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THERMAL MODELING OF A METALLIC THERMAL PROTECTION TILE FOR ENTRY VEHICLES

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SUMMARY

This paper describes the development and usage of the Thermal Energy Flow Simulation (TEFS) computer program. The program's function is to simulate transient heat conduction in composite solids and accurately predict interfacial temperatures.

Development of this program was undertaken in order to analytically test the thermal characteristics of a proposed thermal protection tile system for the Space Shuttle Orbiter. This tile configuration (referred to as a Shell Tile*) consists of an outer metallic shell which is filled with multi-layered flexible insulation. The objective was to determine individual transient temperatures between layers of dissimilar insulation materials and to accurately predict the peak temperature of the underlying thermally protected aluminum structure. A major assumption was that (along with each material layer's thermal properties) the only known variable is the temperature of the outer surface.

The thermal protection tile system was heat tested and a time history of the interfacial temperatures was recorded. Using the TEFS program, a computer simulation was conducted to analytically determine the temperature distribution. The computer simulation provided a peak aluminum temperature that was within 4% of the actual.

*United States patent number 4,456,208 dated June 26, 1984 entitled "Shell Tile Thermal Protection System".

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INTRODUCTION

A new thermal protection system, referred to as a Shell Tile, has been proposed for possible application to future entry vehicles. In order to optimize the tile thickness via an analytical model, the Thermal Energy Flow Simulation (TEFS) computer program was developed. The unique feature of this program is its ability to accurately simulate the thermal characteristics of a composite solid when the only data available are the top surface time dependent temperature and the materials' thermal properties.

The basis for the TEFS program is the THERMAL RESPONSE FACTOR (RESFAC) program used in NASA'S ENERGY COST ANALYSIS PROGRAM (NECAP). In both TEFS and RESFAC, the equation of heat conduction for unsteady state/linear flow is solved using the Laplace transformation method. This method was used due to its:

1) Direct application to composite solids.
2) Easy input requirements.
3) Fast computer execution time.

A detailed analysis of the method can be found in references 1 and 2.

Note that the following assumptions govern the use of the Laplace transformation method as used in TEFS:

1) Heat transfer is by conduction in one dimension.
2) No contact resistance exists between material layers.
3) The composite solid is initially at a uniform temperature.
4) Values of temperature dependent thermal properties are determined by the temperature at the top of the respective material layer.
5) The last layer of the composite solid is either an air or vacuum gap which is held constant at the initial temperature.

In order to obtain an accurate simulation, the following criteria should be observed:

1) Thick materials should be subdivided.
2) The last material of the model being analyzed should be an air/vacuum gap whose only thermal property is a constant resistance.
3) Any material which has negligible thermal mass should have resistance as its only thermal property.
4) The time step selected for the simulation should accurately reflect the supply temperature's duration.
5) Temperature dependent thermal properties should be input such that the temperature range being simulated is accurately represented.

PROGRAM INPUT/OUTPUT

Two input files are required for the TEFS program. The first file, accessed under file name MODEL, contains the temperature dependent thermal properties of each material layer comprising the composite solid. File two, accessed under file name SUPPLY, contains values defining the thermal simulation. Note that data in both files are free formatted.

The contents of file MODEL are:

Item	Description
N, IU	N: integer number of material layers; maximum of 10 IU: integer units flag 0 for English, 1 for Metric
$I_1, I_2, \ldots, I_N$	Integer number of temperature variations in layers 1(top),2,...,N(bottom); maximum of 20 for each layer; note that a layer having a constant resistance must be entered as a -1

NOTE: Repeat the following for all material layers, proceeding from top layer to bottom

$LABEL_a$	Type of material used in the ath layer; alphanumeric data with a maximum of 80 characters

NOTE: The following input is required for each temperature variation in the ath layer

W,K,D,S,T	If layer has thermal mass, enter real values for: thickness W, density D, conductivity K, specific heat S, temperature T
or	
R	Layer has no thermal mass, enter real value for: constant resistance R

The contents of file SUPPLY are:

Item	Description
DT	Real value of time increment between supply temperature pulses

Item	Description
NP	Integer value of number of supply temperature pulses; maximum of 100
$TS_1, TS_2, \ldots, TS_{NP}$	NP real values of supply temperature pulses from TS initial through TS end

The output file from TEFS is named SIMUL and contains the following:

1) Echo of input file MODEL
2) Echo of input file SUPPLY
3) Tabular presentation of simulated temperatures at the top of each material layer for the number (NP) of time steps (DT).

PROGRAM UNITS

Depending on the value of the units flag IU, the appropriate units for the variables in the input files MODEL and SUPPLY and the output file SIMUL are:

Item	English	Metric
W	ft	m
D	lb/ft^3	kg/m^3
K	Btu/h-ft-F	W/m-K
S	Btu/lb-F	W-s/kg-K
T	F	K
R	$h\text{-}ft^2\text{-}F/Btu$	$m^2\text{-}K/W$
DT	s	s
TS	F	K

ANALYTICAL vs RECORDED DATA

A new design for a thermal protection tile has been investigated as a possible alternative to the current space shuttle orbiter tile system or as a heat shield for future aerospace transports. This new design differs significantly from the currently used tiles. Rather then use rigidized ceramic tiles, the proposed design consists of individual metallic shells which are filled with layers of low density flexible insulation. Figure 1 contains a description of this metallic shell concept.

Heating experiments have been conducted on this tile design in order to obtain temperature profiles of the materials' interface regions. Using program TEFS, an analytical solution was obtained. The TEFS input files MODEL and SUPPLY are listed in TABLES I and II respectively; output file SIMUL is presented in TABLE III. A graphics comparison between recorded and analytical data is shown in Figures 2 through 7.

The computer simulation, run interactively on a Control Data Corporation CYBER 160/170 series computer, required 40 CPU seconds and 73000 (octal) 60-bit words of memory to execute.

Probable causes of the discrepencies between recorded data and the analytical solution are:

1) Computer simulation is one dimensional heat conduction.
2) Thermal properties are ideal.
3) There is an initial temperature gradient within the model.
4) Uneven heating rate exists due to staggered pattern of heating elements.
5) Thermocouple inaccuracies, especially at low temperatures.

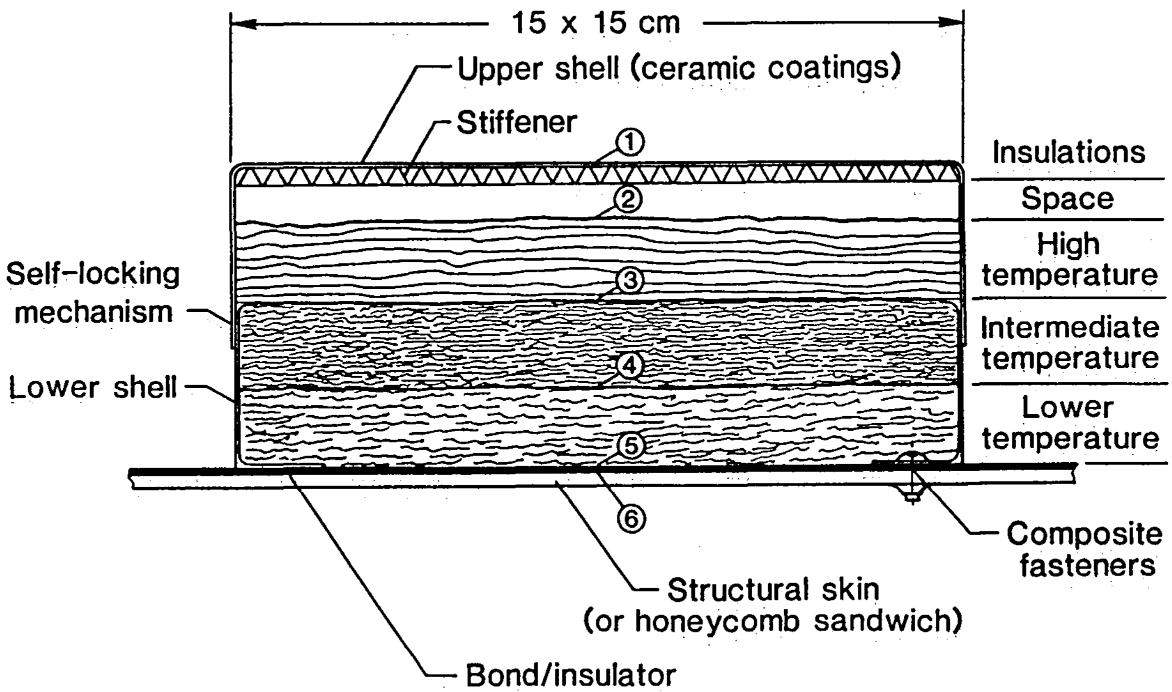

Figure 1. Metallic Shell Tile concept. Numbers refer to thermcouple locations and also comparisons with simulated temperatures.

TABLE I. INPUT FILE MODEL

```
 7 0
17 17 17 17 8 4 -1
   TOP RENE
0.00042   5.1993    512.0    0.0987    0.0    100.0
0.00042   5.8925    512.0    0.103     0.0    200.0
0.00042   6.5858    512.0    0.1072    0.0    300.0
0.00042   7.279     512.0    0.1114    0.0    400.0
0.00042   7.9723    512.0    0.1157    0.0    500.0
0.00042   8.6655    512.0    0.12      0.0    600.0
0.00042   9.1709    512.0    0.1242    0.0    700.0
0.00042   9.6763    512.0    0.1285    0.0    800.0
0.00042   10.182    512.0    0.1327    0.0    900.0
0.00042   10.687    512.0    0.137     0.0    1000.0
0.00042   11.193    512.0    0.1412    0.0    1100.0
0.00042   11.698    512.0    0.1455    0.0    1200.0
0.00042   12.203    512.0    0.1492    0.0    1300.0
0.00042   12.709    512.0    0.1521    0.0    1400.0
0.00042   13.214    512.0    0.1549    0.0    1500.0
0.00042   13.72     512.0    0.1577    0.0    1600.0
0.00042   14.225    512.0    0.1605    0.0    1700.0
   TOP SHELL QUARTZ INSUL
0.0625    0.0108    3.0      0.18      0.0    100.0
0.0625    0.0117    3.0      0.2       0.0    200.0
0.0625    0.0154    3.0      0.215     0.0    300.0
0.0625    0.019     3.0      0.23      0.0    400.0
0.0625    0.0227    3.0      0.24      0.0    500.0
0.0625    0.0263    3.0      0.25      0.0    600.0
0.0625    0.03      3.0      0.255     0.0    700.0
0.0625    0.03371   3.0      0.26      0.0    800.0
0.0625    0.0383    3.0      0.265     0.0    900.0
0.0625    0.0428    3.0      0.27      0.0    1000.0
0.0625    0.0496    3.0      0.275     0.0    1100.0
0.0625    0.0564    3.0      0.28      0.0    1200.0
0.0625    0.0632    3.0      0.285     0.0    1300.0
0.0625    0.07      3.0      0.29      0.0    1400.0
0.0625    0.0788    3.0      0.295     0.0    1500.0
0.0625    0.0875    3.0      0.3       0.0    1600.0
0.0625    0.0963    3.0      0.305     0.0    1700.0
   MIDDLE SHELL QUARTZ INSUL
0.0625    0.0108    3.0      0.18      0.0    100.0
0.0625    0.0117    3.0      0.2       0.0    200.0
0.0625    0.0154    3.0      0.215     0.0    300.0
0.0625    0.019     3.0      0.23      0.0    400.0
0.0625    0.0227    3.0      0.24      0.0    500.0
0.0625    0.0263    3.0      0.25      0.0    600.0
```

TABLE I. (cont.)

0.0625	0.03	3.0	0.255	0.0	700.0
0.0625	0.03371	3.0	0.26	0.0	800.0
0.0625	0.0383	3.0	0.265	0.0	900.0
0.0625	0.0428	3.0	0.27	0.0	1000.0
0.0625	0.0496	3.0	0.275	0.0	1100.0
0.0625	0.0564	3.0	0.28	0.0	1200.0
0.0625	0.0632	3.0	0.285	0.0	1300.0
0.0625	0.07	3.0	0.29	0.0	1400.0
0.0625	0.0788	3.0	0.295	0.0	1500.0
0.0625	0.0875	3.0	0.3	0.0	1600.0
0.0625	0.0963	3.0	0.305	0.0	1700.0
BOTTOM SHELL QUARTZ INSUL					
0.0625	0.0108	3.0	0.18	0.0	100.0
0.0625	0.0117	3.0	0.2	0.0	200.0
0.0625	0.0154	3.0	0.215	0.0	300.0
0.0625	0.019	3.0	0.23	0.0	400.0
0.0625	0.0227	3.0	0.24	0.0	500.0
0.0625	0.0263	3.0	0.25	0.0	600.0
0.0625	0.03	3.0	0.255	0.0	700.0
0.0625	0.03371	3.0	0.26	0.0	800.0
0.0625	0.0383	3.0	0.265	0.0	900.0
0.0625	0.0428	3.0	0.27	0.0	1000.0
0.0625	0.0496	3.0	0.275	0.0	1100.0
0.0625	0.0564	3.0	0.28	0.0	1200.0
0.0625	0.0632	3.0	0.285	0.0	1300.0
0.0625	0.07	3.0	0.29	0.0	1400.0
0.0625	0.0788	3.0	0.295	0.0	1500.0
0.0625	0.0875	3.0	0.3	0.0	1600.0
0.0625	0.0963	3.0	0.305	0.0	1700.0
NOMEX FELT (TIP)					
0.0133	0.0198	5.4	0.312	0.0	100.0
0.0133	0.0232	5.4	0.32	0.0	200.0
0.0133	0.0265	5.4	0.335	0.0	300.0
0.0133	0.0304	5.4	0.338	0.0	400.0
0.0133	0.0347	5.4	0.342	0.0	500.0
0.0133	0.039	5.4	0.345	0.0	600.0
0.0133	0.0434	5.4	0.35	0.0	700.0
0.0133	0.0478	5.4	0.36	0.0	800.0
ALUMINUM STRUCTURE CONDUCTION					
0.02	78.0	175.0	0.2025	0.0	100.0
0.02	84.0	175.0	0.21	0.0	200.0
0.02	90.0	175.0	0.223	0.0	300.0
0.02	97.2	175.0	0.232	0.0	400.0
ALUMINUM RADIATION TO VACUUM					
				46.0	

TABLE II. INPUT FILE SUPPLY

```
60.0
28
65.25 186.7 795.1 706.4 1065.8 994.8 1230.0 1478.4 1614.3
1637.9 1654.9 1663.6 1647.8 1647.4 1652.6 1658.4 1655.9
1477.6 1293.0 1070.0 915.4 809.7 731.9 670.7 620.8 579.7
544.5 514.6
```

TABLE III. OUTPUT FILE SIMUL

----- ECHO OF INPUT FILE MODEL -----

------ ECHO OF INPUT FILE SUPPLY ------

TIME SEC	TEMPERATURE AT TOP OF LAYER 1	2	3	4	5	6
0	65.250	65.250	65.250	65.250	65.250	65.250
60	186.700	186.687	65.629	65.250	65.250	65.250
120	795.100	795.037	72.873	65.269	65.305	65.250
180	706.400	706.395	135.139	65.710	65.265	65.252
240	1065.800	1065.753	298.391	68.758	65.314	65.255
300	994.800	994.786	493.791	82.068	65.871	65.252
360	1230.000	1229.963	664.203	111.341	65.935	65.264
420	1478.400	1478.355	827.058	169.404	67.477	65.292
480	1614.300	1614.261	1046.753	270.142	70.122	65.395
540	1637.900	1637.872	1239.183	471.641	75.749	65.600
600	1654.900	1654.878	1316.532	637.205	85.428	66.037
660	1663.600	1663.580	1328.394	823.630	103.339	66.886
720	1647.800	1647.784	1343.357	940.411	134.277	68.469
780	1647.400	1647.384	1361.861	1014.293	176.813	71.210
840	1652.600	1652.595	1378.793	1045.349	222.287	75.440
900	1658.400	1658.385	1391.546	1057.154	263.437	81.214
960	1655.900	1655.887	1398.751	1059.317	297.873	88.369
1020	1477.600	1477.606	1375.049	1055.764	323.115	96.651
1080	1293.000	1293.012	1299.525	1036.068	339.774	105.760
1140	1070.000	1070.021	1192.310	995.315	348.173	115.339
1200	915.400	915.418	1069.564	935.261	347.975	125.052
1260	809.700	809.715	957.899	863.037	340.490	134.47[illegible]
1320	731.900	731.912	862.834	790.754	328.799	143.339
1380	670.700	670.710	782.520	721.848	315.724	151.420
1440	620.800	620.808	714.288	659.608	303.008	159.666
1500	579.700	579.707	656.117	604.682	291.442	165.104
1560	544.500	544.505	606.381	556.880	281.328	170.80[illegible]
1620	514.600	514.604	563.681	515.592	272.667	175.843

Note: See figure 1 for locations of temperature simulations.

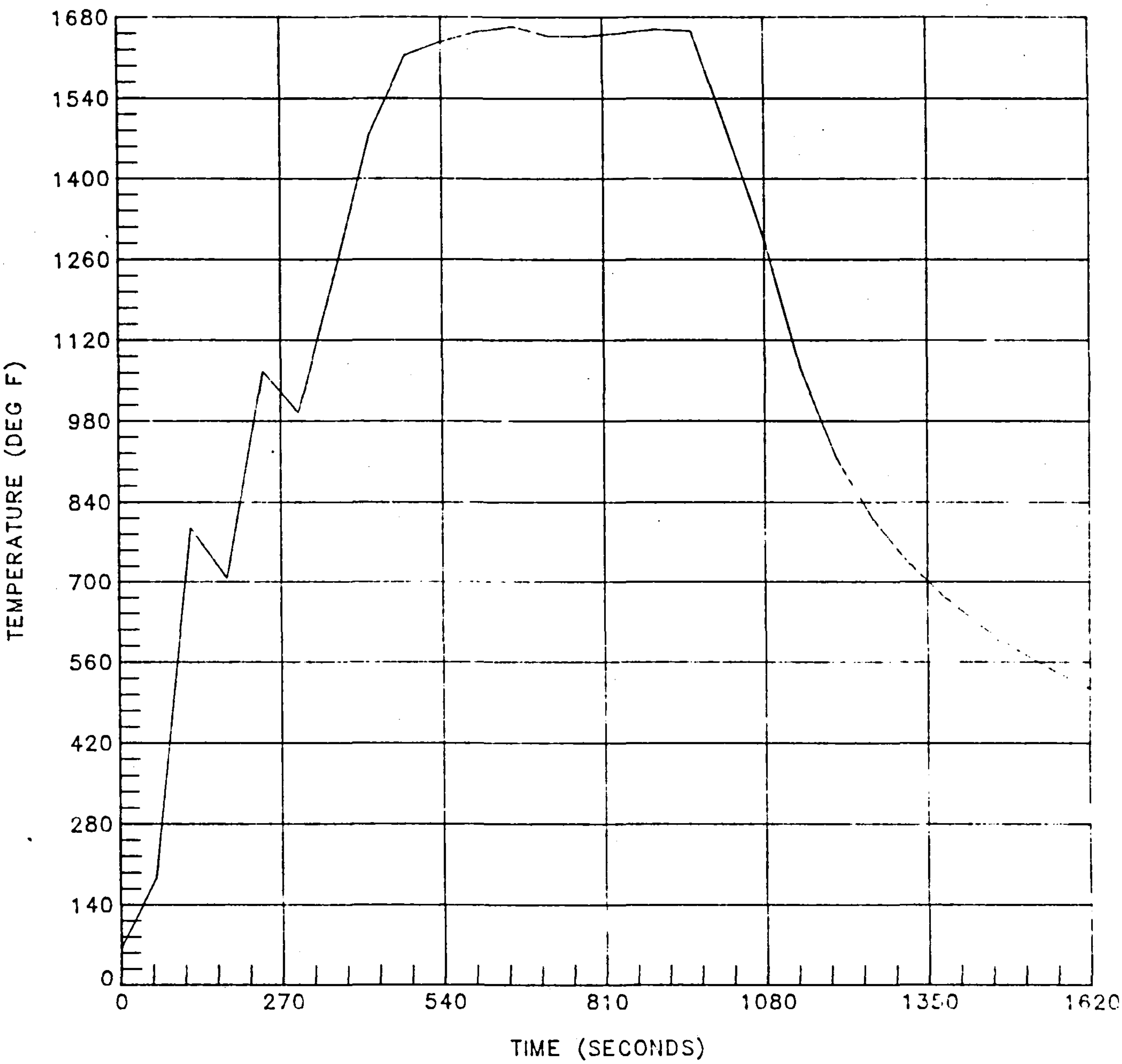

Figure 2. Supply Temperature to Top of Shell

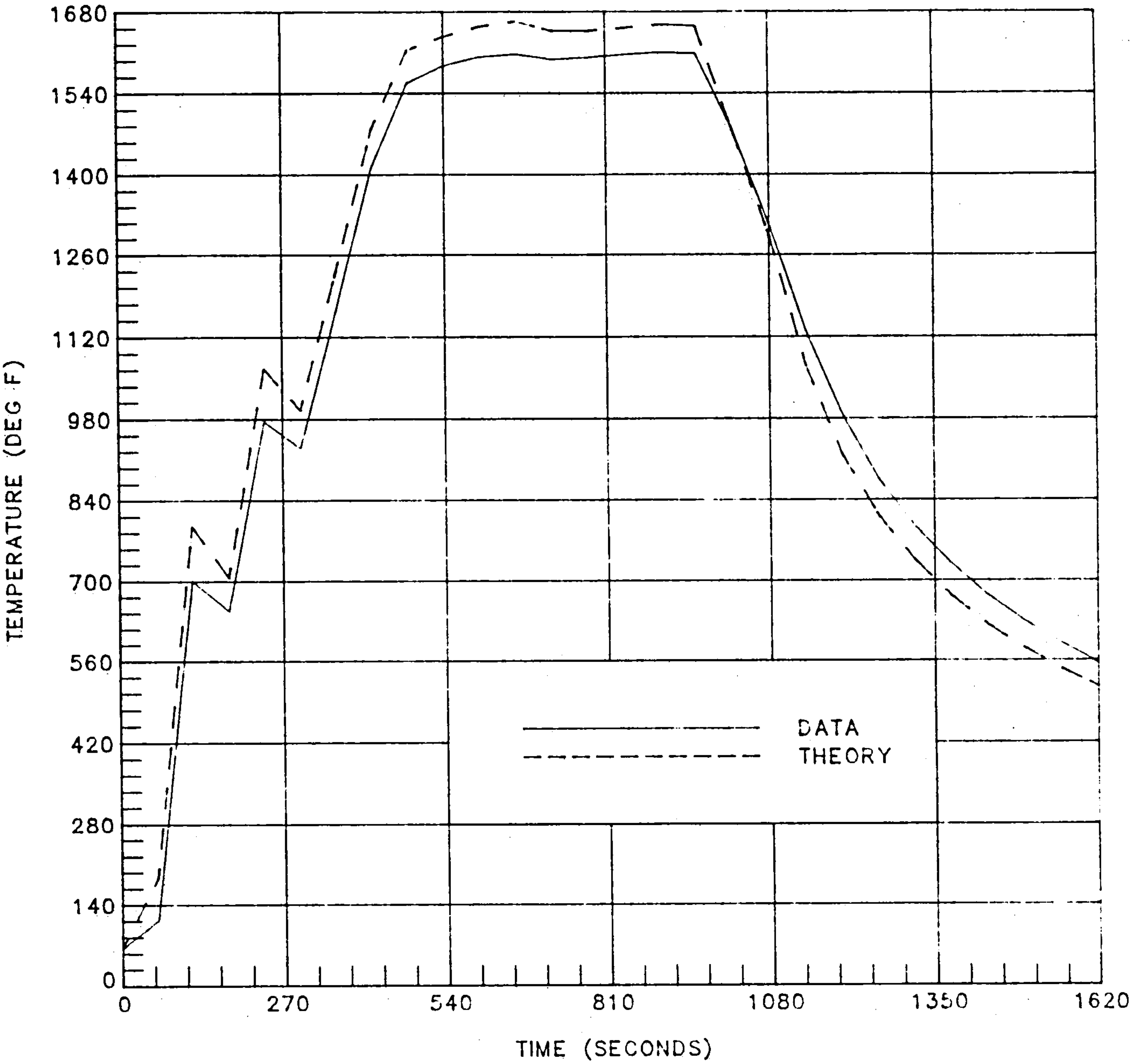

Figure 3. Top of Insulation Pack 1

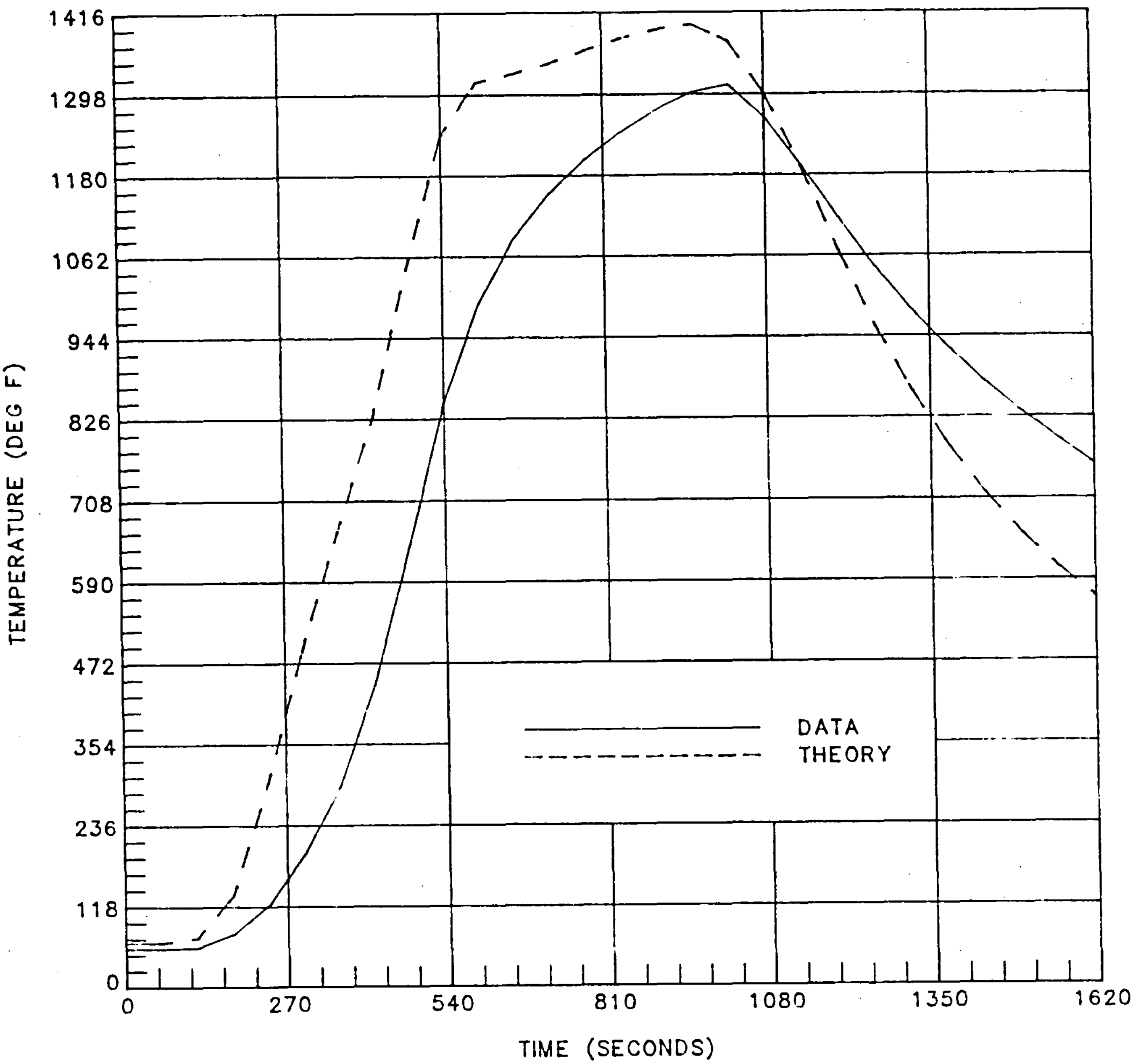

Figure 4. Top of Insulation Pack 2

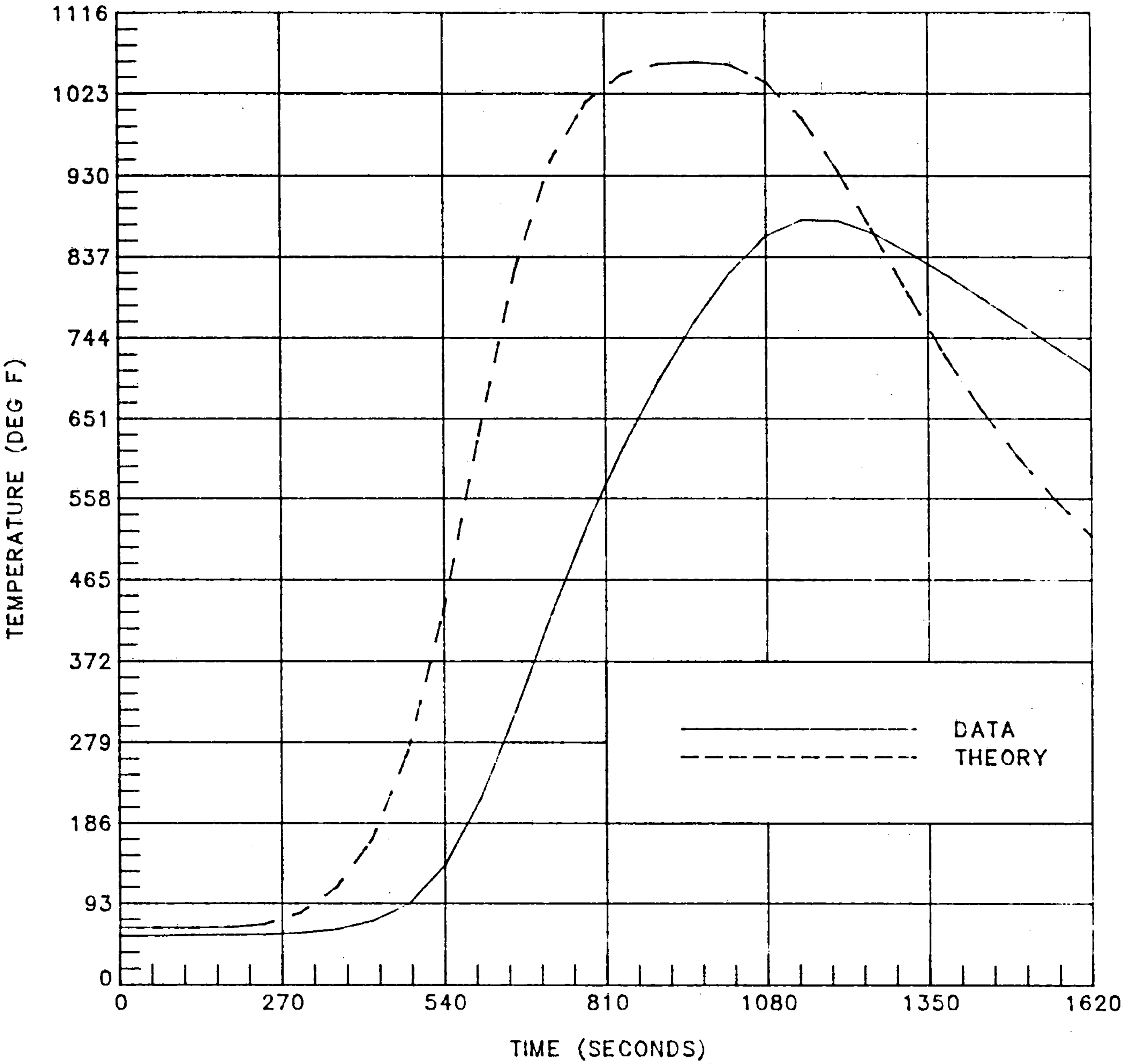

Figure 5. Top of Insulation Pack 3

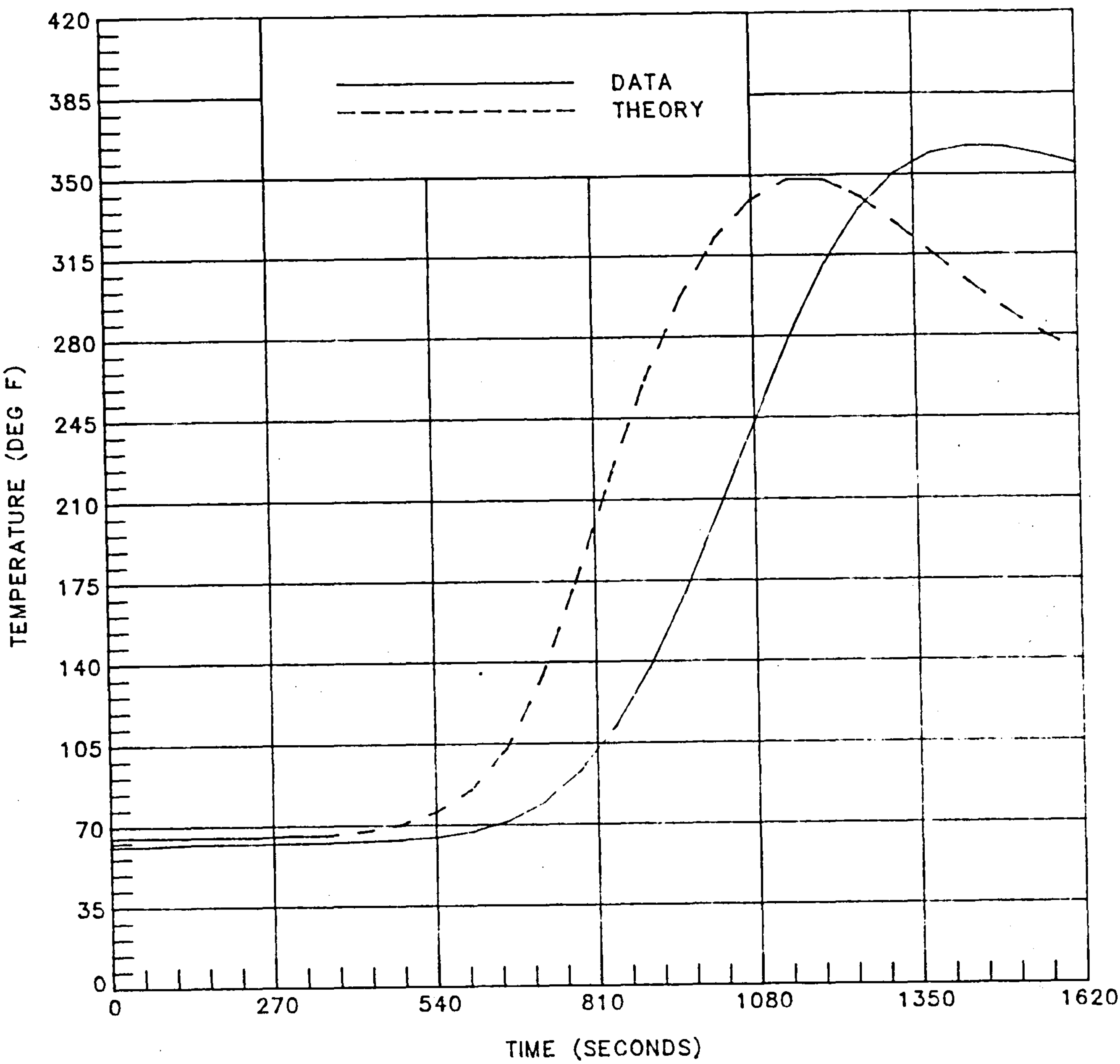

Figure 6. Top of Felt Pad

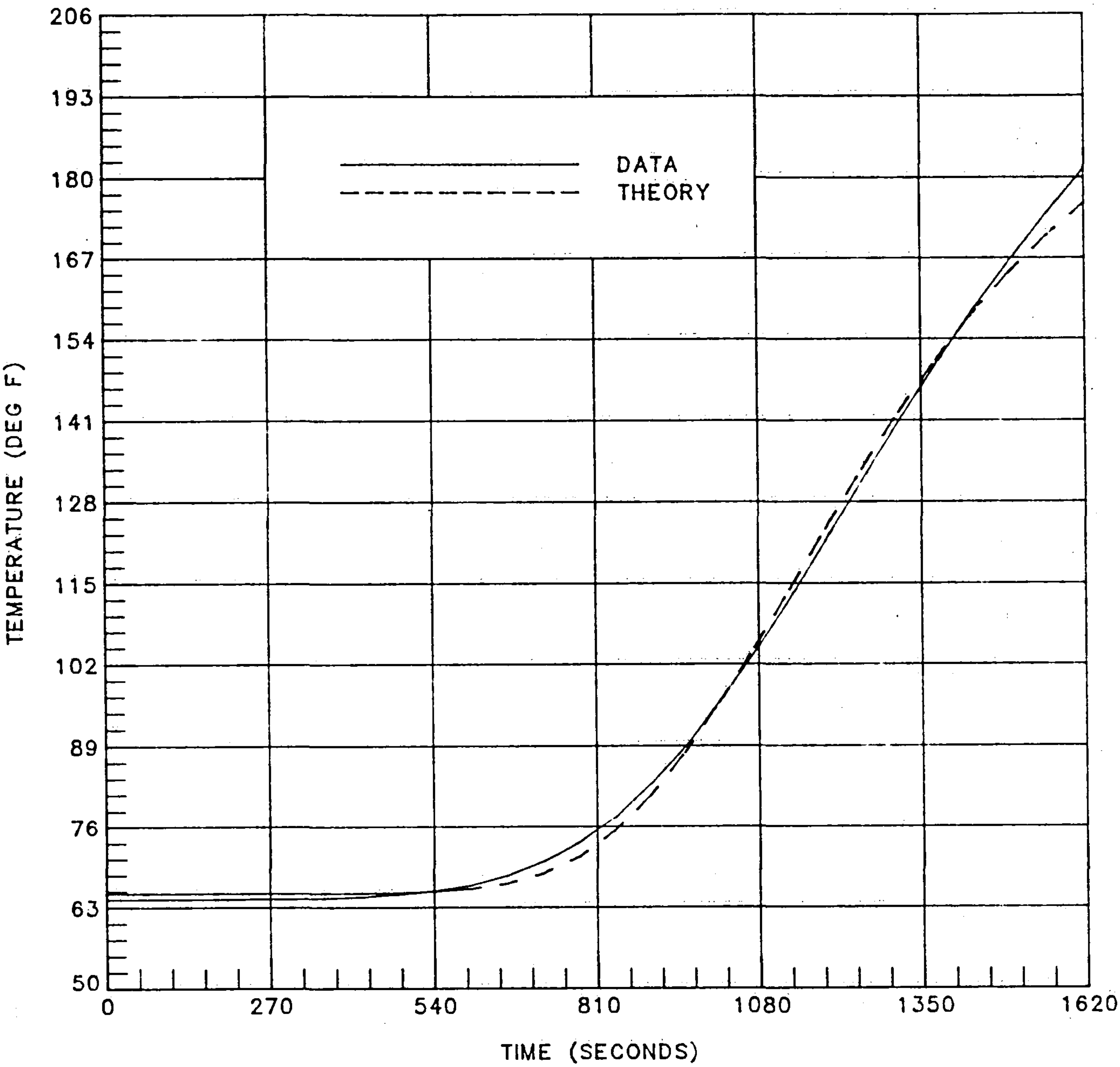

Figure 7. Top of Aluminum Structure

THEORETICAL MODELING

The results obtained from both the heat chamber test and computer simulation show that the peak aluminum temperature of approximately 180 degrees F was well below the allowable maximum of 350. Since the aluminum temperature is the critical area of interest, it is desirable to know the optimum insulation thickness-peak aluminum temperature factor. To obtain this, ten additional computer simulations were conducted, each using a decreased total insulation thickness (rate of reduction was 0.0095 feet per simulation). The results are presented in Figure 8 as an insulation thickness versus peak aluminum temperature operating curve.

This optimization run shows that the tile thickness could be reduced from 2.25 to 1.11 inches without exceeding the allowable 350 degrees F structure temperature. Based on the materials used in the simulation, a 4 tile array which is 2.25 inches thick with a top surface area of one square foot weighs 1.1 pounds. The reduced insulation thickness tile weighs 0.65 pounds, resulting in a weight reduction of about 40%.

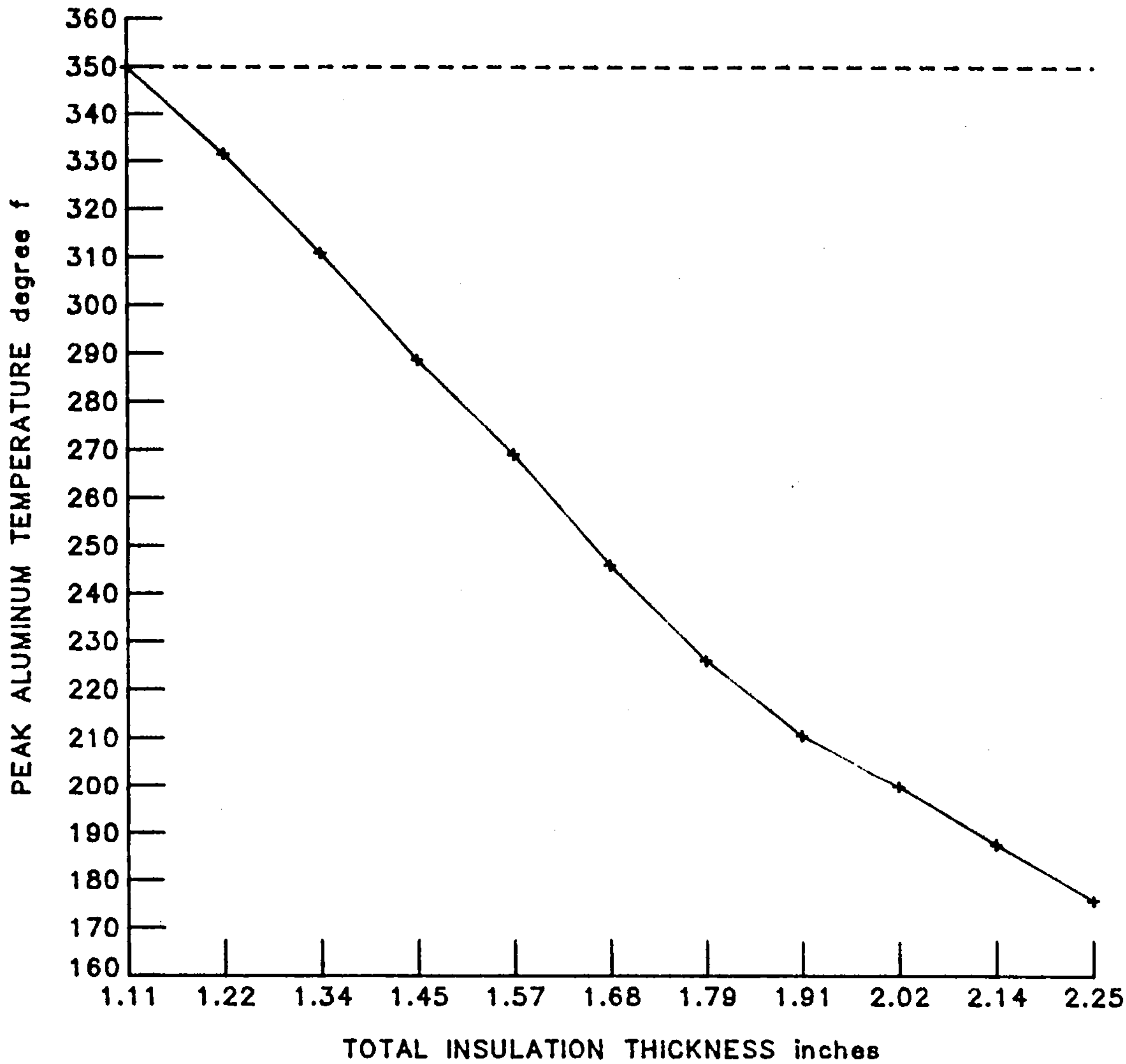

Figure 8. Theoretical Operating Curve

CONCLUSIONS

Within the framework of the governing assumptions, TEFS will provide a fast, low cost, accurate simulation of transient heat flow in a composite solid. As a aid in model design, TEFS enables a multitude of configurations to be analyzed in a short period of time, thus significantly reducing actual construction and testing costs.

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16. Abstract

The Thermal Energy Flow Simulation (TEFS) computer program was developed to simulate transient heat transfer through composite solids and predict interfacial temperatures. This paper describes the program and its usage.

A simulation of the thermal response of a new thermal protection tile design for the Space Shuttle Orbiter is presented and graphically compared with actual data.

An example is also provided which shows the program's usage as a design tool for theoretical models.

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