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Thermal Protection Materials

Thermophysical Property Data

S. D. Williams
Lockheed Engineering & Sciences Company
Houston, Texas

Donald M. Curry
Lyndon B. Johnson Space Center
Houston, Texas

NASA
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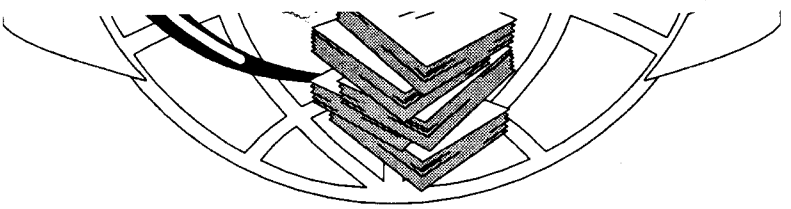

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Contents

Discussion

This publication presents a compilation of two previous reports that were compiled during the **PathFinder** program into a single volume. The **PathFinder** program has been superseded by the Space Exploration Initiative (SEI) program. This publication combines two Lockheed reports[1,2] to provide a thermophysical property database to the scientific community. This report contains the same ablator data reported in the original Lockheed reports, plus additional property data for reusable materials. This data has been included to provide a more comprehensive database for use in the design of a reusable Thermal Protection System (TPS). While data for specific materials are not duplicated, identical materials from various sources may be cited in order to provide a complete set of data.

One of the objectives of the **PathFinder** program was the development of technology required to design transatmospheric vehicles (TAV) which will be required for transportation between the Earth, the Moon, and neighboring planets. It was assumed that aerobraking maneuvers would be performed to place the spacecraft into orbit about the planet, and perhaps to subsequently enter into the atmosphere for a surface landing. One dominant requirement is to provide a TPS for the structure such that the mission objectives can be achieved.

The TAV trajectories will encompass a large range of heating conditions during the excursion through the atmosphere. Accurate heat transfer analyses for both aerobraking and direct entry vehicles are required to design vehicle structures and TPS. Accordingly, detailed knowledge of the thermophysical properties of the material configurations under consideration for TPS are required. An ablative TPS will be required in some areas of the vehicle, while high temperature reusable surface insulation materials will probably be considered for use in other areas. Unfortunately, most of the ablative material development has been dormant for the last twenty years.

An objective of this report is to provide a thermophysical property literature survey on materials that could potentially be used for future spacecraft thermal protection systems. This involved reviewing literature dating back to the 1960's. An attempt has been made to cite the manufacturer as well as the data source in the bibliography, although this does not guarantee that production items are still available for testing.

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1. Williams, S. D.; and Browning, R. E.: PathFinder Thermophysical Property Data - Thermal Protection Materials for High Energy Aerobraking Vehicles, Volume 1, LESC-27438, Lockheed Engineering and Sciences Co., Houston, TX, August 29, 1989.

2. Williams, S. D.; and Gietzel, M. M.: PathFinder Thermophysical Property Data - Thermal Protection Materials for High Energy Aerobraking Vehicles, Volume 2, LESC-28364, Lockheed Engineering and Sciences Co., Houston, TX, May, 1990.

All material properties are in engineering units compatible with the STAB-II[3] and AESOP-STAB[4] computer programs. This means that the units are not in SI units. The primary difference between these programs and other common ablation analysis programs is in the treatment of the Arrhenius equation. The formulation used in the JSC programs is

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T} ,$$

while other programs frequently use the equation in the form of

$$\frac{\partial \rho}{\partial t} = -A\rho_v \left(\frac{\rho - \rho_c}{\rho_v} \right)^n e^{-E/RT} ,$$

where R is the universal gas constant, ρ is the density in the reaction zone, ρ_v is the virgin density, ρ_c is the char density, A and k are the collision frequency factors, E and B are the activation energy coefficients, and T is the temperature of the reaction at time t. Conversion between the two systems is elementary; the only real caution to be observed is in the units.

The ablative materials have been compiled into categories that are descriptive of the material composition. The twelve categories selected are

(1) Nylon-Phenolics
(2) Teflon-Teflons
(3) Phenolic-Nylons
(4) Phenolic-Phenolics
(5) Carbon-Phenolics
(6) Carbon Materials
(7) Silica-Teflon
(8) Silica-Phenolic
(9) Silica-Silicones
(10) Polybenzimidazoles
(11) Inorganics-Silicone Binders
(12) Organics-Silicone Binders
(13) Other,

where the category "other" contains materials whose composition is unknown at the time of this publication.

It should be pointed out that the Arrhenius equations have not been defined for all ablative materials. For some materials the desired char data is not available.

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3. Williams, S. D.: Revised Standard Ablation Program (STAB II), LEMSCO-23439 Lockheed Engineering and Management Services Co., Houston, TX, January 1987.

4. Williams, S. D.: Revised User's Guide to the AESOP-STAB Thermal Model Program, LEMSCO-2353 Lockheed Engineering and Management Services Co., Houston, TX, January 1987.

The materials that can be classified as a reusable material have been compiled into five categories:

(1)	Carbon-Based Materials	(4)	Adhesives
(2)	Silicon-Based Materials	(5)	Metallics
(3)	Polyamides		

While some of these reusable materials can be used in an ablator system, the data presented is for its reuse capability; for example reinforced carbon-carbon (RCC) is considered in this sense as a reusable material, not as a carbon ablator.

The thermophysical properties that are presented for both classes (Ablative/Reusable) of materials are density, specific heat, and thermal conductivity. The specific heat and conductivity data are provided, if applicable, as a function of temperature and pressure. If emissivity is known, it is also provided. For ablative materials, these properties are given for both the virgin and char states, if data are available. Frequently, the char data is provided as a set of irreversible tabular data, where the material was heated up to a prespecified temperature and the char properties were obtained after the preconditioning. In addition, enthalpy as a function of heating may also be provided along with the recession rate. As with some of the other characteristic data, the recession rate data may not exist for every material.

In a similar manner, the conductivity data presented for the porous reusable materials are representative properties measured in air. This volume does not provide property data for exotic atmospheres. Reliable data for rigid surface insulation (tiles) may be available for exotic atmospheres from a companion technical paper which has conductivity predictions in CO_2.[5] Nine metallic materials have been included for the vehicle structure including two aluminum alloys, titanium, and graphite/epoxy.

A comprehensive table of contents is provided as an aid to find a particular material contained in this document.

As an aid to the individual who prefers to check the original article, a complete bibliography is included at the end of the material listing section. Footnote numbers in the materials section correspond to the numbers of the items in the bibliography. The data of M. E. Ihnat* is available only in this document; many of these materials may no longer be in production. These materials have been included, however, to indicate material characteristics.

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5. Williams, S. D.; and Curry, D. M.: Prediction of Rigid Silica-Based Insulation Conductivity Using Morphological Data, NASA TP-3276, November 1992.

* M.E. Ihnat is now deceased.

1

Nylon-phenolics

Material: FM 5015E
Manufacturer: U.S. Polymeric
Composition: nylon; SC-1008 phenolic

Virgin Properties

T (R)	C_p (Btu/lb$_m$ R)
710	0.330

T (R)	k (Btu/ft hr R)	
710	0.100	chopped
710	0.110	parallel

Density 74.88 lb$_m$/ft^3
Emissivity 0.80

Test condition: (not known)

ΔH_{AB} (Btu/lb$_m$)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb$_m$ in^2/sec)	$\dot{q}$ (Btu/ft^2 sec)	q_c^* (Btu/lb$_m$)
1945		2.95×10^{-2}			373
1705		2.22×10^{-2}			246
5384		1.30×10^{-2}			455
4522		1.49×10^{-2}			439
1852		2.06×10^{-2}			249
4068		1.35×10^{-2}			453
1923		3.00×10^{-2}			373
4921		1.19×10^{-2}			382
4491		2.77×10^{-2}			810
4914		1.39×10^{-2}			445
5257		1.15×10^{-2}			394
2926		2.05×10^{-2}			391

Ref 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: PNHD-Hughes No. 4
Manufacturer: Hughes Aircraft
Composition: Phenolic-Novolac Nylon
Phenolic Novolac Resin 37%, Nylon 40%,
Phenolic Microspheres 23% by weight

Virgin Properties

T (R)	Cp (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
492	0.238	582	0.0676
672	0.428	672	0.0688
852	0.613	852	0.0676
942	0.715	942	0.0664

T (R)	Density (lb/ft^3)
527	32.5
672	31.8
852	31.2
1032	30.6

Density 32.5 lb/ft^3 at Room Temperature
Emissivity

Ref. 23: Lagedrost, J. F., et. al.: Thermophysical and Chemical Characterization of Charring Ablative Materials

Material: PNLD-Langley
Manufacturer: Hughes Aircraft
Composition: Phenolic Novolac Nylon
Phenolic Novolac Resin 25%, Nylon (6-6) 40%,
Phenolic Microspheres 35%

Virgin Properties

T (R)	Cp (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
492	0.220	582	0.0451
672	0.462	672	0.0502
852	0.596	852	0.618
942	0.650	942	0.0664

T (R)	Density (lb/ft^3)
527	34.3
672	33.7
852	33.1
1032	32.5

Density 34.3 lb/ft^3 at Room Temperature
Emissivity

Ref. 23: Lagedrost, J. F., et. al.: Thermophysical and Chemical Characterization of Charring Ablative Materials

Material: PNHD-Hughes No. 5
Manufacturer: Hughes Aircraft
Composition: Phenolic-Novolac Nylon
Phenolic Novolac Resin 37%, Nylon (6-6) 40%,
Phenolic Microspheres 23%

Virgin Properties

T (R)	Cp (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
492	0.252	582	0.0722
672	0.402	672	0.0647
852	0.550	852	0.0578
942	0.620		

T (R)	Density (lb/ft^3)
527	35.0
672	34.3
852	33.7
1032	33.1

Density 35.0 lb/ft^3 at Room Temperature
Emissivity

Ref. 23: Lagedrost, J. F., et. al.: Thermophysical and Chemical Characterization of Charring Ablative Materials

Material: PNHD-Hughes No. 5 (Continued)

Char Properties

T (R)	Cp (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
492	0.261	582	0.0497
672	0.337	672	0.0566
852	0.423	852	0.0722
942	0.500	942	0.0867
1032	0.580	1032	0.0890
		1212	0.116

(Pyrolyzed at 1200 R)

Density
Emissivity

Ref. 23: Lagedrost, J. F., et. al.: Thermophysical and Chemical Characterization of Charring Ablative Materials

Material:	Low Density - Phenolic Nylon (Jaworski and Nagler)
Manufacturer:	Unknown
Composition:	50-50 by Weight

Laminar Blowing Factor	0.6
Turbulent Blowing Factor	0.4
Combustion Enthalpy	12,000 Btu/lb
Heat of Vaporization	10,000 Btu/lb
Heat of Decomposition	1,000 Btu/lb

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k=6.2\times10^{18}$ lb/ft^3 hr, n=1.0, B=43,200 R

Virgin Properties

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/ft hr R)
260	0.20	260	0.0575
460	0.29	460	0.0505
860	0.57	780	0.0515
1,300	0.58	900	0.061
		1,360	0.061

Density	35.0 lb/ft^3
Virgin Carbon Weight Fraction	0.25
Emissivity	0.8
Absorptance	1.0

Ref. 20: Jaworski, W.; and Nagler, R. G.: A Parametric Analysis of Venus Entry Heat-Shield Requirements

Material: Low Density - Phenolic Nylon (Jaworski and Nagler) (Continued)

Char Properites

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/ft hr R)
400	0.52	400	0.360
5,000	0.52	1,000	0.505
		3,300	1.260
		4,000	1.370

Specific Heat of Decomposition Gas	
T (R)	(Btu/ lb R)
400	0.60
2,000	0.60
2,250	0.50
2,750	0.30
6,000	0.30

Density	13.1 lb/ft^3
Char Carbon Weight Fraction	0.67
Emissivity	

Ref. 20: Jaworski, W.; and Nagler, R. G.: A Parametric Analysis of Venus Entry Heat-Shield Requirements

Material: Low Density - Phenolic Nylon (Wilson)
Manufacturer: Melpar
Composition: Nylon - Phenolic

Virgin Properties

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/hr ft R)
260	0.165	191	0.0359
310	0.200	299	0.0549
360	0.235	370	0.0614
410	0.267	548	0.0745
460	0.300	794	0.0761
510	0.331	863	0.0751
560	0.361	875	0.0733
610	0.393		
660	0.423		
710	0.453		
760	0.484		
810	0.513		
860	0.542		
910	0.571		
960	0.599		
1010	0.628		
1060	0.659		
1110	0.684		
1160	0.711		
1210	0.740		

T (R)	Density (lb/ft^3)
260	37.53
357	37.31
457	37.08
492	36.98
535	36.83
564	36.39
672	35.73
744	35.14
780	34.97
847	34.36

Density at Room Temperature 37 lb/ft^3
Emissivity

Ref. 36: Wilson, R. Gale: Thermophysical Properties of Six Charring Ablators From 140° to 700° K and Two Chars From 800° to 3000° K

Material: Low Density - Phenolic Nylon (Wilson) (Continued)

Char Properties

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/hr ft R)
1460	0.39	1256	0.57
2460	0.52	1257	0.58
3460	0.52	1805	0.942
4460	0.52	1807	0.883
5460	0.52	2423	1.12
		2426	1.07
		2429	1.07
		3070	1.37
		3090	1.41
		3600	1.47
		4100	1.62
		4130	1.71
		4760	2.39
		4820	2.41

T (R)	H (Btu/lb)
1503	225.6
2985	994.6
3535	1300.2
4060	1581.4
4480	1518.6
4965	2004.7
5005	1881.0
5505	2477.5

Density

Emissivity

Ref. 36: Wilson, R. Gale: Thermophysical Properties of Six Charring Ablators From 140° to 700° K and Two Chars From 800° to 3000° K

Material: High Density - Phenolic Nylon (Wilson)
Manufacturer: Melpar

Virgin Properties

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/hr ft R)
260	0.165	276	0.147
310	0.200	337	0.166
360	0.235	541	0.201
410	0.267	600	0.200
460	0.300	730	0.205
510	0.331	735	0.204
560	0.361	736	0.207
610	0.393	841	0.207
660	0.423	884	0.206
710	0.453		
760	0.484		
810	0.513		
860	0.542		
910	0.571		
960	0.599		
1010	0.628		
1060	0.659		
1110	0.684		
1160	0.711		
1210	0.740		

T (R)	Density (lb/ft^3)
260	73.35
360	72.92
460	72.36
492	72.17
535	71.79
564	70.86
672	68.99
744	67.30
780	66.74
810	65.80
834	65.30

Density at Room Temperature 72.36 lb/ft^3
Emissivity

Ref. 36: Wilson, R. Gale: Thermophysical Properties of Six Charring Ablators From 140° to 700° K and Two Chars From 800° to 3000° K

Material: High Density - Phenolic Nylon (Wilson) (Continued)

Char Properties

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/hr ft R)
960	0.22	1327	0.336
1460	0.35	1330	0.346
1960	0.50	1335	0.351
2460	0.63	1690	0.521
2960	0.67	1694	0.533
3460	0.67	1696	0.561
3960	0.67	1699	0.566
4460	0.67	2064	0.665
4960	0.67	2068	0.700
5460	0.67	2607	0.747
		2614	0.780
		2616	0.795
		2618	0.786
		3030	0.991
		3033	1.02
		3037	1.07
		3040	1.06
		3455	1.42
		3460	1.42
		3970	1.49
		4180	1.32
		4230	1.42
		4376	1.69
		4390	1.81

T (R)	H (Btu/lb)
953	117.2
2030	355.4
2450	654.1
3010	1190.7
3465	1272.5
3500	1344.8
3960	1549.8
4950	2158.6
5470	2759.4
4500	2087.3

Density
Emissivity

Ref. 36: Wilson, R. Gale: Thermophysical Properties of Six Charring Ablators From 140° to 700° K and Two Chars From 800° to 3000° K

Material: Nylon Phenolic (Krash, et. al.)
Manufacturer: Unknown
Composition: Nylon to Phenolic Weight Ratio, 1:1
Heat of Formation: -1, 311 Btu/lb (Ref. Temperature 0 R)

$$\frac{\partial \rho_i}{\partial t} = k_i \left(\frac{\rho_i - \rho_{c_i}}{\rho_{v_i} - \rho_{c_i}} \right)^{n_i} e^{-B_i / T}$$

Nylon	$k = 4.7286 \times 10^{18}$ (lb/ft^3 hr), n = 1.0, B = 47,100 R
Phenolic (1)	$k = 1.0206 \times 10^{9}$ (lb/ft^3 hr), n = 3.0, B = 15,400 R
Phenolic (2)	$k = 3.6288 \times 10^{13}$ (lb/ft^3 hr), n = 3.0, B = 36,800 R

Component	Density (lb/ft^3)
Nylon	71.0
Phenolic (1)	20.25
Phenolic (2)	60.75

$$\frac{d\rho}{dt} = \Gamma \left(\frac{\partial \rho_1}{\partial t} + \frac{\partial \rho_2}{\partial t} \right)_{\text{Phenolic}} + (1-\Gamma) \left(\frac{\partial \rho}{\partial t} \right)_{\text{Nylon}}$$

Γ = Volume fraction of phenolic in composite, $\Gamma = 0.463$

Virgin Properties

T (R)	Cp (Btu/lb R)
0	0
100	0.02
200	0.06
300	0.15
400	0.30
500	0.40
600	0.46
700	0.49
800	0.50
900	0.50
1000	0.50

Density 74.8 lb/ft^3
Emissivity

Ref. 22: Krash, K. M., et. al.: Theory for the Thermophysical Performance of Charring Organic Heat-Shield Composites

Material: Nylon Phenolic (Krash, et. al.) (Continued)

Char Properties

T (R)	Cp (Btu/lb R)
0	0
500	0.15
1000	0.30
1500	0.42
2000	0.48
2500	0.54
3000	0.59
3500	0.60
4000	0.61
4500	0.61
5000	0.61

T (R)	k (Btu/hr ft R)		
	Pre - Condition Char T (R)		
	1460	2460	3460
500	0.72	0.68	1.3
1000	0.11	0.70	1.3
1500	0.22	0.76	1.3
2000	0.43	0.86	1.4
2500	0.72	1.0	1.5
3000	1.1	1.3	1.7
3500	1.5	1.7	2.0
4000	2.0	2.2	2.3
4500	2.5	2.6	2.8

Component	Density (lb/ft^3)
Nylon	0
Phenolic (1)	0
Phenolic (2)	40.5

Density	18.7 lb/ft^3
Emissivity	0.6

Ref. 22: Krash, K. M., et. al.: Theory for the Thermophysical Performance of Charring Organic Heat-Shield Composites

Material: Nylon Phenolic (Krash, et. al.) (Continued)

LMSC NYLON-PHENOLIC LAMINAR SPLASH TEST DATA

Exposure Conditions				Measuared Degradation		Surface Temperature	
q_{cw} (Btu/ft^2-sec)	$H_{s,e}$ (Btu/lb)	$P_{s,e}$ (atm)	Time (sec)	Char Erosion (mil)	Char Thickness (mil)	Ture (R)	Predicted (R)
242	1,550	1.67	15.0	199 ± 3.0	26.4 ± 4.5	2,560	2,380
538	2,050	2.17	10.0	177 ± 3.5	22.6 ± 3.4	3,560	2,690
538	2,050	2.17	12.2	227 ± 10.0	(7.1 ± 2.0)	3,680	2,690
770	3,000	1.86	9.9	152 ± 11.3	22.7 ± 4.5	3,790	3,300
828	4,930	1.38	8.9	123 ± 9.0	(6.0 ± 1.8)	4,120	4,350
1,226	3,310	2.82	5.0	112 ± 6.0	20.8 ± 1.3	4,550	3,600
1,703	5,680	2.19	5.1	126 ± 5.3	22.0 ± 3.0	5,020	4,920
2,225	5,770	2.94	5.0	123 ± 2.0	26.7 ± 1.5	4,650	5,060
2,565*	12,450	1.20	6.1	108	40.0		5,700

* GE MSVD test data (Krash, et. al. Ref. 30: Sheridan, R. A., N. S. Diaconis, and W. R. Warren, Performance of Several Ablation Materials in Simulated Planetary Atmospheres, General Electric Co., Missile and Space Division, R63SD35, Apr 1963)

( ) Char lost

LMSC NYLON-PHENOLIC TURBULENT DUCT DATA

Exposure Conditions				Measuared Degradation		Surface Temperature	
q_{cw} (Btu/ft^2-sec)	$H_{s,e}$ (Btu/lb)	P_e (atm)	Time (sec)	Char Erosion (mil)	Char Thickness (mil)	Ture (R)	Predicted (R)
173	2,600	1.16	33.5	212 ± 38	81.1 ± 26.2	3,380	2,830
186	2,650	1.08	40.2	172 ± 23	67.5 ± 3.0	3,380	2,850
240	2,200	2.14	26.0	266 ± 15	40.7 ± 7.0	3,440	2,730
286	2,650	1.98	24.6	221 ± 21	44.3 ± 5.8	3,440	2,970
244	2,850	1.54	25.2	254 ± 16	(10.9 ± 2.9)	3,440	3,020
285	3,330	1.54	23.0	250 ± 32	17.0 ± 4.8	3,550	3,320
280	1,790	2.89	19.7	283 ± 32	28.8 ± 1.6	3,280	2,660
345	2,170	2.89	16.2	212 ± 38	26.5 ± 3.7	3,280	2,780
357	2,300	2.52	17.1	253 ± 16	34.8 ± 1.7	3,460	2,850
412	2,660	2.52	15.2	246 ± 13	(7.6 ± 6.6)	3,490	3,030
477	2,190	5.24	13.3	275 ± 21	13.7 ± 4.3	3,600	2,890
500	2,200	3.68	13.0	241 ± 39	14.2 ± 5.8	3,550	2,850
581	2,550	3.86	12.3	241 ± 38	15.0 ± 4.0	3,490	3,030

( ) Char lost

Ref. 22: Krash, K. M., et. al.: Theory for the Thermophysical Performance of Charring Organic Heat-Shield Composites

Material:	High Density - Phenolic Nylon (Jaworski and Nagler)
Manufacturer:	Unknown
Composition:	50-50 by Weight

Laminar Blowing Factor	0.6
Turbulent Blowing Factor	0.4
Combustion Enthalpy	12,000 Btu/lb
Heat of Vaporization	10,000 Btu/lb
Heat of Decomposition	1,000 Btu/lb

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k=6.2 \times 10^{18}$ lb/ft^3 hr, n=1.0, B=43,200 R

Virgin Properties

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/ft hr R)
200	0.045	500	0.155
400	0.390	870	0.155
600	0.445	1,280	0.097
800	0.500	1,360	0.061
1,260	0.500		

Density	75.0 lb/ft^3
Virgin Carbon Weight Fraction	0.25
Emissivity	0.8
Absorptance	1.0

Ref. 20: Jaworski, W.; and Nagler, R. G.: A Parametric Analysis of Venus Entry Heat-Shield Requirements

Material: High Density - Phenolic Nylon (Jaworski and Nagler) (Continued)

Char Properites

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/ft hr R)
500	0.200	500	0.500
2,000	0.630	2,400	0.835
5,000	0.670	3,700	1.140
		4,700	2.580

Specific Heat of Decomposition Gas	
T (R)	(Btu/ lb R)
400	0.60
2,000	0.60
2,200	0.50
2,750	0.30
6,000	0.30

Density	22.5 lb/ft^3
Char Carbon Weight Fraction	0.84

Ref. 20: Jaworski, W.; and Nagler, R. G.: A Parametric Analysis of Venus Entry Heat-Shield Requirements

Material: NASA Ames-12, NA-13, NA-14, NA-15
Manufacturer: NASA - Ames
Composition: Nylon Phenolic

Composition	Weight Percent
Phenolic Novolac Resin	25
Nylon (6-6)	40
Phenolic Microspheres	35

Char Properties

T (R)	k (Btu/ft hr R)			
	Pre-Condition Char T (R) (Charred at 2290 R) Pressure 2.6×10^{-5} atm			
	NA-12	NA-13	NA-14	NA-15
582	0.140	0.215	0.179	0.147
672	0.153	0.237	0.195	0.162
852	0.173	0.269	0.221	0.194
1032	0.188	0.289	0.240	0.220
1212	0.196	0.303	0.251	0.239
1392	0.201	0.312	0.263	0.254

Ref. 23: Lagedrost, J. F., et. al.: Thermophysical and Chemical Characterization of Charring Ablative Materials

Teflon-Teflons

2

Material: TEFLON
Manufacturer: E. I. DuPont; Dixon Corp.
Composition: polytetrafluoroethylene; molded - quick quench

Virgin Properties

T (R)	C_p (Btu/lb$_m$ R)
	0.230

T (R)	k (Btu/ft hr R)
	0.145

Density 136.66 lb$_m$/ft^3
Emissivity

Test condition: (not known)

H (Btu/lb$_m$)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb$_m$ in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb$_m$)
		2.36×10^{-2}		96	3827
		3.33×10^{-2}		163	4058
		2.80×10^{-2}		158	4641
		5.60×10^{-2}		339	6018
		2.90×10^{-2}			2342
		3.28×10^{-2}			2680
		3.26×10^{-2}			3303
		2.63×10^{-2}			4056
		2.21×10^{-2}			4402

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Phenolic-Nylons

Material: phenolic nylon
Manufacturer: General Electric
Composition: 50-50 mixture by weight of powdered phenolic and nylon resins

Heat of pyrolysis	1000.00	Btu/lb_m
Pyrolysis gas specific heat	5.30	Btu/lb_m-R
Ablating Temperature (Start of Pyrolysis)	1000.00	R
Charring Temperature (End of Pyrolysis)	2000.00	R

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = 4.450 \times 10^7 (lb_m/ft^3)$, $n = 3$, $B = 5.700 \times 10^4 (R)$

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
250	0.080	250	0.080
500	0.315	500	0.380
600	0.380	600	0.380
700	0.420	700	0.380
800	0.455	800	0.380
900	0.465	900	0.380
1000	0.480	1000	0.380
1250	0.485	1000	0.380
1500	0.490	5000	0.390
1750	0.495	1750	0.400
2000	0.515	2000	0.420

Density	75.00 lb_m/ft^3
Emissivity	0.87

(continued)

Ref. 21 S. Kottock, GE Tech Info Ser., No. 65SD320, 9/65

Material: phenolic nylon *(continued)*

Char Properties

T (R)	C_p (Btu/lb_m R)
2000	0.515
3000	0.590
4000	0.615

T (R)	k (Btu/ft hr R)
1250	0.650
1500	0.950
1750	1.230
2000	1.650
3000	2.650
4000	3.750

Density	18.75 lb_m/ft^3
Emissivity	0.65

Ref. 21 S. Kottock, GE Tech Info Ser., No. 65SD320, 9/65

Phenolic-Phenolics

Material: AVCO 5026-H/CG (STAB-II data)
Manufacturer: AVCO
Composition: Phenolic microballons
Novolac Resin
Phenolic 3/8" honeycomb cells

Heat of pyrolysis	180.00	Btu/Lb_m
Pyrolysis gas specific heat	0.50	Btu/Lb_m-R
Ablating Temperature (Start of Pyrolysis)	1060.00	R
Charring Temperature (End of Pyrolysis)	1460.00	R
Recession Temperature (Start of Recession)	2235.00	R

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = .95 \times 10^8 (lb_m/ft_3\text{-}hr)$, $n = 1$, $B = .233 \times 10^5 (R)$

Virgin Properties

T (R)	C_p (Btu/Lb_m R)	T (R)	k (Btu/ft hr R)
0	0.353	210	0.028
560	0.348	260	0.030
660	0.350	310	0.034
760	0.370	460	0.048
860	0.380	560	0.058
960	0.420	660	0.066
1060	0.440	860	0.072

Density	32.0 Lb_m/ft^3
Emissivity	0.9

Ref. 24 Lee, H. M., Hirasaki, P. N. and Gardner, D. C., Standard Ablation Program (STAB II) User's Manual, 11176-H256-R0-00, TRW Systems Group, Houston, Texas, June 30, 1969.

Material: AVCO 5026-H/CG (Continued)

Char Properties

T (R)	C_p (Btu/Lb_m R)
1460	0.370
2460	0.412
4960	0.412
5460	0.460

T (R)	k (Btu/ft hr R)
460	0.046
760	0.070
1460	0.070
1860	0.146
2060	0.280
2660	0.497
2860	0.525
3710	0.760
3960	0.795
4260	0.795
4860	0.655
5010	0.570
5060	0.303
6000	0.060

Density	20.0 Lb_m/ft^3
Emissivity	0.65

(continued)

Ref. 24 Lee, H. M., Hirasaki, P. N. and Gardner, D. C., Standard Ablation Program (STAB II) User's Manual, 11176-H256-R0-00, TRW Systems Group, Houston, Texas, June 30, 1969.

Material: AVCO 5026-H/CG *(Continued)*

Wall Enthalpy

T (R)	H (Btu/Lb_m)	T (R)	H (Btu/Lb_m)
0	0.0	6395	2600.0
1400	342.9	6497	2700.0
1800	449.7	6597	2800.0
2400	617.2	6699	2900.0
3000	791.0	6805	3000.0
3600	978.0	6918	3100.0
4000	1113.0	7050	3200.0
4224	1200.0	7175	3300.0
4486	1300.0	7350	3400.0
4723	1400.0	7480	3500.0
4936	1500.0	7630	3600.0
5127	1600.	7800	3700.0
5299	1700.0	7970	3800.0
5454	1800.0	8120	3900.0
5596	1900.0	8300	4000.0
5728	2000.0	8500	4100.0
5851	2100.0	8700	4200.0
5968	2200.0	8850	4500.0
6078	2300.0	9000	4400.0
6186	2400.0	9150	4500.0
6291	2500.0	9270	4600.0

Surface Recession Rate

T (R)	S-dot (in/sec)
2235	0.000000
2546	0.000125
2860	0.000300
3072	0.000470
3282	0.000750
3493	0.001100
3707	0.001550
3901	0.002110
4121	0.002810
4335	0.003640
4548	0.004560
4760	0.005560
4973	0.006660
5188	0.008100
5400	0.009700
5615	0.011600
5830	0.013600
6044	0.015600
6260	0.017600
7365	0.028400
8145	0.036500
8867	0.045500
10778	0.071000
13741	0.100800

Ref. 24 Lee, H. M., Hirasaki, P. N. and Gardner, D. C., Standard Ablation Program (STAB II) User's Manual, 11176-H256-R0-00, TRW Systems Group, Houston, Texas, June 30, 1969.

Material: AVCO 5026-H/CG (Rockwell data)
Certification analysis using flight data modified for conservatism
Manufacturer: AVCO
Composition: Phenolic microballons
Novolac Resin
Phenolic 3/8" honeycomb cells

Heat of pyrolysis	800.0	Btu/lb_m
Pyrolysis gas specific heat	0.0	Btu/lb_m-R
Ablating Temperature (Start of Pyrolysis)	960.0	R
Charring Temperature (End of Pyrolysis)		R

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = 2.159 \times 10^{10} (lb_m/ft^3\text{-hr})$, $n = 2.5$, $B = 2.15 \times 10^4$ (R)

Virgin Properties

T (R)	C_p (Btu/lb_m R)
360	0.200
710	0.360
1060	0.430
1460	0.350

T (R)	k (Btu/ft hr R)
460	0.110
660	0.110
860	0.110
1060	0.110
1260	0.110
1460	0.120
1660	0.162
1860	0.212
2060	0.270
2260	0.330
2460	0.390
2660	0.448
2960	0.533
3460	0.660
3960	0.800

Density	32.00 lb_m/ft^3
Emissivity	0.74

(continued)

Ref. 10 Certification Analysis CAR 027001B, Apollo Block II Heat Shield (U). Vol. III Heat Shield Thermal Performance, SD 68-1004-3, Rockwell International, Downey, California, February 1969.

Char Properties

T (R)	C_p (Btu/lb_m R)
360	0.200
710	0.360
1060	0.420
1460	0.350

T (R)	k (Btu/ft hr R)			
	Pre-condition char T			
	1460R	2460R	3460R	3960R
660	.110	.175	.333	.432
860	.110	.185	.338	.437
1060	.111	.198	.344	.442
1260	.110	.212	.352	.448
1460	.120	.230	.361	.453
1660	.162	.253	.372	.462
1860	.212	.280	.383	.469
2060	.270	.313	.400	.480
2260	.330	.350	.420	.490
2460	.390	.390	.448	.504
2660	.448	.448	.486	.523
2960	.533	.533	.547	.562
3460	.660	.660	.660	.667
3960	.800	.800	.800	.800

Density 16.00 lb_m/ft^3
Emissivity 0.70

Ref. 10 Certification Analysis CAR 027001B, Apollo Block II Heat Shield (U). Vol. III Heat Shield Thermal Performance, SD 68-1004-3, Rockwell International, Downey, California, February 1969.

Material:	Avcoat - 5026-39 H/CG
Manufacturer:	AVCO
Composition:	Phenolic-Phenolic

Laminar Blowing Factor	0.7
Turbulent Blowing Factor	0.37
Combustion Enthalpy	11,850 Btu/lb
Heat of Vaporization	11,400 Btu/lb
Heat of Decomposition	500 Btu/lb

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k=7.22 \times 10^8$ lb/ft^3 hr, n=2.5, B=21,800 R

Virgin Properties

T (R)	Cp (Btu/lb R)
460	0.385
660	0.440
960	0.520
1,160	0.575
1,360	0.655

k=0.14 Btu/hr ft R

Density	33.0 lb/ft^3
Virgin Carbon Weight Fraction	0.242
Emissivity	0.667
Absorptivity	1.0

Ref. 20 Jaworski, W.; and Nagler, R. G.: A Parametric Analysis of Venus Entry Heat-Shield Requirements

Material: Avcoat - 5026-39/HC-G (Continued)

Char Properites

Cp = 0.655 Btu/lb R (at 1360 R)

T (R)	k (Btu/ft hr R)
460	0.140
1,660	0.140
1,860	0.220
2,260	0.355
2,460	0.425
2,860	0.540
3,060	0.595
3,460	0.700

Density 16.5 lb/ft^3

Char Carbon Weight Fraction 0.49

Emissivity

Specific Heat of Decomposition Gas	
T (R)	(Btu/ lb R)
540	0.550
1,000	0.660
2,000	0.740
3,000	0.790
4,000	0.830
8,000	0.960

Ref. 20 Jaworski, W.; and Nagler, R. G.: A Parametric Analysis of Venus Entry Heat-Shield Requirements

Material: DEN-438 + Glass Microballoons
Manufacturer: Dow Chemical
Composition: Anhydride-Cured Epoxy Novolac
Epoxy Novolec 53.6%, Nadic Methyl Anhydride 45.6%,
DMP-30 Catalyst 0.8%, Glass Microballoons
Undetermined

T (R)	Cp (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
492	0.227	582	0.081
672	0.300	672	0.081
852	0.325	762	0.078
1032	0.444	852	0.078
		942	0.075
		1032	0.075
		1122	0.075

T (R)	Density (lb/ ft^3)
527	38.1
672	38.1
852	37.5
1032	36.2

Ref. 23: Lagedrost, J. F., et. al.: Thermophysical and Chemical Characterization of Charring Ablative Materials

Material: DEN-438
Manufacturer: Dow Chemical
Composition: Anhydride-Cured Epoxy Novolac
Epoxy Novolec 53.6%, Nadic Methyl Anhydride 45.6%,
DMP-30 Catalyst 0.8%

T (R)	Cp (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
492	0.275	582	0.12
672	0.359	672	0.12
852	0.445	762	0.12
1032	0.527	852	0.11
1122	0.568	942	0.11
		1032	0.11
		1122	0.11

T (R)	Density (lb/ ft^3)
527	77.4
672	76.2
852	74.3
1032	70.5

Ref. 23: Lagedrost, J. F., et. al.: Thermophysical and Chemical Characterization of Charring Ablative Materials

Material: DEN-438 + Chopped Glass
Manufacturer: Dow Chemical
Composition: Anhydride-Cured Epoxy Novolac
Epoxy Novolec 45.6%, Nadic Methyl Anhydride 38.7%,
DMP-30 Catalyst 0.7%, Chopped Glass 15.0%

T (R)	Cp (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
492	0.233	582	0.13
672	0.322	672	0.14
852	0.410	762	0.15
1032	0.493	852	0.15
1122	0.535	942	0.15
		1032	0.16
		1122	0.16

T (R)	Density (lb/ ft^3)
527	83.0
672	81.8
852	79.3
1032	74.9

Ref. 23: Lagedrost, J. F., et. al.: Thermophysical and Chemical Characterization of Charring Ablative Materials

5

Carbon-Phenolics

Material: 5055
Manufacturer: H.I. Thompson, U.S. Polymeric
Composition: Hitco COA-1 cloth; filled phenolic resin, 33.8%; compression molded

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
710	0.254	710	0.590

Density 91.1 lb_m/ft^3

T (R)	Pre-condition char T	
	1960R	2460R
710	0.195	0.220
1460	0.588	0.425

T (R)	Pre-condition char T		
	1460R	2460R	4460R
710	0.48	0.8	1.7
1460	0.72	1.2	2.4

Density 79.6 lb_m/ft^3

(continued)

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: 5055 *(continued)*

Test condition: Splash fabric plies 70° to arc stream

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
	65	3.22×10^{-3}		245	10000
	308	2.66×10^{-3}		1340	66400
	252	2.28×10^{-3}		1340	77500
	193	6.99×10^{-3}		1550	29200
	193	7.03×10^{-3}		1550	29100
	193	4.27×10^{-3}		1140	35200
	196	5.85×10^{-3}		1140	32200

Test condition: 15° half angle, 1/8 in radius, fabric prallel to arc stream

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
	302	1.89×10^{-2}		3400	
	318	1.84×10^{-2}		3400	
	198	2.63×10^{-2}		3750	
	192	2.63×10^{-2}		3450	
	114	1.88×10^{-2}		2350	
	110	1.86×10^{-2}		2100	

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: carbon-phenolic
Manufacturer:
Composition:

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

part leaving residue: $k = 9.950 \times 10^{13}$ (lb_m/ft^3), $n = 3$, $B = 3.672 \times 10^4$ (R), $T > 1000°R$

wholly volatile part: $k = 9.950 \times 10^{9}$ (lb_m/ft^3), $n = 3$, $B = 1{,}541 \times 10^4$ (R), $T < 900°R$

Virgin Properties

T (R)	C_p (Btu/lb_m R)
540	0.210
900	0.359
1800	0.478
2700	0.478
3600	0.502
4500	0.502
5400	0.502

T (R)	k (Btu/ft hr R)
540	0.707
900	0.766
1800	0.825
1800	0.825
3600	0.825
4500	0.825
5400	0.825

Density 60.74 lb_m/ft^3 part leaving residue
20.23 wholly volatile part

Char Properties

T (R)	C_p (Btu/lb_m R)
540	0.210
900	0.406
1800	0.478
2700	0.478
3600	0.502
4500	0.502
5400	0.502

T (R)	k (Btu/ft hr R)
540	0.825
900	1.000
1800	1.590
2700	2.710
3600	4.180
4500	5.890
5400	8.250

Density 32.40 lb_m/ft^3

Ref. 13 W. C. Davy et al., Prog. Astronau.Aeronau. 64: 228-244, 1978

Material: G-1-A
Manufacturer: LTV.
Composition: Graphite fabric; phenolic pyrolyzed; vacuum bag molded

Virgin Properties

T (R)	C_p (Btu/lb_m R)
960	0.300
3960	0.520

T (R)	k (Btu/ft hr R)
960	0.830
3960	2.500

Density 63.65 lb_m/ft^3
Emissivity 0.77 (960°R)
0.85 (3960°R)

Test condition: air plasma evaluation

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
		2.20×10^{-3}	1.58×10^{-3}	500	

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: G-1-C
Manufacturer: LTV.
Composition: Graphite fabric; phenolic pyrolyzed; press molded, pyrolyzed,re-impregnated & re-pyrolyzed

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
400	0.135		
660	0.212		
1194	0.350		

Density 74.3 lb_m/ft^3

Test condition: air plasma evaluation

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
		1.11×10^{-3}	4.9×10^{-5}	264	

Test condition: graphitized

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
		7.00×10^{-1}	3.3×10^{-5}	200	
		5.00×10^{-1}	2.3×10^{-5}	360	
		5.30×10^{-1}	7.8×10^{-5}	1800	

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: V4B carbon & SC-1008 resin
Manufacturer: AVCO Corp.
Composition: V4B carbon-phenolic; SC-1008 phenolic resin, (35-47); molded 3-D

Heat of Ablation 10800 Btu/lb_m

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
	0.250	560	0.470
		710	0.540
		760	0.580
		860	0.600

Density 83.62 lb_m/ft^3
Emissivity

Test condition: (not known)

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ ($lb_m\ in^2/sec$)	$\dot{Q}_I$* ($Btu/ft^2\ sec$)	Q_C* (Btu/lb_m)
				9680	28100
				6950	18600

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: X-6400
Manufacturer: AVCO; Fiberite.
Composition: V4C carbon cloth; SC-1008 phenolic resin, 40%; T.W.-20°
Compression molded

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
710	0.390	710	0.260

Density 84.24 lb_m/ft^3
Emissivity

Test condition: (not known)

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
3980		7.4×10^{-3}		820	15300
4100		6.7×10^{-3}		870	18300
4860		7.2×10^{-3}		950	18000
5060		6.5×10^{-3}		990	21000
5080		8.7×10^{-3}		1230	19900
5990		9.4×10^{-3}		1200	18000
6300		7.9×10^{-3}		1460	26100
6280		7.5×10^{-3}		1420	26900
7870		5.7×10^{-3}		1400	34700
8130		6.1×10^{-3}		1360	31200
8930		3.4×10^{-3}		1280	32800
10250		4.7×10^{-3}		1320	39300

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: Narmco 4028
Manufacturer: Whittaker Corp./Narmco Materials Div.
Composition: carbon fiber (50%) reinforced phenolic; molded

Virgin Properties

T (R)	C_p (Btu/lb_m R)
260	0.126
310	0.164
360	0.192
410	0.221
460	0.245
510	0.267
560	0.287
610	0.304
660	0.320
710	0.334
760	0.346
810	0.358
860	0.367
910	0.375
960	0.390
1010	0.395
1110	0.400
1160	0.405
1210	0.408

T (R)	k (Btu/ft hr R)
265	0.121
349	0.163
472	0.212
539	0.255
272	0.129
369	0.165
454	0.186
632	0.264
760	0.309
801	0.324
935	0.353
1016	0.348
1088	0.321
1140	0.343
1176	0.344
1212	0.332
1215	0.336

T (R)	Density (lb_m/ft^3)
235	87.46
317	87.28
420	87.09
465	86.97
535	86.78
555	86.72
686	86.09
820	85.34
987	84.41
999	80.47
1108	77.60
1210	75.17

(continued)

Ref. 38 Wilson, R. G., Thermophysical Properties of Six Charring..., NASA TN D-2991 Oct. 1965

Material: Narmco 4028 *(continued)*

Char Properties

(no char data available)

Test condition: (not known)

H (Btu/lb_m)	temperature (°R)	$\dot{s}$ (in/sec)	weight loss (%)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
-49.59	239.4		0		
-46.13	265.2		0		
-43.97	280.1		0		
-43.15	282.2		0		
-36.90	324.6		0		
-24.17	393.0		0		
-12.60	447.5		0		
0	492.0		0		
12.28	492.0		0		
13.32	539.1		0		
29.05	596.8		0		
29.05	600.0		0		
88.43	784.5		0.4		
163.46	981.6		1.8		
171.31	1007.2		2.1		
252.02	1212.0		6.6		
251.53	1213.2		6.6		

Ref. 38 Wilson, R. G., Thermophysical Properties of Six Charring..., NASA TN D-2991 Oct. 1965

Material: X6101A
Manufacturer: AVCO & Lewcott
Composition: NOMEX carbon cloth; SC-1008 phenolic resin 27%
Compression molded

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
710	0.313	710	0.300

Density 85.30 lb_m/ft^3

Char Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)

T (R)	Pre-condition char T	
	1960R	2460R
710	0.190	0.195
1460	0.455	0.513

T (R)	Pre-condition char T		
	1460R	2460R	4460R
710	0.220	0.500	2.80
1460	0.290	0.680	3.00

Density 65.58 lb_m/ft^3

(continued)

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: X6101A *(continued)*

Test condition: Splash fabric plies 70° to arc stream

H (Btu/lb_m)	H/RT_o	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	$\dot{q}_c^*$ (Btu/lb_m)
	69	5.07×10^{-3}		245	6780
	285	3.58×10^{-3}		1340	52500
	303	2.30×10^{-3}		1340	81700
	198	7.74×10^{-3}		1540	27900
	199	8.18×10^{-3}		1540	26400
	183	4.20×10^{-3}		1080	36000

Test condition: 15° half angle, 1/8 in radius, fabric parallel to arc stream

H (Btu/lb_m)	H/RT_o	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	$\dot{q}_c^*$ (Btu/lb_m)
	302	1.92×10^{-2}		3400	
	318	1.87×10^{-2}		3400	
	198	2.95×10^{-2}		3750	
	192	2.87×10^{-2}		3450	
	114	1.97×10^{-2}		2350	
	110	1.89×10^{-2}		2100	

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: X6002B
Manufacturer: AVCO, H. I. Thompson, U.S. Polymeric
Composition: Hitco CCA-1 carbon cloth; SC-1008 phenolic resin, 39%; compression molded

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
710	0.251	718	0.590

Density 87.61 lb_m/ft^3

Char Properties

T (R)	C_p (Btu/lb_m R)		T (R)	k (Btu/ft hr R)		
	Pre-condition char T			Pre-condition char T		
	1960R			1460R	2460R	
710	0.207		710	0.357	0.520	
1460	0.563		1460	0.520	0.720	

Density 75.19 lb_m/ft^3

(continued)

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: X6002B *(continued)*

Test condition: Splash fabric plies 70° to arc stream

H (Btu/lb_m)	H/RT_o	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
	69	3.40×10^{-3}		245	9890
	265	3.47×10^{-3}		1340	53000
	203	7.08×10^{-3}		1540	29900
	202	7.37×10^{-3}		1540	28700
	182	3.43×10^{-3}		1080	43200

Test condition: 15° half angle, 1/8 in radius, fabric parallel to arc stream

H (Btu/lb_m)	H/RT_o	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
	302	1.58×10^{-2}		3400	
	318	1.70×10^{-2}		3400	
	198	2.62×10^{-2}		3750	
	194	2.57×10^{-2}		3450	
	114	1.81×10^{-2}		2350	
	110	1.57×10^{-2}		2100	

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: R-6300
Manufacturer: Fiberite Corp.
Composition: Pluton B carbon cloth; SC-1008 phenolic resin, 35%; Compression molded

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
	0.340		0.410

Density 88.61 lb_m/ft^3

Char Properties

T (R)	C_p (Btu/lb_m R)		T (R)	k (Btu/ft hr R)	
	Pre-condition char T			Pre-condition char T	
	1960R			1460R	2460R
710	0.230		710	0.440	
1460	0.430		1460	0.590	

Density 77.69 lb_m/ft^3

(continued)

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: R-6300 *(continued)*

Test condition: Splash fabric plies 70° to arc stream

H (Btu/lb_m)	H/RT_o	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
	67	3.90×10^{-3}		245	8450
	181	4.30×10^{-3}		1080	33700
	202	7.60×10^{-3}		1540	27400
	304	8.10×10^{-3}		1340	58600

Test condition: 15° half angle, 1/8 in radius, fabric parallel to arc stream

H_s (Btu/lb_m)	H/RT_o	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
2280		3.90×10^{-3}		245	8750
4130		6.40×10^{-3}		870	18250
4995		6.40×10^{-3}		990	21000
5290		7.50×10^{-3}		1200	21850
6120		4.30×10^{-3}		1080	33700
6475		7.30×10^{-3}		1420	26850
6820		7.60×10^{-3}		1540	27400
8250		5.80×10^{-3}		1360	32600
9020		4.20×10^{-3}		1320	44900
9300		2.40×10^{-3}		1320	72300
10280		3.10×10^{-3}		1340	58600

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: X6002D
Manufacturer: AVCO Corp.
Composition: Pluton B carbon cloth; SC-1008 phenolic resin 38.7% compression molded

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
710	0.256	710	0.500

Density 88.73 lb_m/ft^3

Char Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)

	Pre-condition char T	
	1960R	
710	0.212	
1460	0.538	

	Pre-condition char T		
	1460R	2460R	4460R
710	0.231	0.440	1.90
1460*	0.350	0.680	2.00

*char delaminated

Density 72.51 lb_m/ft^3

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

(continued)

Material: X6002D *(continued)*

Test condition: Splash fabric plies 70° to arc stream

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
	67	3.93×10^{-3}		245	8450
	300	3.10×10^{-3}		1340	58600
	308	3.10×10^{-3}		1340	58600
	198	7.74×10^{-3}		1540	27000
	205	7.52×10^{-3}		1540	27800
	181	4.34×10^{-3}		1080	33700

Test condition: 15° half angle, 1/8 in radius, fabric prallel to arc stream

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
	302	1.79×10^{-2}		3400	
	318	1.87×10^{-2}		3400	
	158	2.88×10^{-2}		3750	
	192	2.65×10^{-2}		3450	
	114	1.88×10^{-2}		2350	
	110	1.87×10^{-2}		3700	

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: FM5014
Manufacturer: U. S. Polymeric
Composition: WCA Graphite & MIL-R9299 phenolic (37.5%)

Virgin Properties

T (R)	C_p (Btu/lb_m R)
710	0.220

T (R)	k (Btu/ft hr R)	
710	0.520	perpendicular
	0.830	parallel

Density 89.86 lb_m/ft^3
Emissivity 0.85

Test condition: Splash fabric plies 70° to arc stream (assumed)

H (Btu/lb_m)	H/RTo	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
3990		5.80×10^{-3}		815	1008
5247		5.80×10^{-3}		1048	4086
5672		6.90×10^{-3}		1240	3204
7173		6.50×10^{-3}		1380	4467
8498		5.50×10^{-3}		1310	7311
9603		3.80×10^{-3}		1214	9732

(continued)

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: FM5014 *(continued)*

Test condition: 15° half angle, 1/8 in radius, fabric prallel to arc stream (assumed)

H (Btu/lb_m)	H/RTo	$\dot{s}$ (in/sec)	$\dot{m}$ ($lb_m\ in^2/sec$)	$\dot{q}_c$ ($Btu/ft^2\ sec$)	q_c^* (Btu/lb_m)
7500		5.00×10^{-3}		500	12047
7500		6.00×10^{-3}		500	10059
5100		9.90×10^{-3}		500	5640
5300		5.40×10^{-3}		380	6934
5300		6.80×10^{-3}		380	6682
12000		7.90×10^{-3}		480	15634
12000		4.20×10^{-3}		480	-----
12000		4.80×10^{-3}		475	12419
12000		5.30×10^{-3}		475	12326
19000		5.10×10^{-3}		410	10724
19000		6.00×10^{-3}		410	10248

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: 4047
Manufacturer: (not known)
Composition: Hitco CCA 1-1641 carbon cloth; filled phenolic resin, 35%
Compression molded

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
710	0.279	710	0.630

Density 90.04 lb_m/ft^3

Char Properties

T (R)	C_p (Btu/lb_m R)		T (R)	k (Btu/ft hr R)		
	Pre-condition char T			Pre-condition char T		
	1960R			1460R	2460R	
710	0.193		710	0.330	0.600 *	
1460	0.530		1460	0.490	0.930 *	

* Char delaminated

Density 77.69 lb_m/ft^3

(continued)

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: 4047 *(continued)*

Test condition: Splash fabric plies 70° to arc stream

H (Btu/lb_m)	H/RT_o	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
	63	3.39×10^{-3}		245	9620
	290	3.43×10^{-3}		1340	52000
	269	3.21×10^{-3}		1340	55600
	190	6.59×10^{-3}		1550	21300
	207	7.35×10^{-3}		1550	28100
	106	4.62×10^{-3}		1140	32900

Test condition: 15° half angle, 1/8 in radius, fabric parallel to arc stream

H (Btu/lb_m)	H/RT_o	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
	302	1.80×10^{-2}		3400	
	318	1.80×10^{-2}		3400	
	198	2.72×10^{-2}		3750	
	192	2.66×10^{-2}		3450	
	114	1.69×10^{-2}		2350	
	110	1.72×10^{-2}		2100	

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: carbon-phenolic
Manufacturer: General Electric
Composition: (not specified)
Bueche's recommended model (best match of flight data), Table III

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = 2.142 \times 10^3$ (lb_m/ft^3hr), $n = 2$, $B = 4.680 \times 10^3$ (R), $T < 1296°R$

$k = 1.178 \times 10^8$ (lb_m/ft^3hr), $n = 2$, $B = 1.7514 \times 10^4$ (R), $T \geq 1296°R$

Virgin Properties

T (R)	C_p (Btu/lb_m R)
460	0.190
760	0.316
960	0.360
1460	0.400
1960	0.440
2460	0.460
2960	0.490
3460	0.510
5000	0.570

T (R)	k (Btu/ft hr R)
460	0.360
760	0.439
960	0.493
1460	0.641
1960	0.778
2460	0.918
2960	1.055
3460	1.195
5000	1.602

Density	90.4 lb_m/ft^3
Emissivity	0.85

Char Properties

T (R)	k (Btu/ft hr R)
1140	0.468
1520	0.522
2100	0.670
2500	0.800
2880	0.907
3380	1.051

Ref. 9 Bueche, J. F., Effects of Improvements and Uncertainties In Thermophysical Properties. . . AIAA Paper 77-787, 6/30/77

Material: 5055A
Manufacturer: H.I. Thompson, U.S. Polymeric
Composition: Hitco CCA-1-1641 carbon cloth; filled phenolic resin, 34%; Rosette molded

Virgin Properties

T (R)	C_p (Btu/lb_m R)
710	0.244

T (R)	k (Btu/ft hr R)
710	0.530

Density 92.54 lb_m/ft^3

Char Properties

T (R)	C_p (Btu/lb_m R)		
	Pre-condition char T		
	1960R	2460R	
710	0.213	0.232	
1460	0.400	0.425	

T (R)	k (Btu/ft hr R)		
	Pre-condition char T		
	1460R	2460R	4460R
710	0.400	0.80	1.90
1460	0.580	1.30	2.60

Density 77.63 lb_m/ft^3

Test condition: Splash fabric plies 70° to arc stream

H (Btu/lb_m)	H/RT_o	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
	64	3.35×10^{-3}		245	9490
	310	2.37×10^{-3}		1340	73300
	188	6.33×10^{-3}		1550	31800
	205	7.45×10^{-3}		1550	27000
	190	4.05×10^{-3}		1140	36500

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: OTWR
Manufacturer: H.I. Thompson, TRW, AVCO
Composition: Refrasil cloth; SC-1008 phenolic resin, 35%; compression molded

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
710	0.279	710	0.290

Density 104.40 lb_m/ft^3

Char Properties

T (R)	C_p (Btu/lb_m R)		T (R)	k (Btu/ft hr R)	
	Pre-condition char T			Pre-condition char T	
	1960R	2460R		1460R	2460R
710	0.180	0.205	710	0.229	0.247
1460	0.413	0.235	1460	0.289	0.299

Density 94.4 lb_m/ft^3

(continued)

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: OTWR *(continued)*

Test condition: Splash fabric plies 70° to arc stream

H (Btu/lb_m)	H/RT_o	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
	125	1.12×10^{-2}		905	4350
	129	1.12×10^{-2}		920	4530
	129	1.11×10^{-2}		887	4470
	167	1.54×10^{-2}		1168	4850
	168	1.57×10^{-2}		1202	5130
	168	1.50×10^{-2}		1170	5080
	229	1.67×10^{-2}		1326	5740
	261	1.42×10^{-2}		1236	6530
	261	1.43×10^{-2}		1236	6410
	265	1.41×10^{-2}		1283	6580
	278	1.30×10^{-2}		1130	6300
	287	1.16×10^{-2}		978	6320
	297	1.18×10^{-2}		1138	7060

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: G-1-CM
Manufacturer: LTV
Composition: Graphite fabric; phenolic pyrolyzed; press molded, pyrolyzed, re-molded, re-pyrolyzed; coated with Si and SiC

Virgin Properties

Density 127.92 lb_m/ft^3

Test condition: air plasma evaluation

H (Btu/lb_m)	H/RT_0	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
		1.40×10^{-4}	2.50×10^{-5}	200	
		2.40×10^{-4}	4.60×10^{-5}	320	
			1.38×10^{-4}	560	
		1.47×10^{-2}	4.50×10^{-4}	1800	

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: Graphite Cloth/Epoxy Resin
Manufacturer: Unknown
Composition: Graphite Cloth/Epoxy Resin

Virgin and Char Properties

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/hr ft R)
560	0.24	560	1.5
960	0.335	960	1.9
1460	0.380	1460	1.7
1960	0.405	1960	1.9
2460	0.420	2460	2.2
2960	0.430	2960	2.5
3460	0.445	3460	2.8
3960	0.450	3960	3.1
4460	0.460	4460	9.2

Virgin Density 87 ± 7 lb/ft^3
Char Density 76 ± 6 lb/ft^3

Ref 32: Schultz, F. E.: Investigation of the Effects of Material Properties on Composite Ablative Material Behavior

Material: Graphite Cloth/Phenolic Resin
Manufacturer: Unknown
Composition: Graphite Cloth/Phenolic Resin

Virgin and Char Properties

T (R)	k (Btu/hr ft R)
560	1.5
960	1.90
1460	1.87
1960	1.94
2460	2.23
2960	2.52
3460	2.77
3960	3.02
4460	3.31

Virgin Density 87 ± 7 lb/ft^3
Char Density 76 ± 6 lb/ft^3

Ref 32: Schultz, F. E.: Investigation of the Effects of Material Properties on Composite Ablative Material Behavior

Material: X6300
Manufacturer: Unknown
Composition: Carbon Phenolic

Laminar Blowing Factor	0.76
Turbulent Blowing Factor	0.4
Combustion Enthalpy	16,100 Btu/lb
Heat of Vaporization	11,400 Btu/lb
Heat of Decomposition	600 Btu/lb
Specific Heat of Decomposition Gas	0.40 Btu/lb R

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k=1.62 \times 10^8$ lb/ft^3 hr, n=1.0, B=10,000 R

Virgin Properties

T (R)	Cp (Btu/lb R)		k (Btu/ft hr R)
500	0.250		0.33

Density	90.0 lb/ft^3
Virgin Carbon Weight Fraction	0.40
Emissivity	0.8
Absorptivity	1.0

Char Properites

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/ft hr R)
660	0.260	500	0.375
1,460	0.538	2,960	1.130

Density	60.0 lb/ft^3
Char Carbon Weight Fraction	0.71
Emissivity	

Ref 20 Jaworski, W.; and Nagler, R. G.: A Parametric Analysis of Venus Entry Heat-Shield Requirements

Material: MX4500
Manufacturer: Unknown
Composition: Graphite Phenolic

Virgin Properties

T	k (Btu/hr ft R)	
(R)	Layup Angle	
	0°	90°
100	1.1	2.7
200	1.9	3.2
300	3.1	4.8
400	5.0	6.3
500	7.2	8.2
600	9.9	10.5

Specific Heat, Density, and Emissivity data not given.

Ref 4 Baker, D. L., et. al.: A Dynamic Technique for Determining the Thermal Conductivity of Charring Materials

Material: MX4926
Manufacturer: Unknown
Composition: Carbon Phenolic

Virgin Properties

T	k (Btu/hr ft R)	
(R)	Layup Angle	
	0°	90°
100	0.68	1.1
200	0.86	1.6
300	2.0	3.3
400	4.3	5.5
500	6.8	7.7
600	9.5	10.2

Specific Heat, Density, and Emissivity data not given.

Ref 4 Baker, D. L., et. al.: A Dynamic Technique for Determining the Thermal Conductivity of Charring Materials

Material: FM5072
Manufacturer: Unknown
Composition: Carbon Phenolic

Char Properties

T	k (Btu/hr ft R)	
(R)	Layup Angle	
	0°	90°
1500		1.4
2000	0.72	1.7
3000	1.9	3.2
4000	4.3	5.3
5000	6.8	7.4

Specific Heat, Density, and Emissivity data not given.

Ref 4 Baker, D. L., et. al.: A Dynamic Technique for Determining the Thermal Conductivity of Charring Materials

Carbon Materials

with ablation data

Material: ATJ
Manufacturer: Union Carbide
Composition: graphitic carbon molded

Virgin Properties

T (R)	C_p (Btu/lb_m R)
528	0.17
2460	0.45
4460	0.52
5460	0.52
6260	0.55

T (R)	$k_{parallel}$ (Btu/ft hr R)	$k_{perpendicular}$ (Btu/ft hr R)
528	68.0	51.8
1482	42.1	
2630	26.6	
3360	25.2	
3460		18.9
4460		17.3

Density	107.95	lb_m/ft^3
Emissivity	0.77	polished
	0.90	dull

Test condition: (not known)

H_o (Btu/lb_m)	H/RT_o	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	q_c (Btu/ft^2 sec)	q_c^* (Btu/lb_m)	ρ (Atm)
1679		5.10×10^{-2}				48
5050		1.09×10^{-1}				49
5616		1.12×10^{-1}				40
6600		1.77×10^{-1}				72

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: CVD
Manufacturer: Super Temp. Corp; GE; High Temp. Mat.
Composition: pyrolytic graphite; polycrystalline, CVD

Virgin Properties

Density $136.66 lb_m/ft^3$

Test condition: (not known) ρ = 1.0 Atm

H (Btu/lb_m)	H/RT_o	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
3800		1.10×10^{-1}			28
10700		1.40×10^{-1}			87
14600		6.70×10^{-1}			458

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Silica-Teflon

Material: TEFLON/ASTROQUARTZ
Manufacturer: (not known)
Composition: Astroquartz; Teflon; compression molded

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
710	0.220	710	0.253

Density 131.04 lb_m/ft^3

Test condition: parallel to laminate

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
2000					2900
4000					4300
6000					5600
8000					7000
10000					8300

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

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Silica-Phenolic

Material: Silica & SC100B resin
Manufacturer: (not known)
Composition: silica; SC100B resin, 35%; tension wound, compression molded

Virgin Properties

T (R)	C_p (Btu/lb_m R)
710	0.281

T (R)	k (Btu/ft hr R)
710	0.283

Density 103. lb_m/ft^3

Char Properties

T (R)	C_p (Btu/lb_m R)		
	Pre-condition char T		
	1960R	2460R	
710		0.210	

T (R)	k (Btu/ft hr R)		
	Pre-condition char T		
	1460R	2460R	
710		0.247	

Density lb_m/ft^3

Test condition: Splash (fabric plies 70° to arc stream, assumed)

H (Btu/lb_m)	H/RTo	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	q_c (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
	127	1.20×10^{-2}		905	
	168	1.52×10^{-2}		1170	
	197	1.85×10^{-2}		1550	10300
	226	1.70×10^{-2}		1326	
	282	1.07×10^{-2}		970	11200
	295	1.19×10^{-2}		1140	

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: DACLOCK 120
Manufacturer: McDonnell Douglas
Composition: quartz; SC1008 resin, 24%; 3-D panel data

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
560	0.230	613	0.163
660	0.260	802	0.210
760	0.290	950	0.225
860	0.310	1184	0.253
960	0.330		

Density 104.83 lb_m/ft^3

Test condition: P=17.5 Atm; t=2.5 (unit not known)

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
2210 - 2080		4.80×10^{-2}		5300 - 3100	

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: FM5020
Manufacturer: U.S. Polymeric ?
Composition: chopped silica fabric, $^1/_2$ in x $^1/_2$ in; SC1008 phenolic resin, 31.5%

Virgin Properties

T (R)	C_p (Btu/lb_m R)
710	0.271

T (R)	k (Btu/ft hr R)
710	0.322 perpendicular 0.301 parallel

Density 106.70 lb_m/ft^3

Test condition: splash

H (Btu/lb_m)	H/RT_o	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_c$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
	116	9.70×10^{-3}		900	5117
	147	1.36×10^{-2}		1160	5500
	196	1.61×10^{-2}		1390	6305
	287	1.37×10^{-2}		1300	7280

Test condition: cone

ρ_{shear} (lb_f/in^2)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}_s$ (Btu/ft^2 sec)	P (Atm)
205		1.65×10^{-1}		4350	50
265		1.65×10^{-1}		4850	60
365		1.55×10^{-2}		5650	75

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: FM5131/FM5320
Manufacturer: U.S. Polymeric
Composition: silica fabric; filled phenolic resin, 30%

Virgin Properties

T (R)	C_p (Btu/lb_m R)
710	0.277

T (R)	k (Btu/ft hr R)	
710	0.282	
960	0.292	
	0.24	perpendicular
	0.30	parallel
	0.22	20°

Density 109.20 lb_m/ft^3
Emissivity 0.48

Test condition: (not known)

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	q_c (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
4300		1.20×10^{-2}		905	
4415		1.09×10^{-2}		865	9250
5700		1.52×10^{-2}		1170	
6670		1.85×10^{-2}		1550	10300
6990		1.66×10^{-2}		1240	8700
7650		1.70×10^{-2}		1326	
8270		1.43×10^{-2}		1130	9200

ΔH_v	= 2900		Btu/lb_m
ΔE	= 15000	39000	cal/mol
A	$=2.5 \times 10^2$	4.5×10^7	sec^{-1}
η	= 1.5		

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: Quartz, SC100B resin & epoxy
Manufacturer: AVCO Corp.
Composition: quartz; SC1008B resin 22%; epoxy 9%; 3-D (ortho-block)

Heat of ablation = 4800 Btu/lb_m

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
710	0.229	710	0.380

Density 109.89 lb_m/ft^3

Char Properties

Density 81.12 lb_m/ft^3

Test condition: (not known)

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	q_c (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
3500		6.60×10^{-3}		782	6220
4940		1.02×10^{-2}		1060	6640
7000		1.43×10^{-2}		1410	7070
8630		1.34×10^{-2}		1400	7810
9000		1.26×10^{-2}		1400	8450
10800		1.11×10^{-2}		1160	7690

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: Dervy, Quartz roving
Manufacturer: McDonnell Douglas WD
Composition: Dervy (quartz roving) Q-P-3-D; DP-24-2 28.6%; orthogonal panels

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
650	0.210	590	0.290

Density 110.45 lb_m/ft^3

Test condition: pressure = 18 Atm

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	q_c (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
2120		1.17×10^{-1}			
2240		1.27×10^{-1}			

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: X6002
Manufacturer: AVCO Corp.
Composition: Astroquartz; SC1008 phenolic resin (30%); T.W. AHB

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
710	0.206	710	0.345

Density 111.07 lb_m/ft^3
Emissivity 0.5

Test condition: splash

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	q_c (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
3670		8.90×10^{-3}		791	4710
5220		1.35×10^{-2}		1160	5600
6740		1.63×10^{-2}		1420	9910
8450		1.48×10^{-2}		1370	10600
9990		1.31×10^{-2}		1370	7840

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: Very Low Density Elastomeric Ablator
Manufacturer: Unknown
Composition: Phenolic Spheres 71.0%, Silicone Resin 22.8%, Catalyst 2.2%, Silica Fibers 4.0%

Effective Heat of Pyrolysis	367 Btu/lb_m R
Specific Reaction-Rate Constant for Pyrolysis	7.09×10^{13} lb/ft^2 s atm
Activation Temperature for Pyrolysis	6.19×10^4 R
Heat of Combustion of Char	3797 Btu/lb_m
Specific Reaction-Rate Constant for Oxidation	2.00×10^8 lb/ft^2 s atm
Activation Temperature for Oxidation	5.99×10^4 R
Weight of Char Removed per Unit Weight of Oxygen	0.83

Virgin Properties

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/hr ft R)
500	0.332	500	0.0324
630	0.361	600	0.0335
720	0.377	800	0.0329
810	0.392	1000	0.0318
900	0.408	1400	0.0300
1150	0.451	1600	0.0289
1500	0.499	2000	0.0272
1700	0.528		
2000	0.549		

Density 14.0 lb/ft^3

Ref. 29 Olsen, G. C.; and Chapman III, A. J.: Flight and Ground Tests of a Very-Low-Density Elastomeric Ablative Material

Material: Very Low Density - Elastomeric Ablator (Continued)

Char Properties

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/hr ft R)
500	0.119	500	0.0716
1000	0.160	1000	0.0901
1500	0.260	1500	0.144
2000	0.420	2000	0.233
2500	0.568	3000	0.395
3000	0.690	4000	0.575
3500	0.769		

Density 8.00 lb/ft^3
Emissivity 0.8

Specific Heat of Pyrolysis Gases	
T (R)	Cp (Btu/lb R)
540	0.528
1001	0.740
1249	0.850
1500	0.958
1800	1.07
2000	1.13
2250	1.19
2500	1.25
2750	1.30
3000	1.34
3500	1.40
4000	1.43

Ref. 29 Olsen, G. C.; and Chapman III, A. J.: Flight and Ground Tests of a Very-Low-Density Elastomeric Ablative Material

Material: Silica Cloth/Phenolic Resin
Manufacturer: Unknown
Composition: Silica Cloth/Phenolic Resin

Virgin and Char Properties

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/hr ft R)
560	0.245	560	0.30
960	0.310	960	0.33
1460	0.340	1460	0.30
1960	0.365	1960	0.35
2460	0.380	2460	0.461
2960	0.390	2960	0.644
3460	0.395	3460	0.864
3960	0.400	3960	1.17
4460	0.450	4460	1.40

Virgin Density 110 ± 8 lb/ft^3
Char Density 92 ± 7 lb/ft^3

Ref. 32 Schultz, F. E.: Investigation of the Effects of Material Properties on Composite Ablative Material Behavior

Material: MX2600
Manufacturer: Unknown
Composition: Silica Phenolic

Virgin Properties

T (R)	k (Btu/hr ft R)	
	Layup Angle	
	0°	90°
530-1000	0.34	0.41

Density
Emissivity

Char Properties

T (R)	k (Btu/hr ft R)	
	Layup Angle	
	0°	90°
1000	1.1	1.19
2000	1.17	1.28
3000	1.28	1.39
4000	1.44	1.57
5000	1.89	2.09
6000	2.25	2.30

Density
Emissivity

Ref. 4 Baker, D. L., et. al.: A Dynamic Technicque for Determining the Thermal Conductivity of Charring Materials

Material: MX2600-96
Manufacturer: Unknown
Composition: Silica Phenolic

Virgin Properties

T (R)	k (Btu/hr ft R)	
	Layup Angle	
	0°	90°
1000	0.34	0.45

Density
Emissivity

Char Properties

T (R)	k (Btu/hr ft R)	
	Layup Angle	
	0°	90°
1000	0.918	1.28
2000	0.918	1.30
3000	0.936	1.40
4000	0.972	1.58
5000	1.10	2.16
6000	1.53	3.20

Density
Emissivity

Ref. 4 Baker, D. L., et. al.: A Dynamic Technicque for Determining the Thermal Conductivity of Charring Materials

Material: MXS-113
Manufacturer: Unknown
Composition: Silica Phenolic

Char Properties

T (R)	k (Btu/hr ft R)	
	Layup Angle	
	0°	90°
1000	1.1	1.1
2000	1.2	1.5
3000	1.3	3.2
4000	1.4	5.3
5000	1.9	
6000	2.9	

Density
Emissivity

Ref. 4 Baker, D. L., et. al.: A Dynamic Technicque for Determining the Thermal Conductivity of Charring Materials

Silica-Silicones

Material: Silicone A
Manufacturer: Acurex Corp.
Composition: 2% silica fibers, 8% silica particles; 90% Sylgard 182 ($SiO(CH_3)_2$); no catalyst

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = 4.927 \times 10^7$ (lb_m/ft^3),	$n = 1.68$,	$B = 2.622 \times 10^3$ (R):	resin A
$k = 1.232 \times 10^6$ (lb_m/ft^3),	$n = 1$,	$B = 1.399 \times 10^1$ (R):	resin B
$k = 2.458 \times 10^{27}$ (lb_m/ft^3),	$n = 3.1$,	$B = 8.877 \times 10^{23}$ (R):	solid matrix

Virgin Properties

T (R)	C_p (Btu/lb_m R)
492	0.42

T (R)	k (Btu/ft hr R)
53	0.500
100	0.500
150	0.258
225	0.258
400	0.258

Density 107.61 lb_m/ft^3

Char Properties

T (R)	C_p (Btu/lb_m R)
492	0.42

T (R)	k (Btu/ft hr R)
53	0.258
150	0.258
160	0.258
202	0.330
280	0.950
285	0.390
400	0.258

Density 85.75 lb_m/ft^3

(continued)

Ref. 7 R. A. S . Beck & B. Laub, Materials Development for Multiple Performance Requirements, SAE 840920, July 16-19, 1984

Material: Silicone A *(continued)*

Pyrolysis gas enthalpy model

Temp (R)	H (Btu/lb_m)		
	$\bar{h}$	P=1.0 Atm	P=.01 Atm
500	1000		
1000	1350	1900	3400
1500	1387	2300	3900
2000	2025	2700	4300
2700	2317	3300	4900
3000	2700	4400	5350
3500	2737	5800	6200
4000	3375	6400	7500
4500	3412	7350	11050
5000	4050	8700	14700
5500	4087	10800	

$$\bar{h} = (\rho_v H_v - \rho_c H_c) \; / \; (\rho_v - \rho_c)$$

H at 1.0 Atm and 0.01 Atm calculated using ACE computer program. See reference document.

Ref. 7 R. A. S . Beck & B. Laub, Materials Development for Multiple Performance Requirements, SAE 840920, July 16-19, 1984

Material: Silicone A + catalyst
Manufacturer: Acurex Corp.
Composition: 2% silica fibers, 8% silica particles; 90% Sylgard 182 ($SiO(CH_3)_2$); with catalyst

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

k =1.278x 10^9 (lb_m/ft^3), n =1.56, B =2.512x 10^4 (R): resin A
k =1.354x 10^{15} (lb_m/ft^3), n =1.87, B =6.632x 10^9 (R):solid matrix

Virgin Properties

T (R)	C_p (Btu/lb_m R)
492	0.42

T (R)	k (Btu/ft hr R)
53	0.500
100	0.500
150	0.258
225	0.258
400	0.258

Density 123.15 lb_m/ft^3

Char Properties

T (R)	C_p (Btu/lb_m R)
492	0.42

T (R)	k (Btu/ft hr R)
53	0.258
150	0.258
160	0.258
202	0.330
280	0.950
285	0.390
400	0.258

Density 41.8 lb_m/ft^3

Ref. 7 R. A. S . Beck & B. Laub, Materials Development for Multiple Performance Requirements, SAE 840920, July 16-19, 1984

Material: Silicone A + catalyst *(continued)*

Pyrolysis gas enthalpy model

Temp (R)	H (Btu/lb_m)		
	$\bar{h}$	P=1.0 Atm	P=.01 Atm
500	1000		
1000	1350	1900	3400
1500	1387	2300	3900
2000	2025	2700	4300
2700	2317	3300	4900
3000	2700	4400	5350
3500	2737	5800	6200
4000	3375	6400	7500
4500	3412	7350	11050
5000	4050	8700	14700
5500	4087	10800	

$$\bar{h} = (\rho_v H_v - \rho_c H_c) \; / \; (\rho_v - \rho_c)$$

H at 1.0 Atm and 0.01 Atm calculated using ACE computer program. See reference document.

Ref. 7 R. A. S . Beck & B. Laub, Materials Development for Multiple Performance Requirements, SAE 840920, July 16-19, 1984

Material: Silicone B
Manufacturer: Acurex Corp.
Composition: 10% silica particles; 90% Sylgard 182 ($SiO(CH_3)_2$); no catalyst

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = 1.638 \times 10^6$ (lb_m/ft^3),	$n = 1$,	$B = 1.230 \times 10^2$ (R):	resin A
$k = 1.301 \times 10^{12}$ (lb_m/ft^3),	$n = 2.56$,	$B = 1.663 \times 10^7$ (R):	resin B
$k = 1.090 \times 10^{22}$ (lb_m/ft^3),	$n = 3.1$,	$B = 3.218 \times 10^{18}$ (R):	solid matrix

Virgin Properties

T (R)	C_p (Btu/lb_m R)
492	0.42

T (R)	k (Btu/ft hr R)
53	0.357
100	0.357
150	0.178
225	0.185
400	0.184

Density 111.85 lb_m/ft^3

Char Properties

T (R)	C_p (Btu/lb_m R)
492	0.42

T (R)	k (Btu/ft hr R)
53	0.185
160	0.135
202	0.230
280	0.645
285	0.275
400	0.143

Density 87.90 lb_m/ft^3

Ref. 7 R. A. S . Beck & B. Laub, Materials Development for Multiple Performance Requirements, SAE 840920, July 16-19, 1984

Material: Silicone B*(continued)*

Pyrolysis gas enthalpy model

Temp (R)	H (Btu/lb_m)		
	$\bar{h}$	P=1.0 Atm	P=.01 Atm
500	1000		
1000	1350	1900	3400
1500	1387	2300	3900
2000	2025	2700	4300
2700	2317	3300	4900
3000	2700	4400	5350
3500	2737	5800	6200
4000	3375	6400	7500
4500	3412	7350	11050
5000	4050	8700	14700
5500	4087	10800	

$$\bar{h} = (\rho_V H_V - \rho_C H_C) \; / \; (\rho_V - \rho_C)$$

H at 1.0 Atm and 0.01 Atm calculated using ACE computer program. See reference document.

Ref. 7 R. A. S . Beck & B. Laub, Materials Development for Multiple Performance Requirements, SAE 840920, July 16-19, 1984

Material: Silicone B + catalyst
Manufacturer: Acurex Corp.
Composition: 10% silica particles; 90% Sylgard 182 ($SiO(CH_3)_2$); with catalyst

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = 1.963 \times 10^8$ (lb_m/ft^3),	$n = 1.89$,	$B = 1.974 \times 10^3$ (R):	resin A
$k = 4.655 \times 10^{15}$ (lb_m/ft^3),	$n = 1.87$,	$B = 3.806 \times 10^{10}$ (R):	solid matrix

Virgin Properties

T (R)	C_p (Btu/lb_m R)
460	0.420

T (R)	k (Btu/ft hr R)
53	0.357
100	0.357
150	0.178
225	0.185
400	0.184

Density 109.66 lb_m/ft^3

Char Properties

T (R)	C_p (Btu/lb_m R)
53	0.185

T (R)	k (Btu/ft hr R)
160	0.135
202	0.230
280	0.645
285	0.275
400	0.143

Density 51.06 lb_m/ft^3

Ref. 7 R. A. S . Beck & B. Laub, Materials Development for Multiple Performance Requirements, SAE 840920, July 16-19, 1984

Material: Silicone B + catalyst *(continued)*

Pyrolysis gas enthalpy model

Temp (R)	H (Btu/lb_m)		
	$\bar{h}$	P=1.0 Atm	P=.01 Atm
500	1000		
1000	1350	1900	3400
1500	1387	2300	3900
2000	2025	2700	4300
2700	2317	3300	4900
3000	2700	4400	5350
3500	2737	5800	6200
4000	3375	6400	7500
4500	3412	7350	11050
5000	4050	8700	14700
5500	4087	10800	

$$\bar{h} = (\rho_v H_v - \rho_c H_c) \; / \; (\rho_v - \rho_c)$$

H at 1.0 Atm and 0.01 Atm calculated using ACE computer program. See reference document.

Ref. 7 R. A. S . Beck & B. Laub, Materials Development for Multiple Performance Requirements, SAE 840920, July 16-19, 1984

Material: SLA-220
Manufacturer: Martin Marietta
Composition: Silica Filled Elastomeric Silicone

Ablation Temperature 1360 R
Effective Heat of Ablation 6000 Btu/lb for 50 sec @ 60 Btu/ft^2 s
1800 Btu/lb for 250 sec @ 6 Btu/ft^2 s

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k=9.2337 \times 10^{42}$ lb$_m$/ft^3 hr, n=4, B=1.328×10^5 R

Virgin Properties

T (R)	Cp (Btu/lb R)
360	0.19
460	0.22
560	0.23
660	0.25
760	0.26
860	0.265
960	0.27

T (R)	k (Btu/hr ft R)			
	Pressure (atm)			
	1.3×10^{-9}	1.3×10^{-3}	9.2×10^{-2}	1.0
260	0.023			
360	0.028	0.032	0.035	0.038
460	0.031	0.035	0.040	0.043
560	0.034	0.038	0.044	0.048
660	0.037	0.041	0.050	0.054
760	0.039	0.044	0.056	0.059
860	0.042	0.048	0.060	0.065
960	0.044	0.051	0.066	0.071
1060	0.048	0.055	0.071	0.076

Density 14.5 $\pm$ 1.0 lb/ft^3
Emissivity 0.85 to 0.95

Ref 2 Ablative Heat Shield Materials SLA-220, 48.3 A-GH, Martin Marietta, Denver, CO

Material: SLA-220 (Continued)

Char Properties

T (R)	Residue Weight Fraction
660	1.00
860	1.00
1060	0.99
1260	0.96
1460	0.76
1660	0.73
1860	0.72

Char Density 10.6 lb/ft^3

Test Condition: 6° C/min. (10.8 R/min) Heating Rate in Argon

Ref 2 Ablative Heat Shield Materials SLA-220, 48.3 A-GH, Martin Marietta, Denver, CO

Material: SLA-561 (Tompkins, et. al.)
Manufacturer: Martin Marietta
Composition: Elastomeric Silicone

Heat of Pyrolysis	0
Specific Heat of Pyrolysis Gasses	0.6 Btu/lb_m R

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k=1.8126 \times 10^{11}$ lb_m/ft^3 hr, n=3, $B=3.42 \times 10^4$ R

Virgin Properties

T (R)	Cp (Btu/lb_m R)
310	0.211
410	0.250
510	0.275
610	0.289
710	0.299
810	0.301

T (R)	k (Btu/hr ft R)		
	Pressure (atm)		
	10^{-9}	1.3×10^{-3}	1.0
510	0.022	0.026	0.031
560	0.022	0.026	0.032
610	0.022	0.027	0.035
660	0.022	0.027	0.036
710	0.022	0.027	0.038
760	0.022	0.028	0.040
810	0.023	0.028	0.042
860	0.023	0.029	0.044

Density	14.5 lb_m/ft^3
Emissivity	

Ref. 35 Tompkins, S. S., et. al.: An Assessment of the Readiness of Ablative Materials for Preflight Applications to the Shuttle Orbiter

Material: SLA-561 (Continued)

Char Properties

T (R)	Cp (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
600	0.195	400	0.0540
800	0.231	1600	0.0544
1000	0.268	1800	0.0590
1200	0.297	2000	0.0655
1400	0.320	2200	0.0742
1600	0.343	2400	0.0864
1800	0.363	2600	0.0994
2000	0.383	2800	0.114
2200	0.400	3000	0.130
2400	0.413	3200	0.148
		3400	0.169
		3600	0.195

T (R)	Residue Weight Fraction
660	1.00
860	1.00
1060	0.955
1260	0.825
1460	0.620
1660	0.575
1860	0.575

Density	7.98 lb_m/ft^3
Emissivity	0.9

Test Condition: 6° C/min. (10.8 R/min) Heating Rate in Argon

Ref. 35 Tompkins, S. S., et. al.: An Assessment of the Readiness of Ablative Materials for Preflight Applications to the Shuttle Orbiter

Material: SLA-561
Manufacturer: Martin Marietta
Composition: cork & other fillers; elastomeric silicone

Heat of pyrolysis	0.0	Btu/lb_m
Pyrolysis gas specific heat	0.60	Btu/lb_m-R
Ablating Temperature (Start of Pyrolysis)	1060	R
Charring Temperature (End of Pyrolysis)	1660	R

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = 2.360 \times 10^{12}$ (lb_m/ft^3hr), $n = 3$, $B = 3.42 \times 10^4$ (R)

Virgin Properties

T (R)	C_p (Btu/lb_m R)
0	0.055
310	0.210
360	0.232
460	0.267
560	0.285
610	0.293
2000	0.295

T (R)	k (Btu/ft hr R)
0	0.0104
260	0.0225
460	0.0333
760	0.0492
900	0.0540
2000	0.0540

Density	14.50 lb_m/ft^3
Emissivity	0.70

(continued)

Ref. 36 Williams, S. D. , Thermophysical Properties used for Ablation Analysis, LEC-13999, AMD-2309-150, 12/11/79

Material: SLA-561 *(continued)*

Char Properties

T (R)	C_p (Btu/lb$_m$ R)
0	0.160
710	0.233
960	0.259
1260	0.273
1760	0.292
2460	0.312
4000	0.312

T (R)	k (Btu/ft hr R)
0	0.0674
1500	0.0674
2400	0.1808
3200	0.1890
4000	0.4320

Density	7.98lb$_m$/ft^3
Emissivity	0.90

Ref. 36 Williams, S. D. , Thermophysical Properties used for Ablation Analysis, LEC-13999, AMD-2309-150, 12/11/79

Material: ESA-3560
Manufacturer: Martin Marietta
Composition: Filled Elastomeric Silicone

Ablation Temperature	1290 R
Heat of Ablation	5800 Btu/lb for 50 sec @ 60 Btu/ft^2 s
	1500 Btu/lb for 250 sec @ 6 Btu/ft^2 s

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k=2.86\times10^{13}$ lb$_m$/ft^3 hr, n=2, B=3406 R

Virgin Properties

T (R)	Cp (Btu/lb R)	k (Btu/hr ft R)
260	0.145	
310	0.190	0.042
360	0.235	0.046
410	0.275	0.050
460	0.325	0.053
510	0.355	0.056
560	0.385	0.058
610	0.425	0.060
660	0.450	0.063
710	0.475	0.064
760	0.505	0.066
810	0.530	0.068
860	0.555	0.069
910	0.570	0.070
960	0.600	0.071

Density	30 lb/ft^3
Emissivity	0.9

Ref. 1 Ablative Heat Shield Materials ESA-3560, ESA-5500, MTSE E48.4 5-77, Martin Marietta, Denver, CO

Material: ESA-3560 (Continued)

Char Properites

T (R)	Residue Weight Fraction
660	1.0
860	0.99
1060	0.96
1260	0.70
1460	0.39
1660	0.38
2060	0.37

Density 11.1 lb/ft^3

Test Condition: 3° C/min. (5.4 R/min) Heating Rate in Argon

Ref. 1 Ablative Heat Shield Materials ESA-3560, ESA-5500, MTSE E48.4 5-77, Martin Marietta, Denver, CO

Material: ESA-3560 (Tompkins)
Manufacturer: Martin Marietta
Composition: Filled Elastomeric Silicone

Heat of Pyrolysis 0
Specific Heat of Pyrolysis Gasses 0.6 Btu/lb_m R

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k=3.2 \times 10^{11}$ lb_m/ft^3-hr, n=2, $B=3.41 \times 10^4$ R

Virgin Properties

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/ft hr R)
100	0.032	200	0.0343
200	0.100	300	0.04018
300	0.162	400	0.04536
400	0.222	500	0.05616
500	0.280	600	0.05011
600	0.330	700	0.05400
700	0.370	800	0.05616
		900	0.05702

Density 30 lb_m/ft^3
Emissivity

Ref. 1 Ablative Heat Shield Materials ESA-3560, ESA-5500, MTSE E48.4 5-77, Martin Marietta, Denver, CO

Material: ESA-3560 (Tompkins) (Continued)

Char Properties

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/ft hr R)
1400	0.195	1500	0.276
1600	0.225	2500	0.341
1800	0.245		
2000	0.260		
2200	0.270		

Density	22 lb_m/ft^3
Emissivity	0.9

Ref. 1 Ablative Heat Shield Materials ESA-3560, ESA-5500, MTSE E48.4 5-77, Martin Marietta, Denver, CO

Material: ESA-5500
Manufacturer: Martin Marietta
Composition: filled; elastomeric silicone; molded (too gummy to machine)

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = 2.446 \times 10^{13}$ (lb_m/ft^3), $n = 2$, $B = 3.406 \times 10^3$ (R)

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
260	0.180		
310	0.185		
360	0.190		
410	0.200		
460	0.205		
510	0.210		
560	0.220	560	0.1117
610	0.235	610	0.1192
660	0.250	660	0.1250
710	0.270	710	0.1275
760	0.290	760	0.1283
810	0.315	810	0.1267
860	0.335	860	0.1242
910	0.365	910	0.1200
960	0.395	960	0.1158
1010	0.425	1010	0.1108
1060	0.465	1060	0.1067

Density	55.00	lb_m/ft^3
Emissivity	0.85	

(continued)

Ref. 1 Ablative Heat Shield Materials ESA-3560, ESA-5500, MTSE E48.4 5-77, Martin Marietta, Denver, CO

Material: ESA-5500 *(continued)*

Char Properties

Density 31.35 lb_m/ft^3 *

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)	P (Atm)
3800		0.013		600		0.90
7250		0.021		1140		0.87

Ref. 1 Ablative Heat Shield Materials ESA-3560, ESA-5500, MTSE E48.4 5-77, Martin Marietta, Denver, CO

Material: MA-25S (Martin Marietta)
Manufacturer: Martin Marietta
Composition: Filled Elastomeric Silicone

Ablation Temperature	1410 R
Decomposition Endotherm	1320 R
Heat of Deploymerization	75 Btu/lb
Effective Heat of Ablation	7800 Btu/lb for 550 sec @ 8.8 Btu/ft^2 s
	3850 Btu/lb for 550 sec @ 2.1 Btu/ft^2 s

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k=6.378 \times 10^8$ lb/ft^3 hr, n=2, B=24004 R

Virgin Properties

T (R)	Cp (Btu/lb R)	k (Btu/hr ft R)
210	0.17	0.033
260	0.23	0.036
360	0.28	0.043
460	0.30	0.047
560	0.31	0.049
660	0.31	0.051
760	0.31	0.052
860	0.31	0.053
960	0.30	0.054

Density	25 ± 3 lb/ft^3
Emissivity	.80 at 960 R

Ref. 2 Ablative Heat-Shield Materials MA-25S, 48.2 A-GH Martin Marietta Denver, CO.

Material: MA-25S (Continued)

Char Properites

T (R)	Residue Weight Fraction
460	1.0
1060	1.0
1160	0.90
1260	0.97
1360	0.88
1460	0.48
1560	0.38
1660	0.36
1860	0.36

Density 9 lb/ft^3

Test Condition: 6° C/min. (10.8 R/min) Heating Rate in Argon

Ref. 2 Ablative Heat-Shield Materials MA-25S, 48.2 A-GH Martin Marietta Denver, CO.

Material: MA-25S
Manufacturer: Martin Marietta
Composition: elastomeric silicone, filled

Heat of pyrolysis	75	Btu/lb_m
Pyrolysis gas specific heat	0.6	Btu/lb_m-R
Ablating Temperature (Start of Pyrolysis)	1060	R
Charring Temperature (End of Pyrolysis)	1560	R

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = 1.121 \times 10^9$ (lb_m/ft^3), $n = 0$, $B = 2.4004 \times 10^4$ (R)

Virgin Properties

T (R)	C_p (Btu/lb_m R)
0	0.31
5000	0.31

T (R)	k (Btu/ft hr R)
60	0.013
260	0.038
460	0.050
660	0.057
860	0.061
960	0.062
1200	0.062
5000	0.062

Density	43.00 lb_m/ft^3
Emissivity	0.7

Char Properties

T (R)	C_p (Btu/lb_m R)
0	0.31
5000	0.31

T (R)	k (Btu/ft hr R)
0	0.075
460	0.075
3460	0.250
5000	0.250

Density	25.0 lb_m/ft^3
Emissivity	0.9

Ref. 36 Williams, S. D. , Thermophysical Properties used for Ablation Analysis, LEC-13999, AMD-2309-150, 12/11/79

Material:	Foamed Silicone Elastomer
Manufacturer:	Unknown
Composition:	Foamed Silicone Elastomer

Laminar Blowing Factor	0.6
Turbulent Blowing Factor	0.4
Combustion Enthalpy	12,000 Btu/lb
Heat of Vaporization	10,000 Btu/lb
Heat of Decomposition	450 Btu/lb
Specific Heat of Decomposition Gas	0.384

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k=1.3 \times 10^9$ lb/ft^3 hr, n=2.0, B=24,000 R

Virgin Properties

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/ft hr R)
540	0.30	540	0.081
800	0.39	860	0.122
1,000	0.43	1,335	0.158
2,000	0.44	1,710	0.187

Density	35.0 lb/ft^3
Virgin Carbon Weight Fraction	0.35
Emissivity	0.85
Absorptivity	1.0

Char Properties

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/ft hr R)
540	0.20	540	0.079
1,400	0.30	1,335	0.533
2,000	0.44	1,710	0.610
6,000	0.60	2,210	0.720
		6,000	0.720

Density	14.4 lb/ft^3
Char Carbon Weight Fraction	0.71

Ref 6: Jaworski, W.; and Nagler, R. G.: A Parametric Analysis of Venus Entry Heat-Shield Requirements

Material: Dow Corning 325
Manufacturer: Dow Corning
Composition: Silica Silicone

Virgin Properties

T (R)	Cp (Btu/lb R)	T (R)	k (Btu/hr ft R)
537	0.32	560	0.08583
1360	0.33	660	0.08667
		760	0.08750
		860	0.08850
		960	0.09033
		1060	0.09300

Density 54.3 lbs/ft^3
Emissivity 0.90 at 530 R

HEAT ABLATION DATA*

Mean Heating Rate (cold wall) Btu/ft^2-sec	Test Duration Seconds	Mean Total Heat Input (cold wall) Btu/ft^2	Initial Mass Pounds	Mass Loss %	Initial Thickness Inch	Thickness Change (at Center) Inch	Heat of Ablation and Radiation Btu/Pound
55.0 (64.0 max.)	117	7,200	.063	22.3	.250	+ .13	28,700
55.0 (84.5 max.)	307	15,800	.122	21.2	.500	+ .11	35,000
55.0 (83 max.)	799	43,500	.228	24.2	.895	+ .08	50,050
260	154	30,800	.160	32.5	.600	- .30	28,600
340 (high pressure)	51	14,000	.157	48.7	.600	- .40	10,500

* Plasma Enthalpy ≈ 3369 Btu/Pound (after losses)
Plasma Flow Normal to Surface

Ref. 14 Dow Corning Aerospace Materials, Dow Corning 325 Ablative Materials

10

Polybenzimidazoles

Material: DXH-32
Manufacturer: Narmco Division, Whittaker Corp.
Composition: Polybenzimidazole Materials
PBI (I-2801, Unadvanced) 65%,
Silica Microballoons (Eccospheres SI) 20%,
Alumina-Silica Fibers (Kaowool) 15%

T (R)	Cp (Btu/lb_m R)
492	0.145
672	0.256
852	0.305
1032	0.329
1212	0.338
1392	0.342

T (R)	k (Btu/hr ft R)	
	Helium	Argon, Vacuum
582	0.188	0.0982
672	0.177	0.0942
852	0.173	0.0930
1032	0.187	0.101
1212	0.202	0.104
1392	0.216	0.113

Density 31.2 lb/ft^3

Ref. 23 Lagedrost,J. F., et. al.: Thermophysical and Chemical Characterization of Charring Ablative Materials

Material: EXEH-31
Manufacturer: Narmco Division, Whittaker Corp.
Composition: Polybenzimidazole Materials
PBI (I-2801, Unadvanced) 65%,
Alumina-Silica Fibers (Kaowool) 15%
Phenolic Microballoons 20%

T (R)	Cp (Btu/lb_m R)
492	0.101
672	0.325
852	0.342
1032	0.417
1212	0.433
1392	0.463

T (R)	k (Btu/hr ft R)
	Argon
582	0.0491
672	0.0520
852	0.0578
1032	0.0653
1212	0.0688
1392	0.0751

T (R)	Density (lb/ft^3)
527	31.2
672	30.6
852	30.6
1032	30.0
1212	29.3

Ref. 23 Lagedrost,J. F., et. al.: Thermophysical and Chemical Characterization of Charring Ablative Materials

Material: DXH-31
Manufacturer: Narmco Division, Whittaker Corp.
Composition: Polybenzimidazole Materials
PBI (I-2801, Unadvanced) 65%,
Silica Microballoons (Eccospheres SI) 20%,
Alumina-Silica Fibers (Kaowool) 15%

T (R)	Cp (Btu/lb_m R)
492	0.264
672	0.303
852	0.343
1032	0.381
1212	0.419
1392	0.463

T (R)	k (Btu/ft hr R)	
	Argon	Helium
672	0.146	0.0867
852	0.140	0.0815
1032	0.134	0.0792
1212		0.0745
1392		0.0780

T (R)	Density (lb/ft^3)
527	31.2
672	31.2
852	31.2
1032	30.6
1212	30.6

Ref. 23 Lagedrost,J. F., et. al.: Thermophysical and Chemical Characterization of Charring Ablative Materials

Inorganics–Silicone Binders

Material: ESM 1030-1 B
Manufacturer: General Electric
Composition: inorganic fiber; epoxy-silicone; chemically foamed

Heat of pyrolysis	1000.00	Btu/lb_m
Pyrolysis gas specific heat	0.70	Btu/lb_m-R
Ablating Temperature (Start of Pyrolysis)		R
Charring Temperature (End of Pyrolysis)		R

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = 2.352 \times 10^5 (lb_m/ft^3 hr)$, $n = 2$, $B = 2.2496 \times 10^4$ (R)

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
600	0.31	610	0.0396
710	0.36	860	0.0432
1210	0.44	1335	0.0522
2075	0.44	1710	0.0594

Density 16.00 lb_m/ft^3
Emissivity

Char Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
1210	0.44	1335	0.2664
2079	0.44	1710	0.3060
		2210	0.3600

Density 4.80 lb_m/ft^3
Emissivity

Ref. 17 Hiltz, A. A., et al, Selection, Development and Characterization of a Thermal Protection System AIAA Paper 68-304, April 1-3, 1968.

Material: ESM 1004 X (Hiltz data)
Manufacturer: General Electric
Composition: inorganic fiber; phenyl-methyl silicone (silicone elastomer); chemically foamed

Heat of pyrolysis	0.0	Btu/lb_m
Pyrolysis gas specific heat	0.70	Btu/lb_m-R
Ablating Temperature (Start of Pyrolysis)		R
Charring Temperature (End of Pyrolysis)		R

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = 8.8563 \times 10^4 \ (lb_m/ft^3 hr)$, $n = 2$, $B = 2.2496 \times 10^4 \ (R)$

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
600	0.310	610	0.0396
710	0.330	860	0.0612
		1335	0.0792
		1710	0.0936

Density 16.60 lb_m/ft^3
Emissivity

Char Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
1210	0.440	1335	0.2664
2075	0.440	1710	0.306
		2210	0.36

Density 6.70lb_m/ft^3
Emissivity

Ref. 17 Hiltz, A. A., et al, Selection, Development and Characterization of a Thermal Protection System AIAA Paper 68-304, April 1-3, 1968.

Material: ESM 1004 X (Williams data)
Manufacturer: General Electric

Heat of pyrolysis	50	Btu/lb_m
Pyrolysis gas specific heat	0.40	Btu/lb_m-R
Ablating Temperature (Start of Pyrolysis)	1100	R
Charring Temperature (End of Pyrolysis)	1660	R

Arrhenius Equation

.0

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = 2.916 \times 10^8$ (lb_m/ft^3hr), $n = 2$, $B = 2.2599 \times 10^4$ (R)

Virgin Properties

T (R)	C_p (Btu/lb_m R)
250	0.180
500	0.290
600	0.310
700	0.332
800	0.355
900	0.378
1000	0.398
1250	0.400
2000	0.400
2250	0.460
2500	0.550
2750	0.643
3000	0.725
3250	0.850
9000	0.850

T (R)	k (Btu/ft hr R)
250	0.0270
500	0.0378
600	0.0425
700	0.0486
800	0.0558
900	0.0648
1000	0.0720
1250	0.0806
1500	0.0875
1750	0.0954
2000	0.1033

Density	15.00 lb_m/ft^3
Emissivity	0.80

(continued)

Ref. 36 Williams, S. D. , Thermophysical Properties used for Ablation Analysis, LEC-13999, AMD-2309-150, 12/11/79

Char Properties

T (R)	C_p (Btu/lb_m R)
250	0.180
500	0.290
600	0.310
700	0.332
800	0.355
900	0.378
1000	0.398
1250	0.400
2000	0.400
2250	0.460
2500	0.550
2750	0.643
3000	0.725
3250	0.805
9000	0.805

T (R)	k (Btu/ft hr R)
250	0.0878
500	0.123
600	0.138
700	0.158
800	0.181
900	0.211
1000	0.234
1250	0.262
1500	0.284
1750	0.310
2000	0.336
2250	0.365
2500	0.397
2750	0.431
3000	0.467
3250	0.505
9000	0.505

Density	6.00 lb_m/ft^3
Emissivity	0.80

Ref. 36 Williams, S. D. , Thermophysical Properties used for Ablation Analysis, LEC-13999, AMD-2309-150, 12/11/79

Material: ESM 1004 AP
Manufacturer: General Electric
Composition: unsupported; RTV-based silicone; foam

Heat of pyrolysis	50	Btu/lb_m
Pyrolysis gas specific heat	0.384	Btu/lb_m-R
Ablating Temperature (Start of Pyrolysis)	1060	R
Charring Temperature (End of Pyrolysis)	1960	R

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = 1.3997 \times 10^9 (lb_m/ft^3 hr)$, $n = 2$, $B = 2.3905 \times 10^4$ (R)

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
0	0.001	0	0.1224
460	0.235	460	0.0936
760	0.390	760	0.0828
960	0.430	960	0.0792
1460	0.440	1460	0.0792
1960	0.440	1960	0.0936
2460	0.540	2460	0.1116
2960	0.710	2960	0.1332
3460	0.870	3460	0.1584
5000	0.870	5000	0.2664

Density $36.00\ lb_m/ft^3$
Emissivity 0.80

Char Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
0	0.440	0	0.1836
5000	0.440	700	0.2340
		1335	0.2800
		1710	0.3080
		2210	0.3744
		3500	0.5904

Density $14.40\ lb_m/ft^3$
Emissivity 0.80

Ref. 36 Williams, S. D. , Thermophysical Properties used for Ablation Analysis, LEC-13999, AMD-2309-150, 12/11/79

Material: PD 200-16
Manufacturer:
Composition:

Heat of pyrolysis	50	Btu/lb_m
Pyrolysis gas specific heat	0.4	Btu/lb_m-R
Ablating Temperature (Start of Pyrolysis)	1100	R
Charring Temperature (End of Pyrolysis)	1660	R

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = 2.916 \times 10^8 (lb_m/ft^3)$, $n = 2$, $B = 2.2599 \times 10^4$ (R)

Virgin Properties

T (R)	C_p (Btu/lb_m R)
250	0.180
500	0.290
600	0.310
700	0.332
800	0.355
900	0.378
1000	0.398
1250	0.400
2000	0.400
2500	0.550
2750	0.643
3000	0.725
3250	0.850

T (R)	k (Btu/ft hr R)
250	0.0270
500	0.0378
600	0.0425
700	0.0486
800	0.0558
900	0.0648
1000	0.0720
1250	0.0806
1500	0.0875
1750	0.0954

Density	16.00 lb_m/ft^3
Emissivity	0.8

Ref. 36 Williams, S. D., Thermophysical Properties used for Ablation Analysis, LEC-13999, Dec. 1979.

Char Properties

T (R)	C_p (Btu/lb_m R)
250	0.180
500	0.290
600	0.310
700	0.332
800	0.355
900	0.378
1000	0.398
1250	0.400
2000	0.400
2250	0.460
2500	0.550
2750	0.643
3000	0.725
3250	0.805
9000	0.805

T (R)	k (Btu/ft hr R)
250	0.0878
500	0.1230
600	0.1380
700	0.1580
800	0.1810
900	0.2110
1000	0.2340
1250	0.2620
1500	0.2840
1750	0.3100
2000	0.3360
2250	0.3650
2500	0.3970
2750	0.4310
3000	0.4670
3250	0.5050
9000	0.5050

Density	8.0 lb_m/ft^3
Emissivity	0.8

Ref. 36 Williams, S. D., Thermophysical Properties used for Ablation Analysis, LEC-13999, Dec. 1979.

Material: PD 200-28
Manufacturer:
Composition: silicone rubber

Heat of pyrolysis	50	Btu/lb_m
Pyrolysis gas specific heat	0.384	Btu/lb_m-R
Ablating Temperature (Start of Pyrolysis)	1060	R
Charring Temperature (End of Pyrolysis)	1960	R

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = 1.3997 \times 10^9$ (lb_m/ft^3), $n = 2$, $B = 2.3905 \times 10^4$ (R)

Virgin Properties

T (R)	C_p (Btu/lb_m R)
0	0.001
460	0.235
760	0.390
960	0.430
1460	0.440
1960	0.440
2460	0.540
2960	0.710
3460	0.870
5000	0.870

T (R)	k (Btu/ft hr R)
0	0.1224
460	0.0936
760	0.0828
960	0.0792
1460	0.0792
1960	0.0936
2460	0.1116
2960	0.1332
3460	0.1584
5000	0.2664

Density	28.00 lb_m/ft^3
Emissivity	0.80

(continued)

Ref. 36 Williams, S. D. , Thermophysical Properties used for Ablation Analysis, LEC-13999, AMD-2309-150, 12/11/79

Material: PD 200-28 *(continued)*

Char Properties

T (R)	C_p (Btu/lb_m R)
0	0.440
5000	0.440

T (R)	k (Btu/ft hr R)
0	0.1836
700	0.2340
1335	0.2800
1710	0.3080
2210	0.3744
3500	0.5904

Density	11.00 lb_m/ft^3
Emissivity	0.80

Ref. 36 Williams, S. D. , Thermophysical Properties used for Ablation Analysis, LEC-13999, AMD-2309-150, 12/11/79

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Organics–Silicone Binders

Material: S-3
Manufacturer: McDonnell-Douglas
Composition: silicone elastomer; phenolic-fiberglass honeycomb, 3/16 inch cell; flow filled; intumescent: also see DC-325

Heat of pyrolysis	200.0	Btu/lb_m
Heat of gas deposition	100.0	Btu/lb_m
Pyrolysis gas specific heat	0.45	Btu/lb_m-R
Ablating Temperature (Start of Pyrolysis)	920.0	R

Virgin Properties

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
0	0.32	0	0.0792
4000	0.32	4000	0.1710

Density 56.0 lb_m/ft^3

Char Properties (irreducible)

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
0	0.2	0	0.0270
4000	0.2	4000	0.2376

Density 20.0 lb_m/ft^3
Emissivity 0.80

Deposited

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
0	0.3	0	0.068
4000	0.3	4000	0.378

Fraction of gas deposited 0.80
Maximum density 35.0 lb_m/ft^3

(continued)

Ref. 6 P.E. Bauer, 335T Input Constants for S-3 Ablative Material, Oct. 1972

Material: S-3 *(continued)*

Test condition: plasma jet; 0.14 to 0.68 Atm

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ ($lb_m\ in^2/sec$)	q_c ($Btu/ft^2\ sec$)	q_c^* (Btu/lb_m)
2400 to 8100		-1.1×10^{-3}		85	
		-3.0×10^{-4}		150	
		6.0×10^{-4}		235	
		2.2×10^{-3}		410	

Test condition: plasma jet; 1. Atm

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ ($lb_m\ in^2/sec$)	q_c ($Btu/ft^2\ sec$)	q_c^* (Btu/lb_m)
5000 to 19000		0		112	
		2.2×10^{-3}		236	
		2.3×10^{-3}		240	
		3.3×10^{-3}		290	
		3.4×10^{-3}		294	

Test condition: plasma jet; 1.5 Atm

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ ($lb_m\ in^2/sec$)	q_c ($Btu/ft^2\ sec$)	q_c^* (Btu/lb_m)
3000 to 3500		-1.1×10^{-3}		64	
		-7.0×10^{-4}		68	
		-2.0×10^{-4}		73	
		-1.0×10^{-4}		82	
		-3.0×10^{-4}		85	
		-1.0×10^{-4}		87	
		7.9×10^{-3}		345	
		1.3×10^{-2}		590	

Ref. 6 P.E. Bauer, 335T Input Constants for S-3 Ablative Material, Oct. 1972

Material: S-3 *(continued)*

Test condition: plasma jet; 1.22 to 1.63 Atm

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ ($lb_m\ in^2/sec$)	q_c ($Btu/ft^2\ sec$)	q_c^* (Btu/lb_m)
7000 to 20000		-7.00×10^{-4}		53	
		-1.50×10^{-3}		60	
		-1.00×10^{-3}		86	

Ref. 6 P.E. Bauer, 335T Input Constants for S-3 Ablative Material, Oct. 1972

Other

Material: CELCON-ASTROQUARTZ
Manufacturer: Celanese ?
Composition: molded

Virgin Properties

Density 96.72 lb_m/ft^3

Test condition: (not known)

$H-H_w$ (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ ($lb_m\,in^2/sec$)	$\dot{q}$ ($Btu/ft^2\,sec$)	q_c^* (Btu/lb_m)
2000					3150
4000					4600
6000					6000
8000					7400
10000					8900

Ref. 18 Ihnat, M. E., Undocumented Thermophysical Data Compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: RTV-560
(equation matches that for PD 200-28 and ESM 1004 AP, but data is different)
Composition: silicone rubber

Heat of pyrolysis	50	Btu/lb_m
Pyrolysis gas specific heat	0.38	Btu/lb_m-R
Ablating Temperature (Start of Pyrolysis)	1160	R
Charring Temperature (End of Pyrolysis)	1560	R

Arrhenius Equation

$$\frac{\partial \rho}{\partial t} = k \left(\frac{\rho - \rho_c}{\rho_v - \rho_c} \right)^n e^{-B/T}$$

$k = 1.400 \times 10^9 (lb_m/ft^3 hr)$, $n = 2$, $B = 2.3905 \times 10^4$ (R)

Virgin Properties

T (R)	C_p (Btu/lb_m R)
0	0.273
320	0.273
360	0.270
410	0.260
460	0.265
560	0.285
860	0.340
860	0.340
5000	0.340

T (R)	k (Btu/ft hr R)
0	0.2330
260	0.2330
360	0.2500
460	0.2450
660	0.2000
860	0.1630
960	0.1460
5000	0.1460

Density	88.00 lb_m/ft^3
Emissivity	0.80

Char Properties

T (R)	C_p (Btu/lb_m R)
0	0.440
5000	0.440

T (R)	k (Btu/ft hr R)
0	0.1836
700	0.2340
1335	0.2800
1710	0.3080
2210	0.3744
3500	0.5904

Density	39.60 lb_m/ft^3
Emissivity	0.80

Ref. 37 Williams, S. D., Undocumented Analysis Using Stab-II with Arc Jet Test Data, c. 1980.

Material: DELRIN 500
Manufacturer: (not known)
Composition: DELRIN 500; molded

Virgin Properties

T (R)	C_p (Btu/lb_m R)
530	0.290
660	0.290

T (R)	k (Btu/ft hr R)
610	0.190

Density 89.23 lb_m/ft^3

Test condition: (not known)

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
	200				3560*

*identified in source by unit only

Ref. 18 Ihnat, M. E., Undocumented Thermophysical Data Compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: PBN
Manufacturer: Raytheon Co.; Union Carbide
Composition: pyrolytic boron nitride; CVD

Virgin Properties

T (R)	C_p (Btu/lb_m R)
537	0.24
1260	0.37
2060	0.49

T (R)	$k_{parallel}$ (Btu/ft hr R)	$k_{perpendicular}$ (Btu/ft hr R)
460	36.3	
672	36.3	0.98
1260	36.3	1.35
1960	36.3	1.76

Density 93.6 lb_m/ft^3

Test condition: (not known)

H (Btu/lb_m)	H/RT	$\dot{s}$ (in/sec)	$\dot{m}$ (lb_m in^2/sec)	$\dot{q}$ (Btu/ft^2 sec)	q_c^* (Btu/lb_m)
16000					

Ref. 18 Ihnat, M. E., Undocumented Thermophysical Data Compiled for NASA/JSC, AVCO Corp., circa 1969.

Reusable Materials

Carbon-based Materials

Material: carbon cloth
Manufacturer: AVCO and others
Composition: GSCC; Pluton B-1; Pluton H-1

Normally an ablative material, placed in the reusable category since no char data were available.

Density: 87. to 118. lb_m/ft^3

Emissivity: 0.90 to 0.95

T (R)	C_p (Btu/lb_m R)

T (R)	k (Btu/ft hr R)
540	0.0198
585	0.0250
640	0.0289

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: Graphite/Epoxy withTape
Manufacturer:
Composition: epoxy, graphite filled, with tape reinforcement

Density	98.4	lb_m/ft^3
Maximum Temperature	1060	°R

T (R)	C_p (Btu/lb_m R)
160	0.049
360	0.132
560	0.208
760	0.277

T (R)	$k_{parallel}$ (Btu/ft hr R)	$k_{perpendicular}$ (Btu/ft hr R)
170	0.80	0.19
310	1.73	0.31
410	2.29	0.38
560	2.93	0.47
660	3.21	0.52
760	3.42	0.54

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.

Material: Graphite/Epoxy with Fabric
Manufacturer:
Composition: epoxy, graphite filled, with fabric reinforcement

Density	98.4	lb_m/ft^3
Maximum Temperature	1060	°R

T (R)	C_p (Btu/lb_m R)
160	0.049
360	0.132
560	0.208
760	0.277

T (R)	$k_{parallel}$ (Btu/ft hr R)	$k_{perpendicular}$ (Btu/ft hr R)
170	0.48	0.21
310	1.03	0.33
410	1.37	0.40
560	1.76	0.49
660	1.96	0.53
760	2.08	0.57

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.

Material: Graphite/Epoxy with Tape & fabric
Manufacturer:
Composition: epoxy, graphite filled, with tape and fabric reinforcement

Density	98.4	lb_m/ft^3
Maximum Temperature	1060	°R

T (R)	C_p (Btu/lb_m R)
160	0.049
360	0.132
560	0.208
760	0.277

T (R)	$k_{parallel}$ (Btu/ft hr R)	$k_{perpendicular}$ (Btu/ft hr R)
170	0.58	0.15
310	1.19	0.23
410	1.51	0.28
560	1.96	0.36
660	2.14	0.39
760	2.29	1.43

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.

Material: Graphite Polyimide
Manufacturer:
Composition: graphite polyimide sheets

	Density	94.2 lb_m/ft^3	
Maximum	Temperature	1210 R	
	Specific Heat	0.27 Btu/lb_m R	
	Conductivity	0.592 Btu/ft hr R	parallel
		0.392 Btu/ft hr R	normal

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.

Material: Reinforced Carbon-Carbon (RCC)
Manufacturer: Vought Corporation, Systems Division
Composition:

Density 103.4 lb_m/ft^3
Maximum Temperature 2960 °R

T (R)	C_p (Btu/lb_m R)	Emissivity	$k_{parallel}$ (Btu/ft hr R)	$k_{perpendicular}$ (Btu/ft hr R)
260	0.12	0.60	2.33	1.33
460	0.17	0.78	3.96	2.17
660	0.21	0.80	5.25	2.88
860	0.24	0.82	6.22	3.46
960	0.26	0.83	6.63	3.64
1460	0.31	0.87	7.60	4.21
1960	0.34	0.90	8.00	4.42
2460	0.37	0.89	8.13	4.46
2960	0.40	0.83	8.08	4.42
3260	0.41	0.75	8.08	4.42

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.

Material: H205-85
Manufacturer: (not known)
Composition: graphitic carbon molded

Normally an ablative material, placed in the reusable category since no char data were available.

Density 112.94 lb_m/ft^3

T (R)	C_p (Btu/lb_m R)

T (R)	$k_{parallel}$ (Btu/ft hr R)	$k_{perpendicular}$ (Btu/ft hr R)
535	90.	85.
1460	66.	53.
2460	40.	43.
3460	36.	32.

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: P-03
Manufacturer: (not known)
Composition: graphitic carbon

Normally an ablative material, placed in the reusable category since no char data were available.

Density 113.57 lb_m/ft^3

T (R)	C_p (Btu/lb_m R)
535	0.300
1460	0.390
2460	0.400

T (R)	k (Btu/ft hr R)
1460	74.
2460	40.
3460	29.

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: AX5-5Q (POCO)
Manufacturer: (not known)
Composition: graphitic carbon

Normally an ablative material, placed in the reusable category since no char data were available.

Density 112.32 to 114.82 lb_m/ft^3

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
535	0.200	535	65.
1460	0.360	1460	37.
2460	0.450	2460	20.5
3460	0.510	3460	17.3

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

Material: Graphite "G"
Manufacturer: (not known)
Composition: graphitic carbon; extruded

Normally an ablative material, placed in the reusable category since no char data were available.

Density 117.31 lb_m/ft^3

T (R)	C_p (Btu/lb_m R)
535	0.150
1460	0.390
2460	0.480

T (R)	$k_{parallel}$ (Btu/ft hr R)	$k_{perpendicular}$ (Btu/ft hr R)
535	120.	100.
1460	30.	
2460	20.	
3460	13.	

Ref. 18 Ihnat, M. E., undocumented thermophysical data compiled for NASA/JSC, AVCO Corp., circa 1969.

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Silicon-based Material

Material: TG-15000 (3.0 lb_m/ft^3)
Manufacturer: Hitco
Composition: Glass fibers containing a thermosetting silicone resin binder (30% by weight before curing; ~ 5% after curing)

Density	3. lb_m/ft^3
Maximum Temperature	1160 R

T ~ R	C_p ~ Btu/lb
325	0.17
413	0.18
468	0.20
541	0.22
613	0.24
685	0.25
757	0.26
811	0.27

T (R)	k ~ Btu/ft hr R						
	Pressure ~ Atm						
	1.31367546 $x10^{-6}$	1.31367546 $x10^{-4}$	6.56837728 $x10^{-4}$	1.31367546 $x10^{-3}$	6.56837728 $x10^{-3}$	1.31367546 $x10^{-2}$	1.0
260	0.0004	0.0022	0.0043	0.0053	0.0075	0.0082	0.0094
410	0.0007	0.0023	0.0047	0.0063	0.0103	0.0123	0.0143
560	0.0015	0.0029	0.0053	0.0076	0.0137	0.0163	0.0195
710	0.0026	0.0040	0.0068	0.0092	0.0177	0.0204	0.0244
1060	0.0048	0.0065	0.0093	0.0120	0.0209	0.0244	0.0297

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.

Material: TG-15000 (2.0 lb_m/ft^3)
Manufacturer: Hi Temp Insulation, Inc
Composition: Glass fibers containing a thermosetting silicone resin binder (30% by weight before curing; ~ 5% after curing)

Density	2. lb_m/ft^3
Maximum Temperature	1160 R

T ~ R	C_p ~ Btu/lb
325	0.17
413	0.18
468	0.20
541	0.22
613	0.24
685	0.25
757	0.26
811	0.27

T ~ R	k ~ Btu/ft hr R		
	Pressure ~ Atm		
	1.3136746 $x10^{-6}$	6.56899811 $x10^{-4}$	1
260	0.0007	0.0050	0.0093
410	0.0011	0.0059	0.0146
560	0.0015	0.0065	0.0195
710	0.0044	0.0094	0.0255
860	0.0078	0.0128	0.0320

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.

Material: LI-900
Manufacturer: Lockheed Missiles & Space Co.
Composition: silica

Density 9. lb_m/ft^3
Maximum Temperature 2760. R

T ~ (R)	k ~ perpendicular (through the thickness) ~ (Btu/ft hr R)					
	Pressure ~ Atm					
	0	0.0001	0.001	0.01	0.1	1.0
210	0.0050	0.005	0.0075	0.0150	0.0216	0.0233
460	0.0075	0.0075	0.0100	0.0183	0.0250	0.0275
710	0.0092	0.0092	0.0125	0.0225	0.0316	0.0341
960	0.0125	0.0125	0.0167	0.0276	0.0400	0.0433
1210	0.0175	0.0175	0.0216	0.0325	0.0492	0.0534
1460	0.0233	0.0233	0.0275	0.0392	0.0600	0.0658
1710	0.0308	0.0308	0.0350	0.0492	0.0725	0.0782
1960	0.0416	0.0416	0.0459	0.0617	0.0875	0.0942
2210	0.0567	0.0567	0.0610	0.0767	0.1060	0.1130
2460	0.0734	0.0734	0.0782	0.0942	0.1270	0.1360
2760	0.0966	0.0966	0.1020	0.1160	0.1550	0.1670
2960	0.1660	0.1160	0.1230	0.1390	0.1790	0.1940
3260	0.1540	0.1540	0.1620	0.1800	0.2220	0.2420
3460	0.1900	0.1900	0.1960	0.2190	0.2620	0.2900

T ~ (R)	k ~ parallel (in plane) ~ (Btu/ft hr R)				
	Pressure ~ Atm				
	0.0001	0.001	0.01	0.1	1.0
210	0.011	0.013	0.022	0.026	0.030
460	0.015	0.018	0.028	0.033	0.039
710	0.020	0.023	0.033	0.041	0.047
960	0.026	0.030	0.042	0.051	0.057
1210	0.035	0.040	0.051	0.064	0.070
1460	0.049	0.052	0.063	0.081	0.088
1710	0.066	0.071	0.083	0.104	0.111
1960	0.089	0.096	0.109	0.132	0.140
2210	0.119	0.125	0.140	0.167	0.175
2460	0.153	0.162	0.180	0.212	0.221
2760	0.213	0.221	0.240	0.273	0.288

(continued)

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.

T ~R	C_p ~Btu/lb_m R
210	0.070
310	0.105
460	0.150
710	0.210
960	0.252
1210	0.275
1460	0.288
1710	0.296
1960	0.300
2160	0.302
2210	0.303
2460	0.303
3460	0.303

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.

Material: FRCI-12
Manufacturer: Lockheed Missiles & Space Company
Composition: silica fiber (78%), aluminum borosilicate fiber (22%), 320 grit silicon carbide (trace)

Density 12. lb_m/ft^3
Maximum Temperature 3160. R

T ~ (R)	k ~ perpendicular (through the thickness) ~ (Btu/ft hr R)				
	Pressure ~ Atm				
	0.0001	0.001	0.01	0.1	1
290	0.00875	0.0112	0.0175	0.0198	0.0208
535	0.0110	0.0140	0.0238	0.0306	0.0306
960	0.0162	0.0198	0.0325	0.0454	0.0504
1360	0.0244	0.0292	0.0435	0.0646	0.0712
1760	0.0385	0.0417	0.0590	0.0854	0.0981
2160	0.0621	0.0646	0.0798	0.1130	0.1320
2760	0.1020	0.1040	0.1190	0.1630	0.1900

T ~ (R)	k ~ parallel (in plane) ~ (Btu/ft hr R)		
	Pressure (Atm)		
	0.0001	0.01	1.0
290	0.015	0.028	0.032
535	0.020	0.037	0.046
960	0.028	0.050	0.068
1460	0.044	0.066	0.093
1760	0.058	0.078	0.113
2210	0.092	0.106	0.160

T ~R	C_p ~ Btu/lb_m R
210	0.070
310	0.105
460	0.150
710	0.210
960	0.252
1210	0.275
1460	0.288
1710	0.296
1960	0.300
2160	0.302
2210	0.303
2460	0.303
3460	0.303

Ref. 3 Aeroassist Flight Experiment Aerobrake Thermal Design Data Book, JSC-23571, NASA/JSC, Houston, Texas, May, 1989.

Material: FRCI-12 (Lockheed Data)
Manufacturer: Lockheed Missiles & Space Company
Composition: silica fiber (78%), aluminum borosilicate fiber (22%)
320 grit silicon carbide (trace)

Density	12.0	lb_m/ft^3
Maximum Temperature	3160.	R

Ref. 11 Data

T ~ (R)	k ~ perpendicular (through the thickness) ~ (Btu/ft hr R)				
	Pressure ~ Atm				
	0.0001	0.001	0.01	0.1	1
290	0.00833	0.01083	0.01750	0.0200	0.02083
535	0.01083	0.01417	0.02333	0.03083	0.03050
960	0.01667	0.02000	0.03250	0.04583	0.05083
1360	0.02417	0.02917	0.04333	0.06500	0.07167
1760	0.03833	0.04167	0.05917	0.08583	0.09833
2160	0.06250	0.06500	0.08000	0.11333	0.13167

Ref. 27 Data

T ~ (R)	k ~ parallel (in plane) ~ (Btu/ft hr R)		
	Pressure (Atm)		
	0.0001	0.01	1.0
290	0.01500	0.02583	0.03417
535	0.01917	0.03333	0.04250
960	0.02750	0.04750	0.06500
1360	0.03833	0.06250	0.08833
1760	0.06000	0.07833	0.11417
2160	0.08750	0.10500	0.15583

Ref. 3 Aeroassist Flight Experiment Aerobrake Thermal Design Data Book, JSC-23571, NASA/JSC, Houston, Texas, May, 1989.

Ref. 11 FRCI-12 : Fibrous Refractory Composite Insulation Material: Lockheed Missiles & Space Company Data Sheet, January 1987.

Ref. 27 Mc Cormick, M. J.: Undocumented FRCI-12 Thermal Conductivity Test Results, transmitted by R. P. Banas, Lockheed Missiles & Space Company, Sunnyvale, CA, October 10, 1981.

Material: FRCI-12

Ref. 3 Data

T ~R	C_p ~Btu/lb_m R
210	0.070
310	0.105
460	0.150
710	0.210
960	0.252
1210	0.275
1460	0.288
1710	0.296
1960	0.300
2160	0.302
2210	0.303
2460	0.303
3460	0.303

Ref. 3 Aeroassist Flight Experiment Aerobrake Thermal Design Data Book, JSC-23571, NASA/JSC, Houston, Texas, May, 1989.

Ref. 11 FRCI-12 : Fibrous Refractory Composite Insulation Material: Lockheed Missiles & Space Company Data Sheet, January 1987.

Ref. 27 Mc Cormick, M. J.: Undocumented FRCI-12 Thermal Conductivity Test Results, transmitted by R. P. Banas, Lockheed Missiles & Space Company, Sunnyvale, CA, October 10, 1981.

Material: LI-2200
Manufacturer: Lockheed Missiles & Space Co.
Composition: silica

Density 22. lb_m/ft^3
Maximum Temperature 3160. R

T ~ (R)	k ~ perpendicular (through the thickness) ~ (Btu/ft hr R)					
	Pressure ~ Atm					
	0	0.0001	0.001	0.01	0.1	1.0
210	0.014	0.014	0.016	0.026	0.030	0.032
460	0.017	0.017	0.022	0.031	0.038	0.043
710	0.022	0.022	0.026	0.036	0.047	0.054
960	0.024	0.024	0.032	0.040	0.056	0.065
1210	0.029	0.029	0.037	0.045	0.064	0.076
1460	0.034	0.034	0.043	0.052	0.075	0.088
1710	0.041	0.041	0.050	0.060	0.092	0.104
1960	0.050	0.050	0.059	0.071	0.106	0.119
2210	0.060	0.060	0.070	0.084	0.123	0.139
2460	0.070	0.070	0.083	0.100	0.142	0.160
2760	0.085	0.085	0.100	0.120	0.167	0.189
2960	0.096	0.096	0.113	0.135	0.186	0.212
3260	0.116	0.116	0.135	0.164	0.219	0.250
3460	0.131	0.131	0.153	0.189	0.245	0.280

T ~ (R)	k ~ parallel (in plane) ~ (Btu/ft hr R)					
	Pressure ~ Atm					
	0	0.0001	0.001	0.01	0.1	1.0
210	0.028	0.028	0.033	0.038	0.050	0.055
460	0.030	0.030	0.035	0.040	0.054	0.060
710	0.032	0.032	0.037	0.042	0.058	0.065
960	0.040	0.040	0.044	0.052	0.070	0.080
1210	0.045	0.045	0.051	0.058	0.078	0.090
1460	0.052	0.052	0.058	0.067	0.090	0.104
1710	0.058	0.058	0.067	0.077	0.104	0.120
1960	0.067	0.067	0.075	0.088	0.118	0.136
2210	0.075	0.075	0.088	0.098	0.132	0.150
2460	0.086	0.086	0.098	0.113	0.153	0.177
2760	0.100	0.100	0.116	0.133	0.180	0.208
2960	0.112	0.112	0.128	0.147	0.197	0.221
3260	0.130	0.130	0.150	0.173	0.235	0.270
3460	0.146	0.146	0.167	0.193	0.258	0.300

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book., SD73-SH-0226, Vol. 3E, Rockwell Int. January 1981.

T ~R	C_p ~Btu/lb_m R
210	0.070
310	0.105
460	0.150
710	0.210
960	0.252
1210	0.275
1460	0.288
1710	0.296
1960	0.300
2160	0.302
2210	0.303
2460	0.303
3460	0.303

Ref. 3 Aeroassist Flight Experiment Aerobrake Thermal Design Data Book, JSC-23571, NASA/JSC, Houston, Texas, May, 1989.

Ref. 26 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.

Material: LI-2200 (Rockwell Test Data)
Manufacturer: Lockheed Missiles & Space Co.
Composition: silica with a trace of SiC
Guarded Hot Plate Test Data

Density 22. lb_m/ft^3
Maximum Temperature 3160. R

Ref. 19 Data

T ~ (R)	k ~ perpendicular (through the thickness) ~ Btu/ft hr R				
	Pressure (Atm)				
	0.0001	0.001	0.01	0.1	1.0
210	0.01266	0.01481	0.01956	0.02187	0.02337
460	0.01714	0.02171	0.03018	0.03759	0.04089
710	0.02127	0.02620	0.03491	0.04575	0.05395
960	0.02568	0.03062	0.03864	0.05288	0.06696
1210	0.02990	0.03320	0.04250	0.06336	0.07611
1460	0.03448	0.03684	0.04682	0.07161	0.08524
1710	0.03956	0.04207	0.05191	0.07656	0.09434
1960	0.05323	0.05675	0.07287	0.10532	0.11942
2210	0.06911	0.07396	0.09975	0.14032	0.14850

Ref. 19 Data

T ~ (R)	k ~ parallel (in plane) ~ (Btu/ft hr R)				
	Pressure ~ Atm				
	0.0001	0.001	0.01	0.1	1.0
210	0.01926	0.02199	0.02719	0.03029	0.03116
460	0.02329	0.03386	0.04191	0.04943	0.05209
710	0.03099	0.04003	0.04988	0.06114	0.06733
960	0.04041	0.04638	0.05719	0.07127	0.08185
1210	0.04478	0.04987	0.06070	0.07797	0.09098
1460	0.04920	0.05368	0.06470	0.08662	0.10245
1710	0.05390	0.05797	0.06939	0.09813	0.11739
1960	0.06583	0.07050	0.08194	0.11019	0.12983
2210	0.07980	0.08504	0.09491	0.12239	0.14163

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book., SD73-SH-0226, Vol. 3E, Rockwell Int. January 1981.

Ref. 19 Ivy, R. G.; and Striepens, A. H.: Thermal Conductivity of High-Temperature Bulk Insulation for Shuttle TPS Applications, LTR 1848-4438, Laboratory Test Report, Downey, CA, Rockwell International, Feb. 1977.

Ref. 33 Data

T ~R	C_p ~Btu/lb_m R
210	0.070
310	0.105
460	0.150
710	0.210
960	0.252
1210	0.275
1460	0.288
1710	0.296
1960	0.300
2160	0.302
2210	0.303
2460	0.303
3460	0.303

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book., SD73-SH-0226, Vol. 3E, Rockwell Int. January 1981.

Ref. 19 Ivy, R. G.; and Striepens, A. H.: Thermal Conductivity of High-Temperature Bulk Insulation for Shuttle TPS Applications, LTR 1848-4438, Laboratory Test Report, Downey, CA, Rockwell International, Feb. 1977.

Material: Densified LI-900
Manufacturer: Lockheed Missiles & Space Co.
Composition: silica

Density	22.0	lb_m/ft^3
Maximum Temperature	2760	°R
Emissivity:		

T ~ R	k ~ Btu/ft hr R					
	Pressure ~ Atm					
	0	0.000001	0.00001	0.0001	0.001	0.01
360	0.0100	0.0100	0.0165	0.0265	0.0305	0.0335
560	0.0130	0.0130	0.0195	0.0305	0.0375	0.0405
760	0.0170	0.0170	0.0230	0.0355	0.0460	0.0495
960	0.0215	0.0215	0.0270	0.0410	0.0565	0.0600
1160	0.0265	0.0265	0.0315	0.0475	0.0670	0.0720
1360	0.0320	0.0320	0.0370	0.0540	0.0790	0.0850

T ~R	C_p ~Btu/lb_m R
210	0.070
310	0.105
460	0.150
710	0.210
960	0.252
1210	0.275
1460	0.288
1710	0.296
1960	0.300
2160	0.302
2210	0.303
2460	0.303
3460	0.303

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.

Material: AB 312
Manufacturer: Minnesota Mining & Manufacturing Co
Composition: alumina boria silica

Density	61.5	lb_m/ft^3
Maximum Temperature	2760	R

T (R)	k Btu/ft hr R	C_p Btu/lb_m R	ε
530			0.89
660	0.036		
860	0.44	0.202	
960		0.214	
1060	0.053	0.223	
1160		0.230	
1260	0.062	0.236	
1460	0.071	0.244	0.69
1660	0.083	0.251	
1860	0.097	0.256	
1960			0.57
2060	0.114	0.261	
2260	0.135	0.266	
2460	0.158	0.270	0.48
2660		0.275	
2960			0.42

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.

Material: Cerachrome - 8
Manufacturer: Johns-Manville Corp.
Composition: 42.5% Al_2O_3, 55.0% SiO_2, 2.5% Cr_2O_3
Previously known as Dynaflex

Density 8 lb_m/ft^3
Maximum Temperature 3160 R
Emissivity:

T (R)	k ~Btu/ft hr R					
	Pressure ~ Atm					
	0.00001	0.0001	0.001	0.01	0.1	1.0
560	0.00592	0.00683	0.01233	0.02017	0.02217	0.02242
960	0.01608	0.01692	0.02308	0.03650	0.04133	0.04200
1360	0.03950	0.04025	0.04650	0.06392	0.07200	0.07325
1760	0.07342	0.07417	0.08025	0.10067	0.11208	0.11400
2160	0.11167	0.11233	0.11825	0.14083	0.15567	0.15833
2560	0.18042	0.18108	0.18683	0.21083	0.22900	0.23250
2960	0.28058	0.28117	0.28675	0.31192	.033333	0.33775

T (R)	C_p Btu/lb_m R
613	0.20
685	0.22
757	0.22
829	0.23
901	0.23
973	0.24
1045	0.24
1117	0.25
1189	0.25
1261	0.25
1333	0.25
1405	0.26

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.

Material: Cerachrome - 12
Manufacturer: Johns-Manville Corp.
Composition: 42.5% Al_2O_3, 55.0% SiO_2, 2.5% Cr_2O_3
Previously known as Dynaflex

Density	12	lb_m/ft^3
Maximum Temperature	3160	R
Emissivity:		

T (R)	k ~Btu/ft hr R					
	Pressure ~ Atm					
	0.00001	0.0001	0.001	0.01	0.1	1.0
560	0.00667	0.00733	0.01175	0.02042	0.02325	0.02367
960	0.01342	0.01408	0.01875	0.03258	0.03917	0.04017
1360	0.02892	0.02950	0.03417	0.05117	0.06192	0.06375
1760	0.05150	0.05200	0.05642	0.07558	0.09042	0.09325
2160	0.07692	0.07742	0.08175	0.10225	0.12108	0.12500
2560	0.12267	0.12308	0.12725	0.14867	0.17108	0.17625
2960	0.18942	0.18983	0.19375	0.21575	0.24183	0.24825

T (R)	C_p Btu/lb_m R
613	0.20
685	0.22
757	0.22
829	0.23
901	0.23
973	0.24
1045	0.24
1117	0.25
1189	0.25
1261	0.25
1333	0.25
1405	0.26

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Rockwell International, Downey, CA, January 1981.

Material: Cerachrome - 24
Manufacturer: Johns-Manville Corp.
Composition: 42.5% Al_2O_3, 55.0% SiO_2, 2.5% Cr_2O_3
Previously known as Dynaflex

Density	24	lb_m/ft^3
Maximum Temperature	3160	R
Emissivity:		

T (R)	k ~Btu/ft hr R					
	Pressure ~ Atm					
	0.00001	0.0001	0.001	0.01	0.1	1.0
560	0.01092	0.01125	0.01417	0.02367	0.02875	0.02958
960	0.01400	0.01433	0.01725	0.03033	0.04117	0.04333
1360	0.02158	0.02192	0.02467	0.03958	0.05592	0.05923
1760	0.03258	0.03283	0.03550	0.05125	0.07267	0.07850
2160	0.04500	0.04533	0.04783	0.06392	0.08983	0.09783
2560	0.06758	0.06792	0.07025	0.08642	0.11617	0.12650
2960	0.10058	0.10083	0.10308	0.11925	0.15250	0.16525

T (R)	C_p Btu/lb_m R
613	0.20
685	0.22
757	0.22
829	0.23
901	0.23
973	0.24
1045	0.24
1117	0.25
1189	0.25
1261	0.25
1333	0.25
1405	0.26

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Rockwell International, Downey, CA, January 1981.

Material: AFRSI
Manufacturer: Johns-Manville
Composition: Outer sheet: 0.027 inch Quartz fabric, 60 lb_m/ft^3
Insulation: Microquartz (Q-felt)
Inner sheet: 0.011 inch "E" glass fabric, 35 lb_m/ft^3

Density 4 lb_m/ft^3
Maximum Temperature 2260 R

Ref. 33 Data

T (R)	k ~Btu/ft hr R				
	Pressure ~ Atm				
	1.31569 x 10^{-4}	1.31569 x 10^{-3}	1.31569 x 10^{-2}	1.31569 x 10^{-1}	1.0
260	0.0027	0.0042	0.0078	0.0123	0.0140
460	0.0052	0.0079	0.0140	0.0222	0.0248
560	0.0066	0.0099	0.0172	0.0272	0.0305
760	0.0095	0.0139	0.0237	0.0374	0.0417
960	0.0133	0.0185	0.0307	0.0476	0.0534
1160	0.0181	0.0237	0.0381	0.0584	0.0659
1360	0.0242	0.0305	0.0467	0.0699	0.0792
1610	0.0344	0.0419	0.0593	0.0858	0.0962
1760	0.0416	0.0507	0.0689	0.0962	0.1079
1960	0.0533	0.0637	0.0819	0.1105	0.1235

Rockwell Specific Heat
(Fused Silica)

Ref. 33 Data

T (R)	C_p Btu/lb_m R
260	0.095
446	0.150
660	0.175
860	0.195
1060	0.220
1260	0.240
1460	0.260
1660	0.280
1860	0.300
2060	0.315
2460	0.343
2360	0.355
2960	0.360
3460	0.360

AFE Specific Heat

Ref 3 Data

T (R)	C_p Btu/lb_m R
492	0.1167
672	0.2061
852	0.2315
1032	0.2518
1212	0.2696
1392	0.2865
1572	0.2624
1752	0.2714
1932	0.2806
2112	0.2897
2292	0.2989
2472	0.3080
2652	0.3172
2832	0.3264

Ref.3 Aerroassist Flight Experiment Aerobrake Thermal Design Data Book, JSC-23571, NASA/JSC, Houston, TX, May 1989.

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Rockwell International, Downey, CA, January 1981.

Material: AFRSI (Continued)

Ref. 33 Data

T ~ R	ε
530	0.865
660	0.850
860	0.825
1060	0.790
1260	0.725
1460	0.660
1660	0.600
1860	0.555
2060	0.515
2260	0.480

Ref.3 Aerroassist Flight Experiment Aerobrake Thermal Design Data Book, JSC-23571, NASA/JSC, Houston, TX, May 1989.

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Rockwell International, Downey, CA, January 1981.

Material: Min-K — 1301
Manufacturer: Johns-Manville Corp.
Composition:

Density 20 lb_m/ft^3
Maximum Temperature 3160 R
Emissivity:

T (R)	k ~Btu/ft hr R				
	Pressure ~ Atm				
	1.13569 x 10^{-4}	1.13569 x 10^{-3}	1.13569 x 10^{-2}	1.13569 x 10^{-1}	1.0
560	0.00566	0.00666	0.00750	0.01000	0.01750
660	0.00650	0.00750	0.00833	0.01080	0.01830
860	0.00730	0.00833	0.00917	0.01167	0.01917
1060	0.00990	0.01000	0.01083	0.01333	0.02083
1260	0.01100	0.01250	0.01250	0.01583	0.02333
1460	0.01400	0.01500	0.01583	0.01833	0.02583
1660	0.01700	0.01833	0.01917	0.02167	0.02917

T (R)	C_p Btu/ft hr R
460	0.0205
660	0.0205
860	0.225
1060	0.040
1260	0.252
1460	0.261
1660	0.269

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.

Material: HTP-6
Manufacturer: Lockheed Missiles & Space Company
Composition: silica fiber (78%), alumina fiber (22%), 600 grit silicon carbide (trace)
Currently Not Flight Certified

Density	6. lb_m/ft^3
Maximum Temperature	3160 R

Ref. 28 Data

T ~ R	k ~ Btu/ft hr R	
	Pressure ~ Atm	
	0.0001	1
168	0.00669	0.02209
530	0.00729	0.03283
579	0.00883	0.03508
1163	0.02200	0.06183
1460	0.03542	0.08917
1646	0.04842	0.10750
1950	0.07967	0.13817
2254	0.12417	0.19000

C_p continues on next page

Ref. 28 McCormick, M. J.: Undocumented Test Results for HTP-6 & HTP-9 Apparent Thermal Conductivity, transmitted by R. Banas, LMSC, April 1988

Ref. 26 McCormick, M. J.: Characterization of Mechanical and Thermal Properties of HTP-8-22 Material, F381329, LMSC, March 1990.

Material: HTP-6 (continued)

Ref. 26 Data

T ~ R	C_p ~Btu/lbm R
533	0.165
585	0.174
630	0.185
675	0.192
720	0.198
765	0.206
810	0.212
855	0.218
900	0.224
945	0.229
990	0.234
1035	0.237
1080	0.240
1125	0.243
1170	0.245
1215	0.249
1260	0.250
1305	0.253
1350	0.256
1395	0.258
1440	0.260
1485	0.262
1530	0.264
1575	0.266
1620	0.267
1665	0.269
1710	0.271
1755	0.272

Ref. 28 McCormick, M. J.: Undocumented Test Results for HTP-6 & HTP-9 Apparent Thermal Conductivity, transmitted by R. Banas, LMSC, April 1988

Ref. 26 McCormick, M. J.: Characterization of Mechanical and Thermal Properties of HTP-8-22 Material, F381329, LMSC, March 1990.

Material: HTP-9
Manufacturer: Lockheed Missiles & Space Company
Composition: silica fiber (78%), alumina fiber (22%), 600 grit silicon carbide (trace)
Currently Not Flight Certified

Density	9.	lb_m/ft^3
Maximum Temperature	3160	R

Ref. 28 Data

T ~ R	k ~ Btu/ft hr R	
	Pressure ~ Atm	
	0.0001	0.0001
	thru the thickness	in plane
170	0.006893	0.012028
560	0.007743	0.014730
1160	0.019482	0.027893
1460	0.32339	0.044833
1660	0.040987	0.055998

C_p continues on next page

Ref. 28 McCormick, M. J.: Undocumented Test Results for HTP-6 & HTP-9 Apparent Thermal Conductivity, transmitted by R. Banas, LMSC, April 1988

Ref. 26 McCormick, M. J.: Characterization of Mechanical and Thermal Properties of HTP-8-22 Material, F381329, LMSC, March 1990.

Material: HTP-9 (continued)

Ref. 26 Data

T ~ R	C_p ~Btu/lbm R
533	0.165
585	0.174
630	0.185
675	0.192
720	0.198
765	0.206
810	0.212
855	0.218
900	0.224
945	0.229
990	0.234
1035	0.237
1080	0.240
1125	0.243
1170	0.245
1215	0.249
1260	0.250
1305	0.253
1350	0.256
1395	0.258
1440	0.260
1485	0.262
1530	0.264
1575	0.266
1620	0.267
1665	0.269
1710	0.271
1755	0.272

Ref. 28 McCormick, M. J.: Undocumented Test Results for HTP-6 & HTP-9 Apparent Thermal Conductivity, transmitted by R. Banas, LMSC, April 1988

Ref. 26 McCormick, M. J.: Characterization of Mechanical and Thermal Properties of HTP-8-22 Material, F381329, LMSC, March 1990.

Material: HTP-12
Manufacturer: Lockheed Missiles & Space Company
Composition: silica fiber (78%), alumina fiber (22%),
600 grit silicon carbide (trace)
Currently Not Flight Certified

Density 12. lb_m/ft^3
Maximum Temperature 3160 R

Ref. 12 Data

T ~ R	k ~ Btu/ft ht R			
	Pressure ~ Atm			
	0.001	0.01	0.1	1
535	0.01667	0.02667	0.03083	0.03417
960	0.02167	0.03333	0.04333	0.05083
1460	0.03083	0.04750	0.06083	0.06667
1960	0.04583	0.06333	0.08333	0.09167
2460	0.06167	0.08333	0.10833	0.11917
2760	0.07167	0.09167	0.12083	0.13250

C_p continues on next page

Ref. 12 Data Sheet, HTP High Thermal Performance, LMSC, January 1987.
Ref. 26 McCormick, M. J.: Characterization of Mechanical and Thermal Properties of HTP-8-22 Material, F381329, LMSC, March 1990.

Material: HTP-12 (continued)

Ref. 26 Data

T ~ R	C_p ~Btu/lbm R
533	0.165
585	0.174
630	0.185
675	0.192
720	0.198
765	0.206
810	0.212
855	0.218
900	0.224
945	0.229
990	0.234
1035	0.237
1080	0.240
1125	0.243
1170	0.245
1215	0.249
1260	0.250
1305	0.253
1350	0.256
1395	0.258
1440	0.260
1485	0.262
1530	0.264
1575	0.266
1620	0.267
1665	0.269
1710	0.271
1755	0.272

Ref. 12 Data Sheet, HTP High Thermal Performance, LMSC, January 1987.
Ref. 26 McCormick, M. J.: Characterization of Mechanical and Thermal Properties of HTP-8-22 Material, F381329, LMSC, March 1990.

16

Polyamides

Material: Nomex FRSI
Manufacturer: DuPont
Composition: aromatic polyamide felt

Density	5.4	lb_m/ft^3
Maximum Temperature	1210	R long term
	1290	R short term
Emissivity:	0.80	

T (R)	C_p (Btu/lb_m R)
210	0.300
460	0.312
660	0.320
860	0.335
1060	0.345
1260	0.360
1460	0.380

T ~ (R)	k ~ (Btu/ft hr R) Pressure ~ Atm)						
	0	0.00001	0.0001	0.0010	0.0100	0.1000	1.0000
210	0.0065	0.0065	0.0070	0.0080	0.0092	0.0102	0.0110
460	0.0080	0.0080	0.0105	0.0140	0.0171	0.0198	0.0206
560	0.0086	0.0086	0.0120	0.0166	0.0205	0.0238	0.0250
660	0.0095	0.0095	0.0138	0.0194	0.0240	0.0275	0.0290
760	0.0102	0.0102	0.0155	0.0222	0.0275	0.0322	0.0335
860	0.0110	0.0110	0.0170	0.0250	0.0316	0.0370	0.0382
1060	0.0130	0.0130	0.0207	0.0315	0.0407	0.0475	0.0489
1260	0.0150	0.0150	0.0250	0.0380	0.0500	0.0608	0.0620
2460	0.0175	0.0175	0.0300	0.0462	0.0615	0.0775	0.0795

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.

17

Adhesives

Material: RTV-560
Manufacturer:
Composition: Room temperature vulcanizing material, elastomer

Density	88. lb_m/ft^3
Maximum Temperature	1010. R

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
320	0.273	260	0.233
360	0.270	360	0.250
410	0.260	460	0.245
460	0.265	660	0.200
560	0.285	860	0.163
660	0.300	960	0.146
860	0.340		

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, California, January 1981.

18

Coating

Material: RCG Coating
Manufacturer: Lockheed Missiles & Space Co.
Composition: borosilicate glass; reaction-cured

Density 104. lb_m/ft^3
Maximum Temperature 2760 R
Emissivity 0.85 Black coated
$\varepsilon = 0.8436 - 2.4833333 \times 10^{-5}$ T, T in R
(equation from Ref. 8, Bouslog & Cunninton)
$\alpha/\varepsilon = 1$

Emissivity 0.80 White coated
$\alpha/\varepsilon \leq 0.4$

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
210	0.150	210	0.425
310	0.170	310	0.450
460	0.190	460	0.487
710	0.215	710	0.550
960	0.240	960	0.604
1210	0.260	1210	0.654
1460	0.285	1460	0.704
1710	0.300	1710	0.750
1960	0.315	1960	0.796
2160	0.325	2160	0.829
2210	0.330	2210	0.837
2410	0.340	2410	0.871
2460	0.345	2460	0.883
2560	0.350	2560	0.896
2610	0.353	2610	0.904
2760	0.360	2760	0.933
2960	0.375	2960	0.975
3260	0.390	3260	1.080
3460	0.390	3460	1.180

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.
Ref. 8 Bouslog, S. A.; and Cunnington, G. R. Jr.: Emmittance Measurments or RCG Coated Shuttle Tiles, AIAA 92-0851, 30th Aerospace Sciences Meeting & Exhibit, Reno, NV, January 6-9, 1992

Material: DC 92-007 (FRSI Coating)
Manufacturer: Dow Corning
Composition: borosilicate glass; reaction-cured

Density	97.0	lb_m/ft^3
Maximum Temperature	1160	R
Emissivity	0.80	
Specific Heat	0.35	Btu/lb_m R
Conductivity	0.18	Btu/lb hr R

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, CA, January 1981.

19

Metals

Material: Aluminum (2024-T8XX)
Manufacturer: Alcoa, Reynolds
Composition: Aluminum alloy

Density	175.0	lb_m/ft^3
Maximum Temperature	810	R

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
40	0.082		
60	0.088		
160	0.177	160	61.2
260	0.147	260	69.6
460	0.195	460	84.0
660	0.216	660	95.0
760	0.224	760	99.0
860	0.233	860	102.5
1060	0.250	1060	104.5

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, California, January 1981.

Material: Aluminum (2219-T8XX)
Manufacturer: Alcoa, Reynolds
Composition: Aluminum alloy

Density	175.6	lb_m/ft^3
Maximum Temperature	810	R

T (R)	k Btu/ft hr R	T (R)	C_p Btu/lb_m R
40	13.0	535	0.206
110	31.0	660	0.215
160	39.0	760	0.222
260	52.5	860	0.228
360	61.5	960	0.234
460	69.0		
560	74.0		
660	78.0		
760	82.0		
960	87.0		
1060	89.4		
1260	92.0		

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, California, January 1981.

Material: Beryllium
Manufacturer:
Composition:

Density	115	lb_m/ft^3
Maximum Temperature	1460	R

T (R)	k (Btu/ft hr R)	Cp (Btu/lb_m R)
60		0.014
210		0.06
260	65	0.12
360	80	0.28
460	99	0.40
660	98	0.50
860	82	0.56
1060	75	0.61
1260	68	0.65
1660	59	0.70
2060	51	0.75
2460	49	0.81
2860	36	0.86

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, California, January 1981.

Material: Columbium (C-103)
Manufacturer:
Composition:

	Density	175.6	lb_m/ft^3
Maximum	Temperature	2860	R
	Specific Heat	0.82	Btu/lb_m R

T (R)	k (Btu/ft hr R)
260	17.0
532	19.7
852	22.3
1212	25.1
1572	27.7
2292	31.2
2832	33.5
3460	36.0

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, California, January 1981.

Material: Copper
Manufacturer:
Composition:

Density	558	lb_m/ft^3
Maximum Temperature	1060	R

T (R)	K (Btu/ft hr R)	C_p (Btu/lb_m R)
60		0.008
160		0.036
260	244	0.073
460	231	0.092
660	224	0.093
860	222	0.097
1060	218	0.099
1260	215	0.100
1460	210	0.103
1660	209	0.104
1860	200	0.106
2060	196	0.113

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, California, January 1981.

Material: Inconel Alloy 601
Manufacturer: International Nickel Co, Inc
Composition:

Density	503	lb_m/ft^3
Maximum Temperature	1860	R

T (R)	k (Btu/ft hr R)	C_p (Btu/lb_m R)
530	6.5	0.107
660	7.3	0.112
860	8.3	0.119
1060	9.4	0.126
860	10.5	0.133
1460	11.6	0.140
1660	12.8	0.147
1860	13.8	0.155
2060	14.8	0.162
2260	15.8	0.169
2460	16.9	0.176

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, California, January 1981.

Material: Steel Type 321
Manufacturer: Alcoa, Reynolds
Composition: Aluminum alloy

Density	501.1	lb_m/ft^3
Maximum Temperature	1660	R

T (R)	k (But/ft hr R)	T (R)	C_p (Btu/lb_m R)
10	0.2	460	0.130
40	1.4	535	0.135
160	5.1	1260	0.135
360	7.4	1460	0.138
460	8.0	1660	0.140
535	8.5	1860	0.142
660	9.4	2060	0.145
860	10.5	2260	0.147
1060	11.4		
1260	12.3		
1460	13.2		

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, California, January 1981.

Material: Stainless Steel (17-4 PH)
Manufacturer:
Composition:

Density	489	lb_m/ft^3
Maximum Temperature	1360	R

T (R)	k (Btu/ft hr R)	C_p (Btu/lb_m R)
9	0.179	
45	1.44	
180	5.30	
270	6.40	
360	7.30	
460	7.70	0.110
860	9.40	0.110
1720	13.10	0.219
1780	13.40	0.132
2660	17.00	0.176
3060	18.4	

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, California, January 1981.

Material: Titanium (6Al-4V)
Manufacturer: (not known)
Composition: Titanium, aluminum, vandium

Density	277.0	lb_m/ft^3
Maximum Temperature	1260	R

T (R)	C_p (Btu/lb_m R)	T (R)	k (Btu/ft hr R)
60	0.012	60	1.2
260	0.096	260	3.4
460	0.125	460	4.0
660	0.136	660	4.3
860	0.138	860	5.0
1060	0.144	860	6.0
1260	0.153	1260	6.9
1460	0.167	1460	7.9
1660	0.182	1660	8.6
1860	0.205	1860	9.6
2060	0.225	2060	10.4

Ref. 33 Space Shuttle Program Thermodynamic Design Data Book. Penetrations. SD73-SH-0226, Vol. 3E, Book 1, Rockwell International, Downey, California, January 1981.

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S. D. Williams and Donald M. Curry

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13. ABSTRACT *(Maximum 200 words)*

This publication presents a thermophysical property survey on materials that could potentially be used for future spacecraft thermal protection systems (TPS). This includes data that was reported in the 1960's as well as more current information reported through the 1980's. An attempt has been made to cite the manufacturers as well as the data source in the bibliography. This volume represents an attempt to provide in a single source a complete set of thermophysical data on a large variety of materials used in spacecraft TPS analysis.

The property data is divided into two categories: ablative and reusable. The ablative materials have been compiled into twelve categories that are descriptive of the material composition. An attempt has been made to define the Arrhenius equation for each material although this data may not be available for some materials. In a similar manner, char data may not be available for some of the ablative materials. The reusable materials have been divided into three basic categories: thermal protection materials (such as insulators), adhesives, and structural materials.

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