N71-28795

NASA CR-111834
Aerotherm Report No. 70-25

FINAL REPORT

DEMONSTRATION OF THE RANGE OVER WHICH THE LANGLEY RESEARCH CENTER DIGITAL COMPUTER CHARRING ABLATION PROGRAM (CHAP) CAN BE USED WITH CONFIDENCE

TASK I

COLLECTION OF PROPERTIES DATA AND ABLATION TEST DATA FOR THREE CHARRING MATERIALS, AND RESULTS OF QUALIFYING CALCULATIONS WITH CHAP

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December 1970

Prepared under Contract No. NAS1-10136

by

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Moutain View, California

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National Aeronautics and Space Administration
Langley Research Center
Langley Station
Hampton, Virginia

ABSTRACT

Thermophysical and thermochemical material property data and ablation test data have been compiled for three charring ablators: low-density nylon phenolic, the Apollo heat shield material, and a filled silicone elastomer. These data are representative of the published data on these three materials. Comments are made on the accuracy and credibility of these data. Also, the analysis of the ablation test data, with the NASA Langley Research Center Charring Ablation Program (CHAP), is discussed.

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A	pre-exponential factor in reaction plane pyrolysis relation (2-5) and (A-5)	lb/ft^2-sec
A_{o_i}	pre-exponential factor in pyrolysis equation (A-1)	sec^{-1}
A_k	pre-exponential factor in Equation (2-6)	$lb/ft^2 sec\ atm^n$
B	activation energy in reaction plane pyrolysis relation (2-5) and (A-5)	Btu/lb-mol
B_k	activation energy in Equation (2-6)	^oR
C_p	specific heat	Btu/lb^oR
Cw	mass concentration of uncombined oxygen (e.g., O_2) at ablating surface in Equation (2-6)	lb/lb
E, E_i	activation energy in pyrolysis relations (2-2)	Btu/lb-mol
f_o	oxygen mass fraction in stream	lb_O/lb
H, H_f	see ΔH, $\overline{\Delta}H$, ΔH_f	---
h	enthalpy	Btu/lb
h_T	total enthalpy	Btu/lb
k	thermal conductivity	$Btu/sec\text{-}ft^oR$
k_{f_i}	temperature function in pyrolysis equations (2-1), (2-2), (2-4)	sec^{-1}
k_{o_i}	pre-exponential factor in equation (2-2)	sec^{-1}
$\dot{m}$	surface recession rate	lb/ft^2-sec
$\dot{m}_p$	pyrolysis rate	lb/ft^2-sec

n	reaction order in Equation (2-6)	---
n_i	reaction order in pyrolysis equations (2-2), (2-4)	---
p_{t_2}	stagnation pressure at test model	atm
p_w	local pressure at ablating surface	atm
$\dot{q}_{cw}$	cold wall heat flux	Btu/ft^{2}sec
R	universal gas constant	Btu/lb-mol$^\circ$R
S	surface recession	ft
T	temperature	$^\circ$R
T_{c_1}, T_{c_2}	pre-char temperature	$^\circ$R
T_p	temperature at pyrolysis plane	$^\circ$R
T/C	denotes thermocouple	---
TGA	denotes thermgravimetric analysis	---
w	mass (or weight) of TGA sample	lb
x	resin mass fraction	lb$_{resin}$/lb
y	depth	ft

GREEK

Γ	volume fraction of resin	ft$^3_{resin}$/ft^3
ΔH	heat of pyrolysis	Btu/lb
$\overline{\Delta H}$	dimensionless heat of pyrolysis	---

$$\frac{\Delta H R \rho_{i_o}}{E_i c_{p_p} \rho_p}$$

ΔH_f	heat of formation	Btu/lb
ε	emittance	---
η_s	distance error on recession	ft
η_t	distance error in pyrolysis penetration depth	ft
θ	time	sec
ρ	density	lb/ft^3
ρ_i	i constituent density	lb_i/ft^3

SUBSCRIPTS

a,b,c	denote individual tests in a sequence
c	denotes char
calc	denotes calculated
f	see k_{f_i}, ΔH_f
i	denotes constituent in pyrolysis
m	denotes measured
N	denotes nylon
o	denotes original or virgin state; see also A_o, f_{o_i}, k_{o_i}
p	denotes virgin plastic; also see T_p
r	denotes residual or char state for constituent i
s	denotes recession, see η_s
T	see h_T

T see h_T

t denotes pyrolysis penetration depth, η_t

w at ablating surface ("wall")

1,2 denotes sequence of i values; also see T_{c_1}, T_{c_2}

SECTION 1

INTRODUCTION

The present program aims to define the range of applicability of the Langley Research Center Charring Ablation Program (CHAP), described in References 1-1 and 1-2, using two versions of CHAP to predict test data over a wide range of conditions for three charring ablators: low density nylon phenolic, the Apollo heat shield material, and filled silicone elastomer.* The program has two major tasks, scheduled to run successively. Task I involves the collection of material properties data and ablation test data and the conduct of qualifying calculations to demonstrate successful operation of the CHAP code. For reporting purposes, Task I is organized into sub-tasks as follows:

Task	Activity
I	Properties and Test Data Collection; Qualifying Calculations
I.1	Properties Collection
I.2	Test Data Collection
I.3	Establishment of Agreement Criteria; Qualifying Calculations
I.4	Reporting and Review

Task II will involve extensive computer runs to determine one set of thermophysical and thermochemical properties for each kind of material and the range of applicability of the CHAP program for each material.

The present report is the Task I Final Report. It presents the material properties data and ablation test data which will subsequently be used in Task II, and describes the results of the qualifying calculations with the simpler CHAP I version of the ablation code**. Section 2 presents the properties data; Section 3 describes the ablation test data, and Section 4

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*The thrust of this program is toward possible space shuttle studies, which will feature lower density materials. The three materials chosen represent a compromise between similarity to shuttle candidate materials on the one hand and the current availability of sufficient test data on the other.

**Chap II includes a complex "coking" or char densification model. Since no good test data exist to evaluate this code, qualifying calculations are less applicable.

reports the agreement criteria and the qualifying calculations. Because of the volume of data reported, references, figures and tables are numbered by section (with section number prefixes) and are placed at the end of the individual sections.

Mr. Stephen S. Tompkins of the Materials Division, Langley Research Center, Hampton, Virginia, was the technical representative for this project.

REFERENCES

1-1 Swann, Robert T., and Pittman, Claud M.: Numerical Analysis of the Transient Response of Advanced Thermal Protection Systems for Atmospheric Entry. NASA TN D-1370, July 1962.

1-2 Swann, Robert T., Pittman, Claud M., and Smith, J. C.: One-Dimensional Numerical Analysis of the Transient Response of Thermal Protection Systems. NASA TN D-2976, September 1965.

SECTION 2

MATERIAL PROPERTIES

Subtask I.1 of the program involved the collection of material properties data on three materials, defined as follows:

- Low density nylon phenolic; composition by mass of about 23 to 37 percent phenolic (phenol formaldehyde) resin, 22 to 27 percent hollow phenolic microspheres (or Microballoons), 40 to 60 percent nylon (cloth or powder); nominal virgin density about 36 lb/ft^3
- Low density silicone elastomer; composition by mass of about 72 to 78 percent silicone elastomer (polydimethyl siloxane or polymethylphenyl/dimethyl siloxane), 12 to 16 percent hollow silica microspheres, 8 to 12 percent hollow phenolic microspheres (or Microballoons), nominal virgin density about 34 to 40 lb/ft^3
- Apollo heat shield material, commercially designated Avcoat 5026-39-HC/G; principally epoxy novolac with phenolic microspheres, with silica fibers added, gunned into phenolic/fiberglass honeycomb; nominal density 32 lb/ft^3

Properties to be covered included those properties required as input to the CHAP code: virgin and char densities, pyrolysis kinetics, thermal conductivity, specific heat, emittance, heat of combustion (or equivalent thermochemical information), heat of pyrolysis (or equivalent heat of formation information), and the specific heat of the pyrolysis gases.

The following subsections summarize the data obtained. For each material, a descriptive summary table identifies the sources of all data collected. It should be noted that with few exceptions only measured property data are considered; inferential properties (such as properties "backed out" of reported ablation test data with charring ablator computer codes) were not collected. A subsidiary summary table for each property lists in some detail the temperature range considered by each of the measurements, the material preparation in each case, the method employed, and the reported accuracy of the measurements (usually not given). The tables also give an estimate of the overall accuracy of the data. This estimate was arrived at in each case by considering:

- The reported random error of the measurement technique and/or apparatus
- The observed randomness in the reported data
- The scatter in the data for different material specimens or samples
- Any anticipated bias in the data

These estimates are of necessity somewhat crude; they do provide, however, a useful idea of the approximate nature of the data.

The actual data are presented in graphs and tabulations. In most cases, the amounts of data points are sufficient to have allowed the original reporters to draw a line of "best interpretation"; in such cases it is this line which is reported, and not the original test data.

2.1 LOW-DENSITY NYLON PHENOLIC

The low density nylon phenolic considered here has been very thoroughly studied. The tables, graphs, and tabulations of this section summarize the data extracted from the literature. Table 2-1 summarizes pertinent information about the data sources for nylon-phenolic.

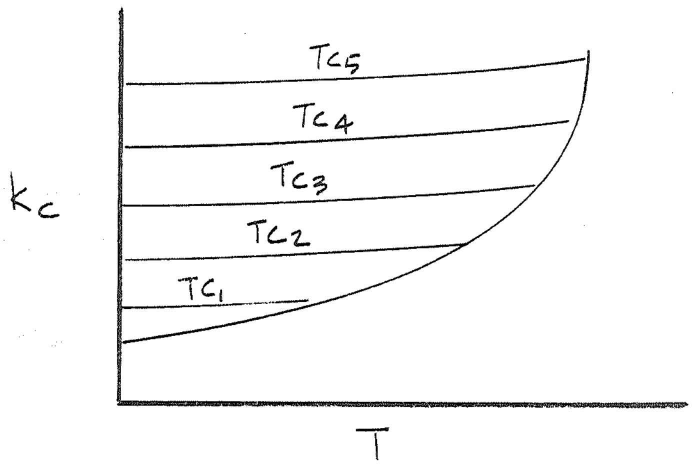
2.1.1 Thermal Conductivity

Table 2-2 summarizes the thermal conductivity source of information. Table 2-3 summarizes the virgin material thermal conductivity as a function of temperature; the same data is shown in Figure 2-1.

Table 2-4 and Figure 2-2 present the char conductivity as a function of temperature. The reported data cover a very wide range, indicating that char conductivity is a function of other parameters besides temperature. Various additional correlating parameters have been suggested:

- The "charring" or "pre-char" temperature, i.e., the highest temperature which the specimen has ever reached
- The length of time the specimen was exposed to this charring temperature
- The charring heating rate, or temperature rise rate during the charring process (which controls the pore size and other mechanical features of the char)
- The ambient pressure and atmosphere

These suggested correlating parameters are intended to clarify in some useful way the presentation of thermal conductivity data which are, in fact, functions of the entire previous history of the specimen. At the present time only attempts to correlate in terms of the first additional variable above could be tried, since data on the others are sparse and often not reported. One might hope to construct a plot with a form like the one shown in the following sketch:



The data of Figure 2-2 do not allow the construction of an orderly picture of this type, however.

The major part of the pyrolysis of nylon phenolic occurs between 1100°R and 1400°R. Thermal conductivity data for this temperature domain (except for materials pre-charred at a much higher temperature) are missing. This lack of data leaves open the interesting question of conductivity values for the pyrolysis zone of partially degraded material. Reference 2-5 contains some data for partially-pyrolyzed high density nylon phenolic which indicates that the conductivity for such material may be lower than the virgin values by substantial amounts.

2.1.2 Specific Heat

Table 2-5 summarizes the source information for specific heat measurements. Figure 2-3 shows the virgin material specific heat for temperatures up to a little over 1200°R. Appreciable pyrolysis of this material begins at about this temperature. These data are tabulated in Table 2-6.

Table 2-7 and Figure 2-4 present the char specific heat for low density nylon phenolic. The data show good consistency since the char is very nearly pure carbon; the complexities affecting the thermal conductivity data are largely irrelevant in this case.

2.1.3 Emittance

Table 2-8 summarizes the emittance source data for nylon phenolic. Table 2-9 and Figure 2-5 present the available emittance data for the chars of low density nylon-phenolic. Reported values at a given temperature vary; at 2850°R for example the values range from 0.60 to 0.93, a substantial variation. Differences in reported emittance presumably stem from

- The different surface appearances caused by different heating rates
- Surface coatings formed of compounds of trace species existing in the virgin material

The depression in the emittance values of Reference 2-1 in the domain 3000°R to 4000°R is believed due to this latter possibility.

2.1.4 Pyrolysis Kinetics

References 2-5 and 2-11 present pyrolysis kinetic data in reduced form, as derived from thermogravimetric laboratory data. In the case of Reference 2-5 the reduced data are presented as the constants in an equation of the form

$$\frac{d\rho_i}{d\theta} = - k_{f_i} \rho_{o_i} \left(\frac{\rho - \rho_{r_i}}{\rho_{o_i}} \right)^{n_i} \qquad (2\text{-}1)$$

where

$$k_{f_i} = k_{o_i} e^{-E_i/RT} \qquad (2\text{-}2)$$

where the i index identifies a specific reaction from the TGA data (which may or may not be readily associated with any specifically identifiable pyrolysis mechanism), and the subscripts o and r identify original (virgin) and residual (char) states. Reference 2-5 reports the following values for the kinetic constants in Equation (2-1):

i	k_{o_i} (sec^{-1})	E_i/R (°R)	n	ρ_{o_i} (lb/ft^3)	ρ_{r_i} (lb/ft^3)
Nylon	1.85×10^{13}	47,100	1.0	71.0	0
Phenolic (1)	1.40×10^{4}	15,400	3.0	20.25	0
Phenolic (2)	4.48×10^{9}	36,800	3.0	60.75	40.5

Nylon phenolic is a composite of nylon and phenolic; the material density may be written

$$\rho = \Gamma(\rho_1 + \rho_2) + (1 - \Gamma)\rho_N \tag{2-3}$$

where 1 and 2 denote the two phenolic quantities and N denotes nylon, and Γ is the volume fraction of resin in the composite.* Note that ρ_1 and ρ_2 have the units lb_i/ft^3 resin, and ρ_N has the units (lbs nylon)/(ft^3nylon).

Nelson (Ref. 2-11) presents reduced TGA data for nylon and for some phenolic resins of interest, all based on the pyrolysis rate equations (2-1). The phenolics tested had pyrolysis curves best fitted by a three-component model in two cases. The following table summarizes the Nelson results

Material	Reaction No. i	k_{o_i} sec^{-1}	E_i/R °R	n_i	$\rho_{o_i}/\rho_{o_{resin}}$	$\rho_{r_i}/\rho_{o_{resin}}$
Phenolic I (Union Carbide "Bakelite" phenolic resin BRP-5549	1	5.17×10^{8}	24,865	3.0	0.052	0
	2	2.50×10^{5}	21,838	1.3	0.068	0
	3	2.17×10^{7}	30,270	3.1	0.880	0.540
Phenolic II (Union Carbide BJO-0930 microspheres)	1	2.17×10^{5}	15,135	2.0	0.097	0
	2	9.67×10^{6}	26,378	3.0	0.165	0
	3	1.30×10^{10}	37,189	3.0	0.738	0.558
Phenolic III (Evercoat Chemical liquid casting resin EC-251)	1	2.17×10^{2}	9,730	2.0	0.105	0
	2	3.33×10^{3}	17,946	2.0	0.895	0.453
Nylon (DuPont Zytel 103 powder)		8.33×10^{14}	50,162	1.0	1.000	0.070

*The resin mass fraction is, in terms of Γ, $x = \dfrac{\Gamma(\rho_{1_0} + \rho_{2_0})}{\rho_p}$

Farmer in Reference 2-12 presents rate constants for a variety of phenolic materials; these constants are based, however, on a single component pyrolysis rate equation slightly different from Equation (2-1) above

$$\frac{d\rho}{d\theta} = - k_f \rho_o \left[\frac{\rho_o}{\rho_o - \rho_r}\right]^{n-1} \left(\frac{\rho - \rho_r}{\rho_o}\right)^n \qquad (2-4)$$

Farmer's values for k_f should be multiplied by the factor $[(\rho_o - \rho_r)/\rho_o]^{n-1}$ to obtain k_f values for comparison to values from References 2-5 and 2-11.

We do not tabulate Farmer's data here since the phenolics used are not exactly the phenolics used in the materials of interest in this program. The report does provide, however, much background data of general interest.

Data based on either of the two pyrolysis equations (2-1) and (2-4) are not directly useful as CHAP code input, since the computer program pyrolysis calculation is based on the "reaction plane " approximation that the total pyrolysis rate in the material is given by

$$\dot{m}_p = Ae^{-B/T_p} \qquad (2-5)$$

where T_p is the temperature at the current location of the pyrolysis plane. Appendix A describes how the reported data can be related to the constants required for CHAP input.

2.1.5 Heats of Formation or Heat of Pyrolysis

The heat of pyrolysis for a nylon phenolic (60% resin, 40% nylon) has been reported in Reference 2-20 as 200 ± 20 Btu/lb. Heat of combustion information was used to compute the following heats of formation at 25°C:

$$\Delta H_{f_{\text{nylon 6-6}}} = -959 \text{ Btu/lb}$$

$$\Delta H_{f_{\text{phenolic resin}}} = -823 \text{ Btu/lb}$$

Various measured pyrolysis gas compositions were verified by using these heats of formation to compute a heat of pyrolysis which compared well with the reported value cited above. Appendix G of Reference 2-20 lists the final recommended composition; the inferred heat of formation for this "best estimate" pyrolysis gas was not reported, however.

2.1.6 Specific Heat of Pyrolysis Gas

Using the "best estimate" pyrolysis gas composition obtained in the manner described in Section 2.1.5 above, Reference 2-20 reports frozen and equilibrium specific heats for the pyrolysis gas. These are plotted in Figure 2-6 and tabulated in Table 2-10.

2.1.7 Surface Oxidation Kinetics

The basic thermochemical ablation model of the CHAP code is one of carbon oxidation. At low temperatures, the oxidation rate is controlled by chemical kinetic factors, represented in the code by the relation

$$\dot{m}_c = A_k e^{-B_k/T_w} (C_w p_w)^n \tag{2-6}$$

The user must specify as input the pre-exponential factor A_k, the activation energy B_k, and the reaction order n.

The literature search did not discover any experimental work specifically aimed at quantifying the oxidation kinetic constants for nylon phenolic chars. Many experiments have of course been done on carbon oxidation kinetics, but since these are observed to depend strongly on the physical state of the surface and on small amounts of impurities in the carbon, it is not felt that the resulting data are particularly relevant to chars. For reference purposes, it is customary to use "Scala fast" kinetics (Reference 1-2), which are

$$n = 1/2$$

$$A_k = 6.73 \times 10^8 \text{ lb/ft}^2\text{sec atm}^{1/2}$$

$$B_k = 39{,}872^{\circ}R$$

An alternative set of "slower constants suggested in the contract work statement is

$$n = 1$$

$$A_k = 1 \times 10^{10} \text{ lb/ft}^2\text{sec-atm}$$

$$B_k = 76{,}500^{\circ}R$$

The CHAP code surface oxidation formulation of Reference 1-2 also introduces a constant λ representing the mass of char removed per mass of oxygen reacting at the surface. For a carbon char such as that of nylon phenolic, λ = 0.75, representing the ratio of the molecular weight of carbon to that of oxygen.

For very high temperatures, sublimation is an important mechanism of carbon removal. It is modeled in the CHAP code with an exponential law requiring input constants. The cases of interest in the current study all fall below sublimation temperatures; hence the literature review did not cover sublimation.

2.2 AVCOAT 5026-39-HC/G

The material designated Avcoat 5026-39 is a phenolic novolac reinforced with silica fibers and lightened with phenolic Microballoons. The manufacturer regards the exact composition of this material as proprietary information. When used as the Apollo heat shield material, the composition is hand-filled into the cells of a low density phenolic glass hexagonal honeycomb (HC) with an injection gun (G). Despite the important practical use of this material, property data are relatively scarce, particularly at high temperatures.* Furthermore, most existing data are obtainable only from informal reports published during periods of compressed schedules during the Apollo development program; consequently, much supporting detail has not been included in the reports.

Table 2-11 presents the data source summary information for Avcoat. Specific properties are discussed in the following subsections.

2.2.1 Thermal Conductivity

Table 2-12 summarizes the thermal conductivity source information for Avcoat. Figure 2-7 shows virgin material thermal conductivity up to 1400°R. Appreciable decomposition of Avcoat begins at about 1000°R; decomposition is nearly complete at 1400°R. Table 2-13 lists these virgin material conductivity data.

Table 2-14 and Figure 2-8 present Avcoat char thermal conductivity as a function of temperature. The data are sparse and scattered.

2.2.2 Specific Heat

Table 2-15 lists the summary data source information for Avcoat specific heat. Figure 2-9 shows specific heat data for both virgin material and a number of oven pre-chars for various charring temperatures, as well as some flight core data. The data show a good decreasing parametric trend of $C_p(T)$ curve-location with pre-char temperature. Table 2-16 lists these data.

2.2.3 Emittance

Table 2-17 presents the data source summary for Avcoat emittance. Table 2-18 and Figure 2-10 present the emittance data for Avcoat chars and one virgin sample charred during the test.

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*Apollo program reports (Refs. 2-21 - 2-24) were mostly concerned with flight core studies and basic ablation mechanism studies, with property value determination not having a central role. This emphasis resulted from an obvious priority assignment: the material response needed to be clarified before improved design computing procedures could be used.

2.2.4 Pyrolysis Kinetics

Reference 2-24 lists reduced TGA data for Avcoat 5026-39-HC/G, based on a single component model. These data are apparently based on Equation 2-1, although the discussion is unclear on this point. The data presented are as follows:

Test No.	k_o (sec^{-1})	E/R (°R)	n
T222	$.518 \times 10^5$	$.161 \times 10^5$	1.7
T223	$.232 \times 10^5$	$.151 \times 10^5$	1.7
T224	$.405 \times 10^5$	$.140 \times 10^5$	1.7
T225	$.258 \times 10^6$	$.181 \times 10^5$	2.0
T222/4	$.667 \times 10^7$	$.219 \times 10^5$	2.1
1488	$.786 \times 10^5$	$.143 \times 10^5$	2.0
C2/14	$.493 \times 10^9$	$.299 \times 10^5$	3.0

This data reduction apparently encompasses all worthwhile data collected previous to 1969, specifically including the unreduced TGA data reported in Reference 2-23.

2.2.5 Heats of Formation or Heat of Pyrolysis

No reduced heat of formation data were discovered. References 2-21 and 2-23 present some bomb calorimeter heat of combustion data, but these values may be influenced to an undetermined extent by reactions between silica and carbon in the char. Figure 2-11 shows these data.

No heat of pyrolysis data are reported in the literature.

2.2.6 Specific Heat of Pyrolysis Gas

The literature has no data on the pyrolysis gas of Avcoat 5026-39.

2.2.7 Surface Oxidation Kinetics

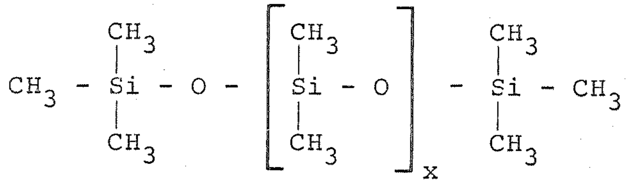
The general thermochemical ablation model of CHAP is discussed in Section 2.1.7. As was the case with nylon phenolic, no specific data covering the oxidation kinetics of Avcoat 5026-39-HC/G were discovered. The fast kinetics of Section 2.1.7 will be used for the initial Task II calculations.

In the case of Avcoat the quantity λ (the amount of char removed per lb of oxygen reacting at the surface) is twice the value for pure carbon since half the Avcoat char is silica, and it is assumed that as carbon is removed by oxidation, a corresponding amount of silica flows away from the surface in condensed form. Thus $\lambda = 2 \times 0.75 = 1.5$.

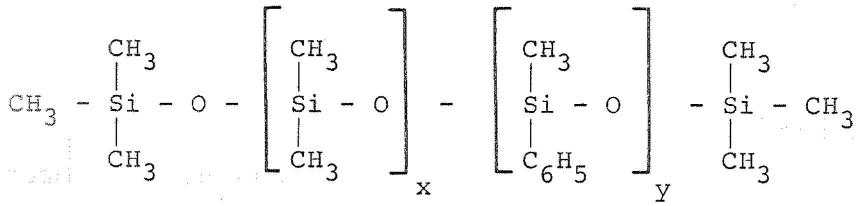
The ablation literature for Avcoat does not include a data analysis of sufficient extent to clarify whether this oxidation model will be an adequate representation.

2.3 SILICONE ELASTOMER

The silicone elastomer to be considered during this program is described in the Introduction to Section 2. Appropriate silicone elastomers for the material considered can vary in chemical make-up between polydimethyl siloxane and polymethylphenyl siloxane, which are illustrated in the following sketch:



Polydimethyl Siloxane Structure



Methylphenyl and Dimethylpolysiloxane copolymer

Usually the specific material featured in a data report will be specified only by the manufacturer's resin identification number. In most cases these are described simply as a dimethyl/methylphenyl product; the exact composition is not reported and indeed in most cases is not known. The data tabulations presented below identify the material in each case with all descriptions reported originally. Table 2-19 lists the general data source information.

2.3.1 Thermal Conductivity

Table 2-20 identifies the thermal conductivity source information for the silicone elastomers of interest here. Only virgin material conductivity data are reported in the literature. These are presented in Table 2-21 and Figure 2-12.

2.3.2 Specific Heat

Table 2-22 describes the specific heat data sources. Table 2-23 and Figure 2-13 give the C_p data uncovered for the filled silicone elastomer material. The data are sparse but agree fairly well if one low temperature point is neglected.

2.3.3 Emittance

Only one emittance data point is presented in the literature. Pope (Ref. 2-15) measured ε equal to 0.71 ± 0.05 over the range 1750 K° (3150°R) to 2200°K (3960°R) for an arc heated char. Tables 2-8 and 2-17 contain descriptions of Pope's experimental method.

2.3.4 Pyrolysis Kinetics

The only reduced TGA data reported are by Nelson (Ref. 2-11). For General Electric RTV-602 dimethyl polysiloxane, Nelson gives the following single component values:

k_o (sec^{-1})	E/R (°R)	n	ρ_r/ρ_o
5.33×10^{10}	39,135	1.0	0.040

Nelson also reports constants for the phenolic microspheres used with the elastomer compound of interest here; these data were listed under the identification "Phenolic II" in Section 2.1.4 above.

Potentially useful unreduced TGA curves were presented in References 2-25, 2-26, and 2-28. These are reproduced in Figures 2-14 through 2-17. Note that the material of Figure 2-14 is a filled composite of the type of interest here; the other figures are for silicone resins only.

2.3.5 Heats of Formation or Heat of Pyrolysis

No information of this type is available in the literature.

2.3.6 Specific Heat of Pyrolysis Gas

No information on the pyrolysis gas specific heat appears in the literature. The pyrolysis of silicone resins is a subject of some conjecture.

2.3.7 Surface Oxidation Kinetics and Melting

The general thermochemical ablation model of CHAP is discussed in Section 2.1.7. As was the case of nylon phenolic and Avcoat 5026-39-HC/G, no specific data covering the oxidation kinetics of the silicone elastomer material were discovered. The fast kinetics of Section 2.1.7 will be used for the initial Task II calculations.

The quantity λ (the amount of char removed per lb of oxygen reacting at the surface) is not well defined for this material. The contract gives a value of $\lambda = 0.1$ which is from earlier unpublished data correlation studies conducted by the NASA Langley Research Center.

The chars of the silicone elastomer materials appear to show melting at higher temperatures. The current version of the CHAP code does not include the fixed melt temperature option available in earlier versions of the code. Instead, melting must be simulated by an appropriate choice of sublimation constants. The literature to date contains no complete study which would verify the adequacy of such a model. Unpublished data correlation studies by the NASA Langley Research Center suggest melting at about $3800^{o}R$.

REFERENCES

2-1. Wilson, R. Gale, "Thermophysical Properties of Six Charring Ablators from 140° to 700°K and Two Chars from 800° to 3000°K," NASA TN D-2991, October 1965.

2-2. Engelke, W. T., Pyron, C. M., Jr., and Pears, C. D.,"Thermophysical Properties of a Low-Density Phenolic-Nylon Ablation Material," NASA CR-809, July 1967.

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TABLE 2-1

PROPERTY DATA SOURCES
LOW DENSITY NYLON PHENOLIC

Reference Identification	Ref. No.2-	Material Description	ρ_p	ρ_c	Pyrolysis Kinetics	Δh_f	h or C_p	Heat of Pyrolysis	C_p of Pyrolysis Gas	k	ε
Wilson, R. Gale	1	25% resin (UC)* 25% balloons 50% nylon powder (DuPont)	37.4 ± 0.1 lb/ft^3	13.1 lb/ft^3	None	No	Virgin: to 800°F, Char: 1000°F to 5000°F	No	No	Virgin: to 800°F Char: 900°F to 4500°F	Char 1400°F to 4000°F
Engelke, Pyron, Pears	2	25% resin (UC)* 35% balloons 40% nylon powder (DuPont)	36.5 ± 0.3 lb/ft^3	15 lb/ft^3	None	No	Virgin: -200°F to 600°F Char: 1000°F to 5000°F	No	No	Virgin: -200°F to 750°F Char: 1000°F to 5000°F	
Smyly, Pyron, Pears	3 4	25% resin (UC)* 35% balloons 40% nylon powder (DuPont)	19, 30, & 42 lb/ft^3	12 ± 0.3, 16.9 ± 0.8, 19.9 ± 0.2 lb/ft^3	None	No	No	No	No	Chars: 400°F to 1000°F with different gases at different pressures	No
Kratsch, Hearne, McChesney	5	50% resin 50% nylon cloth	75.6 lb/ft^3	18.8 lb/ft^3	Yes - 3 component model	-1311 Btu/lb (virgin)	Char: 0 to 5000°R	No	No	Char: 500°R to 5000°R approximate virgin data; data for partial degradation zone	Char 2300°R to 3900°R
Sanders, Smyly, Pears	6	37% resin (Hughes) 23% balloons 40% nylon powder (DuPont)	38.0-34.9 lb/ft^3	15.6-18.7 lb/ft^3	None	No	No	No	No	Char 720°R to 5460°R	No
Rindal, Kratsch	7	40% resin and balloons 60% nylon fabric ρ_p ≈ 35 lb/ft^3 ρ_c ≈ 15 lb/ft^3	No	No	No	No	Virgin: 460°R-260°R Char: 500°R-5500°R	No	No	Virgin: 460°R-1260°R Char: 500°R-5500°R	No
Lagedrost, J.F.	8	37% resin 23% balloons 40% nylon (Hughes 4 & 5)	33.7 ± 1.2 lb/ft^3	No	No	No	Virgin: 0-240°C Char: (400°C): 0-400°C	No	No	Virgin: 20-300°C Char: (400°C): 20-400°C	No
		25% resin 35% balloons 40% nylon (Langley)	34.4 lb/ft^3	No	No	No	Virgin: 0-240°C	No	No	Virgin: 0°C-480°C Char: (1000°C) 100-500°C	No
Nagler, R.G.	9 10	50% resin 50% nylon	No	No	No	No	No	No	No	Char: 1050°R-3250°R	No
Nelson, J.B.	11	Resin (UC)* Balloons (UC)* Nylon (DuPont)	No	No	TGA data for all three; resins expressed as three components; nylons as one	No	No	No	No	No	No
Farmer, R.W.	12	Phenolic resins	No	No	Reduced TGA data, survey	No	No	No	No	No	No
Goldstein, H.E.	13 14	Nylon 6 & CTL-91 LD resin;w/analysis	No	0.50 ρ_p for phenolic	No	Yes	No	No	No	No	No
Pope	15	Low density nylon phenolic	No	No	No	No	No	No	No	No	Char: 1900°K 2400°K
Wilson, R.Gale & Spitzer, C.R.	16 17 18	Low density nylon phenolic 25% resin, 35% balloons, 40% nylon; 25,25 & 50%	No	No	No	No	No	No	No	No	Char: 2900°K .3μm to 2.5μm
Sykes, G.F., Jr.	19	Phenol-formaldahyde resin, (UC)* BRP-5549	No	No	No	No	No	Yes	No	No	No
Pike, April,	20	60% phenolic resin 40% nylon	No	No	No	Yes	No	Yes	Calculation for frozen & equilibrium cases from measured pyrolysis gas composition	No	No

*UC = Union Carbide

TABLE 2-2

THERMAL CONDUCTIVITY SOURCES
LOW DENSITY NYLON PHENOLIC

Reference Identification	Ref. No.2-	Material Description	Material State & Preparation	Vacuum Conditions	Temperature Range of Measurements	Experimental Method	Reported Accuracy	Estimated Accuracy
Wilson, R. Gale	1	25% resin (UC)* 25% balloons 50% nylon powder (DuPont)	Virgin, ρ_p = 37.4 ± 0.1 lb/ft^3	Not described	-269°F to 480°F	Radial outflow, 1" OD x 1" specimen (Melpar)	Not given	± 5%
					-267°F to 923°F	Guarded hot plate, 3"D specimen (SoRI)*		
			Char, 3"D disks exposed to arc-heated nitrogen, 100 Btu/ft^{2}sec for 120 seconds, surface temperature about 3000°F, 1/4" char produced		797°F to 4360°F	Hybrid apparatus, radial inflow through four symmetrically located strips 1/4" x 1/2" x 2-1/4"	Not given	± 20%
Engelke, Pyron, Pears	2	25% resin (UC)* 35% balloons 40% nylon powder (DuPont)	Virgin, ρ_p = 36.5 ± 0.3 lb/ft^3	1 atm helium	-242°F to 821°F	Guarded hot plate, 3"D specimen	Not given	± 15%
			Char, 3"D disks exposed to arc-heated nitrogen, 140 Btu/ft^{2}sec for 90 seconds	Not described	814°F to 4925°F	Hybrid apparatus, radial inflow through four symmetrically located strips 3/8" x 3/16" x 2"	Not given	± 20% (Cooling curve factor of two higher - due to cracking?)
Smyly, Pyron, Pears	3 4	25% resin (UC)* 35% balloons 40% nylon powder (DuPont)	Char, 1¼"D disks exposed to induction heated mixture of 30% nitrogen and 70% argon at 170 Btu/ft^2 sec for 125-130 seconds, T_w = 4200°F	Vacuum, nitrogen at 1 atm, and helium at 1 atm	237°F to 1073°F	Guarded comparative rod 1"OD specimens	± 10% with poss. bias of 15%	Accept report
Kratsch, Hearne, McChesney	5	50% resin 50% nylon cloth	ρ_p = 75.6 lb/ft^3 charred to 18.8 lb/ft^3 at 3 temperatures: 1460°R, 2460°R, 3460°R	Not described	500°R to 4500°R	Not described	Not given	± 15%
Sanders, Smyly, Pears	6	37% resin (Hughes) 23% balloons 40% nylon powder (DuPont)	ρ_p = 38.0 to 34.9 lb/ft^3 ρ_c = 15.6 to 18.7 lb/ft^3 Furnace chars performed slowly to different temperatures, one rapid char to 5460°R at about 430 Btu/ft^{2}sec	1 atm argon	500°R to 5400°R	Most data: hybrid radial in flow through four symmetrically located strips 3/8" x 5/16" x 2"	± 7% with poss. bias of + 4%	Accept report
Rindal, Kratsch	7	40% resin 60% nylon fabric ρ_p = 35 lb/ft^3 ρ_c = 15 lb/ft^3	Virgin and char; otherwise not described	Not described	Virgin: 460°R to 1260°R Char: 500°R to 5500°R	Not described	Not given	Unknown
Lagedrost, J.F.	8	37% resin 23% balloons 40% nylon (Hughes 4 & 5)	Virgin	Vacuum and 1 atm argon	200°R to 300°C	Guarded hot plate, 3"D x 1/2"	Not given	± 10%
		25% resin 35% balloons 40% nylon (Langley)	Virgin and char prepared by unspecified means at about 1000°C (2290°R)	Virgin: 1 atm argon Char: Vacuum	Virgin: 0°C-480°C Char: 100°C-500°C	Guarded hot plate, 3"D x 1/2"	Not given	Virgin: ± 20% Char: ± 50%
Nagler, R.G.	9 10	Resins 50% Nylon 50% "low density"	Charred in oxy-acetylene torch at about 2000 Btu/ft^{2}sec	Not described	1050°R to 1250°R	Helium arc and oxy-acetylene torch transient exposures, thermocouple responses matched with heat conduction computer code	± 13%	

*UC = Union Carbide
SoRI = Southern Research Institute

TABLE 2-3

THERMAL CONDUCTIVITY VS TEMPERATURE LOW DENSITY ($\rho_p \approx 35$ lb/ft^3) NYLON PHENOLIC VIRGIN MATERIAL

	Units: 10^{-5} Btu/sec ft °R						
Reference	2-1	2-1	2-2	2-7	2-8	2-8	2-8
Material Resin/Balloons/Nylon	25/25/50	25/25/50	25/35/40	40/60	37/23/40	37/23/40	25/35/40
Temperature (R)	Run 1	Run 2	Run 1	Run 1	Run 1	Run 2	Run 1
160	1.556						
200	1.561	1.106	1.250				
250	1.593	1.361	1.308				
300	1.661	1.547	1.450				
350	1.842	1.686	1.700				
400	2.014	1.792	1.380				
450	1.630	1.872	1.286	1.253			1.250
500	1.486	1.939	1.278	1.278	1.633	2.480	1.278
550	1.428	1.992	1.278	1.292	1.683	2.089	1.294
600	1.417	2.025	1.286	1.311	1.722	1.889	1.311
700	1.419	2.056	1.342	1.347	1.775	1.675	1.344
800	1.467	2.044	1.383	1.383	1.780	1.611	1.383
900	1.583	1.992	1.422	1.422	1.783		1.464
1000	1.689	1.894	1.458	1.458	1.783		1.606
1100	1.694		1.483	1.497			1.814
1200	1.694		1.500	1.530			2.094
1300	1.694		1.508	1.569			2.475
1400	1.694						3.008

TABLE 2-4

THERMAL CONDUCTIVITY VS. TEMPERATURE
LOW DENSITY NYLON PHENOLIC CHARS

UNITS: 10^{-4} Btu/secft°R

Reference:	2-1	2-2	2-3	2-3	2-3	2-3	2-3	2-3	2-5	2-5	2-5
Material: (Resin/Balloons/Nylon)	25/25/50	25/35/40	25/35/40						50/50	50/50	50/50
Nominal ρ_p (lb/ft³)	37	37	19	30	42	19	30	42	76	76	76
Nominal ρ_c (lb/ft³)	13	15	12	17	20	12	17	20	19	19	19
Pre-Char Temperature: (°R)	3500	?	4200	--	--	4200	--	--	1460	2460	3460
Charring Heat Flux: (Btu/ft sec)	100	140	170	--	--	170	--	--	?	?	?
Vacuum: (1 atm)	Helium	?	Vacuum	Vacuum	Vacuum	Helium	Helium	Helium	?	?	?
Temp (°R)											
500									0.186	0.680	3.611
750			0.944	0.825	1.356	1.944	2.147	1.944	0.242	1.900	3.633
1000	1.467		0.944	0.999	1.439	2.061	2.278	2.355	0.347	1.967	3.666
1250	1.694	1.142	0.944	1.158	1.506	2.180	2.411	2.739	0.469	2.022	3.722
1500	1.925	1.164	0.944	1.317	1.564	2.272	2.544	3.111	0.647	2.130	3.786
1750	2.167	1.217							0.856	2.278	3.844
2000	2.403	1.283							1.130	2.450	3.953
2250	2.666	1.383							1.494	2.666	4.064
2500	2.916	1.525							1.906	2.950	4.222
3000	3.480	1.928							2.972	3.694	4.703
3500	4.094	2.536							4.200	4.805	5.444
4000	4.814	3.455							5.514	6.028	6.514
4500	5.694	4.578							6.889	7.355	7.728
4750	6.416	5.275									
5000		6.022									
5250		6.869									

Reference:	2-6	2-6	2-6	2-6	2-6	2-6	2-6	2-7	2-8	2-9
Material: (Resin/Balloons/Nylon)	37/23/40	37/23/40	37/23/40	37/23/40	37/23/40	lower	upper	40/60	25/35/40	50/50
Nominal ρ_p (lb/ft³)	35	35	35	35	35	35	35	35	34	35?
Nominal ρ_c (lb/ft³)	17	17	17	17	17	17	17	15	?	?
Pre-Char Temperature: (°R)	1460	2460	3460	4460	5460	5460	5460	?	2300	?
Charring Heat Flux: (Btu/ft sec)	Low	Low	Low	Low	Low	430	430	?	?	2000
Vacuum: (1 atm)	Argon	Argon	Argon	Argon	Argon	Argon	Argon	?	Vacuum	?
Temp (°R)										
500	0.183	0.589								
750	0.214	0.653			3.533	6.772			0.5166	
1000	0.297	0.744	1.611	2.122	3.550	6.619		1.467	0.6110	1.344
1250	0.389	0.839	1.739	2.167	3.566	6.480		1.694	0.6610	0.7860
1500	0.503	0.944	1.872	2.244	3.605	6.350		1.925	0.6868	0.6222
1750	0.564	1.067	2.050	2.353	3.658	6.233	10.325	2.167		0.6610
2000	0.800	1.283	2.239	2.480	3.708	6.136	9.300	2.403		0.7222
2250	0.997	1.411	2.455	2.639	3.792	6.055	8.528	2.666		0.7860
2500	1.222	1.630	2.833	2.828	3.897	5.991	7.866	2.916		0.8555
3000	1.744	2.186	3.289	3.297	4.194	5.953	7.228	3.480		1.0110
3500	2.444	2.947	3.936	3.936	4.611	6.022	7.086	4.094		1.1999
4000	3.325	3.880	4.650	4.650	5.186	6.203	7.205	4.814		
4500	4.494	4.916	5.416	5.416	5.939	6.480	7.389	5.694		
4750	5.122	5.464	5.819	5.819	6.341	6.653	7.502	6.413		
5000	5.833	6.022	6.222	6.222	6.769	6.855	7.630			
5250	6.611	6.639	6.639	6.639	7.222	7.097	7.778			

TABLE 2-5

SPECIFIC HEAT SOURCES
LOW DENSITY NYLON PHENOLIC

Reference Identification	Ref. No.2-	Material Description	Material State & Preparation	Temperature Range of Measurements	Experimental Method	Reported Accuracy on C_p	Estimated Accuracy on C_p
Wilson, R.Gale	1	25% resin (UC)* 25% ballons 50% nylon powder	Virgin, ρ_p = 37.4 ± 0.1 lb/ft^3	$-200^{o}F$ to $750^{o}F$	Bunsen ice calorimeter, enthalpy measurement; sample 1/2" D x 1" (Melpar) Dry drop calorimeter enthalpy measurement, samples 3/4" cubes (SoRI)*	Not given	± 10%
			Char, 3" D disks exposed to arc heated nitrogen, 100 Btu/ft^2sec for 120 seconds, surface temperature about $3000^{o}F$, 1/4" char produced	$-320^{o}F$ to $799^{o}F$	Drop type ice calorimeter, enthalpy measurement	Not given	± 10%
Engelke, Pyron, Pears	2	25% resin (UC)* 35% balloons 40% nylon powder (DuPont)	Virgin, ρ = 36.5 ± 0.3 lb/ft^3		Dry drop calorimeter, enthalpy measurement $-262^{o}F$ to $790^{o}F$		
			Char, 3" D disks exposed to arc-heated nitrogen, 140 Btu/ft^2sec for 90 seconds		Drop type ice calorimeter, enthalpy measurement $1025^{o}F$ to $5055^{o}F$	Not given	± 10%
Kratsch, Hearne, McChesney	5	50% resin 50% nylon cloth	Virgin, ρ_p = 75.6 lb/ft^3 Char, ρ_p = 18.8 lb/ft^3	Virgin: $200^{o}R$ to $1000^{o}R$ Char:	Not described	Not given	Unknown
Rindal, Kratsch	7	40% resin 60% nylon fabric	Virgin and char; otherwise not described	Virgin: $460^{o}R$ to $1260^{o}R$ Char: $500^{o}R$ to $6000^{o}R$	Not described	Not given	Unknown
Lagedrost, J.F.	8	37% resin 23% balloons 40% nylon (Hughes 4 & 5)	Virgin and $400^{o}C$ ($1210^{o}R$) char	Virgin: $0^{o}F$ to 24 $240^{o}C$ Char: $0^{o}C$ to $400^{o}C$	Bunsen ice calorimeter, enthalpy measurement	Not given (± 10% on enthalpy)	± 10%
		25% resin 35% balloons 40% nylon (Langley)	Virgin, 34.4 lb/ft^3	$0^{o}C$ - $240^{o}C$	Bunsen ice calorimeter, enthalpy measurement	Not given (± 10% on enthalpy)	± 10%

*UC = Union Carbide
SoRI = Southern Research Institute

TABLE 2-6

SPECIFIC HEAT VS TEMPERATURE - LOW DENSITY NYLON PHENOLIC VIRGIN MATERIAL

Units: Btu/lb°R

Reference	2-1	2-1	2-2	2-5	2-7	2-8	2-8	2-8
Material: (Resin/Balloons/ Nylon)	25/25/50	25/25/50	25/35/40	50/50 (75.6 lb/ft³)	40/60	37/23/40	37/23/40 (400 C°Char)	25/35/40
Temp (°R)								
200				0.060				
250	0.158	0.201	0.191	0.097	0.191			
300	0.193	0.217	0.209	0.141	0.209			
350	0.226	0.237	0.252	0.198	0.252			
400	0.260	0.259	0.282	0.289	0.282			
450	0.293	0.284	0.311	0.355	0.311			
500	0.311	0.314	0.338	0.396	0.338	0.256	0.267	0.242
550	0.357	0.347	0.367	0.426	0.367	0.297	0.286	0.313
600	0.387	0.385	0.395	0.447	0.395	0.338	0.307	0.384
650	0.417	0.426	0.422	0.466	0.422	0.381	0.326	0.451
700	0.448	0.475	0.447	0.478	0.447	0.421	0.347	0.521
750	0.478	0.501	0.471	0.486	0.471	0.463	0.367	0.587
800	0.506	0.528	0.496	0.489	0.496	0.505	0.388	0.618
850	0.535	0.552	0.519	0.489	0.519	0.546	0.410	0.638
900	0.564	0.567	0.539	0.489	0.539	0.587	0.432	0.648
950	0.592	0.578	0.553	0.489	0.553	0.627	0.454	0.650
1000	0.621	0.583	0.564	0.489	0.564		0.476	
1050	0.648	0.584	0.568		0.568		0.500	
1100	0.677	0.583	0.570		0.570		0.523	
1150	0.705	0.583	0.570		0.570		0.548	
1200	0.733						0.573	

TABLE 2-7

SPECIFIC HEAT VS TEMPERATURE - LOW DENSITY NYLON PHENOLIC CHARS

Units: Btu/lb°R

Reference	2-1	2-2	2-5	2-7
Material (Resin/Balloons/ Nylon)	25/25/50	25/35/40	50/50	40/60
Temp (R)				
500			0.150	0.100
750			0.233	0.187
1000	0.260		0.304	0.268
1250	0.332		0.362	0.335
1500	0.406	0.395	0.413	0.402
1750	0.469	0.446	0.459	0.458
2000	0.503	0.478	0.494	0.484
2250	0.516	0.502	0.524	0.497
2500	0.520	0.517	0.548	0.500
2750	↓	0.528	0.568	↓
3000		0.531	0.583	
3250		0.536	0.596	
3500		0.540	0.606	
3750		0.542	0.614	
4000		0.546	0.620	
4250		0.548	0.624	
4500		0.552	0.626	
4750		0.555	0.628	
5000		0.558	0.628	
5250		0.561		
5500		0.565		

TABLE 2-8

EMISSIVITY (EMITTANCE) SOURCES
LOW DENSITY NYLON PHENOLIC

Reference Identification	Ref. No.2-	Material Description	Material State & Preparation	Temperature Range of Measurements	Experimental Method	Reported Accuracy	Estimated Accuracy
Wilson, R. Gale	1	25% resin (UC)* 25% balloons 50% nylon powder (DuPont)	Char, 3"D disks exposed to arc-heated nitrogen, 100 Btu/ft^{2}sec for 120 seconds, surface temperature about 3000°F, 1/4" char produced	1468°F to 3861°F	Blackbody comparison with radiometer, sample 1/2"D 3/16" to 1/8" thick, sample temp. by thermocouple and pyrometer, ε discovered by trial and error to convergence (assumed grey body)	Not given	± 5%
Engelke, Pyron, Pears	2	25% resin (UC)* 35% balloons 40% nylon powder (DuPont)	Char, 3"D disks exposed to arc-heated nitrogen, 140 Btu/ft^{2}sec for 90 seconds	1524°F to 3913°F	Same as Reference 1	Not given	± 5%
Kratsch, Hearne, McChesney	5	50% resin 50% nylon cloth	Char	2300°R to 4500°R	Not described	Not given	Unknown
Pope	15	Low density nylon phenolic	Char, produced in arc-heated stream	1900°K to 2400°K	Simultaneous measurements with total pyrometer and monochromatic pyrometer plus grey body assumption allows determination of ε_{normal} and surface temperature. Lambert law assumed.	±10% plus unknown bias due to grey body assumption, gas radiation, etc. Grey body assumption may cause data to be 5% to 10% low	Accept report
Wilson, R. Gale, & Spitzer, C.R.	16 17 18	Low density nylon phenolic a. 25% phenolic 35% balloons 40% nylon b. 25% phenolic 25% balloons 50% nylon ρ_p = 37 lb/ft^3 ρ_{c_a} = 15 lb/ft^3 ρ_{c_b} = 13 lb/ft^3	Arc-jet chars, 1/2"D 1/4" thick a. 140 Btu/ft^{2}sec, 90 seconds b. 100 Btu/ft^{2}sec, 120 seconds	2900°K (5220°R) in range .25 to 2.5 μm	Arc-image reflectance measurement at various wavelengths; measures arc intensity, sample intensity with arc on (measuring emission + reflection), sample intensity with arc off (giving emission for subtraction)	± 2%	± 3%

*UC = Union Carbide

TABLE 2-9

EMITTANCE - LOW DENSITY NYLON PHENOLIC CHARS

Reference	2-1	2-2	2-5	2-15	2-15	2-16
Temp (°R)						
2000	0.852	0.792				
2250	0.872	0.818				
2500	0.883	0.840	0.600			
2750	0.924	0.857	↓			
2900	0.931	0.865				
3000	0.927	0.870				
3100	0.911	0.874				
3250	0.876	0.878				
3500	0.775	0.880		0.670	0.660	
3650	0.716	0.878		↓	↓	
3750	0.711	0.874				
3850	0.759	0.870				
4000	0.837	0.858	0.616			
4100	0.866	0.850	0.632	0.670		
4200	0.883	0.837	0.650			
4300	0.893	0.825	0.666		0.660	
4500	0.900	0.791	0.700			
5225						0.812

TABLE 2-10

COMPUTED SPECIFIC HEAT OF "BEST ESTIMATE" PYROLYSIS OF LOW DENSITY NYLON PHENOLIC

(40% Nylon, 60% Phenolic Resin)

Reference - 2-20

Temperature (°R)	Frozen (Btu/lb°R)	Equilibrium (Btu/lb°R)
-200	0.450	0.483
0	0.547	0.552
250	0.615	0.670
500	0.680	0.772
750	0.746	0.862
1000	0.803	0.921
1250	0.862	0.962
1500	0.907	0.987
1750	0.940	1.006
2000	0.960	1.018
2250	0.978	1.027
2500	0.997	1.035

TABLE 2-11

PROPERTY DATA SOURCES
AVCOAT 5026-39-HC/G

Reference Identification	Ref. No.2-	Material Description	ρ_p	ρ_c	Pyrolysis Kinetics	Δh_f	h or C_p	k	$\bar{\varepsilon}$
Wilson, R. Gale,	1	Virgin only	33.1 lb/ft^3	---	No	No	Both to 800^oF	Virgin to 8000^oF	No
Ihnat, M. E. (9/66)	21	Virgin and oven pre-chars	Various	Various	No	Heat of combustion	C_p from -2000^oF to 1000^oF for virgin and various pre-char temperature chars	Virgin: -300^oF to 1000^oF Chars: 100^oF to 1100^oF for various pre-char temperatures up to 2000^oF	No
Ihnat, M. E. (8/67)	22	Virgin, arc core samples, flight core samples	Various	Various	No	No	Single drop calorimeter value, direct measurement (200^oF to 930^oF) of specific heat	Virgin: 100^oF to about 400^oF Chars: 1000^oF to 400^oF for various inferred pre-char temperatures	No
Alexander, J.G., et al. (7/68)	23	Flight 501 (Spacecraft 017) cores, and virgin samples plus oven chars to 4500^oF	Various	Various	Unreduced TGA data	Heat of combustion	Virgin and char to about 800^oF but not directly associated with pre-char temperatures, virgin and oven char to 800^oF	Virgin and char from about 100^oF to 500^oF; char values at 1930^oF to 2080^oF, not directly related to pre-char temperature	100^oF to 1900^oF
Alexander, J.G., et al (9/69)	24	Flight 502, 205, 503 cores, virgin samples and oven chars to 4000^oF	Various	Various	Reduced TGA data	Heat of combustion	Virgin and oven chars various pre-char temperatures (to 400^oF) from 0^oF to 400^oF; flight cores to 800^oF	Flight cores from 1350^oF to 2150^oF, not explicitly related to pre-char temperatures	No
Pope, R. B.	15	Arc char	No	No	No	No	No	No	Char in range 1950^oK to 2400^oK
Wilson, R.Gale, Spitzer, C.R.	16 17 18	Arc char	33 lb/ft^3	---	No	No	No	No	One value at 2950^oK

TABLE 2-12

THERMAL CONDUCTIVITY SOURCES
AVCOAT 5026-39-HC/G

Reference Identification	Ref. No.2-	Material Description	Material State & Preparation	Temperature Range of Measurements	Experimental Method	Reported Accuracy on C_p	Estimated Accuracy
Wilson, R. Gale	1	Laboratory Sample	Virgin only $\rho_p = 33.1$ lb/ft^3	-22^oF to 733^oF	Bunsen ice calorimeter, enthalpy measurement, sample 1/2" D x 1" (Melpar)	Not given	± 10%
Ihnat, M.E. (9/66)	21	Laboratory Sample $\rho_p = 29.1$ to 31.4 lb/ft^3	Virgin and oven prepared chars at 1000^oF & 1750^oF, .37"D x 1"	-320^oF to 1010^oF	Water calorimeter (ASTM)	Not given	± 10%
Ihnat, M.E. (8/67)	22	Cores from spacecrafts 009 and 011, one virgin specimen	Virgin specimen & flight cores; virgin and char zone samples of about 30 mg size	100^oF to 932^oF	Perkin-Elmer differential scanning calorimeter (electrically heated calorimeter); one virgin sample - water calorimeter measurement	Not given	± 30%
Alexander, J.G. et al. (7/68)	23	Flight 501 (Spacecraft 017) cores, laboratory samples	Flight cores: virgin & char zone samples of about 30 mg size; oven chars produced at 2000^oF, 2500^oF, 3500^oF, 4000^oF, 4500^oF	cores: 200^oF to 800^oF chars: 200^oF to 800^oF	Perkin-Elmer diferential scanning calorimeter	Not given	± 10%
Alexander, J.G. et al. (9/69)	24	Flight 502, 205, 503 cores; and laboratory samples	Flight cores - small specimens covering char, pyrolysis, & virgin zones	70^oF to 930^oF	Perkin-Elmer differential scanning calorimeter	Not given	± 30%
			Oven specimens, same as used in Ref. 18; 3/4"D x 1"	1000^oF to 3500^oF	Adiabatic water calorimeter built from modified Parr bomb calorimeter	± 6% on enthalpy	± 10%

TABLE 2-13

THERMAL CONDUCTIVITY, AVCOAT 5026-39-HC/G - VIRGIN MATERIALS AND LOW TEMPERATURE CHARS

Units: 10^{-5} Btu/sec ft °R

Reference	2-1	2-4	2-21	2-21	2-21	2-21	2-22	2-22	2-22	2-22	2-23	2-23
Pre Char Temp (R)	Virgin	Virgin	1460	1660	1960	2210	Virgin	Virgin/ Vacuum	Lower	Upper	Lower	Upper
Temp (°R)												
260	0.817	0.925	0.611	0.925		1.389						
350	0.953	1.133	0.775	1.133		1.750						
450	1.092	1.322	0.906	1.322		2.089						
560	1.242	1.478	1.000	1.478		2.397	2.086	1.247	2.500	3.333	0.694	2.222
650	1.353	1.564	1.053	1.564	2.703	2.606	2.147	1.175	↓	↓	↓	↓
750	1.467	1.630	1.100	1.630	2.836	2.792	1.883	1.097	↓	↓	↓	↓
860	1.589	1.667	1.128	1.667	2.953	2.950	1.406	1.000	2.500	3.333	0.694	2.222
950	1.675	1.672	1.142	1.672	3.022	3.067	1.389					
1000	1.700	1.672	1.136	1.672	3.047	3.117						
1050	1.683	1.669	1.130	1.669	3.064	3.158						
1100	1.630		1.119	1.667	3.080	3.189						
1150	1.567		1.114	1.667	3.083	3.214						
1200	1.480		1.100	1.667	↓	3.222						
1260	1.342		1.080	1.661	↓	3.225						
1300			1.072	1.647	↓	3.222						
1350			1.050	1.614	↓	3.219						
1400			1.028	1.564	↓	3.214						
1460			1.000	1.461	3.083	3.197						

TABLE 2-14

THERMAL CONDUCTIVITY, AVCOAT 5026-39-HC/G - CHARRED PORTIONS OF FLIGHT AND ARC CORES AND ONE 2460°R OVEN CHAR

Units: 10^{-4} Btu/sec ft °R

Reference	2-21	2-22	2-22	2-23	2-23	2-23	2-23	2-24	2-24	2-24	2-24	2-24	2-24
				a	a	b	b	a	a	b	b	c	c
	2460°R Char	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Temp (°R)													
620		0.269	0.917	0.139	1.333								
840		0.269	0.917	↓	↓								
1020				0.139	1.333								
1120	0.511												
1220	0.542												
1320	0.567												
1420	0.592												
1520	0.614					0.383							
1620	0.636					0.453							
1720	0.658					0.522							
1820	0.678					0.603		1.003		0.647	1.167		
1920	0.697					0.681	1.842	1.047	2.872	0.703	1.175		
2020	0.722					0.769	1.931	1.100	2.919	0.778	1.217		
2120	0.733					0.861	2.075	1.167	2.969	0.800	1.283	1.031	1.642
2220						0.972	2.306	1.256	3.022	0.806	1.383	1.050	1.908
2320						1.111	2.861	1.383	3.067			1.067	2.150
2400						1.244	3.233	1.547	3.106			1.081	2.333
2500							4.633		3.153			1.094	2.553
2600									3.200			1.114	2.750

TABLE 2-15

SPECIFIC HEAT SOURCES
AVCOAT 5026-39-HC/G

Reference Identification	Ref. No.2-	Material Description	Material State & Preparation	Temperature Range of Measurements	Experimental Method	Reported Accuracy on C_p	Estimated Accuracy
Wilson, R. Gale	1	Laboratory Sample	Virgin only ρ_p = 33.1 lb/ft^3	$-22^{\circ}F$ to $733^{\circ}F$	Bunsen ice calorimeter, enthalpy measurement, sample 1/2" D x 1" (Melpar)	Not given	± 10%
Ihnat, M.E. (9/66)	21	Laboratory Sample ρ_p = 29.1 to 31.4 lb/ft^3	Virgin and oven prepared chars at $1000^{\circ}F$ & $1750^{\circ}F$, .37"D x 1"	$-320^{\circ}F$ to $1010^{\circ}F$	Water calorimeter (ASTM)	Not given	± 10%
Ihnat, M.E. (8/67)	22	Cores from spacecrafts 009 and 011, one virgin specimen	Virgin specimen & flight cores; virgin and char zone samples of about 30 mg size	$100^{\circ}F$ to $932^{\circ}F$	Perkin-Elmer differential scanning calorimeter (electrically heated calorimeter); one virgin sample - water calorimeter measurement	Not given	± 30%
Alexander, J.G. et al. (7/68)	23	Flight 501 (Spacecraft 017) cores, laboratory samples	Flight cores: virgin & char zone samples of about 30 mg size; oven chars produced at $2000^{\circ}F$, $2500^{\circ}F$, $3500^{\circ}F$, $4000^{\circ}F$, $4500^{\circ}F$	cores: $200^{\circ}F$ to $800^{\circ}F$ chars: $200^{\circ}F$ to $800^{\circ}F$	Perkin-Elmer diferential scanning calorimeter	Not given	± 10%
Alexander, J.G. et al. (9/69)	24	Flight 502, 205, 503 cores; and laboratory samples	Flight cores - small specimens covering char, pyrolysis, & virgin zones	$70^{\circ}F$ to $930^{\circ}F$	Perkin-Elmer differential scanning calorimeter	Not given	± 30%
			Oven specimens, same as used in Ref. 18; 3/4"D x 1"	$1000^{\circ}F$ to $3500^{\circ}F$	Adiabatic water calorimeter built from modified Parr bomb calorimeter	± 6% on enthalpy	± 10%

TABLE 2-16

SPECIFIC HEAT VS TEMPERATURE, AVCOAT 5026-39-HC/G

Units: Btu/lb°R

Ref.	2-1	2-22 Virgin Lower	2-22 Virgin Upper	2-23 Char Core Lower	2-23 Char Core Upper	2-24 1460°R Oven Char	2-24 2460°R Oven Char	2-24 3460°R Oven Char	2-24 3960°R Oven Char	2-24 4460°R Oven Char	2-24 Char Core Lower	2-24 Char Core Upper	2-24 Envelope
Temp (°R)													
210													0.370
260	0.192												
360	0.277												
460	0.345					0.175	0.209	0.176	0.169	0.140			
560	0.395					0.206	0.216	0.185	0.181	0.159			
660	0.429	0.270	0.400	0.110	0.330	0.237	0.225	0.195	0.195	0.180	0.110	0.260	
710	0.439	↓	↓	↓	↓	0.253	0.227	0.200	0.201	0.190	↓	↓	
860	0.461	↓	↓	↓	↓	0.300	0.238	0.215	0.220	0.283	↓	↓	
960	0.469	0.270	0.400	↓	↓	0.332	0.246	0.225	0.234	0.243	↓	↓	
1060	0.475			↓	↓	0.339	0.257	0.231	0.246	0.263	↓	↓	
1160	0.476			↓	↓	0.347	0.268	0.246	0.257	0.285	↓	↓	
1260				0.110	0.330	0.354	0.278	0.257	0.270	0.306	0.110	0.260	
1360						0.362	0.290	0.243	0.287	0.328			
1460						0.369	0.300	0.278	0.295	0.350			0.370
1600							0.316	0.291	0.307	0.373			0.375
1800							0.335	0.307	0.325	0.407			0.383
1960							0.350	0.319	0.339	0.435			0.389
2000							0.355	0.322	0.342	0.439			0.391
2200							0.378	0.329	0.353	0.459			0.398
2460							0.410	0.350	0.369	0.485			0.410
2600								0.357	0.375	0.485			0.407
3000								0.377	0.390	0.485			0.399
3500								0.388	0.400	0.485			0.390
4000									0.400	0.485			0.400

TABLE 2-17

EMISSIVITY (EMITTANCE) SOURCES
AVCOAT 5026-39-HC/G

Reference Identification	Ref. No. 2-	Material Description	Material State & Preparation	Temperature Range of Measurements	Experimental Method	Reported Accuracy	Estimated Accuracy
Alexander, J.G., et al. (7/68)	23	Laboratory Samples	Virgin material charred during emittance test, & $2000^{\circ}F$ oven chars	$100^{\circ}F$ to $600^{\circ}F$ for virgin material, $250^{\circ}F$ to $1900^{\circ}F$ for chars	Not described	Not given	± 5%,
Pope, R.B.	15	Laboratory samples	Char produced in arc-heated stream	$1900^{\circ}F$ to $2400^{\circ}K$	Simultaneous measurements with total pyrometer & monochromatic pyrometer plus grey body assumption allows determination of ε normal & surface temperature. Lambert law assumed.	± 10% plus unknown bias due to grey body assumption, gas radiation, etc., Grey body assumption may cause data to be 5% to 10% low.	Accept Report
Wilson, R.Gale & Spitzer, C.R.	16 17 18	$\rho_p = 33\ lb/ft^3$	Arc jet produced char in nitrogen at 120 Btu/ft^2sec for 60 seconds	$2950^{\circ}K$ ($5320^{\circ}R$) in range 0.25 to 2.5μm	Arc-image reflectance measurement at various wavelengths; measures arc intensity, samples intensity with arc on (measuring emission + reflection); sample intensity with arc off (giving emission for subtraction)	± 2%	± 3%

TABLE 2-18

EMITTANCE VS TEMPERATURE

AVCOAT 5026-39-HC/G

Reference Temp	2-15	2-16	2-23 Charred During Test	2-23 2460°R Char
650				0.828
700			0.960	0.822
750			0.943	0.814
1000			0.863	0.778
1075			0.841	0.767
1250				0.743
1500				0.708
1750				0.673
2000				0.638
2250				0.603
2450				0.574
3400	0.630			
3750	↓			
4000	↓			
4300	0.630			
5400		0.720		

TABLE 2-19

PROPERTY DATA SOURCES
FILLED SILICONE ELASTOMER

Reference Identification	Ref. No.2-	Material Identification	Material Description	ρ_p	ρ_c	Pyrolysis Kinetics	Δh_c	h or C_p	k	ε
Wilson, R. Gale	1	NASA Langley filled silicone resin	70% Dow Corning Sylgard 182 resin 7% Sylgard 182 catalyst 14% Emerson & Cumings silica spheres 9% phenolic balloons (UC)*	40 lb/ft^3	No	No	No	-200°F to 800°F (SoRI)*	-250°F to 750°F (Melpar & SoRI)	No
		NASA Langley filled silicone resin in honeycomb	Same material, imbedded in phenolic-glass Hexcel 1/4" honeycomb of 3.5 lb/ft^3 density	41.8 lb/ft^3	No	No	No	-200°F to 800°F (Melpar)	-200°F to 700°F (Melpar)	No
Ihnat, M.E.	21	NASA Langley Purple Blend	Not given	36.9 and 37.1 lb/ft^3	No	No	No	No	100°F to 420°F	No
Dolan, C.M.	25	NASA 182	75% Dow Corning Sylgard 182 resin 15% silica spheres 10% phenolic balloons	39.4 lb/ft^3 less phenolic glass honeycomb	No	No	No	h from -250°F to 35°F	No	No
		NASA 602	75% LTV 602 dimethyl silicone resin (GE) 15% silica spheres 10% phenolic balloons	36.4 to 39.5 lb/ft^3 less phenolic glass honeycomb	No	Single unreduced TGA curve	No	h from -240°F to 350°F	No	No
		NASA 602-G-H/c-S	Same as NASA 602, but with phenolic glass honeycomb cut apart at each cell face	39.5 lb/ft^3	No	No, but see NASA 602 above	No	C_p from -200°F to 400°F	100°F to 500°F	No
Pope, R.B.	15	NASA Langley modified purple blend silicone elastomer	As Ref. 1, use of honeycomb not mentioned	No	No	No	No	No	No	1750°K to 2200°K
Nelson, J.B.	11	Silicone; dimethyl polysiloxane	GE RTV-602 with GE SRC-04 catalyst	No	.04 of ρ_p	Single component reduced TGA data	No	No	No	No
		Phenolic balloons	Union Carbide BJO-0930	No	.415 of ρ_p	Three component reduced TGA data	No	No	No	No
Thomas, H.K.	26	Methyl silicone	GE RVT-615 (dimethyl)	42.4 lb/ft^3	No	Unreduced TGA curves in helium to 1472°F	No	No	No	No
		Phenyl-methyl silicone	GE RVT-655							
		"	Dow Corning XR-6-1049							
		"	Dow Corning XR-6-3492	42.4 lb/ft^3						
		"	Dow Corning Q93-050 Dow Corning Silastic 440							
		Phenolic balloons	Union Carbide BJO-093							
Schwartzkopf	27	Charred elastomeric models	Not given	37.0 lb/ft^3 to 37.4 lb/ft^3	9.88 to 38.0 lb/ft^3	No		No	Scattered values	No
General Electric	28	Elastomeric	ESM-1000 series in Hexcel HRP-1/4-GF-12-5.5 honeycomb	53 lb/ft^3 45 lb/ft^3 39 lb/ft^3 26 lb/ft^3	No	Unreduced TGA curve	No			

*UC = Union Carbide
SoRI = Southern Research Institute

TABLE 2-20

THERMAL CONDUCTIVITY SOURCES
FILLED SILICONE ELASTOMER

Reference Identification	Ref. No.2-	Material Identification	Material Description	Material State & Preparation	Vacuum Conditions	Temperature Range of Measurements	Experimental Method	Reported Accuracy	Estimated Accuracy
Wilson, R. Gale	1	NASA Langley filled silicone resin	70% Dow Corning Sylgard 182 resin 7% Sylgard 182 catalyst 14% Emerson & Cumming silica spheres 9% phenolic balloons (UC)*	Virgin, no honeycomb, $\rho_p = 40$ lb/ft^3	Not described	a. -1970°F to 693°F	Radial outflow, 1" OD x 1" specimens (Melpar)	Not given	± 10%
						b. -253°F to 728°F	Guarded hot plate 3"D specimen (SoRI)*	Not given	± 10%
		NASA Langley filled silicone resin in honeycomb	c. Virgin in honeycomb, one primary cross cell direction aligned with heat flow, $\rho_p = 41.8$ lb/ft^3	Not described		-177°F to 669°F	Radial outflow, 1" OD x 1" specimens (Melpar)	Not given	± 5%
			d. Virgin in honeycomb, other primary cross cell direction aligned with heat flow			-173°F to 682°F	"	Not given	± 5%
			e. Virgin in honeycomb, heat flow through cells			-188°F to 692°F	"	Not given	± 5%
Ihnat, M.E.	21	NASA Langley Purple Blend	Not given	Virgin, $\rho_p = 36.9$ lb/ft^3 and 37.1 lb/ft^3	Not described	105° to 420°F	ASTM Guarded hot plate, 4.62" D specimens	Not given	± 5%
Dolan, C.M.	25	NASA 602-G-H/c-S	75% Dow Corning Sygard 182 resin 15% silica spheres 10% phenolic balloons in phenolic glass honeycomb cut apart at each cell face	Virgin, $\rho_p = 39.5$ lb/ft^3	Not described	100°F to 500°F	Dynatech Comparative Thermal Conductivity Instrument TC-1000, 2.5" x 2.5" x 1/4" specimen sandwiched between "heat meter" slabs	± 5%	Accept Report
General Electric	28	Elastomeric	ESM-1000 series in Hexcel HRP-1/4-GF-12-5.5 honeycomb	Virgin a. $\rho = 26$ lb/ft^3 b. $\rho = 39$ lb/ft^3 c. $\rho = 45$ lb/ft^3	Not described	131°F	Not described	Not given	Unknown

*UC = Union Carbide
SoRI = Southern Research Institute

TABLE 2-21

THERMAL CONDUCTIVITY - FILLED SILICONE ELASTOMERS - VIRGIN STATE

Units: 10^{-5} Btu/sec ft^2 °R

Reference	2-1	2-1	2-1	2-1	2-1	2-21	2-21	2-25	2-28	2-28	2-28
Density (lb/ft^3)	40	40	41.8	41.8	41.8	36.9	37.1	39.5	26	39	45
Honeycomb	No	No	Across Cells	Across Cells	With Cells	?	?	Yes	Yes	Yes	Yes
Temp (°R)											
200	1.250	1.167									
250	1.417	1.392	1.156	1.236	1.408						
300	1.556	1.611	1.333	1.428	1.592						
350	1.689	1.828	1.475	1.578	1.730						
400	1.778	1.836	1.586	1.694	1.842						
450	1.833	1.742	1.667	1.778	1.919						
500	1.856	1.619	1.719	1.817	1.967						
560	1.875	1.544	1.747	1.850	2.003	1.894		2.047		1.728	2.616
590	1.889	1.530	1.753	1.861	2.017	1.922	2.111		1.511		
660	1.933	1.536	1.769	1.872	2.028	2.008	2.119			1.633	
685	1.950	1.550	1.772	1.878	2.028	2.030	2.122				2.661
750	2.011	1.653	1.778	1.883	2.017	2.150	2.156				
800	2.061	1.811	1.786	1.883	2.006	2.167	2.183				
850	2.050	1.889	1.786	1.875	1.992	2.167	2.217				
900	2.000	1.833	1.775	1.861	1.972						
950	1.936	1.703	1.758	1.842	1.953			2.047			
1000	1.853	1.547	1.730	1.822	1.933						
1050	1.767	1.447	1.689	1.789	1.883						
1100	1.669	1.483	1.633	1.750	1.869						
1150	1.550	1.550	1.547	1.694	1.806						
1200	1.464	1.642	1.419	1.622	1.697						

TABLE 2-22

SPECIFIC HEAT SOURCES
FILLED SILICONE ELASTOMER

Reference Identification	Ref. No.2-	Material Identification	Material Description	Material State & Preparation	Temperature Range of Measurements	Experimental Method	Reported Accuracy	Estimated Accuracy
Wilson, R. Gale	1	NASA/Langley filled silicone resin	70% Dow Corning Sylgard 182 resin 7% Sylgard 182 catalyst 14% Emerson & Cummings silica spheres 9% phenolic balloons (UC)	a. virgin, ρ_p = 40 lb/ft^3	-203^{o}F to 754^{o}F	Bunsen ice calorimeter, enthalpy measurement, sample 1/2"D x 1" (Melpar)	Not given	± 10%
		NASA/Langley filled silicone resin in honeycomb	Same	b. Virgin in phenolic glass, Hexcel 1/4" honeycomb of 3.5 lb/ft^3 density, ρ_p = 41.8 lb/ft^3	-202^{o}F to 763^{o}F	Same	Not given	± 10%
		NASA/Langley filled silicone resin	Same	Virgin, ρ_p = 40 lb/ft^3	-313^{o}F to 760^{o}F	Dry drop calorimeter, enthalpy measurement, 3/4" cubes (SoRI)	Not given	± 10%
Dolan, C.M.	25	NASA 602-G-H/c-S	75% Dow Corning Sylgard 182 resin 15% silica spheres 10% phenolic balloons in phenolic glass honeycomb cut apart at each cell face	Virgin, ρ_p = 39.5 lb/ft^3	-200^{o}F to 400^{o}F	Dynatech Automatic Continuous Specific Heat Instrument (SHC Series), differential calorimeter	± 2%, -200^{o}F to 400^{o}F ± 5%, 200^{o}F to 600^{o}F	Accept report

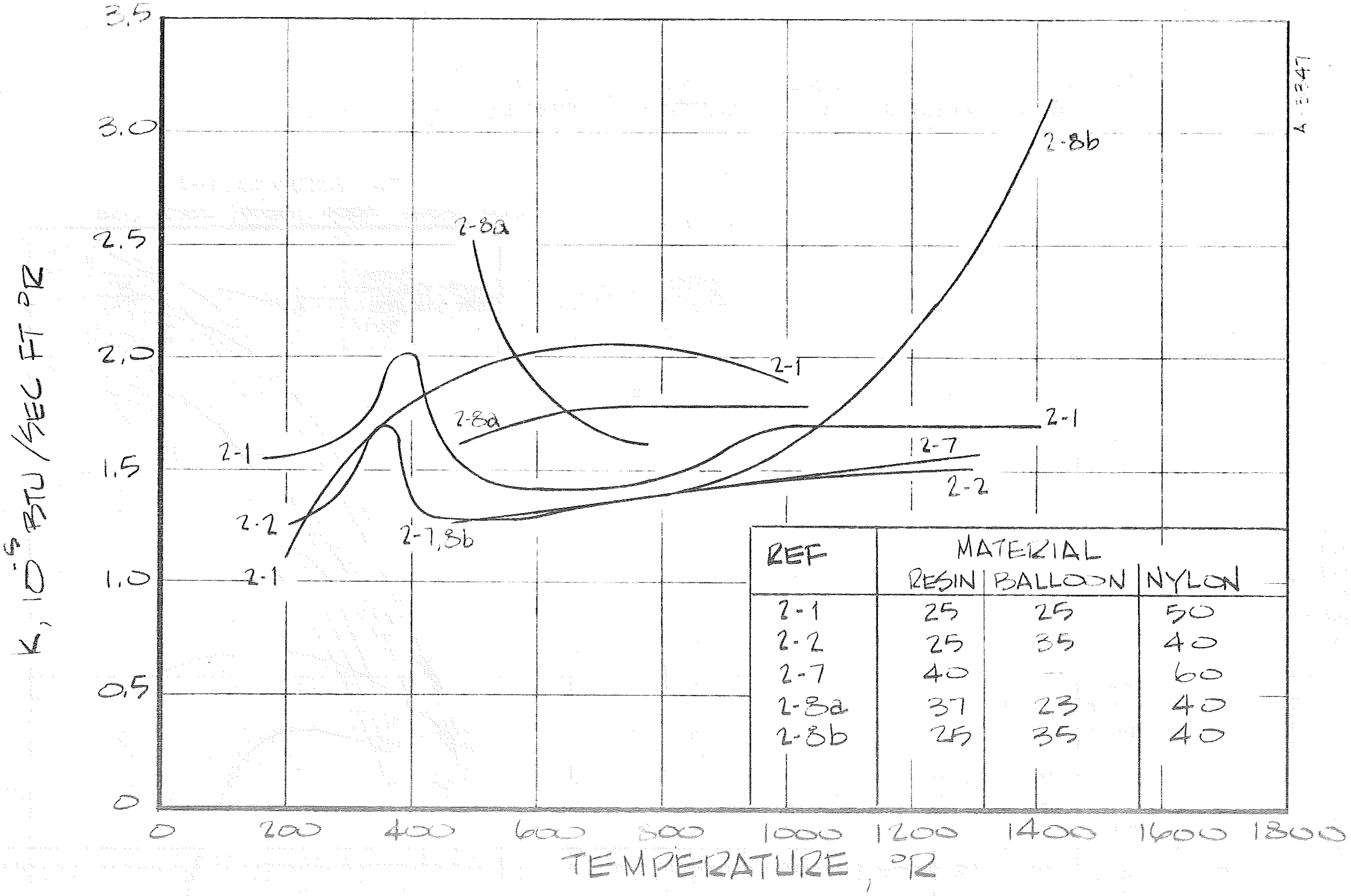
TABLE 2-23

SPECIFIC HEAT VS TEMPERATURE - FILLED SILICONE ELASTOMERS

ρ = 40 lb/ft^3, Nominal Composition
10% Phenolic Balloons
15% Silica Spheres
75% Silicone Resin

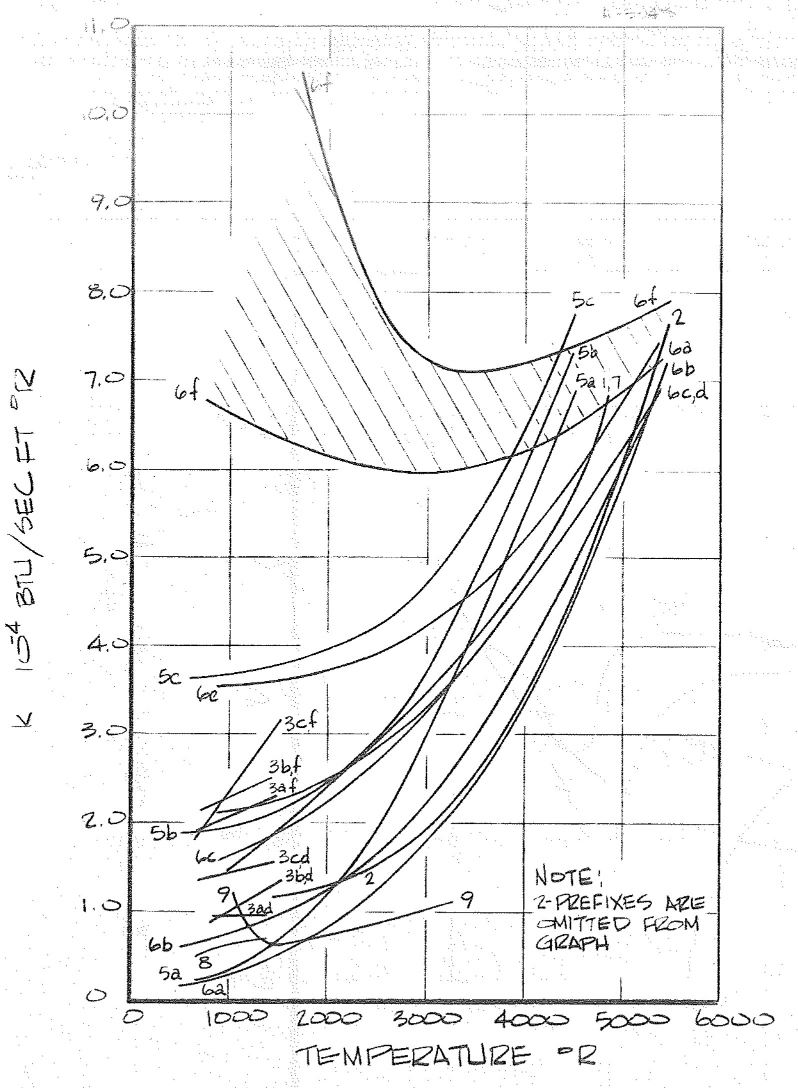
Units: Btu/lb$^\circ$R

Reference	2-1	2-1	2-1	2-25
Temp ($^\circ$R)				
260	0.283	0.283	0.201	0.105
300	0.294	0.294	0.241	0.212
350	0.309	0.309	0.282	0.333
400	0.323	0.323	0.311	0.436
410	0.326	0.326	0.316	0.455
420	0.329	0.329	0.321	0.600
430	0.331	0.331	0.326	0.765
435	0.333	0.333	0.328	0.861
440	0.334	0.334	0.330	0.540
445	0.335	0.335	0.332	0.300
450	0.336	0.336	0.334	0.320
460	0.338	0.338	0.337	0.334
500	0.349	0.349	0.350	0.391
550	0.360	0.360	0.363	0.398
600	0.372	0.372	0.372	0.402
700	0.388	0.388	0.382	0.406
800	0.401	0.401	0.384	0.409
860	0.409	0.409		0.410
900	0.413	0.413		
1000	0.423	0.423		
1100	0.432	0.432		
1200	0.437	0.437		
1220	0.437	0.437	0.384	



REF	MATERIAL RESIN	BALLOON	NYLON
2-1	25	25	50
2-2	25	35	40
2-7	40	–	60
2-8a	37	23	40
2-8b	25	35	40

FIGURE 2-1 THERMAL CONDUCTIVITY VS TEMPERATURE
LOW DENSITY ($\rho_p \approx 35$ LB/FT^3) NYLON PHENOLIC
VIRGIN MATERIAL



REF	MATERIAL RESIN	BALLOONS	NYLON	NOMINAL ρ_P LB/FT³	ρ_C LB/FT³	PRE CHAR TEMP (°R)	CHARRING HEAT FLUX BTU/FT² SEC	VACUUM
2-1	25	25	50	37	13	3500	100	1 ATM HELIUM
2-2	25	35	40	37	15	?	140	?
2-3, 2-4	25	35	40	a 19 b 30 c 42	12 17 20	4200	170	d VACUUM f 1 ATM HELIUM
2-5	50	0	50	76	19	a 1460 b 2460 c 3460	?	?
2-6	37	23	40	35	17	a 1460 b 2460 c 3460 d 4460 e 5460 f 5460	LOW LOW LOW LOW LOW 430	1 ATM ARGON 1 ATM ARGON 1 ATM ARGON 1 ATM ARGON 1 ATM ARGON 1 ATM ARGON
2-7	40	0	60	35	15	?	?	?
2-8	a 25	35	40	34	?	2300	?	VACUUM
2-9				35?	?	?	2000	?

FIGURE 2-2 THERMAL CONDUCTIVITY vs. TEMPERATURE
LOW DENSITY NYLON PHENOLIC CHARRED MATERIAL

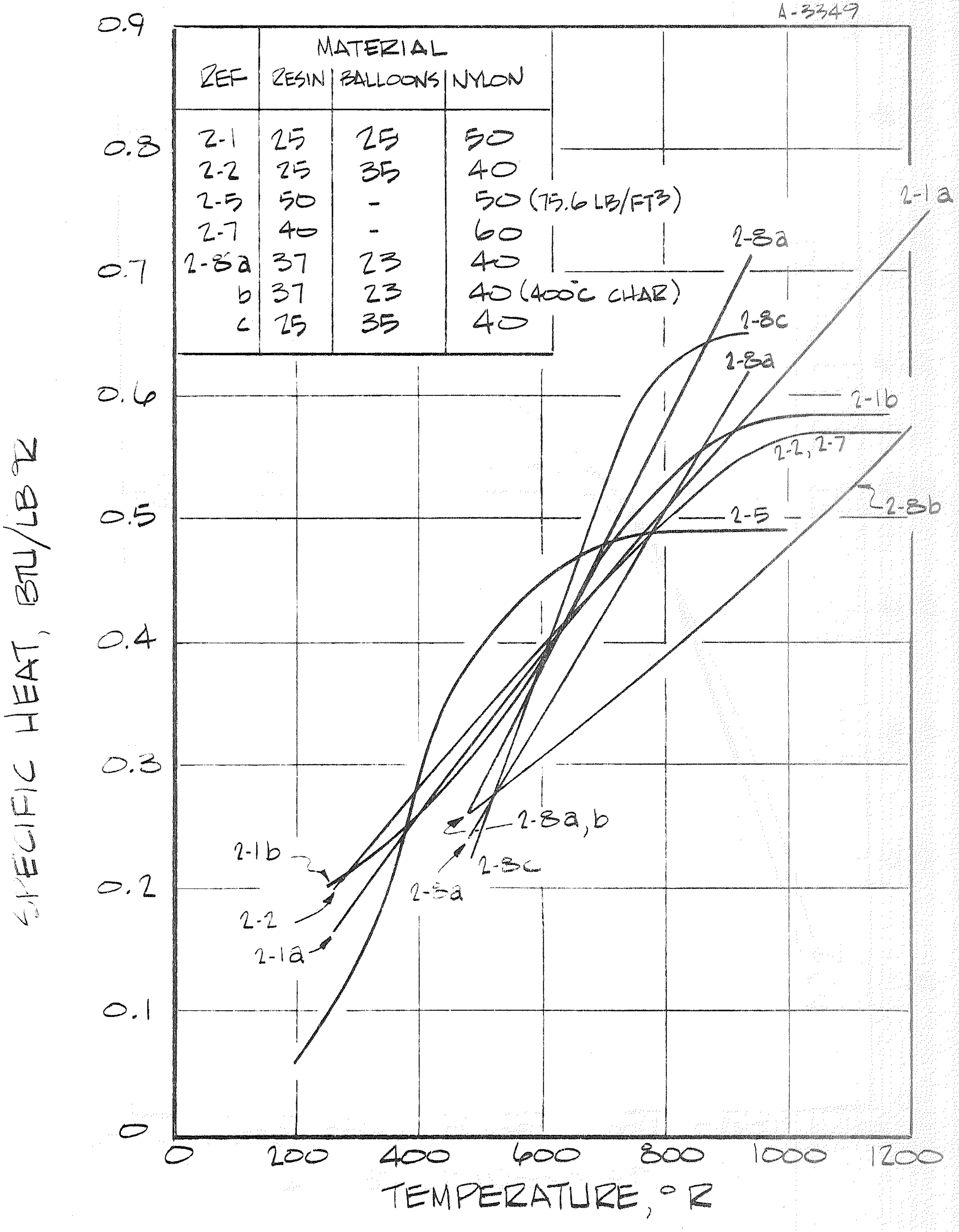


FIGURE 2-3 SPECIFIC HEAT VS. TEMPERATURE
LOW DENSITY NYLON PHENOLIC
VIRGIN MATERIAL

REF	MATERIAL RESIN	BALLOONS	NYLON
2-1	25	25	50
2-2	25	35	40
2-5	50	-	50 (75.6 LB/FT3)
2-7	40	-	60
2-8a	37	23	40
b	37	23	40 (400°C CHAR)
c	25	35	40

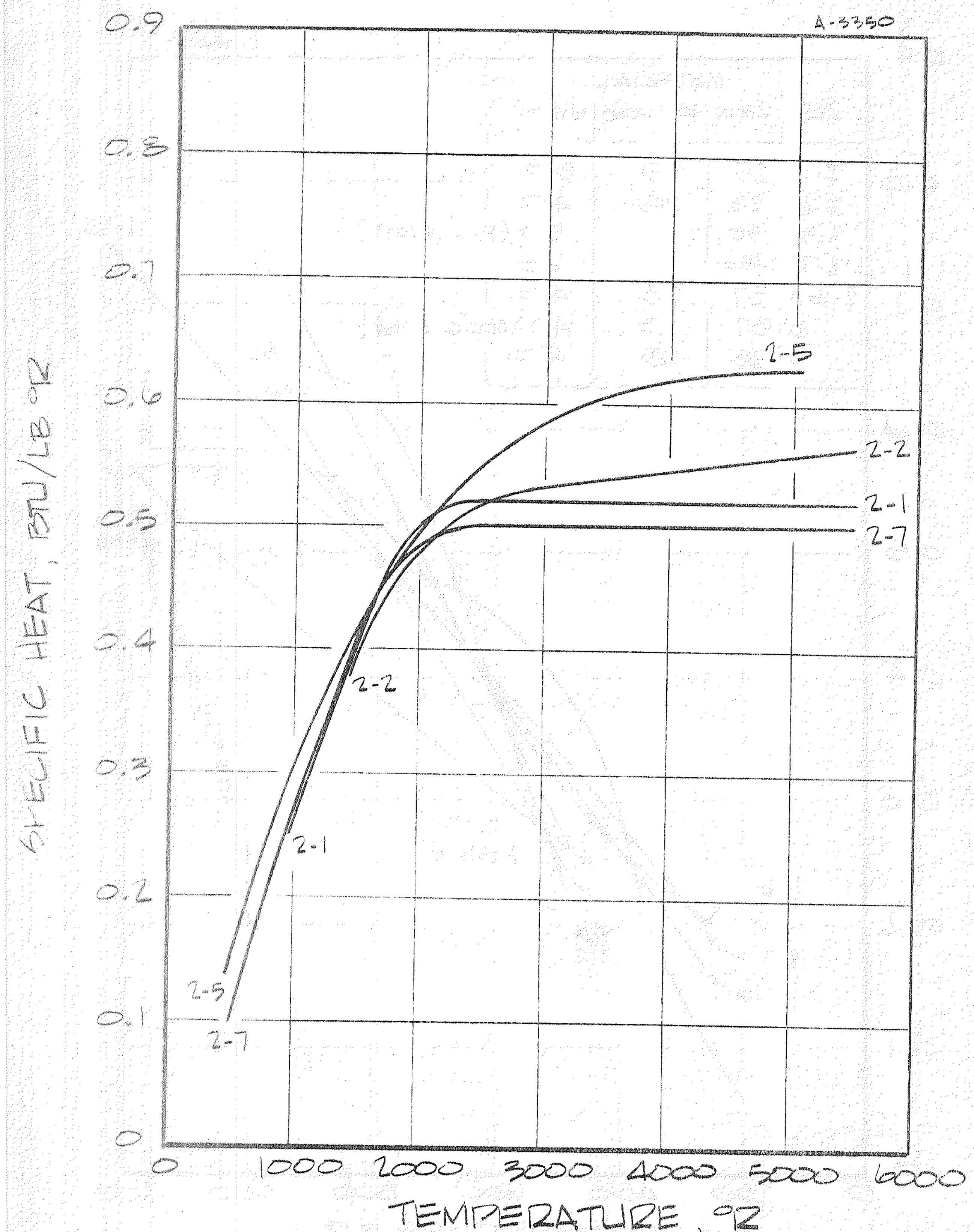


FIGURE 2-4 SPECIFIC HEAT VS. TEMPERATURE
LOW DENSITY NYLON PHENOLIC CHAR

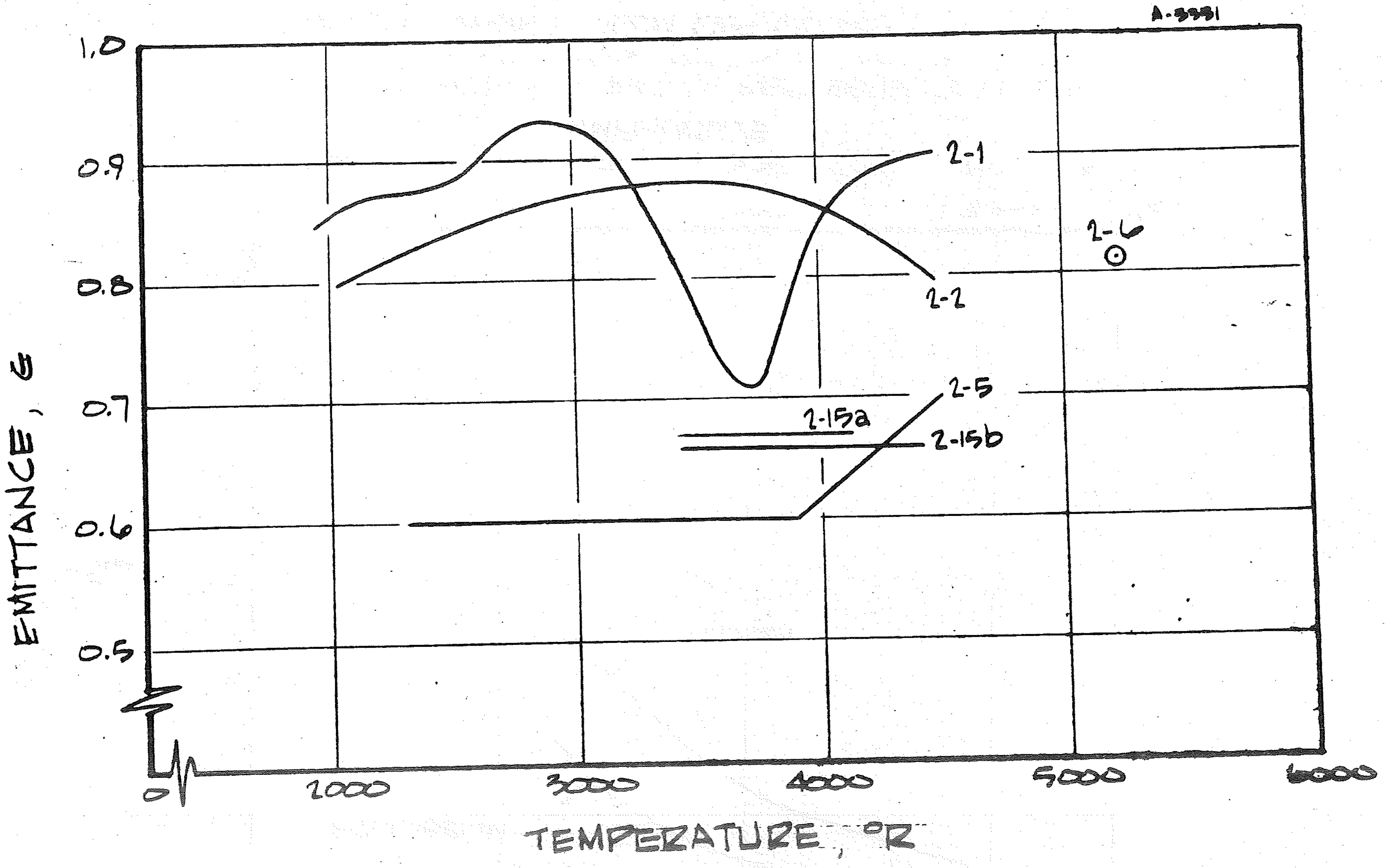


FIGURE 2-5 EMITTANCE LOW DENSITY NYLON PHENOLIC CHARS

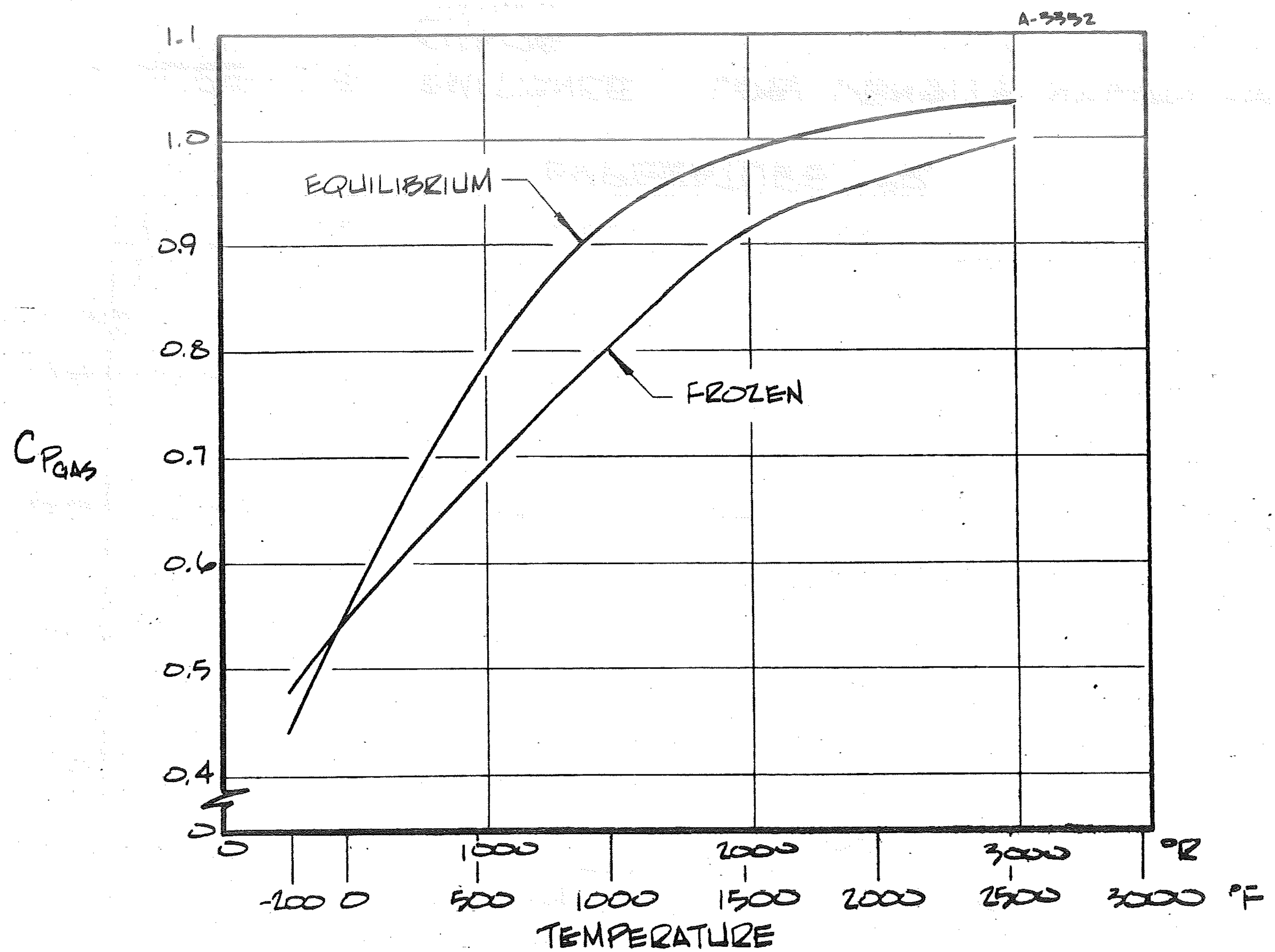


FIGURE 2-6 COMPUTED SPECIFIC HEAT OF "BEST ESTIMATE" PYROLYSIS GAS OF LOW DENSITY NYLON PHENOLIC (40% NYLON, 60% PHENOLIC RESIN), FROM REF (2-20)

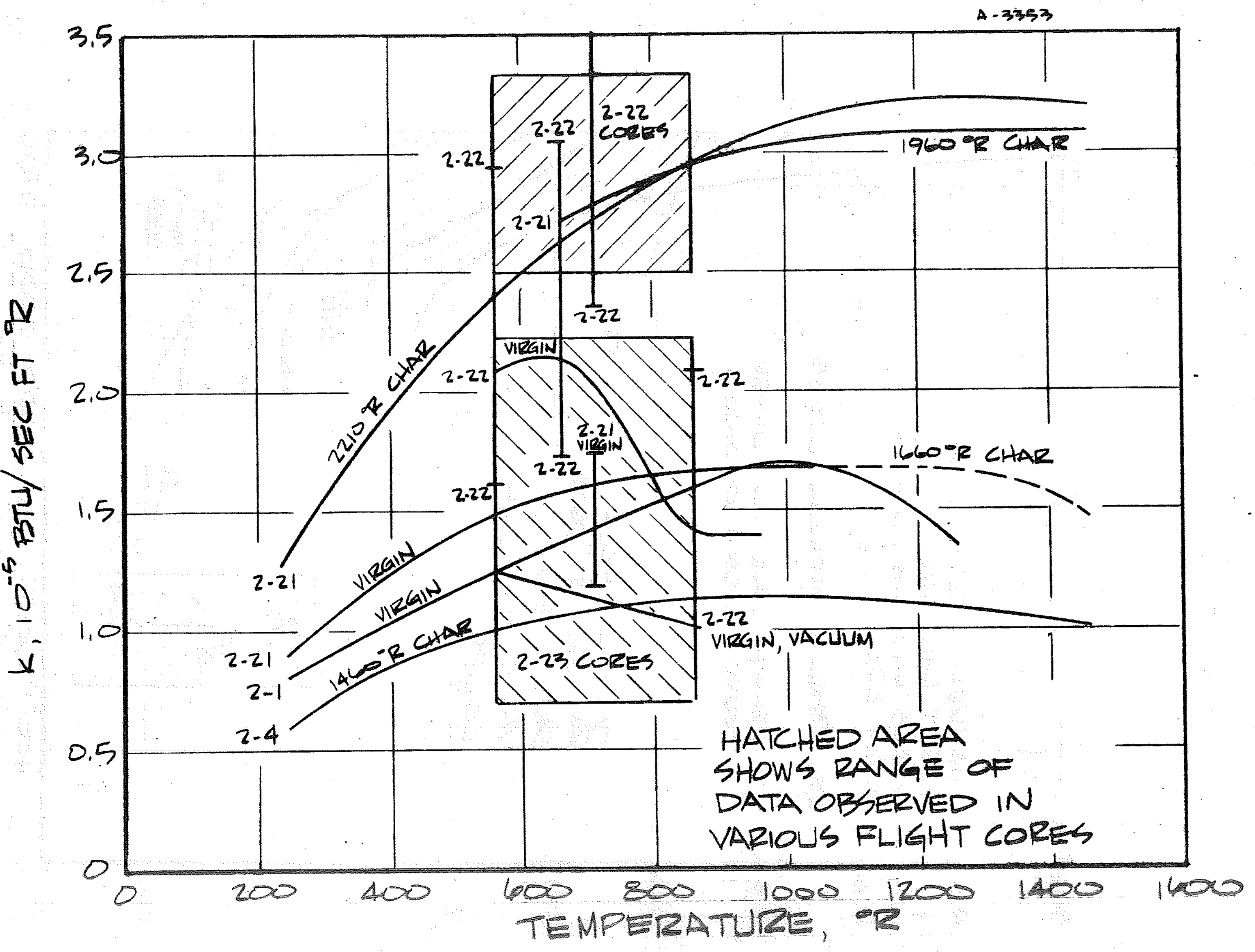


FIGURE 2-7 THERMAL CONDUCTIVITY AVCOAT 5026-39-HC/G VIRGIN MATERIALS AND LOW TEMPERATURE CHARS

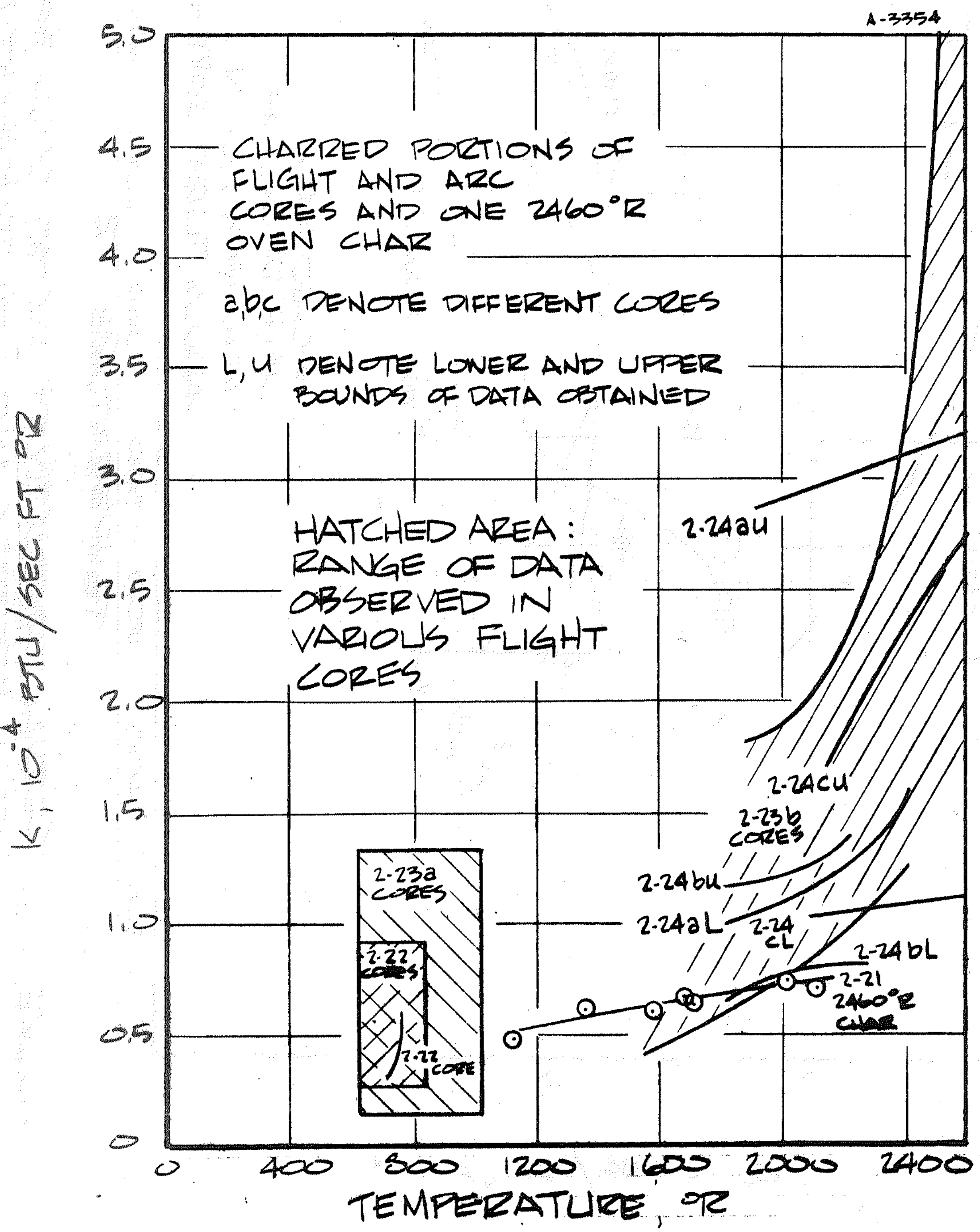


FIGURE 2-8 THERMAL CONDUCTIVITY AVCOAT 5026-39-HC/G

A-3355

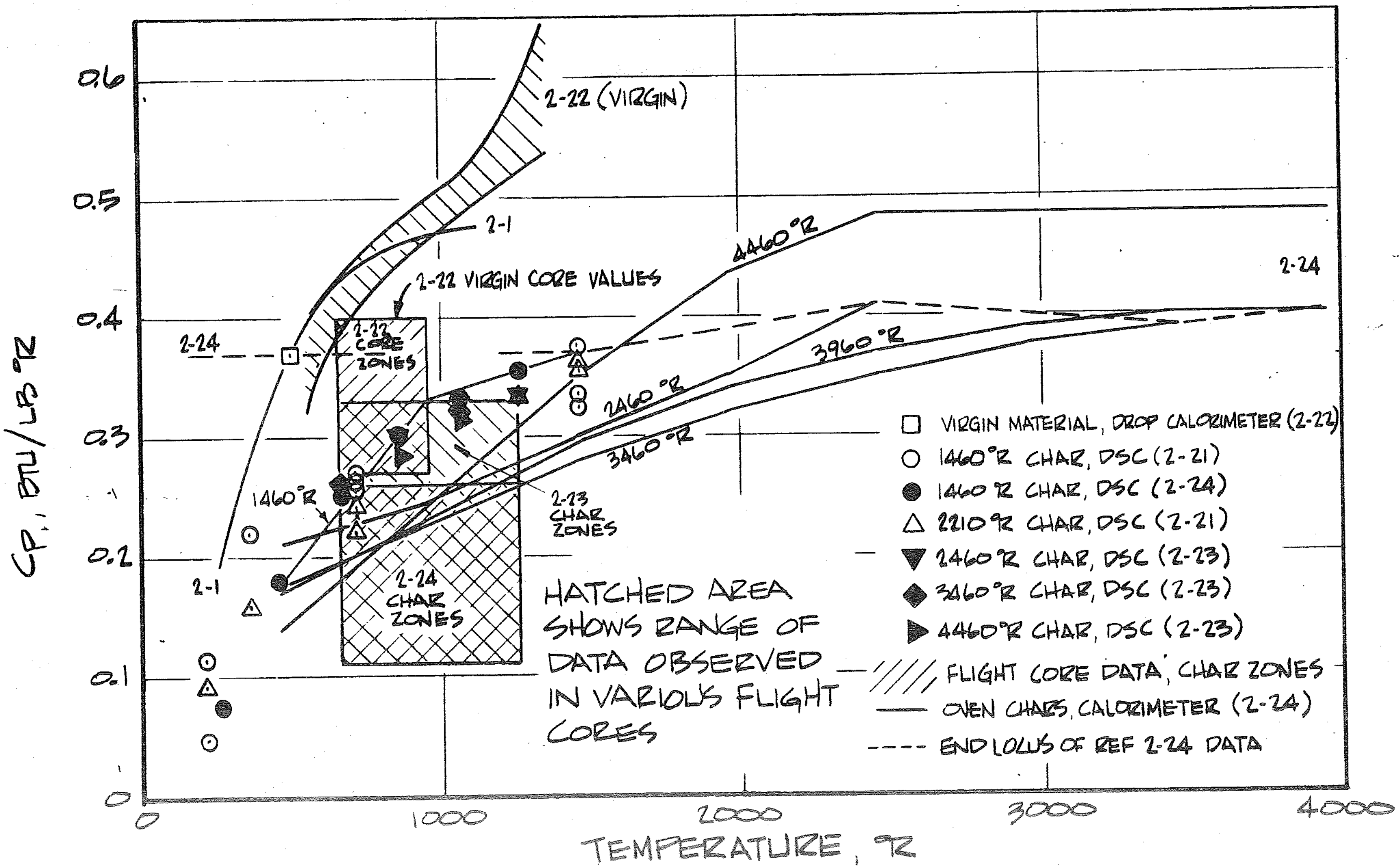


FIGURE 2-9 AVCOAT 5026-39-HC/G SPECIFIC HEAT VS. TEMPERATURE

A-3356

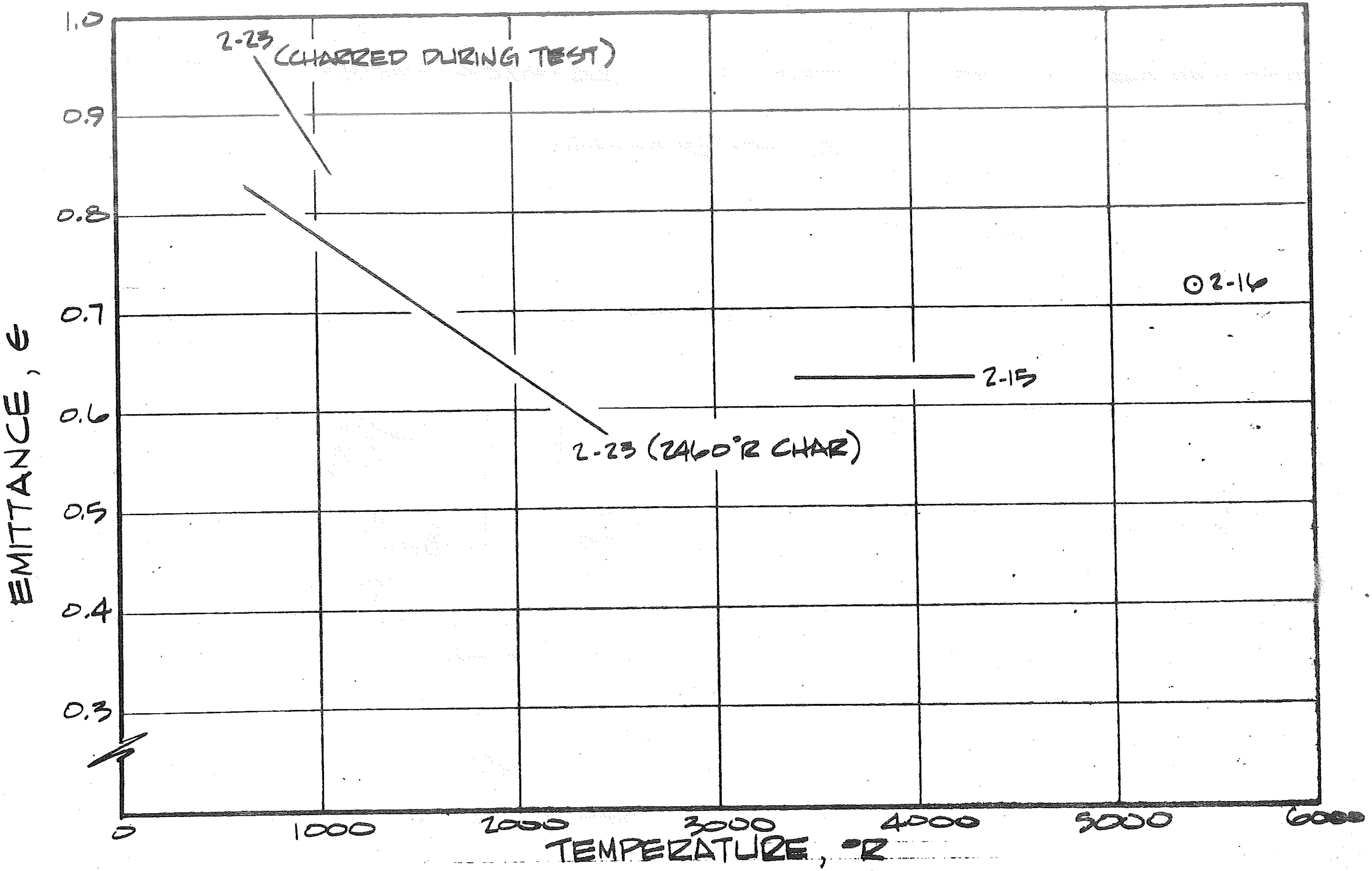


FIGURE 2-10 EMITTANCE VS. TEMPERATURE - AVCOAT 5026-39-HC/G

A-3357

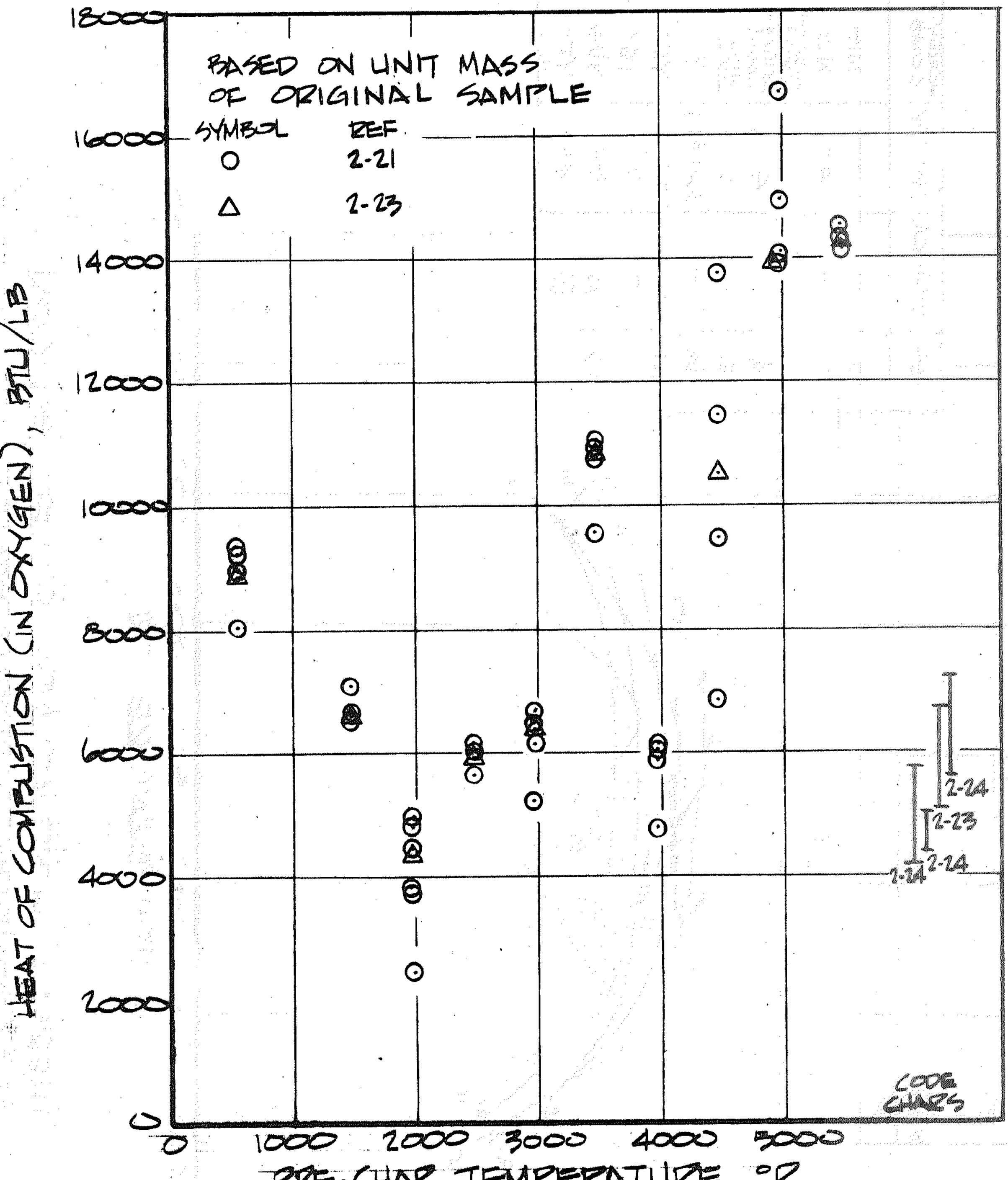


FIGURE 2-11 MEASURED HEATS OF COMBUSTION – VIRGIN MATERIALS, OVEN CHARS, AND FLIGHT CORES

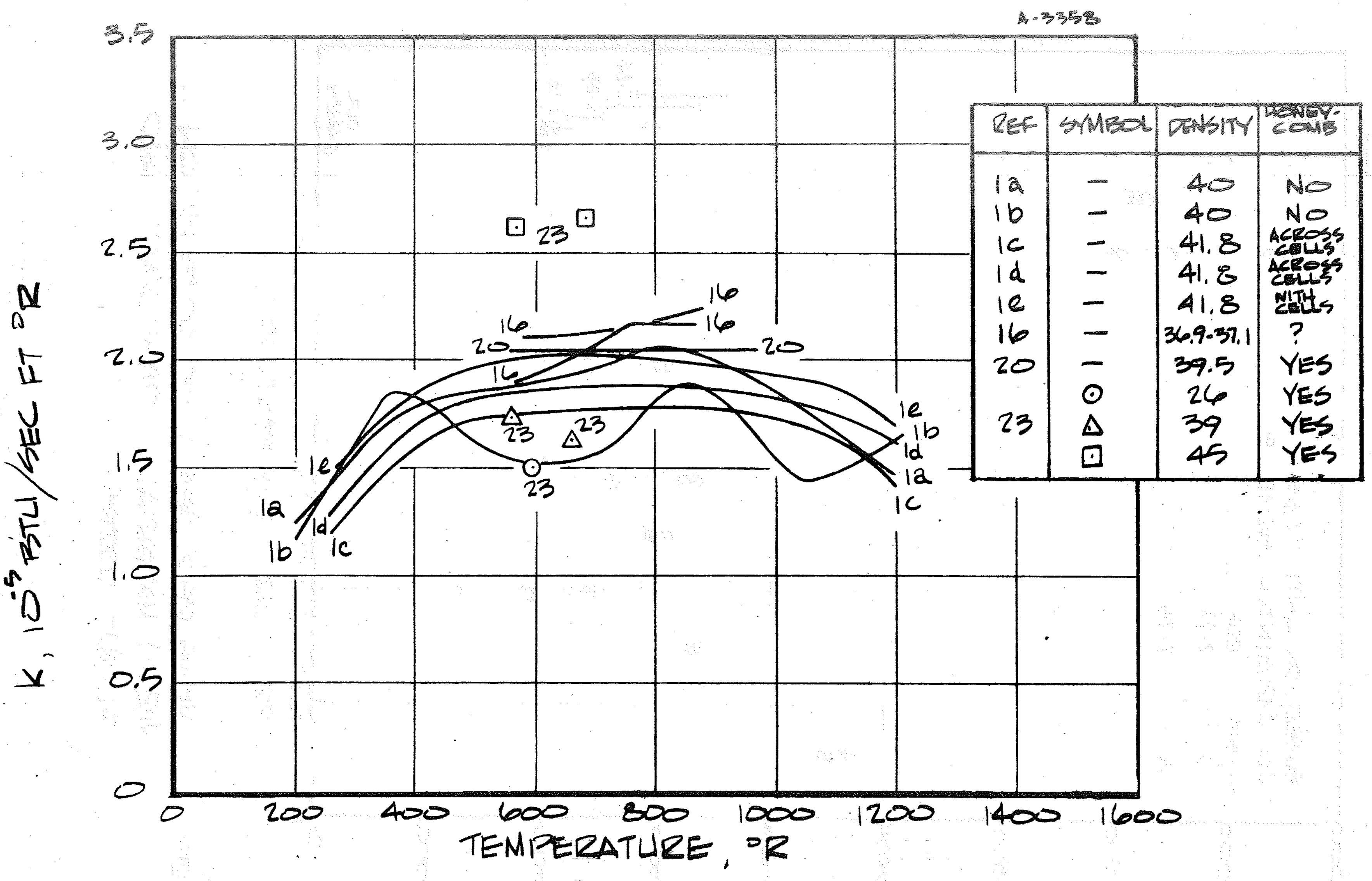


FIGURE 2-12 THERMAL CONDUCTIVITY FILLED SILICON ELASTOMERS - VIRGIN STATE

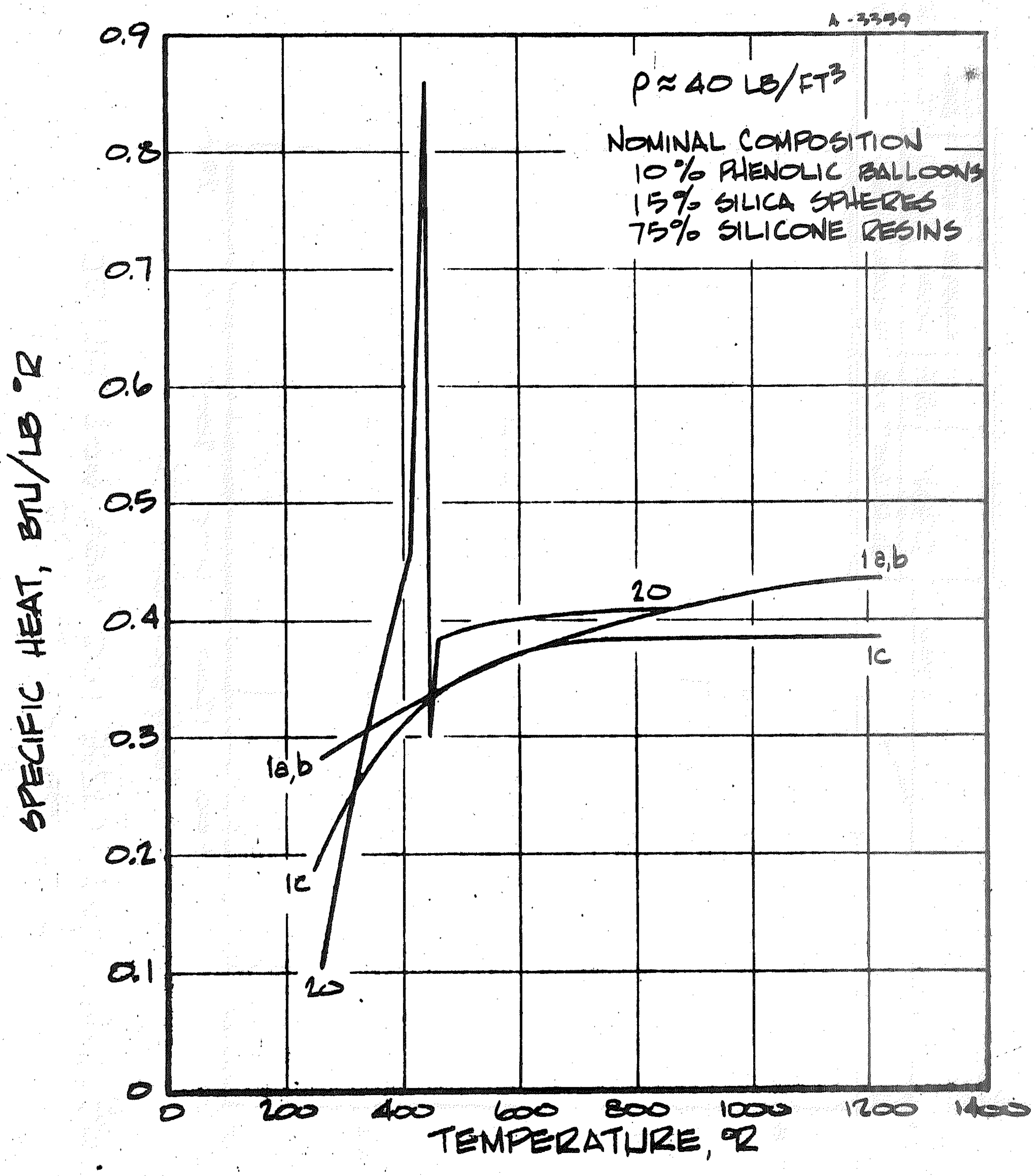


FIGURE 2-13 SPECIFIC HEAT vs TEMPERATURE FILLED SILICON ELASTOMERS

IDENT	REF.	SAMPLE FORM	SAMPLE WT (m.g.)	HEAT RATE (°R/m)	ATM
NASA-602	2-25	SLIVERS	100	2.1	NITROGEN

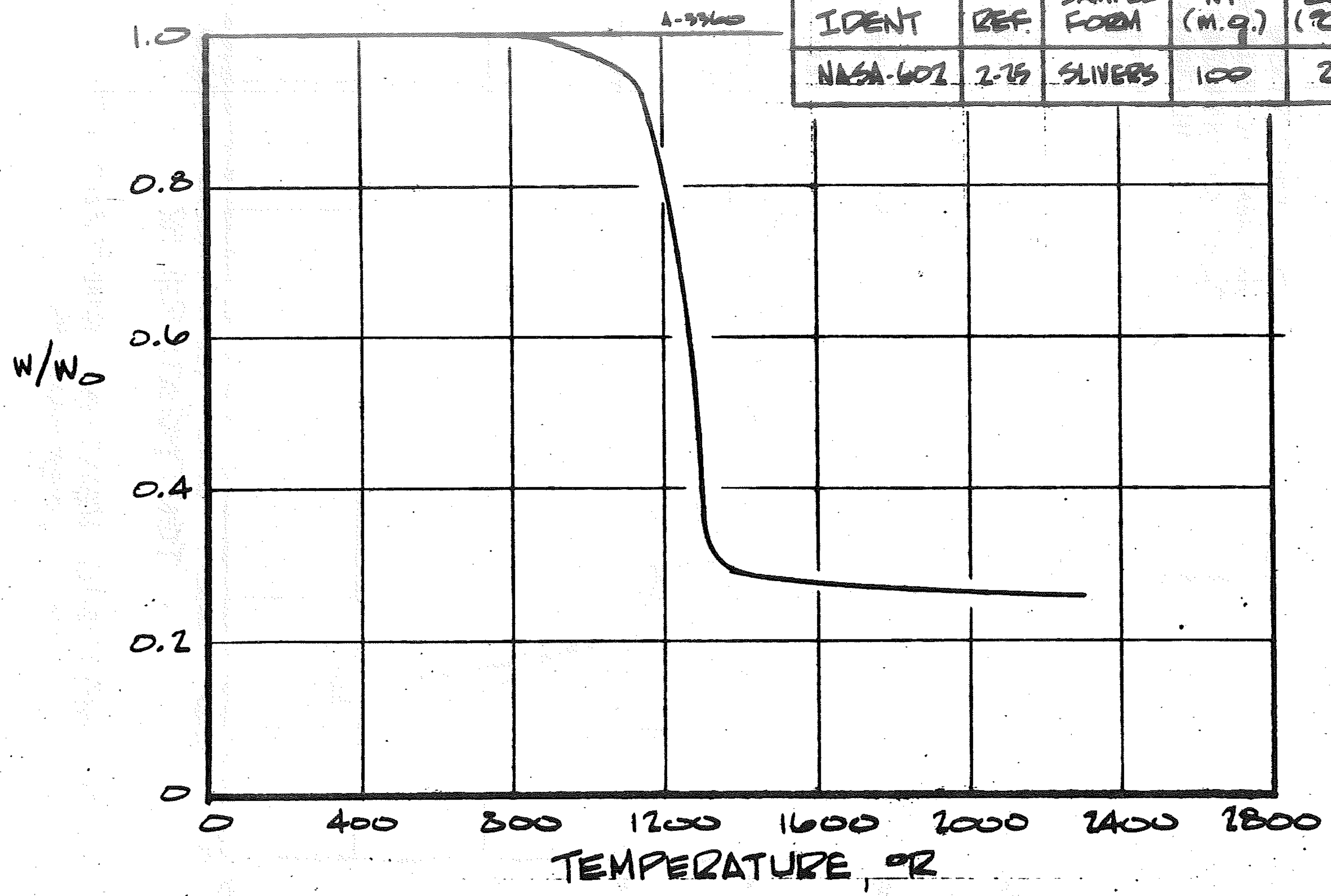


FIGURE 2-14 TGA CURVE FOR NASA 602 FILLED SILICONE ELASTOMER

IDENT.	REF	SAMPLE FORM	SAMPLE WT	HEAT RATE °/M	ATM
A-GE RTV-615	2-26	SOLID		5.0	HELIUM
B GE RTV-655	2-26	SOLID		5.0	↓
C DOW CORNING VR-6-1049	2-26	SOLID		5.0	

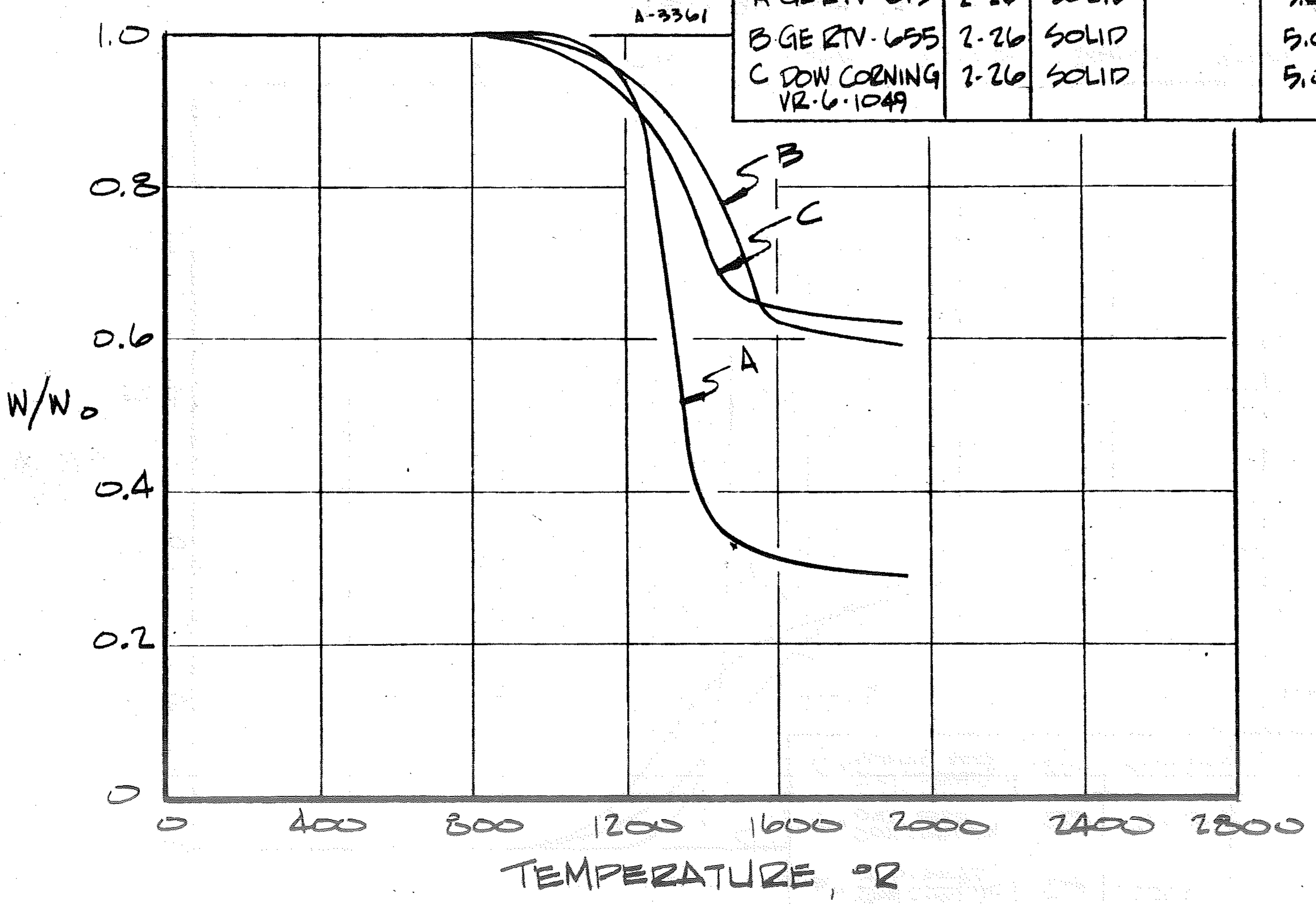
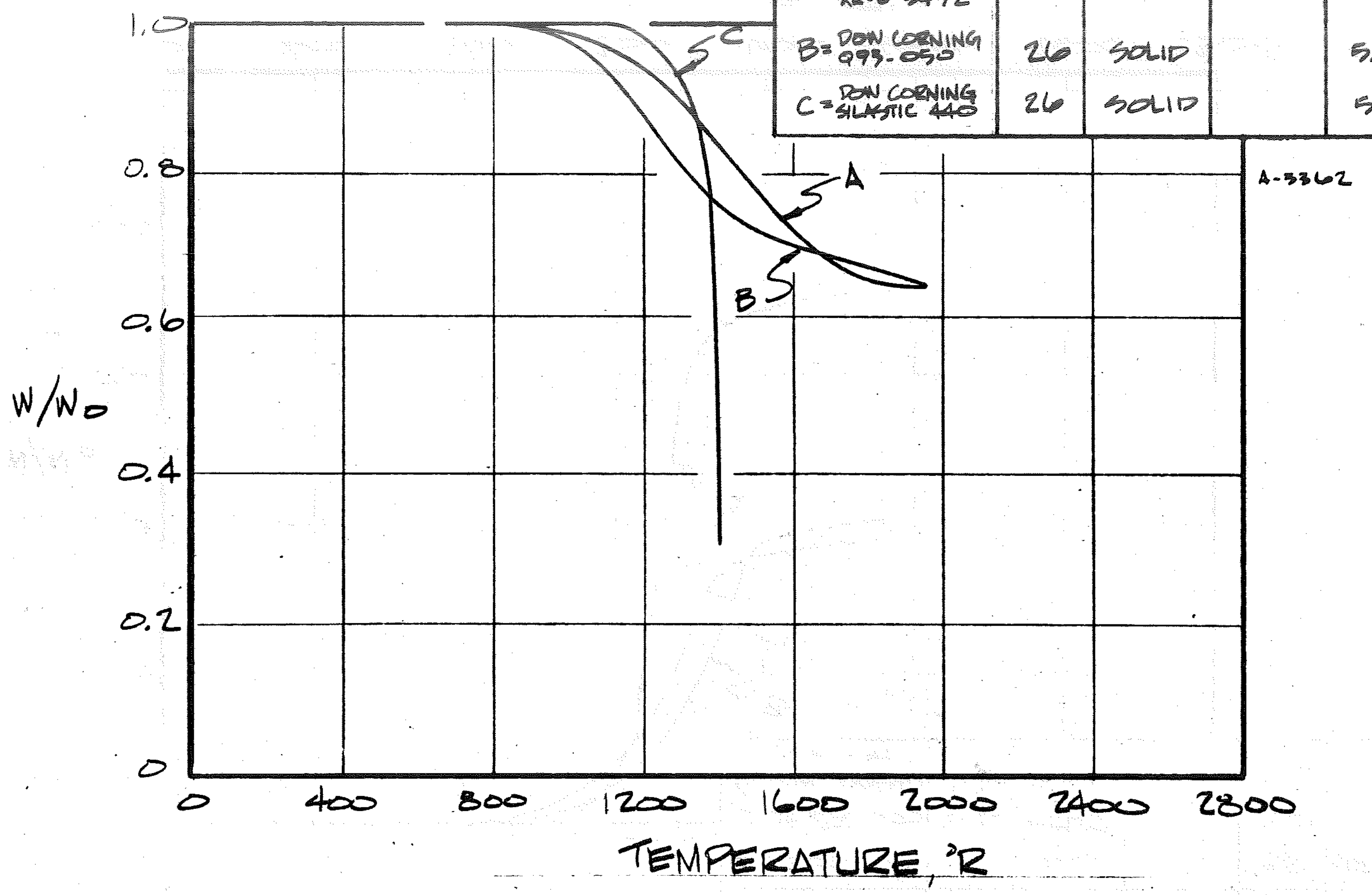
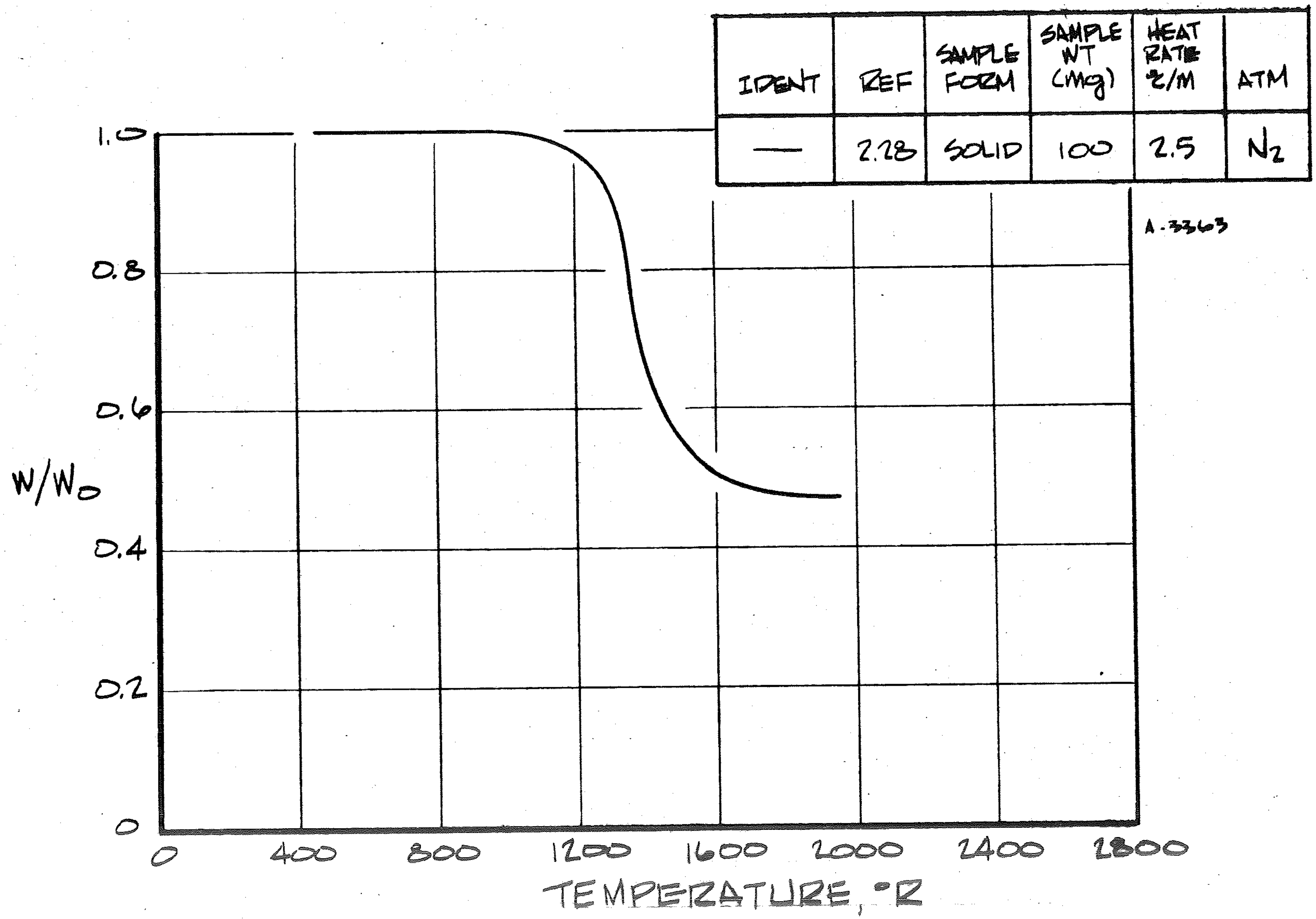


FIGURE 2-15 TGA CURVES FOR VARIOUS UNFILLED SILICONE ELASTOMERS



IDENT	REF	SAMPLE FORM	SAMPLE LOT	HEAT RATE °/M	ATM
A = DOW CORNING XR-6-3492	26	SOLID		5.0	HELIUM
B = DOW CORNING 993-050	26	SOLID		5.0	↓
C = DOW CORNING SILASTIC 440	26	SOLID		5.0	↓

FIGURE 2-16 TGA CURVES FOR VARIOUS UNFILLED SILICONE ELASTOMERS



IDENT	REF	SAMPLE FORM	SAMPLE WT (mg)	HEAT RATE °/M	ATM
—	2.28	SOLID	100	2.5	N_2

FIGURE 2-17 TGA CURVES FOR UNFILLED SILICONE ELASTOMERS

SECTION 3

ABLATION TEST DATA COMPILATION

3.1 DATA PRESENTATION

Ablation test data have been compiled from available literature for the 3 heat shield materials: low density phenolic nylon, low density silicone elastomer, and Apollo heat shield material (Avcoat 5026-39HC/G). The data fall in the following range of test conditions:

- stagnation pressure ≤ 1.0 atm.
- stagnation point heating rate = 10 to 600 Btu/ft^{2}sec.
- test stream total enthalpy = 2,000 to 20,000 Btu/lbm.
- stream oxygen mass fraction = 0 to 0.23

Tables 3-1 through 3-3 present the test data for nylon phenolic, silicone elastomer and Avcoat 5026-39-HC/G, respectively. The tabulations include: the test facility, report referenced, material composition, model geometry, total enthalpy, stagnation point heat flux, stagnation pressure, oxygen mass fraction, run time, surface recession, final char thickness and char density (if given). In addition the test measurement techniques are outlined, indicating the type of enthalpy measurement used, the calorimeter used, the pyrometer or radiometer employed and the number of published temperature points. Relative to temperature measurement, Tables 3-4 through 3-6 present the histories of internal and surface temperatures for the tests on nylon phenolic, silicone elastomer, and Apollo heat shield material, respectively.

Space did not permit listing the type of stagnation pressure transducers that were employed for each test calibration. However, good accuracy is the rule in pressure measurements by pitot probe or strain guage transducer, so the specific method used is of minor importance.

Figures 3-1, 3-2 & 3-3 present plots of the tabulated test conditions in terms of cold wall heat flux and stagnation pressure, with enthalpy listed. Unfortunately test results were not available that match the space shuttle environment, namely, heating rates of 50 Btu/ft^{2}sec and less at an enthalpy of 10,000 to 15,000 Btu/lbm with a total pressure of 0.1 atmosphere. However the shuttle condition is reasonably well bounded by available data so that conclusions on the applicability of CHAP to shuttle analysis should be possible.

The specified limitations on material composition and on test environment conditions were strictly maintained. It was desirable, but not made an absolute requirement, that internal and surface temperature measurements were included in the published data. In cases where internal temperatures were not published, the data are included in Tables 3-1, 3-2 & 3-3 if the test condition provides information in the test environment matrix not covered by instrumented models. In some cases, data without temperatures is included where the test condition is the same as for instrumented models but the run time is shorter, thus reducing the computer cost. As an added benefit in such cases a cross check on recession data is obtained.

The longest run times recorded (up to 10 minutes) appeared in Reference 3-7 for a series of duct flow tests on Apollo heat shield material performed by Boeing (Table 3-3). The long runs make computer simulation prohibitively expensive and this data probably will not be used in the CHAP evaluation. In addition, uncertainties in heat flux levels were large in those tests because of the time-varying model surface shape. The recession and char thickness information data is incomplete in that the locations of the post test material thickness measurements is not defined in Reference 3-7.

3.2 MEASUREMENT UNCERTAINTIES

Although thermocouple data contribute significantly to test results, uncertainties in the measurement of temperature are inherent but difficult to assess. Heat leak errors are the primary concern in internal and backface temperature measurements. Frequently backface temperatures are employed in testing to evaluate relative response times of various heat shield candidates. The measurement is made with an instrumented copper plate bonded to the backface of the model. The resulting measurement will differ from the true backface temperature by a magnitude that depends on the temperature level, the type of bonding, the relative thermal masses of the instrumented plate and the model, and potential heat leak paths away from the plate. The documented data are usually not complete enough to evaluate the error. Therefore the planned approach in the analytical studies will be to assume the "backface" and in-depth temperatures are accurate. Then, if discrepancies develop between analysis and test data as the study proceeds, an assessment of temperature uncertainties will be considered.

The data from sources such as the round-robin ablation series (Reference 3-1) in which more than one technique was used to measure enthalpy and heat flux, points out some of the problems of obtaining accurate calibration measurements. Bulk average enthalpy measurements by energy balance or sonic flow calculations were generally in good agreement. However, the derivation of enthalpy from the cold wall heat flux and model stagnation pressure using the Fay-Riddell equation resulted in a value that tended to be significantly greater than the bulk value. The explanation is primarily that the centerline enthalpy, in the region of the model, was higher than the average enthalpy. Non-uniformities are more pronounced in some facilities than others as shown in Reference 3-1 with plotted surveys of heat flux and stagnation pressure versus radial position. Heat flux enthalpy, if available, is probably preferable to average enthalpy for ablation analysis with CHAP.

Since stagnation point heat flux is a function of the shape and diameter of the calorimeter, the primary calorimeter data, where multiple measurements were made, is from a calorimeter of the same shape as the test model. The second calorimeter measurement, if listed, is for a different shape, either hemispherical or flat face with a different diameter, which has been corrected to the actual model shape. In Reference 3-1, a comparison of the results of the SRI 1.25 inch diameter flat face calorimeter in each facility with the facility calorimeter adjusted to a 1.25 inch diameter flat face indicated a standard deviation of 13%. The plots of Figures 3-1, 3-2, and 3-3, presenting the test environment points, employ the averaged heat transfer and enthalpy values from the tabulated data.

3.3 REJECTED DATA

Flight data is not included in the collected test tabulation for a number of reasons. A complete description of the local free stream environment (heat flux, pressure and enthalpy) was usually not published. The environment was complicated by the fact that it was time dependent. Some of the Apollo heat shield flight data is classified confidential placing restrictions on the duplicated data that would not be warranted in this document.

Of the literature surveyed on nylon phenolic, silicone elastomer, and Avocat 5026-39-HC/G, a significant number of reports had to be rejected as not appropriate. The attached reference list includes those references that were discarded and the reason for rejection. Incomplete data from some of the rejected list, such as References 3-15 and 3-18, is available but it does not provide a unique contribution to the matrix of test conditions and was consequently not included. Reference 3-1 of the applicable list contains numerous test points that have not been listed only because temperature data was missing. In all other respects, the unused data of Reference 3-1 is more complete than any of the points in the above-mentioned references from the rejected list.

SECTION 3 REFERENCES

I. ABLATION TEST SOURCES

3-1. Heister, Nevin K. and Clark, Carroll F., "Comparative Evaluation of Ablating Materials in Arc Plasma Jets," NASA CR-1207, December 1968.

3-2. Tompkins, Stephen S., "Simulation in Ground-Test Facilities of Ablation Performance of Charring Ablators During Atmospheric Entry," NASA TN-5769, April 1970.

3-3. McLain, Allen G., Sutton, Kenneth, and Walberg, Gerald D., "Experimental and Theoretical Investigation of the Ablative Performance of Five Phenolic-Nylon-Based Materials," NASA TN D-4374, April 1968.

3-4. Chapman, Andrew J., "Effect of Weight, Density and Heat Load on Thermal-Shielding Performance of Phenolic Nylon," NASA TN D-2196, June 1964.

3-5. Clark, Ronald K., "Effect of Environmental Parameters on the Performance of Low-Density Silicone-Resin and Phenolic-Nylon Ablation Material," NASA TN D-2543, January 1965.

3-6. Vojvodich, Nick S. and Winkler, Ernest L., "The Influence of Heating Rate and Test Stream Oxygen Content on the Insulation Efficiency of Charring Material," NASA TN D-1889, July 1963.

3-7. Gaudette, R. S., Del Casal, E. P., Crowder, P. A., "Charring Ablation Performance in Turbulent Flow," Boeing Company Report No. D2-114031-1 Prepared under NASA Contract No. NAS9-6288, September 1967.

3-8. Schaefer, John W., Flood, Donald T., Reese, John J. Jr., and Clark, Kimble J., "Experimental and Analytical Evaluation of the Apollo Thermal Protection System Under Simulated Reentry Conditions," Aerotherm Final Report No. 67-16, Prepared under NASA Contract No. NAS9-5430, July 1967.

3-9. Diaconis, N. S., Metzger, J. W., Florence, D., Kohr, J., Weber, H. E., Pater, K., and Warren, W. R., "Experimental and Analytical Study of the Behavior of Thermal Protection Systems in Convective Heating, Radiative Heating and Shear Stress Environments," General Electric Co. Report Prepared under NASA Contract No. NAS9-4771, February 1967.

II. NONAPPLICABLE SOURCES

(Reason for rejection is given for each)

3-10. Moss, James, N. and Howell, William E., "A Study of the Performance of Low-Density Phenolic-Nylon Ablators," NASA TN D-5257, June 1969. Reason: Densities too low (10-20 lb/ft^3)

3-11. Chapman, Andrew J., "Evaluation of Several Silicone, Phenolic, and Epoxy Base Heat-Shield Materials at Various Heat-Transfer Rates and Dynamic Pressures," NASA TN D-3619, June 1964. Reason: Various: Virgin Material reduced to zero thickness; or $p_{t_2} > 1.4$ atm; or temperature histories incomplete.

3-12. Swann, Robert T., Dow, Marvin D., and Tompkins, Stephen S., "Analysis of the Effects of Environmental Conditions on the Performance of Charring Ablators," J. Spacecraft & Rockets, Vol. 3, No. 1, January 1966. Reason: High density phenolic nylon, density and composition of silicone elastomer not specified.

3-13. Lundell, John H., Dickey, Robert R., and Jones, Jerold W., "Performance of Charring Ablative Materials in the Diffusion Controlled Surface Combustion Regime," AIAA Paper No. 67-328, April, 1967. Reason: Test data tabulation not presented, no internal measurements.

3-14. Wakefield, Roy M., Lundell, John W., and Dickey, Robert R.,"The Effects of Oxygen Depletion in Gas-Phase Chemical Reactions on the Surface Recession of Charring Ablators, AIAA Paper No. 68-302, April 1968." Reason: Refers to AIAA Paper 67-328 above for most of data, balance of data not given in detail, no temperature measurements.

3-15. Swann, Robert T., Brewer, William D., and Clark, Ronald K.,"Effect of Composition, Density and Environment on the Ablative Performance of Phenolic Nylon." NASA TND-3908, April 1967. Reason: For the appropriate stagnation pressures, P_{t_2}=1.0 atm, data contained either time to 300°F rise or char thickness but not both; surface recession not given.

3-16. Dow, Marvin B. and Brewer, William D., "Performance of Several Ablation Materials Exposed to Low Convective Heating Rates in an Arc-Jet Stream." NASA TN D-2577, January 1965. Reason: Heating rates very low (2 and 6 Btu/hr-ft^2).

3-17. Graves, Randolph A. and Witte, Wm. G., "Flight-Test Analysis of Apollo Heat-Shield Material Using the Pacemaker Vehicle System." NASA TN D-4713 August 1968. Reason: Peak pressure reached 8 atmospheres at stagnation point. No internal temperature data was obtained.

3-18. Peters, Roger W. and Wodlin, Kenneth L., "The Effect of Resin Composition and Fillers on the Performance of a Molded Charring Ablator." NASA TN D-2024, December 1963. Reason: No temperature data published for Microballoon-filled material.

3-19. Bonasi, J. J., Moodie, D. M., Gluck, R., and Zeh, W., "Low Density Shear Resistant Ablators for Lifting Reentry Vehicles." Proceedings of AIAA/ASME Eighth Structures, Structural Dynamics and Materials Conference, March, 1967. Reason: Reference material tested may be Avcoat 5026-39 HC/G but it is not specifically defined as such, p_{t_2}>1.4 atm.

3-20. Strauss, Eric L., "Superlight Ablative Systems for Mars Lander Thermal Protection." Proceedings of AIAA/ASME Eighth Structures, Structural Dynamics and Material Conference, March, 1967. Reason: No recession or char thickness data given, techniques for measuring heat flux or enthalpy not given.

3-21. Crouch, Roger K. and Walberg, Gerald D., "An Investigation of Ablation Behavior of Avcoat 5026/39M Over a Wide Range of Thermal Environments." NASA TM X-1778, April 1969. Reason: Material tested is molded without honeycomb structure. Thermophysical properties are presumably different than Avcoat 5026-39-HG/G.

3-22. Curry, Donald M. and Stephens, Emily W., "Apollo Ablator Thermal Performance at Superorbital Entry Velocities." NASA TN D-5969, September 1970. Reason: Incomplete data on heat flux, pressure and enthalpy at locations instrumented with thermocouples. Heat flux data, if available, would be variable, introducing a complexity that is not desirable in CHAP study.

3-23. Low, George M., "Apollo 6 Mission Report," NASA Report No. MSC-PA-R-68-9, June 1968. Reason: Same as for Reference 3-22 above.

3-24. Lundell, John H., Wakefield, Roy M. and Jones, Jerold W., "Experimental Investigation of a Charring Ablative Material Exposed to Combined Convective and Radiative Heating," AIAA Journal Vol. 3, No. 11, November 1965. Reason: Material tested was high density phenolic nylon (ρ=75 lb/ft^3).

3-25. Dow, Marvin B. and Swann Robert T., "Determination of Effects of Oxidation on Performance of Charring Ablators." NASA TR-R-196, June 1964. Reason: Material tested was high density phenolic nylon (ρ=75 lb/ft^3).

3-26. Tompkins, Stephen S., "A Study of the Simulation of the Flight Performance of Charring Ablators in Ground Facilities." NASA TM X-61509, June 1968. Reason: Data is contained in Reference 3-2.

3-27. Walberg, Gerald D. and Crouch, Roger K., "Exploratory Investigation of the Effect of Nylon Grain Size on Ablation of Phenolic Nylon," NASA TN D-3465, August 1966. Reason: Stagnation pressures on order of 6 atmos.

3-28. Peters, Roger W. and Wilson, R. Gale, "Experimental Investigation of the Effect of Convective and Radiative Heat Loads on the Performance of Subliming and Charring Ablators," NASA TN D-1355, July 1962. Reason: The phenolic-nylon tested was 50% phenolic and 50% nylon, density 74.5 lb/ft^3.

3-29. Chapman, Andrew J., "An Experimental Evaluation of Three Types of Thermal Protection Materials at Moderate Heating Rates and High Total Heating Loads," NASA TN D-1814, July 1963. Reason: No recession data or char thickness data.

3-30: Moss, James N. and Howell, William E., "Recent Developments in Low-Density Ablation Material: Proceedings of the 12th National Symposium of SAMPE," October 1967. Reason: For the appropriate density phenolic nylon, data is lacking on recession and char thickness. Also only the 300°F temperature point at backface is given. For the appropriate elastomer, no temperature data is given.

3-31: Brooks, William A. Jr., Tompkins, Stephen S. and Swann, Robert T., "Flight and Ground Tests of Apollo Heat-Shield Material, (C) Conference on Langley Research Related to Apollo Mission," June 1965. Reason: 1. Classified. 2) p_{t2}>1.0 atm (up to 3 atm) over much of the flight test.

3-32. Raper, James L., "Results of a Flight Test of the Apollo-Heat Shield Material at 28,000 Feet Per Second," (C) February 1966. Reason: Same test as discussed in Reference 3-22.

3-33. Dow, M. B., Bush, H. G., and Tompkins, S. S., "Analysis of the Supercircular Reentry Performance of a Low-Density Phenolic-Nylon Ablator," NASA TMX-1577, May 1968. Reason: Flight data; document classified.

TABLE 3-1

ABLATION TEST DATA, LOW DENSITY NYLON PHENOLIC

Tab No.	Test[1] Facility	Ref.	Material Density (lbm/ft^3)	Material Composition[2] (%)	Model No.	Initial Model Geometry	Average Total Enthalpy h_T (Btu/lbm) I	Average Total Enthalpy h_T (Btu/lbm) II	Heat Trans. Rate q_{cw} ($Btu/ft^2 sec$) I	Heat Trans. Rate q_{cw} ($Btu/ft^2 sec$) II	Model Stagnation Pressure P_{t_2} (atm)	Oxygen Mass Fraction f_o	Run Time (sec)	Total Surface Recession, S (in)	Char Thickness (in)	Char Density (lb/ft^3)	No of Int. T/C's w/ History Pub.	Surface Temp. History Pub.	Enthalpy Measurement Technique[3]	Calorimeter Types	Pyrometer Type
1	NASA Ames GDB	3-1	35.5	PR=25 PM=25 N=50	PLL54	Flat face 1.25 in total dia., 0.625 in dia. core, 0.75 in thick core	10,430	10,170	77	67.6	0.0106	.23	19.3	0.023	0.065	14.5	--	--	I. E.B. II. S.P.	I. Flat face slug same dimen. as model (SRI built) II. Hemisphere/cyl. slug, corr. to flat face	--
2					PLL57		10,430	10,170	77	67.6	0.0106		38.6	0.058	0.093	14.3	--	--			--
3					PLL96		10,670	10,670	85	68.5	0.0109		75.4	0.107	0.122	16.3	4	yes			Inst.dev.lab 0.653
4					PLL60		15,360	16,590	178	141.9	0.0182		11.2	0.019	0.074	14.1	--	--			--
5					PLL61		15,360	16,590	178	141.9	0.0182		28.2	0.052	0.122	15.3	--	--			--
6			35.7	PR=51 PM=23 N=40	PLH6		10,216	10,170	78	68.1	0.0106		38.4	0.044	0.097	15.0	--	--			--
7					PLH58		10,322	10,730	85	67.1	0.0111		75.3	0.115	0.132	15.5	4	yes			Inst. dev.lab 0.653
8					PLH24		15,870	16,620	166	163.1	0.0185		11.4	0.011	0.067	13.2	--	--			--
9					PLH50		15,870	16,620	166	163.1	0.0185		11.7	0.012	0.066	13.2	--	--			--
10	NASA Ames MPDB		35.5	PR=25 PM=25 N=50	PLL70		6,736	12,664	117.1	103.8	0.00572		12.4	0.008	0.054	14.5	--	--	I. E.B. II H.F.		--
11					PLL69								24.6	0.019	0.079	14.0	--	--			--
12					PLL87								50.6	0.064	0.117	15.2	3	--			--
13			35.7	PR=37 PM=23 N=40	PLH65		12,162	19,094	223.9	190.0	0.00787		6.1	0.004	0.004	13.8	--	--			--
14					PLH64								12.1	0.010	0.069	12.1	--	--			--
15					PLH63								24.9	0.027	0.111	12.9	--	--			--
16	NASA Langley AMPD		35.5	PR=25 PM=25 N=50	PLL93		4,900	--	256.	--	0.284		30	0.137	0.099	14.4	3	--	H.F.	Flat face slug same dimen as model (SRI built)	--
17			35.7	PR=37 PM=23 N=40	PLH93		4,900	--	250	--	0.284		30	0.119	0.115	--	3	--			--
18	Aerotherm Corp.		35.5	PR=25 PM=25 N=50	PLL97		4,748	5,583	80.1	92.1	0.0204		60.5	0.096	0.126	14.5	4	yes	I. E.B. II. H.F.	I. SRI-type II. Gardon flat face corr. to 1.25 in dia face.	Thermodot pyro. 0.8 ± 0.015
19	Giannini Scientific				PLL90		10,200	--	145	--	0.0199		34.7	0.073	0.159	16.7	2	yes	E.B.	Giannini steady-state hemisphere water cooled calibrated w/0.25 dia. flat face slug.	Thermodot pyro. 1.6-2.7μ
20			35.7	PR=37 PM=23 N=40	PLH90			--	144	--			48.8	0.025	0.135	15.0	2	yes			
21	Martin Company		35.5	PR=25 PM=25 N=50	PLL91		5,140	--	43.2	--	0.0070		120	0.107	0.178	16.7	4	yes		Gardon flat face 1.25 in dia.	Inst. dev. lab opt. pyrometer
22			35.7	PR=37 PM=23 N=40	PLH91		5,180	--	44.2	--				0.078	0.171	14.7	4	yes			
23	Space General Corp.		35.5	PR=25 PM=25 N=50	PLL94		14,855	14,990	103	--	0.00511		50	0.054	0.124	15.4	3	yes	I. E.B. II. S.P.	Asymptotic steady state 1.25 in dia flat face.	L&N optical pyro. 0.653
24			35.7	PR=37 PM=23 N=40	PLH94		15,035	14,990	98	--			50	0.049	0.122	15.3	2	yes			
25	NASA Langley ESB	3-2	34.	PR=37 PM=23 N=40	LD-6	Blnt Hemi, 4.7" R. nose on 2.5" OD cyl, 1.25" thick	3,500	--	164	--	0.37	.058	90	0.19	0.23	--	--	--	H.F.	Thin skin calorimeter same shape as model	--
26					LD-7		13,000	--	175	--	0.04	.23	120	0.29	0.23	--	4	--			--
27					LD-8		3,500	--	164	--	0.37	.058	120	0.28	0.21	--	4	--			--
28	NASA Langley AMPD	3-3	44	PR=25 PM=25 PN=2 N=50	--	2.0 in. dia. disk w/3.14" rad. nose, 0.5" max thickness	4,800	--	119	--	0.066	.23	30	0.04	0.07	--	1	yes	E.B.	Thin wall S.S. slug calorimeter same shape as model	Langley photo. pyrometer
29								--		--			60	0.08	0.08	--	1	--			
30								--		--			90	0.12	0.115	--	1	yes			
31								--		--			120	0.20	0.130	--	1	yes			
32								--		--			150	0.23	0.120	--	1	--			
33	NASA Langley 2500 KW Arc	3-4	39	PR=25 PM=25 N=50	--	All models flat face 3" dia. by thickness=.925"	3,000	--	113	--	1.0	.23	257	0.721	0.204	--	1	---	S.P.	3/8 in dia. S.S. water cooled calorimeter corr. to flat face.	--
34					--	.927"		--	96	--			258	0.739	0.188	--	1 time given for back-face temp rise =50°F &300°F	--			--
35					--	.476"		--	93	--			119	0.311	0.165	--		--			--
36					--	.450"		--	114	--			125	0.283	0.167	--		--			--
37					--	.930"		--	112	--			210	0.610	0.148	--		--			--
38					--	.934		--	97	--			130	0.354	0.140	--		--			--
39					--	.933		--	105	--			129	0.319	0.134	--		--			--
40					--	.417		--	94	--			93	0.161	0.163	--		--			--
41	NASA Langley 2500 KW Arc	3-5	36	PR=23 PM=25 SIM=5 N=47	2	Flat face 3" dia x 1" thk.	3,650	--	206	--	~1	.23	101	0.85	0.03	--	1	--	S.P.		--
42					13		3,550	--	198	--	~1		292	0.25	0.70	--	1				
43	NASA Ames GDB	3-6	45	PR=25 PM=25 N=50	--	Half cylinder, 0.8" long x .375" rad. x 0.10" thick, on after-body of hemisphere cylinder.	5,800	--	8	--	0.01	.23	39	no data	no data	--	1	yes	E.B.	Slug calorimeter same shape as model	Radiometer
44					--		6,200	--	9	--			80				1	yes --			
45					--	Flat face 0.75" dia x 0.10" thick	5,200	--	71	--		.23	20			--	1	--			--
46					--		5,500	--	78	--			19			--	1	--			--

TABLE 3-2

ABLATION TEST DATA, LOW DENSITY SILICONE ELASTOMER

Tab. No.	Test[1] Facility	Ref. No.	Material Density (lbm/ft³)	Material Comp.[1] (%)	Model No.	Initial Model Geometry	Average Total Enthalpy, h_T (Btu/lbm) I	Average Total Enthalpy, h_T (Btu/lbm) II	Heat Transfer Rate, $\dot{q}_{cw}$ (Btu/ft²sec) I	Heat Transfer Rate, $\dot{q}_{cw}$ (Btu/ft²sec) II	Model Stagnation Pressure P_{t_2} (atm)	Oxygen Mass Fraction f_o	Run Time (sec)	Total Surface Recession, S (in)	Char Thickness (in)	Char Density (lb/ft³)	No. of Int. T/C's w/ History Pub.	Surface Temp History Pub.	Enthalpy Measurement Technique[1]	Calorimeter Types	Pyrometer Type
1	NASA Ames GDB	1	33.5	SR = 75 SH = 15 PH = 10	SP96	Flat face, 1.25 in. tot. dia., 0.625 in. dia. core, 0.75 in. thick core	10,678	10,670	87	62.9	0.0109	0.23	75.5	+ 0.052	0.205	12.1	4	Yes	I. E.B. II. S.P.	I. Flat face slug same dimen. as model II. Hemisphere slug corr. to flat face	Inst. Dev. Lab. 0.653μ
2					SP49		10,134	10,170	73	70	0.0105		38.4	0.065	0.155	11.6	--	--			--
3					SP50		15,970	16,480	172	159.8	0.0185		28.1	0.019	0.116	17.1	--	--			
4	NASA Ames HPDB				SP89		12,561	19,721	221	185.9	0.00847		25.0	0.004	0.121	16.7	4	Yes	I. E.B. II. H.F.	I. Flat face slug same dimen. as model II. Hemisphere slug corr. to flat face	Honeywell 0.3-3.9μ
5	NASA Langley AMPD				SP93		4,900	--	273	--	0.284		30.	0.070	0.117	16.0	2	--	HF	Flat face slug, same dimen. as model (SRI type)	--
6					SP29		9,700	--	481	--	0.293		11.	0.082	0.049	14.2	--	--			--
7					SP31		9,700	--	539	--	0.293		30.	0.412	0.022	18.1	--	--			--
8	Aerotherm Corp.				SP97		4,566	5,469	77.7	83.2	0.020		100	+ 0.025	0.217	15.8	4	Yes	I. E.B. II. H.F	I. SRI type, II. Gardon flat face corr. to 1.25 in. dia. face	Thermodot Pyro. 0.8 ± 0.015μ
9	Giannini Scientific				SP90		10,200	--	145.	--	0.0199		35	0.004	0.127	19.1	2	Yes	EB	Gianinni S.S. Hemi. water cooled, calib. w/ 0.25D flat face slug	Thermodot Pyro. 1.6-2.7μ
10					SP3		10,100	--	66	--	0.0041		32.7	+ 0.036	0.109	13.2	--	--			--
11					SP6		15,400	--	457	--	0.095		10.7	0.070	0.056	16.4	--	--			--
12	Martin Co.				SP91		5,180	--	44.2	--	0.0070		120.	+ 0.048	0.200	15.7	4	Yes	EB	Gardon flat face, 1.25 in. dia.	Inst. Dev. Lab. Opt. Pyro.
13					SP12		18,642	--	455	--	0.0341		13.4	0.053	0.063	15.4	--	--			--
14					SP8		10,647	--	417	--	0.139		17.	0.190	0.032	11.6	--	--			
15	Space General Corp.				SP94		14,925	14,990	105.	--	0.0051		50.3	+ 0.033	0.167	14.2	2	Yes	I. E.B. II. S.P.	Asymptotic steady state 1.25 in. dia. flat face	L&N Opt. Pyro. 0.655μ
16					SP27		5,127	5,015	157	--	0.093		14.	0.052	0.077	16.8	--	--			
17					SP28		5,093	5,020	155	--	0.092		16.1	0.176	0.077	16.1	--	--			

TABLE 3-3

ABLATION TEST DATA, AVCOAT 5026-39-HC/G

Tab No.	Test Facility(1)	Ref.	Material Designation	Model No.	Initial Model Geometry	Average Total Enthalpy, h_T (Btu/lbm) I	Average Total Enthalpy, h_T (Btu/lbm) II	Heat Transfer Rate $\dot{q}_{cw}$ (Btu/ft²sec) I	Heat Transfer Rate $\dot{q}_{cw}$ (Btu/ft²sec) II	Model Stagnation Pressure P_{t_2} (atm)	Oxygen Mass Fract. f_o	Run Time (sec)	Total Surface Recession s (in)	Char Thickness (in)	Char Density (lb/ft³)	No. of Int. T/C's with History Published	Surface Temp. Hist. Published	Enthalpy Measurement Technique(3)	Calorimeter Used	Pyrometer Used
1	NASA-Ames GDB	3-1	AVCOAT 5026-39-HC/G	A93	Flat face 1.25"	10,449	10,750	89	62.4	0.0108	.23	75.5	0.101	0.167	19.6	3	yes	I-EB II-SF	I-Flat face slug same dimen as model. SRI-slug	I-Dev Lab [illegible]
2	NASA-Ames MPDB			A84	total dia, 0.625"	6,973	13,109	105.3	105.3	0.00582		50.2	0.069	0.143	18.0	4	--	I-EB II-HF	II-Hemisphere slug corrected to flat face	[illegible] 0.3-3.9
3	NASA-Ames MPDB			A85	dia. core 0.75"	12,320	19,342	215.2	202.8	0.00947		24.8	0.045	0.125	16.3	4	yes	HF	flat face slug same	Langley photo-
4	NASA-Langley AMPD			A90	thick core.	4,900	--	280	--	0.264		20	0.177	0.061	17.3	4	--		dimen (SRI model)	pyro.
5	Aerotherm Corp.			A98		4,783	5,644	76.5	86.2	0.0182		99.8	0.251	0.171	17.3	4	yes	I-EB II-HF	I-SRI type, II-Gardon flat face cor 1.25" dia	Thermodot pyro @0.8 ± 0.15μ
6	Giannini Scientific			A94		10,200	--	144	--	0.0199		34.7	0.072	0.144	18.3	2	yes	EB	Giannini SS hemi. H_2O cooled cal. w/0.25" dia flat face slug	Thermodot pyro @1.6-2.7μ
7	Martin Company			A95		5,140	--	43.2	--	0.0070		120	0.060	0.236	17.8	2	yes	|	Asymptotic flat face 1.25" dia.	Inst dev labs opt pyro
8	Space General Corp.			A97		14,955	15,000	101	--	0.00511		50.4	0.063	0.168	17.7	2	yes	I-EB II-SF		L&N opt pyro [illegible]
9	Boeing Miniarc E	3-7		2	Flat plate, 4" wide	3,130	--	11.6	--	0.038(4)	0.	280	0.03	0.18	--	10	yes	EB	5 H_2O cooled asymptotic	L&N Ray-O-Tube
10				3	x 8" long x 2"	3,065	--	14.5	--	0.033	.23	~400	0.07	0.33	--	9			flat face cals. distr.	total radiation
11				4	thick in duct flow	3,396	--	17.0	--	0.036		320	0.06	0.21	--	7			over plate of same	pyro, assumed
12				6	orientation	2,045	--	18.3	--	0.057		555	0.15	0.48	--	8			dimen as models	ε = .75
13				7		2,264	--	22.8	--	0.062		570	0.25	0.53	--	9				
14				8		2,376	--	22.4	--	0.062		485	0.21	0.49	--	9				
15				9		2,779	--	29.6	--	0.067		625	0.38	0.55	--	10				
16				10		2,560	--	29.7	--	0.068		580	0.40	0.45	--	9				
17				11		2,078	--	21.9	--	0.078		515	0.39	0.55	--	10				
18				13		2,304	--	25.1	--	0.084		690	0.59	0.47	--	8				
19				14		2,335	--	25.2	--	0.084		530	0.54	0.42	--	10				
20	NASA Ames Entry Heating Simulator	3-8		46/FF/1.25	Flat face, 1.25"	3,090	--	157(5)	0(5)	0.112		20.1	0.070	0.09	--	2	yes	SF	convection: polished slug same dimen. as model	Thermodot pyro @0.8 ± 0.015μ
21				45/FF/1.25	dia. w/core .312"	3,210	--	168	153			15.1	0.090	0.07	--	3			radiation: blackened	
22				50/FF/1.25	OD x .875" thick	3,120	--	|	336			10.1	0.069	|	--				slug same dimen. as	
23				51/FF/1.25		3,290	--	148	0			30.2	0.112	0.07	--				model, w/arc heater	
24				54/FF/1.25		3,250	--	|	150			20.2	0.138	0.05	--				off	
25				55/FF/1.25		3,420	--		351			20.1	0.121	0.07	--					
26				37/FF/1.25		5,020	--	102	0	0.071		25.1	0.025	0.11	--					
27				39/FF/1.25		5,130	--	|	66			26.0	0.081	0.09	--					
28				63/FF/1.25		5,120	--	95	107			25.1	0.032	0.11	--					
29				40/FF/1.25		5,130	--	|	215			25.2	0.072	0.12	--					
30				47/FF/1.25		5,060	--		473			15.1	0.090	0.08	--					
31				49/FF/1.25		6,290	--	214	0	0.099		25.3	0.103	0.09	--					
32				50/FF/1.25		6,410	---	214	215			20.2	0.082	0.10	--					
33				52/FF/1.25		6,390	--	214	349			15.1	0.065	0.105	--					
34				44/FF/1.25		6,170	--	214	391			15.2	0.082	0.10	--					
35	Aerotherm Corp.			95/BH/2.0	Blunt hemisphere/	3,539	--	33.9	--	0.0082		120.3	0.076	0.16	--	5		EB	calorimeter same shape	
36				94/BH/2.0	cyl., cyl.dia = nose	|		|		|		60.6	0.049	0.10	--				as model w/copper slug	
37				88/BH/2.0	rad. = 2.0" with	5,044	--	45.6	--	0.011		121.1	0.077	0.16	--				insert at stagnation	
38				87/BH/2.0	1.0" dia. core x	4,910	--	47.1	--	0.0112		61.0	0.055	0.10	--				point	
39				91/BH/2.0	.875" thick	10,969	--	117	--	0.0079		60.5	0.152	0.085	--	4				
40				90/BH/2.0		|		|		|		30.3	0.077	0.07	--	5				
41				108/BH/2.0		16,301	--	155	--	0.0080		60.4	0.147	0.10	--			HF		
42				99/BH/2.0		|		|		|		30.3	0.078	|				EB		
43				74/BH/2.0		6,322	--	131	--	0.0261	.15	60.7	0.160	0.10	--					
44				78/BH/2.0		5,640	--	88.8	--	0.0253	.07	60.6	0.144	0.15	--					
45				77/BH/2.0		5,511	--	76.1	--	0.0296	0	61.4	0.114	0.16	--					
46				23/BH/2.0		5,801	--	151	--	0.0278	|	60.8	0.050	0.21	--					
47				76/BH/2.0		5,961	--	189	--	0.0297	|	60.5	0.082	|	--					
48				84/BH/2.0		10,918	--	189	--	0.0293	|	60.3	0.023	0.19	--					
49				85/BH/2.0		|	--	189		|	.23	60.9	0.022	0.25	--					
50				75/BH/2.0		11,578	--	201	--	0.0263	.15	60.6	0.301	0.10	--					
51				83/BH/2.0		10,851	--	174	--	0.0290	.07	61.0	0.242	0.14	--					
52				82/BH/2.0		10,445	--	215	--	|	0	60.3	0.215	0.16	--					
53				80/BH/2.0		9,960	--	272	--	0.0276	|	60.6	0.172	0.12	--					
54				24/BH/2.0		11,013	--	280	--	0.0264	.23	60.4	0.109	0.22	--					
55				101/BH/2.0		17,400	--	313	--	0.0287	.15	45.2	0.215	0.08	--			HF		
56				98/BH/2.0		17,290	--	290	--	0.0283	.07	45.0	0.181	0.125	--					
57				107/BH/2.0		18,040	--	298	--	0.0275	0	|	0.135	0.16	--					
58				105/BH/2.0		16,980	--	364	--	0.0254	|	45.3	0.120	0.19	--					
59				161/BH/2.0		17,000	--	420	--	0.0254	|	44.9	0.107	0.20	--					
60				86/BH/2.0		18,019	--	300	--	0.0278		45.0	0.029	0.27	--					
61				116/BH/4.0	Blunt hemisphere/	4,944	--	34	--	0.009	.23	60.4	0.035	0.10	--			EB	slug cal, blunt hemi./	
62				128/BH/4.0	cyl.,cyl. dia. =	13,500	--	91	--	0.0081		90.2	0.137	0.13	--	4		HF	2" cyl. corrected to	
63				126/BH/4.0	nose rad.=4.0"	14,480	--	97	--	|		30.6	0.043	0.10	--			|	model shape	
64				117/BH/4.0	w/1.0" dia. core x	4,612	--	56	--	0.0279		30.3	0.026	0.08	--			EB		
65				122/BH/4.0	1.875" thick	10,434	--	134	--	0.0275		60.6	0.168	0.14	--	5				

TABLE 3-3 (CONCLUDED)

Tab No.	Test Facility	Ref.	Material Designation	Model No.	Initial Model Geometry	Average Total Enthalpy, h_T (Btu/Lbm) I	Average Total Enthalpy, h_T (Btu/Lbm) II	Heat Transfer Rate $\dot{q}_{cw}$ (Btu/ft²sec) I	Heat Transfer Rate $\dot{q}_{cw}$ (Btu/ft²sec) II	Stagnation Pressure P_{t_2} (atm)	Oxygen Mass. Fract. f_o	Run Time (sec)	Total Surface Recession s (in)	Char Thickness (in)	Char Density (Lb/ft³)	No. of Int. T/C's with History Published	Surface Temp. Hist. Published	Enthalpy Measurement Technique(3)	Calorimeter Used	Pyrometer Used
66	Aerotherm Corp.	3-8	AVCOAT 5026-39-HGC	119/BH/4.0	Blunt hemisphere/ cyl., Cyl. dia. = nose rad. = 4.0" with 1.0" dia. core x 1.875"thk.	10,976	--	119	--	0.0279	.23	30.8	0.096	0.10	--	5	yes	EB	slug cal., blunt hemi/ 2" dia cyl corrected to model shape	Thermodot pyro 60.8 ± 0.015
67				125/BH/4.0		15,891	--	198	--	0.0279		29.8	0.056	0.12	--			HF		
68				124/BH/4.0		19,040	--	238	--	—		20.0	0.045	0.08	--					
69				25/BH/2.0	Blunt hemisphere/ cyl., $D_{cy}=R_N=2$"w/ core 1"D"x .875"thk	5,447	--	121	--	0.0270		45.6	0.112	0.12	--	3		EB	cal same shape as model w/copper slug insert at stagnation point	
70				19/FF/2.0	Flat face, 2" dia.	5,582	--	63	--			90.0	0.139	0.17	--	5				
71				33/H/2.0	Hemisphere/2" dia. w/core 1"x.875"thk	5,640	--	159	--	0.0275		93.5	0.356	0.11	--	4				
72				29/BH/2.0	(see mod. 25/BH/2.0)	9,554	--	159	--	0.0263		45.2	0.171	0.11	--	2				
73				17/FF/2.0	(see mod 19/FF/2.0)	10,357	--	142	--	0.0281		90.0	0.293	0.12	--	5	--			
74				35/H/2.0	(see mod 33/H/2.0)	10,463	--	241	--				0.499	0.11	--	4	yes			
75				100/BH/2.0	(see mod 25/BH/2.0)	15,800	--	332	--	0.0285		27.3	0.132	0.09	--			HF		
76				165/BH/2.0		17,300	--	305	--	0.0283		45.4	0.177	0.13	--					
77				164/BH/2.0		15,800	--	332	--	0.0265		30.5	0.106	0.11	--	5				
78				21/FF/2.0	(see mod 19/FF/2.0)	14,287	--	225	--	0.0287		45.7	0.147	0.12	--	4				
79				20/FF/2.0		14,844	--	245	--			30.4	0.083	0.11	--	5				
80				159/H/2.0	(see mod 33/H/2.0)	17,204	--	416	--	0.0279		30.0	0.154	0.085	--	4				
81				26/BH/2.0	(see mod 25/BH/2.0)	5,549	--	87	--	0.0269		90.0	0.255	0.16	--			EB		
82				22/FF/2.0	(see mod 19/FF/2.0)	7,236	--	86	--	0.0265			0.205	0.14	--	5				
83				34/H/2.0	(see mod 33/H/2.0)	3,692	--	115	--	0.0269			0.241	0.125	--	4				
84				27/BH/2.0	(see mod 25/BH/2.0)	10,269	--	181	--	0.0282			0.391	0.16	--	5				
85				16/FF/2.0	(see mod 19/FF/2.0)	14,200	--	170	--	0.0271		90.1	0.300	0.11	--	5		HF		
86				36/H/2.0	(see mod 33/H/2.0)	7,145	--	172	--	0.0272		90.0	0.402	0.09	--	4		EB		
87				102/BH/2.0	(see mod 25/BH/2.0)	16,517	--	288	--	0.0271		44.7	0.218	0.11	--	5		HF		
88				18/FF/2.0	(see mod 19/FF/2.0)	19,201	--	259	--	0.0293		42.5	0.165	0.13	--	5				
89				32/H/2.0	(see mod 33/H/2.0)	10,692	--	321	--	0.0286		45.0	0.261	0.11	--	4		EB		
90				96/BH/2.0	(see mod 25/BH/2.0)	18,860	--	337	--	0.0265		30.8	0.148	0.11	--	5		HF		
91				97/BH/2.0	(see mod 25/BH/2.0)		--		--			31.0	0.155	0.13	--	5				
92				111/BH/1.0	Blunt hemisphere/cyl	10,588	--	560	--	0.0817		39.6	0.368	0.08	--	4		EB		
93				112/BH/1.0	$D_{cyl}=R_N=1$"x.88"thk.	10,548	--	545	--	0.0831		40.7	0.382	0.08	--					
94				31/H/2.0	(see mod 33/H/2.0)	10,443	--	528	--	0.0842		40.5	0.338	0.045	--					
95				129/BH/1.0	(see mod 111/BH/1.0)	3,515	--	507	--	0.373		20.1	0.325	0.04	--					
96				138/BH/1.0			--		--			15.4	0.247	0.055	--					
97	General Electric SSL	3-9		345	Flat face, 1.5" or 0.75" dia. cylinder with 0.625" dia. core x 0.75" thk	10,800	--	75	--	0.0082		100.	0.121	0.101	--	2	--	H_2O cooled gas calorimeter	cal same shape as model w/ copper slug inserts at stagnation point & 2 other locations	two-color pyro
98				346								100.	0.121	0.101	--	3	--			
99				373								70.	0.120	0.103	--	3	yes			
100				364		3,390	--	145	--	0.0028		40.	0.074	0.077	--	2	--			
101				365								25.	0.081	0.044	--	3	--			
102				366								20.	0.075	0.070	--	3	--			
103				396								25.	0.077	0.078	--	3	yes			
104				397								15.	0.079	0.056	--	3	yes			
105				418		13,400	--	490	--	0.049		8.	0.052	0.013	--		--			
106				419								12.	0.040	0.013	--		--			
107				492		5,420	--	330	--	1.0		7.	0.059	0.024	--		yes			
108				493								11.3	0.069	0.021	--					
109				501			--	250	--	0.50		9.9	0.059	0.067	--					
110				502A								7	0.059	0.058	--					
111				502B								15.	0.067	0.066	--					
112				522		13,400	--	595	--			9.1	0.028	0.022	--					
113				523								4	0.035	0.034	--					

Notes for Tables 3-1, 3-2, and 3-3

1. Facility Designations

   - NASA-Ames Gas Dynamics Branch (GDB) Planetary Entry Ablation Facility
   - NASA-Ames Magneto Plasma Dynamics Branch (MPDB) Low Density Constricted-Arc Supersonic Jet
   - NASA-Langley Applied Materials and Physics Division (AMPD) 20 inch Hypersonic Arc Heated Tunnel
   - Aerotherm Corporation 1 MW Arc Plasma Facility
   - Giannini Scientific Corporation 1 MW Hyperthermal Test Facility
   - Martin Company Plasma Arc Laboratory, Facility B
   - Space General Corporation Electro-Thermal Facility
   - NASA-Langley Entry Structures Branch (ESB) 5 MW Arc Powered Tunnel and 1 MW Arc Powered Tunnel
   - NASA-Langley 2500 KW Arc-Powered Jet, Subsonic Flow
   - Boeing Miniarc E Arc-heated Plasma Facility
   - General Electric Space Sciences Laboratory (SSL) Hypersonic Arc Tunnel

2. Material Composition Code

   - Phenolic Nylon
     - PR = phenolic resin
     - PM = phenolic microspheres
     - N = nylon
     - SIM = silica microspheres
   - Silicone Elastomer
     - SR = silicone resin
     - SM = silicone microspheres
     - PM = phenolic microspheres

3. Enthalpy Measurement Techniques

   EB = Energy balance on arc generator
   SF = Frozen sonic flow technique (or mass balance)
   HF = Heat flux at stagnation point using Fay-Riddell equation
   SP = Spectrographic method to determine static temperature; enthalpy read from Mollier diagram

4. In Boeing tests, pressure listed is test section entrance static pressure.

5. In NASA-Ames Entry Heating Simulator tests, convection heat flux (Column I) and radiation heat flux (Column II) were applied simultaneously. Radiation source was a carbon arc lamp.

TABLE 3-4

MODEL INTERNAL AND SURFACE TEMPERATURE DATA, LOW DENSITY NYLON PHENOLIC
(Except where specified, all initial temperature = 530°R)

Reference - 3-1

Facility - NASA Ames GDB

Model - PLL96

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Surface				
	0.094	0.226	0.328	0.426	Front Surface (ε=1.0)
5	610				2860
10	780				3050
15	1170				3150
20	1700	580			3230
25	2110				3300
30			590	540	
40		730			3450
50		930	630	580	3500
60		1150	640		3480
70		1670	700		3480
90				620	

Reference - 3-1

Facility - NASA Ames GDB

Model PLH98

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Surface				
	0.115	0.212	0.314	0.431	Front Surface (ε=1.0)
5	560				2900
10	650				3110
15	820				3200
20	1060				3260
25	1410				3300
30	1890	640		540	3340
40	2600	770	570		3400
50		990	600	560	3440
60		1380	640		3500
70		2070	730	580	3520
75		2270			

TABLE 3-4 (continued)

Reference - 3-1

Facility - NASA Ames MPDB

Model - PLL87

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface		
	0.095	0.220	0.310
5	540		
10	580	540	535
15	700		
20	900	580	540
25	1160		
30		610	570
40		660	610
50		780	620

Reference - 3-1

Facility - NASA Langley AMPD

Model - PLL93

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface			
	0.114	0.198	0.314	Front Surface (ε=1.0)
4	600			
6	640			
8	810			
10	1250	600		
12	1960			4400
15		630	560	
20		840	600	
22		1170		
24		1810		
25			610	

TABLE 3-4 (continued)

Reference - 3-1
Facility - NASA Langley AMPD
Model - PLH93

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface			
	0.114	0.216	0.309	Front Surface (ε=1.0)
4	550			
6	610			
8	740			
10	1110	535		
12	1790			4400
15		570		
20		680	540	
25		1190	555	
30			630	

Reference - 3-1
Facility - Aerotherm Corporation
Model - PLL97

Time (sec)	Temperature (°R) at Location Indicated (in) from Initial Front Surface				
	0.095	0.220	0.310	0.399	Front Surface (ε=1.0)
5	580				
10	780	550			3210
15	1180				
20	1710	600	570	570	3340
25	2130				
30		650			3360
40		780	600	600	3420
50		1040			3510
60			680	640	3590
80			1030	700	
100			2130	1350	

TABLE 3-4 (continued)

Reference - 3-1

Facility - Giannini Scientific

Model - PLL90

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Surface		
	0.119	0.220	Front Surface (ε=1.0)
5	540		3560
10	710	545	3910
15	1480		3880
20	1980	600	4040
25		660	4070
30		890	4130
35		1490	4120

Reference - 3-1

Facility - Giannini Scientific

Model - PLH90

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface		
	0.111	0.204	Front Surface (ε=1.0)
5	540		2760
10	640	540	3210
15	890		3410
20	1400	570	3590
25	1930	620	3660
30		690	3760
35		790	3830

TABLE 3-4 (continued)

Reference - 3-1
Facility - Martin Company
Model - PLL91

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface				
	0.111	0.221	0.314	0.415	Front Surface (ε=1.0)
5	550				
10	600				2660
15	660				
20	710	570	550		2780
30	820				
40	1680	670	580	560	2920
60		830	620		3020
80		1090	690	610	3100
100		1540	910		3160
120				700	

Reference - 3-1
Facility - Martin Company
Model - PLH91

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface				
	0.115	0.211	0.313	0.405	Front Surface (ε=1.0)
10	620				2620
15	680				
20	780	560	540		2710
25	910				
30	1040				
40	1420	670	550	540	2840
50	1810				
60		830	600		2940
80		1120	660	570	3020
100			770		3100
120				760	

TABLE 3-4 (continued)

Reference - 3-1

Facility - Space General

Model - PLL94

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface			
	0.104	0.211	0.284	Front Surface (ε=1.0)
5	580			
10	700			3260
15	990			3320
20	1330	550		3360
25	1700			3380
30		600	560	3400
40		740	580	3420
50		980	610	3470

Reference - 3-1

Facility - Space General

Model - PLH94

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface		
	0.111	0.211	Front Surface (ε=1.0)
10	640		3210
15	800		3300
20	1050	570	3360
25	1380		3400
30	1810	660	3400
40		770	3420
50		970	3430

TABLE 3-4 (continued)

Reference - 3-2

Facility - NASA Langley ESB

Models - LD-7, LD-8

Time (sec)	Temperatures (°R) at Locations Indicated (in) fron Initial Front Surface							
	Model LD-7				Model LD-8			
	0.126	0.249	0.378	0.505	0.126	0.250	0.379	0.500
0	530	530	530	530	560	560	560	560
5	575				600			
10	770				770			
15	1435	545			1435	565		
20	2005	565			2150	580		
25		600				630		
30		690				700		
35		850	540			820		
40		1090	550			1000	565	
45		1500	560			1320	585	
50		2140	595			1910	625	
55		2465	630	540		2305	675	
60		2665	660	545		2500	710	565
65			730	550			795	570
70			850	565			940	580
75			1100	577			1165	605
80			1445	605			1580	623
85			1950	630			2080	653
90			2280	665			2415	680
95			2560	720			2680	737
100				795				800
105				937				937
110				1130				1100
115				1460				1350
120				1880				1640

Reference - 3-3

Facility - NASA Langley AMPD

Models - PN-2 Material at Various Exposure Times

Time (sec)	Temperature (°R) at Back Face, 0.5 in. from Initial Front Face				
	30 sec Exposure	60 sec Exposure	90 sec Exposure	120 sec Exposure	150 sec Exposure
20	530	530	530	530	530
30	531				
40			532.5	532.5	
60		539	541	540.8	
80			559.3	560	560.2
90			573		
100				599	595
120				673	646.3
140					720
150					771

Time (sec)	Temperature (°R) at Front Surface		
	30 sec Exposure	90 sec Exposure	120 sec Exposure
0	3280	3110	3560
5	3440	3540	3610
10	3490	3390	3690
20	3460		3835
30	3595	3410	3850
40			3690
45		3530	
50			3830
60		3620	3885
70		3650	3860
80		3625	3865
90		3710	3930
100			3880
110			3950

TABLE 3-4 (continued)

Reference - 3-4

Facility - NASA Langley 2500 KW Arc

Models - 8 Models of Low Density Phenolic Nylon

Model Initial Thickness (in)	Run Time (sec)	Temperature History at Back Face, T_{init} = 530 R		
		Time to Reach 580°R (sec)	Time to Reach 830°R (sec)	Temp at End of Run (°R)
0.925	257	158	257	830
0.927	258	140	256	870
0.476	119	85	115	1025
0.450	125	92	120	989
0.930	210	112	---	745
0.934	130	130	---	580
0.933	129	123	---	589
0.417	93	89	---	594

Reference - 3-5

Facility - NASA Langley 2500 KW Arc

Models - 2, 13

Time (sec)	Temperature (R) at Back Face, Initially 1.0 in from Front Surface	
	Model 2	Model 13
0	530	530
75	531	532
80	536	534
85	539	535
90	541	536
95	554	537
100	830	538
125		546
150		560
175		580
200		600
225		614
250		629
275		672
290		730
294		828

TABLE 3-4 (concluded)

Reference - 3-6

Facility - NASA Ames GDB

Models - Various Phenolic Nylon Models

Time (sec)	Temperature (°R)					
	Back Face, 0.1 in from Initial Front Surface				Front Surface	
	19 sec Exposure	20 sec Exposure	39 sec Exposure	80 sec Exposure	39 sec Exposure	80 sec Exposure
0	530	530	530	530	530	530
5	530	536	534	530	1435	935
10	601	600	559	542	1720	1100
15	711	702	603	567	1910	1165
20	864	850	650	595	2010	1185
30			756	660	2120	1255
40			869	704	2180	1305
50				755	2220	1315
60				794	2250	1325
70				835		
80				872		

TABLE 3-5

MODEL INTERNAL AND SURFACE TEMPERATURE DATA, LOW DENSITY SILICONE ELASTOMER
(All initial temperatures = 530°R)

Reference 3-1

Facility - NASA Ames GDB

Model - SP96

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface				
	0.095	0.220	0.337	0.405	Front Surface (ε=1.0)
5	580				3000
10	700				3000
15	840				3000
20	1020				2970
30	1370	630	550	540	2930
40	1650	680			2890
50	1810	730	590	550	2860
60		810			2820
70		880	630	580	2800
75		930			

Reference 3-1

Facility - NASA Ames MPDB

Model - SP89

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface				
	0.120	0.241	0.311	0.421	Front Surface (ε=1.0)
5	590	535	532	532	3070
10	740	540			3310
15	1050	555	534	534	3340
20	1690	580			3350
25	2210	605	536	536	3350

TABLE 3-5 (continued)

Reference 3-1

Facility - NASA Langley AMPD

Model - SP93

Time	Temperature (°R) at Locations Indicated (in) from Initial Front Surface		
(sec)	0.085	0.189	Front Surface (ε=1.0)
2	550		
4	640		
6	810		
8	1110		
10	1530	550	
12	2040		4060
15		600	
20		700	
25		940	

Reference 3-1

Facility - Aerotherm Corporation

Model - SP97

Time	Temperature (°R) at Locations Indicated (in) from Initial Front Surface				
(sec)	0.101	0.208	0.303	0.409	Front Surface (ε=1.0)
5	630				2600
10	880	550			2740
15	1130				
20		580	550	550	2750
30		630			2730
40		730	590	580	2720
50		840			2710
60		950	670	630	2700
80			780	670	
100			860	740	

TABLE 3-5 (continued)

Reference 3-1

Facility - Giannini Scientific

Model - SP90

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface		
	0.099	0.216	Front Surface (ε=1.0)
5	550		3060
10	730		3260
15	1030		3310
20	1530	560	3460
25	1930		
30		630	3460

Reference 3-1

Facility - Martin Company

Model - SP91

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface				
	0.097	0.198	0.314	0.411	Front Surface (ε=1.0)
10	600				2690
20	750	570			2750
30	870				
40	1000	690	550	540	2780
50	1080				
60	1140	850			
80		1010	650	580	2840
120			790	650	

TABLE 3-5 (concluded)

Reference 3-1

Facility - Space General

Model - SP94

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface		
	0.097	0.189	Front Surface (ε=1.0)
5	610		3180
10	740		3260
15	980		3300
20	1300	580	3330
25	1600		3360
30	1830	670	3380
35	1990		3400
40		780	3410
50		900	3420

TABLE 3-6*

MODEL INTERNAL AND SURFACE TEMPERATURE DATA,
AVCOAT 5026-39 HC/G
(Except where specified, all initial temperatures = 530°R)

Reference - 3-1
Facility - NASA Ames GDB
Model - A93

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface 0.113	0.226	0.330	Front Surface (ε=1.0)
5	610			3120
10	900			3220
15	1320			3250
20	1810			3290
25	2210			3310
30	2460	580		3340
40	2940	620		3360
50		700	590	3390
60		830	610	3360
70		980	650	3390
75		1080		

Reference - 3-1
Facility - NASA Ames MPDB
Model - A84

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface 0.104	0.222	0.305	0.410
5	560			
10	700	550	540	535
15	1070			
20	1660	605	550	
25	2120			
30		810	580	550
40		1160	650	
50		1640	770	585

*Note: Due to the large quantity of AVCOAT material data, temperature histories are presented here for only a representative sampling of test runs in Table 3-1.

TABLE 3-6 (continued)

Reference - 3-1

Facility - NASA Ames MPDB

Model - A85

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface				
	0.103	0.211	0.321	0.424	Front Surface (ε=1.0)
4	550				3160
5		540	540	535	
8	800				3470
10		545	545	540	
12	1220				3610
15		580	550	550	
16	2120				3680
20	2600	670	650	550	3740
25			660	555	

Reference - 3-1

Facility - NASA Langley AMPD

Model - A90

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface				
	0.107	0.209	0.311	0.420	Front Surface (ε=1.0)
4	560				
55			535		
6	600	570			
8	680	600			
10	850	670	570	535	
12	1320	800			
14	1950	1110			4380
15			600		
20			730	580	

TABLE 3-6 (continued)

Reference - 3-1

Facility - Aerotherm Corporation

Model - A98

Time	Temperature (°R) at Locations Indicated (in) from Initial Front Surface				
	0.113	0.215	0.313	0.424	Front Surface (ε=1.0)
5	630				3160
10	1010	570			3270
15	1490				
20	1960	660	550	540	3320
25	2350				
30		890			3370
40		1340	660	560	3410
50		1930			3460
60			1060	640	3630
80			1840	830	3630
100				1350	

Reference - 3-1

Facility - Giannini Scientific

Model - A94

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface		
	0.101	0.213	Front Surface (ε=1.0)
2	535		2910
5	560		3260
8	720		3410
10	890	540	3560
13	1340		
15	1740		3620
18	2190		
20		650	3670
25		820	
30		1130	3820
35		1620	

TABLE 3-6 (continued)

Reference - 3-1
Facility - Martin Company
Model - A95

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface				
	0.103	0.216	0.314	0.415	Front Surface (ε=1.0)
5	560				
10	730				2830
15	940				
20	1190	590	540		2960
25	1440				
30	1730	700			
40		860	590	540	3060
50		1050			
60		1260	730		3080
80			920	620	3060
100			1160		3080
120				900	

Reference - 3-1
Facility - Space General
Model - A97

Time (sec)	Temperature (°R) at Locations Indicated (in) from Initial Front Surface		
	0.110	0.203	Front Surface (ε=1.0)
5	600		
10	820		3410
15	1220	600	
20	1780	670	3460
25	2230	790	
30		980	3510
35		1200	
40		1470	3530
45		1730	

TABLE 3-6 (continued)

Reference - 3-8

Facility - NASA Ames Entry Heating Simulator

Model-50/FF/1.25

Time (sec)	Temperature (^{O}R) at Locations Indicated (in) from Initial Front Surface 0.131	0.288	0.422	Front Surface (ε=.75)
0.5	530	530	530	4250
1				4400
3	570			4510
6	650			4540
8	1220			4570
10	2070	530	530	4580

Reference - 3-8

Facility - NASA Ames Entry Heating Simulator

Model - 63/FF/1.25

Time (sec)	Temperature (^{O}R) at Location Indicated (in) from Initial Front Surface 0.126	0.288	0.434	Front Surface (ε=.75)
1	520	520	520	3230
2				3700
4	560			3820
6				3880
8	630			
12	950	530	540	
13				3940
17	1760			4050
21	2360			4130
25	2870	550	610	4210

TABLE 3-6 (continued)

Reference - 3-8

Facility - Aerotherm

Model - 95/BH/2.0

Time (sec)	Temperature (^{O}R) at Location Indicated (in) from Initial Front Surface					
	0.136	0.279	0.460	0.669	0.842	Front Surface (ε=.75)
10	578	539	543	545	543	2548
20		534				2680
21	865					
30	1195	552	539	542	541	2711
40		599				2700
45	1744	639				
60	2116	795	543	532	536	2686
80	2352	1061				2678
90	2415	1194	606	537	532	
100	2470	1327				2678
121	2555	1618	749	550	533	2678

Reference - 3-8

Facility - Aerotherm

Model - 88/BH/2.0

Time (sec)	Temperature (^{O}R) at Location Indicated (in) from Initial Front Surface					
	0.131	0.272	0.456	0.675	0.842	Front Surface (ε=.75)
10	678	534	534	540	537	2713
20	1238					
30	1831	586	530			2847
40	2054	673				
50	2222	816	548			2850
60	2517	973				
69	2724	1164	588			2850
80		1391	628	539		
90		1605	677			
100		1793	748		533	2841
110		1944	819			
122		2077	908	539	539	2841

TABLE 3-6 (continued)

Reference - 3-8

Facility - Aerotherm

Model - 108/BH/2.0

Time (sec)	Temperature (^{O}R) at Location Indicated (in) from Initial Front Surface					
	0.132	0.284	0.446	0.664	0.837	Front Surface (ε=.75)
10	681	539	533	541	542	3355
15	1043					
20	1595	552	534	539		3480
25	2112					
30		608	544	537	541	3533
40		789	551			3548
50		1202	561			3566
60		1900	596	539	533	3577

Reference - 3-8

Facility - Aerotherm

Model - 74/BH/2.0

Time (sec)	Temperature (^{O}R) at Location Indicated (in) from Initial Front Surface					
	0.148	0.282	0.480	0.673	0.846	Front Surface (ε=.75)
8.8	601	530				
12.8	818	534				
16.8	1150	543				3475
20.8	1780	556	530	530	530	3427
25.8		599	530			3427
30.8		685	534	538	535	3506
40.8		961	539	541	538	3485
50.8			557	544	543	3544
52.8		1772				
60.8		2327	592	549	547	3552

TABLE 3-6 (continued)

Reference - 3-8

Facility - Aerotherm

Model - 83/BH/2.0

Time (sec)	Temperature (^{O}R) at Location Indicated (in) from Initial Front Surface					
	0.152	0.277	0.460	0.678	0.842	Front Surface (ε=.75)
0.8	534	534	543	552	546	3056
10.8	858	556	530	549	543	4043
14.8	1753					
20.8		616	534	544	541	4120
25.8		754				
30.8		1009	539	539	536	4241
40.8		1940	574	536	532	4300
50.8			680	531	531	4318
61.0			914	538	536	4300

Reference - 3-8

Facility - Aerotherm

Model - 101/BH/2.0

Time (sec)	Temperature (^{O}R) at Location Indicated (in) from Initial Front Surface					
	0.136	0.287	0.455	0.673	0.846	Front Surface (ε=.75)
5	642					
8	928					4399
9	1542					
10		551	530	532	534	4454
15		611				
20		658	546	533	530	4537
30		1350	558	543	538	4600
33		1818				
40			586	552	547	4624
45				556	549	
46			637			

TABLE 3-6 (continued)

Reference - 3-8

Facility - Aerotherm

Model - 116/BH/4.0

Time (sec)	Temperature (^{O}R) at Location Indicated (in) from Initial Front Surface				
	0.132	0.455	0.668	0.852	Front Surface (ε=.75)
10	608	530	544	545	2429
20	922	530	543	545	2705
32	1480				
40	1828	539	539	543	2826
53	2146				
60.5	2259	552	533	541	2829

Reference - 3-8

Facility - Aerotherm

Model - 122/BH/4.0

Time (sec)	Temperature (^{O}R) at Location Indicated (in) from Initial Front Surface					
	0.132	0.279	0.460	0.661	0.847	Front Surface (ε=.75)
10	823			551		
13	1257	534				3830
15	1703		542			3840
17	2011	551			551	3840
20	2340	586		541		
30		878	542	531	545	3792
40		1546		535	538	
45			567			3781
50		2194	595	539	531	
60		2600	699	542	535	3894

TABLE 3-6 (continued)

Reference - 3-8

Facility - Aerotherm

Model - 33/H/2.0

Time (sec)	Temperature (^{O}R) at Location Indicated (in) from Initial Front Surface				
	0.223	0.406	0.599	0.762	Front Surface (ε=.75)
10.5	697	534	539	542	3381
20.5	1326	543	534	543	3445
30.5	2160	579	539	553	3455
40.5	2488	689	543	562	3470
50.5	2812	867	552	567	3485
60.5	2935	1137	566		3548
68.6	3057				
70.5		1518	593	581	3585
80.5			638	590	3615
90.5		2305			

Reference - 3-8

Facility - Aerotherm

Model - 17/FF/2.0

Time (sec)	Temperature (^{O}R) at Location Indicated (in) from Initial Frton Surface				
	0.158	0.287	0.460	0.673	0.832
10.3	562	539	553	551	543
20.3	1346	552	539		
30.3	2645	606	544	548	
40.3		872	548		
50.3		1740	557		
60.3			580	548	558
61.1		2440			
70.3			679		
80.3			895		
89.3			1502	560	567

TABLE 3-6 (continued)

Reference - 3-8

Facility - Aerotherm

Model - 164/BH/2.0

Time (sec)	Temperature (°R) at Location Indicated (in) from Initial Front Surface					
	0.129	0.287	0.446	0.669	0.849	Front Surface (ε=.75)
6	599	538	530			4258
8	763	530				4336
10	1108	560		541	540	4406
12	1602					4458
20		581	557		534	4545
30			561	548	546	4587
31		801				

Reference - 3-8

Facility - Aerotherm

Model - 22/FF/2.0

Time (sec)	Temperature (°R) at nocation Indicated (in) from Initial Front Surface					
	0.144	0.284	0.460	0.673	0.832	Front Surface (ε=.75)
10.5	677	547	534	535	530	3566
20.5	1463	565	539			3599
30.5	2265	621	548		540	3670
40.5	2753	782	561			
50.5		1040	565	541		3726
60.5		1542	588			3749
70.5		2075	623	564	569	3774
80.5		2456	690			3785
90.5		2810	809	568	583	3821

TABLE 3-6 (continued)

Reference - 3-8

Facility - Aerotherm

Model - 18/FF/2.0

Time (sec)	Temperature (°R) at Location Indicated (in) from Initial Front Surface					
	0.140	0.294	0.462	0.678	0.842	Front Surface (ε=.75)
10	962	552	534	530	530	
12	1446					4154
15	2280	565				4211
20		612	556			4269
30		974	561			4300
40		2013	578	557	534	4252

Reference - 3-8

Facility - Aerotherm

Model - 97/BH/2.0

Time (sec)	Temperature (°R) at Location Indicated (in) from Initial Front Surface					
	0.134	0.282	0.450	0.673	0.846	Front Surface (ε=.75)
6	658					4294
8	906	543				4342
10	1320		539	541	538	
20		720	552	535		4537
28		1543				
30			556	541	534	4640

TABLE 3-6 (concluded)

Reference - 3-8

Facility - Aerotherm

Model - 112/BH/1.0

Time (sec)	Temperature (^{O}R) at Location Indicated (in) from Initial Front Surface				
	0.146	0.298	0.458	0.667	Front Surface (ε=.75)
5.6	663			537	4721
8.6	1802		534		4750
10.6	2636				
12.6		586			4770
20.6		985	575	534	
24.6		2422			
30.6				562	
32.6			584		

Reference - 3-8

Facility - Aerotherm

Model - 138/BH/1.0

Time (sec)	Temperature (^{O}R) at Location Indicated (in) from Initial Front Surface				
	0.129	0.294	0.458	0.662	Front Surface (ε=.75)
5	1559	603	580	558	
5.6	2144				
12		680	592		4731
15		1515	600	567	

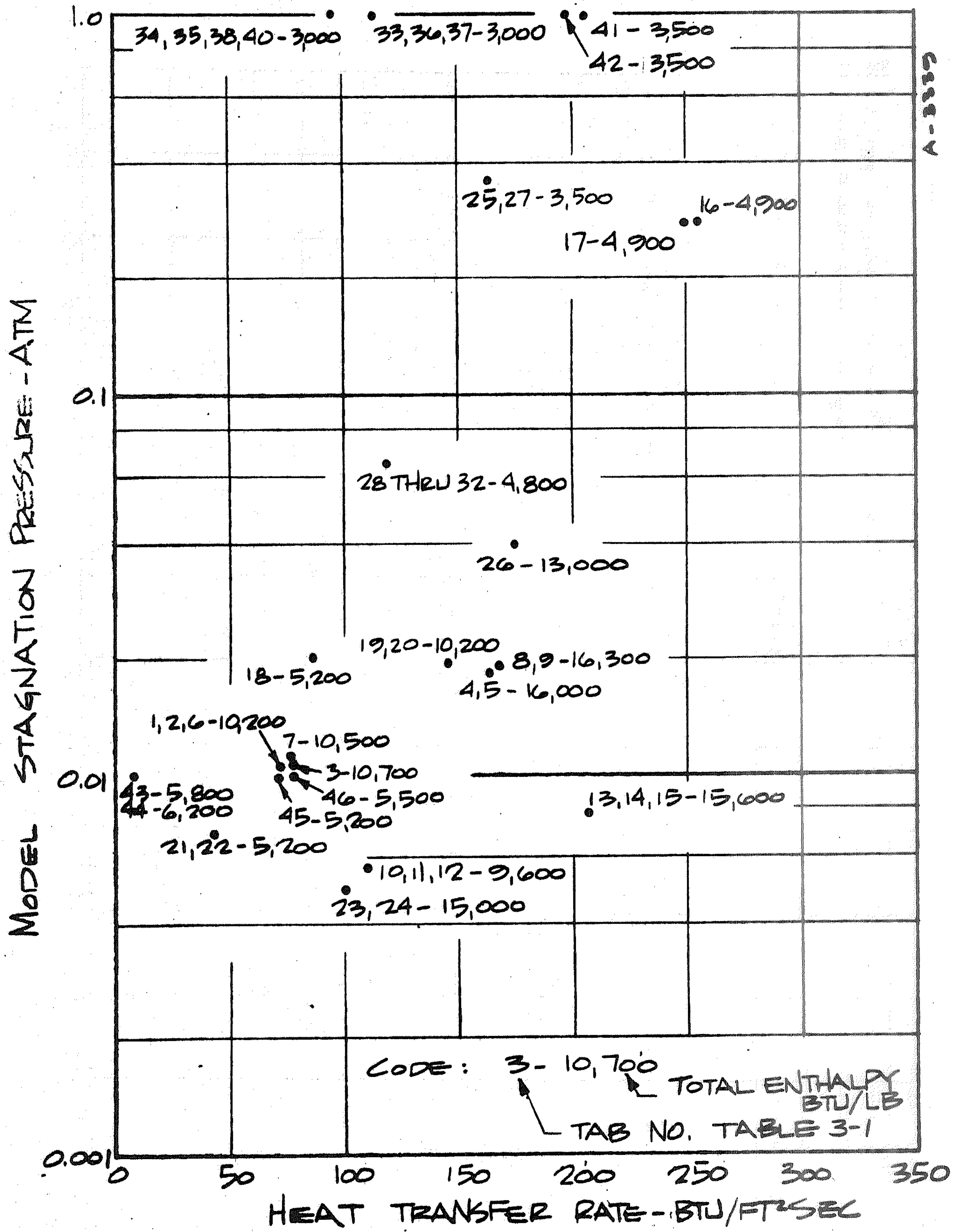


FIGURE 3-1 ABLATION TEST DATA, LOW DENSITY PHENOLIC NYLON

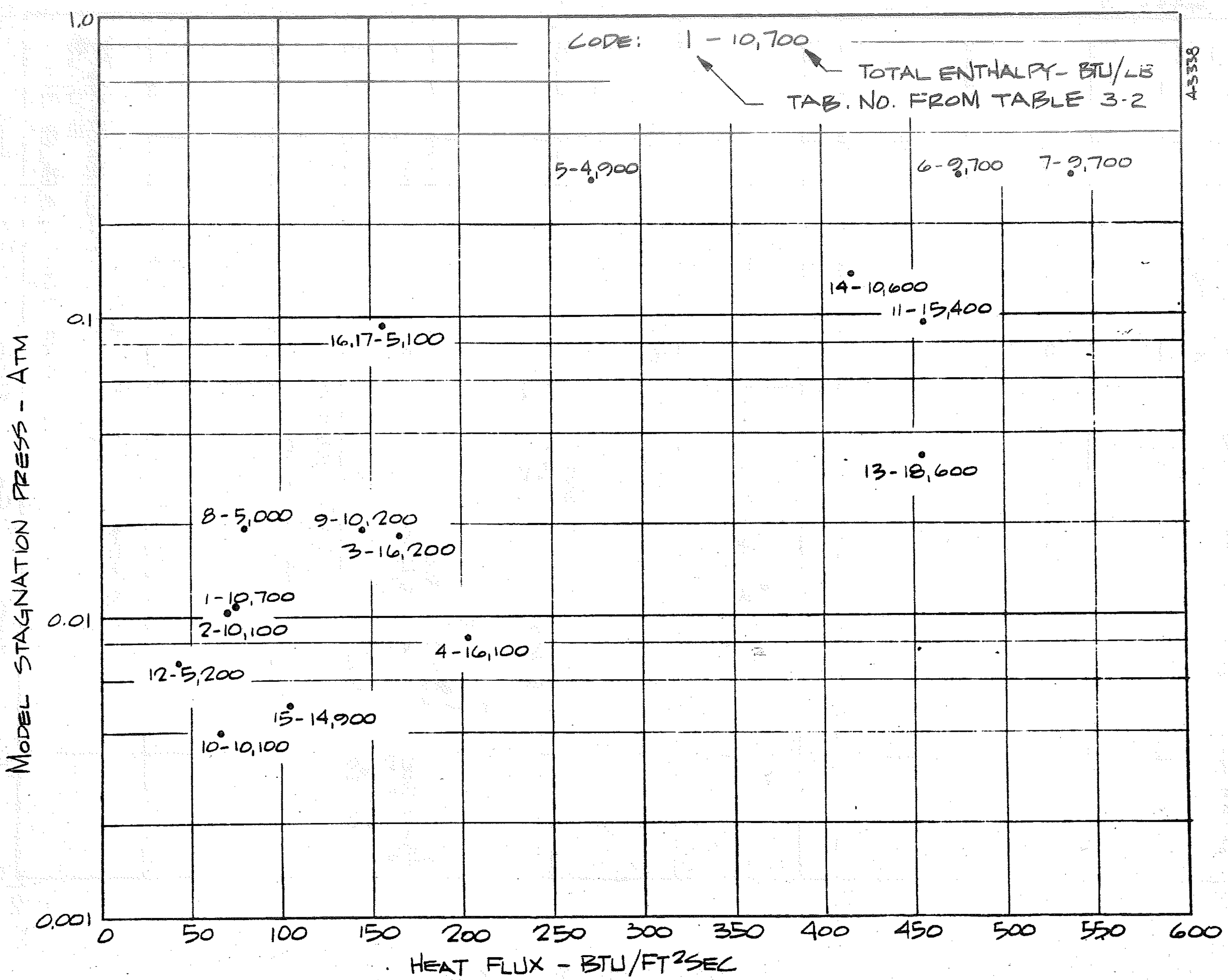


FIGURE 3-2 ABLATION TEST DATA, LOW DENSITY SILICONE ELASTOMER

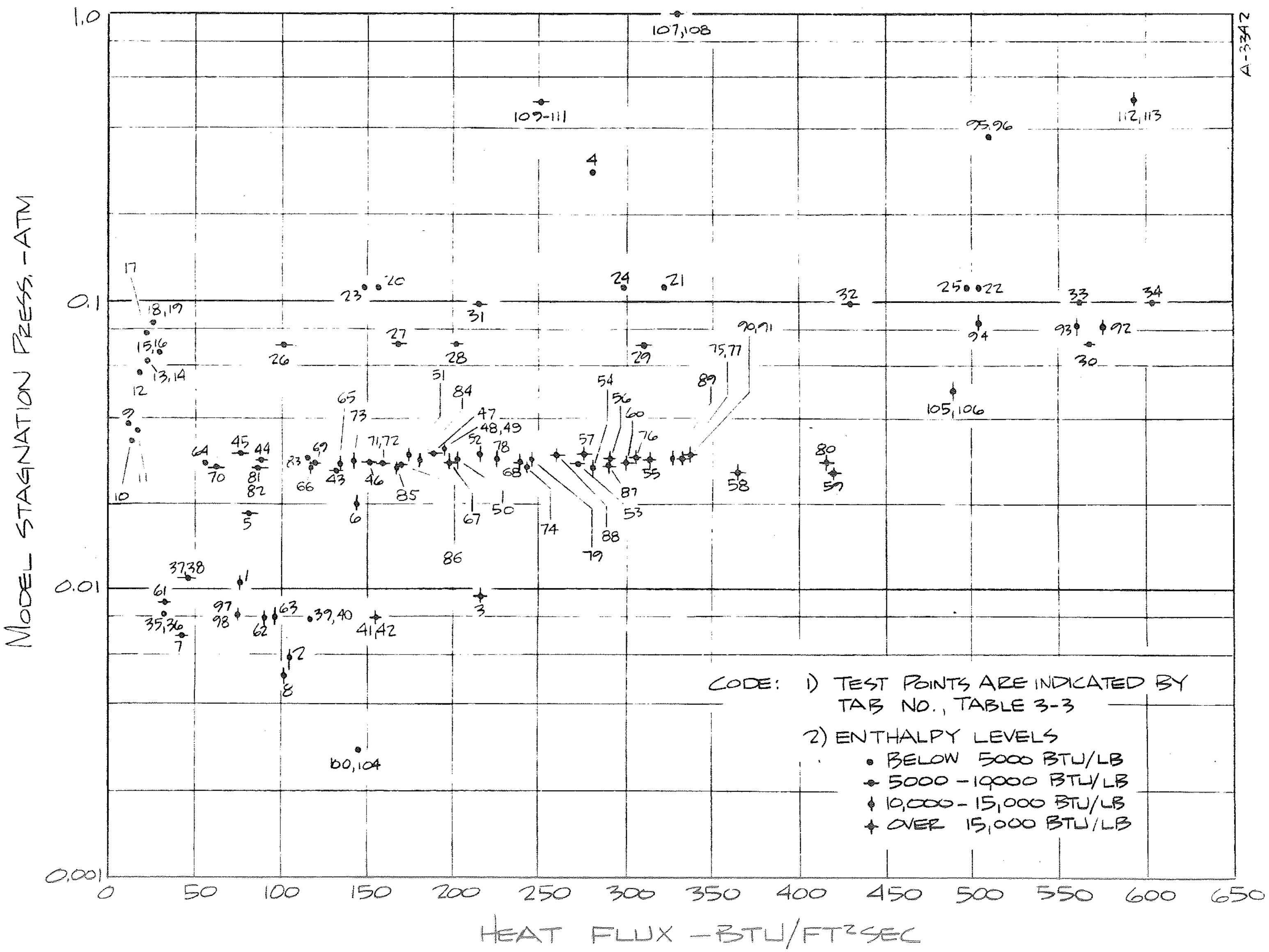


FIGURE 3-3 ABLATION TEST DATA, AVCOAT 5026-39HC/G

SECTION 4

QUALIFYING CALCULATIONS

Using CHAP I, qualifying calculations were performed to demonstrate an ability to operate the program successfully prior to initiating Task II of the study. One test condition was chosen for each of the three materials. Calculations were performed with CHAP and the results (total surface recession, final char thickness, and temperature histories) were compared with the test data. The results were reviewed with the technical monitor, and where the data match needed improvement, revisions were made in the input and the code rerun. In the process the program, which was originally running on the CDC 6600 computer, was successfully transferred to the Univac 1108 in order to accelerate turn-around time. The machine-time cost differential, which is approximately 10 percent in favor of the 6600, is outweighed by the operating efficiency achieved by faster turn-arounds on the 1108. In addition, with the program operating on both machines, calculations can continue when one computer is down.

The following sections describe the qualifying calculations on each ablating material and the criteria for determining satisfactory agreement between calculated and experimental data.

4.1 CRITERIA FOR AGREEMENT BETWEEN CALCULATIONS AND MEASUREMENT

4.1.1 General Remarks

Successful operation of an ablation code such as CHAP allows surface temperatures, surface recessions, char thicknesses, and thermocouple responses to be predicted with a fair degree of accuracy. This demonstration task required the definition of "satisfactory" agreement between predictions and experimental data. The definition of "satisfactory" shall apply to both Task I, reported here, and to the subsequent, more extensive Task II calculations. All in all, the agreement criteria will have the following uses

Task	Use of Criteria
I.3	Evaluate ability to operate the CHAP code and obtain satisfactory predictions
II.1	Obtain good properties data for iterative calculations
II.3	Final calculations, evaluation of range of applicability of CHAP

The criteria will be applied rather strictly in Task II.1 in order to arrive at the best possible set of properties data before beginning the more wide scale calculations of Task II.3. In the evaluation phase of Task II.3, the criteria will be used to define the range of applicability of CHAP. The exact nature of this range definition activity remains to be established during Task II.3. Since it is unlikely in a battery of calculations covering a wide range of conditions that all the criteria will be met in any one case, some caution will be necessary in the final assessment of the applicability range. Too rigid adherence to pre-established criteria may artificially restrict the indicated range of applicability.

Somewhat similarly, the criteria need not be applied too literally in Task I.3, where considerations of economy discourage an extensive search for close agreement in all respects between prediction and data. Here, predictions satisfactory in most criteria, plus an adequate explanation of any important discrepancies, suffice to indicate successful operation of the CHAP code.

The subsections of Section 4.1.2 discuss individual agreement criteria.

4.1.2 Agreement Criteria

4.1.2.1 Surface Temperature

Surface temperatures are measured by pyrometric (radiative) means, for which the expected random error of the basic instruments is often about ± 1 percent of the full scale. Usually, random errors of data recording and reduction add at least another ± 1 percent to this figure. In addition, many other errors of calibration and instrument handling (placement and focusing) can take on a random character of a magnitude of some ± 3 percent. All in all, surface temperature measurements of this type have a random uncertainty of ± 5 percent or ± 150°R to ± 300°R for the temperature range of most interest here.

Systematic errors can also be important. These can stem from uncorrected window and mirror losses, gas cap radiation interference, non-normal viewing angle effects, and emittance assumptions. The importance of these must be judged according to the particular test set-up in each case studied.

The surface temperature criterion is set at ± 200°R, with a cautionary note about potentially important systematic errors.

4.1.2.2 Surface Recession

Due to surface roughness effects, surface recession can seldom be measured accurately to within ± 0.010 inches. Various other uncertainties in such quantities as recovery enthalpy, convective transfer coefficient, and char density, make it difficult to predict recession amounts to within ± 20 percent of the observed recession.

Therefore the recession prediction will be considered satisfactory if the predicted recession matches the observed recessions to within $\pm \eta_s$, where η_s is the maximum of:

1. 20 percent of the observed recession
2. 0.010 inches

For char thicknesses comparable to the surface recession, char swelling or shrinkage may be an important factor. The actual amounts of shrinkage or swelling can sometimes be discovered from inert environment tests. If the char dimensional stability can be quantified , it should be considered in the comparisons of predictions with data.

4.1.2.3 Pyrolysis Penetration Depth

The basic uncertainty on pyrolysis penetration depth measurements is approximately 0.010 inches. Char shrinkage or swelling may amount to 20 percent of the char thickness. Otherwise, penetration depth should be predictable to within ± 10 percent.

Therefore the pyrolysis penetration depth prediction will be considered satisfactory if the predicted depth matches the observed depth to within $\pm \eta_t$, where η_t is the maximum of:

1. 10 percent of the observed pyrolysis penetration depth
2. 0.010 inches

In the specified (input) surface temperature and recession runs during Task II, this criterion can apply strictly. In other runs, note must be taken of the influence of faulty predictions of surface temperature and surface recession on predicted pyrolysis penetration depth.

4.1.2.4 Thermocouple Criteria

For runs made with specified (input) surface temperature and recession, thermocouple matching ought to be relatively good, provided of course that the input surface temperature and recession histories are adequately characterized. During times of "low" temperature rise rates thermocouple predictions should be within 10 percent of the current absolute temperature. Experience shows that it is not possible to maintain this accuracy during periods of rapid temperature rise. A smooth blend with the first criterion cited above would be (for the temperature rises and rise rates of interest in this program)

$$(T_{calc} - T_m) \leq 4 \text{ sec } \frac{dT_m}{d\theta} + 0.1\ T_m$$

This criterion in effect specifies a permissible 4 to 5 second time lead for a thermocouple response prediction during rapid temperature rise periods. The criterion is therefore biased in favor of over-prediction since thermocouples generally lag the material response due to thermocouple capacitance and thermal contact effects.

4.2 GENERAL ASSUMPTIONS AND REMARKS

The experimental runs for nylon phenolic, silicone elastomer, and Avcoat 5026-39-HC/G were all chosen from Reference 3-1. The test model shape was a flat faced disk, 1.25 in. diameter, with a 0.625 in. diameter instrumented core plug, 0.75 in. thick. The model was bonded on the back-side to a steel base plate with the cavity behind the core filled with RTV silicone rubber. The CHAP runs were modeled with no heat sink (conduction or radiation) at the back face, an assumption that introduced no error because the model thickness prevented any temperature rise at the back face for the conditions run. The virgin material was divided into J = 10 stations in all cases. Initially, the char layer was divided into I = 4 stations, but, for later runs, broken into I = 8 stations. The effect on the results of the finer division was negligible, The relatively large spacing between stations in the virgin material caused problems when the program interpolated thermocouple temperatures in regions of rapidly changing temperature gradient. The interpolation scheme was a 2nd order curve fit and as a result, the thermocouple temperature plots exhibited an apparent oscillatory behavior. The plotted temperature data in this report will present both the thermocouple results as computed by CHAP and "corrected" results as deduced from an inspection of the in-depth temperature profile determined from the nodal temperatures. To eliminate thermocouple error, future CHAP cases will incorporate smaller nodes and a linear thermocouple interpolation technique.

All runs were made with the oxidation option of the CHAP code. (In the case of silicone elastomer, the oxidation mechanism was supplemented by simulated melting by modifying the sublimation mechanism as discussed in Section 4.4.) All cases used the second degree approximation for aerodynamic blockage (blowing reduction) of convective energy to the surface.

4.3 LOW DENSITY PHENOLIC NYLON

The test condition simulated was tabulation no. 23 of Table 3-1 (Space General Corp. Model No. PLL94) taken from Reference 3-1. The conditions were as follows:

Enthalpy, h	=	14,922 Btu/lb
Heat Transfer Rate, $\dot{q}_{cw}$	=	103 Btu/ft^{2}sec
Stagnation Pressure, p_{t_2}	=	0.00511 atm
Run Time	=	50 seconds

Two runs were made with CHAP on this material. The first run employed thermophysical properties listed in Table B-1 with heat of combustion listed in Table B-4. The second run used "faster" oxidation kinetics in an effort to increase the recession rate and the surface temperature. The results are compared with the test data in Table 4-1. Plots of internal and surface temperatures appear in Figures 4-1 through 4-3. The thermocouple at 0.284 inches from the initial front surface rose 80 degrees in the test and increased about 45 degrees in both calculation runs.

Run 1 showed a surface recession that was too small and a surface temperature that was low by 600°R at the end of the run (for char $\varepsilon = 0.8$). The internal temperatures were also lower in the calculation. The experimental recession rate was substantiated by two other tests at the same conditions reported in Reference 3-1. An alternate surface temperature measurement in the test using an SRI-supplied radiometer read 400°R lower (only the maximum reading was published). Therefore the calculated results were lower than the average measurement by about 400°R.

Run 2 employed oxidation reaction rate constants that are listed in Table B-2 of Appendix B for silicone elastomer and are termed "Scala's fast kinetics." The results showed an increased recession rate, but the surface temperature decreased another 100 degrees. Hand calculations have indicated that, in Run 2, the char mass removal rate reached the "plateau" asymptote as governed by the oxygen concentration very early in the run. Therefore still faster kinetics will not alter the results to any significant degree.

The predicted results and the measured results do not compare especially well for this case, and except for thermocouple response generally do not meet the agreement criteria of Section 4.1. The predicted surface temperature is reasonably close (200°R) to the lower of the two reported pyrometer measurements, but the surface recession misses the measured value badly. It seems likely that the reported test data are erroneous in some respect: the reported enthalpy and cold wall heat flux yield an oxygen diffusion-limited recession rate which, with no blowing reduction, can account for only 60 mils (compared with the reported value of 54 mils) of recession. Blowing reduction effects should reduce this value by some 20 percent; departures from the diffusion-limited plateau value of $\dot{m}$ at early times will acount for another 10 percent reduction, having an expected recession of 42 mils, much closer to the predicted value of 27 mils. Char shrinkage may account for the 12 mil discrepancy between expected and observed recession (this would imply a 10 percent shrinkage); the remaining 15 mil discrepancy between observed and predicted results may in large part be measurement error.

Predicted char thicknesses are somewhat in general harmony with the low recession predictions. Essentially the same rationalizations apply in both cases.

There are no apparent flaws in the reported test conditions. Calculation of enthalpy from p_{t_2} and $\dot{q}_{cw}$ verify that the stream was quite uniform.

4.4 LOW DENSITY SILICONE ELASTOMER

The test condition calculated was tabulation no. 9 of Table 3-2 (Giannini Scientific Corp., Model SP90) from Reference 3-1. The conditions were:

Enthalpy, h	=	10,200 Btu/lb
Heat transfer rate, $\dot{q}_{cw}$	=	145 Btu/ft^{2}sec
Stagnation pressure, p_{t_2}	=	0.0199 atm
Run time	=	35 seconds

The results of two CHAP runs are presented in Table 4-2 and the plots of surface temperature and the temperature indicated by the thermocouple nearest the surface are shown in Figures 4-4 and 4-5 respectively. The temperature indicated by a second thermocouple, located 0.216 inch from the original surface but not shown, increased 100 degrees by the end of the test and rose 140 degrees in both computation runs.

Run 1 employed thermophysical properties presented in Table B-2 for silicone elastomer. Since the predicted surface temperature of Run 1 exceeded the melt temperature cited in the Work Statement (3800°R), a second run was made with melting simulated with the exponential sublimation feature of CHAP.* Sublimation constants ABEXP = 1.5×10^{35} and BBEXP = 331,632 simulated melting or failing in a narrow ± 200°R band centered at 3800°R.

Overall, the agreement between predictions and data is excellent. The Run 1 predicted surface temperature appears somewhat high (by about 400°R). The measured surface temperature was substantiated by the SRI radiometer used

*For this purpose, pressure effects in the sublimation computations were deleted with appropriate Fortran changes.

in the test. However both the Thermodot pyrometers and the radiometer viewed the model through a chamberport, evidently with no correction factor considered in the results. A third temperature surface measurement with an L&N optical pyrometer peaked at 4020°R (ϵ = 0.8), but information on the location of the instrument is not given.

Reported surface temperatures may therefore be somewhat low, perhaps by 100°R. The 0.8 emittance assumption is higher than the data reported by Pope (Ref. 2-15) of 0.71; this accounts for another 100°R and brings the adjusted experimental data up to an acceptably close match to both Run 1 and Run 2 predictions.

The predicted Run 1 recession matches the test data quite well in that both are negligible; Run 2 experienced melting which raised the recession to 29 mils. A preference between Run 1 and Run 2 would depend on the quantification of char swell, which for the 127 mil char might easily amount to 20 mils.

The char thickness prediction is excellent for Run 1, and about 20 percent low for Run 2. Again, a study of a char swell is necessary to allow a rational choice between the two predictions.

The thermocouple match is quantitatively good, although the shapes of the predicted and measured responses do not correspond particularly well. Study of this possible problem would have to involve other cases.

4.5 APOLLO HEAT SHIELD MATERIAL, AVCOAT 5026-39HC/G

The test condition simulated was tabulation no. 4 of Table 3-3 (NASA Langley AMPD, Model A90) from Reference 3-1. The conditions were as follows:

Enthalpy, h	=	4900 Btu/lb
Heat transfer rate, $\dot{q}_{cw}$	=	280 Btu/ft^{2}sec
Stagnation pressure, p_{t_2}	=	0.284 atm
Run time	=	20 seconds

CHAP was run twice on the Apollo material. The first run employed the material thermophysical properties of Table B-3, Appendix B, as given in the contract work statement. The results appear in Table 4-3; thermocouple histories are shown in Figures 4-6 and 4-7. Reference 3-1 presented only the final surface temperature. The surface temperature and recession predictions matched the data very well; char thickness was a factor of two too high and the deep thermocouple response was overpredicted. (The shallower of the two thermcouples was inadvertently not called out in this run.)

A second run aimed to reduce these two discrepancies with reduced values of the char conductivity at high temperatures (above 2260°R). The char thermal conductivity used in Run 2 (see Table 4-4) was taken from Reference 4-1. In that study revised conductivity values (above 2260°R) were derived from the existing Avco data in an effort to match in-depth thermal response on Apollo flights AS-501 and AS-502. The second run satisfactorily reduced the char thickness to match very well with the test results. However, the temperature gradient became too large. It is noted in Figures 4-6 and 4-7 that the thermocouple nearest the surface (and in the char after ~ 6 seconds) was high in the calculation and the thermocouple 0.10 in. deeper was calculated lower than the test value. Undoubtedly, further computer runs could fit the test temperature response data with a refined char thermal conductivity featuring somewhat lower k_c values at high temperature and higher values at low temperatures. Some study of the pyrolysis gas enthalpy might also be in order. However the effort is more appropriate for Task II of the study, particularly since the agreement is already fairly good and meets the suggested criterion of Section 4.1 above.

REFERENCE

4-1 Bartlett, E.P., Abbett, M.J., Nicolet, W.E., and Moyer, C.B., "Improved Heat-Shield Design Procedures for Manned Entry Systems, Part II, Application to Apollo", Aerotherm Corporation, Mountain View, California, Aerotherm Report No. 70-15, June 22, 1970.

TABLE 4-1

COMPARISON OF RESULTS FOR LOW DENSITY PHENOLIC NYLON

Tab. No. 23, Table 3-1

	Test Results	CHAP Results	
		Run 1	Run 2
Total surface recession (in.)	0.054	0.0015	0.027
Final char thickness (in)	0.124	0.177	0.156
Final surface temperature (°R)	3670 (ε=0.8)	3059	2967

TABLE 4-2

COMPARISON OF RESULTS FOR LOW DENSITY SILICONE ELASTOMER
Tab. no. 9, Table 3-2

	Test Results	CHAP Results	
		Run 1	Run 2
Total surface recession (in)	0.004	0.005	0.029
Final char thickness (in)	0.127	0.125	0.103
Final surface temperature (°R)	3660 (ε=0.8)	4058	3804

TABLE 4-3

COMPARISON OF RESULTS FOR AVCOAT 5026-39HC/G

Tab. No. 4, Table 3-3

	Test Results	CHAP Results	
		Run 1	Run 2
Total surface recession (in)	0.177	0.167	0.172
Final char thickness (in)	0.061	0.126	0.059
Final surface temperature (R)			
Langley photo pyrometer	4230 (ε=0.75)	4268	4301
SRI radiometer	3985* (ε=0.75)		

*Uncorrected for losses in tunnel window and a mirror

TABLE 4-4

CHAR THERMAL CONDUCTIVITY

(From Reference 4-1)

T °R	k Btu/ft sec°R
460	1.33×10^{-5}
860	2.00×10^{-5}
1,060	1.86×10^{-5}
1,360	1.94×10^{-5}
1,460	2.03×10^{-5}
1,710	2.89×10^{-5}
1,860	4.03×10^{-5}
2,060	6.81×10^{-5}
2,260	1.00×10^{-4}
2,460	1.16×10^{-4}
2,660	1.38×10^{-4}
2,860	1.27×10^{-4}
3,060	1.11×10^{-4}
3,260	9.00×10^{-5}
3,460	1.93×10^{-5}
3,660	2.08×10^{-5}
3,860	2.18×10^{-5}
4,060	2.22×10^{-5}
4,260	2.20×10^{-5}
4,460	2.08×10^{-5}
4,660	1.94×10^{-5}
4,860	1.82×10^{-5}
5,060	8.5×10^{-6}
5,260	7.4×10^{-6}
5,660	4.0×10^{-6}
5,860	2.1×10^{-6}
6,060	1.5×10^{-6}
6,460	7.0×10^{-7}

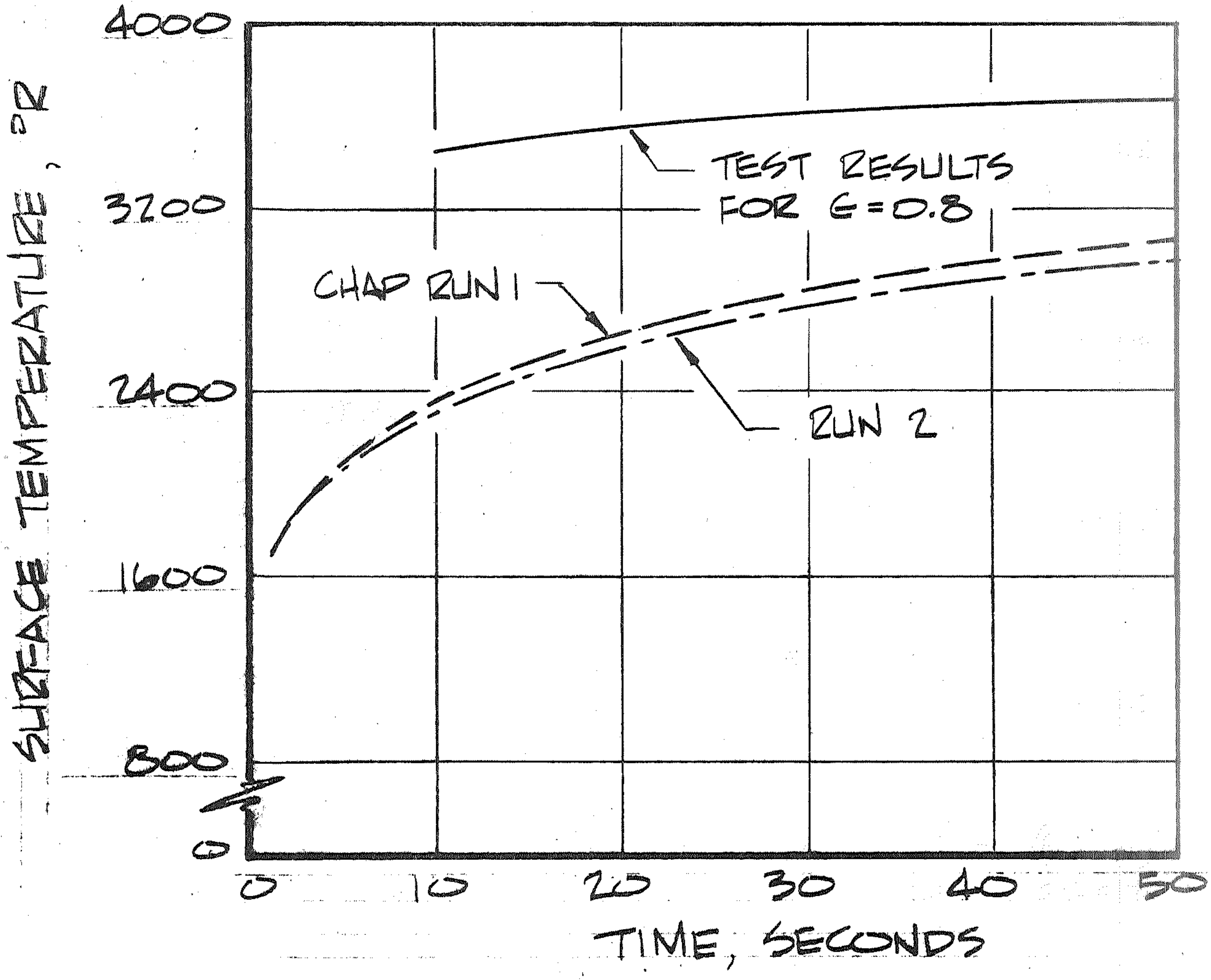


FIGURE 4-1 PHENOLIC NYLON, TAB No. 23 TABLE 3-1, SURFACE TEMPERATURE HISTORY

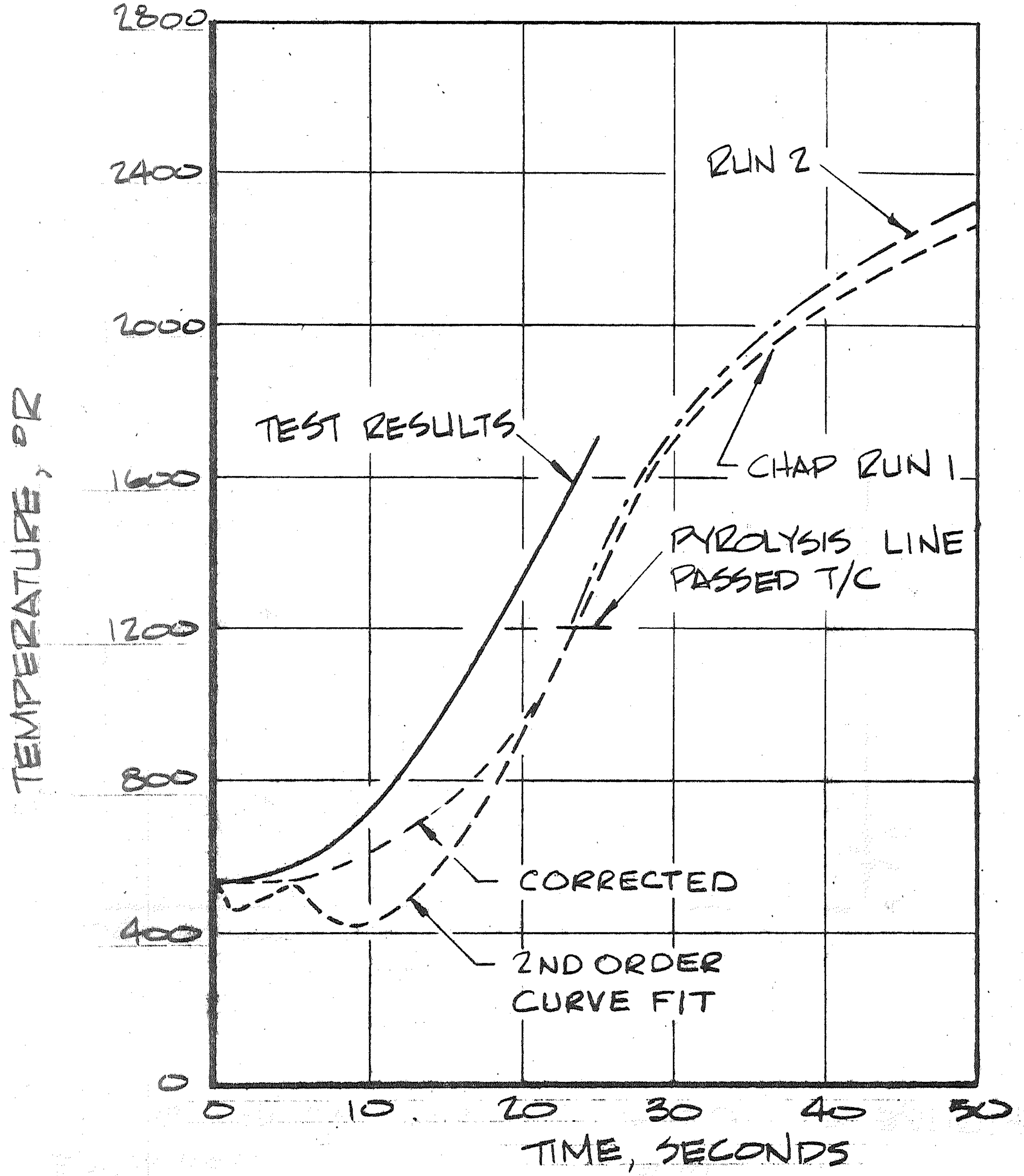


FIGURE 4-2 PHENOLIC NYLON, TAB No. 23 TABLE 3-1, TEMPERATURE HISTORY FOR T/C INITIALLY 0.104 IN FROM SURFACE

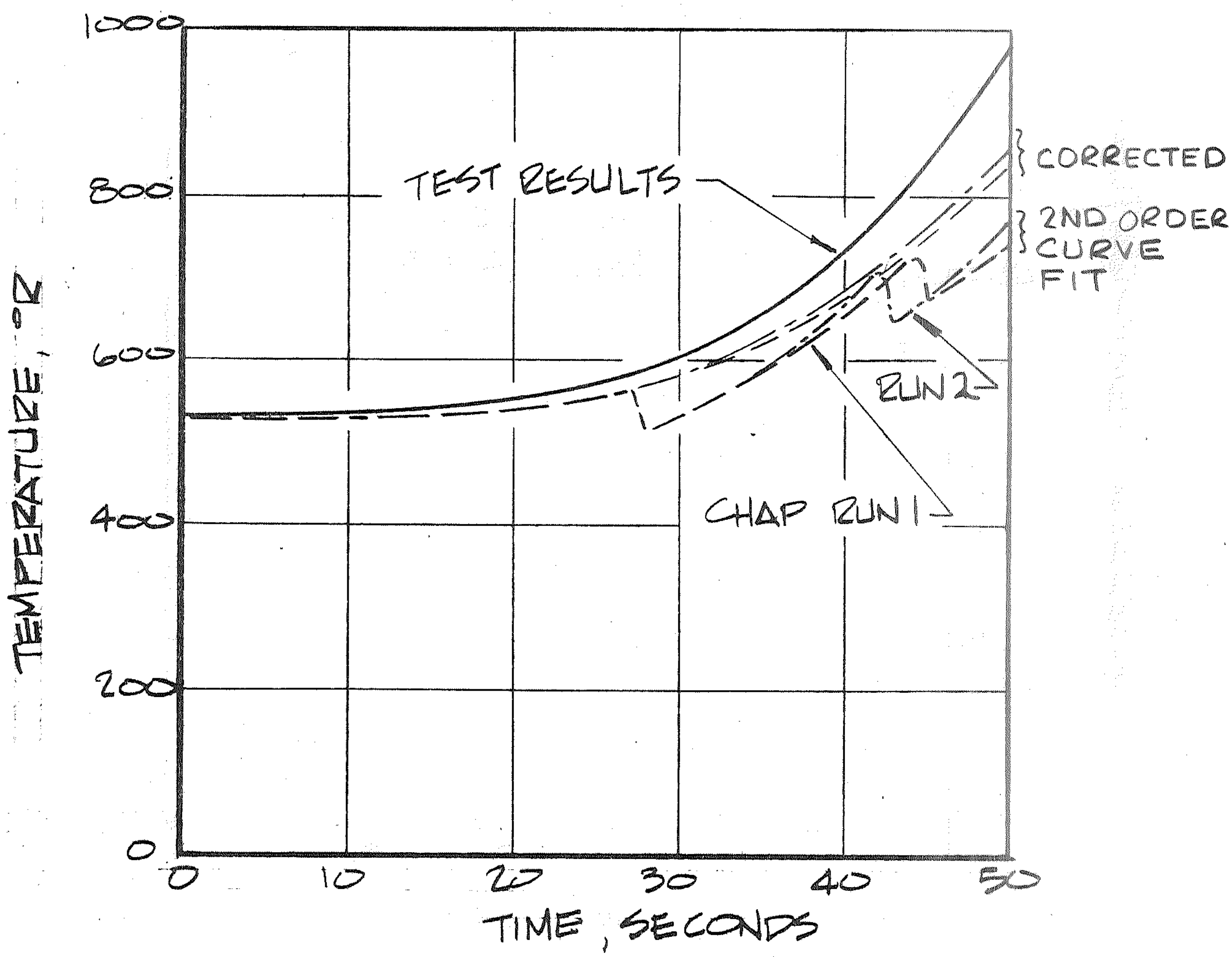


FIGURE 4-3 PHENOLIC NYLON, TAB NO. 23 TABLE 3-1, TEMPERATURE HISTORY FOR T/C INITIALLY 0.211 IN FROM SURFACE

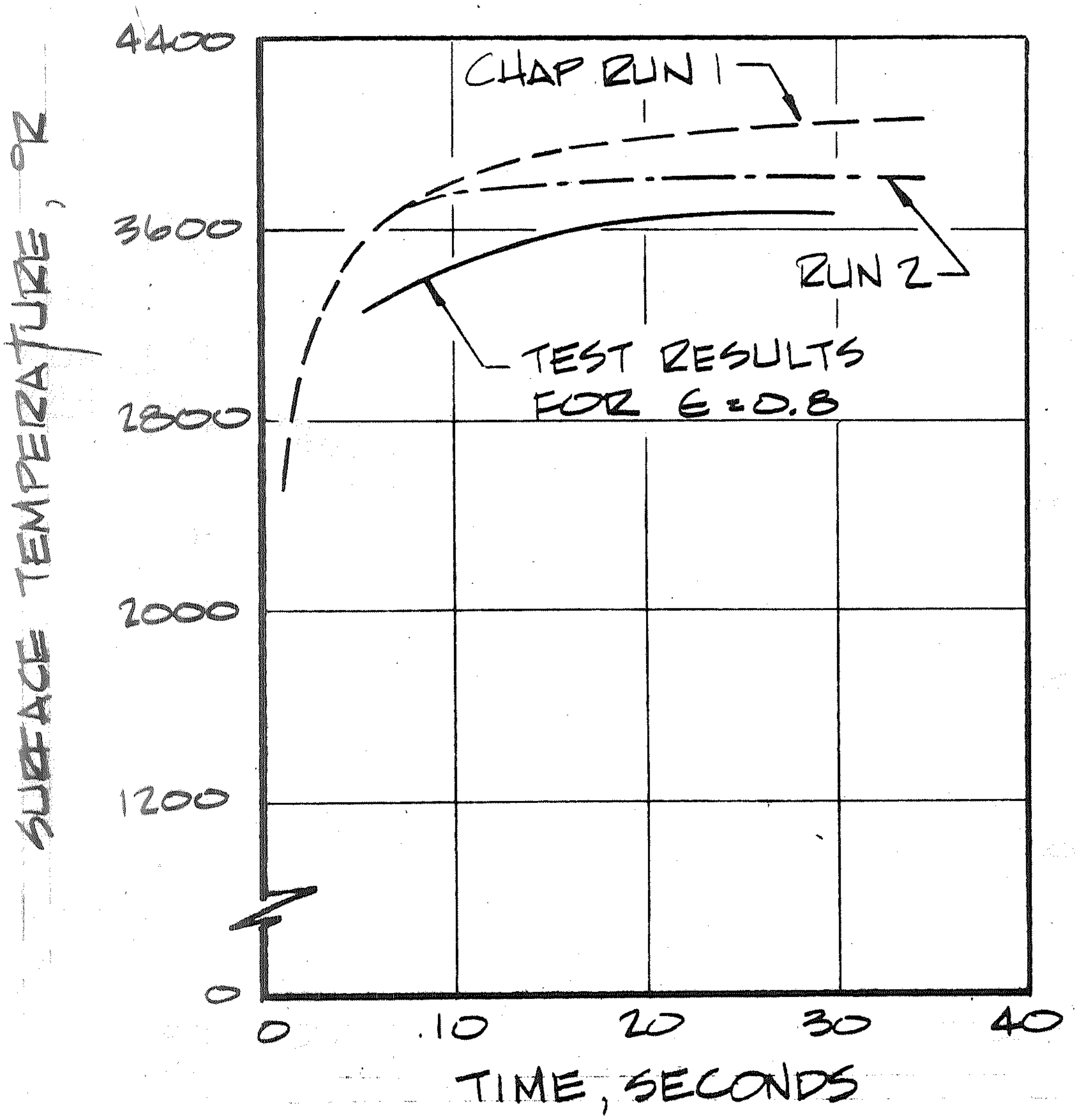


FIGURE 4-4 SILICONE ELASTOMER
TAB No. 9 TABLE 3-2
SURFACE TEMPERATURE
HISTORY

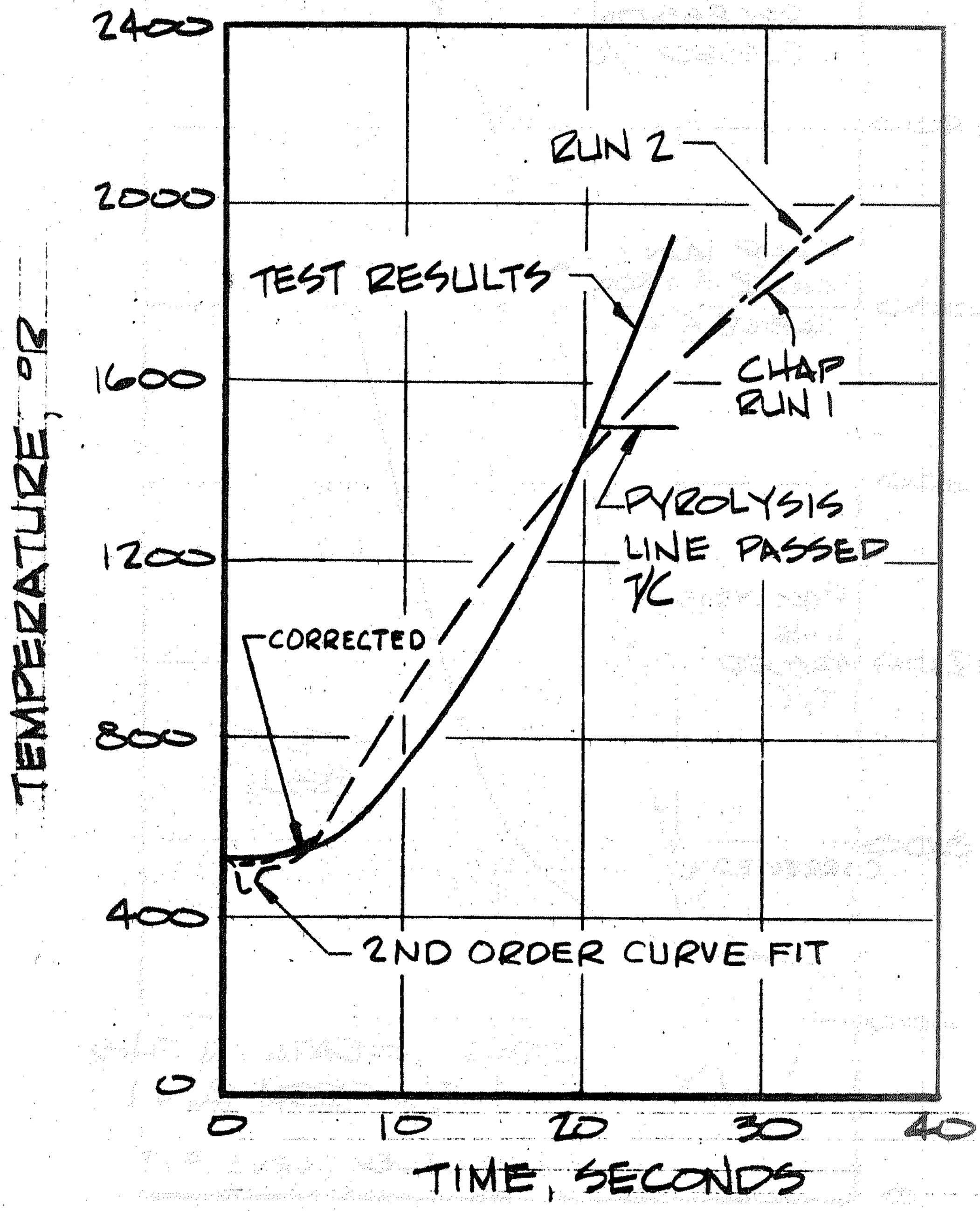


FIGURE 4-5 SILICONE ELASTOMER TAB No. 9 TABLE 3-2, TEMPERATURE HISTORY FOR T/C INITIALLY 0.099 IN FROM SURFACE

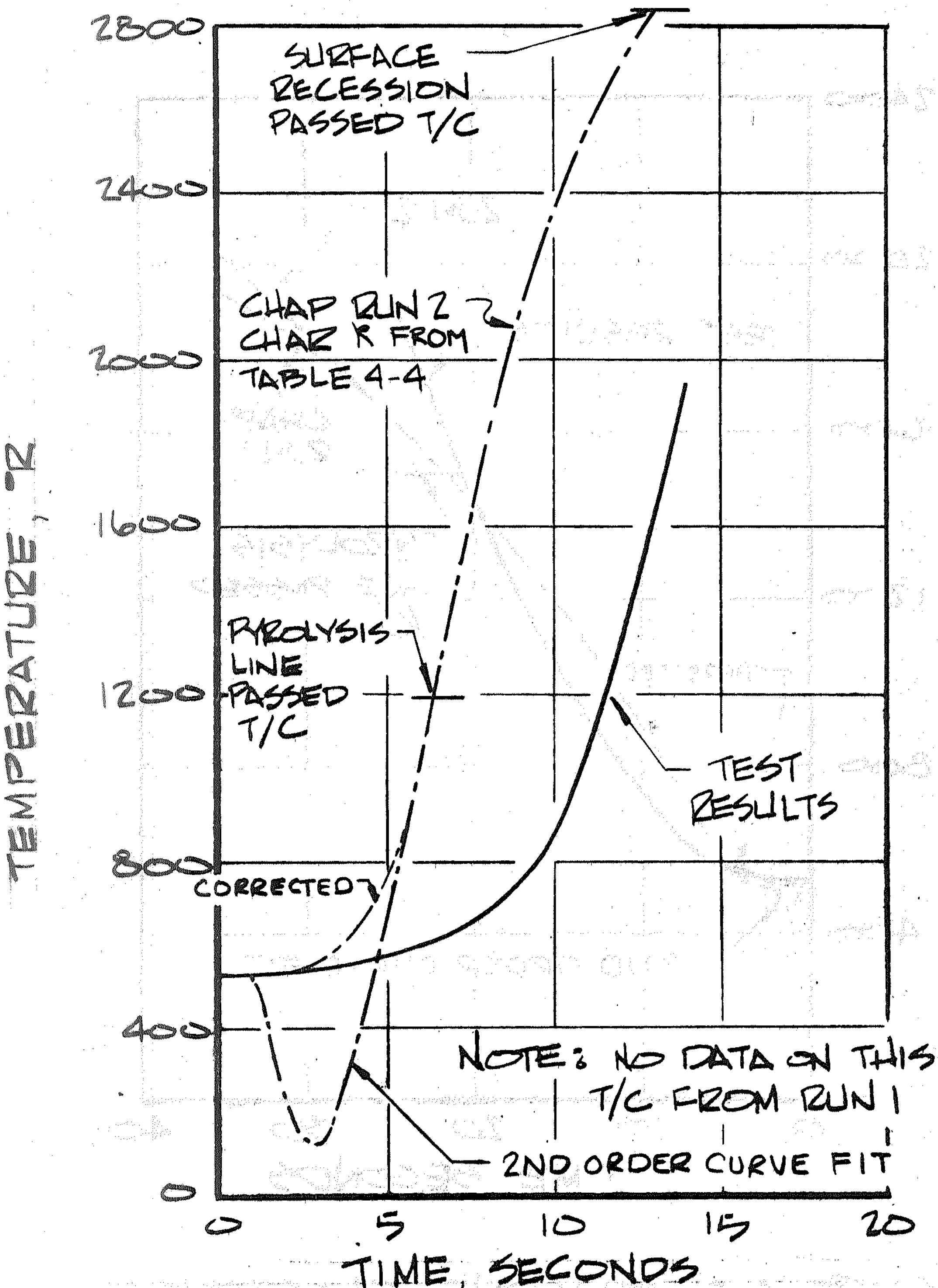


FIGURE 4-6 AVCOAT 5026-39 HC/G, TAB No. 4 TABLE 3-3, TEMPERATURE HISTORY FOR T/C INITIALLY 0.107 IN FROM SURFACE

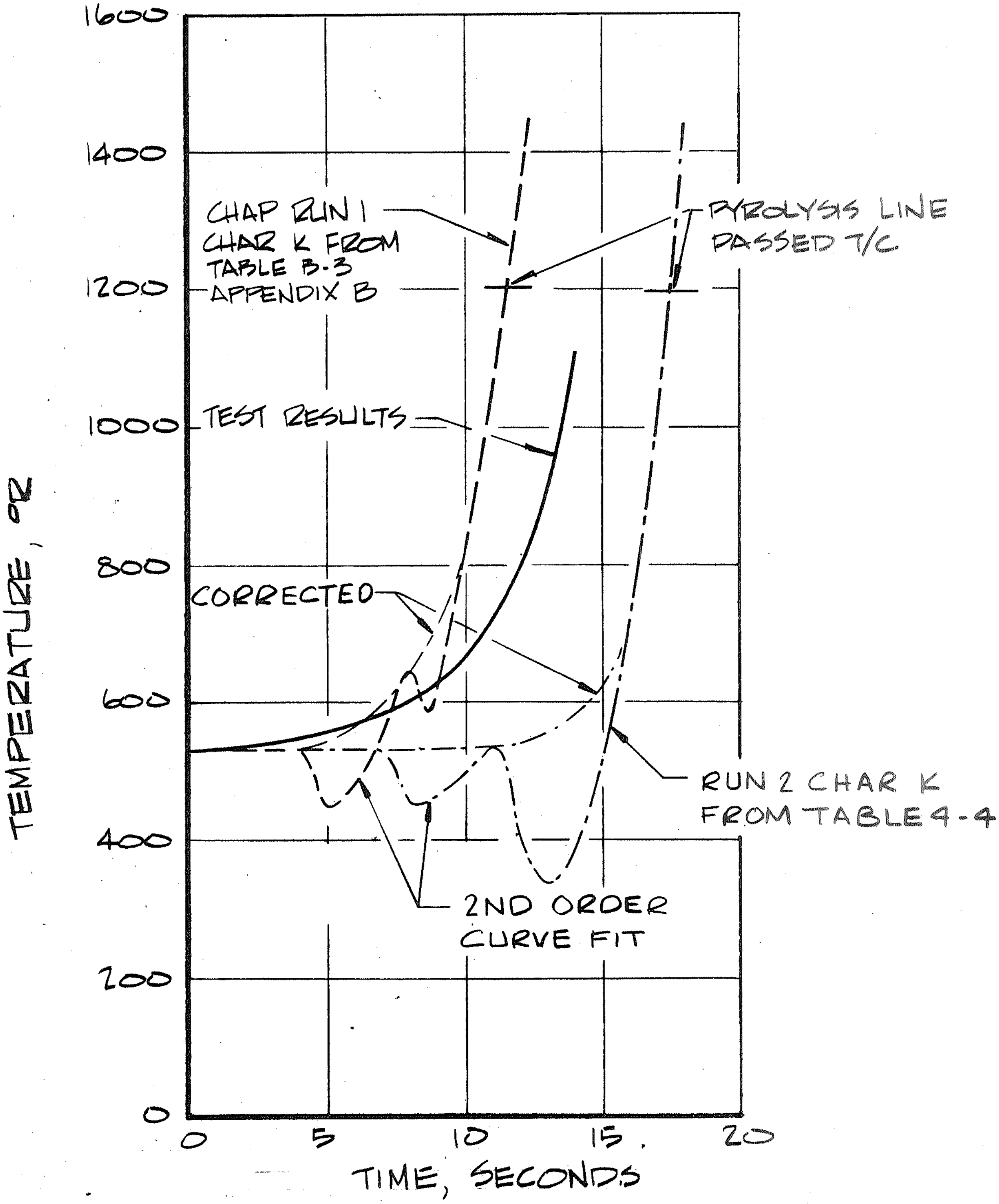


FIGURE 4-7 AVCOAT 5026-39 HC/G, TAB No. 4
TABLE 3-3, TEMPERATURE HISTORY
FOR T/C INITIALLY 0.209 IN FROM
SURFACE

APPENDIX A

CONVERSION OF PYROLYSIS KINETICS DATA TO REACTION PLANE KINETIC CONSTANTS

A.1 BASIC EQUATIONS

Thermogravimetric (TGA) data for charring materials are usually reduced and reported as "kinetic constants" in a pyrolysis equation:

$$\frac{\partial \rho}{\partial \theta} = f(\rho, \rho_c, T) \tag{A-1}$$

Often the most exact fits to the TGA curves require that the pyrolysis be modeled with more than one component

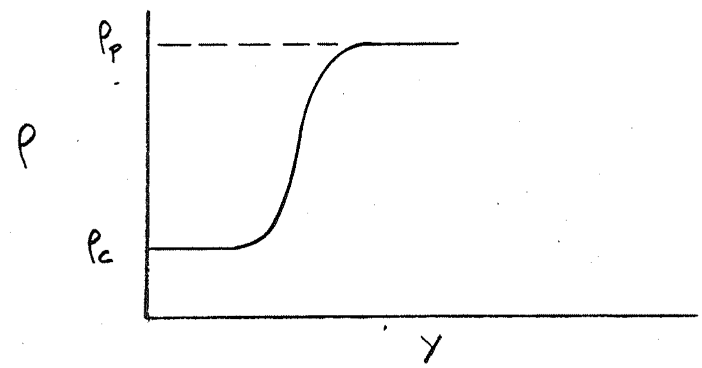
$$\rho = \sum \rho_i \tag{A-2}$$

$$\frac{\partial \rho_i}{\partial \theta} = f_i(\rho_i, \rho_{r_i}, T) \tag{A-3}$$

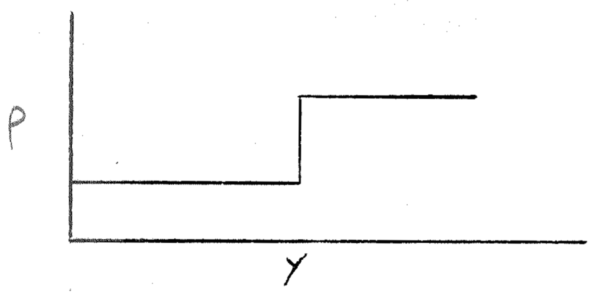
Usually Equation (A-3) is assumed to be of the form

$$\frac{\partial \rho_i}{\partial \theta} = - \rho_{o_i} k_{o_i} e^{-E_i/RT} \left[\frac{\rho_i - \rho_{r_i}}{\rho_{o_i}}\right]^{n_i} \tag{A-4}$$

Use of this equation, or any equation of the form (A-3), in an in-depth thermal response calculation would produce a predicted density profile with depth which varies smoothly between the virgin density and the char density



The CHAP code is based upon a different model which simplifies in-depth calculations. Densities in-depth are either char density or virgin density; pyrolysis occurs at a "reaction plane". The density profile therefore looks like



The rate of pyrolysis $\dot{m}_p$ is related to the temperature at the pyrolysis plane location by the assumed relation:

$$\dot{m}_p = Ae^{-B/T_1} \tag{A-5}$$

It is not obvious how values for A and B can be obtained from pyrolysis kinetics numbers reported in the literature. Stroud in Reference A-1 has performed a number of computational experiments with a specially written code to explore this question. From his computed results for a variety of charring problems, Stroud extracted "empirical" relationships between the pyrolysis law constants in an equation of the form (A-3) and the reaction plane constants A and B. Stroud assumed a pyrolysis law

$$\frac{\partial \rho}{\partial \theta} = - \rho_{o_i} \left(\frac{\rho_i}{\rho_{o_i}} \right)^{n_i} A_{o_i} e^{-E/RT} \tag{A-6}$$

Stroud's correlations for single component pyrolysis are for the pre-exponential factor

$$A = (\rho_o - \rho_c) \left(\frac{k_p A_o}{\rho_o C_{p_p}} \right)^{\frac{1}{2}} e^{-\frac{0.7+2.2\overline{\Delta H}}{1.91}} \qquad n = 1/2 \tag{A-7}$$

$$A = (\rho_o - \rho_c) \left(\frac{k_p A_o}{\rho_o C_{p_p}} \right)^{\frac{1}{2}} e^{-\frac{1.5+3.6\overline{\Delta H}}{1.91}} \qquad n = 1 \tag{A-8}$$

$$A = (\rho_o - \rho_c)\left(\frac{k_p A_o}{\rho_o C_{p_p}}\right)^{1/2} e^{-\frac{1.7+1.8\overline{\Delta H}}{1.89}} \qquad n = 2 \qquad \text{(A-9)}$$

and for the activation energy

$$B = \frac{E}{1.91R} \qquad n = 1/2 \text{ and } 1 \qquad \text{(A-10)}$$

$$B = \frac{E}{1.89R} \qquad n = 2 \qquad \text{(A-11)}$$

If decomposition takes place in more than one reaction it is sufficient to use constants from the dominating reaction in Equations (A-7) through (A-11).

It should be noted that the pyrolysis law (A-6) used by Stroud differs from the commonly used expression (A-4) in that the density driving potential is ρ_i/ρ_{o_i} and not $(\rho_i - \rho_{r_i})/\rho_{o_i}$. This discrepancy will require an adjustment to the pre-exponential factor k_o to convert it to an effective A_o. (The equivalence is of course not exact since the two pyrolysis laws are fundamentally different.) If we choose to match the two expressions at the half-pyrolyzed point $\rho = (\rho_o + \rho_r)/2$, then we can derive that

$$A_{o_i} = k_{o_i}\left(\frac{\rho_{o_i} + \rho_{r_i}}{\rho_{o_i} - \rho_{r_i}}\right)^{n_i} \qquad \text{(A-12)}$$

Equations (A-7) through (A-11) and (A-12) allow, therefore, most of the pyrolysis data in the literature to be converted to the "reaction plane" constants required as input to the CHAP code.

REFERENCE

A-1 Stroud, C. W., "A Study of the Reaction Plane Approximation in Ablation Analyses", NASA TN D-4817, October 1968.

APPENDIX B

PROPERTY VALUES USED IN QUALIFYING CALCULATIONS

Table B-1 - Nominal Thermo-chemical Properties for Low Density Phenolic Nylon

Undegraded material

density, lbm/ft^3	36
specific heat, Btu/lbm R, at temperature of-	
560 R	.36
660 R	.43
760 R	.495
860 R	.535
950 R	.545
1060 R	.545
thermal conductivity, Btu/ft-s-R, at temperature of-	
540R	1.28×10^{-5}
700R	1.28×10^{-5}
900R	1.41×10^{-5}
1100R	1.48×10^{-5}
1280R	1.51×10^{-5}
activation temperature, R	23200
reaction-rate constant, lbm/ft^2s	1.586×10^6
effective heat of pyrolysis, Btu/lbm	550
effective specific heat of pyrolysis gages, Btu/lbm R, at temperatures of-	
500 R	.87
1000 R	.87
1500 R	.87
1800 R	1.15
2000 R	1.97

Table B-1 - (concluded)

2100 R	2.80
2500 R	3.25
2800 R	2.80
3000 R	1.80
3300 R	1.24
3500 R	1.05
4000 R	1.2
5000 R	2.2
6000 R	4.78

Degraded material

density, lbm/ft^3,		12
activation temperature, R	1^{st} order	76500
reaction rate constant, lbm/ft^2 satm	oxidation	1×10^{10}
mass of char removed per mass of oxygen		.75
surface emittance		.8
specific heat, Btu/lbm R		.54
thermal conductivity, Btu/ft-s-R, at temperature of-		
500 R		2.5×10^{-5}
1500 R		2.5×10^{-5}
2000 R		8×10^{-5}
2500 R		20×10^{-5}
3000 R		30×10^{-5}
3500 R		42.5×10^{-5}
4000 R		60×10^{-5}
4500 R		76.2×10^{-5}
5000 R		100×10^{-5}
5500 R		123×10^{-5}
heat of combustion, Btu/lbm		5000

Table B-2 - Nominal Thermo-chemical Properties for Filled Silicone Resin in Honeycomb

Undegraded material	
density, lbm/ft^3	40
specific heat, Btu/lbm R, at temperature of-	
510 R	.354
560 R	.365
660 R	.382
760 R	.396
860 R	.410
960 R	.419
1060 R	.427
thermal conductivity, Btu/ft s R	1.98×10^{-5}
activation temperature, R,	20000
reaction rate constant, lbm/ft^{2}s	2700
effective heat of pyrolysis, Btu/lbm	250
effective specific heat of phrolysis gases, Btu/lbm R	1
Degraded material	
density, lbm/ft^3,	20
specific heat, Btu/lbm R	.43
thermal conductivity, Btu/ft s R, at temperature of –	
500 R	1.9×10^{-5}
1000 R	2.4×10^{-5}
1500 R	2.9×10^{-5}
2000 R	3.3×10^{-5}
2500 R	3.7×10^{-5}
3000 R	4.0×10^{-5}
3500 R	4.2×10^{-5}
4000 R	4.4×10^{-5}

Table B-2 - (concluded

surface emittance	.8
temperature of fussion, R	3800
heat of fussion, Btu/lbm	60
activation temperature, R, ...	39872
reaction rate constant, $lbm/ft^2 s\ atm^{1/2}$	6.73×10^8
order of oxidation	.5
mass of char removed per mass of oxygen	.1

Table B-3 - Normal Thermo-chemical Properties for the Apollo Heat Shield Material

Undegraded material

density, lbm/ft^3,	32
specific heat, Btu/lbm R at temperature of-	
560 R	.329
660 R	.364
760 R	.397
860 R	.406
960 R	.418
1060 R	.424
1160 R	.425
thermal conductivity, Btu/ft s R, at temperature of-	
500 R	1.4×10^{-5}
600 R	1.4×10^{-5}
723 R	1.46×10^{-5}
973 R	1.68×10^{-5}
1070 R	1.71×10^{-5}
1135 R	1.59×10^{-5}
1244 R	1.42×10^{-5}
1250 R	1.31×10^{-5}
1400 R	1.31×10^{-5}
activation temperature, R,	19600
reaction rate constant, lbm/ft^2s	128000
effective heat of pyrolysis, Btu/lbm	250
effective specific heat of pyrolysis gases, Btu/lbm R	1.0

Table B-3 - (concluded)

Degraded Material

density, lbm/ft^3	20
specific heat, Btu/lbm R, at temperature of-	
720 R	.25
1080 R	.3
1440 R	.348
1800 R	.397
2160 R	.445
2520 R	.494
2574 R	.5
5000 R	.5
thermal conductivity, Btu/ft s R, at temperature of-	
540 R	3.88×10^{-5}
1660 R	3.88×10^{-5}
1860 R	6.1×10^{-5}
2060 R	8.33×10^{-5}
2460 R	11.7×10^{-5}
3060 R	16.7×10^{-5}
3460 R	19.5×10^{-5}
5460 R	20×10^{-5}
emittance	.75
mass of char removed per mass of oxygen	1.5
activation temperature, R	76500
reaction rate constant, lbm/ft^2 s-atm	1×10^{10}
order of oxidation	1.0
heat of combustion, Btu/lbm	2500

Table B-4 Heat of Combustion (Btu/lb_m) for Carbon

Temperature (°R)	Pressure (atm) 0.1	1.0	10.0	100.0
1800	4110	4110	4110	4110
2700	4266	4266	4266	4266
3600	4454	4447	4446	4445
4500	4871	4697	4656	4643
5400	6265	5295	4983	4884
6300	10220	6995	5679	5245
7200	13540	13050	7134	5869