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THERMOD, an Enhanced Thermal Model for Determining Aircraft Operational Temperatures: User's Manual

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Final Report

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Nathan Govindarajoo, Ph.D, PE.	
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16. Abstract

An enhanced version of a thermal analysis computer program called THERMOD has been developed for determining the maximum operating limit (MOL) temperatures of general aviation aircraft. This report is the second of two reports prepared in conjunction with this project. Enhancements included program debugging and corrections as well as development of an alternate implicit finite difference method, which is used in transient analysis. Numerical validation of THERMOD was undertaken with respect to the finite element methods. Good correlation was found. Experimental validation was also performed. The validated THERMOD can be used to determine the MOL temperatures of a typical aircraft that has a low wing.

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EXECUTIVE SUMMARY

Composite aircraft structural elements are unfavorably affected by an increase in their temperatures due to exposure to the thermal environment. For design purposes, the synergistic effects of extreme ambient temperatures and the accompanying solar radiation should be taken into consideration in determining the maximum operating limit (MOL) temperatures experienced by the structural elements. Allowable design properties of composite materials may then be generated based on these MOL temperatures. THERMOD is a computer model that was developed for determining the MOL temperatures for aircraft under various paint schemes. The selected low-wing geometry is best suited to general aviation aircraft.

In determining the MOL temperatures, THERMOD considers the effects of radiation, convection, and conduction. Radiation includes direct solar radiation, infrared sky radiation, and their reflections from the tarmac. Infrared emission from the surrounding structures, including the tarmac, wings, fuselage, and its interaction among these structures, are also considered. Convection due to the wind, as well as turbulent convection within the cabin is also simulated, as are one-dimensional conduction through element thickness. The model incorporates the effect of fillets at the wing-fuselage junction. Due consideration is also given to the greenhouse effect within the cabin, which allows for a realistic modeling of the thermal environment within the cabin. The effect of shade underneath the wing is also modeled.

The soaked temperatures of an aircraft are predicted based on steady-state assumptions, giving conservative steady-state temperatures. Because limit loads generally occur in flight conditions, a transient (unsteady-state) thermal analysis is used to simulate the thermal conditions while the aircraft executes the following maneuvers: taxi, takeoff, climb and cruise. These maneuvers are cooling effects which, in addition to intentional cooling of the cabin through opening the door, simulate a more realistic thermal environment for predicting the MOL temperature.

THERMOD formulates a total of 67 independent equations within a nonlinear system of equations. The nonlinearity is introduced through radiation effects and through convective properties with the cabin, which are modeled as temperature dependent. The system of equations is solved using the Newton-Raphson iteration technique.

This report, the fourth of four reports prepared in conjunction with this project, will serve as an instructive guide for those who wish to use THERMOD for determining aircraft MOL temperatures.

1. INTRODUCTION.

An enhanced version of a thermal analysis computer program called THERMOD has been developed for simulating maximum operating limit (MOL) temperatures for general aviation aircraft.

This report, the fourth of four reports prepared in conjunction with this project, will serve as a guide for users who wish to use THERMOD for simulating aircraft MOL temperatures. The third report, "An Enhanced Thermal Model (THERMOD) for Determining Maximum Operating Temperatures" [1], provides additional technical details and analytical validations.

To help the user get acquainted with THERMOD, a brief background on pertinent thermal aspects of the program is presented. This is followed by a description of all aspects of the input data that are necessary for a successful execution of THERMOD.

2. A BRIEF DESCRIPTION OF THERMOD.

Composite aircraft structural elements are unfavorably affected by an increase in their temperatures due to exposure to the thermal environment. For design purposes, the combined effects of extreme ambient temperature and the accompanying solar radiation should be taken into consideration in determining the MOL temperatures experienced by the structural elements. Design properties of composite materials may then be generated based on these MOL temperatures. THERMOD was developed for determining the MOL temperatures of low-wing aircraft under various paint schemes.

In determining the MOL temperatures, THERMOD considers the effects of radiation, convection, and conduction. Radiation includes direct solar radiation, infrared sky radiation, and their reflections from the tarmac. Infrared emission from the surrounding structures, including the tarmac, wings and the fuselage and its interaction among these structures, are also considered. Convection due to the wind as well as turbulent convection within the cabin, is also simulated, as are one-dimensional conduction through element thickness. The model incorporates the effect of fillets at the wing-fuselage junction. Due consideration is also given to the greenhouse effect within the cabin that allows for a realistic modeling of the thermal environment within the cabin. The effect of shade underneath the wing is also modeled.

In addition to the above factors, the following assumptions are made in THERMOD: (1) nonparticipating medium (air); (2) discretized space and time domains; (3) discretized elements being isothermal, opaque, diffuse, gray and characterized by uniform radiosity, irradiation and material properties; (4) nonopaque materials such as windows and windshields are considered transparent with associated transmissivity values; and (5) constant material properties with respect to time (and hence temperature). These assumptions are necessary in simplifying the complexities involved in a three-dimensional thermal problem being addressed.

The soaked temperatures of an aircraft are predicted based on steady-state assumptions, giving conservative steady-state temperatures. Because limit loads generally occur in flight conditions, a transient (unsteady-state) thermal analysis is used to simulate the thermal conditions while the aircraft executes the following maneuvers: taxi, takeoff, climb, and cruise. These maneuvers are cooling effects that, in addition to intentional cooling of the cabin through opening the door, simulate realistic thermal environment for predicting the MOL temperature.

THERMOD formulates a total of 67 independent equations within a nonlinear system of equations. The non-linearity is introduced through radiation effects and through convective properties with the cabin, which are modeled as temperature-dependent. This system of equations is solved using the Newton-Raphson iteration technique [3].

As previously noted, THERMOD considers all three heat transfer mechanisms normally associated with an aircraft parked in the open: convection, conduction, and radiation. Figure 1 is a schematic representation of this thermal environment showing short wavelength solar radiation, long wavelength sky (infrared) radiation, convective heat transfer due to the wind, and one-dimensional conduction (through the thickness). Also considered are reflected solar energy between the fuselage and wing, diffused solar energy reflected from the tarmac, and infrared reflections. The fillets and greenhouse effects are considered as well. Because THERMOD simulates a total of 67 independent equations, 67 unknowns are needed. These unknowns are 53 temperatures and 14 radiosity functions. These 53 temperatures and their locations are noted in figure 1.

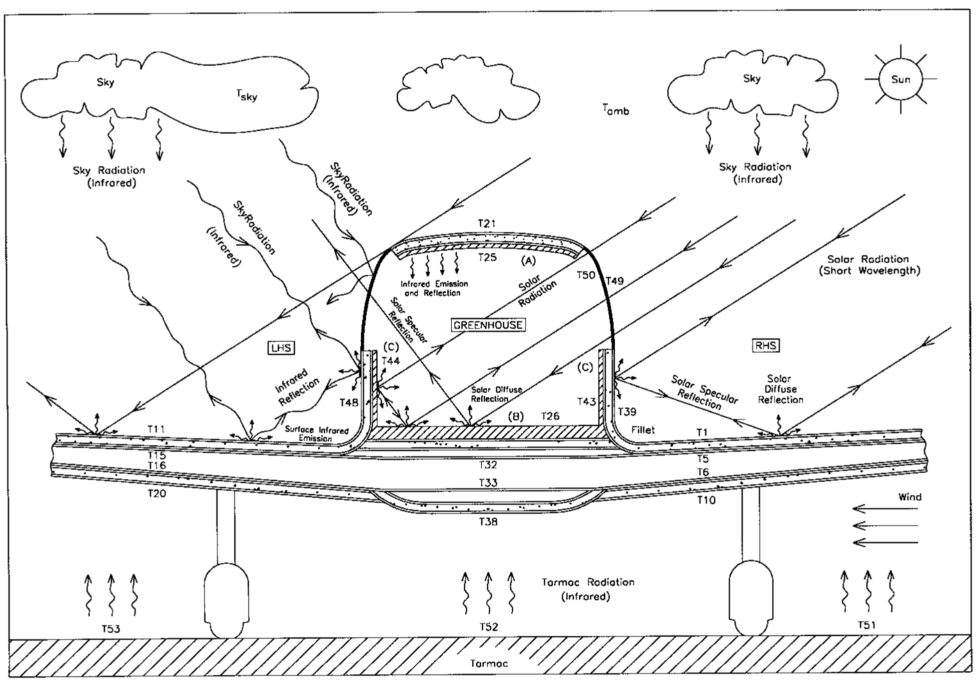

FIGURE 1. A SCHEMATIC PRESENTATION OF THERMOD

Note that not all the unknown temperatures are shown. T2, for example, is located immediately below T1 at the skin-core interface (see figure 2 for further clarity). Similarly, T27 is located immediately below T26 at the insulatory material B-composite floor interface.

The geometry of the aircraft shown is low wing with sandwich construction for skins. The sandwich can be either foam or honeycomb. Nonsandwich skins are also admissible if the thickness of the core is assumed to be very small.

A typical THERMOD analysis begins at the steady-state phase and continues on to the transient phase; a phase in which cooling is introduced due to aircraft maneuvers. At the point of application of limit or gust load, the temperatures at all 53 locations are noted. Of these 53 temperatures, 9 temperatures are considered nonstructural. These nonstructural temperatures are the three tarmac temperatures (T51, T52, and T53); four insulatory material temperatures (T25, T26, T43, and T44); and two transparent material temperatures (T49 and T50), leaving 44 temperatures that are structural.

THERMOD repeats its analysis over different time periods, as requested. The maximum temperature over these time periods is then reported as the MOL temperature. This MOL temperature may be located at the surface (depending on how dark the paint is), inside the cabin, within the floor space, or located anywhere else in the aircraft.

3. THERMOD GEOMETRY AND INPUT DATA.

Figure 1 shows a typical cross section of a small general aviation aircraft. A simplified rendering of the model is shown in figure 2. Fuselage is modeled as a box and treated as an enclosure in modeling the greenhouse effect. The fuselage roof is treated as a surface with an equivalent transmissivity, allowing solar radiation to enter the cabin. The insulatory materials (A), (B), and (C) are simplified representations of cabin roof interior, cabin floor, and cabin side interior. THERMOD is built on this simplified model. Figure 2 also shows typical sections at critical locations. In addition to the overall geometry as indicated in figure 2, a set of input data characterizing each layer, as shown in figure 3, is also needed. A total of 28 distinct layers are considered. Each of these layers, marked P_1 to P_{28}, is assigned four properties, i.e., thickness, density, thermal conductivity, and specific heat capacity. The wing, fuselage, and the interior (B) and (C) surfaces are assigned scatter factors (*sf*). The aircraft is subjected to climatic factors that include solar radiation (Q_{sol}), wind (V_{wind}), ambient temperature (T_{amb}), and sky temperature (T_{sky}). The layer properties include thickness, density, thermal conductivity, and specific heat capacity. To consider surface effects, all exposed aircraft surfaces are assigned their respective absorptivity and emissivity values. These values are dependent on paint color and surface texture. The tarmac is also considered a surface, whose surface and other thermal properties are required as well. THERMOD models the greenhouse and fillet effects. Transmissivity and fillet color information is needed to consider these two effects. The degree of greenhouse effect is also dependent on the percentage of transparent material. This information is input in the form of transparent surface area in relation to the overall cabin surface area. To simulate convective coefficients, the kinematic viscosity and Prandtl number are needed. Because the aircraft is left in the open, it is subjected to the environment. The climatic data of the environment, for each time period, include ambient temperature, sky temperature, solar radiation, and wind speed.

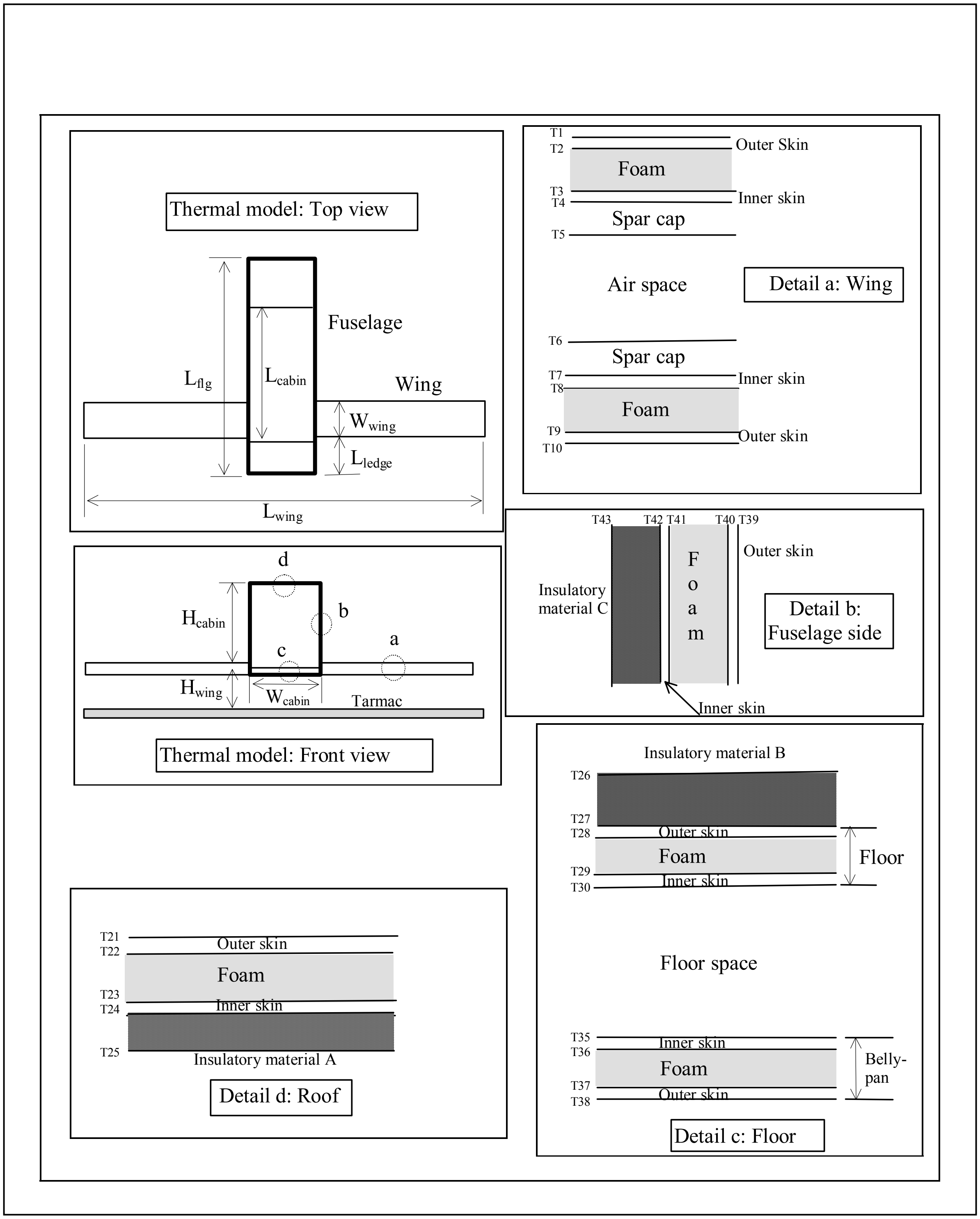

FIGURE 2. OVERALL MODEL GEOMETRY AND TYPICAL TEMPERATURE PROFILES AT CRITICAL LOCATIONS

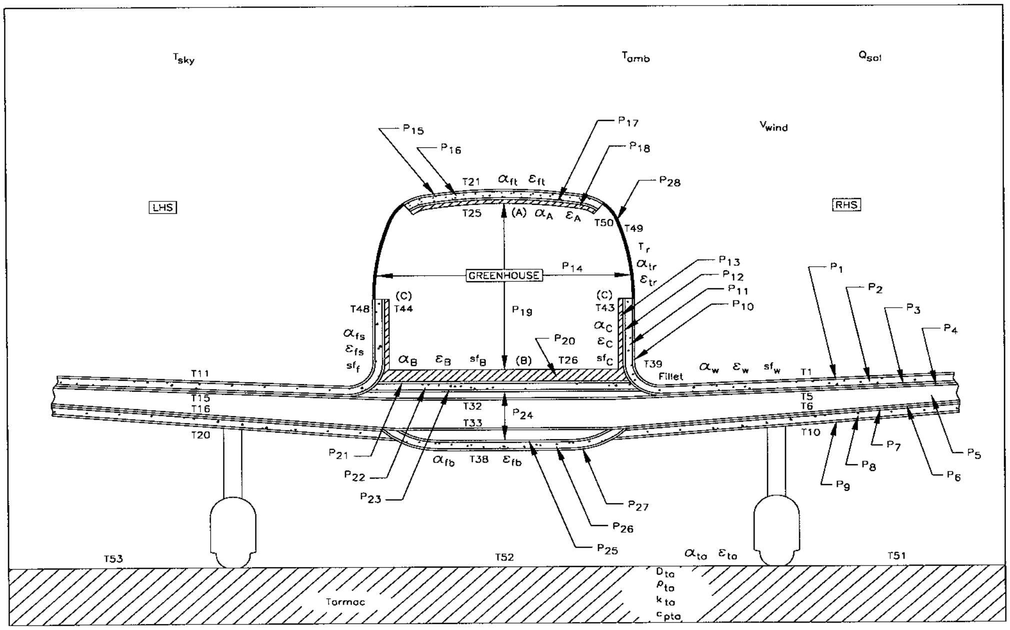

FIGURE 3. INPUT THERMAL PROPERTIES FOR THERMOD MODEL

The final piece of information concerns cooling that takes place when the aircraft executes the following maneuvers: taxi, takeoff, climb and cruise. These data are furnished through a flight profile that is unique to a particular aircraft. The flight profile provides information on typical aircraft maneuvering speed with respect to time, from which time-varying convective coefficient is determined. This coefficient is then used in a subsequent transient cooling process. An example of a flight profile is shown in figure 4.

Cooling is assumed to occur as soon as the door is opened. The greenhouse cooling duration is a function of the soaked steady state ambient temperature of the cabin and of tolerable ambient temperature desired before closing the door. This tolerable temperature, arbitrarily selected, is input into THERMOD as *ambcabt*. MOL temperature is determined at the point when limit load is applied as shown. This moment in time is located at 395 seconds from point V_0 in the above sample flight profile. The ambient wind speed is added to the flight speed to give the total relative wind speed. THERMOD uses this relative wind speed at selected time to determine convective coefficient, which is a required input in the cooling process.

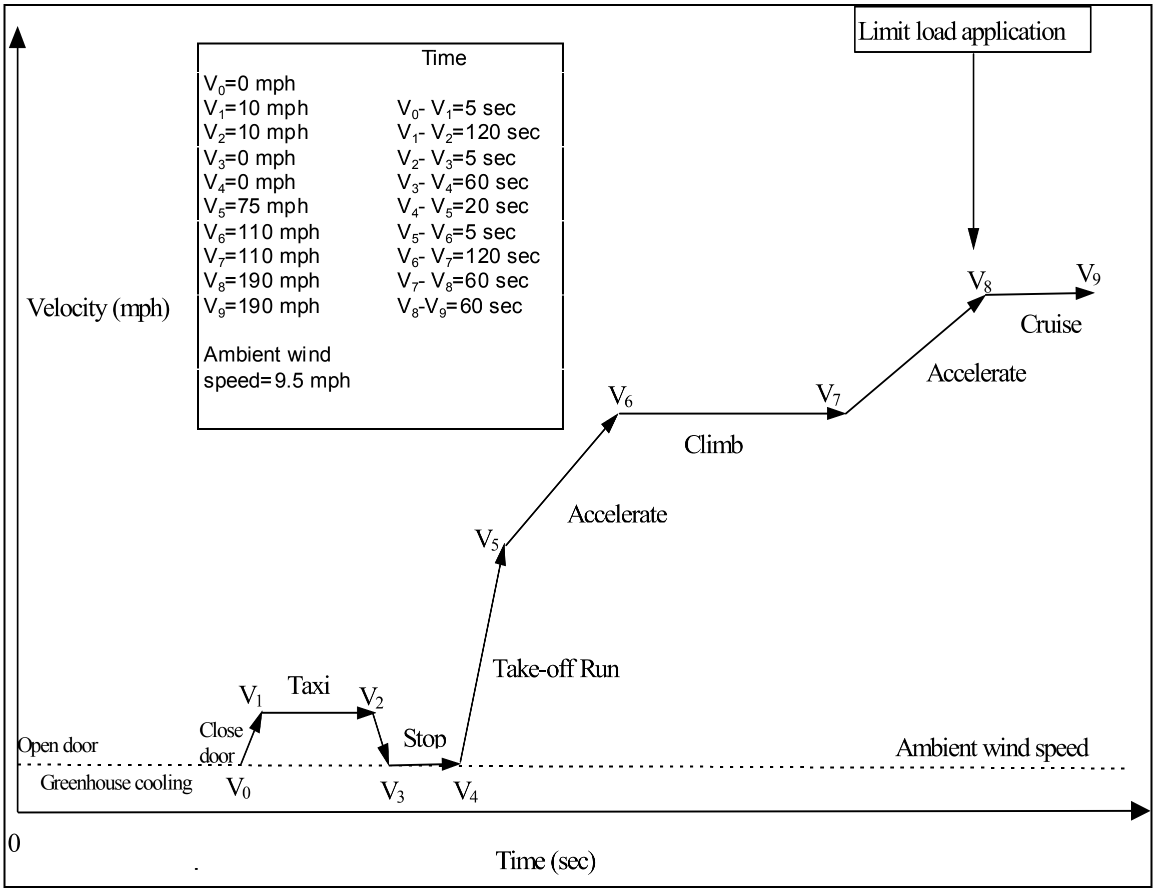

FIGURE 4. A TYPICAL FLIGHT PROFILE DURING TRANSIENT COOLING

4. THERMOD INPUT AND OUTPUT FILES.

THERMOD requires one input file, which is named input.dat and is shown in figure 5. This information is for demonstration purposes only. It is not part of the input file. Fifteen data sets are required to completely define the input file. Some sets have subsets as indicated. For example, 28 subsets define data set 2. Data set 2 must always have 28 subsets. On the other hand, data set 12 may have a minimum of two subsets (data set 12-1 and data set 12-2) or as many as indicated by the entry in data set 12-1. A comma or a space must separate each entry in a data set. Once invoked (by double-clicking THERMOD), THERMOD automatically reads in the input.dat file and reads out two output files: summary.dat and transient.dat. The summary.dat file summarizes the temperature results and prints the maximum operating temperatures for steady state and transient state, as shown in figure 6. This file summarizes the analytical results generated by THERMOD. Both the steady-state and transient state results are presented. Results are shown for all seven periods in the example problem. The maximum operating limit temperature is found at the end of transient analysis and it is 178.18 °F, occurring at location T24 and at period 3. The transient.dat file prints the transient temperatures with respect to time and is shown in figure 7. This file prints the transient temperature results for all periods analyzed. The truncated results are shown for five temperature locations and for period 1 only. This type of data can be used in studying the rate of cooling at various locations in the aircraft.

```
198e-6,0.704                                                  Data Set 1-1
1, 0.020,125,0.300,0.30                                       Data Set 2-1
2, 0.375,4.4,0.021,0.24                                       Data Set 2-2
3, 0.020,125,0.300,0.30                                       Data Set 2-3
4, 0.350,125,0.300,0.30                                       Data Set 2-4
5, 10.70,0.067,0.016,0.24                                     Data Set 2-5
6, 0.350,125,0.300,0.30                                       Data Set 2-6
7, 0.020,125,0.300,0.30                                       Data Set 2-8
8, 0.375,4.4,0.021,0.24                                       Data Set 2-9
9, 0.020,125,0.300,0.30                                       Data Set 2-10
10,0.030,125,0.300,0.30                                       Data Set 2-11
11,0.375,4.4,0.021,0.24                                       Data Set 2-12
12,0.020,125,0.300,0.30                                       Data Set 2-13
13,0.250,10.,0.020,0.24                                       Data Set 2-14
14,48.00,0.067,0.016,0.24                                     Data Set 2-15
15,0.020,125,0.300,0.30                                       Data Set 2-15
16,0.375,4.4,0.021,0.24                                       Data Set 2-16
17,0.020,125,0.300,0.30                                       Data Set 2-17
18,0.250,10.,0.020,0.24                                       Data Set 2-18
19,30.00,0.067,0.016,0.24                                     Data Set 2-19
20,5.000,10.,0.020,0.24                                       Data Set 2-20
21,0.020,125,0.300,0.30                                       Data Set 2-21
22,0.375,4.4,0.021,0.24                                       Data Set 2-22
23,0.020,125,0.300,0.30                                       Data Set 2-23
24,2.500,0.067,0.016,0.24                                     Data Set 2-24
25,0.020,125,0.300,0.30                                       Data Set 2-25
26,0.375,4.4,0.021,0.24                                       Data Set 2-26
27,0.020,125,0.300,0.30                                       Data Set 2-27
28,0.250,130,0.800,0.20                                       Data Set 2-28
3.5,34.0,2.5,5.5,2.2,1.1,0.3,4.0,30,24,28                     Data Set 3-1
0.70,1.0,0.999,2.0,150,0.80,0.22                              Data Set 4-1
0.3,0.9,0.3,0.9,0.3,0.9,0.1,0.9                               Data Set 5-1
3,100                                                         Data Set 6-1
0.9,0.9,0.0,0.0                                               Data Set 7-1
1.0,0.0,0.9,0.9,1.0,0.0,1.0,0.0                               Data Set 8-1
9                                                             Data Set 9-1
0,10,10,0,0,75,110,110,190,190                                Data Set 10-1
5,120,5,60,20,5,120,60,60                                     Data Set 11-1
7                                                             Data Set 12-1
60 570.67 459.67 14 330 10 10 0.36                            Data Set 12-2
75 573.67 459.67 14 355 10 10 0.31                            Data Set 12-3
90 578.67 459.67 14 355 10 12 0.33                            Data Set 12-4
75 581.67 459.67 14 330 10 10 0.31                            Data Set 12-5
60 582.67 459.67 14 291 10 10 0.36                            Data Set 12-6
45 583.67 459.67 14 231 10 10 0.44                            Data Set 12-7
30 582.67 459.67 14 160 10 10 0.57                            Data Set 12-8
1,100,180,1                                                   Data Set 13-1
10,1.0,1.0                                                    Data Set 14-1
10,10,10,10,10,10,10,10,10,10,10,10,10,10,10,                 Data Set 15-1
10,10,10,10,10,10,10,10,10,10,10,10,10,10,10,                 Data Set 15-2
10,10,10,10,10,10,10,10,10,10,10,10,10,10,10,                 Data Set 15-3
10,10,10,10,10,10,10,10,10,10,10,10,10,10,10,                 Data Set 15-4
10,10,10,10,10,10,10                                          Data Set 15-5
```

FIGURE 5. A SAMPLE INPUT FILE: input.dat

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
THERMOD:  A THERMAL PROGRAM FOR AIRCRAFTS
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$



SUMMARY OF STEADY-STATE AND TRANSIENT ANALYSIS



(Temperatures are shown for all time periods)


TEMPERATURES AT THE END OF STEADY STATE ANALYSIS

       TEMPERATURES IN DEGREES FAHRENHEIT
        1     2     3     4     5     6     7

  1 124.0 132.5 136.1 134.0 126.4 115.2 102.8
  2 124.0 132.5 136.1 134.0 126.4 115.2 102.8
  3 123.7 132.2 135.8 133.7 126.2 115.3 103.0
  4 123.7 132.2 135.8 133.7 126.2 115.3 103.0
  5 123.7 132.2 135.8 133.7 126.2 115.3 103.0
  6 114.4 120.2 124.7 124.6 121.1 116.3 110.5
  7 114.3 120.2 124.7 124.6 121.1 116.4 110.5
  8 114.3 120.2 124.7 124.6 121.1 116.4 110.5
  9 114.1 119.9 124.4 124.3 121.0 116.4 110.7
 10 114.1 119.9 124.4 124.3 121.0 116.4 110.7
 11 122.1 131.4 135.9 132.9 124.8 113.5 101.4
 12 122.1 131.4 135.9 132.9 124.8 113.5 101.4
 13 121.9 131.1 135.6 132.7 124.7 113.6 101.6
 14 121.9 131.1 135.6 132.7 124.7 113.6 101.6
 15 121.9 131.1 135.6 132.7 124.7 113.6 101.6
 16 114.3 120.2 124.7 124.6 121.1 116.3 110.5
 17 114.3 120.2 124.7 124.6 121.1 116.3 110.5
 18 114.3 120.2 124.7 124.6 121.1 116.3 110.5
 19 114.1 119.9 124.4 124.3 121.0 116.4 110.7
 20 114.1 119.9 124.4 124.3 121.0 116.4 110.7
 21 205.8 225.9 231.9 222.2 200.7 169.4 134.2
 22 205.8 225.8 231.8 222.1 200.7 169.5 134.2
 23 207.4 216.5 217.2 213.6 202.4 180.2 143.1
 24 207.4 216.4 217.2 213.6 202.4 180.2 143.1
 25 208.4 209.9 206.9 207.6 203.6 187.7 149.4
 26 198.9 198.2 195.5 196.8 195.4 183.4 146.2
 27 150.5 153.0 154.4 155.5 153.6 146.5 127.6
```

FIGURE 6. A SAMPLE OUTPUT FILE: summary.dat

28	150.4	153.0	154.4	155.4	153.6	146.5	127.6
29	147.0	149.8	151.5	152.5	150.6	143.9	126.3
30	147.0	149.8	151.5	152.5	150.6	143.9	126.3
31	131.8	135.6	138.7	139.6	137.5	132.4	120.5
32	131.8	135.6	138.7	139.6	137.5	132.4	120.5
33	131.8	135.6	138.7	139.6	137.5	132.4	120.5
34	131.8	135.6	138.7	139.6	137.5	132.4	120.5
35	116.7	121.5	125.8	126.6	124.5	120.8	114.7
36	116.7	121.5	125.8	126.6	124.4	120.8	114.7
37	113.2	118.3	122.9	123.7	121.5	118.2	113.3
38	113.2	118.3	122.9	123.7	121.4	118.2	113.3
39	199.5	179.7	148.8	180.0	196.6	194.7	173.9
40	199.5	179.7	148.9	180.1	196.6	194.6	173.9
41	197.6	186.6	168.7	186.2	194.5	188.4	162.3
42	197.6	186.6	168.8	186.2	194.5	188.4	162.3
43	196.2	191.4	182.7	190.5	193.1	184.1	154.2
44	191.8	188.5	182.6	187.8	189.2	180.4	151.1
45	169.9	170.8	168.7	171.5	170.2	161.4	138.9
46	169.8	170.7	168.7	171.5	170.0	161.3	138.8
47	138.6	145.3	148.8	148.2	142.9	134.1	121.3
48	138.4	145.2	148.7	148.0	142.7	133.9	121.2
49	145.6	148.6	149.7	150.4	147.7	139.7	123.0
50	147.6	150.5	151.3	152.1	149.5	141.3	123.9
51	113.6	120.8	125.1	123.7	118.1	110.0	100.6
52	108.2	115.1	119.2	118.0	112.7	105.1	96.2
53	113.6	120.8	125.1	123.7	118.1	110.0	100.6

Maximum Structural Temperature for Period 1 = 207.37 Occurring at Location 24
Maximum Structural Temperature for Period 2 = 225.86 Occurring at Location 21
Maximum Structural Temperature for Period 3 = 231.88 Occurring at Location 21
Maximum Structural Temperature for Period 4 = 222.15 Occurring at Location 21
Maximum Structural Temperature for Period 5 = 202.43 Occurring at Location 24
Maximum Structural Temperature for Period 6 = 194.68 Occurring at Location 39
Maximum Structural Temperature for Period 7 = 173.92 Occurring at Location 39

Maximum Structural Temperature Over All 7 Periods =231.88 Occurring at Location 21 at Period 3

FIGURE 6. A SAMPLE OUTPUT FILE: summary.dat (Continued)

TEMPERATURES AT THE END OF TRANSIENT ANALYSIS

TEMPERATURES IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7
1	112.0	115.6	120.5	123.0	123.2	123.1	121.1
2	112.3	116.0	120.9	123.3	123.3	122.9	120.6
3	122.6	130.8	134.5	132.8	126.1	115.7	104.5
4	122.9	131.3	135.0	133.0	126.2	115.4	104.0
5	123.2	131.6	135.3	133.3	126.2	115.3	103.6
6	114.4	120.2	124.7	124.6	121.1	116.3	111.0
7	114.3	120.1	124.6	124.6	121.2	116.5	111.3
8	114.3	120.0	124.5	124.6	121.3	116.7	111.6
9	112.2	115.7	120.7	123.2	123.5	123.5	121.7
10	112.1	115.6	120.6	123.2	123.5	123.7	122.0
11	112.0	115.5	120.5	123.0	123.2	123.1	121.1
12	112.2	116.0	120.9	123.2	123.2	122.8	120.6
13	121.3	129.8	134.3	132.1	124.6	114.1	103.2
14	121.5	130.3	134.8	132.4	124.7	113.8	102.7
15	121.8	130.6	135.1	132.7	124.7	113.6	102.2
16	114.3	120.2	124.7	124.6	121.1	116.3	110.9
17	114.3	120.1	124.6	124.6	121.2	116.5	111.2
18	114.2	120.0	124.5	124.5	121.3	116.7	111.5
19	112.2	115.7	120.7	123.2	123.5	123.5	121.7
20	112.1	115.6	120.6	123.2	123.5	123.7	122.0
21	121.5	126.7	131.9	133.3	131.6	128.9	124.2
22	123.1	128.2	133.4	134.7	132.8	129.9	124.6
23	169.8	175.0	176.9	175.1	169.9	160.9	137.9
24	171.3	176.5	178.2	176.3	171.1	162.0	138.4
25	177.8	179.5	178.8	178.5	176.0	169.0	142.7
26	171.4	171.6	171.2	171.5	170.8	166.5	141.6
27	150.7	153.2	154.6	155.6	153.8	146.7	127.7
28	149.6	152.2	153.8	154.8	152.9	145.9	127.4
29	146.9	149.7	151.5	152.5	150.7	143.9	126.3
30	146.9	149.6	151.5	152.5	150.6	143.9	126.3
31	131.8	135.3	138.5	139.7	138.1	133.6	122.4
32	131.8	135.3	138.5	139.7	138.1	133.6	122.4
33	131.8	135.3	138.5	139.7	138.1	133.6	122.4
34	131.8	135.3	138.5	139.7	138.1	133.6	122.4
35	116.8	121.1	125.5	127.0	125.7	123.4	118.5
36	116.7	120.9	125.3	126.9	125.6	123.4	118.5
37	111.9	115.3	120.3	122.9	123.4	123.6	121.9
38	111.8	115.1	120.1	122.8	123.3	123.6	122.0
39	117.4	119.2	122.0	126.5	128.2	128.6	125.9
40	118.8	120.4	123.0	127.6	129.3	129.7	126.5

FIGURE 6. A SAMPLE OUTPUT FILE: summary.dat (Continued)

```
  41 160.3 157.0 151.6 158.9 162.2 160.5 144.0
  42 161.6 158.3 152.7 160.0 163.3 161.5 144.5
  43 165.8 164.0 160.6 165.0 166.6 163.7 144.0
  44 164.7 163.1 160.6 164.2 165.6 163.1 143.6
  45 154.8 154.3 152.7 156.2 157.2 155.0 138.8
  46 153.4 153.1 151.6 155.2 156.1 154.0 138.4
  47 118.3 120.1 123.0 127.3 128.8 129.2 126.1
  48 117.1 119.0 122.0 126.4 127.9 128.4 125.7
  49 117.2 120.4 124.7 127.0 127.2 126.7 122.8
  50 119.7 122.7 126.8 129.0 129.1 128.3 123.5
  51 169.0 187.2 193.0 184.0 164.8 137.5 109.0
  52 157.9 174.6 180.0 172.0 154.5 129.7 103.8
  53 169.0 187.2 193.0 184.0 164.8 137.5 109.0
```

Maximum Structural Temperature for Period 1 = 171.35 Occurring at Location 24
Maximum Structural Temperature for Period 2 = 176.49 Occurring at Location 24
Maximum Structural Temperature for Period 3 = 178.18 Occurring at Location 24
Maximum Structural Temperature for Period 4 = 176.31 Occurring at Location 24
Maximum Structural Temperature for Period 5 = 171.07 Occurring at Location 24
Maximum Structural Temperature for Period 6 = 162.03 Occurring at Location 24
Maximum Structural Temperature for Period 7 = 144.54 Occurring at Location 42

Maximum Structural Temperature Over All 7 Periods =178.18 Occurring at Location 24 at Period 3

FIGURE 6. A SAMPLE OUTPUT FILE: summary.dat (Continued)

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
THERMOD:  A THERMAL PROGRAM FOR AIRCRAFTS
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$


TRANSIENT TEMPERATURES FOR PERIOD:           1

COOLING WHILE DOOR IS OPENED:

time(sec)      1     2     3     4     5
   0.0000   124.0 124.0 123.7 123.7 123.7
   2.0000   124.0 123.9 123.7 123.7 123.7
   4.0000   124.0 123.9 123.7 123.7 123.7
   6.0000   124.0 123.9 123.7 123.7 123.7
    .    .    .    .    .    .
    .    .    .    .    .    .
    .    .    .    .    .    .

COOLING DURING AIRCRAFT MANEUVERS:

time(sec)      1     2     3     4     5
  68.0000   123.9 123.9 123.7 123.7 123.7
  70.0000   123.9 123.9 123.7 123.7 123.7
  72.0000   123.9 123.9 123.7 123.7 123.7
  74.0000   123.8 123.8 123.7 123.7 123.7
  76.0000   123.7 123.8 123.7 123.7 123.7
  78.0000   123.6 123.7 123.7 123.7 123.7
  80.0000   123.6 123.6 123.7 123.7 123.7
    .    .    .    .    .
    .    .    .    .    .
```

FIGURE 7. A SAMPLE OUTPUT FILE: transient.dat

5. REFERENCES.

1. Govindarajoo, N., "An Enhanced Thermal Model for Determining Aircraft Operating Temperatures," FAA report DOT/FAA/AR-04/51, December 2004.

2. Press, W.H. et al., "Numerical Recipes in FORTRAN: The Art of Scientific Computing," Second edition, Cambridge Univ. Press, New York, NY. 1994.

APPENDIX A—INPUT DATA

A total of 15 data sets are required to define the input file. Some data sets have subsets, as indicated in figure 5, and all data input is in free-format. A comma or a space must separate each entry in a data set.

Figures A-1 through A-16 provide definitions of the variables involved in each data set. Data must be entered in the units indicated. Data format and input examples are given for each data set. Remarks at the end of each data set description provides further explanations on the variables involved in the set.

For those interested in learning the fundamentals of heat transfer and to have a more in-depth understanding of the principles involved in THERMOD, reference A-1 is recommended.

Data set 1-1 defines the air kinematic viscosity and Prandtl number.

ν = Air kinematic viscosity (ft^2/sec)
Pr = Prandtl number (dimensionless)

Format and Example:

1	2
ν	Pr

198E–6	0.704

Field	Contents	Data Type and Value
ν	Air kinematic viscosity (ft^2/sec)	Real > 0.0
Pr	Prandtl number (dimensionless)	Real > 0.0

Remarks:

1. A comma or a space must separate each entry in a row. Data input is in free-format.

2. Air kinematic viscosity and Prandtl number are used in automatic convective coefficient calculations. They are temperature-dependent to a degree. It is recommended that these properties be based on an anticipated average temperature.

Figure A-1. Data Entry for Data Set 1-1

Data set 2-1 to 2-28 defines geometric and material properties for each layer. These properties are thickness, density, thermal conductivity, and specific heat capacity.

t = Thickness (in.)
ρ = Density (lb/ft^3)
k = Thermal conductivity ((Btu/hr)/(ft °F))
c_p = Specific heat capacity (Btu/(lbm °F))

Format and Example:

1	2	3	4	5
Layer #	t	ρ	k	c_p
1	0.02	125.0	0.30	0.30

Field	Contents	Data Type and Value
Layer #	Layer number	Integer 1-28
t	Layer thickness (in.)	Real > 0.0
ρ	Layer density (lb/ft^3)	Real > 0.0
k	Layer thermal conductivity ((Btu/hr)/(ft °F))	Real > 0.0
c_p	Layer specific heat capacity (Btu/(lbm °F))	Real > 0.0

Figure A-2. Data Entry for Data Sets 2-1 to 2-28

Remarks:

1. A comma or a space must separate each entry in a row. Data input is in free-format.

2. There are a total of 28 layers in THERMOD. This indicates that there are a total of 28 rows of data to be input. All 28 rows must be present. Each row must have all five entries as indicated in the table above. If for some reason, a layer is not needed, the row otherwise representing this layer must still be filled with all five entries. However, the thermal effects of this layer are rendered ineffective by doing one of the following: (1) use a relatively small value for *t*, the layer thickness; (2) use a relatively high value for *k*, the layer thermal conductivity; or (3) carry out (1) and (2) simultaneously. A sensitivity study of sorts involving the thickness and thermal conductivity of the nonexistent layer in question could shed light on the satisfactory values of *t* and *k* to be used that will not affect the overall thermal behavior of the model. It should be noted, however, that too low a value for these two variables may cause numerical problems.

3. In some cases, a layer may actually be made of more than one material. In such instances, composite values should be used for the layer. The composite values are derived as follows, where n = number of materials within the layer in question.

$$t = \frac{1}{n}\sum_{i=1}^{n} t_i$$

$$k = \sum_{i=1}^{n} t_i \Bigg/ \sum_{i=1}^{n} \left(t_i / k_i\right)$$

$$\rho = \sum_{i=1}^{n} \left(\rho_i t_i\right) \Bigg/ \sum_{i=1}^{n} t_i$$

$$c_p = \sum_{i=1}^{n} \left(c_{p_i} t_i\right) \Bigg/ \sum_{i=1}^{n} t_i$$

4. The 28 layers must be entered in a sequential manner.

Figure A-2. Data Entry for Data Sets 2-1 to 2-28 (Continued)

Data set 3-1 defines the overall geometry of an aircraft. This includes the wing and fuselage dimensions and transparency areas such as windows and windshields. Refer figures 1, 2, and 3 for an understanding of the variables involved.

W_{wing} = Average width of the wing from the leading edge to the trailing edge (ft.)

L_{wing} = Length of the wing from tip to tip (ft.)

H_{wing} = Average height of the wing from the tarmac to its mid-depth when the plane is on the ground (ft.)

L_{ledge} = Average distance of the wing leading edge to the front of the fuselage (ft.)

L_{flg} = Overall fuelage length (ft.)

L_{cabin} = Cabin length (ft.)

H_{cabin} = Average cabin height (ft.)

W_{cabin} = Average cabin width (ft.)

A_1 = Total surface area of the transparencies in the cabin area (ft^2)

A_2 = Total surface area of the cabin top (ft^2)

A_3 = Total surface area of transparencies that intercept diffused solar rays reflected from the tarmac (ft^2)

Format and Example:

1	2	3	4	5	6	7	8	9	10	11
W_{wing}	L_{wing}	H_{wing}	L_{ledge}	L_{flg}	L_{cabin}	H_{cabin}	W_{cabin}	A_1	A_2	A_3
4.0	39.0	3.5	5.5	26.0	15.0	3.5	4.5	25.0	20.0	15.0

Figure A-3. Data Entry for Data Set 3-1

Field	Contents	Data Type and Value
W_{wing}	Average width of the wing from the leading edge to the trailing edge (ft.)	Real > 0.0
L_{wing}	Length of the wing from tip to tip (ft.)	Real > 0.0
H_{wing}	Average height of the wing from the tarmac to its mid-depth when the plane is on the ground (ft.)	Real > 0.0
L_{ledge}	Average distance of the wing leading edge to the front of the fuselage (ft.)	Real > 0.0
L_{flg}	Overall fuselage length (ft.)	Real > 0.0
L_{cabin}	Cabin length (ft.)	Real > 0.0
H_{cabin}	Average cabin height (ft.)	Real > 0.0
W_{cabin}	Average cabin width (ft.)	Real > 0.0
A_1	Total surface area of the transparencies in the cabin area (ft^2)	Real > 0.0
A_2	Total surface area of the cabin top (ft^2)	Real > 0.0
A_3	Total surface area of transparencies that intercept diffused solar rays reflected from the tarmac (ft^2)	Real > 0.0

Remarks:

1. A comma or a space must separate each entry in a row. Data input is in free-format.
2. THERMOD simplifies the complex thermal problem by approximating the fuselage as a box with the dimensions as indicated.
3. THERMOD simulates the green-house effect within the cabin. The areas A_1, A_2 and A_3 are needed to simulate this effect.
4. The distance of the fuselage and wing from the tarmac influences the radiation effects of the tarmac underneath these structures.
5. The wing width, wing length, distance of wing leading edge to the fuselage front, and the overall fuselage length are needed for simulating solar reflections as well as for simulating radiation effects within enclosures.

Figure A-3. Data Entry for Data Set 3-1 (Continued)

Data set 4-1 defines the transmissivity property of transparencies and the relevant tarmac thermal properties.

Tr = Transmissivity of transparencies (dimensionless)
α_{ta} = Tarmac absorptivity (dimensionless)
ε_{ta} = Tarmac emissivity (dimensionless)
D_{ta} = Tarmac depth (ft.)
ρ_{ta} = Tarmac density (lb/ft^3)
k_{ta} = Tarmac thermal conductivity ((Btu/hr)/(ft °F))
c_{pta} = Tarmac specific heat capacity (Btu/(lbm °F))

Format and Example:

1	2	3	4	5	6	7
Tr	α_{ta}	ε_{ta}	D_{ta}	ρ_{ta}	k_{ta}	c_{pta}
0.70	0.9	0.9	2.0	150	0.80	0.25

Field	Contents	Data Type and Value
Tr	Transmissivity of transparencies (dimensionless)	Real: 0.0-1.0
α_{ta}	Tarmac absorptivity (dimensionless)	Real: 0.0-1.0
ε_{ta}	Tarmac emissivity (dimensionless)	Real: 0.0-1.0
D_{ta}	Tarmac depth (ft.)	Real > 0.0
ρ_{ta}	Tarmac density (lb/ft^3)	Real > 0.0
k_{ta}	Tarmac thermal conductivity ((Btu/hr)/(ft°F))	Real > 0.0
c_{pta}	Tarmac specific heat capacity (Btu/(lbm°F))	Real > 0.0

Figure A-4. Data Entry for Data Set 4-1

Remarks:

1. A comma or a space must separate each entry in a row. Data input is in free-format.

2. THERMOD models the greenhouse effect within the cabin. The transmissivity of the transparent materials, including the windows and the windshields and the percentage of their areas, influence the amount of radiation that gets into the cabin. Only one transmissivity value is used for the entire cabin, even though a cabin may be made of transparencies with different transmissivity values. It is, therefore, essential to obtain one representative transmissivity value for the entire cabin. This value, based on a weighted average, is estimated as follows, where n = the number transparency surfaces and A_i = the area of each individual surface.

$$Tr = \frac{1}{\sum_{i=1}^{n} A_i} \sum_{i=1}^{n} A_i Tr_i$$

Figure A-4. Data Entry for Data Set 4-1 (Continued)

Data set 5-1 defines the absorptivity and emissivity properties within the cabin. A total of four surfaces are involved. Three of these surfaces are attributed to the symbolic insulatory materials (A), (B), and (C) as indicated in figures 1 and 2, where (A) = insulatory material below the cabin roof, (B) = insulatory material above the cabin floor, and (C) = insulatory material on the sides of the cabin. The fourth surface symbolically represents collective transparencies.

α_A = Absorptivity of material A (dimensionless)
ε_A = Emissivity of material A (dimensionless)
α_B = Absorptivity of material B (dimensionless)
ε_B = Emissivity of material B (dimensionless)
α_C = Absorptivity of material C (dimensionless)
ε_C = Emissivity of material C (dimensionless)
α_{tr} = Absorptivity of transparency (dimensionless)
ε_{tr} = Emissivity of transparency (dimensionless)

Format and Example:

1	2	3	4	5	6	7	8
α_A	ε_A	α_B	ε_B	α_C	ε_C	α_{tr}	ε_{tr}
0.50	0.90	0.60	0.95	0.45	0.85	0.10	0.90

Field	Contents	Data Type and Value
α_A	Absorptivity of material A (dimensionless)	Real: 0.0-1.0
ε_A	Emissivity of material A (dimensionless)	Real: 0.0-1.0
α_B	Absorptivity of material B (dimensionless)	Real: 0.0-1.0
ε_B	Emissivity of material B (dimensionless)	Real: 0.0-1.0

Figure A-5. Data Entry for Data Set 5-1

Field	Contents	Data Type and Value
α_C	Absorptivity of material C (dimensionless)	Real: 0.0-1.0
ε_C	Emissivity of material C (dimensionless)	Real: 0.0-1.0
α_{tr}	Absorptivity of transparency (dimensionless)	Real: 0.0-1.0
ε_{tr}	Emissivity of transparency (dimensionless)	Real: 0.0-1.0

Remarks:

1. A comma or a space must separate each entry in a row. Data input is in free-format.

2. THERMOD simulates the greenhouse effect within the cabin. The absorptivity and emissivity values of the cabin interior surfaces influence the greenhouse effect, and in turn the temperatures within the cabin, in a significant manner.

3. The cabin interior surfaces are symbolically represented by Materials A, B, and C as shown in figures 1 and 2. These surfaces are typically nonstructural in nature. However, their thermal properties have significant bearing on the resulting interior temperatures.

4. The absorptivity and emissivity values for these three surfaces are estimated averages. The values for each surface may be obtained by employing a weighting scheme that takes into consideration individual areas comprising the surface and the associated absorptivity and emissivity values, as shown below, where n = the number of surfaces within a material group and A_i = the area of each individual surface within the material group.

$$\alpha = \frac{1}{\sum_{i=1}^{n} A_i} \sum_{i=1}^{n} A_i \alpha_i \qquad \varepsilon = \frac{1}{\sum_{i=1}^{n} A_i} \sum_{i=1}^{n} A_i \varepsilon_i$$

5. The absorptivity and emissivity of the transparent materials, including the windows, windshields, and the percentage of their areas, influence the greenhouse effect within the cabin. Only one set of values is used for the entire cabin even though a cabin may be made of transparencies with different transmissivity values. It is, therefore, essential to obtain one representative set of absorptivity and emissivity values for the entire cabin. This value may be obtained in a fashion similar to calculations indicated in remark 4 above.

Figure A-5. Data Entry for Data Set 5-1 (Continued)

Data set 6-1 defines the paint scheme demarcation used in the fillet region of the fairing where the wing meets the fuselage. The fillet is modeled as a perfect quadrant. It acts as a partial cavity, thereby contributing to an increase in temperature in this region. The type of paint to be used on this fillet is governed by two entries.

pfillet = Paint scheme demarcation code
percent = Percentage of fillet painted with wing paint

Format and Example:

1	2
pfillet	*percent*

3	80.0

Field	Contents	Data Type and Value
pfillet	Paint scheme demarcation code	Integer: 1-3
percent	Percentage of fillet painted with wing paint	Real: 0.0-100.0

Remarks:

1. A comma or a space must separate each entry in a row. Data input is in free-format

2. The paint scheme demarcation code, *pfillet,* assumes one of three integers, 1, 2, and 3, where:

   1: the fillet is completely painted with the same paint that was used on the wing.
   2: the fillet is completely painted with the same paint that was used on the fuselage.
   3: the fuselage/wing paint boundary falls within the fillet.

3. The *percent* entry = 0.0 when the *pfillet* entry = 1 or 2. When *pfillet* = 3, the *percent* entry ranges from 0.0 to 100.0. For example, when *percent* = 0.0, the entire fillet assumes the fuselage paint; and when *percent* = 100.0, the entire fillet assumes the wing paint.

Figure A-6. Data Entry for Data Set 6-1

Data set 7-1 defines the scatter factors of the various surfaces. A scatter factor for a surface is defined as the fraction of reflected light that is diffused in nature. Reflected light that is not diffused, but rather is concentrated in a band is called specular reflection. The degree of scatter is a collective function of the surface texture as well as the degree to which it is polished. A dull surface will have a high scatter factor, while a mirror-like surface will have a low scatter factor. A total of four scatter factors are used in THERMOD. They are:

sf_B = Scatter factor for the floor surface of the cabin (material B)
sf_C = Scatter factor for the interior sides of the cabin (material C)
sf_w = Scatter factor for the exterior wing surfaces
sf_f = Scatter factor for the exterior fuselage surfaces

Format and Example:

1	2	3	4
sf_B	sf_C	sf_w	sf_f
0.80	0.60	0.20	0.20

Field	Contents	Data Type and Value
sf_B	Scatter factor for the floor surface (material B)	Real: 0.0-1.0
sf_C	Scatter factor for the interior sides of the cabin (material C)	Real: 0.0-1.0
sf_w	Scatter factor for the wing surfaces	Real: 0.0-1.0
sf_f	Scatter factor for the exterior fuselage surfaces	Real: 0.0-1.0

Remarks:

1. A comma or a space must separate each entry in a row. Data input is in free-format.

2. A very dull surface may have a scatter factor of about 80 percent, while a polished surface may have a scatter factor of about 20 percent. In the first case, 20 percent of the reflected light is specular in nature, while in the second case, 80 percent of reflected light is specular in nature.

Figure A-7. Data Entry for Data Set 7-1

Data set 8-1 defines the absorptivity and emissivity properties of the aircraft exterior surfaces. A total of four surfaces are involved—one representing the exterior wing surface and the other three representing the fuselage surfaces. The properties are defined as follows:

α_{fs} = Absorptivity of fuselage sides (dimensionless)
ε_{fs} = Emissivity of fuselage sides (dimensionless)
α_w = Absorptivity of wing (dimensionless)
ε_w = Emissivity of wing (dimensionless)
α_{ft} = Absorptivity of fuselage top (dimensionless)
ε_{ft} = Emissivity of fuselage top (dimensionless)
α_{fb} = Absorptivity of fuselage bottom (dimensionless)
ε_{fb} = Emissivity of fuselage bottom (dimensionless)

Format and Example:

1	2	3	4	5	6	7	8
α_{fs}	ε_{fs}	α_w	ε_w	α_{ft}	ε_{ft}	α_{fb}	ε_{fb}
0.50	0.90	0.60	0.95	0.45	0.85	0.50	0.90

Field	Contents	Data Type and Value
α_{fs}	Absorptivity of fuselage sides (dimensionless)	Real: 0.0-1.0
ε_{fs}	Emissivity of fuselage sides (dimensionless)	Real: 0.0-1.0
α_w	Absorptivity of wing (dimensionless)	Real: 0.0-1.0
ε_w	Emissivity of wing (dimensionless)	Real: 0.0-1.0
α_{ft}	Absorptivity of fuselage top (dimensionless)	Real: 0.0-1.0
ε_{ft}	Emissivity of fuselage top (dimensionless).	Real: 0.0-1.0
α_{fb}	Absorptivity of fuselage bottom (dimensionless).	Real: 0.0-1.0
ε_{fb}	Emissivity of fuselage bottom (dimensionless).	Real: 0.0-1.0

Figure A-8. Data Entry for Data Set 8-1

Remarks:

1. A comma or a space must separate each entry in a row. Data input is in free-format.

2. The exterior surface temperatures are influenced by paint color. The darker the paint, the higher the surface temperature, and conversely, the lighter the paint color, the lower the surface temperature. Note that darker paints will have higher absorptivity than lighter paints. Emissivity, on the other hand, serves to lower surface temperatures, i.e., the higher the emissivity, the lower the temperature, and vice versa.

3. In addition to influencing surface temperatures, paint color also influences the interior temperatures due to the dynamics of a thermal system.

4. Note that there is only one set of absorptivity and emissivity values for the entire wing (regardless of whether it is the right-hand side or left-hand side, or whether it is the top or the bottom). The fuselage, on the other hand, could have three sets of values—one for the side; one for the top, and one for the bottom.

Figure A-8. Data Entry for Data Set 8-1 (Continued)

Data set 9-1 defines the number of time intervals needed to describe a flight profile. The flight profile is required as a means to generate time-varying convective coefficients. It is through these coefficients that heat is removed from the aircraft while it is in motion. An example flight profile is shown in figure 4.

ntintvl = Number of time intervals in a flight profile

Format and Example:

1
ntintvl
22

Field	Contents	Data Type and Value
ntintvl	Number of time intervals in a flight profile	Integer ≥ 1

Remarks:

1. The flight profile must be unique to the aircraft in consideration. It describes the motion of the aircraft on the ground and in the air. The end of the flight profile is defined when the aircraft is subjected to the most critical limit loads at the earliest possible time, which generally is while the aircraft is in the air.

2. The flight profile is used in THERMOD to simulate time-varying convective coefficients, which are the transport agents through which heat is removed from the aircraft. Operating limit temperatures are determined at the end of the flight profile.

Figure A-9. Data Entry for Data Set 9-1

Data set 10-1 defines the speed at the beginning of each time interval. The speeds are needed to describe a flight profile. The flight profile is required as a means to generate time-varying convective coefficients. It is through these coefficients that heat is removed from the aircraft while it is in motion. An example flight profile is shown in figure 4.

v_i = Speed at the beginning of each time interval for describing a flight profile (mph)

Format and Example:

1	2	3	4	5	6	7	8	9	10
v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	v_9	v_{10}
v_{11}	v_{12}	v_{13}	v_{14}	.....	.....	*Cont.*	....	....	.....
....	$v_{ntintvl}$	$v_{ntintvl+1}$							

0.0	10.0	10.0	0.0	0.0	75.0	110.0	110.0	190.0	190.0
200.0	205.0	220.0	225.0	....	....	....	....	....	....
250.0	250.0	250.0							

Field	Contents	Data Type and Value
v_i	Speed at the beginning of each time interval for describing a flight profile (mph)	Real ≥ 0.0

Remarks:

1. A comma or a space must separate each entry in a row. Data input is in free-format

2. The flight profile must be unique to the aircraft in consideration. It describes the motion of the aircraft on the ground and in the air. The end of the flight profile is defined when the aircraft is subjected to the most critical limit loads at the earliest possible time, which generally is while the aircraft is in the air.

3. The flight profile is used in THERMOD to simulate time-varying convective coefficients, which are the transport agents through which heat is removed from the aircraft. Operating limit temperatures are determined at the end of the flight profile.

4. If the number of time intervals, *ntintvl*, is greater than 10, data are continued in the next row, and so on. The end of each row must end with a comma or a space, except for the last row. There must be a total of *ntintvl*+1 data points.

Figure A-10. Data Entry for Data Set 10-1

Data set 11-1 defines the duration of each time interval of the flight profile. The flight profile is required as a means to generate time-varying convective coefficients. It is through these coefficients that heat is removed from the aircraft while it is in motion. An example flight profile is shown in figure 4.

$time_i$ = Duration of each time interval (sec)

Format and Example:

1	2	3	4	5	6	7	8	9	10
$time_1$	$time_2$	$time_3$	$time_4$	$time_5$	$time_6$	$time_7$	$time_8$	$time_9$	$time_{10}$
$time_{11}$	$time_{12}$	$time_{13}$	$time_{14}$	.....	.....	*Cont.*	....	....	.....
....	$time_{ntintvl}$								

5.0	10.0	15.0	25.0	5.0	15.0	10.0	20.0	20.0	30.0
30.0	30.0	35.0	35.0	….	….	….	….	….	….
45.0	45.0								

Field	Contents	Data Type and Value
$time_i$	Duration of each time interval (sec)	Real > 0.0

Remarks:

1. A comma or a space must separate each entry in a row. Data input is in free-format.

2. The flight profile must be unique to the aircraft in consideration. It describes the motion of the aircraft on the ground and in the air. The end of the flight profile is defined when the aircraft is subjected to the most critical limit loads at the earliest possible time, which generally is while the aircraft is in the air.

3. The flight profile is used in THERMOD to simulate time-varying convective coefficients, which are the transport agents through which heat is removed from the aircraft. Operating limit temperatures are determined at the end of the flight profile.

4. If the number of time intervals, *ntintvl*, is greater than 10, data are continued in the next row, and so on. The end of each row must end with a comma or a space, except for the last row. There must be a total of *ntintvl* data points.

Figure A-11. Data Entry for Data Set 11-1

Data set 12-1 defines the number of requested times of the day at which thermal analysis is performed. For example, an analysis could be performed at 11:00 in the morning and another at 2:00 in the afternoon. At each time, a complete set of data describing the climatic data is needed.

ntime = Number of requested times of the day at which thermal analysis is performed

---

Format and Example:

1
ntime
7

Field	Contents	Data Type and Value
ntime	Number of requested times of the day at which thermal analysis is performed	Integer ≥ 1

Remarks:

1. THERMOD loops over all requested times of the day to give the maximum operating limit (MOL) temperature.

2. Note that the maximum temperature in an aircraft does not necessarily occur at noon. The primary reason being that the maximum ambient temperature and the maximum solar radiation do not necessarily occur at the same time.

Figure A-12. Data Entry for Data Set 12-1

Data set 12-2 to 12-8 define the climatic- and transparency-related data at given times of day. The climatic data include the sun's incident angle, ambient temperature, effective sky temperature, ambient wind speed, and total solar radiation. The transparency-related data provide information necessary to simulate the greenhouse effect.

θ_i = The sun's incident angle at a given time of day (degrees)

T_{ambi} = Ambient temperature at a given time of day (° Rankine)

T_{skyi} = Effective sky temperature at a given time of day (° Rankine)

V_{windi} = Ambient wind speed at a given time of day (ft/sec)

Q_{soli} = Total solar radiation (includes both direct and diffused solar radiation) at a given Time of day ((Btu/hr)/ft^2)

Avi = Total projected area of the transparency that intercepts the vertical component of the sun's radiation at a given time of day (ft2)

A_{hi} = Total projected area of the transparency that intercepts the horizontal component of the sun's radiation at a given time of day (ft^2)

Fr_{Qi} = Fraction of solar radiation that is intercepted by the transparency (in terms of the projected areas) at a given time of day

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Format and Example:

1	2	3	4	5	6	7	8
θ_1	T_{amb1}	T_{sky1}	V_{wind1}	Q_{sol1}	A_{v1}	A_{h1}	Fr_{Q1}
θ_2	T_{amb2}	T_{sky2}	V_{wind2}	Q_{sol2}	A_{v2}	A_{h2}	Fr_{Q2}
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
θ_{ntime}	$T_{ambntime}$	$T_{skyntime}$	$V_{windntime}$	$Q_{solntime}$	A_{vntime}	A_{hntime}	$Fr_{Q\ ntime}$

60.0	565.67	459.67	10.0	250.0	10.0	12.0	0.30
75.0	570.67	459.67	12.0	260.0	11.0	13.0	0.45
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
30.0	560.67	459.67	8.0	210.0	10.0	10.0	0.50

Figure A-13. Data Entry for Data Set 12-2 to 12-8

Field	Contents	Data Type and Value
θ_i	The sun's incident angle at a given time of day (degrees)	Real: 0.0-90.0
T_{ambi}	Ambient temperature at a given time of day (° Rankine)	Real > 0.0
T_{skyi}	Effective sky temperature at a given time of day (° Rankine)	Real > 0.0
V_{windi}	Ambient wind speed at a given time of day (ft/sec)	Real ≥ 0.0
Q_{soli}	Total solar radiation (includes both direct and diffused-solar radiation) at a given time of the day ((Btu/hr)/ft^2)	Real ≥ 0.0
A_{vi}	Total projected area of the transparency that intercepts the vertical component of the sun's radiation at a given time of day (ft^2)	Real ≥ 0.0
A_{hi}	Total projected area of the transparency that intercepts the horizontal component of the sun's radiation at a given time of day (ft^2)	Real ≥ 0.0
Fr_{Qi}	Fraction of solar radiation that is intercepted by the transparency (in terms of the projected areas) at a given time of day	Real ≥ 0.0

Remarks:

1. A comma or a space must separate each entry in a row. Data input is in free-format.

2. THERMOD loops over all requested times of the day to give the MOL temperature.

3. Note that the maximum temperature in an aircraft does not necessarily occur at noon. The primary reason being that the maximum ambient temperature and the maximum solar radiation do not necessarily occur at the same time. This makes it necessary to loop over different times of the day to obtain the MOL temperature.

Figure A-13. Data Entry for Data Set 12-2 to 12-8 (Continued)

Data set 13-1 defines the type of finite difference method of analysis to be employed, the time increment involved, the tolerable ambient cabin temperature before taxi, and the amount of data to be printed.

fdmethod = Type of finite difference method selected in the transient phase (cooling phase): explicit forward finite difference method or the implicit backward finite difference method.

deltime = Delta time increment in the transient phase (cooling phase) (sec.).

ambcabt = Tolerable ambient cabin temperature immediately before taxi, i.e., after cooling has taken place by deliberately opening the door (°F).

intvprnt = The number of deltime before the next set of data is printed in the transient phase.

Format and Example:

1	2	3	4
fdmethod	*deltime*	*ambcabt*	*intvprnt*
2	0.01	135.0	100

Field	Contents	Data Type and Value
fdmethod	Type of finite difference method selected in the transient phase (cooling phase): explicit forward finite difference method; or the implicit backward finite difference method.	Integer: 1-2
deltime	Delta time increment in the transient phase (cooling phase) (sec.).	Real > 0.0
ambcabt	Tolerable ambient cabin temperature immediately before taxi, i.e., after cooling has taken place by deliberately opening of the door (°F).	Real > 0.0
intvprnt	The number of deltime before the next set of data is printed in the transient phase.	Real > 0.0

Figure A-14. Data Entry for Data Set 13-1

Remarks:

1. A comma or a space must separate each entry in a row. Data input is in free-format.

2. Two types of finite difference methods have been developed under THERMOD: the original explicit forward finite difference method (fdmethod = 1), and the more recent implicit backward finite difference method (fdmethod = 2). The explicit forward finite difference method, while relatively less complicated in terms of coding, is not unconditionally stable. The spatial and time-domain discretization cannot be performed arbitrarily. For example, too large a time increment may render the solution unstable, requiring a smaller time increment. In some cases, the time increment required is so small that a significant amount of time is needed for a solution, rendering the exercise impractical. These problems have been addressed through the use of the implicit backward finite difference method. This method is unconditionally stable. No spatial and time-domain restriction exists. Too large a time increment, however, may affect the accuracy of the results.

3. THERMOD models the greenhouse effect, thereby simulating high temperatures within the enclosed cabin. It is only reasonable, then, to take advantage of whatever relief that can be likely expected, short of artificial cooling through air conditioning or a fan. THERMOD accomplishes this by stipulating that a comfortable temperature is reached within the cabin before entering the aircraft. This is simulated within the program by opening the door and allowing the relatively cooler outside air to cool the interiors to an average ambient temperature indicated by *ambcabt*. Once this temperature is reached, the door is closed and the aircraft is subjected to further cooling, according to a defined flight profile.

Figure A-14. Data Entry for Data Set 13-1 (Continued)

Data set 14-1 defines the number of iterations and convergence criteria used in the thermal analysis. These parameters are needed because of the nonlinear nature of THERMOD.

niter = The number of iterations allowed in the thermal analysis
tolx = A variable-based convergence criterion (dimensionless)
tolfn = A function-based convergence criterion (dimensionless)

Format and Example:

1	2	3
niter	*tolx*	*tolfn*
10	0.01	0.1

Field	Contents	Data Type and Value
niter	The number of iterations allowed in the thermal analysis	Integer ≥ 1
tolx	A variable-based convergence criterion	Real > 0.0
tolfn	A function-based convergence criterion	Real > 0.0

Remarks:

1. A comma or a space must separate each entry in a row. Data input is in free-format.
2. The variable-based convergence criterion satisfies the following condition.

$$\frac{\sum_{j=1}^{67} abs\left(X_{j_{i+1}} - X_{j_i}\right)}{\sum_{j=1}^{67} X_{j_{i+1}}} \leq tolx$$

Where:

$X_{j_{i+1}}$ = The current value of the unknown variable X_j
X_{j_i} = The previous value of the unknown variable X_j

Figure A-15. Data Entry for Data Set 14-1

Remarks:

3. The function-based convergence criterion satisfies the following condition.

$$\frac{\sum_{j=1}^{67} abs\left(fn_{j_{i+1}} - fn_{j_i}\right)}{\sum_{j=1}^{67} fn_{j_{i+1}}} \leq tolfn$$

Where:

$fn_{j_{i+1}}$ = The current value of the function fn_j
fn_{j_i} = The previous value of the function fn_j

4. THERMOD ensures that both the criteria are satisfied before a satisfactory solution is reached.

5. Trial and error and by comparison to previous results determine all three entries in this row.

Figure A-15. Data Entry for Data Set 14-1 (Continued)

Data Entry: Data Set 15-1 to

Data set 15-5 defines the initial values of the unknown variables. An initial input set is required. This set is made of 67 initial values, as THERMOD is a nonlinear system with 67 independent equations.

X_j = Initial value of the unknown variable X_j (°F or (Btu/hr)/ft^2).

Format and Example:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
X_{16}	X_{17}	X_{18}	X_{19}	X_{20}	X_{21}	X_{22}	X_{23}	X_{24}	X_{25}	X_{26}	X_{27}	X_{28}	X_{29}	X_{30}
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
X_{61}	X_{62}	X_{63}	X_{64}	X_{65}	X_{66}	X_{67}								

10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
10	10	10	10	10	10	10								

Field	Contents	Data Type and Value
X_j	Initial value of the unknown variable X_j (°F or (Btu/hr)/ft^2).	Real

Figure A-16. Data Entry for Data Set 15-1 to 15-5

Remarks:

1. A comma or a space must separate each entry in a row. Data input is in free-format.

2. A total of 67 entries are needed. To avoid possible problems, it is recommended that each row have 15 entries. The row must end with a comma or a space at the end of the 15^{th} entry to signify the continuation to the next row. The last entry should not end with a comma.

3. The first 53 entries are temperature entries and are in (°F). The final 14 entries are radiosity entries and are in ((Btu/hr)/ft^2). Radiosity is defined as the total energy emanating from a surface that includes both the reflected as well as emitted energy.

4. It is recommended that positive initial values be used for all 67 variables.

Figure A-16. Data Entry for Data Set 15-1 to 15-5 (continued)

REFERENCES.

A-1. Incropera, F.P. and Dewitt, D.P., "Fundamentals of Heat and Mass Transfer," third edition, John Wiley & Sons, New York, NY, 1990.