES A SET OF THREE-TERM LINEAR EQUATIONS USING GAUSSIAN
C   ELIMINATION AND BACK SUBSTITUTION
C   REFERENCE: APPLIED NUMERICAL METHODS - CARNAHAN ET ALIAE
C   MODULE NAME=GPS04
      DIMENSION A(3,51),X(51),Y(51),BETA(51),GAMMA(51)
      BETA(I1)=A(2,I1)
      GAMMA(I1)=Y(I1)/BETA(I1)
      I11=I1+1
      DO 2 I=I11,I2
      BETA(I)=A(2,I)-A(1,I)*A(3,I-1)/BETA(I-1)
    2 GAMMA(I)=(Y(I)-A(1,I)*GAMMA(I-1))/BETA(I)
      X(I2)=GAMMA(I2)
      L=I2-I1
      DO 5 K=1,L
      I=I2-K
    5 X(I)=GAMMA(I)-A(3,I)*X(I+1)/BETA(I)
      RETURN
      END
```