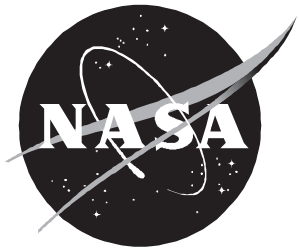

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Thermal Conductivity Database of Various Structural Carbon-Carbon Composite Materials

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Abbreviations

C-C	carbon-carbon composites
CCAT	Carbon-Carbon Advanced Technologies
CVD	chemical vapor deposition
CVI	chemical vapor infiltration
Condit	conditioning
FAW	fabric areal weight
fab	fabrication
HSW	harness satin weave
HT	heat treatment
ip	in-plane
LaRC	Langley Research Center
LoPIC	Low-pressure Pitch Impregnation and Carbonization
Max	maximum
orth	orthogonal
PPC	preceramic polymer coating
t-t-t	through-the-thickness
temp	temperature
3-D	three-dimensional

Abstract

Advanced thermal protection materials envisioned for use on future hypersonic vehicles will likely be subjected to temperatures in excess of 1811 K (2800°F) and, therefore, will require the rapid conduction of heat away from the stagnation regions of wing leading edges, the nose cap area, and from engine inlet and exhaust areas. Carbon-carbon composite materials are candidates for use in advanced thermal protection systems. For design purposes, high temperature thermophysical property data are required, but a search of the literature found little thermal conductivity data for carbon-carbon materials above 1255 K (1800°F). Because a need was recognized for in-plane and through-the-thickness thermal conductivity data for carbon-carbon composite materials over a wide temperature range, Langley Research Center (LaRC) embarked on an effort to compile a consistent set of thermal conductivity values from room temperature to 1922 K (3000°F) for carbon-carbon composite materials on hand at LaRC for which the precursor materials and thermal processing history were known. This report documents the thermal conductivity data generated for these materials. In-plane thermal conductivity values range from 10 to 233 W/m-K, whereas through-the-thickness values range from 2 to 21 W/m-K.

Introduction

Advanced thermal protection systems envisioned for use on future hypersonic vehicles will likely be subjected to temperatures in excess of 1811 K and, therefore, will require the rapid conduction of heat away from the stagnation regions of wing leading edges, the nose cap area, and from engine inlet and exhaust areas. Carbon-carbon (C-C) composite materials are lightweight, retain their strength at high temperatures, and have high and tailorable thermal conductivity. These characteristics make them attractive candidates as advanced thermal system materials.

Carbon-carbon composites comprise a family of materials having a carbon matrix reinforced with carbon fibers. A large variety of both fibers and matrix precursor materials is used. The choice of precursor materials and the thermal processing used to fabricate the composites are major factors which determine the thermophysical properties of the materials. Availability of this information enables the user (designer or researcher) to better utilize the thermophysical property data and allows for more meaningful comparisons between data sets. A search of the literature found little thermal conductivity data for C-C materials above 1255 K. In some instances, thermal conductivity data were reported, but an adequate description of the precursor materials and the thermal processing history was not reported.

Because a need was recognized for in-plane and through-the-thickness thermal conductivity data for C-C composite materials over a wide temperature range, Langley Research Center (LaRC) embarked on an effort to compile a consistent set of thermal conductivity values from room temperature to 1922 K for C-C composite materials on hand at LaRC for which the precursor materials and thermal processing history were known. This report documents the thermal conductivity data generated for these materials.

Experimental Procedures

Table 1 gives a description of the 28 materials for which thermal diffusivity measurements were made and reported in this report. All the materials were derived from previous studies aimed at improving mechanical properties and/or oxidation resistance. Material specimens 1 through 10 and 16 through 18 were fabricated to investigate the effects of different reinforcements and different densification techniques on mechanical properties. Material specimens 11 through 15 were fabricated to explore the benefits of candidate substrate oxidation inhibitors and coating types. Material specimens 19 through 26 were fabricated to investigate the effects of chemical vapor infiltration (CVI) processing parameters on the thermal conductivity and mechanical properties of carbon-carbon composites. Material specimens 27 and 28 were fabricated as candidate materials for a thermal shield on a proposed NASA Solar Probe Spacecraft.

The source of each material is in the second column of table 1. The fiber type and tow size are in the third column. Most of the materials were made with Amoco T-300 fiber. Two materials were made with Amoco T-50 fiber, four were made with Celanese Celion fiber, and two were made with Mitsubishi Kasel DIALEAD K321 fiber. All specimens except the four that were made with Celion fibers were constructed by using an 8 harness satin weave (8HSW) fabric. The number of tows per inch in both the warp and fill direction is given. Material specimens 16, 17, and 18 are stitched panels. A detailed description of their construction is given in reference 1. The weave construction for the materials made with the Celion fiber were 3-D orthogonal. A detailed description of the construction of these four material panels (material

specimens 7 through 10) is given in reference 2. The layup for all materials except those made with the Celion fiber was 0/90°, and most of them were 7- or 8-ply laminates.

All the materials were initially prepared by prepregging the fabric/3-D preforms with a phenolic resin and molding into carbon-phenolic composites. The phenolic resin was then converted into the carbon matrix by inert-environment pyrolysis. A variety of densification methods was used to increase the densities of these composites to desired levels. Phenolic resin was the matrix for about one-third the materials. CVI-deposited pyrolytic carbon was the matrix for another third. Two Rohr, Inc., densification processes, designated by them as "Low-pressure Pitch Impregnation and Carbonization (LoPIC)" and "hybrid," were used on the remaining third of the materials. In the LoPIC process, both phenolic resin and pitch are used as matrix material. The hybrid process is a combination of using CVI and LoPIC processes.

The fiber heat treatment temperature and maximum composite fabrication temperature are also given in the table. For material specimens 1 through 18, the fabric had heat treatment temperatures of 2273 K except the three made by the Boeing Company and Rohr which were heat treated at 2423 K. The maximum composite fabrication temperature was either 1173 K or 1923 K except for specimen 15; this material had been coated at a temperature of about 2033 K. In order to get a more direct comparison of results between the uncoated materials in the original set of 18, the decision was made that the finished composite materials (1–10 and 16–18) should all be conditioned to the same final temperature. The finished composites were heated to the fiber heat treatment temperature of 2273 K. None of the commercial materials (11 through 15) were conditioned, since the thermophysical property data would not be representative of off-the-shelve commercial material. The fiber heat treatment temperature for material specimens 19 through 26 was 2623 K and the CVI densification was done at 1323 K. The fibers in both material specimens 27 and 28 were heat treated to 2273 K. Material 27 had a maximum composite fabrication temperature of 2373 K, whereas material 28 had a maximum composite fabrication temperature of 2973 K.

The tenth column in table 1 indicates whether the material contained inhibitors and/or had been coated. The three Boeing/Rohr materials are the only ones to have inhibitors. The nomenclature of 0.2 FAW designates 20 percent by fabric areal weight. Two of the Boeing/Rohr materials (12 and 13) and material 15 are the only three coated materials. The next to last column lists the direction in which the thermophysical properties were measured. Coated materials were only measured in the through-the-thickness direction for reasons discussed in the next paragraph. The last column gives additional information on the construction of the 3-D and stitched materials.

Material specimens were provided to D. P. H. Hasselman at the Virginia Polytechnic Institute and State University for thermal diffusivity characterization. The thermal diffusivity was measured by the flash diffusivity method, which basically consists of subjecting one side of a sample to a single laser flash and then monitoring the transient temperature response on the other side (refs. 3 and 4). A round specimen, 0.45 inch in diameter, was used for through-the-thickness direction measurements. For in-plane measurements, a square specimen was used. This square specimen was fabricated by cutting rectangular pieces 0.118 inch wide by 0.340 inch high and then stacking sufficient pieces together in the thickness direction to make the stack approximately 0.340 inch thick. In-plane diffusivity measurements were not made on the three coated materials because the stacking of the rectangular pieces required for the in-plane specimen would have left columns of coating within the stacked thickness and thus would have invalidated the measurement. Data were taken in increments of approximately 373 K from room temperature to 1938 K for material specimens 1 through 26 and to 2448 K for material specimens 27 and 28. The data reported by Hasselman to LaRC were temperature and thermal diffusivity.

The thermal conductivity k of a material is related to its thermal diffusivity data by the following equation (ref. 4):

$$k = \rho \alpha c_p$$

where ρ is the density; α, the thermal diffusivity; and c_p, the heat capacity (specific heat). Bulk density measurements at room temperature were obtained from mass and volume measurements. Although the density of carbon-carbon material does change slightly with temperature, this change was neglected because only minimal error is introduced. Carbon-carbon composites made with T-300 fibers have an in-plane coefficient of thermal expansion (CTE) of 0.56×10^{-6}/K and through-the-thickness CTE of 2.04×10^{-6}/K values from 811 K to 1366 K (ref. 5). With the use of these CTE values, the volume of the material would increase a maximum of about 1.5 percent from room temperature to 1922 K. This volume change was considered to be sufficiently small so that density could be taken as a constant for the thermal conductivity calculations reported in this paper.

Experimental values of the specific heat of graphitic materials taken from figure 2B-1 of reference 6 are

plotted in figure 1. These data were curve fitted with the following empirical equation:

$$c_p = -38.0528 + 0.041618T + 741.254/T - 0.707584\sqrt{T} + 19.0915 \log_{10} T \quad \text{J/g-K}$$

where T is temperature in kelvins.

The values of specific heat reported in this report and subsequently used to calculate thermal conductivity were calculated by this equation. This equation cannot be used to calculate the specific heat for coated materials because it does not take into account the coating. Since specific heat was not experimentally measured, there are no heat capacity data for the three coated materials; thus, thermal conductivity values are not reported for those materials.

Results

Figures 2 and 3 summarize the thermal conductivity results. Figure 2 shows the range of in-plane thermal conductivity data for materials evaluated in this report, and figure 3 shows the range of through-the-thickness thermal conductivity data. The temperatures and corresponding thermophysical property data for the individual materials are shown in tables 2 through 29. Thermal diffusivity as a function of temperature is plotted for all materials (figs. 4 through 31). Values are given in both square centimeters per second (cm^2/s) and square feet per hour (ft^2/hr). Temperatures are shown in both kelvin (K) and degrees Fahrenheit (°F). For uncoated materials, both in-plane and through-the-thickness values are plotted. For coated materials, only through-the-thickness values are shown because that was the only direction in which measurements were made. For both in-plane and through-the-thickness directions, thermal diffusivity values are maximum at room temperature and decrease with increasing temperature. Values are fairly flat from 1200 to 1900 K.

Thermal conductivity values for each of the uncoated materials are plotted in figures 32 through 56. Thermal conductivity in units of both watts per meter-kelvin (W/m-K) and British thermal units per hour-feet-degrees Fahrenheit (Btu/hr-ft-°F) are given as a function of temperature in both kelvins and degrees Fahrenheit. For the in-plane direction, maximum thermal conductivity values ranged from 20 to 68 W/m-K for all materials except that of material 28, which had a maximum value of 233 W/m-K. For the through-the-thickness direction, maximum thermal conductivity values ranged from 3 to 12 W/m-K for all materials except that of material 28 which had a maximum value of 21 W/m-K. In general maximum thermal conductvity occurred around 500 K. As with the thermal diffusivity values, thermal conductivity values were fairly flat from 1200 to 1900 K.

Concluding Remarks

Carbon-carbon composite materials are candidates for use in advanced thermal protection systems. Because a need was recognized for in-plane and through-the-thickness thermal conductivity data for carbon-carbon composite materials over a wide temperature range, Langley Research Center (LaRC) embarked on an effort to compile a consistent set of thermal conductivity values from room temperature to 1922 K (3000°F) for carbon-carbon composite materials on hand at LaRC for which the precursor materials and thermal processing history were known. This report documents the thermal conductivity data generated for these materials. In-plane thermal conductivity values range from 10 to 233 W/m-K, whereas through-the-thickness values range from 2 to 21 W/m-K.

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Table 1. Summary of Materials in Database

Material specimen	Material source	Fiber/Tow	Construction tows/in.	Layup, number of plies	Densification type	Fiber HT temp, K	Max fab temp, K	Condit temp, K	Inhibitor/ Coating	Measurements	Comments
1	LaRC panel 7A	T-300/3k	8HSW, 24 × 23	0/90°, 7	Phenolic	2273	1173	2273	No/No	ip/t-t-t	
2	LaRC panel 7B	T-300/3k	8HSW, 24 × 23	0/90°, 7	LoPIC	2273	1923	2273	No/No	ip/t-t-t	
3	LaRC panel 6 thin fabric	T-300/3k	8HSW, 24 × 23	0/90°, 7	Hybrid	2273	1923	2273	No/No	ip/t-t-t	
4	LaRC panel 7C	T-300/3k	8HSW, 24 × 23	0/90°, 7	CVI	2273	1923	2273	No/No	ip/t-t-t	
5	LaRC panel 1P thin fabric	T-50/3k	8HSW, 23 × 23	0/90°, 7	Phenolic	2273	1173	2273	No/No	ip/t-t-t	
6	LaRC 9H thin fabric	T-50/3k	8HSW, 23 × 23	0/90°, 7	Hybrid	2273	1923	2273	No/No	ip/t-t-t	
7	LaRC panel 10-1	Celion/3k	333 3-D orth	5.5 layers	Phenolic	2273	1173	2273	No/No	ip/t-t-t	3k tows/site
8	LaRC panel 10-3	Celion/3k	333 3-D orth	5.5 layers	LoPIC	2273	1923	2273	No/No	ip/t-t-t	3k tows/site
9	LaRC panel 9-1	Celion/3k,2k	333 3-D orth	5.5 layers	Phenolic	2273	1173	2273	No/No	ip/t-t-t	2,1k tows/site
10	LaRC panel 9-3	Celion/3k,2k	333 3-D orth	5.5 layers	LoPIC	2273	1923	2273	No/No	ip/t-t-t	2,1k tows/site
11	Boeing/Rohr	T-300/1k	8HSW, 35 × 35	0/90°	Hybrid	2423	1923	None	0.2FAW/ No	ip/t-t-t	
12	Boeing/Rohr	T-300/1k	8HSW, 35 × 35	0/90°	Hybrid	2423	1923	None	0.2FAW/ CVD	t-t-t	
13	Boeing/Rohr	T-300/1k	8HSW, 35 × 35	0/90°	Hybrid	2423	1923	None	0.2FAW/ PPC	t-t-t	
14	CCAT	T-300/3k	8HSW, 24 × 23	0/90°, 8	Phenolic	2273	1173	None	No/No	ip/t-t-t	

Table 1. Concluded

Material specimen	Material source	Fiber/Tow	Construction tows/in.	Layup, number of plies	Densification type	Fiber HT temp, K	Max fab temp, K	Condit temp, K	Inhibitor/ Coating	Measurements	Comments
15	CCAT	T-300/3k	8HSW, 24 × 23	0/90°, 8	Phenolic	2273	2033	None	No/ Type III	t-t-t	
16	LaRC stitched panel 2	T-300/3k	8HSW, 24 × 23	0/90°, 7	Phenolic	2273	1173	2273	No/No	ip/t-t-t	7/in; 97k/in^2
17	LaRC stitched panel 5	T-300/3k	8HSW, 24 × 23	0/90°, 7	Phenolic	2273	1173	2273	No/No	ip/t-t-t	12/in; 277k/in^2
18	LaRC stitched panel 8	T-300/3k	8HSW, 24 × 23	0/90°, 7	Phenolic	2273	1173	2273	No/No	ip/t-t-t	10/in; 218k/in^2
19	LaRC J1	T-300/3k	8HSW, 24 × 23	0/90°, 7	CVI	2623	1323	None	No/No	ip/t-t-t	
20	LaRC J2	T-300/3k	8HSW, 24 × 23	0/90°, 7	CVI	2623	1323	None	No/No	ip/t-t-t	
21	LaRC J3	T-300/3k	8HSW, 24 × 23	0/90°, 7	CVI	2623	1323	None	No/No	ip/t-t-t	
22	LaRC J4	T-300/3k	8HSW, 24 × 23	0/90°, 7	CVI	2623	1323	None	No/No	ip/t-t-t	
23	LaRC J5	T-300/3k	8HSW, 24 × 23	0/90°, 7	CVI	2623	1323	None	No/No	ip/t-t-t	
24	LaRC J6	T-300/3k	8HSW, 24 × 23	0/90°, 7	CVI	2623	1323	None	No/No	ip/t-t-t	
25	LaRC J7	T-300/3k	8HSW, 24 × 23	0/90°, 7	CVI	2623	1323	None	No/No	ip/t-t-t	
26	LaRC J8	T-300/3k	8HSW, 24 × 23	0/90°, 7	CVI	2623	1323	None	No/No	ip/t-t-t	
27	LaRC F1	K321/2k	8HSW, 18 × 18	0/90°, 8	Phenolic	2273	2373	None	No/No	ip/t-t-t	
28	LaRC P1	K321/2k	8HSW, 18 × 18	0/90°, 8	[1]AR	2273	2973	None	No/No	ip/t-t-t	

[1]Mitsubishi Gas Chemical mesophase pitch (AR).

Table 2. Thermophysical Property Data of LaRC Panel 7A, Which Is T-300 3k Phenolic Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
1	In-plane	23	296	73.4	0.69	1.547	0.231	0.8953	24.667	14.253
		124	397	255.2	0.983	1.547	0.178	0.6899	27.065	15.638
		207	480	404.6	1.176	1.547	0.162	0.6279	29.464	17.024
		304	577	579.2	1.351	1.547	0.151	0.5852	31.57	18.241
		416	689	780.8	1.503	1.547	0.143	0.5542	33.253	19.213
		509	782	948.2	1.598	1.547	0.13	0.5038	32.142	18.571
		608	881	1126.4	1.677	1.547	0.122	0.4728	31.648	18.286
		714	987	1317.2	1.742	1.547	0.114	0.4418	30.723	17.752
		816	1089	1500.8	1.791	1.547	0.111	0.4302	30.758	17.772
		912	1185	1673.6	1.829	1.547	0.109	0.4225	30.835	17.816
		1022	1295	1871.6	1.864	1.547	0.112	0.4341	32.293	18.659
		1239	1512	2262.2	1.918	1.547	0.105	0.407	31.163	18.006
		1455	1728	2651	1.964	1.547	0.103	0.3992	31.288	18.078
		1657	1930	3014.6	2.004	1.547	0.0985	0.3818	30.542	17.647
1	t-t-t or normal	23	296	73.4	0.69	1.547	0.0449	0.174	4.795	2.77
		124	397	255.2	0.983	1.547	0.0368	0.1426	5.595	3.233
		206	479	402.8	1.174	1.547	0.0336	0.1302	6.1	3.525
		304	577	579.2	1.351	1.547	0.0285	0.1105	5.959	3.443
		402	675	755.6	1.487	1.547	0.0263	0.1019	6.049	3.495
		499	772	930.2	1.589	1.547	0.0268	0.1039	6.588	3.807
		596	869	1104.8	1.668	1.547	0.0259	0.1004	6.685	3.862
		706	979	1302.8	1.738	1.547	0.0238	0.0922	6.398	3.697
		804	1077	1479.2	1.786	1.547	0.0239	0.0926	6.603	3.815
		915	1188	1679	1.83	1.547	0.0246	0.0953	6.963	4.023
		1004	1277	1839.2	1.859	1.547	0.0231	0.0895	6.642	3.837
		1241	1514	2265.8	1.919	1.547	0.0227	0.088	6.739	3.894
		1463	1736	2665.4	1.965	1.547	0.0227	0.088	6.901	3.988
		1664	1937	3027.2	2.006	1.547	0.0226	0.0876	7.013	4.052

Table 3. Thermophysical Property Data of LaRC Panel 7B, Which Is T-300 3k LOPIC Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
2	In-plane	23	296	73.4	0.69	1.634	0.227	0.8798	25.603	14.793
		124	397	255.2	0.983	1.634	0.19	0.7364	30.514	17.631
		207	480	404.6	1.176	1.634	0.17	0.6589	32.658	18.87
		304	577	579.2	1.351	1.634	0.151	0.5852	33.345	19.267
		400	673	752	1.484	1.634	0.141	0.5465	34.196	19.758
		515	788	959	1.604	1.634	0.13	0.5038	34.063	19.682
		615	888	1139	1.682	1.634	0.121	0.469	33.25	19.212
		707	980	1304.6	1.738	1.634	0.113	0.438	32.095	18.545
		808	1081	1486.4	1.788	1.634	0.111	0.4302	32.425	18.735
		917	1190	1682.6	1.83	1.634	0.111	0.4302	33.198	19.182
		1019	1292	1866.2	1.863	1.634	0.112	0.4341	34.094	19.699
		1247	1520	2276.6	1.92	1.634	0.109	0.4225	34.201	19.761
		1463	1736	2665.4	1.965	1.634	0.107	0.4147	34.359	19.853
		1665	1938	3029	2.006	1.634	0.105	0.407	34.417	19.886
2	t-t-t or normal	23	296	73.4	0.69	1.634	0.0473	0.1833	5.335	3.083
		124	397	255.2	0.983	1.634	0.0357	0.1384	5.733	3.313
		207	480	404.6	1.176	1.634	0.0321	0.1244	6.167	3.563
		304	577	579.2	1.351	1.634	0.0306	0.1186	6.757	3.904
		402	675	755.6	1.487	1.634	0.0266	0.1031	6.462	3.734
		521	794	969.8	1.609	1.634	0.0248	0.0961	6.52	3.767
		616	889	1140.8	1.682	1.634	0.0229	0.0888	6.295	3.637
		709	982	1308.2	1.739	1.634	0.0215	0.0833	6.111	3.531
		818	1091	1504.4	1.792	1.634	0.0227	0.088	6.647	3.841
		910	1183	1670	1.828	1.634	0.0221	0.0857	6.601	3.814
		1013	1286	1855.4	1.861	1.634	0.0226	0.0876	6.873	3.971
		1242	1515	2267.6	1.919	1.634	0.0226	0.0876	7.087	4.095
		1439	1712	2622.2	1.96	1.634	0.0221	0.0857	7.079	4.09
		1673	1946	3043.4	2.008	1.634	0.0227	0.088	7.447	4.303

Table 4. Thermophysical Property Data of LaRC Panel 6, Which Is T-300 3k Hybrid Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
3	In-plane	23	296	73.4	0.69	1.575	0.209	0.81	22.722	13.129
		124	397	255.2	0.983	1.575	0.174	0.6744	26.936	15.563
		207	480	404.6	1.176	1.575	0.166	0.6434	30.738	17.76
		304	577	579.2	1.351	1.575	0.145	0.562	30.864	17.833
		455	728	851	1.546	1.575	0.121	0.469	29.461	17.023
		512	785	953.6	1.601	1.575	0.115	0.4457	28.996	16.754
		622	895	1151.6	1.686	1.575	0.108	0.4186	28.687	16.575
		720	993	1328	1.745	1.575	0.102	0.3953	28.038	16.2
		801	1074	1473.8	1.785	1.575	0.101	0.3915	28.39	16.404
		915	1188	1679	1.83	1.575	0.101	0.3915	29.105	16.817
		1011	1284	1851.8	1.861	1.575	0.0996	0.386	29.187	16.864
		1234	1507	2253.2	1.917	1.575	0.0961	0.3725	29.021	16.768
		1456	1729	2652.8	1.964	1.575	0.0931	0.3608	28.796	16.638
		1664	1937	3027.2	2.006	1.575	0.0939	0.3639	29.664	17.14
3	t-t-t or normal	23	296	73.4	0.69	1.575	0.0509	0.1973	5.534	3.197
		124	397	255.2	0.983	1.575	0.0455	0.1763	7.043	4.07
		207	480	404.6	1.176	1.575	0.0381	0.1477	7.055	4.076
		304	577	579.2	1.351	1.575	0.0348	0.1349	7.407	4.28
		402	675	755.6	1.487	1.575	0.0304	0.1178	7.118	4.113
		508	781	946.4	1.597	1.575	0.0271	0.105	6.818	3.939
		609	882	1128.2	1.678	1.575	0.0252	0.0977	6.658	3.847
		718	991	1324.4	1.744	1.575	0.0237	0.0919	6.511	3.762
		820	1093	1508	1.793	1.575	0.0251	0.0973	7.088	4.095
		912	1185	1673.6	1.829	1.575	0.0243	0.0942	6.999	4.044
		1007	1280	1844.6	1.859	1.575	0.0239	0.0926	6.999	4.044
		1243	1516	2269.4	1.919	1.575	0.0232	0.0899	7.013	4.052
		1447	1720	2636.6	1.962	1.575	0.0231	0.0895	7.138	4.124
		1664	1937	3027.2	2.006	1.575	0.0231	0.0895	7.298	4.217

Table 5. Thermophysical Property Data of LaRC Panel 7C, Which Is T-300 3k CVI Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
4	In-plane	23	296	73.4	0.69	1.534	0.218	0.8449	23.083	13.337
		124	397	255.2	0.983	1.534	0.186	0.7209	28.044	16.204
		207	480	404.6	1.176	1.534	0.169	0.655	30.479	17.611
		304	577	579.2	1.351	1.534	0.154	0.5969	31.926	18.447
		419	692	786.2	1.507	1.534	0.131	0.5077	30.276	17.493
		522	795	971.6	1.61	1.534	0.122	0.4728	30.126	17.407
		620	893	1148	1.685	1.534	0.119	0.4612	30.761	17.774
		726	999	1338.8	1.748	1.534	0.116	0.4496	31.113	17.977
		817	1090	1502.6	1.792	1.534	0.111	0.4302	30.507	17.627
		916	1189	1680.8	1.83	1.534	0.108	0.4186	30.318	17.518
		1021	1294	1869.8	1.864	1.534	0.107	0.4147	30.588	17.674
		1241	1514	2265.8	1.919	1.534	0.0945	0.3663	27.817	16.073
		1457	1730	2654.6	1.964	1.534	0.0926	0.3589	27.898	16.12
		1681	1954	3057.8	2.009	1.534	0.0931	0.3608	28.696	16.581
4	t-t-t or normal	23	296	73.4	0.69	1.534	0.051	0.1977	5.4	3.12
		207	480	404.6	1.176	1.534	0.042	0.1628	7.575	4.377
		304	577	579.2	1.351	1.534	0.0376	0.1457	7.795	4.504
		403	676	757.4	1.488	1.534	0.0344	0.1333	7.851	4.536
		534	807	993.2	1.62	1.534	0.0308	0.1194	7.654	4.423
		624	897	1155.2	1.688	1.534	0.0284	0.1101	7.353	4.249
		708	981	1306.4	1.739	1.534	0.0265	0.1027	7.068	4.084
		814	1087	1497.2	1.79	1.534	0.0254	0.0984	6.976	4.031
		922	1195	1691.6	1.832	1.534	0.025	0.0969	7.026	4.06
		1021	1294	1869.8	1.864	1.534	0.0241	0.0934	6.889	3.981
		1254	1527	2289.2	1.922	1.534	0.0244	0.0946	7.193	4.156
		1467	1740	2672.6	1.966	1.534	0.0231	0.0895	6.967	4.025
		1618	1891	2944.4	1.996	1.534	0.0229	0.0888	7.013	4.052

Table 6. Thermophysical Property Data of LaRC Panel 1P, Which Is T-50 3k Phenolic Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
5	In-plane	23	296	73.4	0.69	1.586	0.305	1.1821	33.39	19.293
		124	397	255.2	0.983	1.586	0.245	0.9496	38.191	22.067
		207	480	404.6	1.176	1.586	0.232	0.8992	43.259	24.995
		304	577	579.2	1.351	1.586	0.2	0.7752	42.868	24.769
		452	725	845.6	1.543	1.586	0.169	0.655	41.352	23.893
		512	785	953.6	1.601	1.586	0.157	0.6085	39.863	23.033
		614	887	1137.2	1.681	1.586	0.145	0.562	38.659	22.337
		718	991	1324.4	1.744	1.586	0.141	0.5465	39.005	22.537
		818	1091	1504.4	1.792	1.586	0.135	0.5232	38.37	22.17
		914	1187	1677.2	1.829	1.586	0.128	0.4961	37.137	21.457
		1014	1287	1857.2	1.861	1.586	0.124	0.4806	36.609	21.153
		1251	1524	2283.8	1.921	1.586	0.121	0.469	36.868	21.302
		1482	1755	2699.6	1.969	1.586	0.119	0.4612	37.162	21.472
		1665	1938	3029	2.006	1.586	0.121	0.469	38.496	22.243
5	t-t-t or normal	23	296	73.4	0.69	1.586	0.0412	0.1597	4.51	2.606
		124	397	255.2	0.983	1.586	0.035	0.1357	5.456	3.152
		207	480	404.6	1.176	1.586	0.0319	0.1236	5.948	3.437
		304	577	579.2	1.351	1.586	0.0288	0.1116	6.173	3.567
		402	675	755.6	1.487	1.586	0.0257	0.0996	6.06	3.501
		528	801	982.4	1.615	1.586	0.0228	0.0884	5.84	3.374
		614	887	1137.2	1.681	1.586	0.0217	0.0841	5.785	3.343
		715	988	1319	1.743	1.586	0.0214	0.0829	5.914	3.417
		821	1094	1509.8	1.793	1.586	0.0213	0.0826	6.058	3.5
		908	1181	1666.4	1.827	1.586	0.0209	0.081	6.057	3.5
		1015	1288	1859	1.862	1.586	0.0207	0.0802	6.112	3.532
		1254	1527	2289.2	1.922	1.586	0.0203	0.0787	6.187	3.575
		1478	1751	2692.4	1.968	1.586	0.0207	0.0802	6.462	3.734
		1697	1970	3086.6	2.013	1.586	0.0215	0.0833	6.863	3.965

Table 7. Thermophysical Property Data of LaRC Panel 9H, Which Is T-50 3k Hybrid Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
6	In-plane	19	292	66.2	0.678	1.566	0.274	1.062	29.077	16.8
		127	400	260.6	0.991	1.566	0.225	0.872	34.904	20.167
		207	480	404.6	1.176	1.566	0.194	0.7519	35.717	20.637
		304	577	579.2	1.351	1.566	0.17	0.6589	35.979	20.788
		403	676	757.4	1.488	1.566	0.155	0.6007	36.115	20.867
		534	807	993.2	1.62	1.566	0.141	0.5465	35.771	20.668
		609	882	1128.2	1.678	1.566	0.131	0.5077	34.415	19.885
		724	997	1335.2	1.747	1.566	0.127	0.4922	34.753	20.08
		814	1087	1497.2	1.79	1.566	0.125	0.4845	35.046	20.25
		920	1193	1688	1.831	1.566	0.124	0.4806	35.563	20.548
		1026	1299	1878.8	1.865	1.566	0.121	0.469	35.339	20.419
		1237	1510	2258.6	1.918	1.566	0.119	0.4612	35.744	20.653
		1453	1726	2647.4	1.963	1.566	0.113	0.438	34.741	20.073
		1664	1937	3027.2	2.006	1.566	0.113	0.438	35.494	20.508
6	t-t-t or normal	19	292	66.2	0.678	1.566	0.0466	0.1806	4.945	2.857
		124	397	255.2	0.983	1.566	0.0443	0.1717	6.819	3.94
		204	477	399.2	1.169	1.566	0.0401	0.1554	7.344	4.243
		305	578	581	1.353	1.566	0.0374	0.145	7.925	4.579
		403	676	757.4	1.488	1.566	0.0331	0.1283	7.712	4.456
		518	791	964.4	1.606	1.566	0.0265	0.1027	6.666	3.851
		634	907	1173.2	1.694	1.566	0.025	0.0969	6.634	3.833
		729	1002	1344.2	1.75	1.566	0.0244	0.0946	6.687	3.864
		823	1096	1513.4	1.794	1.566	0.0243	0.0942	6.828	3.945
		906	1179	1662.8	1.826	1.566	0.0244	0.0946	6.979	4.032
		1008	1281	1846.4	1.86	1.566	0.0247	0.0957	7.193	4.156
		1252	1525	2285.6	1.921	1.566	0.0252	0.0977	7.582	4.381
		1459	1732	2658.2	1.964	1.566	0.0255	0.0988	7.844	4.533
		1673	1946	3043.4	2.008	1.566	0.0254	0.0984	7.986	4.614

Table 8. Thermophysical Property Data of LaRC Panel 10-1, Which Is Celion 3k Phenolic Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
7	In-plane	19	292	66.2	0.678	1.493	0.161	0.624	16.289	9.412
		127	400	260.6	0.991	1.493	0.13	0.5038	19.227	11.109
		205	478	401	1.172	1.493	0.12	0.4651	20.989	12.127
		304	577	579.2	1.351	1.493	0.105	0.407	21.186	12.241
		403	676	757.4	1.488	1.493	0.0972	0.3767	21.592	12.476
		532	805	989.6	1.618	1.493	0.088	0.3411	21.262	12.285
		617	890	1142.6	1.683	1.493	0.0808	0.3132	20.304	11.732
		720	993	1328	1.745	1.493	0.0765	0.2965	19.934	11.518
		822	1095	1511.6	1.794	1.493	0.0751	0.2911	20.113	11.621
		912	1185	1673.6	1.829	1.493	0.072	0.2791	19.657	11.358
		1029	1302	1884.2	1.866	1.493	0.0719	0.2787	20.029	11.573
		1230	1503	2246	1.916	1.493	0.0735	0.2849	21.031	12.151
		1458	1731	2656.4	1.964	1.493	0.0797	0.3089	23.373	13.505
		1673	1946	3043.4	2.008	1.493	0.0806	0.3124	24.159	13.959
7	t-t-t or normal	21	294	69.8	0.684	1.493	0.0594	0.2302	6.066	3.505
		124	397	255.2	0.983	1.493	0.0542	0.2101	7.953	4.596
		204	477	399.2	1.169	1.493	0.0503	0.195	8.782	5.074
		306	579	582.8	1.355	1.493	0.0429	0.1663	8.676	5.013
		411	684	771.8	1.497	1.493	0.0373	0.1446	8.338	4.818
		504	777	939.2	1.594	1.493	0.0352	0.1364	8.375	4.839
		609	882	1128.2	1.678	1.493	0.0324	0.1256	8.115	4.689
		709	982	1308.2	1.739	1.493	0.0316	0.1225	8.206	4.741
		808	1081	1486.4	1.788	1.493	0.0313	0.1213	8.354	4.827
		916	1189	1680.8	1.83	1.493	0.0315	0.1221	8.606	4.973
		1018	1291	1864.4	1.863	1.493	0.0316	0.1225	8.788	5.078
		1240	1513	2264	1.919	1.493	0.0315	0.1221	9.024	5.214
		1465	1738	2669	1.966	1.493	0.0319	0.1236	9.362	5.409
		1697	1970	3086.6	2.013	1.493	0.0327	0.1267	9.826	5.677

Table 9. Thermophysical Property Data of LaRC Panel 10-3, Which Is Celion 3k LoPIC Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
8	In-plane	19	292	66.2	0.678	1.609	0.162	0.6279	17.663	10.206
		127	400	260.6	0.991	1.609	0.139	0.5387	22.155	12.801
		207	480	404.6	1.176	1.609	0.129	0.5	24.402	14.1
		304	577	579.2	1.351	1.609	0.115	0.4457	25.007	14.449
		403	676	757.4	1.488	1.609	0.109	0.4225	26.094	15.077
		527	800	980.6	1.614	1.609	0.0963	0.3732	25.009	14.45
		612	885	1133.6	1.68	1.609	0.0897	0.3477	24.242	14.007
		719	992	1326.2	1.745	1.609	0.0859	0.3329	24.115	13.934
		819	1092	1506.2	1.793	1.609	0.0813	0.3151	23.448	13.548
		913	1186	1675.4	1.829	1.609	0.0799	0.3097	23.513	13.586
		1020	1293	1868	1.863	1.609	0.0793	0.3073	23.774	13.737
		1232	1505	2249.6	1.917	1.609	0.0789	0.3058	24.335	14.061
		1467	1740	2672.6	1.966	1.609	0.0774	0.3	24.484	14.147
		1664	1937	3027.2	2.006	1.609	0.0776	0.3008	25.044	14.47
8	t-t-t or normal	21	294	69.8	0.684	1.609	0.0706	0.2736	7.769	4.489
		124	397	255.2	0.983	1.609	0.0609	0.236	9.631	5.565
		204	477	399.2	1.169	1.609	0.0551	0.2136	10.368	5.99
		304	577	579.2	1.351	1.609	0.0496	0.1922	10.786	6.232
		449	722	840.2	1.54	1.609	0.0411	0.1593	10.182	5.883
		524	797	975.2	1.611	1.609	0.039	0.1512	10.112	5.843
		614	887	1137.2	1.681	1.609	0.036	0.1395	9.737	5.626
		725	998	1337	1.748	1.609	0.0338	0.131	9.506	5.493
		806	1079	1482.8	1.787	1.609	0.0329	0.1275	9.459	5.465
		920	1193	1688	1.831	1.609	0.0327	0.1267	9.636	5.568
		1008	1281	1846.4	1.86	1.609	0.0326	0.1263	9.755	5.636
		1252	1525	2285.6	1.921	1.609	0.0323	0.1252	9.985	5.77
		1456	1729	2652.8	1.964	1.609	0.0326	0.1263	10.301	5.952
		1676	1949	3048.8	2.008	1.609	0.0342	0.1326	11.051	6.385

Table 10. Thermophysical Property Data of LaRC Panel 9-1, Which Is Celion 3k/2k Phenolic Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
9	In-plane	19	292	66.2	0.678	1.519	0.158	0.6124	16.264	9.397
		127	400	260.6	0.991	1.519	0.136	0.5271	20.464	11.824
		207	480	404.6	1.176	1.519	0.129	0.5	23.037	13.311
		304	577	579.2	1.351	1.519	0.118	0.4573	24.224	13.997
		403	676	757.4	1.488	1.519	0.112	0.4341	25.312	14.626
		506	779	942.8	1.596	1.519	0.0995	0.3856	24.114	13.933
		622	895	1151.6	1.686	1.519	0.0952	0.369	24.388	14.091
		727	1000	1340.6	1.749	1.519	0.0922	0.3573	24.495	14.153
		816	1089	1500.8	1.791	1.519	0.0888	0.3442	24.161	13.96
		916	1189	1680.8	1.83	1.519	0.0842	0.3263	23.406	13.524
		1017	1290	1862.6	1.862	1.519	0.0831	0.3221	23.509	13.583
		1237	1510	2258.6	1.918	1.519	0.081	0.3139	23.599	13.636
		1459	1732	2658.2	1.964	1.519	0.0809	0.3135	24.14	13.948
		1674	1947	3045.2	2.008	1.519	0.0803	0.3112	24.491	14.151
9	t-t-t or normal	21	294	69.8	0.684	1.519	0.0583	0.226	6.057	3.5
		124	397	255.2	0.983	1.519	0.0493	0.1911	7.36	4.253
		204	477	399.2	1.169	1.519	0.0433	0.1678	7.692	4.444
		305	578	581	1.353	1.519	0.0359	0.1391	7.378	4.263
		417	690	782.6	1.504	1.519	0.0311	0.1205	7.106	4.106
		536	809	996.8	1.622	1.519	0.0293	0.1136	7.218	4.17
		610	883	1130	1.678	1.519	0.0286	0.1108	7.291	4.213
		721	994	1329.8	1.746	1.519	0.0285	0.1105	7.558	4.367
		823	1096	1513.4	1.794	1.519	0.0288	0.1116	7.849	4.535
		919	1192	1686.2	1.831	1.519	0.0288	0.1116	8.01	4.628
		1004	1277	1839.2	1.859	1.519	0.0285	0.1105	8.046	4.649
		1229	1502	2244.2	1.916	1.519	0.0281	0.1089	8.179	4.726
		1466	1739	2670.8	1.966	1.519	0.0276	0.107	8.242	4.762
		1694	1967	3081.2	2.012	1.519	0.0276	0.107	8.435	4.874

Table 11. Thermophysical Property Data of LaRC Panel 9-3, Which Is Celion 3k/2k LoPIC Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
10	In-plane	19	292	66.2	0.678	1.636	0.184	0.7131	20.399	11.786
		127	400	260.6	0.991	1.636	0.167	0.6473	27.064	15.638
		205	478	401	1.172	1.636	0.151	0.5852	28.941	16.722
		304	577	579.2	1.351	1.636	0.136	0.5271	30.07	17.374
		404	677	759.2	1.489	1.636	0.128	0.4961	31.182	18.017
		516	789	960.8	1.604	1.636	0.107	0.4147	28.086	16.228
		625	898	1157	1.689	1.636	0.102	0.3953	28.176	16.28
		724	997	1335.2	1.747	1.636	0.0979	0.3794	27.987	16.171
		823	1096	1513.4	1.794	1.636	0.0954	0.3697	28.003	16.18
		910	1183	1670	1.828	1.636	0.0931	0.3608	27.841	16.087
		1018	1291	1864.4	1.863	1.636	0.0909	0.3523	27.7	16.005
		1244	1517	2271.2	1.92	1.636	0.094	0.3643	29.52	17.057
		1461	1734	2661.8	1.965	1.636	0.0924	0.3581	29.701	17.161
		1676	1949	3048.8	2.008	1.636	0.0867	0.336	28.485	16.459
10	t-t-t or normal	21	294	69.8	0.684	1.636	0.0817	0.3167	9.142	5.282
		124	397	255.2	0.983	1.636	0.0649	0.2515	10.436	6.03
		204	477	399.2	1.169	1.636	0.0586	0.2271	11.211	6.478
		306	579	582.8	1.355	1.636	0.0535	0.2074	11.856	6.851
		411	684	771.8	1.497	1.636	0.0452	0.1752	11.072	6.398
		520	793	968	1.608	1.636	0.0404	0.1566	10.628	6.141
		630	903	1166	1.692	1.636	0.0384	0.1488	10.628	6.141
		721	994	1329.8	1.746	1.636	0.0358	0.1388	10.225	5.908
		819	1092	1506.2	1.793	1.636	0.0344	0.1333	10.088	5.829
		913	1186	1675.4	1.829	1.636	0.0342	0.1326	10.233	5.913
		1026	1299	1878.8	1.865	1.636	0.0327	0.1267	9.977	5.765
		1246	1519	2274.8	1.92	1.636	0.032	0.124	10.052	5.808
		1487	1760	2708.6	1.97	1.636	0.0308	0.1194	9.927	5.736
		1662	1935	3023.6	2.005	1.636	0.0318	0.1232	10.433	6.028

Table 12. Thermophysical Property Data of Boeing/Rohr T-300 1k Hybrid Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
11	In-plane	18	291	64.4	0.674	1.73	0.189	0.7325	22.054	12.743
		126	399	258.8	0.988	1.73	0.165	0.6395	28.203	16.296
		205	478	401	1.172	1.73	0.149	0.5775	30.198	17.449
		305	578	581	1.353	1.73	0.134	0.5194	31.366	18.123
		401	674	753.8	1.485	1.73	0.123	0.4767	31.609	18.264
		526	799	978.8	1.613	1.73	0.107	0.4147	29.862	17.254
		616	889	1140.8	1.682	1.73	0.102	0.3953	29.688	17.154
		713	986	1315.4	1.742	1.73	0.099	0.3837	29.827	17.234
		807	1080	1484.6	1.787	1.73	0.0977	0.3787	30.209	17.455
		905	1178	1661	1.826	1.73	0.0949	0.3678	29.981	17.323
		1015	1288	1859	1.862	1.73	0.0915	0.3546	29.471	17.028
		1239	1512	2262.2	1.918	1.73	0.0859	0.3329	28.51	16.473
		1464	1737	2667.2	1.965	1.73	0.0856	0.3318	29.105	16.817
		1663	1936	3025.4	2.006	1.73	0.0832	0.3225	28.868	16.68
11	t-t-t	18	291	64.4	0.674	1.73	0.059	0.2287	6.884	3.978
		127	400	260.6	0.991	1.73	0.0471	0.1825	8.072	4.664
		205	478	401	1.172	1.73	0.0419	0.1624	8.492	4.907
		304	577	579.2	1.351	1.73	0.0383	0.1484	8.955	5.174
		405	678	761	1.49	1.73	0.0356	0.138	9.178	5.303
		521	794	969.8	1.609	1.73	0.0304	0.1178	8.461	4.889
		605	878	1121	1.675	1.73	0.0282	0.1093	8.171	4.721
		716	989	1320.8	1.743	1.73	0.0261	0.1012	7.871	4.548
		803	1076	1477.4	1.786	1.73	0.0261	0.1012	8.062	4.658
		909	1182	1668.2	1.828	1.73	0.0261	0.1012	8.252	4.768
		1011	1284	1851.8	1.861	1.73	0.026	0.1008	8.369	4.836
		1221	1494	2229.8	1.914	1.73	0.0264	0.1023	8.744	5.052
		1456	1729	2652.8	1.964	1.73	0.0268	0.1039	9.105	5.261
		1664	1937	3027.2	2.006	1.73	0.0269	0.1043	9.334	5.393

Table 13. Thermophysical Property Data of CVD-Coated Boeing/Rohr T-300 1k Hybrid Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity	
		°C	K	°F			cm^2/s	ft^2/hr
12	t-t-t	18	291	64.4	0.674	1.8	0.06	0.2325
		127	400	260.6	0.991	1.8	0.0514	0.1992
		205	478	401	1.172	1.8	0.0456	0.1767
		304	577	579.2	1.351	1.8	0.0419	0.1624
		405	678	761	1.49	1.8	0.0394	0.1527
		521	794	969.8	1.609	1.8	0.0365	0.1415
		623	896	1153.4	1.687	1.8	0.0354	0.1372
		720	993	1328	1.745	1.8	0.0324	0.1256
		817	1090	1502.6	1.792	1.8	0.0315	0.1221
		912	1185	1673.6	1.829	1.8	0.03	0.1163
		1012	1285	1853.6	1.861	1.8	0.0299	0.1159
		1231	1504	2247.8	1.917	1.8	0.0289	0.112
		1457	1730	2654.6	1.964	1.8	0.0289	0.112
		1652	1925	3005.6	2.003	1.8	0.0288	0.1116

Table 14. Thermophysical Property Data of PPC-Coated Boeing/Rohr T-300 1k Hybrid Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity	
		°C	K	°F			cm^2/s	ft^2/hr
13	t-t-t	18	291	64.4	0.674	1.87	0.0412	0.1597
		127	400	260.6	0.991	1.87	0.0335	0.1298
		207	480	404.6	1.176	1.87	0.0325	0.126
		304	577	579.2	1.351	1.87	0.0286	0.1108
		405	678	761	1.49	1.87	0.0273	0.1058
		530	803	986	1.617	1.87	0.0253	0.0981
		605	878	1121	1.675	1.87	0.0243	0.0942
		702	975	1295.6	1.735	1.87	0.0233	0.0903
		808	1081	1486.4	1.788	1.87	0.0219	0.0849
		911	1184	1671.8	1.828	1.87	0.022	0.0853
		1016	1289	1860.8	1.862	1.87	0.0203	0.0787
		1242	1515	2267.6	1.919	1.87	0.0199	0.0771
		1439	1712	2622.2	1.96	1.87	0.0208	0.0806
		1654	1927	3009.2	2.004	1.87	0.0219	0.0849

Table 15. Thermophysical Property Data of CCAT T-300 3k Phenolic Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
14	In-plane	18	291	64.4	0.674	1.593	0.208	0.8062	22.349	12.913
		126	399	258.8	0.988	1.593	0.178	0.6899	28.016	16.188
		205	478	401	1.172	1.593	0.159	0.6162	29.673	17.145
		305	578	581	1.353	1.593	0.139	0.5387	29.96	17.311
		402	675	755.6	1.487	1.593	0.132	0.5116	31.261	18.062
		490	763	914	1.581	1.593	0.127	0.4922	31.979	18.477
		612	885	1133.6	1.68	1.593	0.121	0.469	32.376	18.707
		720	993	1328	1.745	1.593	0.118	0.4573	32.807	18.956
		811	1084	1491.8	1.789	1.593	0.113	0.438	32.205	18.608
		909	1182	1668.2	1.828	1.593	0.112	0.4341	32.606	18.84
		1018	1291	1864.4	1.863	1.593	0.111	0.4302	32.936	19.031
		1231	1504	2247.8	1.917	1.593	0.11	0.4263	33.586	19.406
		1436	1709	2616.8	1.96	1.593	0.111	0.4302	34.654	20.023
		1656	1929	3012.8	2.004	1.593	0.111	0.4302	35.438	20.476
14	t-t-t	18	291	64.4	0.674	1.593	0.013	0.0504	1.397	0.807
		127	400	260.6	0.991	1.593	0.0128	0.0496	2.02	1.167
		205	478	401	1.172	1.593	0.0126	0.0488	2.351	1.359
		304	577	579.2	1.351	1.593	0.0121	0.0469	2.605	1.505
		405	678	761	1.49	1.593	0.0118	0.0457	2.801	1.619
		517	790	962.6	1.605	1.593	0.0114	0.0442	2.915	1.684
		619	892	1146.2	1.684	1.593	0.0112	0.0434	3.005	1.736
		716	989	1320.8	1.743	1.593	0.0113	0.0438	3.138	1.813
		809	1082	1488.2	1.788	1.593	0.0116	0.045	3.304	1.909
		913	1186	1675.4	1.829	1.593	0.0122	0.0473	3.555	2.054
		1023	1296	1873.4	1.864	1.593	0.0133	0.0515	3.949	2.282
		1241	1514	2265.8	1.919	1.593	0.0168	0.0651	5.136	2.967
		1447	1720	2636.6	1.962	1.593	0.0182	0.0705	5.688	3.287
		1667	1940	3032.6	2.006	1.593	0.0199	0.0771	6.36	3.675

Table 16. Thermophysical Property Data of Type III Coated CCAT T-300 3k Phenolic Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity	
		°C	K	°F			cm^2/s	ft^2/hr
15	t-t-t	18	291	64.4	0.674	1.814	0.0289	0.112
		127	400	260.6	0.991	1.814	0.0283	0.1097
		205	478	401	1.172	1.814	0.0263	0.1019
		304	577	579.2	1.351	1.814	0.0238	0.0922
		405	678	761	1.49	1.814	0.0216	0.0837
		521	794	969.8	1.609	1.814	0.0198	0.0767
		602	875	1115.6	1.673	1.814	0.0222	0.086
		710	983	1310	1.74	1.814	0.0217	0.0841
		807	1080	1484.6	1.787	1.814	0.0214	0.0829
		907	1180	1664.6	1.827	1.814	0.0208	0.0806
		1015	1288	1859	1.862	1.814	0.0204	0.0791
		1231	1504	2247.8	1.917	1.814	0.0197	0.0764
		1449	1722	2640.2	1.962	1.814	0.0204	0.0791
		1664	1937	3027.2	2.006	1.814	0.0203	0.0787
15	t-t-t remeasured	20	293	68	0.681	1.814	0.0293	0.1136
		126	399	258.8	0.988	1.814	0.0252	0.0977
		206	479	402.8	1.174	1.814	0.0243	0.0942
		304	577	579.2	1.351	1.814	0.0219	0.0849
		403	676	757.4	1.488	1.814	0.0206	0.0798
		543	816	1009.4	1.628	1.814	0.02	0.0775
		601	874	1113.8	1.672	1.814	0.0198	0.0767
		721	994	1329.8	1.746	1.814	0.0195	0.0756
		815	1088	1499	1.791	1.814	0.0193	0.0748
		909	1182	1668.2	1.828	1.814	0.0191	0.074
		1021	1294	1869.8	1.864	1.814	0.0186	0.0721
		1231	1504	2247.8	1.917	1.814	0.0202	0.0783
		1457	1730	2654.6	1.964	1.814	0.0204	0.0791
		1664	1937	3027.2	2.006	1.814	0.0204	0.0791

Table 17. Thermophysical Property Data of LaRC Stitched Panel 2, Which Is T-300 3k Phenolic Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
16	In-plane	19	292	66.2	0.678	1.535	0.182	0.7054	18.931	10.939
		127	400	260.6	0.991	1.535	0.156	0.6046	23.721	13.706
		205	478	401	1.172	1.535	0.146	0.5659	26.255	15.17
		303	576	577.4	1.35	1.535	0.132	0.5116	27.351	15.804
		421	694	789.8	1.509	1.535	0.116	0.4496	26.867	15.524
		533	806	991.4	1.619	1.535	0.107	0.4147	26.594	15.366
		630	903	1166	1.692	1.535	0.0988	0.3829	25.658	14.825
		721	994	1329.8	1.746	1.535	0.0974	0.3775	26.102	15.081
		822	1095	1511.6	1.794	1.535	0.0947	0.367	26.075	15.066
		909	1182	1668.2	1.828	1.535	0.0922	0.3573	25.865	14.945
		1013	1286	1855.4	1.861	1.535	0.0898	0.348	25.655	14.824
		1255	1528	2291	1.922	1.535	0.0861	0.3337	25.402	14.677
		1453	1726	2647.4	1.963	1.535	0.0841	0.326	25.344	14.644
		1669	1942	3036.2	2.007	1.535	0.0824	0.3194	25.383	14.666
16	t-t-t or normal	19	292	66.2	0.678	1.535	0.0472	0.1829	4.91	2.837
		127	400	260.6	0.991	1.535	0.0396	0.1535	6.021	3.479
		206	479	402.8	1.174	1.535	0.0379	0.1469	6.828	3.945
		303	576	577.4	1.35	1.535	0.0344	0.1333	7.128	4.119
		431	704	807.8	1.52	1.535	0.0314	0.1217	7.327	4.233
		519	792	966.2	1.607	1.535	0.0301	0.1167	7.425	4.29
		628	901	1162.4	1.691	1.535	0.0287	0.1112	7.447	4.303
		722	995	1331.6	1.746	1.535	0.0272	0.1054	7.291	4.213
		823	1096	1513.4	1.794	1.535	0.0267	0.1035	7.353	4.249
		920	1193	1688	1.831	1.535	0.0259	0.1004	7.281	4.207
		1015	1288	1859	1.862	1.535	0.0252	0.0977	7.202	4.161
		1248	1521	2278.4	1.92	1.535	0.0261	0.1012	7.694	4.446
		1484	1757	2703.2	1.969	1.535	0.0265	0.1027	8.011	4.629
		1662	1935	3023.6	2.005	1.535	0.0277	0.1074	8.527	4.927

Table 18. Thermophysical Property Data of LaRC Stitched Panel 5, Which Is T-300 3k Phenolic Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
17	In-plane	19	292	66.2	0.678	1.444	0.179	0.6938	17.515	10.12
		127	400	260.6	0.991	1.444	0.147	0.5697	21.027	12.15
		205	478	401	1.172	1.444	0.143	0.5542	24.191	13.978
		303	576	577.4	1.35	1.444	0.127	0.4922	24.755	14.304
		429	702	804.2	1.518	1.444	0.11	0.4263	24.11	13.931
		525	798	977	1.612	1.444	0.0989	0.3833	23.026	13.304
		630	903	1166	1.692	1.444	0.0978	0.379	23.893	13.805
		719	992	1326.2	1.745	1.444	0.0899	0.3484	22.65	13.087
		814	1087	1497.2	1.79	1.444	0.0869	0.3368	22.466	12.981
		915	1188	1679	1.83	1.444	0.0866	0.3356	22.88	13.22
		1015	1288	1859	1.862	1.444	0.0851	0.3298	22.878	13.219
		1256	1529	2292.8	1.922	1.444	0.0859	0.3329	23.844	13.777
		1457	1730	2654.6	1.964	1.444	0.0857	0.3322	24.305	14.043
		1664	1937	3027.2	2.006	1.444	0.0851	0.3298	24.648	14.242
17	t-t-t or normal	19	292	66.2	0.678	1.444	0.0748	0.2899	7.319	4.229
		127	400	260.6	0.991	1.444	0.0695	0.2694	9.941	5.744
		206	479	402.8	1.174	1.444	0.0657	0.2546	11.134	6.433
		303	576	577.4	1.35	1.444	0.0612	0.2372	11.929	6.893
		431	704	807.8	1.52	1.444	0.0525	0.2035	11.524	6.659
		538	811	1000.4	1.623	1.444	0.0472	0.1829	11.064	6.393
		635	908	1175	1.695	1.444	0.0445	0.1725	10.892	6.294
		723	996	1333.4	1.747	1.444	0.0428	0.1659	10.796	6.238
		822	1095	1511.6	1.794	1.444	0.0409	0.1585	10.594	6.121
		918	1191	1684.4	1.831	1.444	0.0403	0.1562	10.654	6.156
		1013	1286	1855.4	1.861	1.444	0.0395	0.1531	10.616	6.134
		1251	1524	2283.8	1.921	1.444	0.0407	0.1577	11.291	6.524
		1466	1739	2670.8	1.966	1.444	0.0414	0.1605	11.752	6.79
		1669	1942	3036.2	2.007	1.444	0.0408	0.1581	11.823	6.831

Table 19. Thermophysical Property Data of LaRC Stitched Panel 8, Which Is T-300 3k Phenolic Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
18	In-plane	19	292	66.2	0.678	1.439	0.174	0.6744	16.967	9.804
		127	400	260.6	0.991	1.439	0.146	0.5659	20.812	12.025
		205	478	401	1.172	1.439	0.129	0.5	21.747	12.565
		303	576	577.4	1.35	1.439	0.11	0.4263	21.367	12.346
		423	696	793.4	1.511	1.439	0.104	0.4031	22.615	13.067
		514	787	957.2	1.603	1.439	0.0983	0.381	22.671	13.099
		626	899	1158.8	1.689	1.439	0.0914	0.3542	22.217	12.837
		717	990	1322.6	1.744	1.439	0.0886	0.3434	22.231	12.845
		805	1078	1481	1.786	1.439	0.0864	0.3349	22.211	12.833
		912	1185	1673.6	1.829	1.439	0.0852	0.3302	22.419	12.954
		1025	1298	1877	1.865	1.439	0.0838	0.3248	22.486	12.992
		1252	1525	2285.6	1.921	1.439	0.0813	0.3151	22.478	12.988
		1481	1754	2697.8	1.969	1.439	0.0805	0.312	22.807	13.178
		1659	1932	3018.2	2.005	1.439	0.081	0.3139	23.367	13.502
18	t-t-t or normal	19	292	66.2	0.678	1.439	0.0531	0.2058	5.178	2.992
		127	400	260.6	0.991	1.439	0.0483	0.1872	6.885	3.978
		205	478	401	1.172	1.439	0.0461	0.1787	7.772	4.49
		303	576	577.4	1.35	1.439	0.0415	0.1608	8.061	4.658
		443	716	829.4	1.533	1.439	0.0353	0.1368	7.788	4.5
		506	779	942.8	1.596	1.439	0.0331	0.1283	7.6	4.391
		640	913	1184	1.698	1.439	0.0324	0.1256	7.918	4.575
		728	1001	1342.4	1.75	1.439	0.032	0.124	8.056	4.655
		817	1090	1502.6	1.792	1.439	0.0325	0.126	8.379	4.841
		915	1188	1679	1.83	1.439	0.032	0.124	8.425	4.868
		1018	1291	1864.4	1.863	1.439	0.0315	0.1221	8.443	4.878
		1253	1526	2287.4	1.922	1.439	0.0322	0.1248	8.904	5.145
		1453	1726	2647.4	1.963	1.439	0.0315	0.1221	8.899	5.142
		1674	1947	3045.2	2.008	1.439	0.0315	0.1221	9.101	5.259

Table 20. Thermophysical Property Data of LaRC J1, Which Is T-300 3k CVI Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
19	In-plane	19	292	66.2	0.678	1.35	0.14	0.5426	12.807	7.4
		208	481	406.4	1.178	1.35	0.121	0.469	19.238	11.116
		305	578	581	1.353	1.35	0.106	0.4108	19.362	11.187
		403	676	757.4	1.488	1.35	0.0944	0.3659	18.961	10.956
		435	708	815	1.525	1.35	0.0879	0.3407	18.091	10.453
		541	814	1005.8	1.626	1.35	0.0832	0.3225	18.262	10.552
		631	904	1167.8	1.692	1.35	0.0801	0.3104	18.302	10.575
		736	1009	1356.8	1.754	1.35	0.0784	0.3039	18.561	10.724
		814	1087	1497.2	1.79	1.35	0.076	0.2946	18.369	10.614
		937	1210	1718.6	1.837	1.35	0.0763	0.2957	18.924	10.935
		1000	1273	1832	1.857	1.35	0.074	0.2868	18.555	10.721
		1271	1544	2319.8	1.926	1.35	0.0735	0.2849	19.106	11.039
		1576	1849	2868.8	1.988	1.35	0.0723	0.2802	19.403	11.211
		1726	1999	3138.8	2.019	1.35	0.0748	0.2899	20.391	11.782
19	t-t-t	20	293	68	0.681	1.35	0.0207	0.0802	1.902	1.099
		206	479	402.8	1.174	1.35	0.0172	0.0667	2.725	1.575
		304	577	579.2	1.351	1.35	0.0155	0.0601	2.828	1.634
		449	722	840.2	1.54	1.35	0.0149	0.0577	3.097	1.789
		527	800	980.6	1.614	1.35	0.0149	0.0577	3.247	1.876
		636	909	1176.8	1.696	1.35	0.0143	0.0554	3.274	1.892
		717	990	1322.6	1.744	1.35	0.0144	0.0558	3.391	1.959
		818	1091	1504.4	1.792	1.35	0.0137	0.0531	3.314	1.915
		910	1183	1670	1.828	1.35	0.0141	0.0546	3.479	2.01
		1009	1282	1848.2	1.86	1.35	0.0139	0.0539	3.491	2.017
		1302	1575	2375.6	1.932	1.35	0.013	0.0504	3.391	1.959

Table 21. Thermophysical Property Data of LaRC J2, Which Is T-300 3k CVI Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
20	In-plane	19	292	66.2	0.678	1.57	0.39	1.5115	41.492	23.974
		208	481	406.4	1.178	1.57	0.27	1.0465	49.924	28.846
		304	577	579.2	1.351	1.57	0.233	0.9031	49.438	28.565
		403	676	757.4	1.488	1.57	0.205	0.7945	47.886	27.669
		530	803	986	1.617	1.57	0.181	0.7015	45.939	26.544
		619	892	1146.2	1.684	1.57	0.154	0.5969	40.727	23.532
		716	989	1320.8	1.743	1.57	0.147	0.5697	40.23	23.245
		820	1093	1508	1.793	1.57	0.141	0.5465	39.69	22.933
		913	1186	1675.4	1.829	1.57	0.14	0.5426	40.201	23.228
		1014	1287	1857.2	1.861	1.57	0.139	0.5387	40.623	23.472
		1263	1536	2305.4	1.924	1.57	0.129	0.5	38.962	22.512
		1589	1862	2892.2	1.99	1.57	0.124	0.4806	38.751	22.39
		1716	1989	3120.8	2.017	1.57	0.135	0.5232	42.742	24.696
20	t-t-t	20	293	68	0.681	1.57	0.0319	0.1236	3.41	1.97
		204	477	399.2	1.169	1.57	0.0267	0.1035	4.902	2.832
		304	577	579.2	1.351	1.57	0.024	0.093	5.092	2.942
		459	732	858.2	1.55	1.57	0.0222	0.086	5.403	3.122
		517	790	962.6	1.605	1.57	0.021	0.0814	5.293	3.058
		632	905	1169.6	1.693	1.57	0.0203	0.0787	5.396	3.118
		705	978	1301	1.737	1.57	0.0199	0.0771	5.427	3.136
		813	1086	1495.4	1.79	1.57	0.0188	0.0729	5.283	3.053
		906	1179	1662.8	1.826	1.57	0.0191	0.074	5.477	3.165
		1006	1279	1842.8	1.859	1.57	0.0194	0.0752	5.662	3.272
		1277	1550	2330.6	1.927	1.57	0.018	0.0698	5.445	3.146
		1474	1747	2685.2	1.967	1.57	0.0182	0.0705	5.622	3.248
		1669	1942	3036.2	2.007	1.57	0.0187	0.0725	5.892	3.404

Table 22. Thermophysical Property Data of LaRC J3, Which Is T-300 3k CVI Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
21	In-plane	19	292	66.2	0.678	1.51	0.157	0.6085	16.065	9.282
		208	481	406.4	1.178	1.51	0.121	0.469	21.518	12.433
		304	577	579.2	1.351	1.51	0.113	0.438	23.06	13.324
		403	676	757.4	1.488	1.51	0.103	0.3992	23.141	13.371
		524	797	975.2	1.611	1.51	0.0902	0.3496	21.948	12.682
		630	903	1166	1.692	1.51	0.0853	0.3306	21.791	12.591
		732	1005	1349.6	1.752	1.51	0.0799	0.3097	21.133	12.21
		819	1092	1506.2	1.793	1.51	0.0765	0.2965	20.706	11.964
		927	1200	1700.6	1.834	1.51	0.0753	0.2918	20.851	12.048
		1015	1288	1859	1.862	1.51	0.0743	0.288	20.888	12.069
		1272	1545	2321.6	1.926	1.51	0.0706	0.2736	20.53	11.862
		1519	1792	2766.2	1.976	1.51	0.0712	0.276	21.249	12.278
		1685	1958	3065	2.01	1.51	0.0721	0.2794	21.884	12.645
21	t-t-t	20	293	68	0.681	1.51	0.0308	0.1194	3.166	1.829
		204	477	399.2	1.169	1.51	0.0258	0.1	4.556	2.632
		304	577	579.2	1.351	1.51	0.0241	0.0934	4.918	2.842
		446	719	834.8	1.536	1.51	0.0222	0.086	5.15	2.976
		512	785	953.6	1.601	1.51	0.0207	0.0802	5.004	2.891
		627	900	1160.6	1.69	1.51	0.0189	0.0733	4.823	2.787
		717	990	1322.6	1.744	1.51	0.0185	0.0717	4.871	2.814
		813	1086	1495.4	1.79	1.51	0.0188	0.0729	5.081	2.936
		909	1182	1668.2	1.828	1.51	0.0187	0.0725	5.16	2.982
		1007	1280	1844.6	1.859	1.51	0.0177	0.0686	4.97	2.871
		1251	1524	2283.8	1.921	1.51	0.0168	0.0651	4.874	2.816
		1476	1749	2688.8	1.968	1.51	0.0165	0.064	4.903	2.833
		1677	1950	3050.6	2.008	1.51	0.0176	0.0682	5.338	3.084

Table 23. Thermophysical Property Data of LaRC J4, Which Is T-300 3k CVI Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
22	In-plane	19	292	66.2	0.678	1.65	0.442	1.7131	49.42	28.555
		208	481	406.4	1.178	1.65	0.289	1.1201	56.16	32.45
		304	577	579.2	1.351	1.65	0.27	1.0465	60.208	34.788
		403	676	757.4	1.488	1.65	0.22	0.8527	54.009	31.206
		516	789	960.8	1.604	1.65	0.198	0.7674	52.418	30.287
		636	909	1176.8	1.696	1.65	0.172	0.6666	48.126	27.807
		716	989	1320.8	1.743	1.65	0.153	0.593	44.006	25.426
		818	1091	1504.4	1.792	1.65	0.146	0.5659	43.171	24.944
		917	1190	1682.6	1.83	1.65	0.143	0.5542	43.187	24.954
		1007	1280	1844.6	1.859	1.65	0.136	0.5271	41.725	24.109
		1259	1532	2298.2	1.923	1.65	0.124	0.4806	39.343	22.732
		1545	1818	2813	1.982	1.65	0.122	0.4728	39.891	23.049
		1708	1981	3106.4	2.015	1.65	0.121	0.469	40.228	23.244
22	t-t-t	20	293	68	0.681	1.65	0.0347	0.1345	3.898	2.252
		203	476	397.4	1.167	1.65	0.0274	0.1062	5.278	3.049
		304	577	579.2	1.351	1.65	0.0265	0.1027	5.909	3.414
		449	722	840.2	1.54	1.65	0.0236	0.0915	5.995	3.464
		529	802	984.2	1.616	1.65	0.0215	0.0833	5.732	3.312
		625	898	1157	1.689	1.65	0.0193	0.0748	5.377	3.107
		714	987	1317.2	1.742	1.65	0.019	0.0736	5.461	3.156
		814	1087	1497.2	1.79	1.65	0.0188	0.0729	5.554	3.209
		921	1194	1689.8	1.832	1.65	0.0178	0.069	5.38	3.108
		1012	1285	1853.6	1.861	1.65	0.0175	0.0678	5.373	3.105
		1256	1529	2292.8	1.922	1.65	0.0175	0.0678	5.55	3.207
		1461	1734	2661.8	1.965	1.65	0.018	0.0698	5.835	3.372
		1678	1951	3052.4	2.009	1.65	0.0177	0.0686	5.866	3.39

Table 24. Thermophysical Property Data of LaRC J5, Which Is T-300 3k CVI Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
23	In-plane	19	292	66.2	0.678	1.39	0.32	1.2402	30.142	17.416
		208	481	406.4	1.178	1.39	0.252	0.9767	41.254	23.836
		304	577	579.2	1.351	1.39	0.198	0.7674	37.195	21.491
		403	676	757.4	1.488	1.39	0.173	0.6705	35.778	20.673
		523	796	973.4	1.611	1.39	0.143	0.5542	32.014	18.498
		635	908	1175	1.695	1.39	0.136	0.5271	32.044	18.515
		723	996	1333.4	1.747	1.39	0.127	0.4922	30.838	17.818
		819	1092	1506.2	1.793	1.39	0.125	0.4845	31.145	17.995
		901	1174	1653.8	1.825	1.39	0.121	0.469	30.689	17.732
		1006	1279	1842.8	1.859	1.39	0.116	0.4496	29.976	17.32
		1262	1535	2303.6	1.924	1.39	0.111	0.4302	29.679	17.148
		1561	1834	2841.8	1.985	1.39	0.112	0.4341	30.9	17.854
		1693	1966	3079.4	2.012	1.39	0.113	0.438	31.599	18.258
23	t-t-t	20	293	68	0.681	1.39	0.0448	0.1736	4.239	2.45
		205	478	401	1.172	1.39	0.0339	0.1314	5.52	3.19
		304	577	579.2	1.351	1.39	0.0297	0.1151	5.579	3.224
		440	713	824	1.53	1.39	0.0291	0.1128	6.189	3.576
		550	823	1022	1.633	1.39	0.027	0.1046	6.13	3.542
		602	875	1115.6	1.673	1.39	0.0259	0.1004	6.022	3.479
		718	991	1324.4	1.744	1.39	0.024	0.093	5.819	3.362
		818	1091	1504.4	1.792	1.39	0.0222	0.086	5.53	3.195
		913	1186	1675.4	1.829	1.39	0.0212	0.0822	5.39	3.114
		1005	1278	1841	1.859	1.39	0.0194	0.0752	5.012	2.896
		1247	1520	2276.6	1.92	1.39	0.0174	0.0674	4.644	2.684
		1457	1730	2654.6	1.964	1.39	0.0161	0.0624	4.395	2.54
		1655	1928	3011	2.004	1.39	0.0151	0.0585	4.206	2.43

Table 25. Thermophysical Property Data of LaRC J6, Which Is T-300 3k CVI Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
24	In-plane	19	292	66.2	0.678	1.61	0.548	2.1239	59.787	34.545
		208	481	406.4	1.178	1.61	0.352	1.3643	66.745	38.565
		304	577	579.2	1.351	1.61	0.286	1.1085	62.23	35.956
		403	676	757.4	1.488	1.61	0.252	0.9767	60.365	34.879
		506	779	942.8	1.596	1.61	0.23	0.8914	59.081	34.137
		620	893	1148	1.685	1.61	0.209	0.81	56.703	32.763
		717	990	1322.6	1.744	1.61	0.198	0.7674	55.585	32.117
		812	1085	1493.6	1.789	1.61	0.185	0.717	53.3	30.797
		903	1176	1657.4	1.825	1.61	0.173	0.6705	50.843	29.377
		1008	1281	1846.4	1.86	1.61	0.166	0.6434	49.703	28.718
		1274	1547	2325.2	1.926	1.61	0.13	0.5038	40.315	23.294
		1543	1816	2809.4	1.981	1.61	0.13	0.5038	41.467	23.96
		1699	1972	3090.2	2.013	1.61	0.137	0.531	44.402	25.655
24	t-t-t	20	293	68	0.681	1.61	0.0657	0.2546	7.201	4.161
		205	478	401	1.172	1.61	0.0495	0.1919	9.336	5.395
		304	577	579.2	1.351	1.61	0.0451	0.1748	9.813	5.67
		427	700	800.6	1.516	1.61	0.0361	0.1399	8.809	5.09
		526	799	978.8	1.613	1.61	0.031	0.1201	8.051	4.652
		626	899	1158.8	1.689	1.61	0.0296	0.1147	8.05	4.651
		707	980	1304.6	1.738	1.61	0.0294	0.1139	8.228	4.754
		811	1084	1491.8	1.789	1.61	0.0284	0.1101	8.18	4.727
		911	1184	1671.8	1.828	1.61	0.0276	0.107	8.124	4.694
		1002	1275	1835.6	1.858	1.61	0.0266	0.1031	7.957	4.597
		1254	1527	2289.2	1.922	1.61	0.0258	0.1	7.983	4.612
		1456	1729	2652.8	1.964	1.61	0.0245	0.095	7.746	4.476
		1673	1946	3043.4	2.008	1.61	0.0238	0.0922	7.693	4.445

Table 26. Thermophysical Property Data of LaRC J7, Which Is T-300 3k CVI Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
25	In-plane	19	292	66.2	0.678	1.54	0.398	1.5426	41.534	23.998
		208	481	406.4	1.178	1.54	0.268	1.0387	48.608	28.085
		304	577	579.2	1.351	1.54	0.223	0.8643	46.412	26.817
		403	676	757.4	1.488	1.54	0.193	0.748	44.222	25.551
		541	814	1005.8	1.626	1.54	0.154	0.5969	38.559	22.279
		621	894	1149.8	1.686	1.54	0.142	0.5504	36.865	21.301
		722	995	1331.6	1.746	1.54	0.138	0.5349	37.113	21.444
		807	1080	1484.6	1.787	1.54	0.125	0.4845	34.406	19.88
		907	1180	1664.6	1.827	1.54	0.12	0.4651	33.76	19.506
		1012	1285	1853.6	1.861	1.54	0.111	0.4302	31.81	18.38
		1251	1524	2283.8	1.921	1.54	0.112	0.4341	33.136	19.146
		1514	1787	2757.2	1.975	1.54	0.101	0.3915	30.726	17.753
		1703	1976	3097.4	2.014	1.54	0.108	0.4186	33.495	19.353
25	t-t-t	20	293	68	0.681	1.54	0.0718	0.2783	7.528	4.35
		206	479	402.8	1.174	1.54	0.0461	0.1787	8.332	4.814
		304	577	579.2	1.351	1.54	0.0424	0.1643	8.825	5.099
		448	721	838.4	1.539	1.54	0.0388	0.1504	9.193	5.312
		508	781	946.4	1.597	1.54	0.0345	0.1337	8.487	4.904
		628	901	1162.4	1.691	1.54	0.0306	0.1186	7.966	4.603
		714	987	1317.2	1.742	1.54	0.03	0.1163	8.048	4.65
		808	1081	1486.4	1.788	1.54	0.0287	0.1112	7.902	4.565
		901	1174	1653.8	1.825	1.54	0.0291	0.1128	8.177	4.725
		1004	1277	1839.2	1.859	1.54	0.0281	0.1089	8.043	4.647
		1249	1522	2280.2	1.921	1.54	0.0256	0.0992	7.572	4.375
		1388	1661	2530.4	1.95	1.54	0.026	0.1008	7.808	4.511
		1684	1957	3063.2	2.01	1.54	0.0244	0.0946	7.552	4.364

Table 27. Thermophysical Property Data of LaRC J8, Which Is T-300 3k CVI Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
26	In-plane	19	292	66.2	0.678	1.66	0.547	2.12	61.531	35.553
		208	481	406.4	1.178	1.66	0.322	1.248	62.952	36.374
		304	577	579.2	1.351	1.66	0.304	1.1782	68.2	39.406
		403	676	757.4	1.488	1.66	0.269	1.0426	66.438	38.388
		528	801	982.4	1.615	1.66	0.232	0.8992	62.193	35.935
		634	907	1173.2	1.694	1.66	0.204	0.7907	57.381	33.155
		722	995	1331.6	1.746	1.66	0.193	0.748	55.949	32.328
		825	1098	1517	1.795	1.66	0.17	0.6589	50.656	29.269
		915	1188	1679	1.83	1.66	0.169	0.655	51.329	29.658
		1012	1285	1853.6	1.861	1.66	0.158	0.6124	48.808	28.201
		1273	1546	2323.4	1.926	1.66	0.155	0.6007	49.555	28.633
		1485	1758	2705	1.97	1.66	0.141	0.5465	46.101	26.637
		1698	1971	3088.4	2.013	1.66	0.15	0.5814	50.12	28.959
26	t-t-t	20	293	68	0.681	1.66	0.074	0.2868	8.363	4.832
		206	479	402.8	1.174	1.66	0.0515	0.1996	10.033	5.797
		304	577	579.2	1.351	1.66	0.0442	0.1713	9.916	5.729
		432	705	809.6	1.521	1.66	0.0407	0.1577	10.278	5.939
		511	784	951.8	1.6	1.66	0.038	0.1473	10.093	5.832
		633	906	1171.4	1.694	1.66	0.0334	0.1295	9.391	5.426
		722	995	1331.6	1.746	1.66	0.0322	0.1248	9.335	5.394
		823	1096	1513.4	1.794	1.66	0.0289	0.112	8.608	4.973
		913	1186	1675.4	1.829	1.66	0.0286	0.1108	8.683	5.017
		1020	1293	1868	1.863	1.66	0.027	0.1046	8.351	4.825
		1238	1511	2260.4	1.918	1.66	0.022	0.0853	7.006	4.048
		1468	1741	2674.4	1.966	1.66	0.0217	0.0841	7.083	4.092
		1683	1956	3061.4	2.01	1.66	0.0205	0.0795	6.839	3.952

Table 28. Thermophysical Property Data of LaRC F1, Which Is K321 2k Phenolic Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
27	In-plane	22	295	71.6	0.687	1.77	0.451	1.748	54.85	31.692
		126	399	258.8	0.988	1.77	0.336	1.302	58.76	33.952
		206	479	402.8	1.174	1.77	0.313	1.213	65.019	37.568
		307	580	584.6	1.356	1.77	0.269	1.043	64.572	37.309
		405	678	761	1.49	1.77	0.246	0.953	64.888	37.492
		524	797	975.2	1.611	1.77	0.214	0.829	61.039	35.268
		617	890	1142.6	1.683	1.77	0.198	0.767	58.986	34.082
		720	993	1328	1.745	1.77	0.181	0.702	55.914	32.307
		812	1085	1493.6	1.789	1.77	0.171	0.663	54.163	31.295
		911	1184	1671.8	1.828	1.77	0.162	0.628	52.423	30.29
		1007	1280	1844.6	1.859	1.77	0.154	0.597	50.684	29.285
		1316	1589	2400.8	1.935	1.77	0.145	0.562	49.666	28.697
		1633	1906	2971.4	1.999	1.77	0.138	0.535	48.838	28.219
		1867	2140	3392.6	2.049	1.77	0.131	0.508	47.522	27.458
		2083	2356	3781.4	2.102	1.77	0.118	0.457	43.897	25.364
27	t-t-t	22	295	71.6	0.687	1.77	0.0427	0.165	5.193	3.001
		206	479	402.8	1.174	1.77	0.0328	0.127	6.813	3.937
		307	580	584.6	1.356	1.77	0.028	0.109	6.721	3.884
		405	678	761	1.49	1.77	0.0249	0.097	6.568	3.795
		537	810	998.6	1.623	1.77	0.023	0.089	6.605	3.817
		625	898	1157	1.689	1.77	0.0221	0.086	6.605	3.816
		722	995	1331.6	1.746	1.77	0.0192	0.074	5.935	3.429
		810	1083	1490	1.789	1.77	0.0181	0.07	5.73	3.311
		910	1183	1670	1.828	1.77	0.0177	0.069	5.727	3.309
		1002	1275	1835.6	1.858	1.77	0.0182	0.071	5.985	3.458
		1339	1612	2442.2	1.94	1.77	0.0177	0.069	6.078	3.512
		1680	1953	3056	2.009	1.77	0.016	0.062	5.69	3.288
		1934	2207	3513.2	2.065	1.77	0.0158	0.061	5.775	3.337
		2173	2446	3943.4	2.126	1.77	0.014	0.054	5.268	3.044

Table 29. Thermophysical Property Data of LaRC P1, Which Is K321 2k AR Pitch Densified Material

Material specimen	Direction	Temperature			Heat capacity, J/g-K	Density, g/cm^3	Thermal diffusivity		Thermal conductivity	
		°C	K	°F			cm^2/s	ft^2/hr	W/m-K	Btu/hr-ft-°F
28	In-plane	22	295	71.6	0.687	1.884	1.804	6.9919	233.53	134.934
		126	399	258.8	0.988	1.884	1.097	4.2517	204.201	117.988
		206	479	402.8	1.174	1.884	0.836	3.2401	184.845	106.803
		307	580	584.6	1.356	1.884	0.653	2.5309	166.844	96.402
		405	678	761	1.49	1.884	0.532	2.0619	149.365	86.303
		540	813	1004	1.625	1.884	0.482	1.8681	147.568	85.265
		600	873	1112	1.671	1.884	0.415	1.6084	130.667	75.499
		715	988	1319	1.743	1.884	0.394	1.5271	129.353	74.74
		815	1088	1499	1.791	1.884	0.35	1.3565	118.085	68.229
		914	1187	1677.2	1.829	1.884	0.315	1.2209	108.562	62.727
		998	1271	1828.4	1.857	1.884	0.283	1.0968	98.995	57.199
		1294	1567	2361.2	1.93	1.884	0.243	0.9418	88.38	51.066
		1645	1918	2993	2.002	1.884	0.22	0.8527	82.974	47.942
		1898	2171	3448.4	2.057	1.884	0.206	0.7984	79.817	46.118
		2109	2382	3828.2	2.109	1.884	0.165	0.6395	65.546	37.872
28	t-t-t	22	295	71.6	0.687	1.884	0.158	0.6124	20.453	11.818
		126	399	258.8	0.988	1.884	0.113	0.438	21.034	12.154
		206	479	402.8	1.174	1.884	0.0829	0.3213	18.33	10.591
		307	580	584.6	1.356	1.884	0.0699	0.2709	17.86	10.319
		405	678	761	1.49	1.884	0.0567	0.2198	15.919	9.198
		516	789	960.8	1.604	1.884	0.0421	0.1632	12.726	7.353
		617	890	1142.6	1.683	1.884	0.0384	0.1488	12.176	7.036
		707	980	1304.6	1.738	1.884	0.0343	0.1329	11.233	6.49
		819	1092	1506.2	1.793	1.884	0.031	0.1201	10.469	6.049
		914	1187	1677.2	1.829	1.884	0.0305	0.1182	10.512	6.074
		1004	1277	1839.2	1.859	1.884	0.0276	0.107	9.664	5.584
		1296	1569	2364.8	1.931	1.884	0.0263	0.1019	9.567	5.528
		1639	1912	2982.2	2.001	1.884	0.0249	0.0965	9.385	5.423
		1971	2244	3579.8	2.074	1.884	0.0229	0.0888	8.947	5.17
		2173	2446	3943.4	2.126	1.884	0.0233	0.0903	9.331	5.392

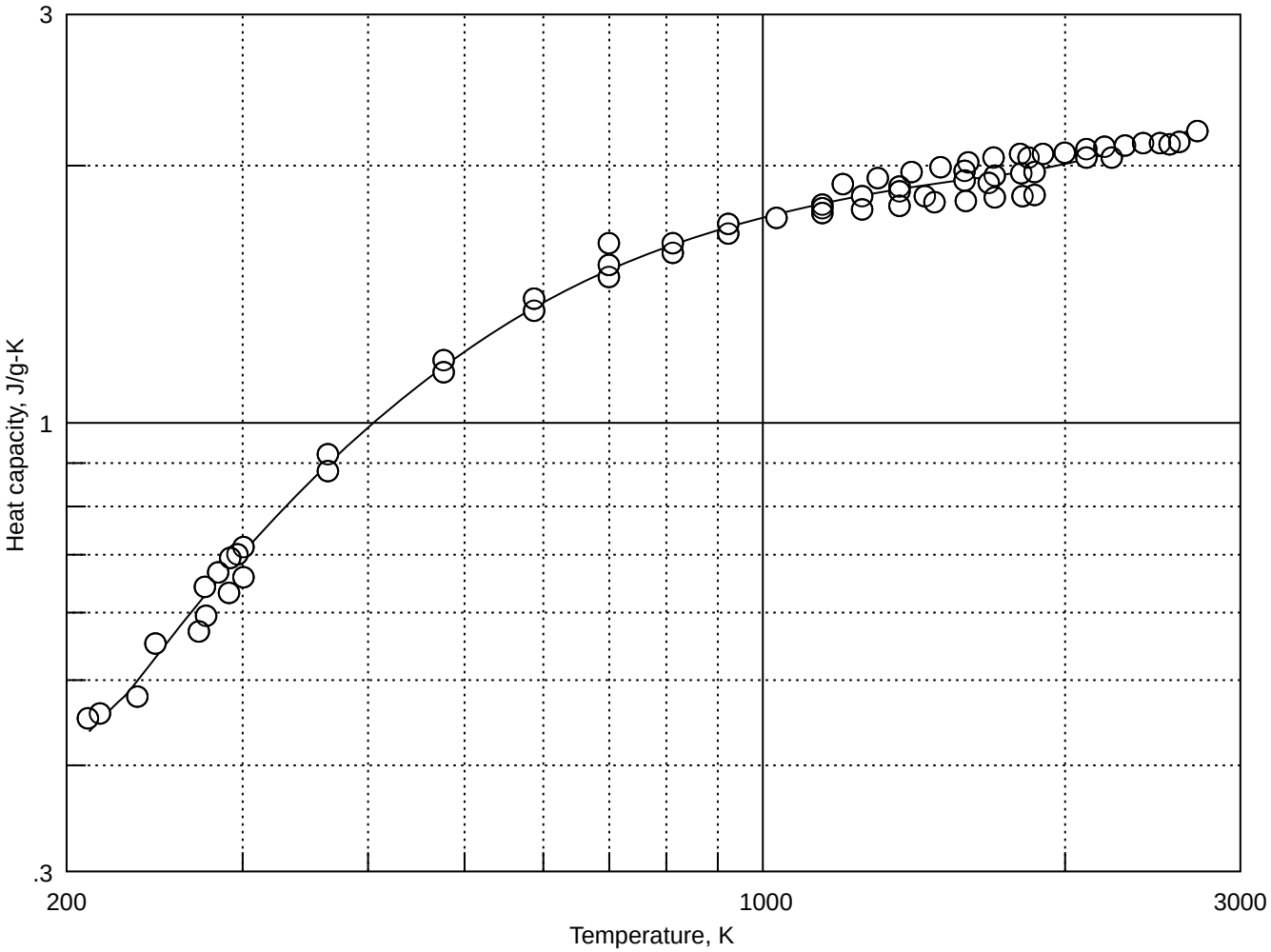

Figure 1. Specific heat for carbon-graphite from TPRC (Thermophysical Properties Research Center) data (ref. 6).

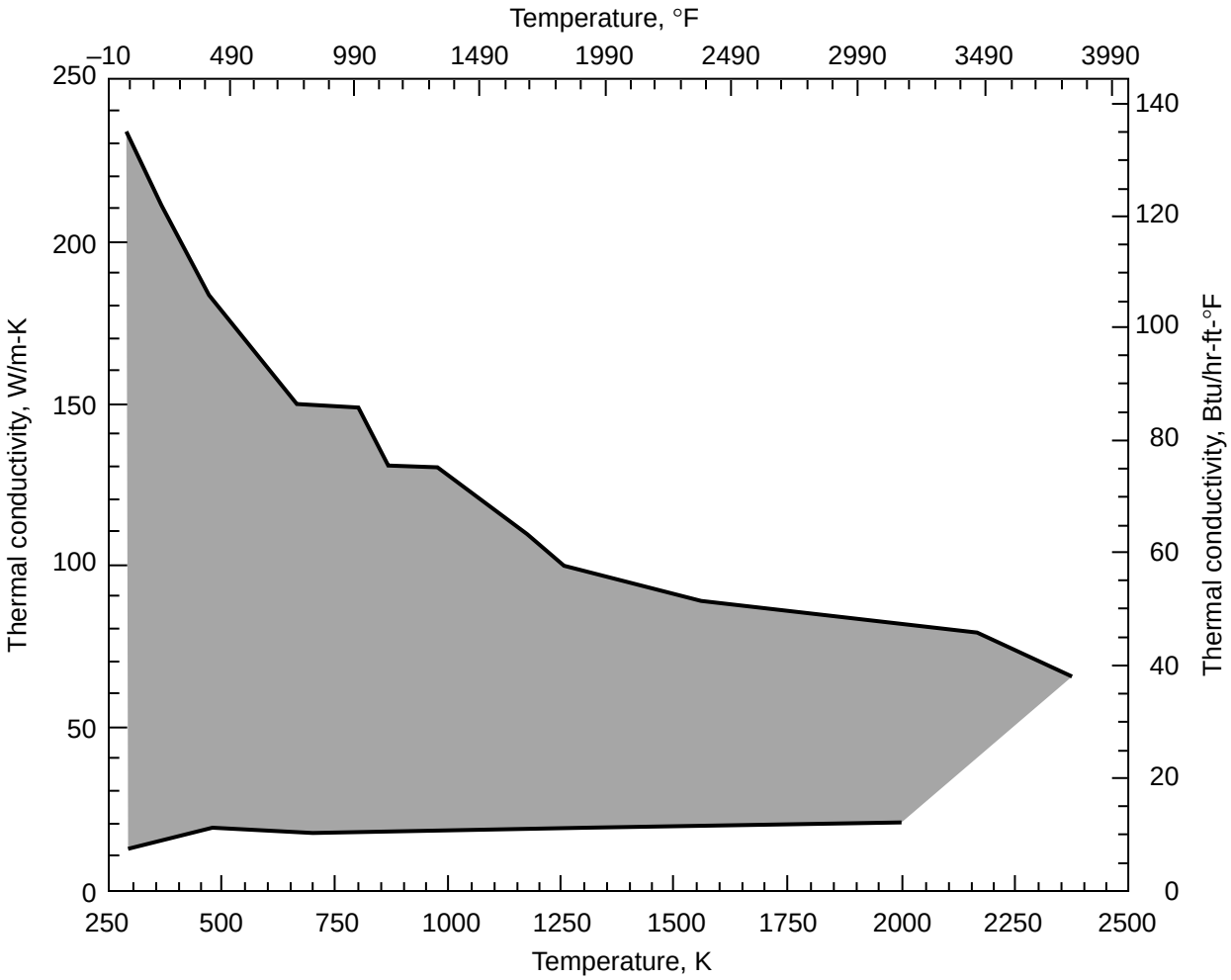

Figure 2. Range of in-plane thermal conductivity values for materials reported in paper.

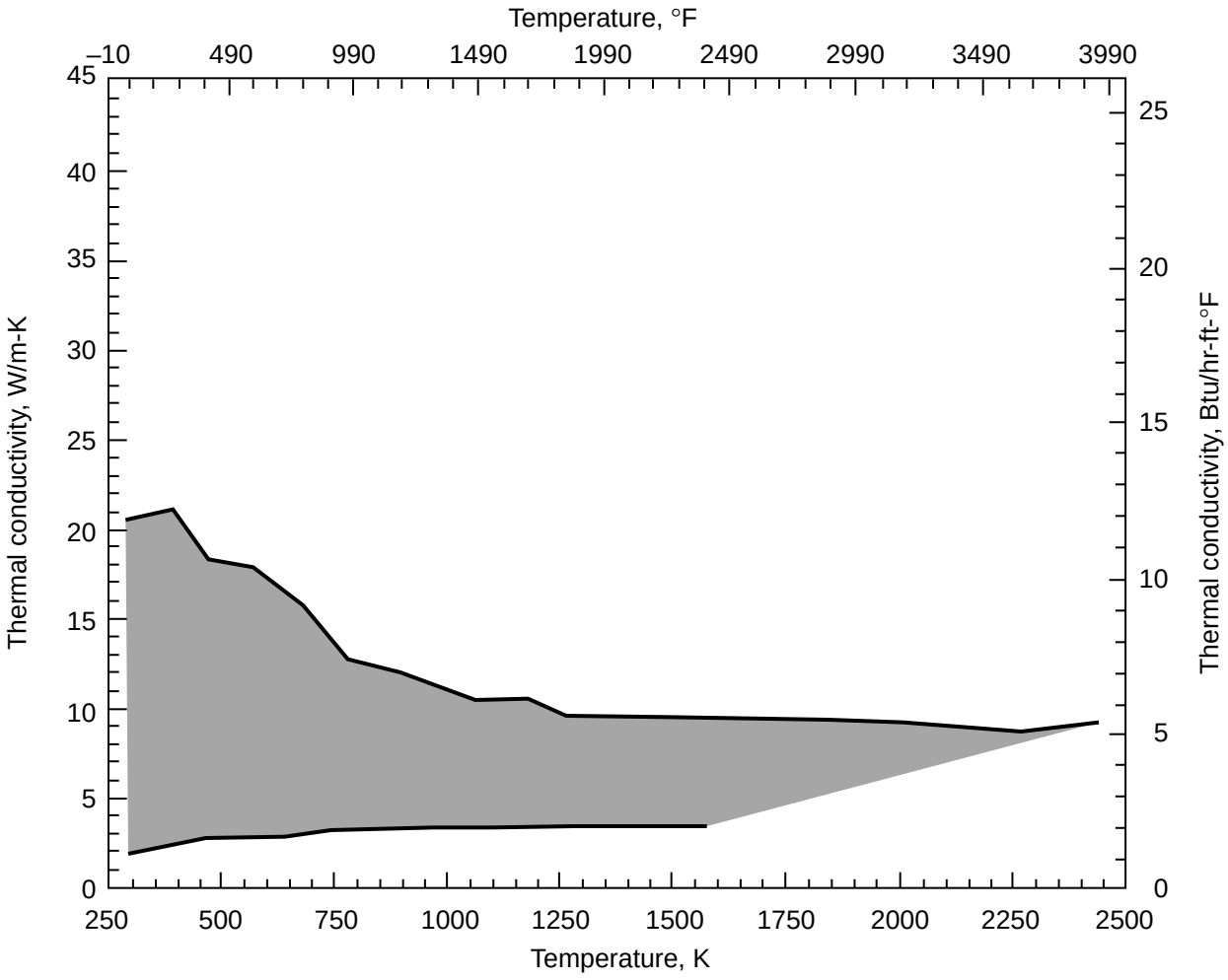

Figure 3. Range of through-the-thickness thermal conductivity values for materials reported in paper.

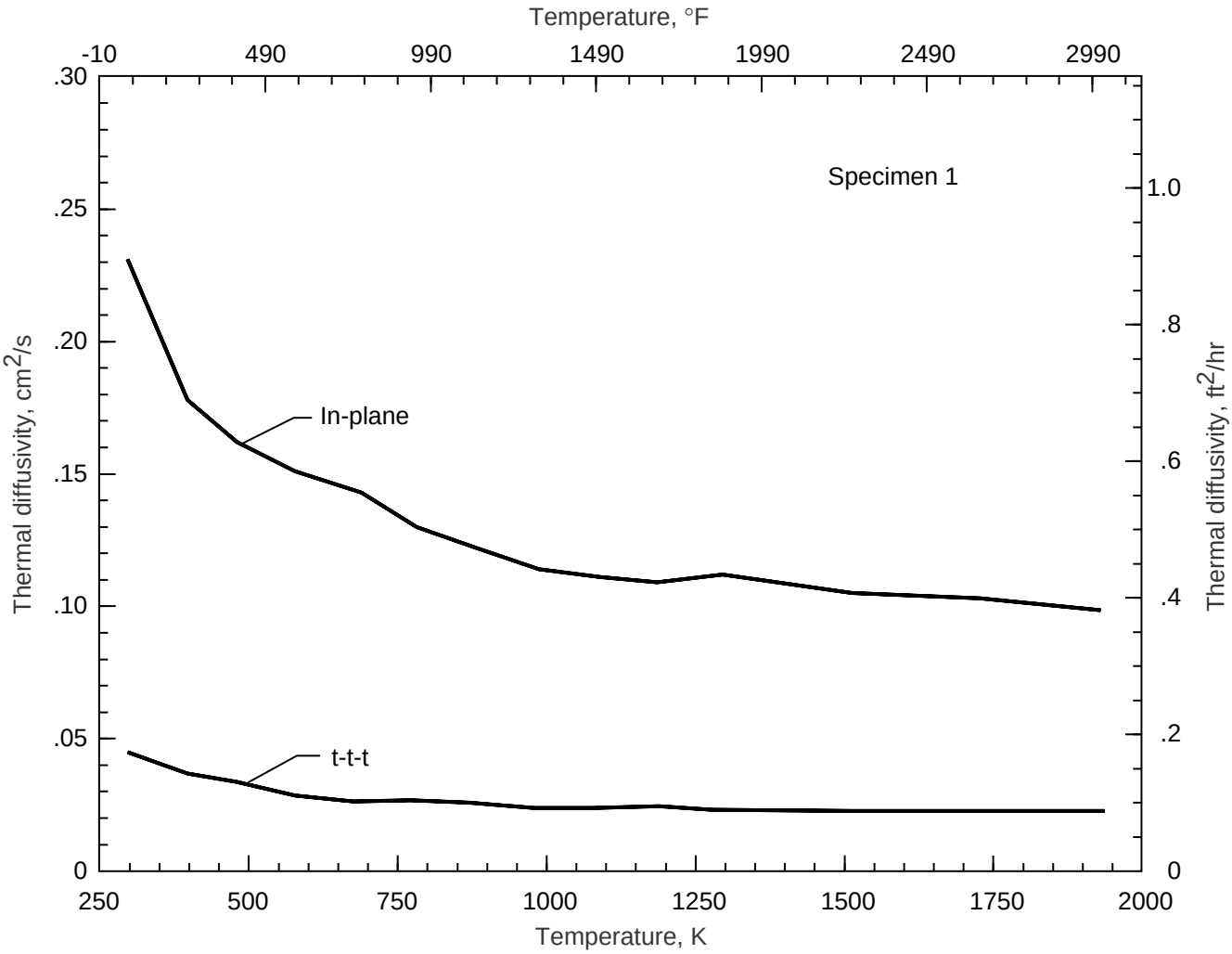

Figure 4. Thermal diffusivity versus temperature for LaRC panel 7A, which is T-300 3k phenolic densified material.

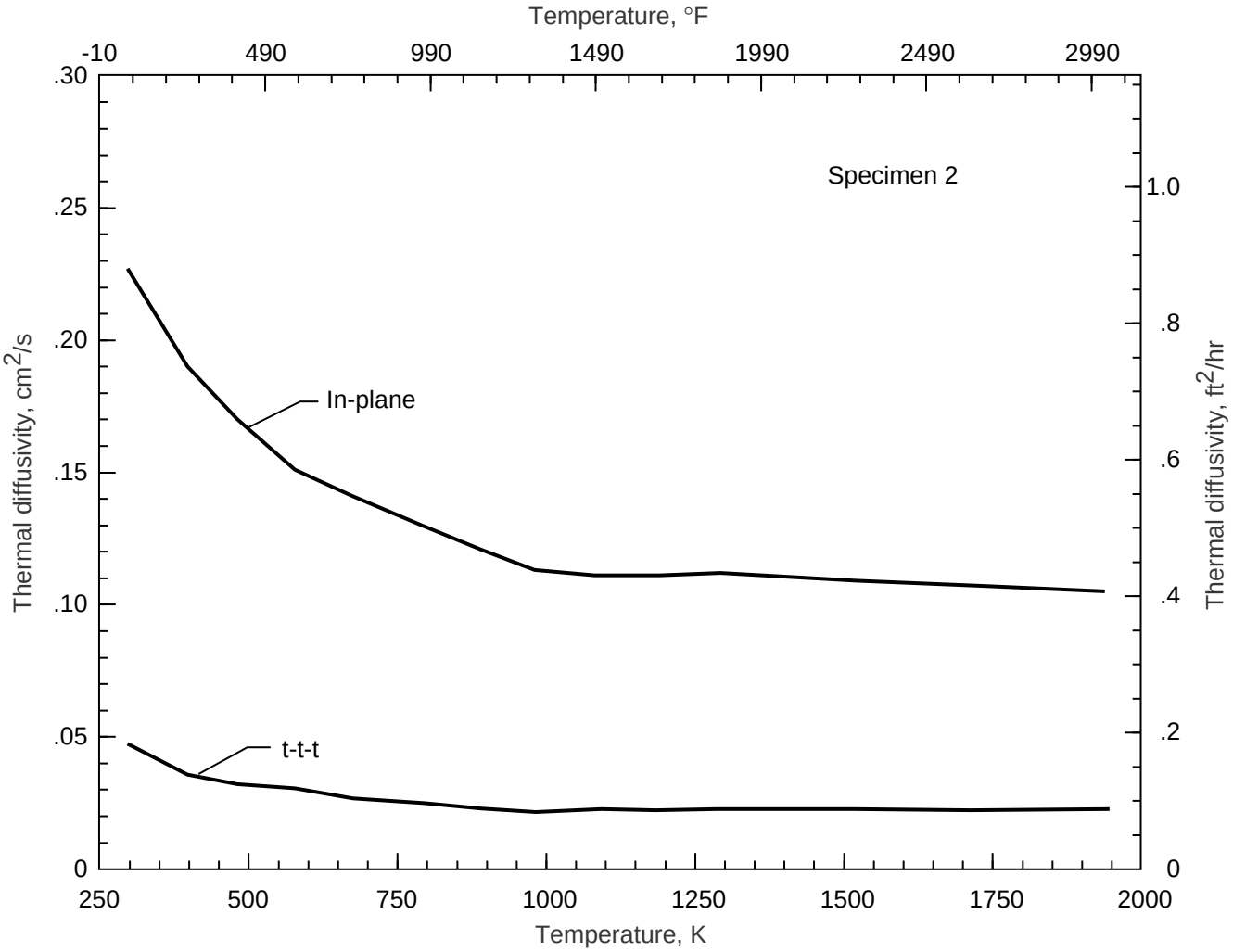

Figure 5. Thermal diffusivity versus temperature for LaRC panel 7B, which is T-300 3k LoPIC densified material.

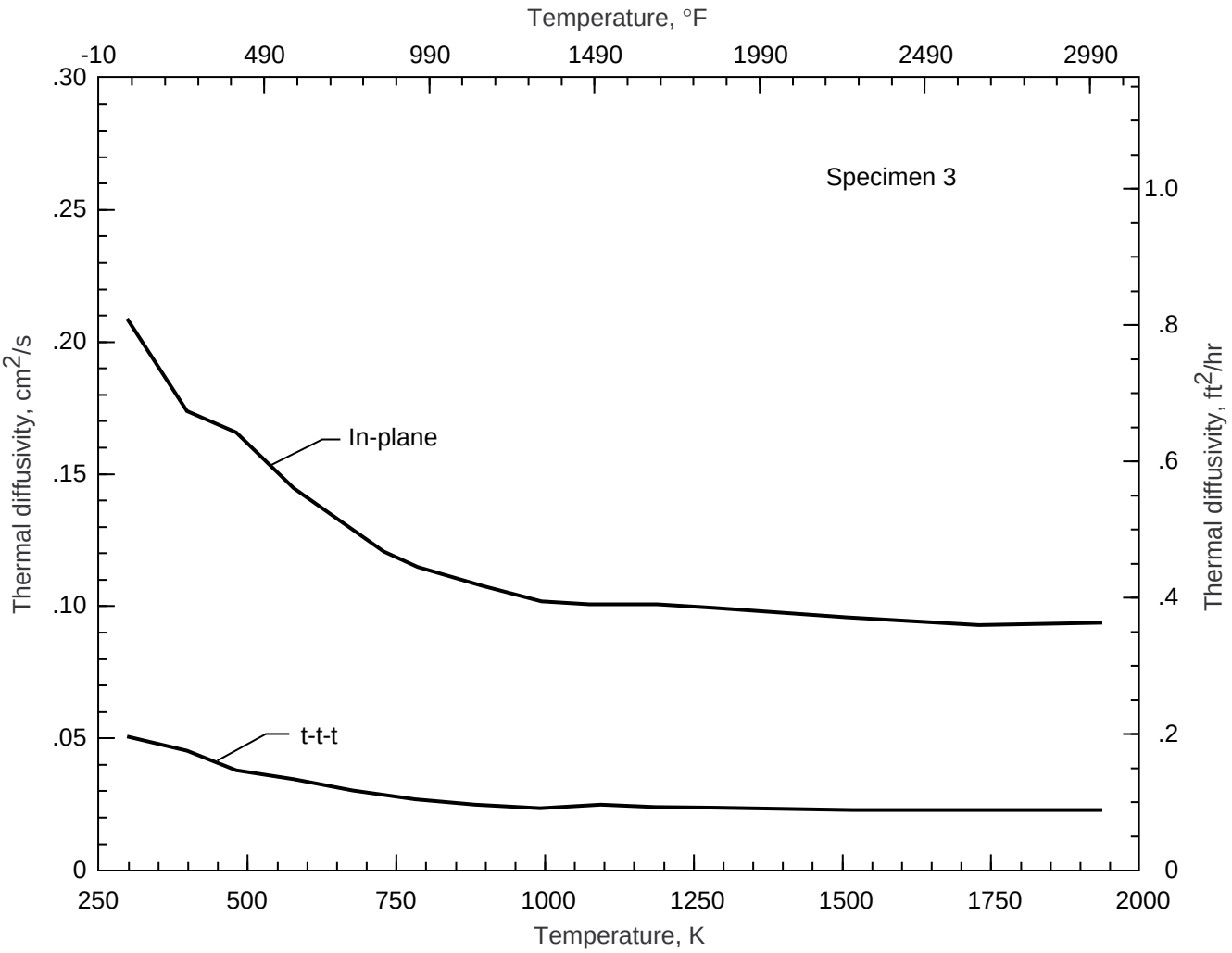

Figure 6. Thermal diffusivity versus temperature for LaRC panel 6, which is T-300 3k hybrid densified material.

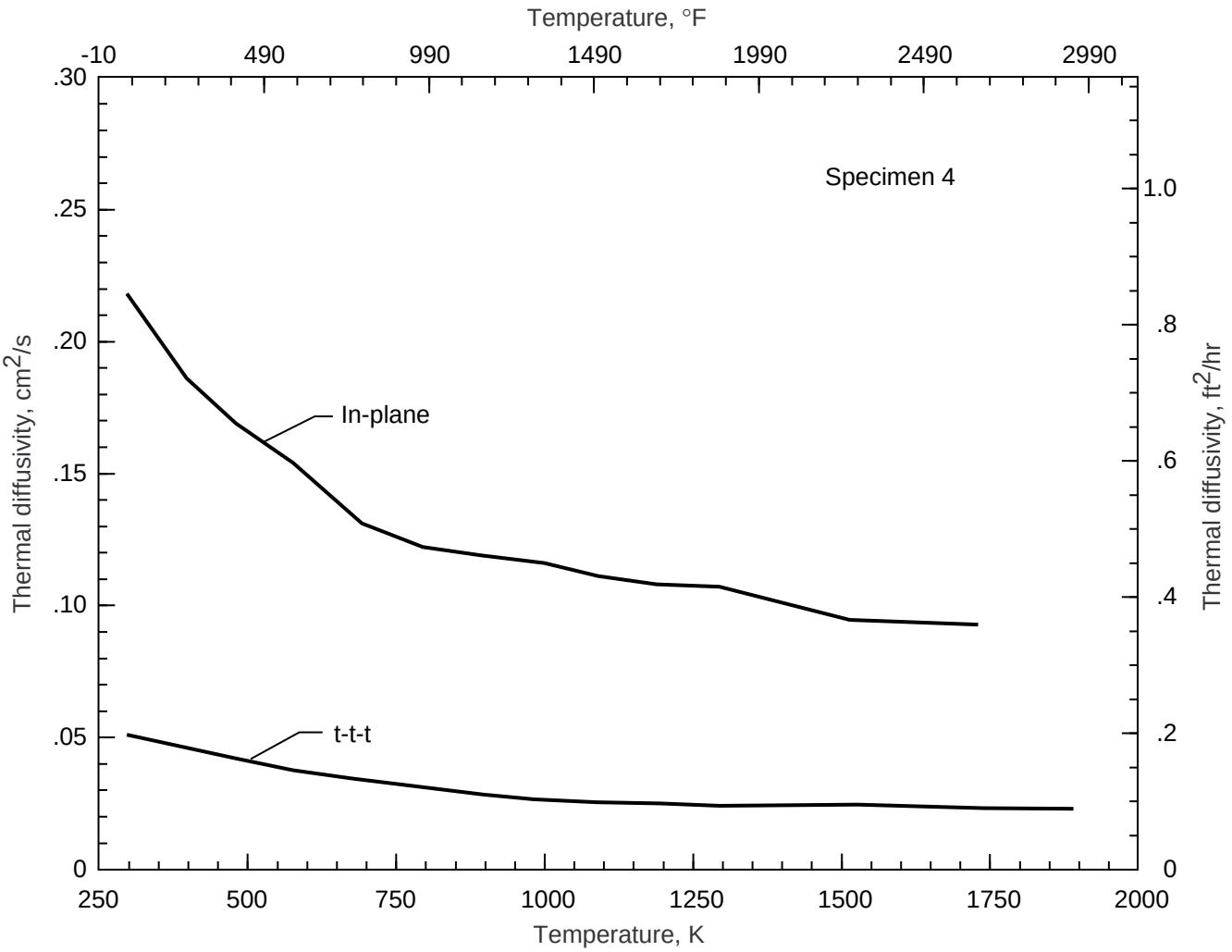

Figure 7. Thermal diffusivity versus temperature for LaRC panel 7C, which is T-300 3k CVI densified material.

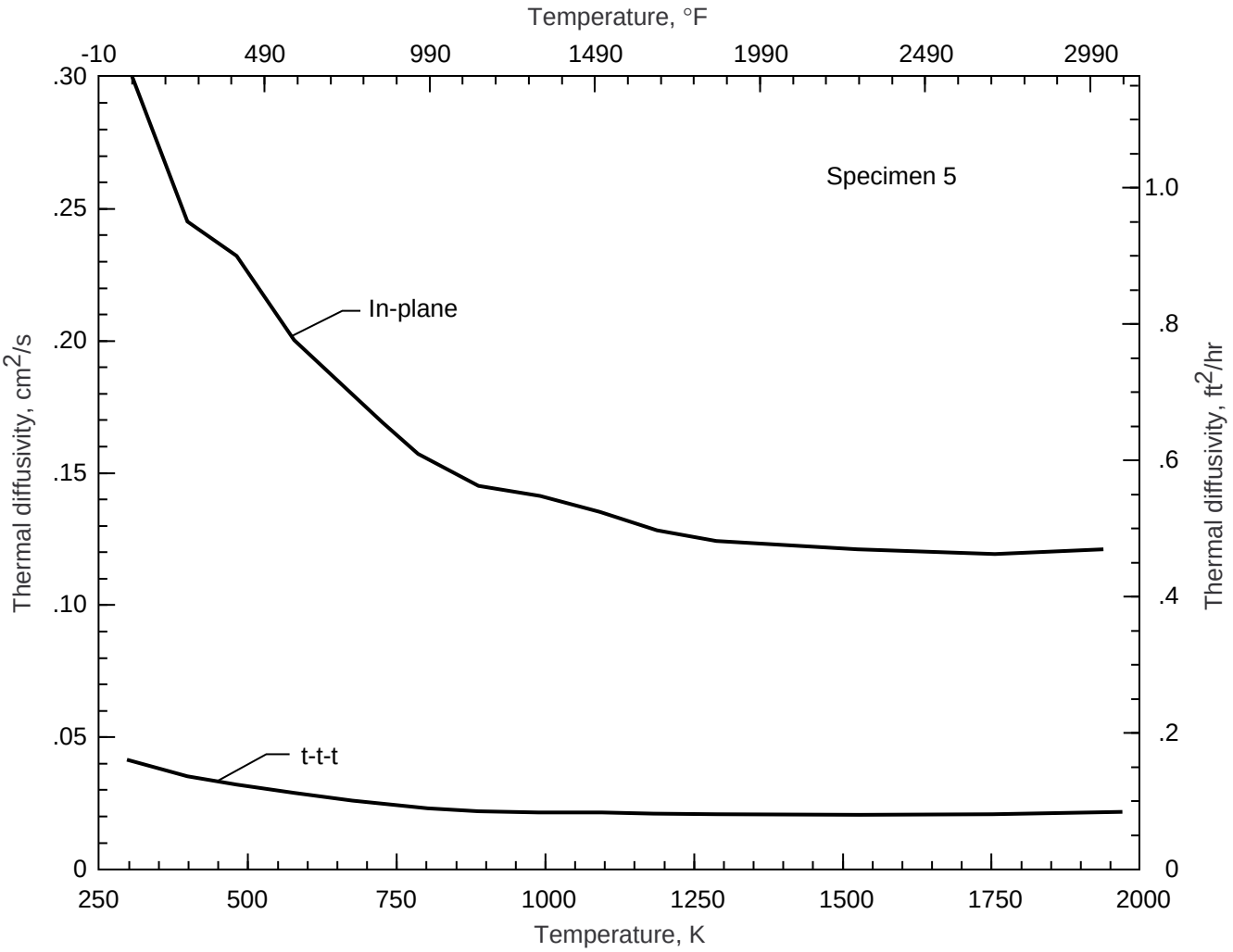

Figure 8. Thermal diffusivity versus temperature for LaRC panel 1P, which is T-50 3k phenolic densified material.

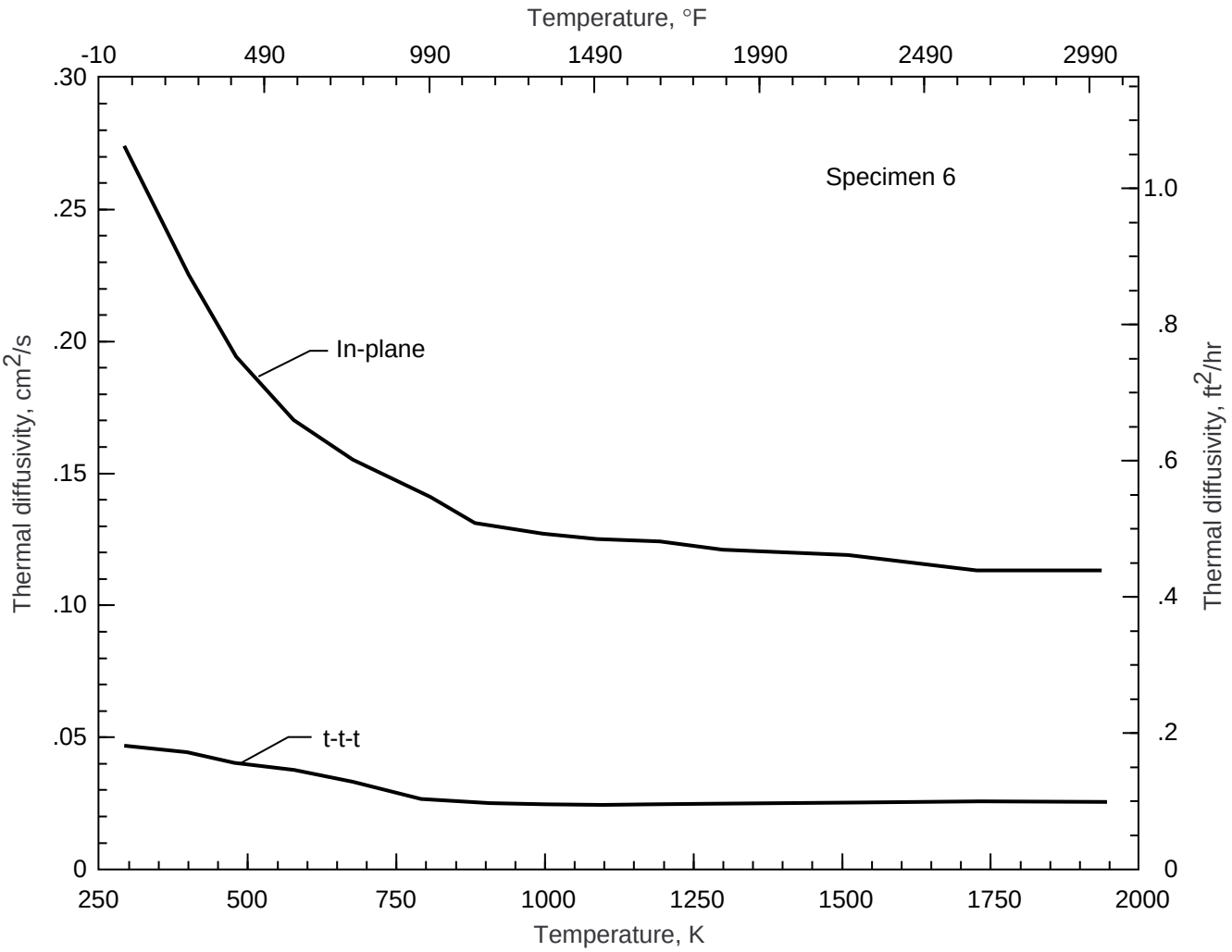

Figure 9. Thermal diffusivity versus temperature for LaRC panel 9H, which is T-50 3k hybrid densified material.

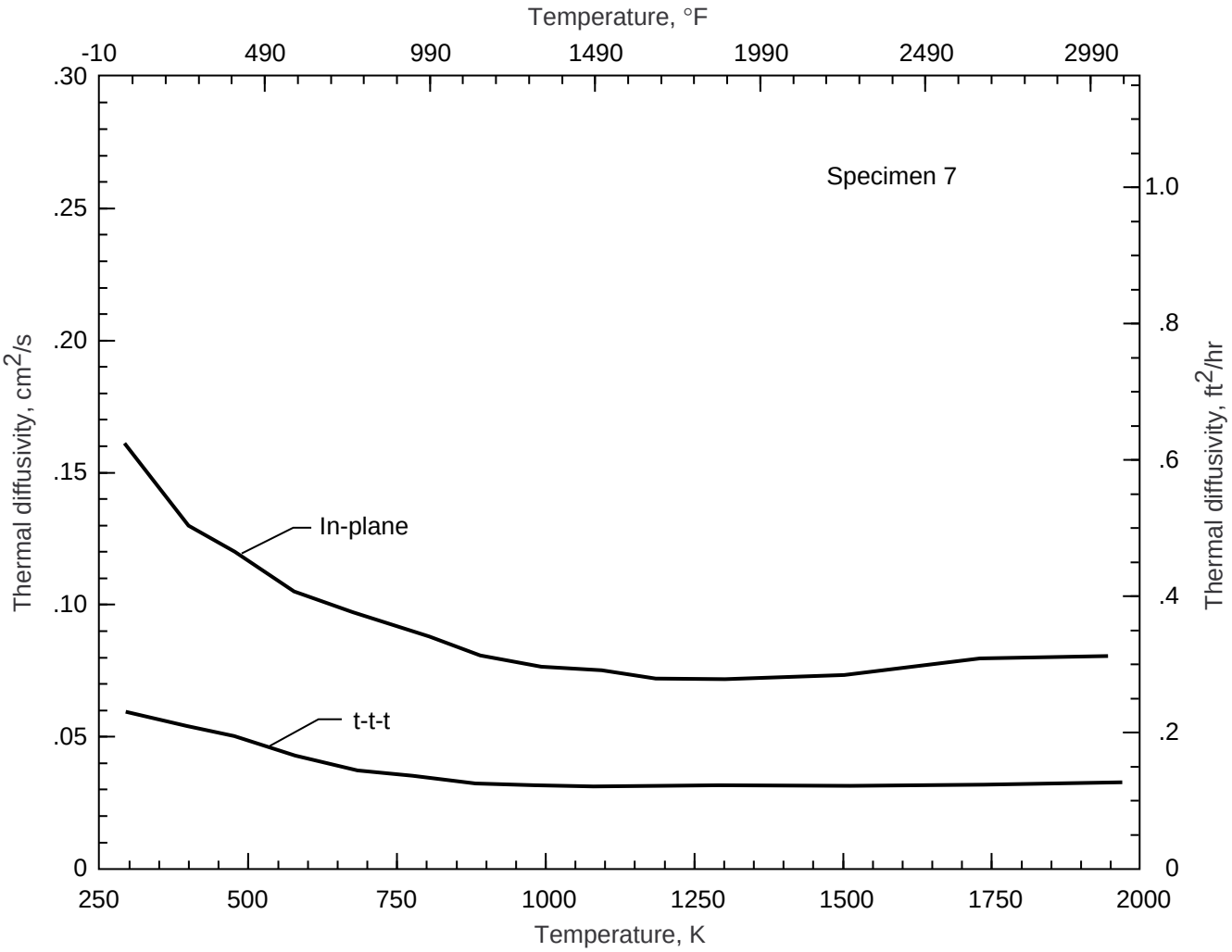

Figure 10. Thermal diffusivity versus temperature for LaRC panel 10-1, which is Celion 3k phenolic densified material.

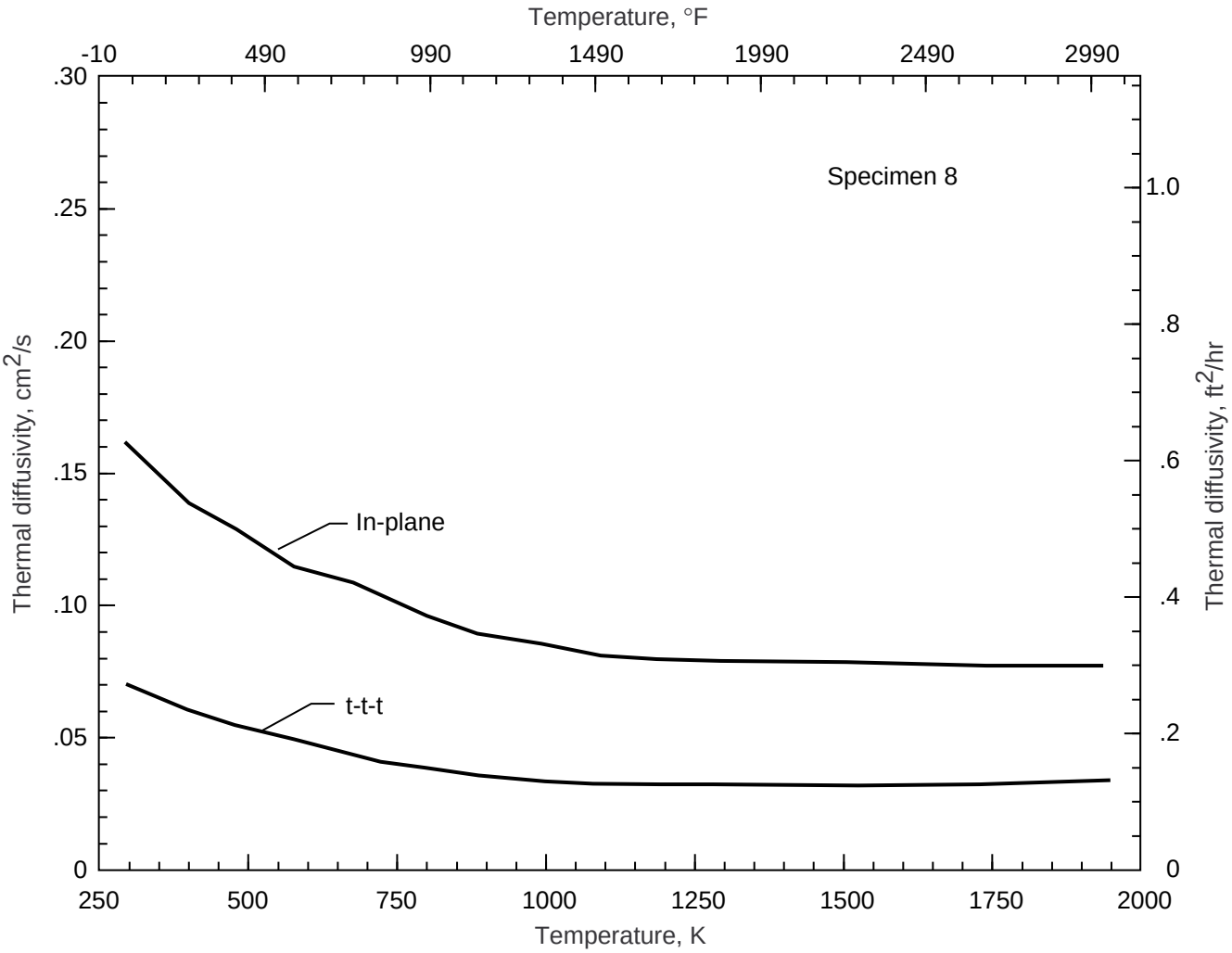

Figure 11. Thermal diffusivity versus temperature for LaRC panel 10-3, which is Celion 3k LoPIC densified material.

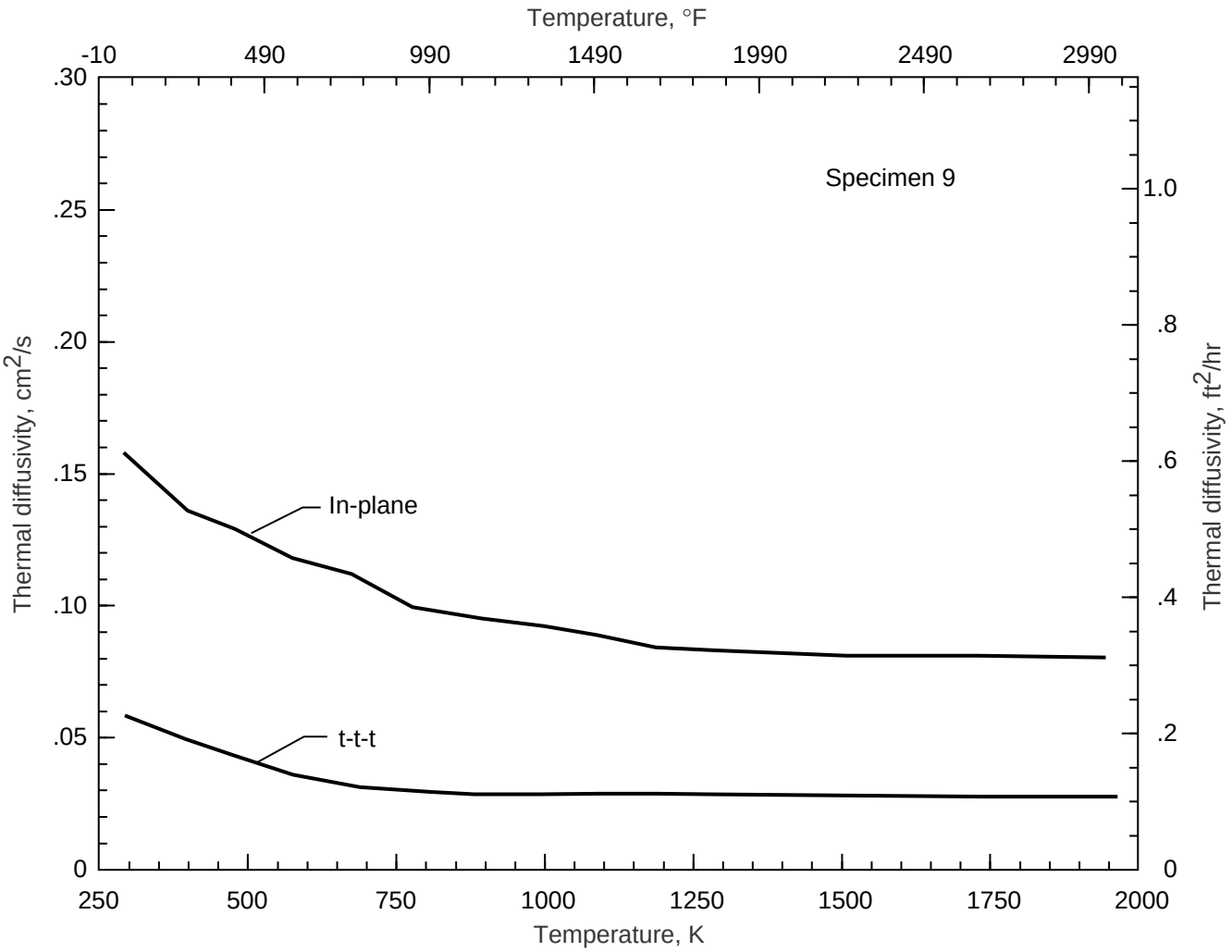

Figure 12. Thermal diffusivity versus temperature for LaRC panel 9-1, which is Celion 3k/2k phenolic densified material.

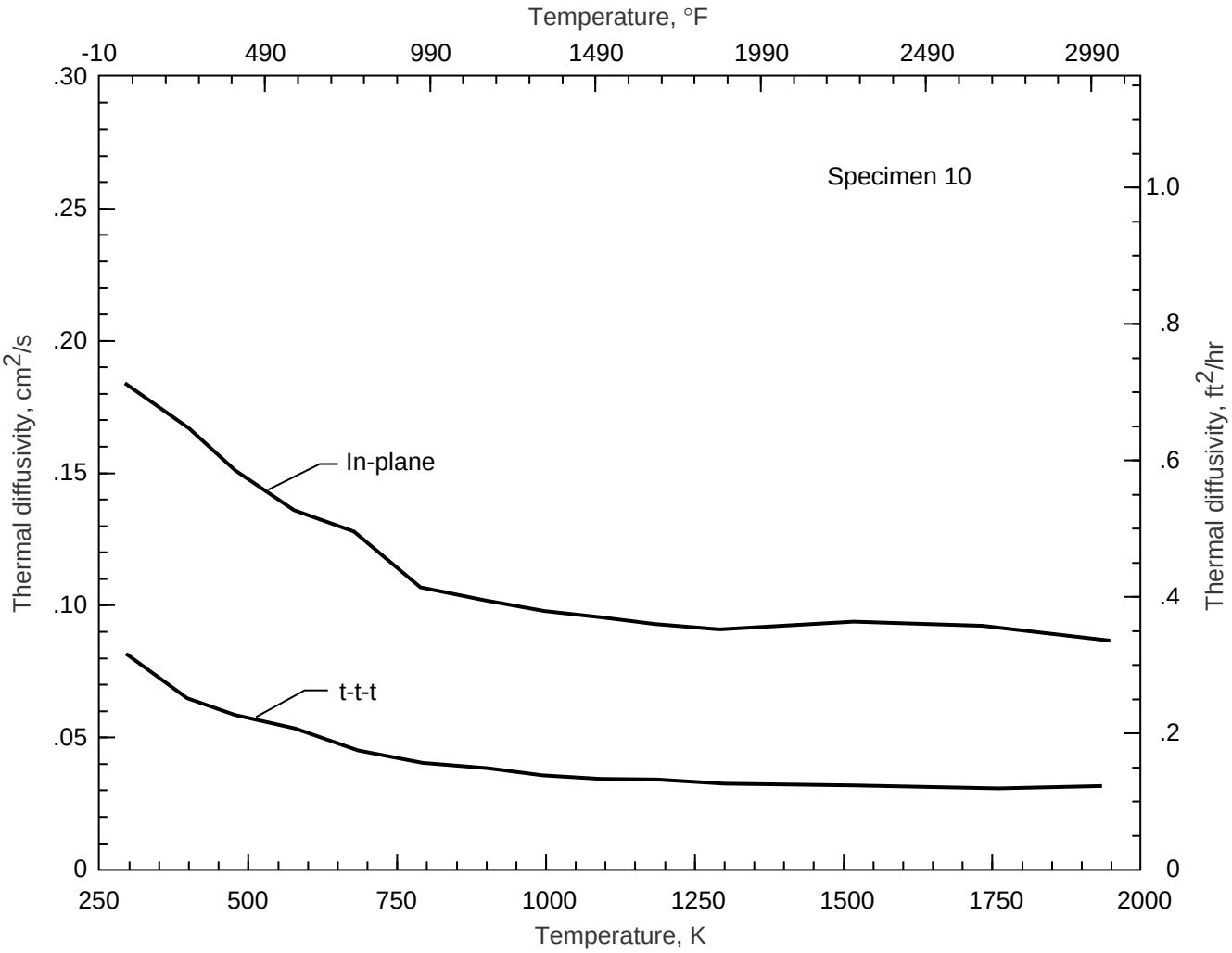

Figure 13. Thermal diffusivity versus temperature for LaRC panel 9-3, which is Celion 3k/2k LoPIC densified material.

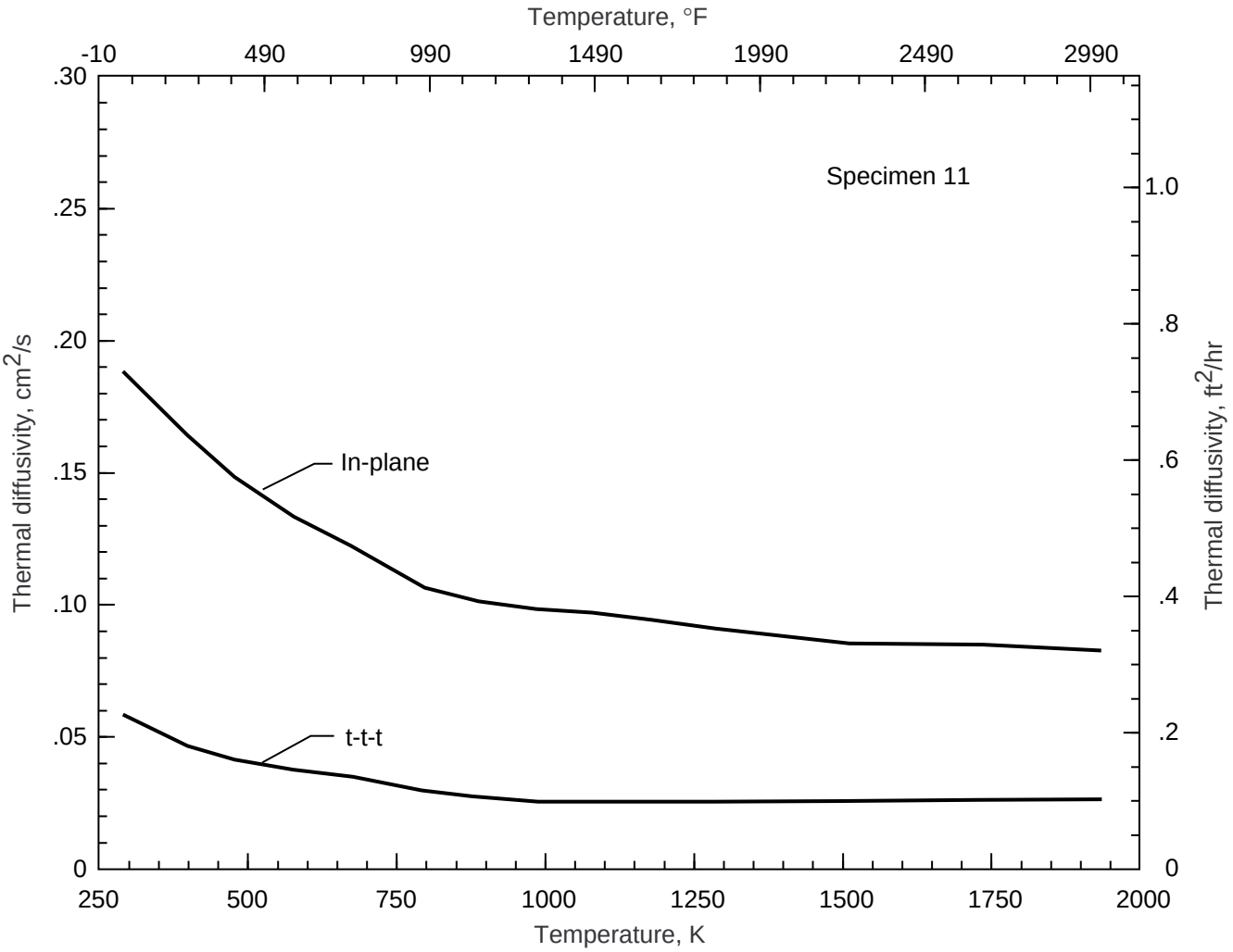

Figure 14. Thermal diffusivity versus temperature for Boeing/Rohr T-300 1k hybrid densified material.

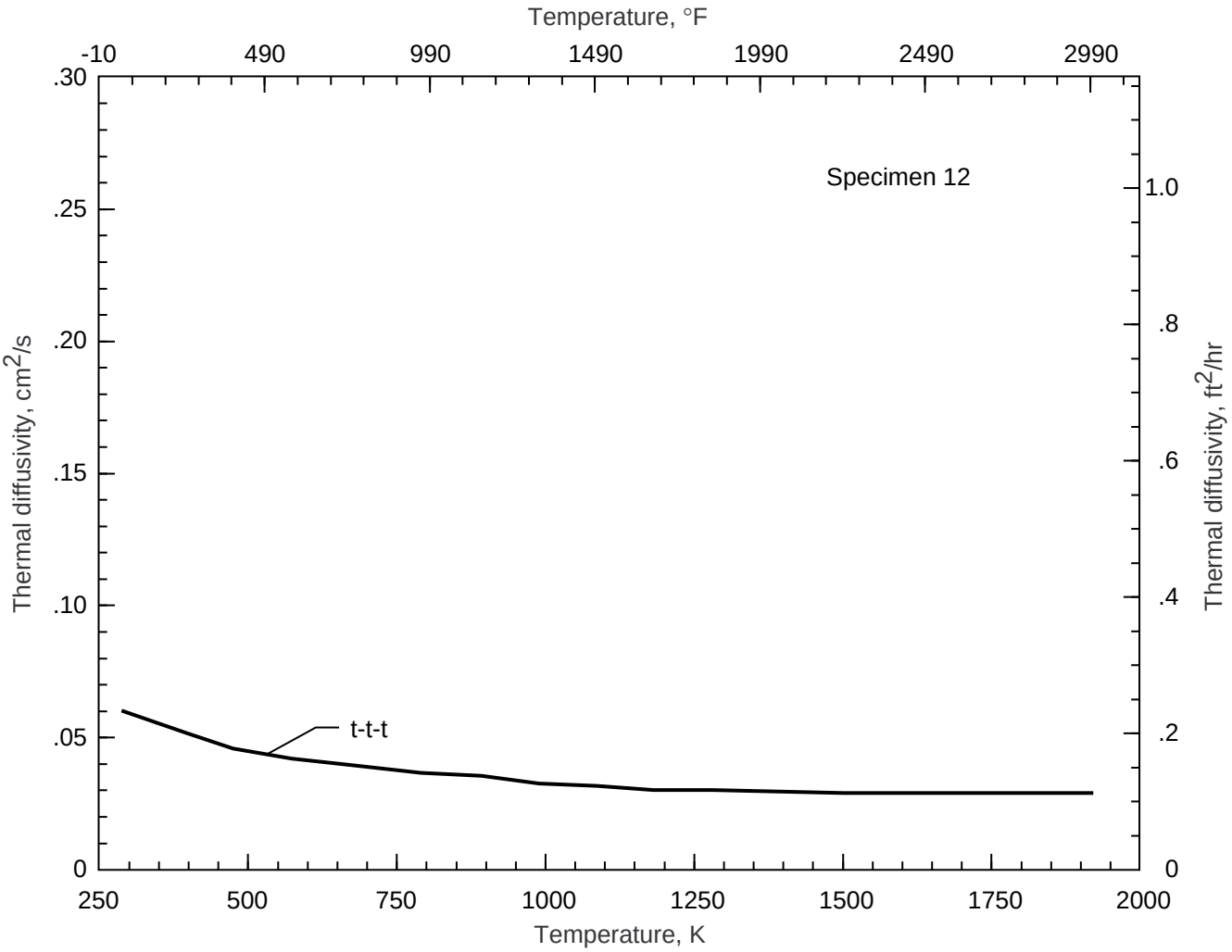

Figure 15. Thermal diffusivity versus temperature for CVD-coated Boeing/Rohr T-300 1k hybrid densified material.

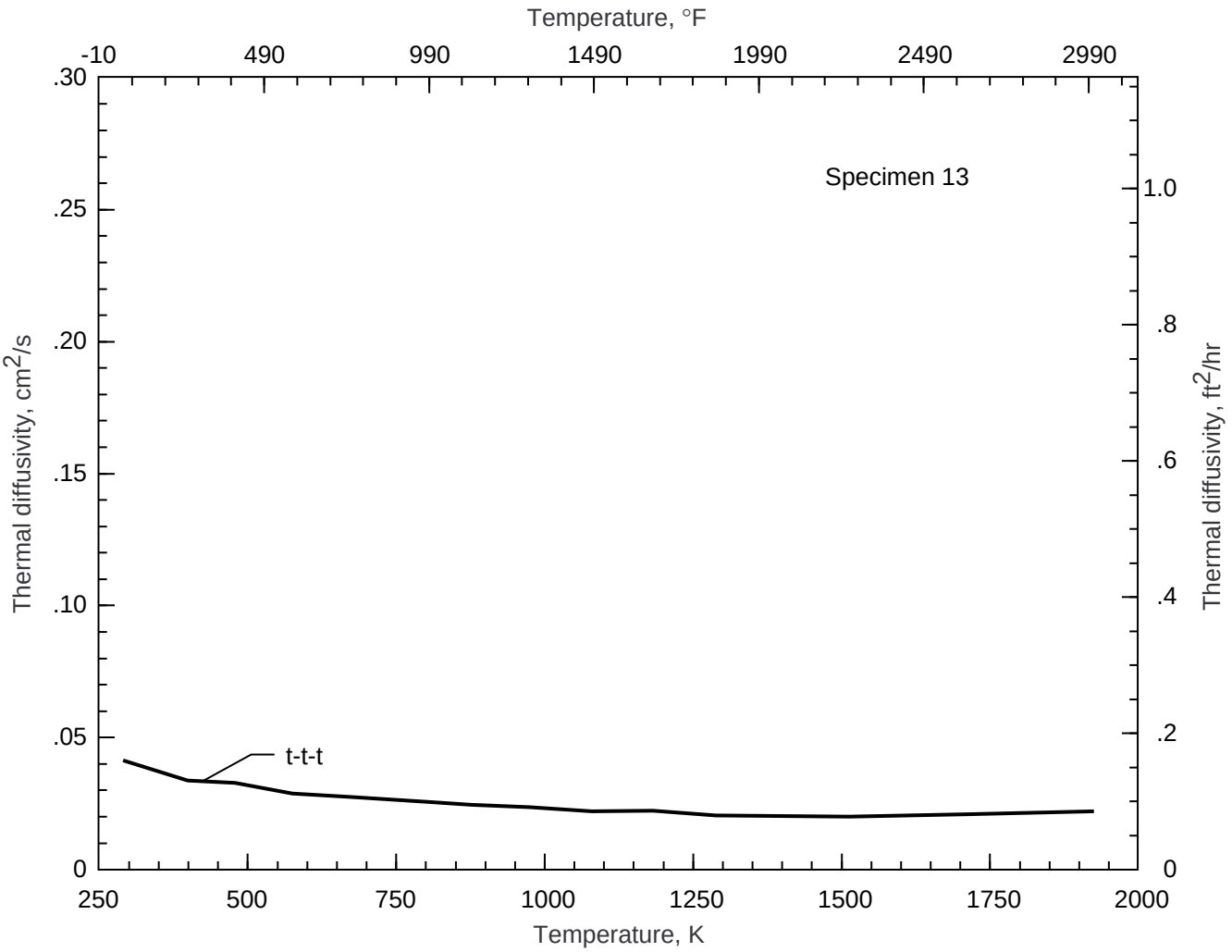

Figure 16. Thermal diffusivity versus temperature for PPC-coated Boeing/Rohr T-300 1k hybrid densified material.

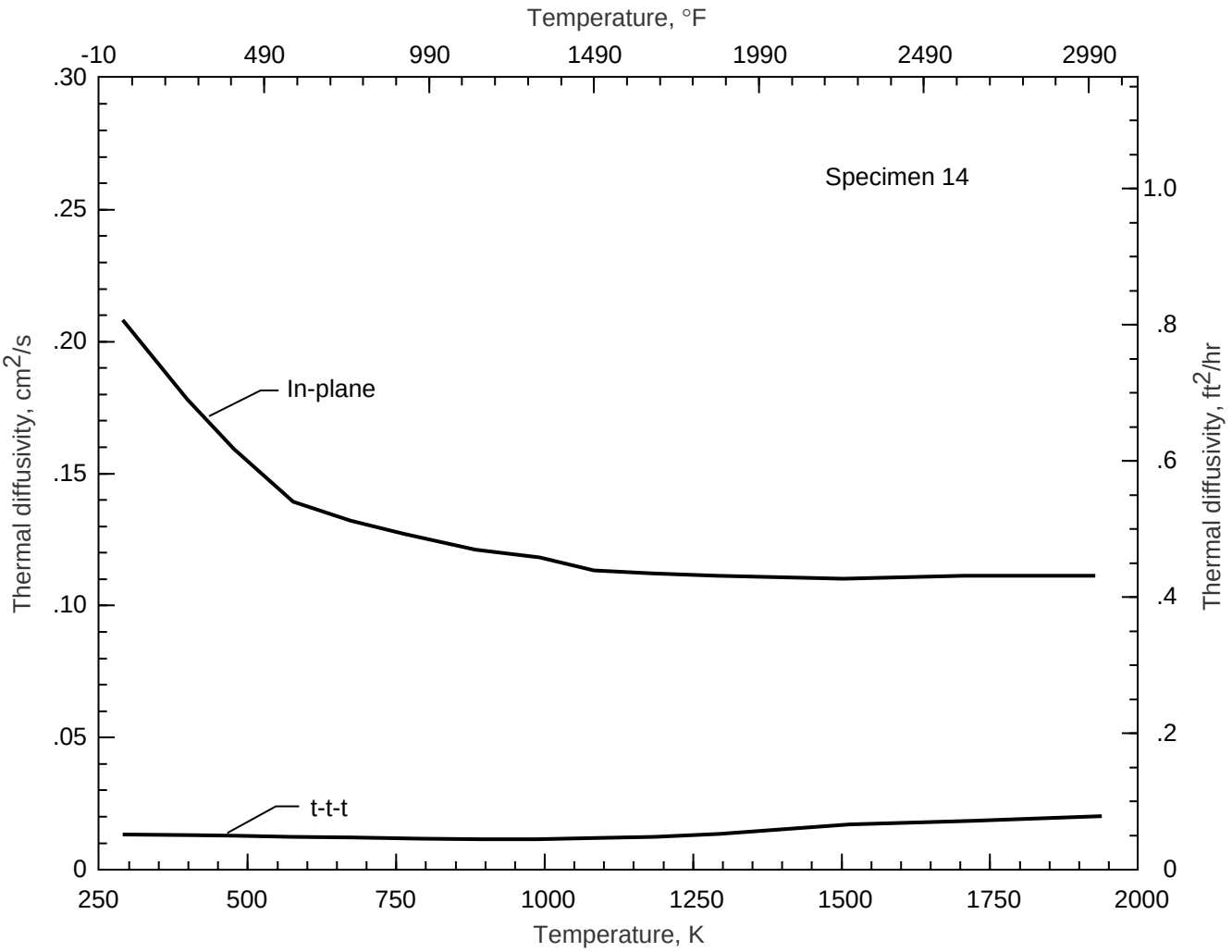

Figure 17. Thermal diffusivity versus temperature for CCAT T-300 3k phenolic densified material.

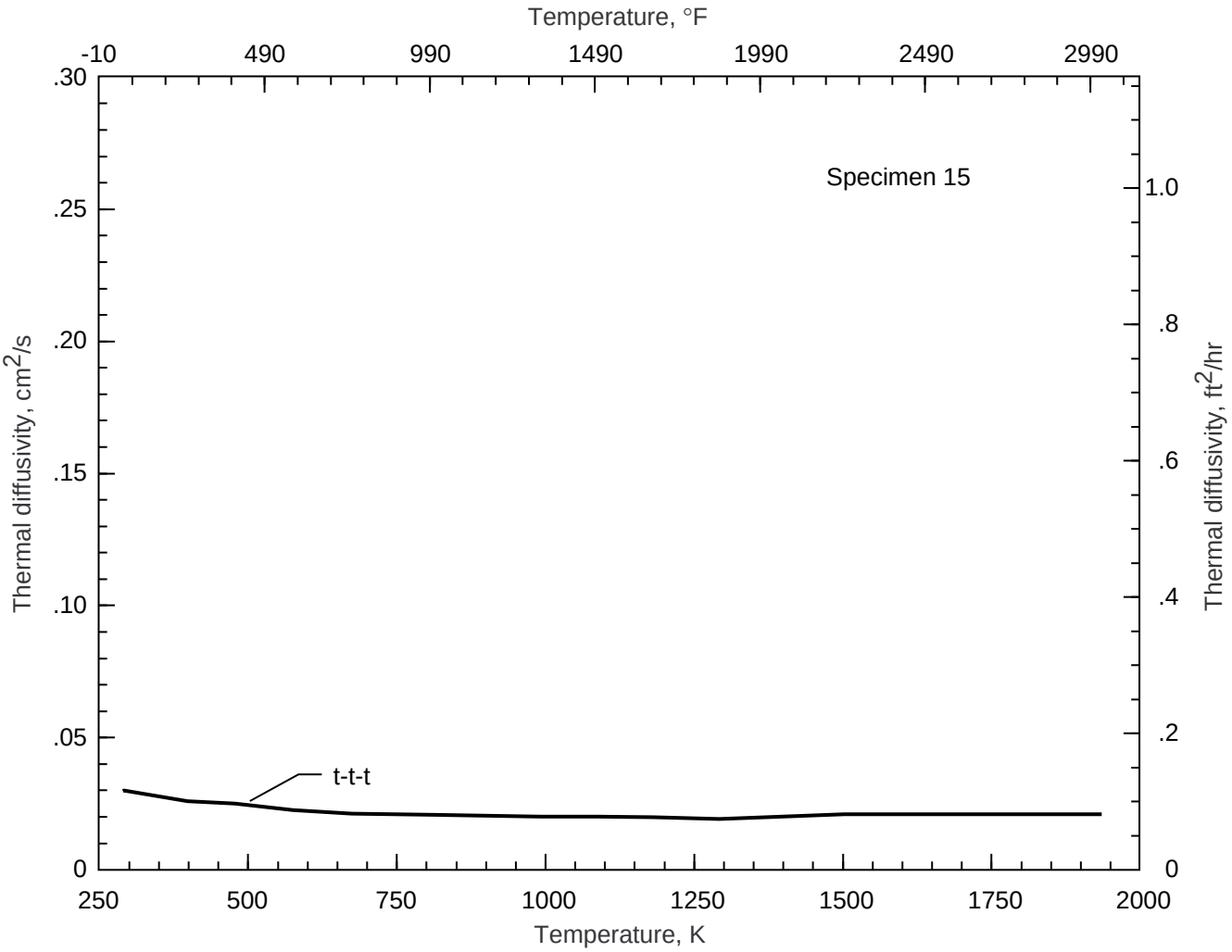

Figure 18. Thermal diffusivity versus temperature for Type III coated CCAT T-300 3k phenolic densified material.

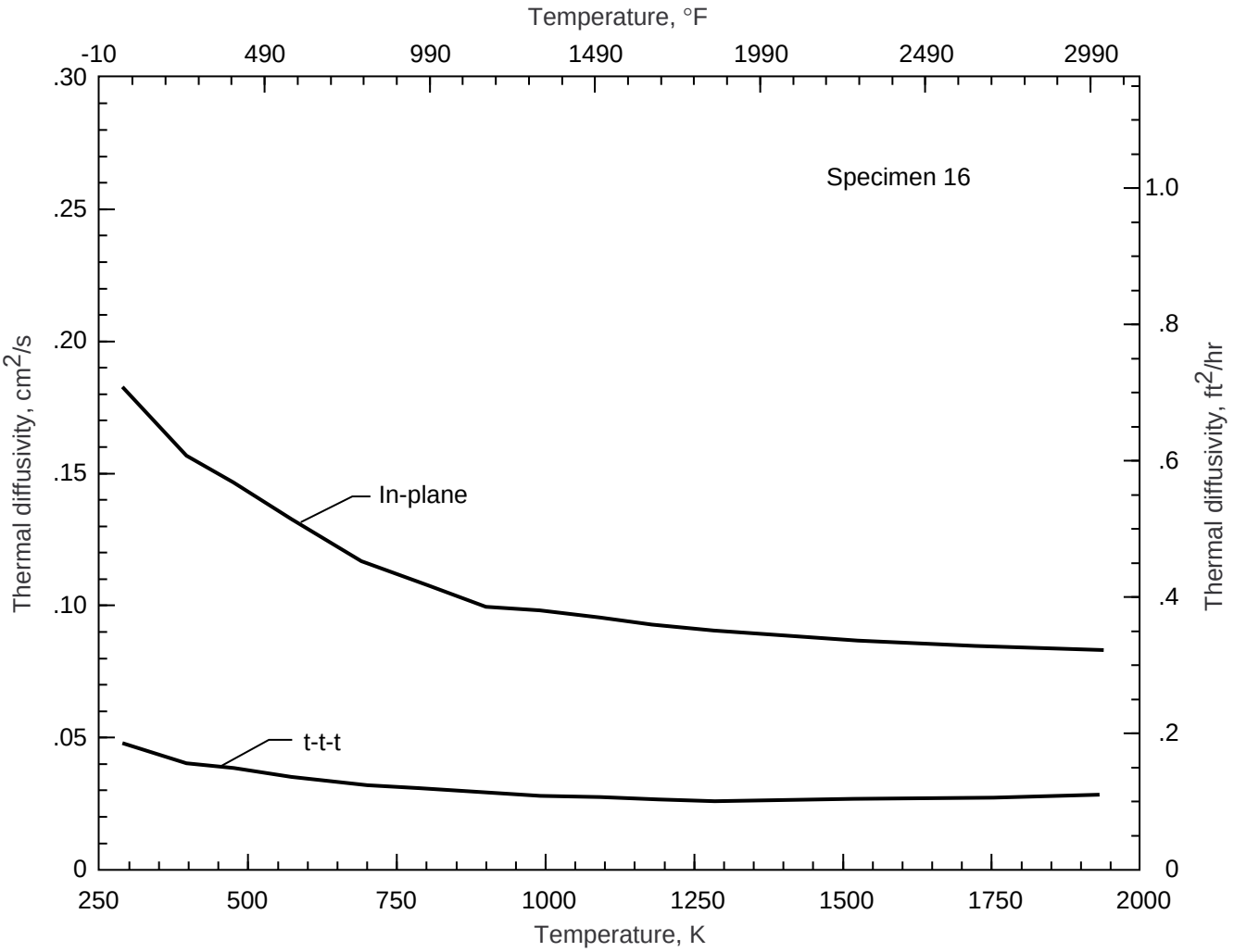

Figure 19. Thermal diffusivity versus temperature for LaRC stitched panel 2, which is T-300 3k phenolic densified material.

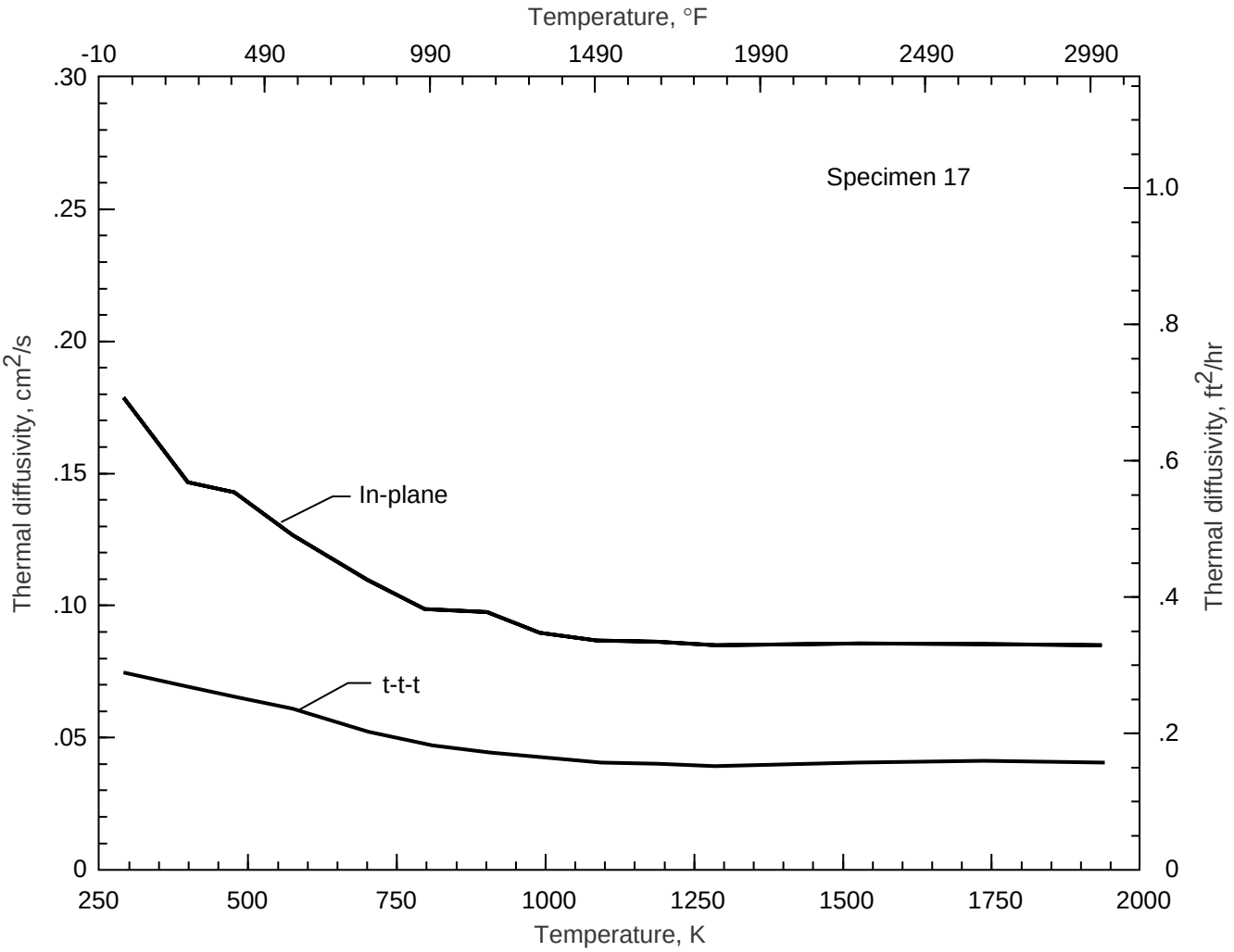

Figure 20. Thermal diffusivity versus temperature for LaRC stitched panel 5, which is T-300 3k phenolic densified material.

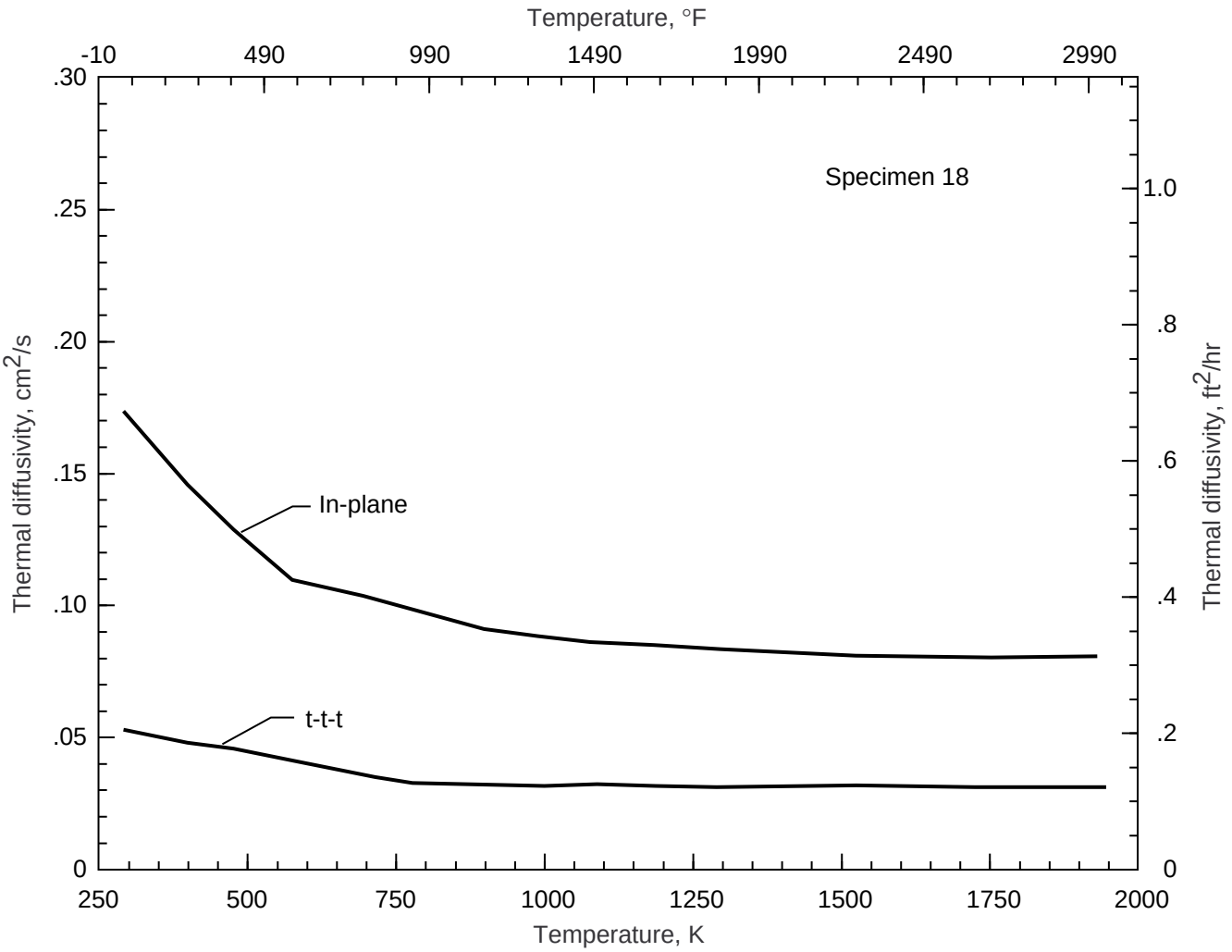

Figure 21. Thermal diffusivity versus temperature for LaRC stitched panel 8, which is T-300 3k phenolic densified material.

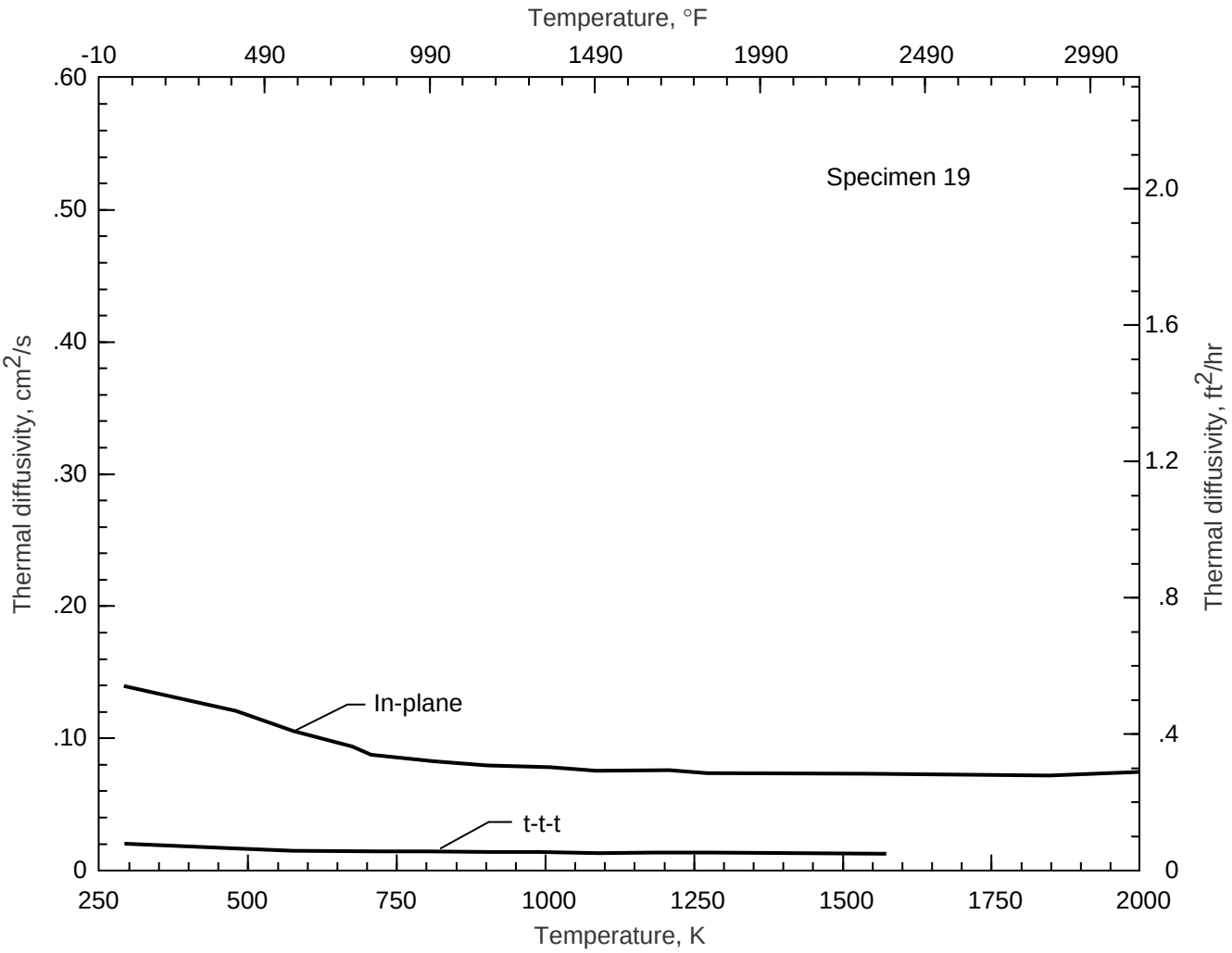

Figure 22. Thermal diffusivity versus temperature for LaRC J1, which is T-300 3k CVI densified material.

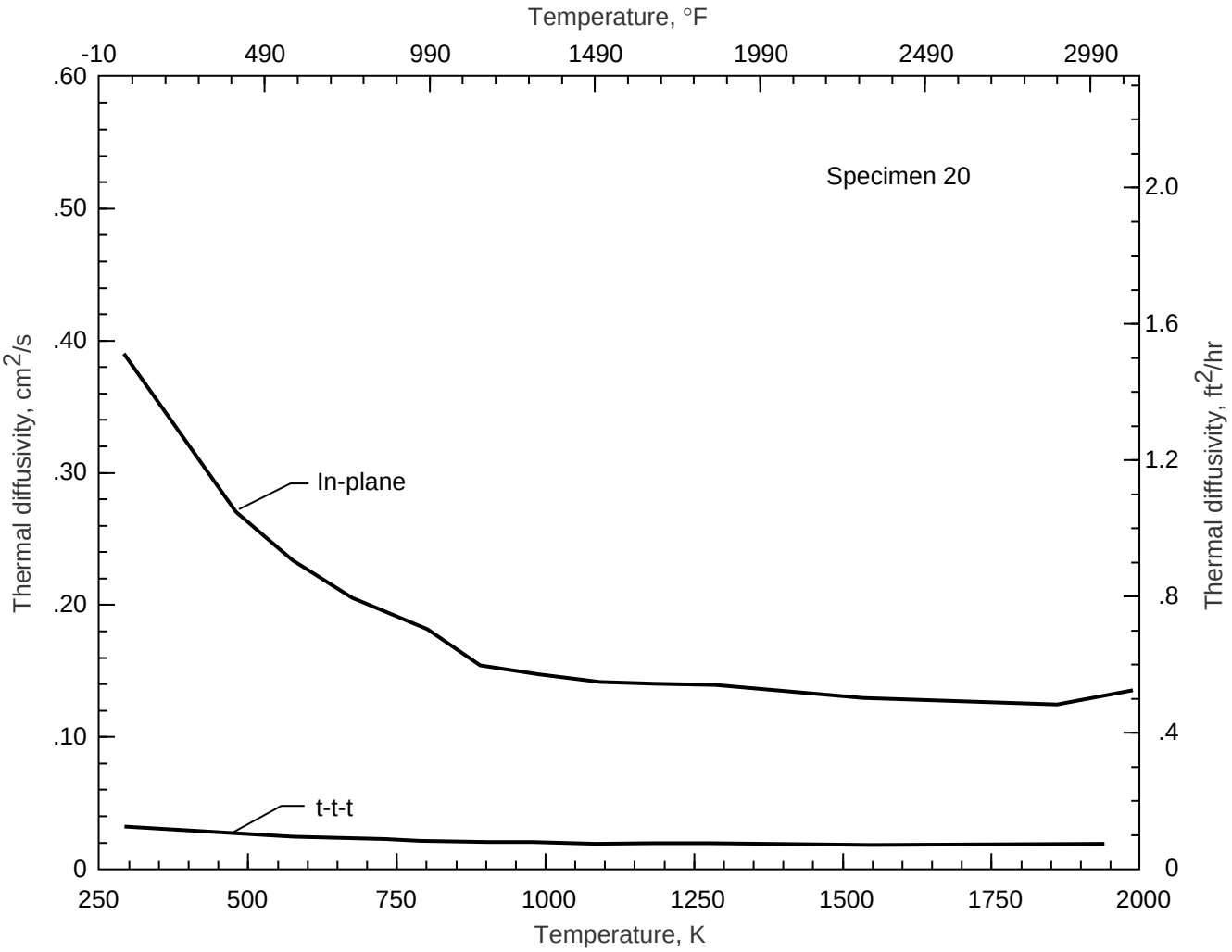

Figure 23. Thermal diffusivity versus temperature for LaRC J2, which is T-300 3k CVI densified material.

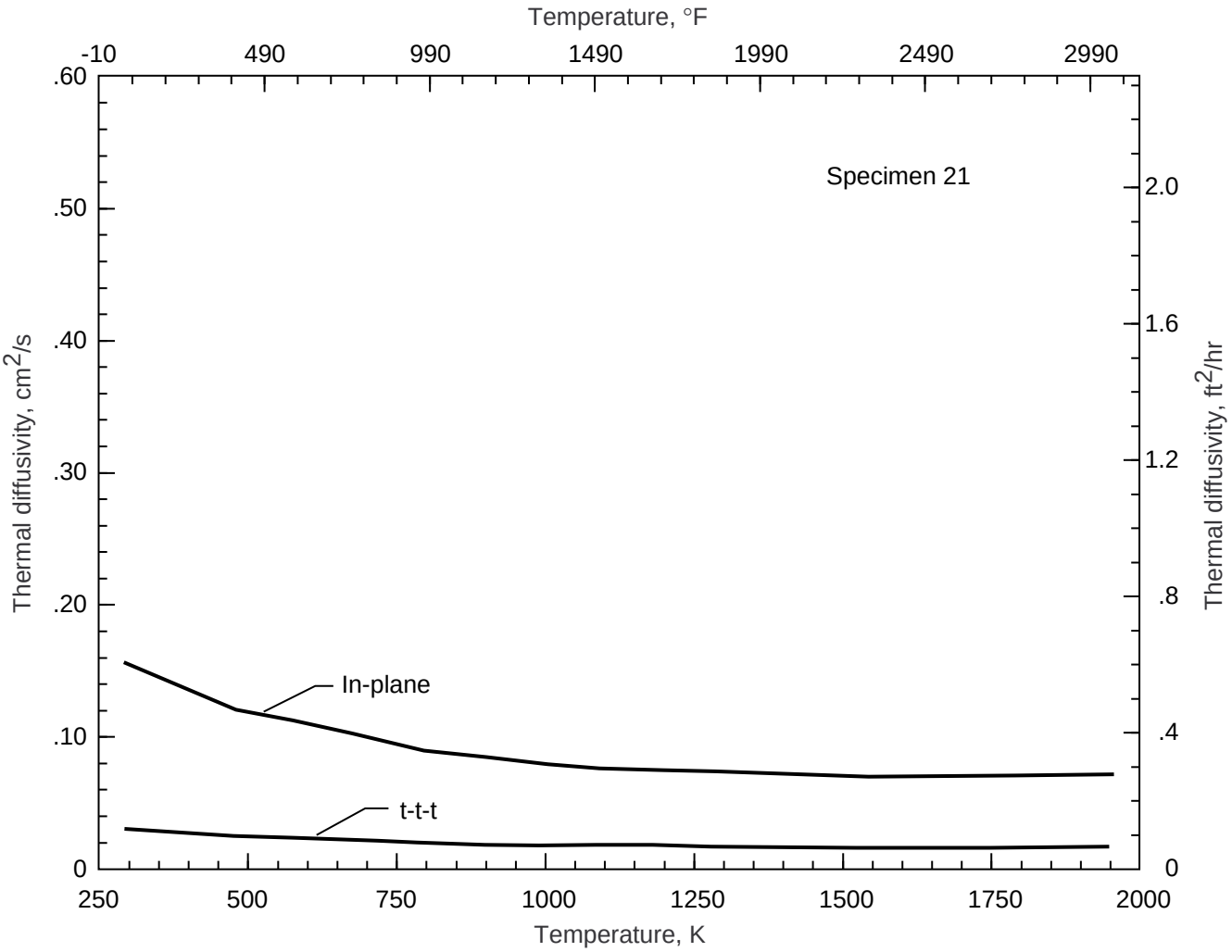

Figure 24. Thermal diffusivity versus temperature for LaRC J3, which is T-300 3k CVI densified material.

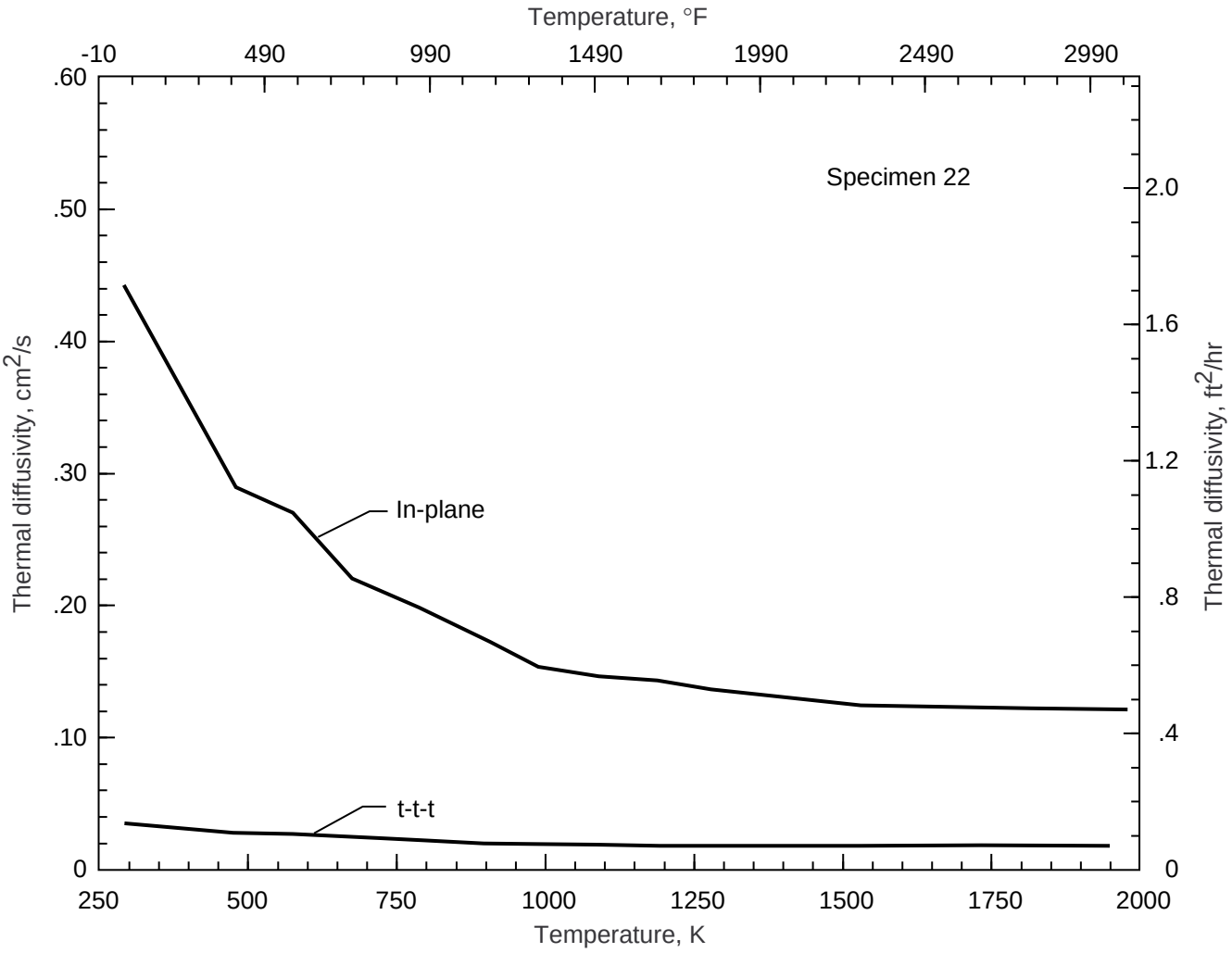

Figure 25. Thermal diffusivity versus temperature for LaRC J4, which is T-300 3k CVI densified material.

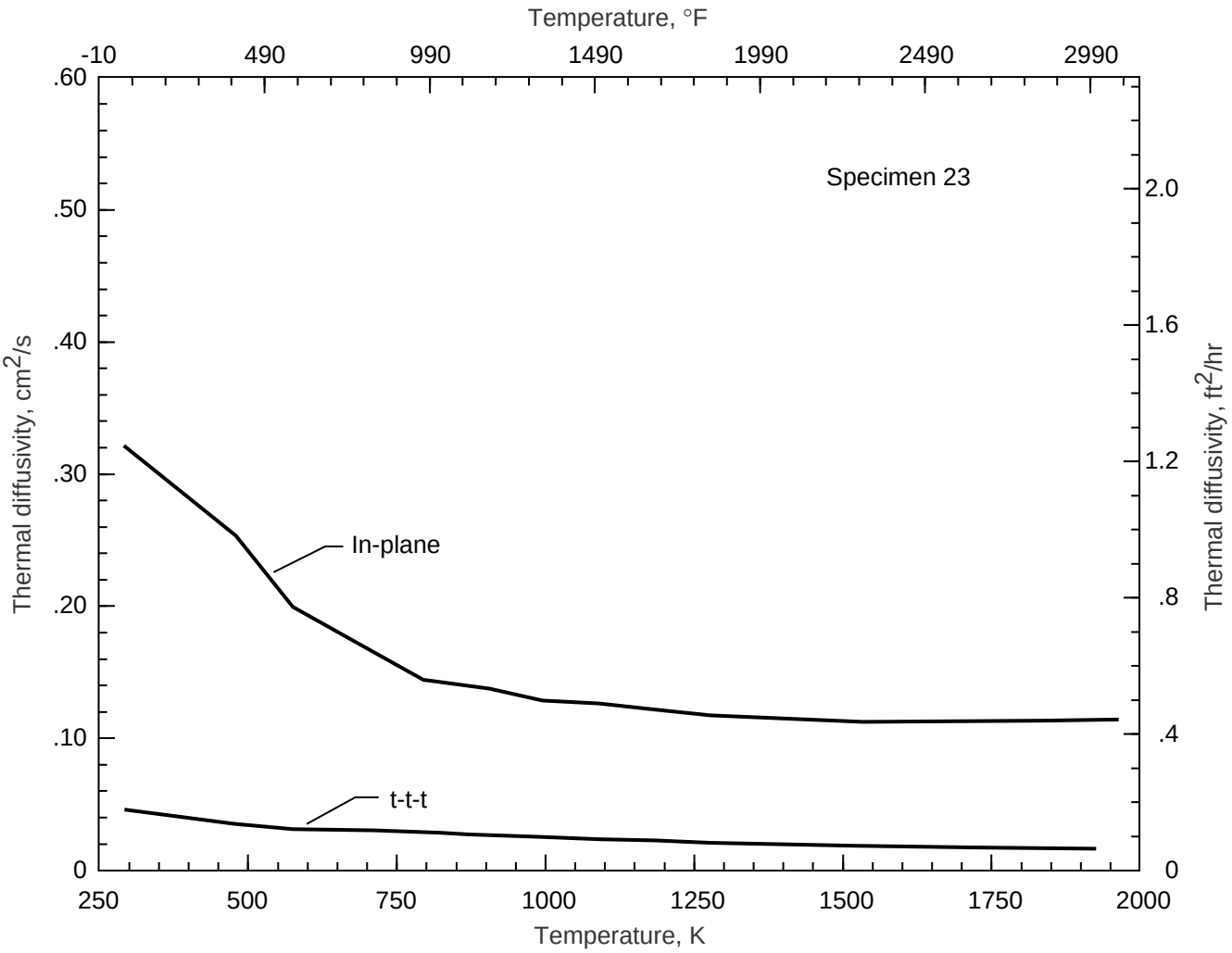

Figure 26. Thermal diffusivity versus temperature for LaRC J5, which is T-300 3k CVI densified material.

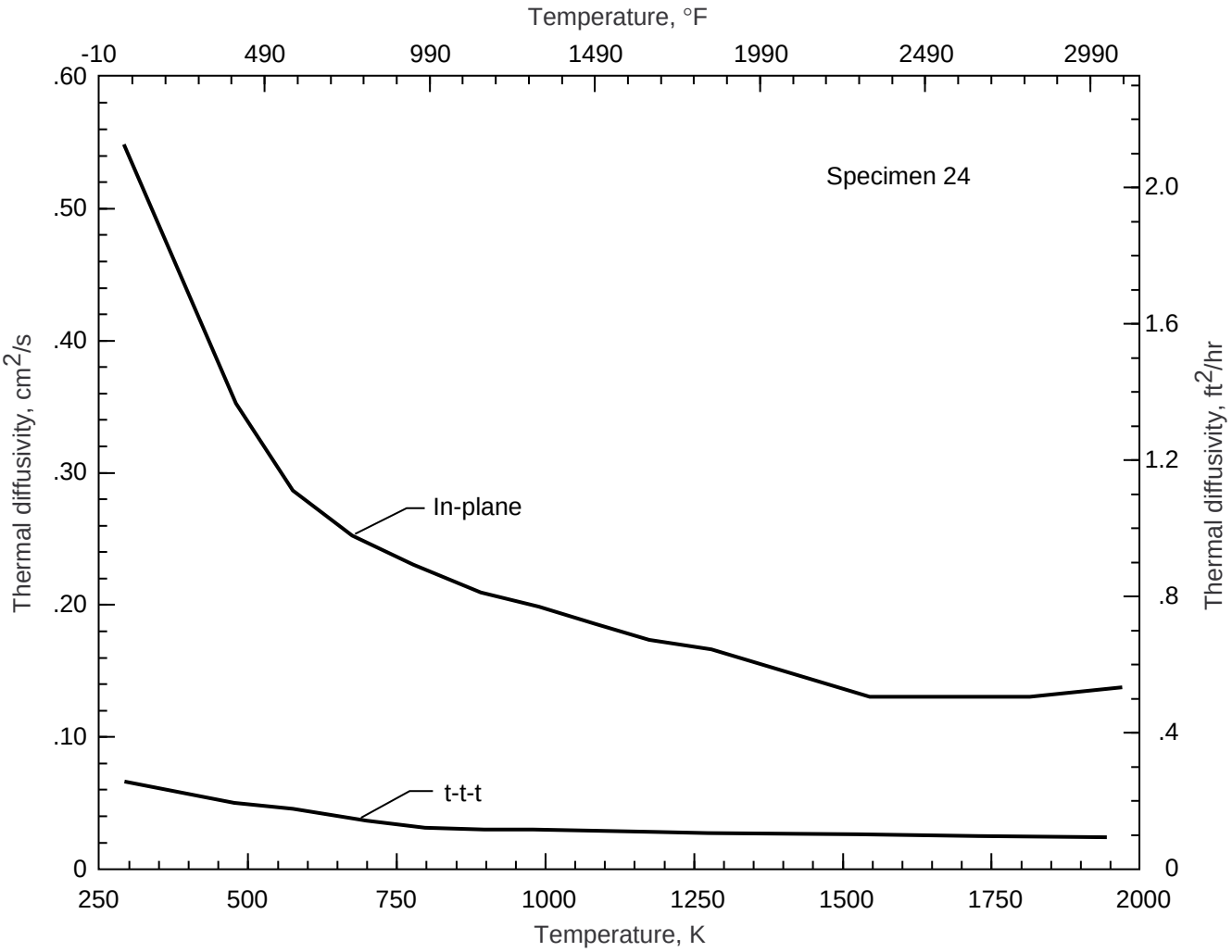

Figure 27. Thermal diffusivity versus temperature for LaRC J6, which is T-300 3k CVI densified material.

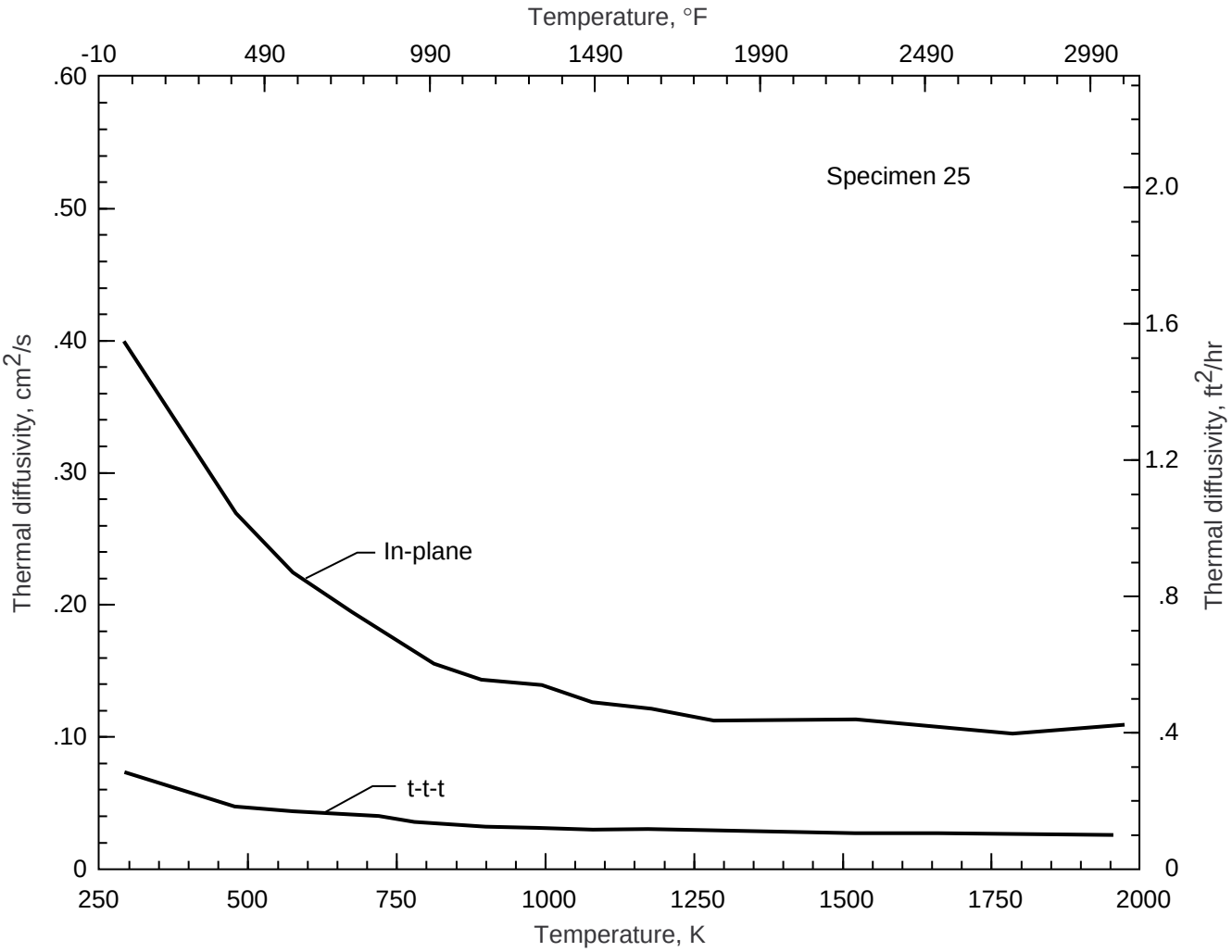

Figure 28. Thermal diffusivity versus temperature for LaRC J7, which is T-300 3k CVI densified material.

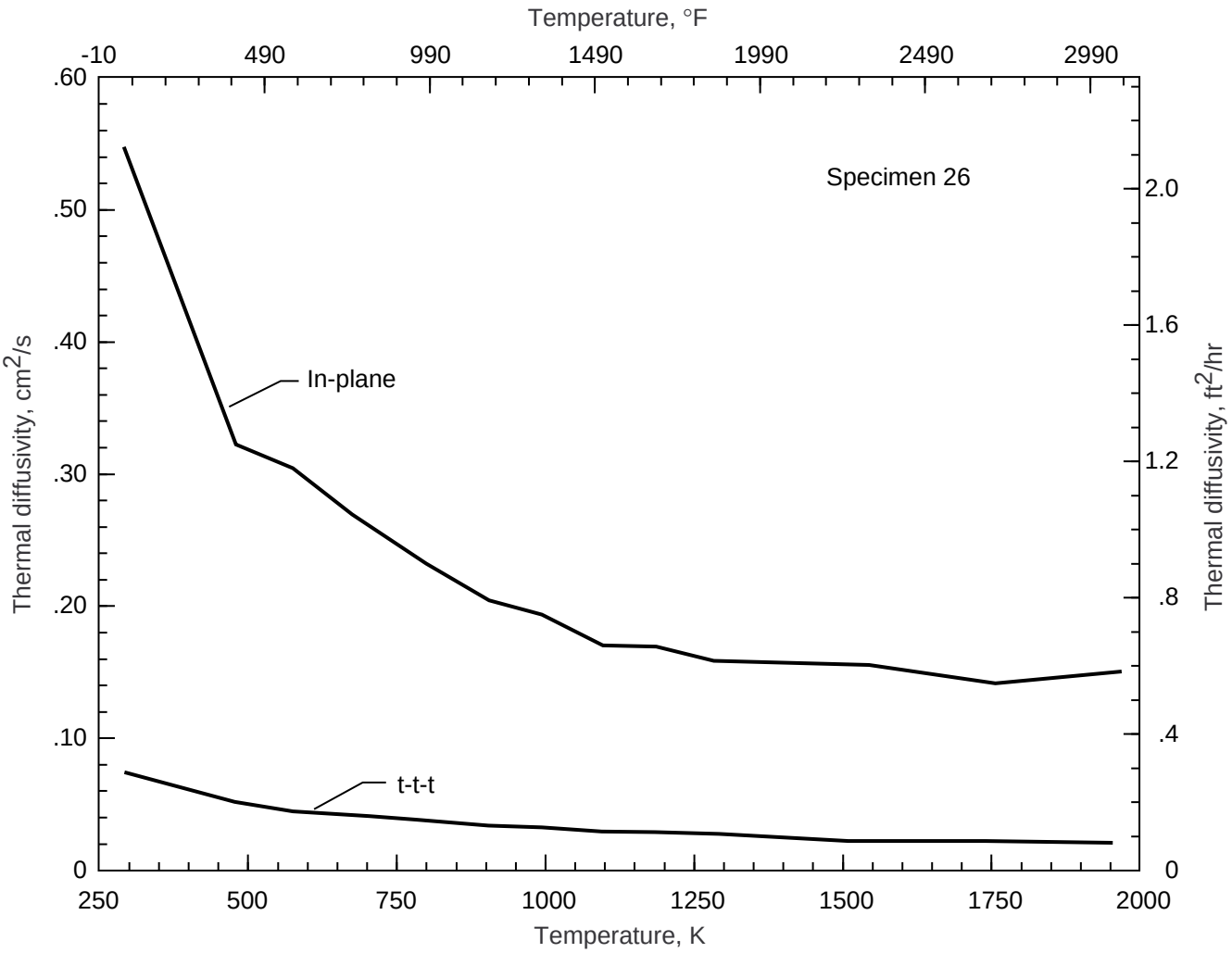

Figure 29. Thermal diffusivity versus temperature for LaRC J8, which is T-300 3k CVI densified material.

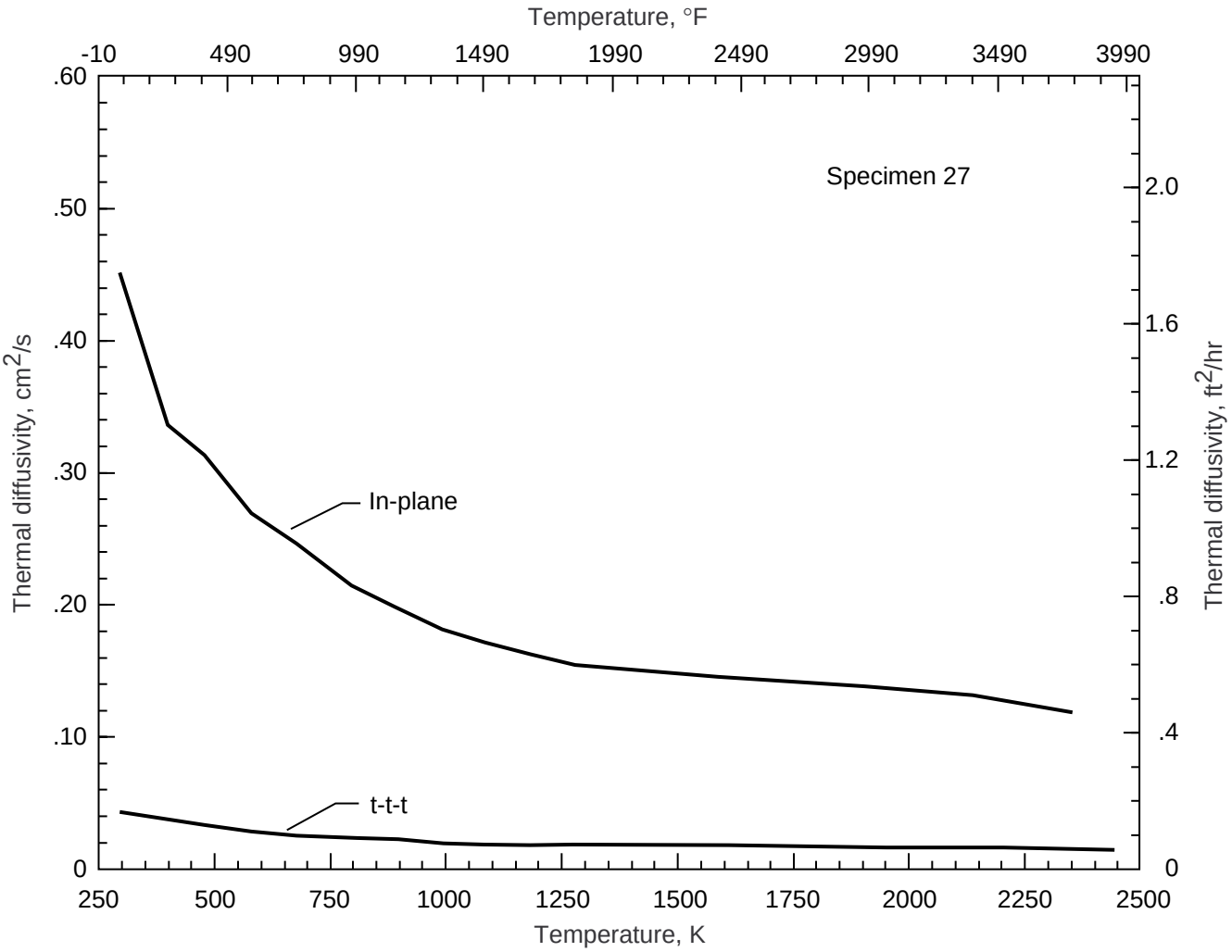

Figure 30. Thermal diffusivity versus temperature for LaRC F1, which is K321 2k phenolic densified material.

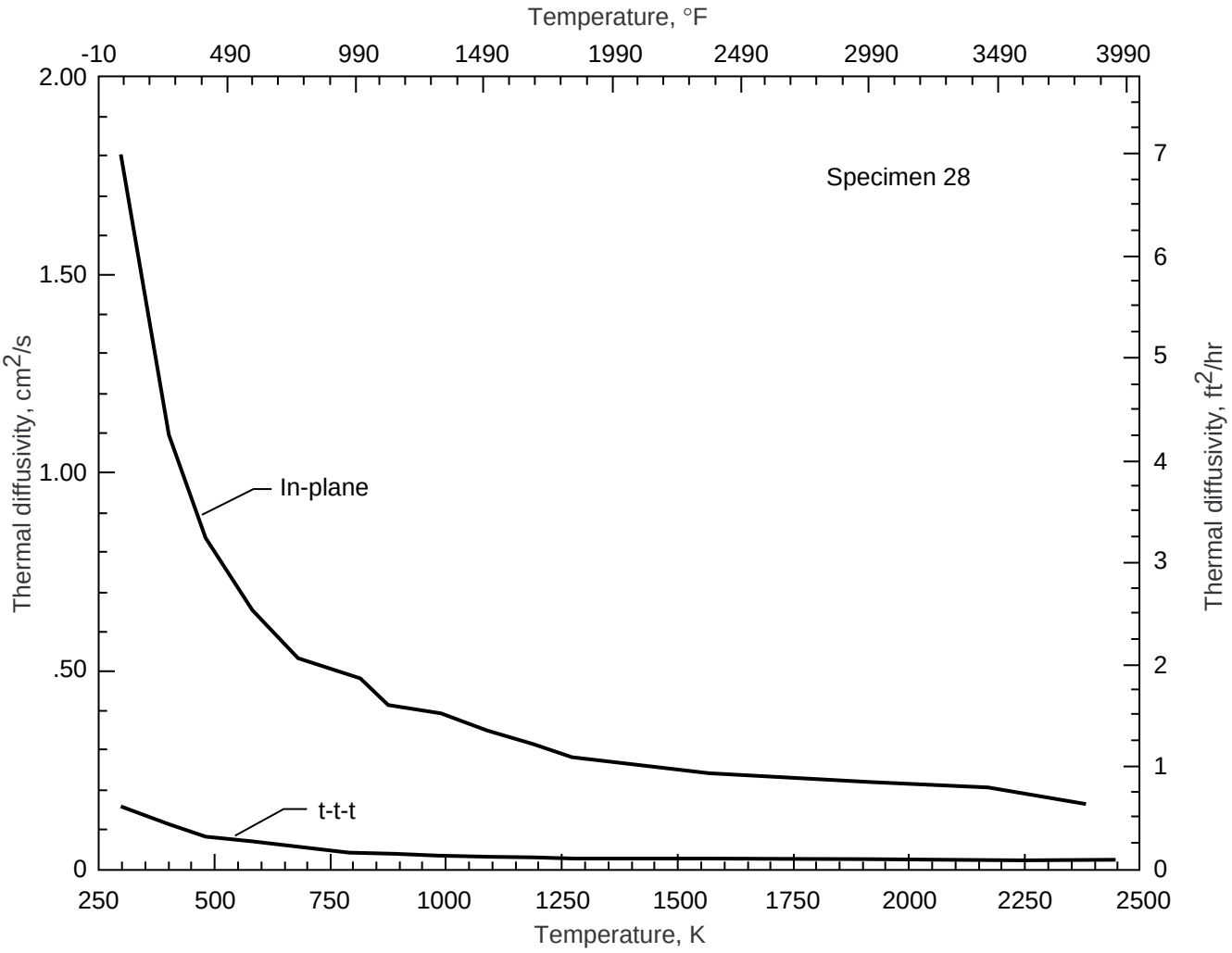

Figure 31. Thermal diffusivity versus temperature for LaRC P1, which is K321 2k AR pitch densified material.

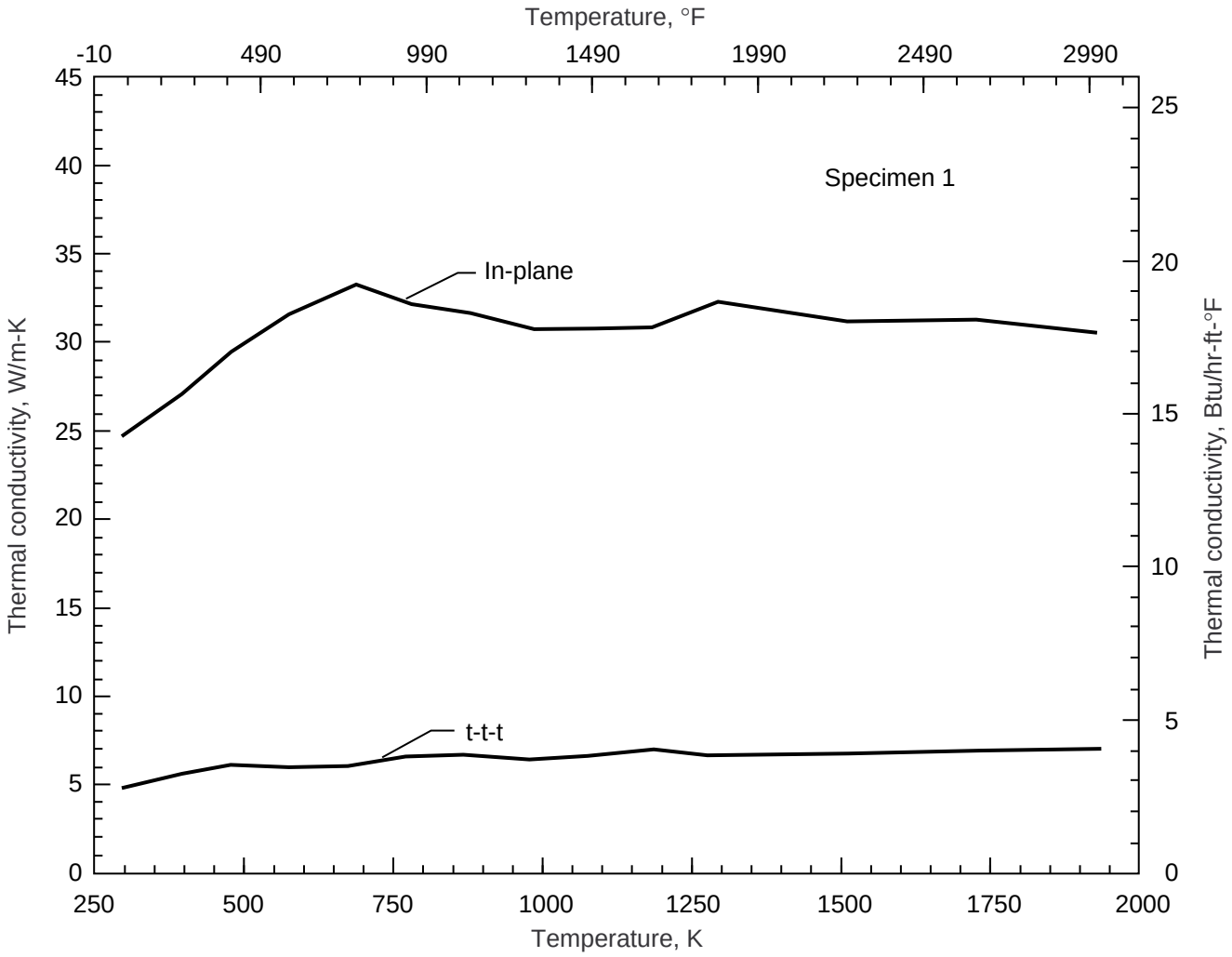

Figure 32. Thermal conductivity versus temperature for LaRC panel 7A, which is T-300 3k phenolic densified material.

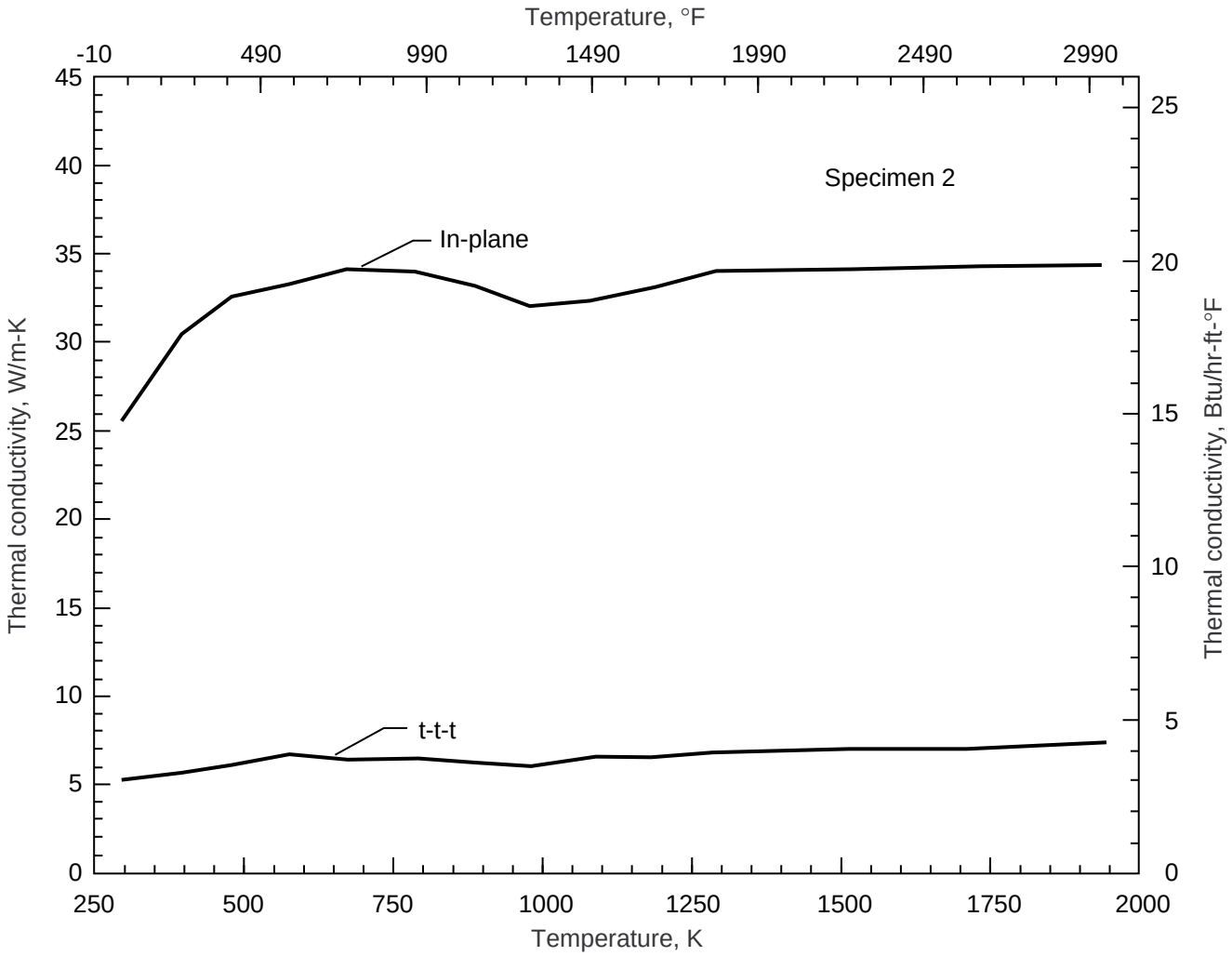

Figure 33. Thermal conductivity versus temperature for LaRC panel 7B, which is T-300 3k LoPIC densified material.

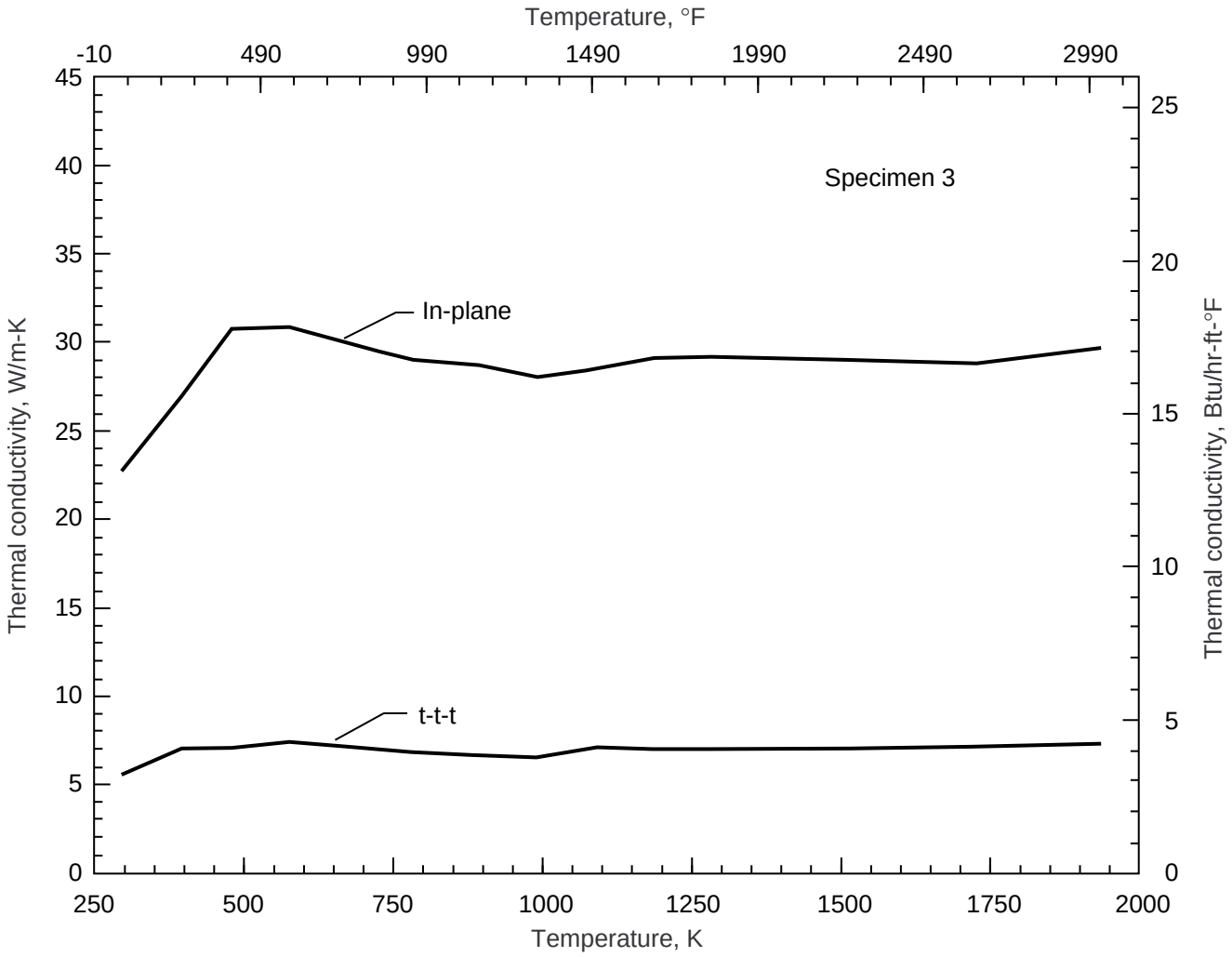

Figure 34. Thermal conductivity versus temperature for LaRC panel 6, which is T-300 3k hybrid densified material.

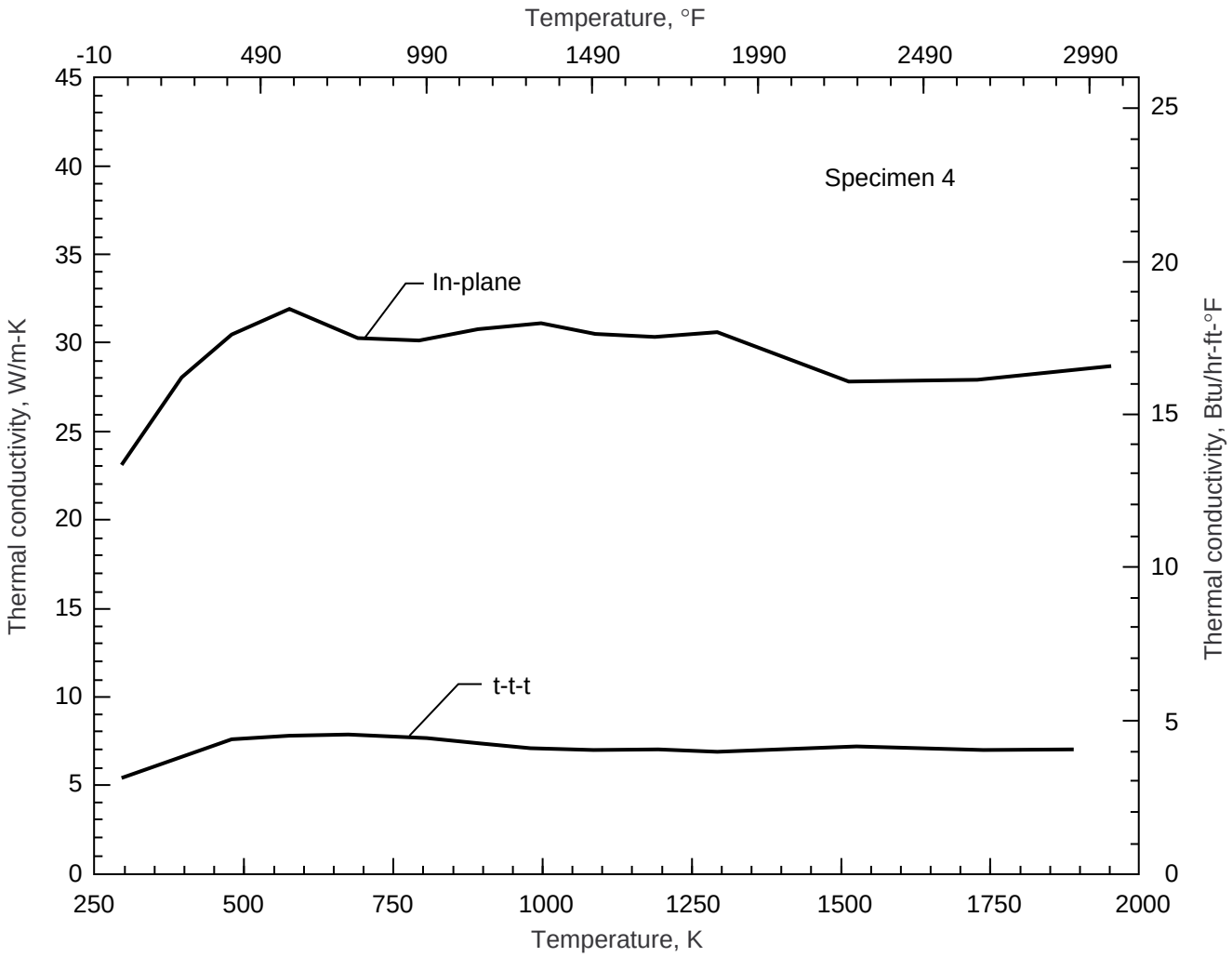

Figure 35. Thermal conductivity versus temperature for LaRC panel 7C, which is T-300 3k CVI densified material.

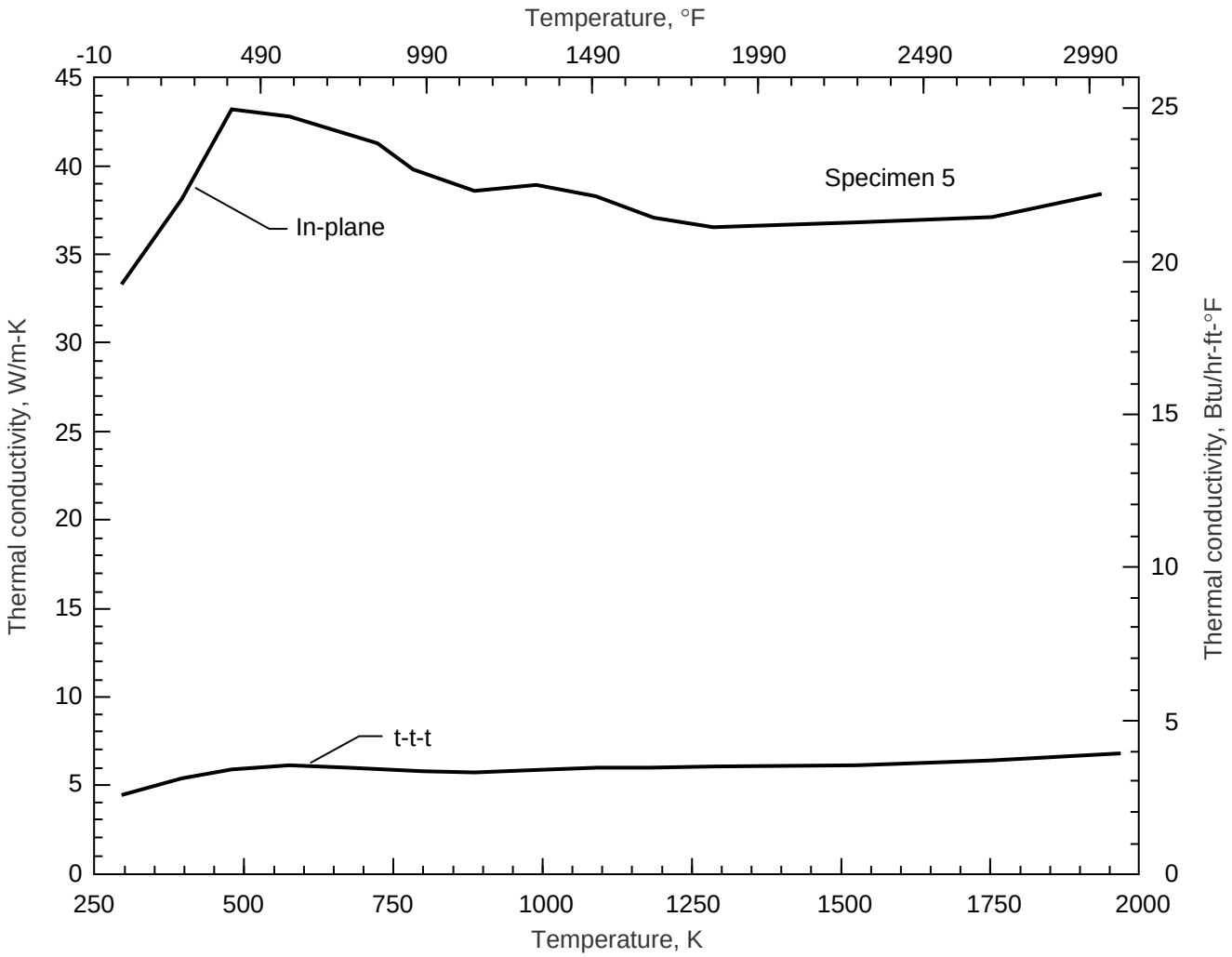

Figure 36. Thermal conductivity versus temperature for LaRC panel 1P, which is T-50 3k phenolic densified material.

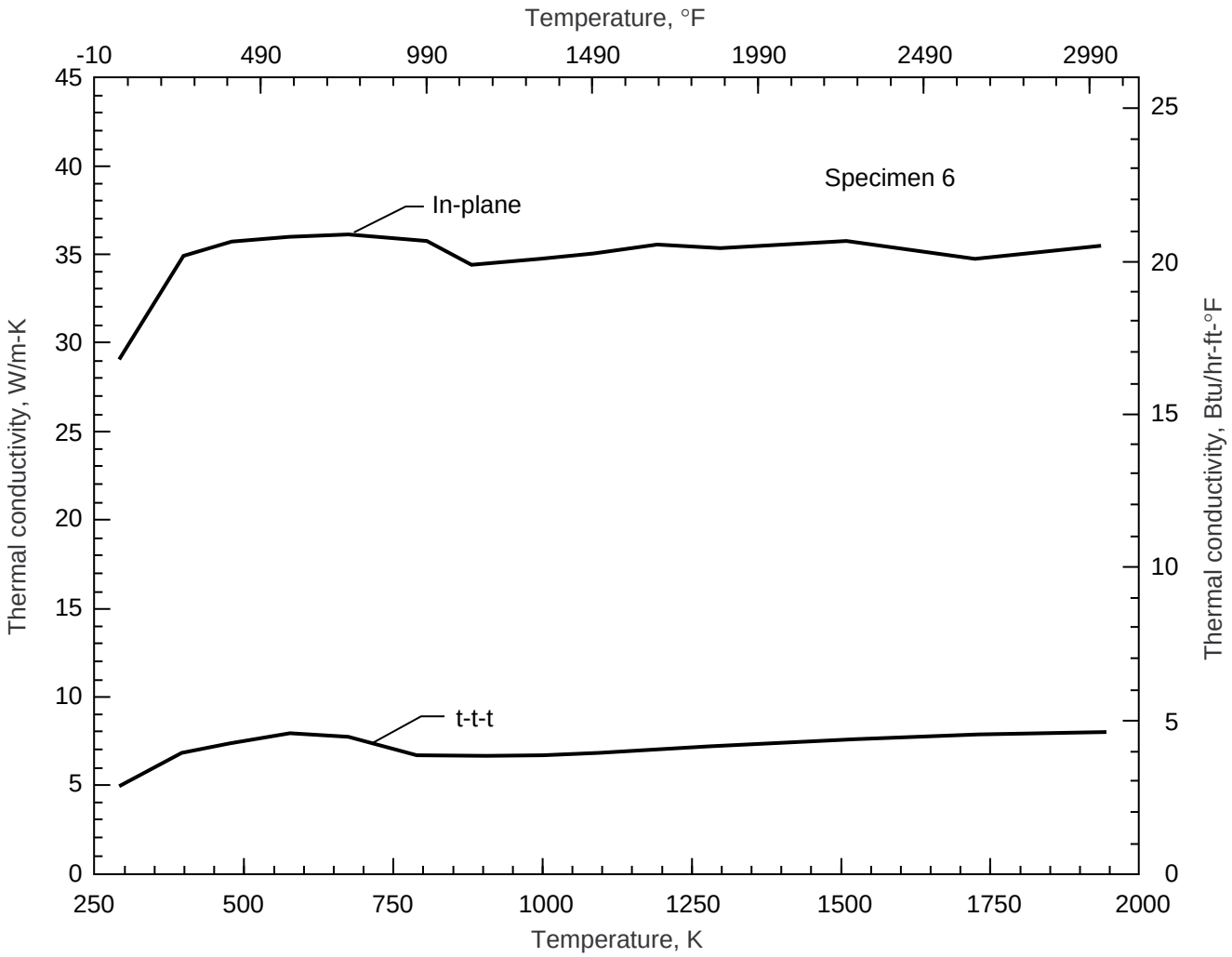

Figure 37. Thermal conductivity versus temperature for LaRC panel 9H, which is T-50 3k hybrid densified material.

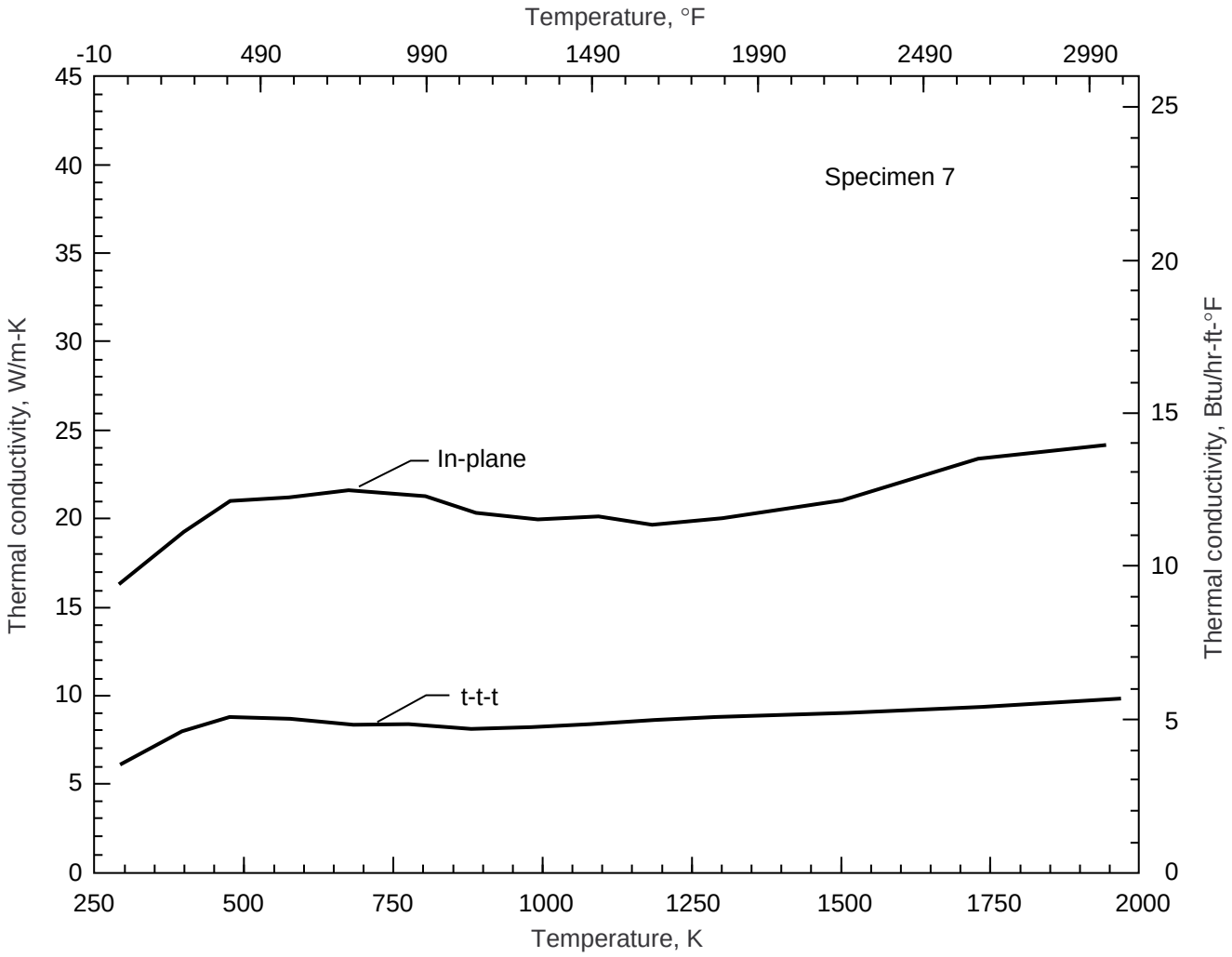

Figure 38. Thermal conductivity versus temperature for LaRC panel 10-1, which is Celion 3k phenolic densified material.

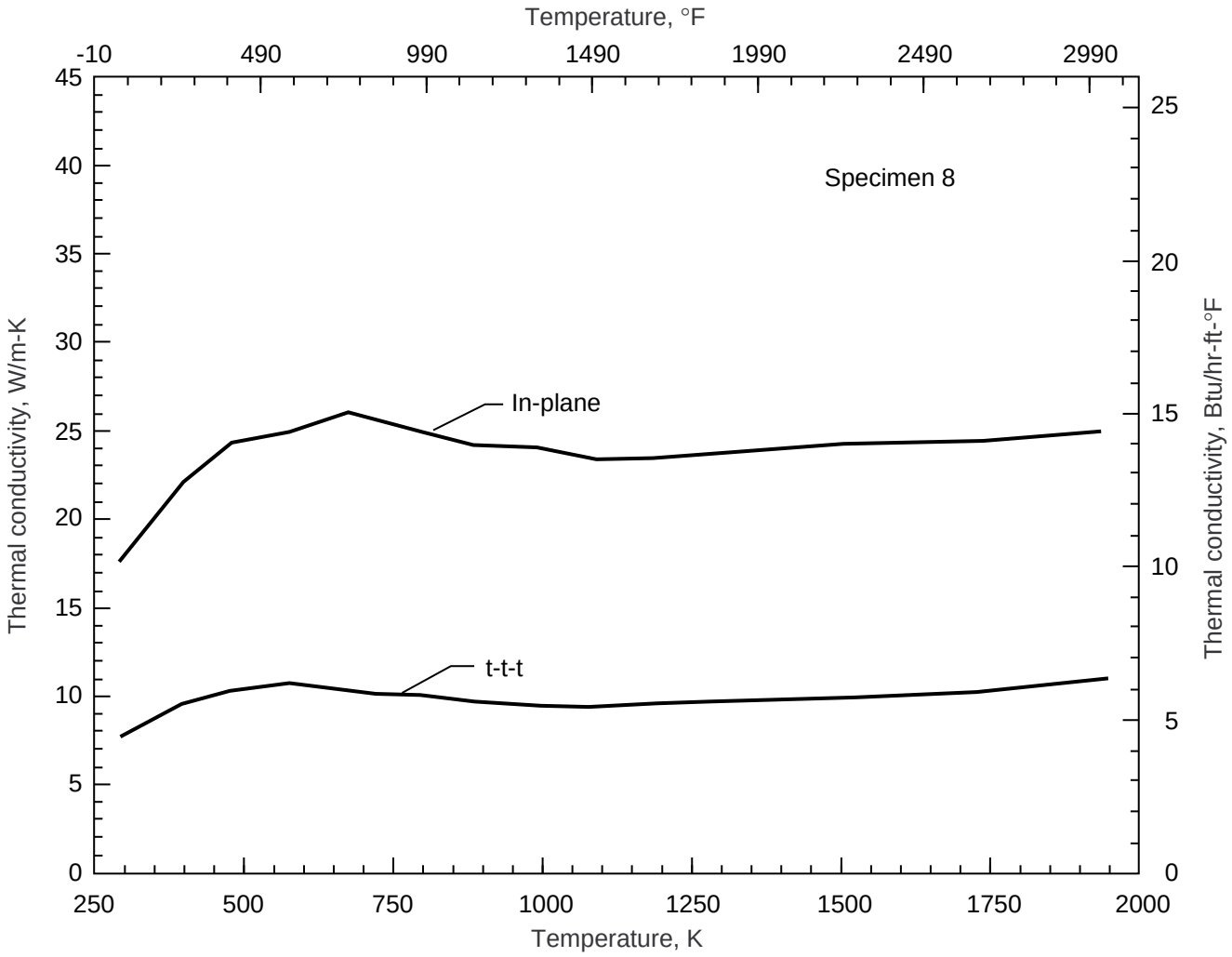

Figure 39. Thermal conductivity versus temperature for LaRC panel 10-3, which is Celion 3k LoPIC densified material.

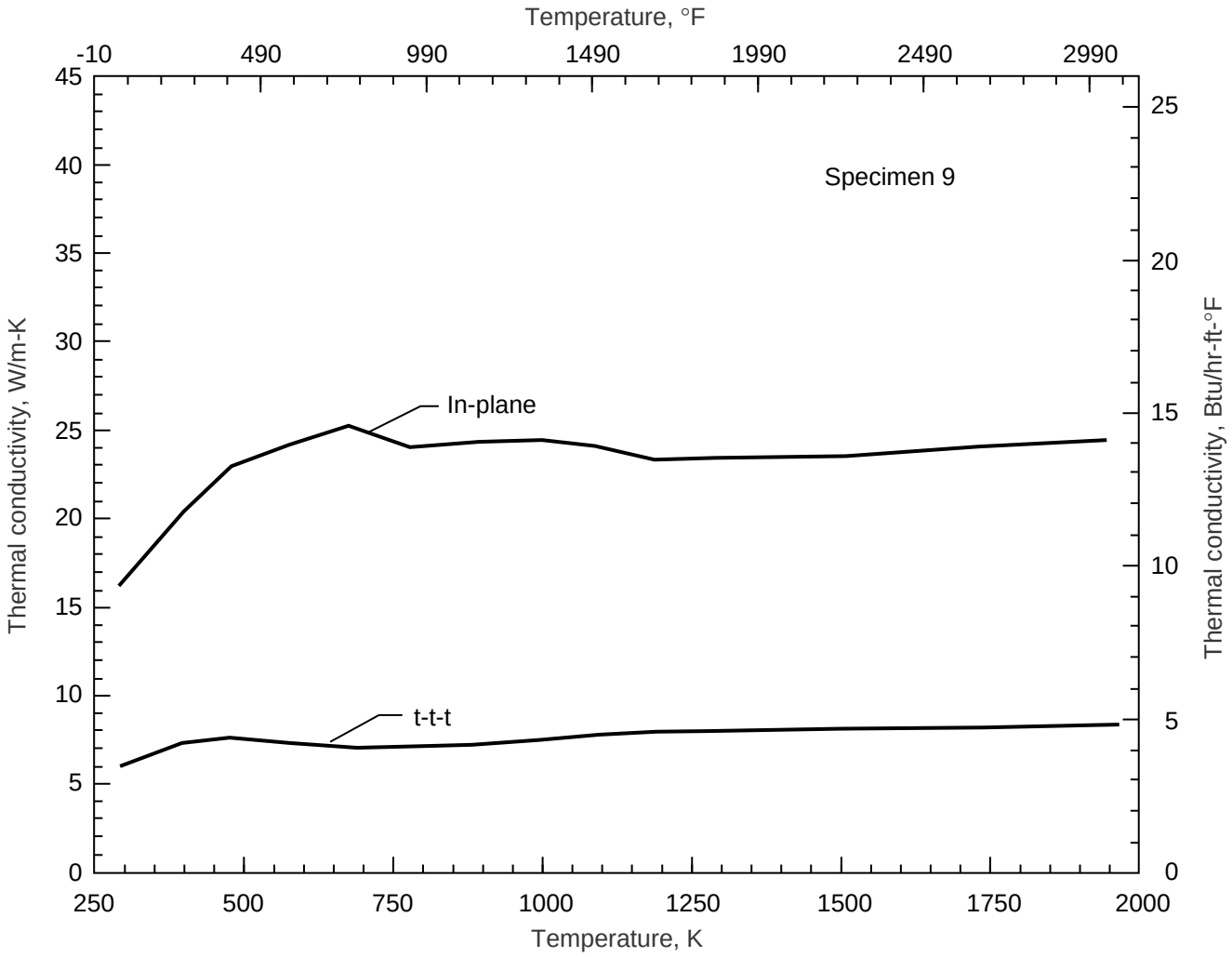

Figure 40. Thermal conductivity versus temperature for LaRC panel 9-1, which is Celion 3k/2k phenolic densified material.

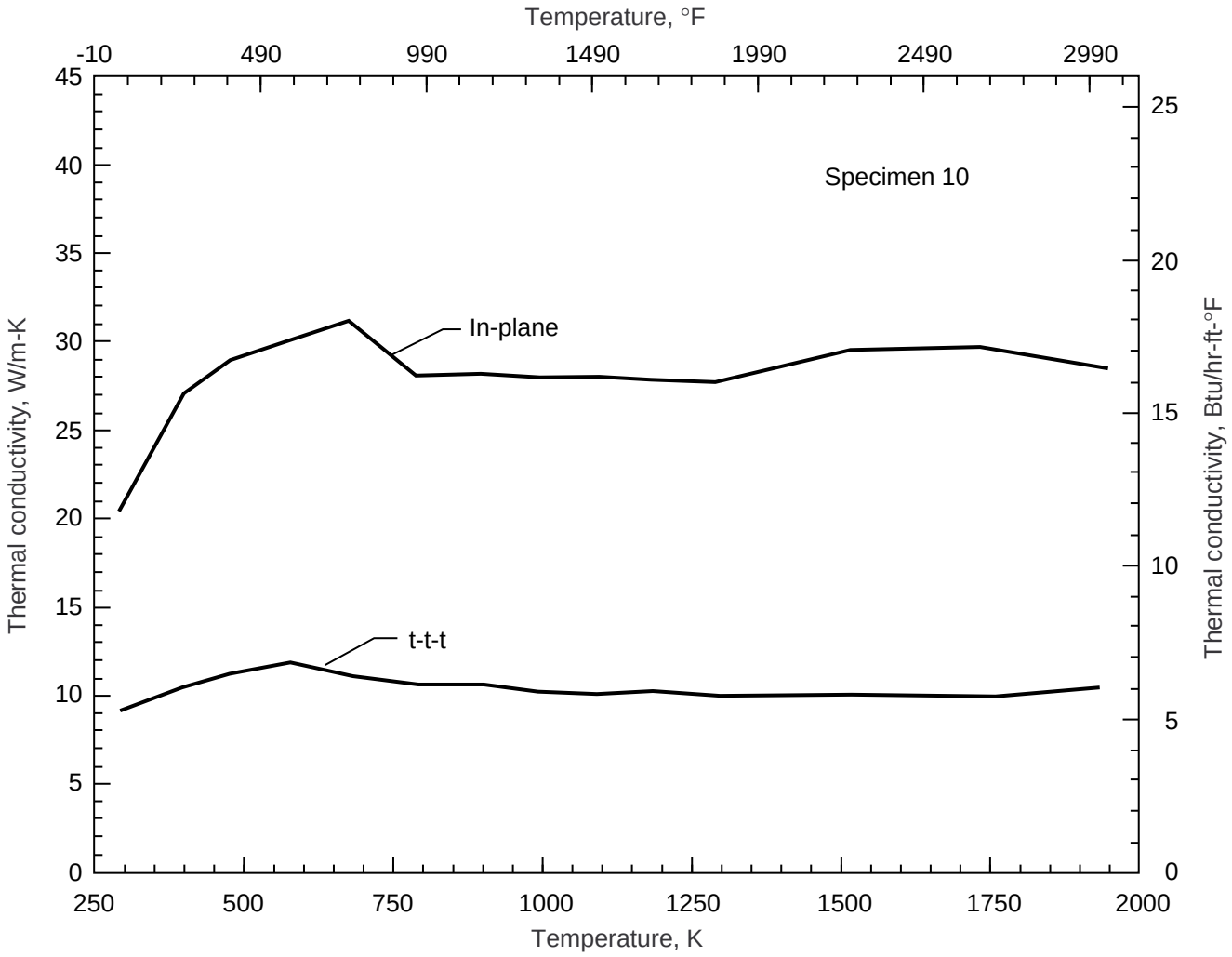

Figure 41. Thermal conductivity versus temperature for LaRC panel 9-3, which is Celion 3k/2k LoPIC densified material.

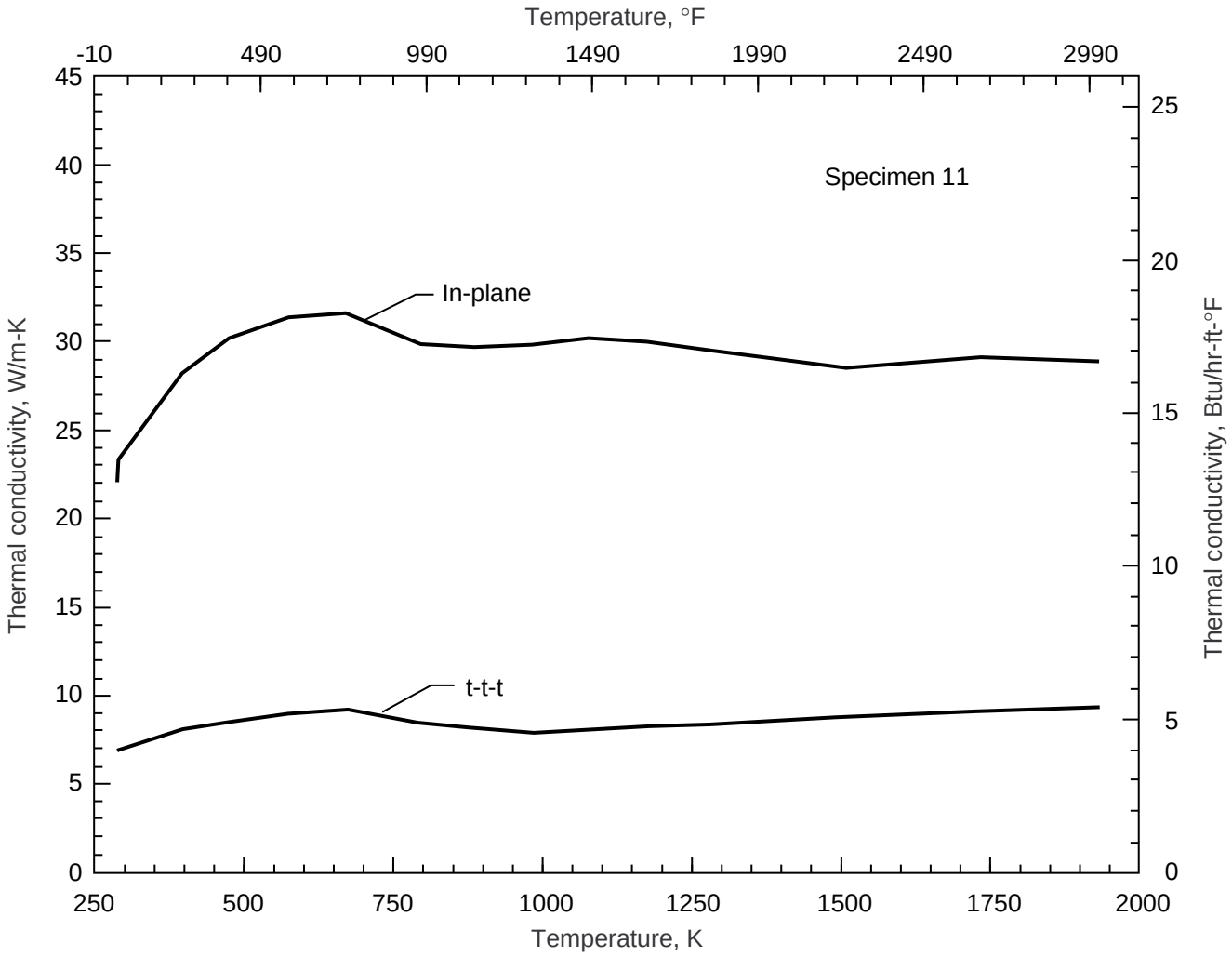

Figure 42. Thermal conductivity versus temperature for Boeing/Rohr T-300 1k hybrid densified material.

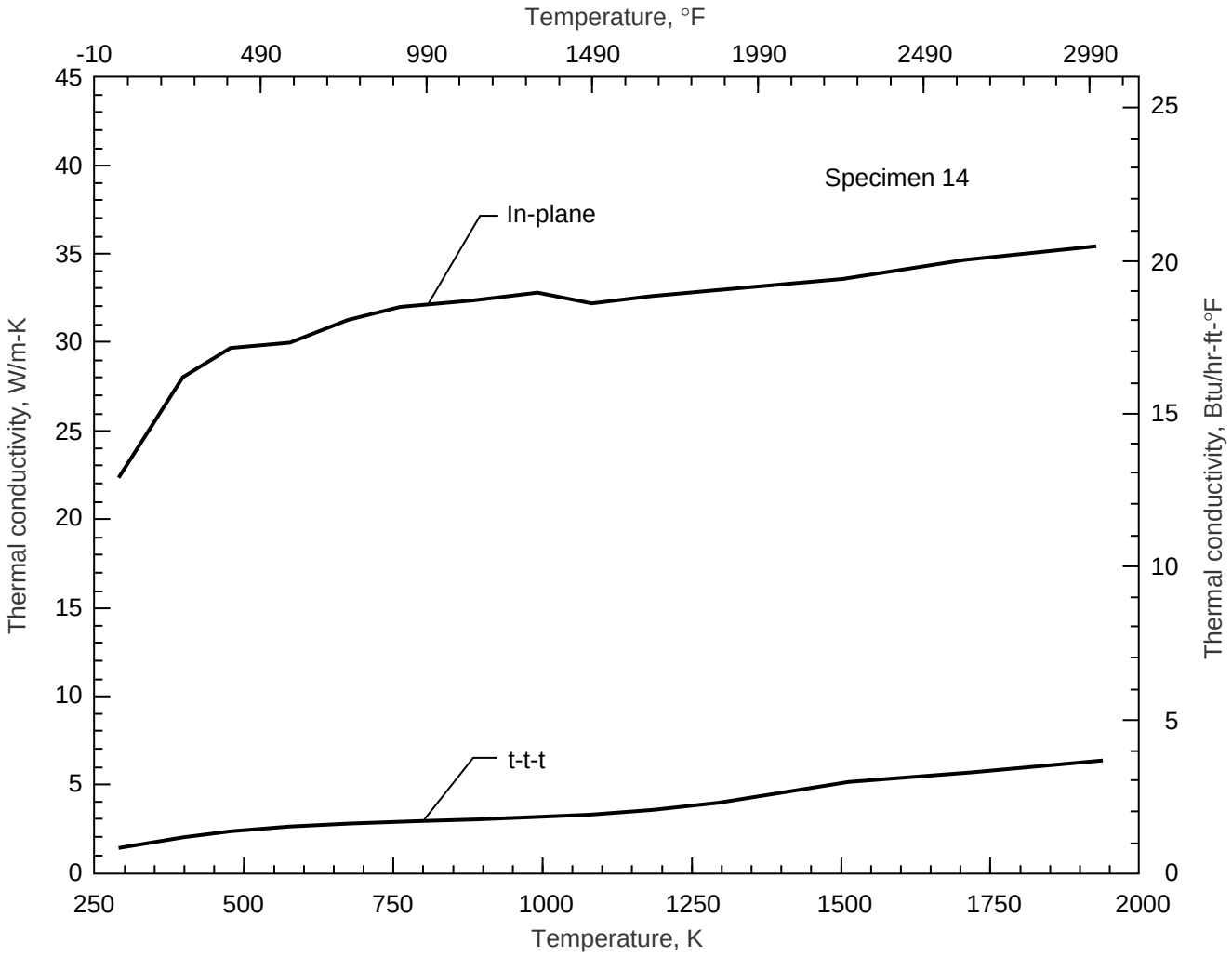

Figure 43. Thermal conductivity versus temperature for CCAT T-300 3k phenolic densified material.

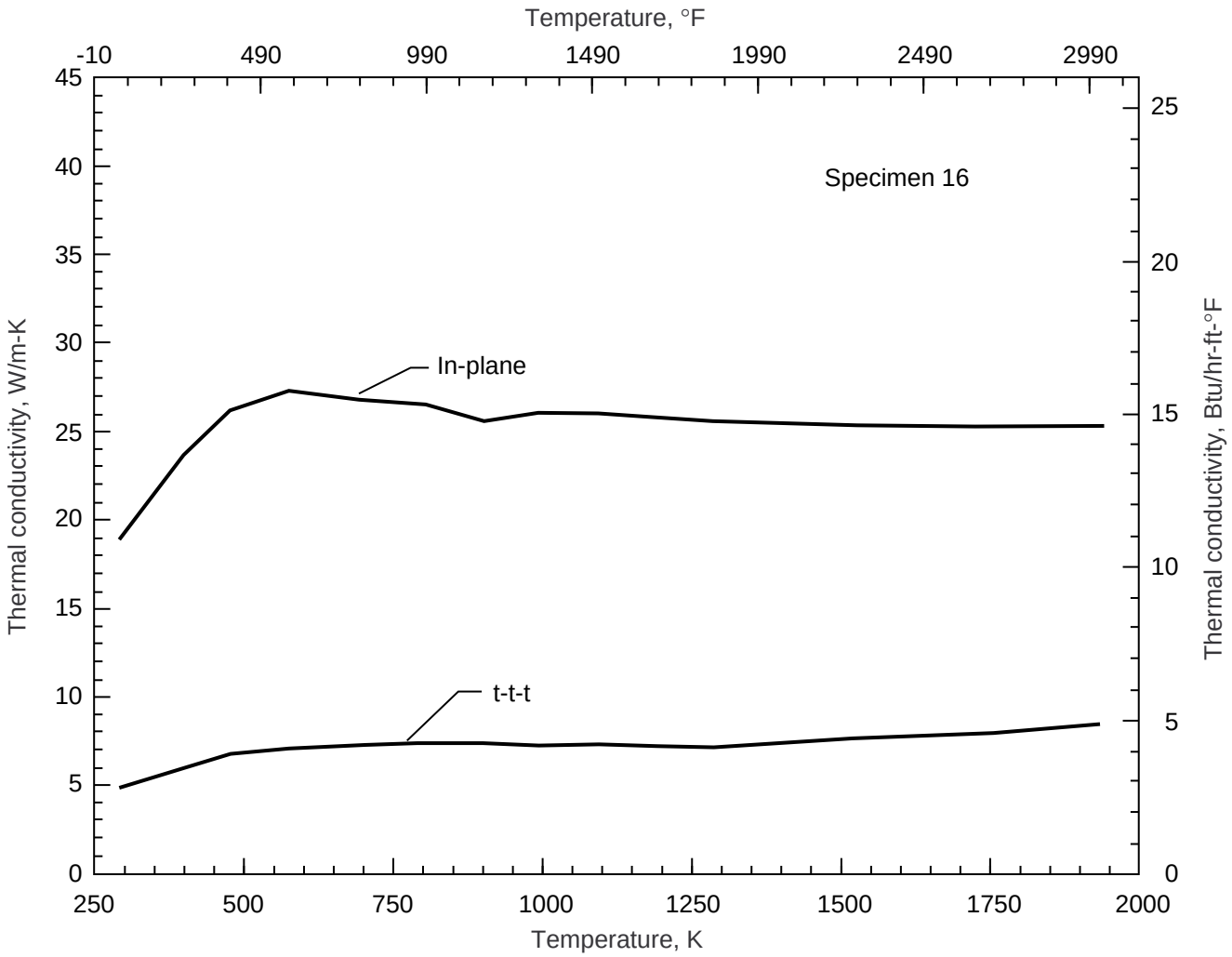

Figure 44. Thermal conductivity versus temperature for LaRC stitched panel 2, which is T-300 3k phenolic densified material.

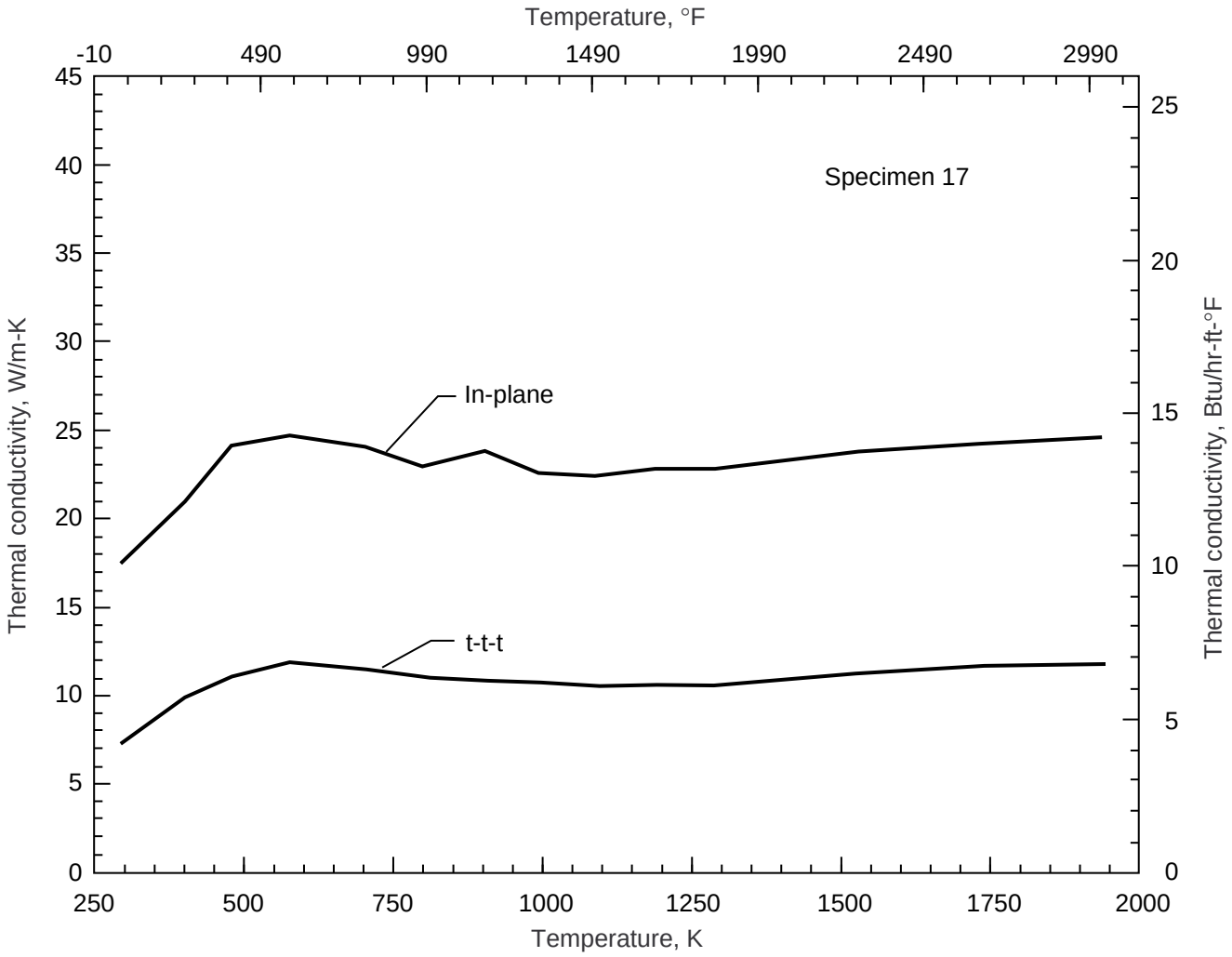

Figure 45. Thermal conductivity versus temperature for LaRC stitched panel 5, which is T-300 3k phenolic densified material.

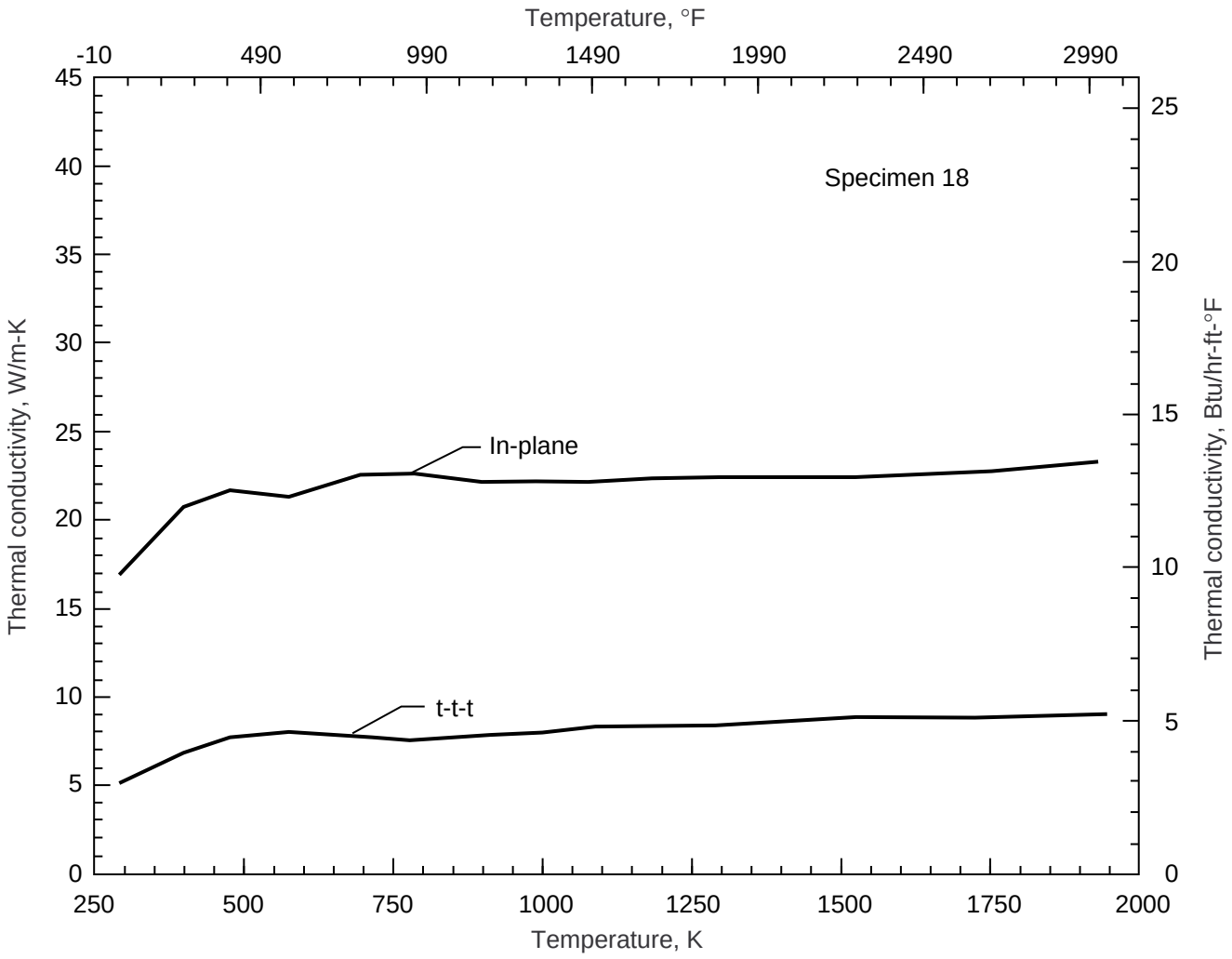

Figure 46. Thermal conductivity versus temperature for LaRC stitched panel 8, which is T-300 3k phenolic densified material.

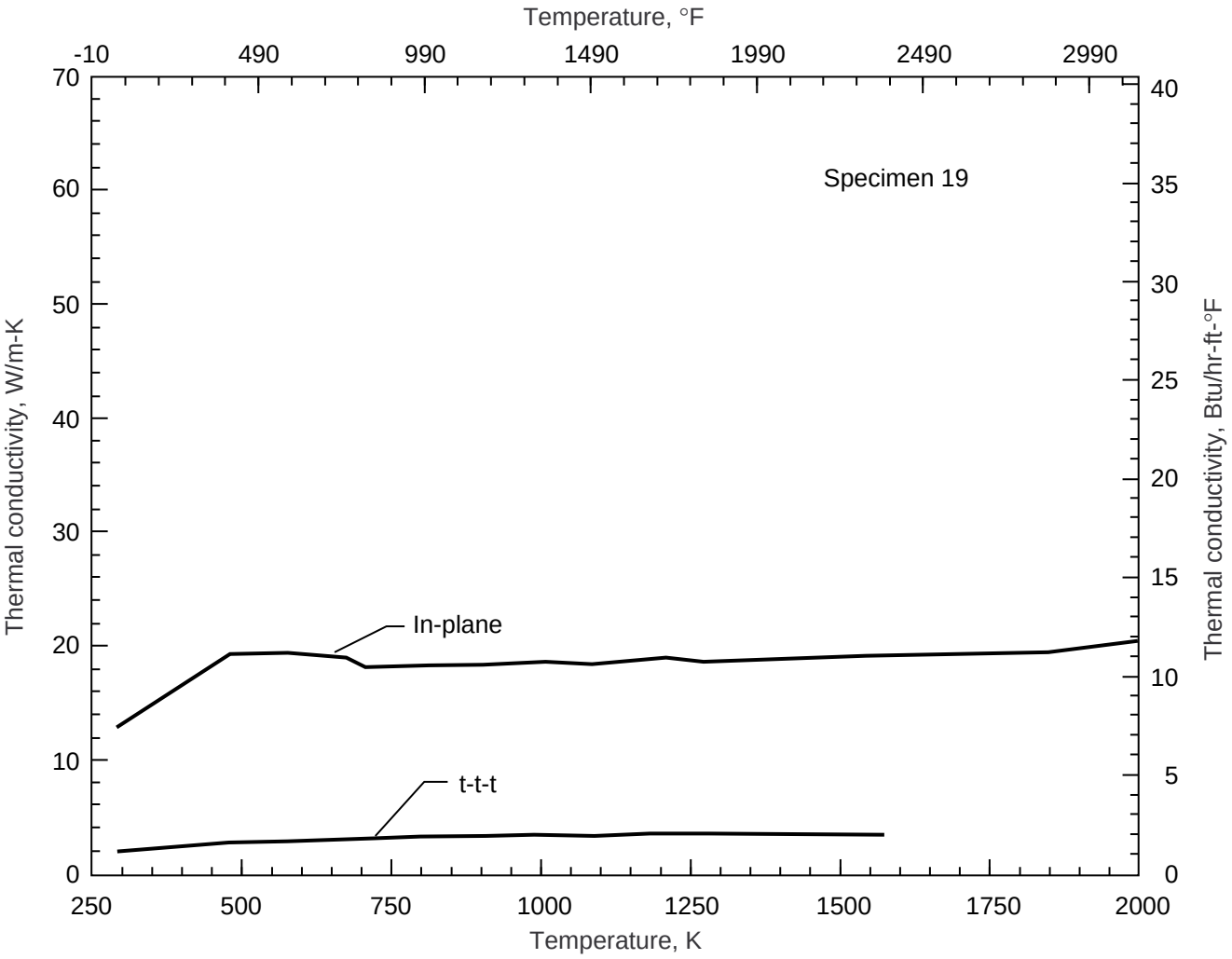

Figure 47. Thermal conductivity versus temperature for LaRC J1, which is T-300 3k CVI densified material.

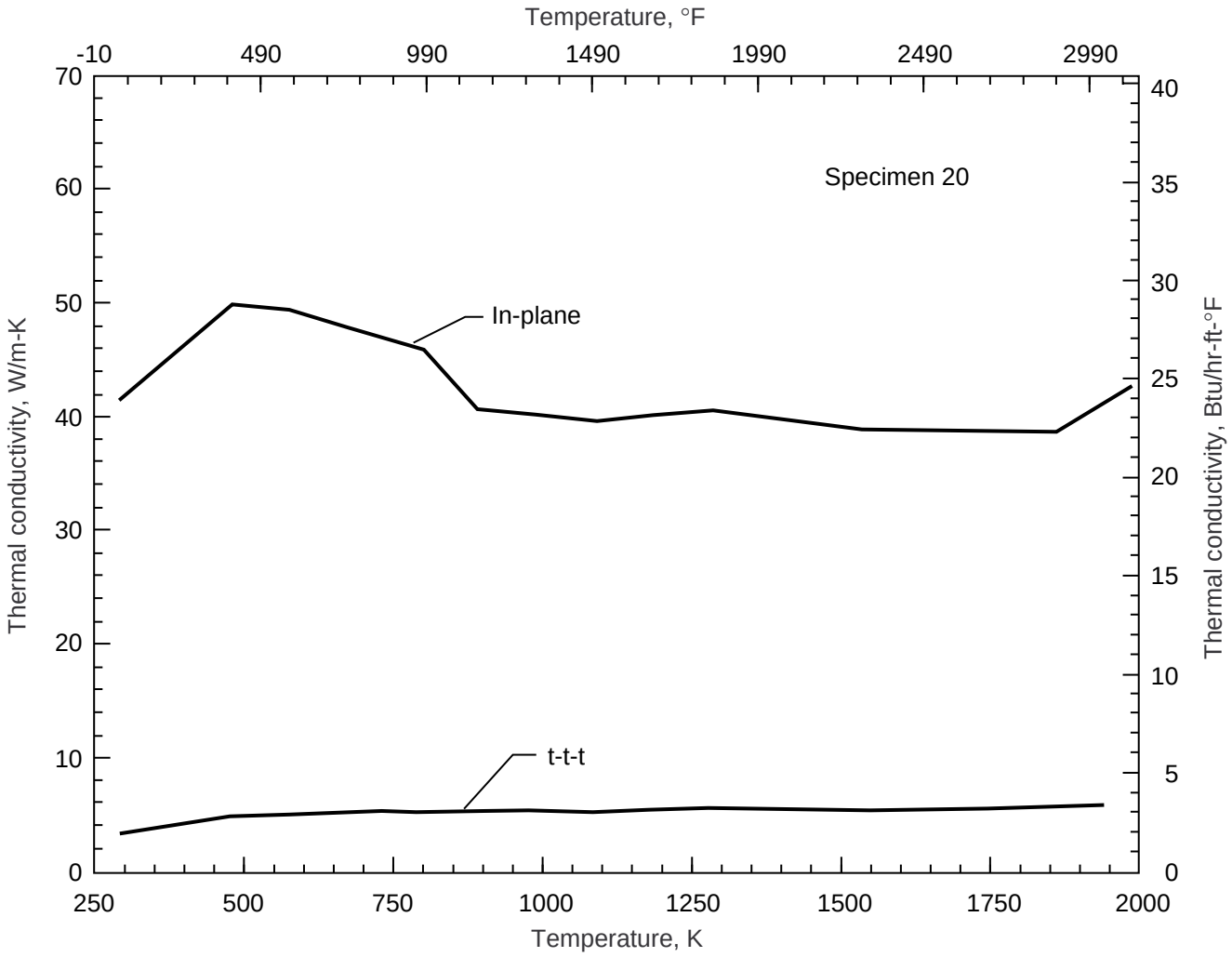

Figure 48. Thermal conductivity versus temperature for LaRC J2, which is T-300 3k CVI densified material.

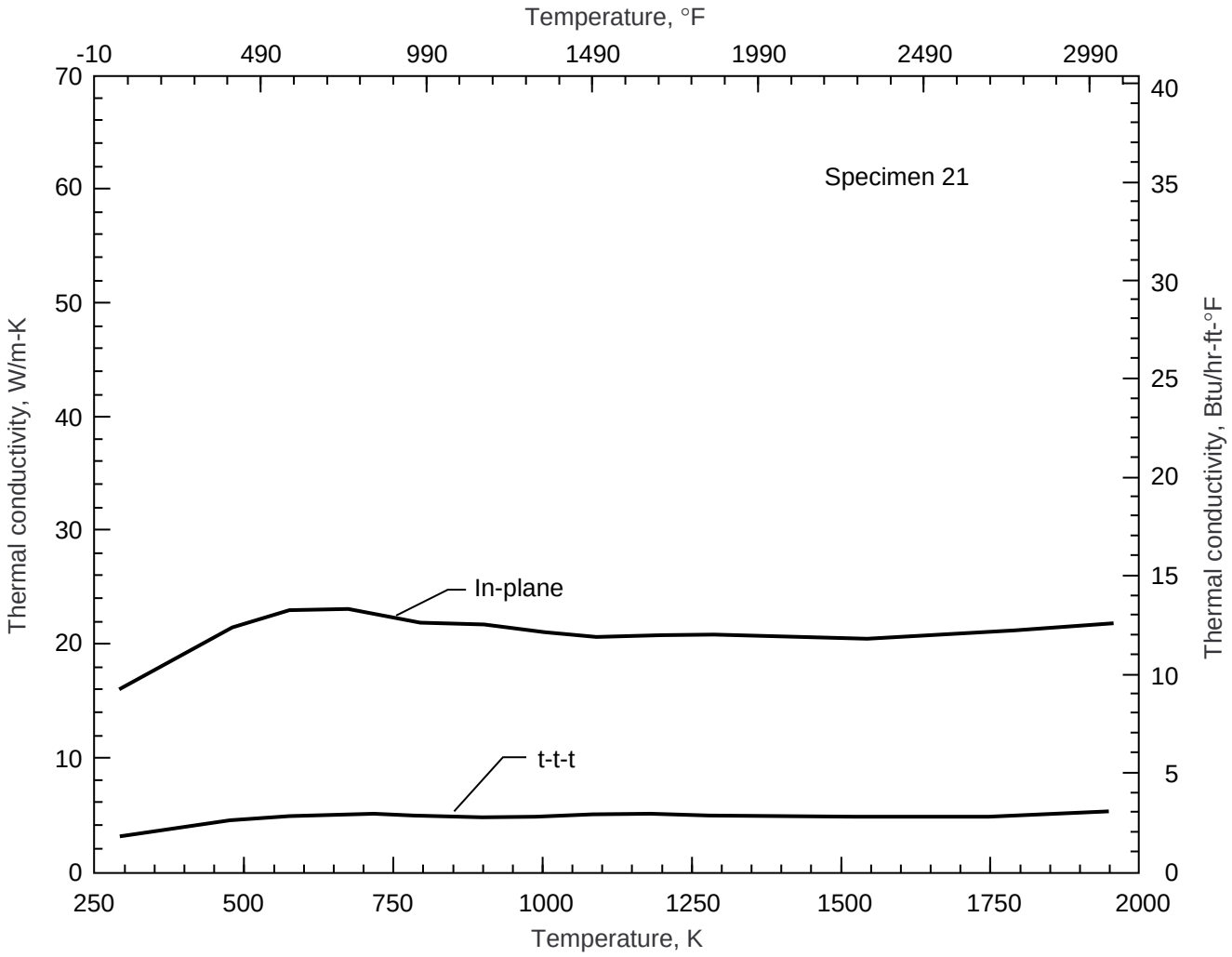

Figure 49. Thermal conductivity versus temperature for LaRC J3, which is T-300 3k CVI densified material.

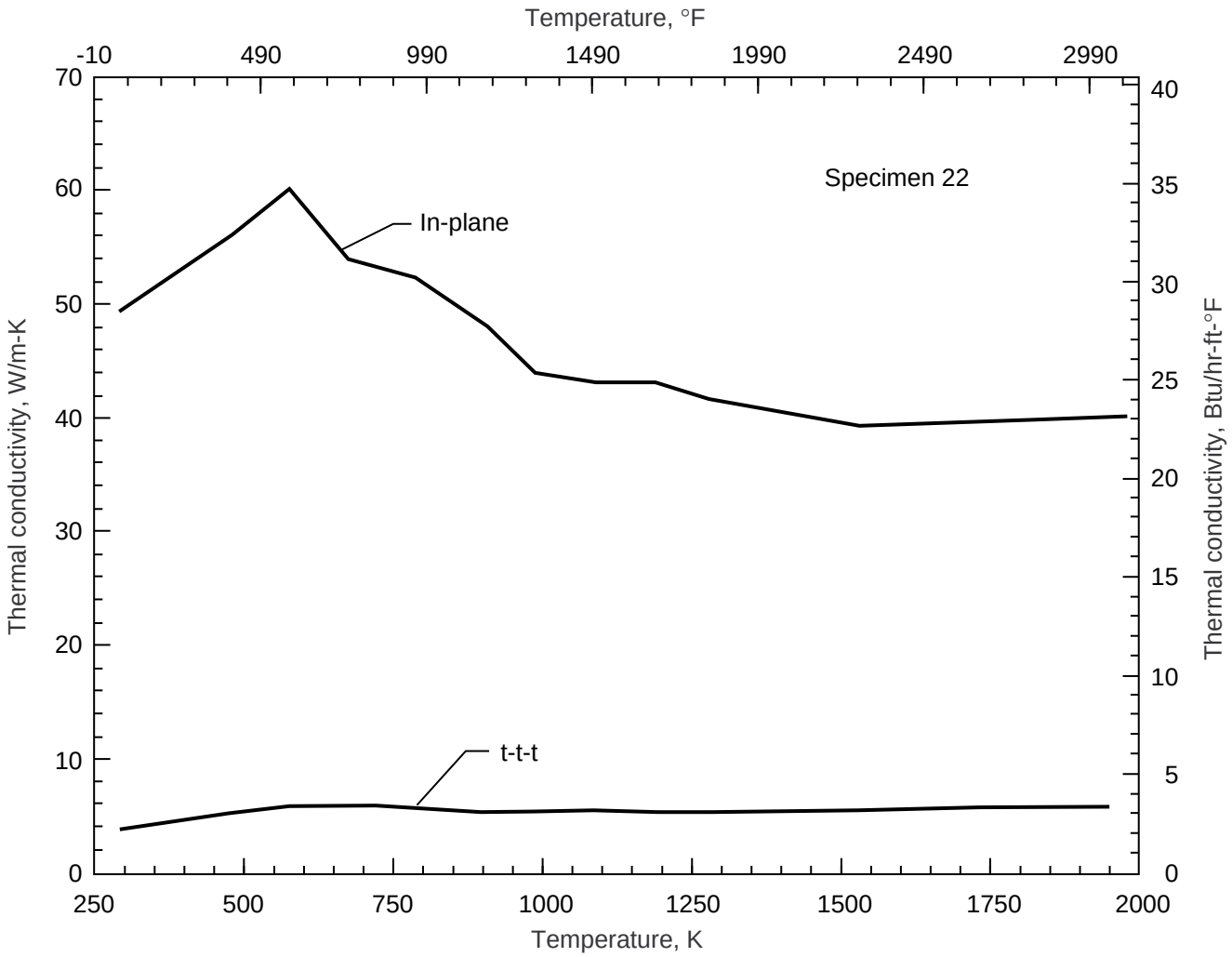

Figure 50. Thermal conductivity versus temperature for LaRC J4, which is T-300 3k CVI densified material.

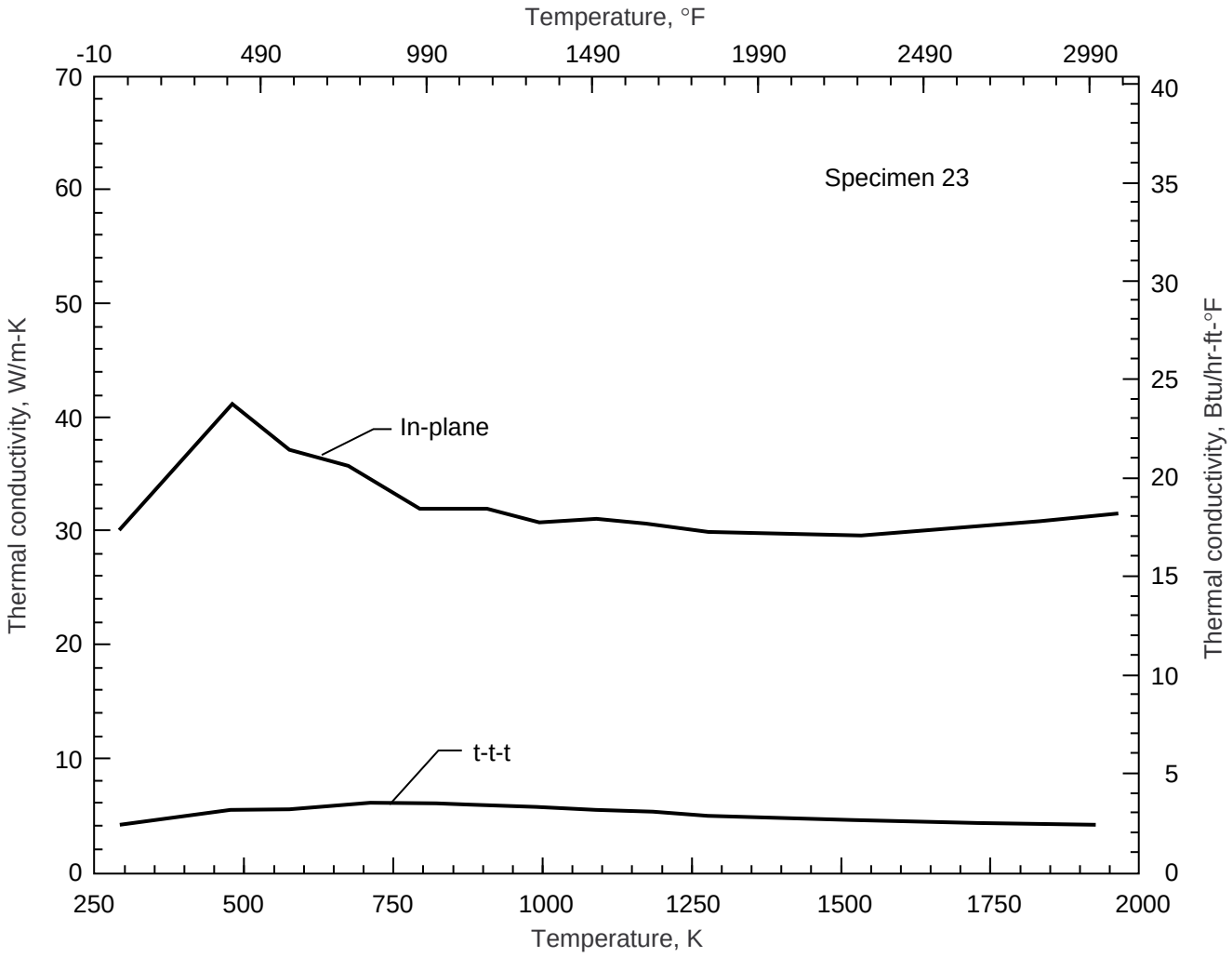

Figure 51. Thermal conductivity versus temperature for LaRC J5, which is T-300 3k CVI densified material.

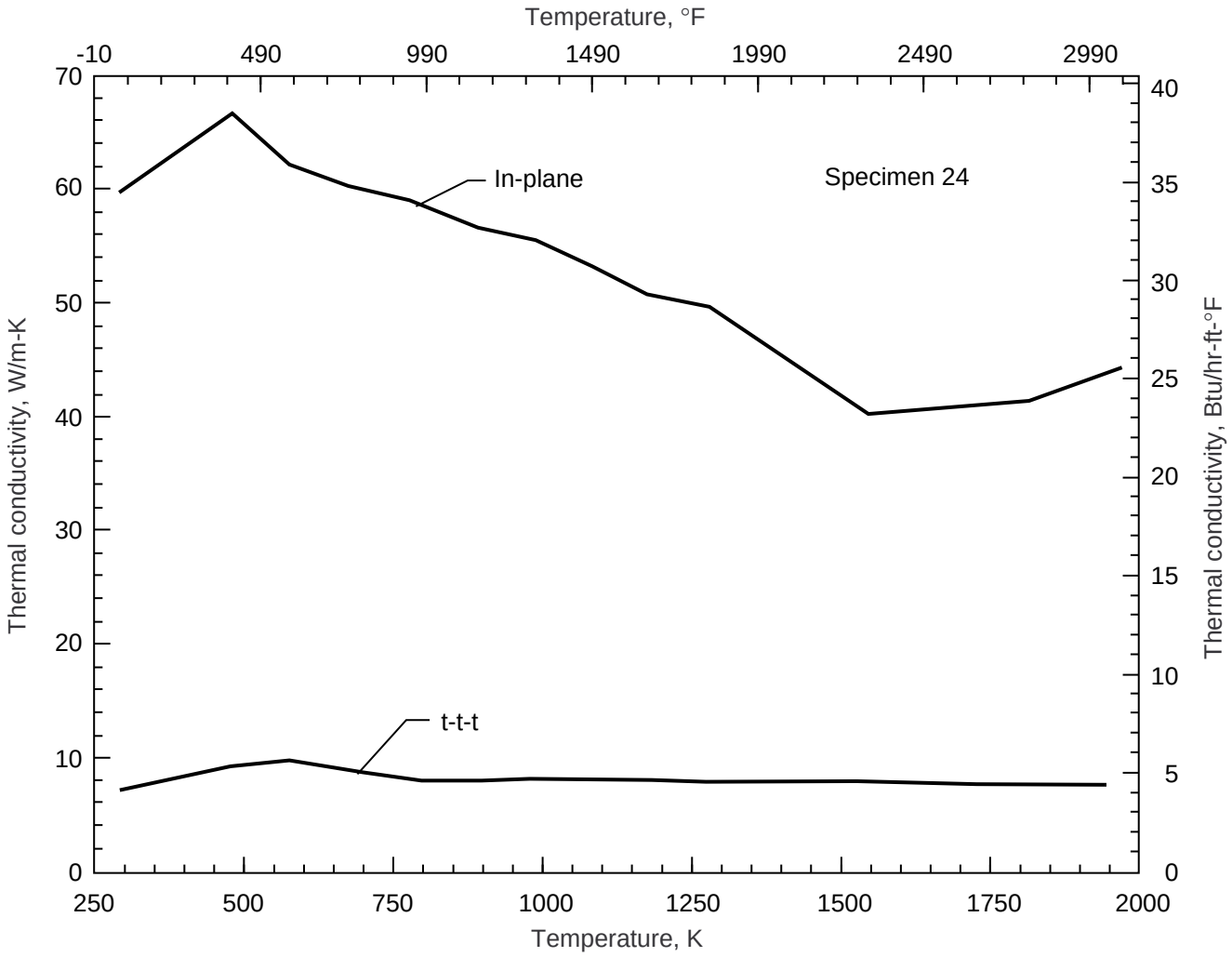

Figure 52. Thermal conductivity versus temperature for LaRC J6, which is T-300 3k CVI densified material.

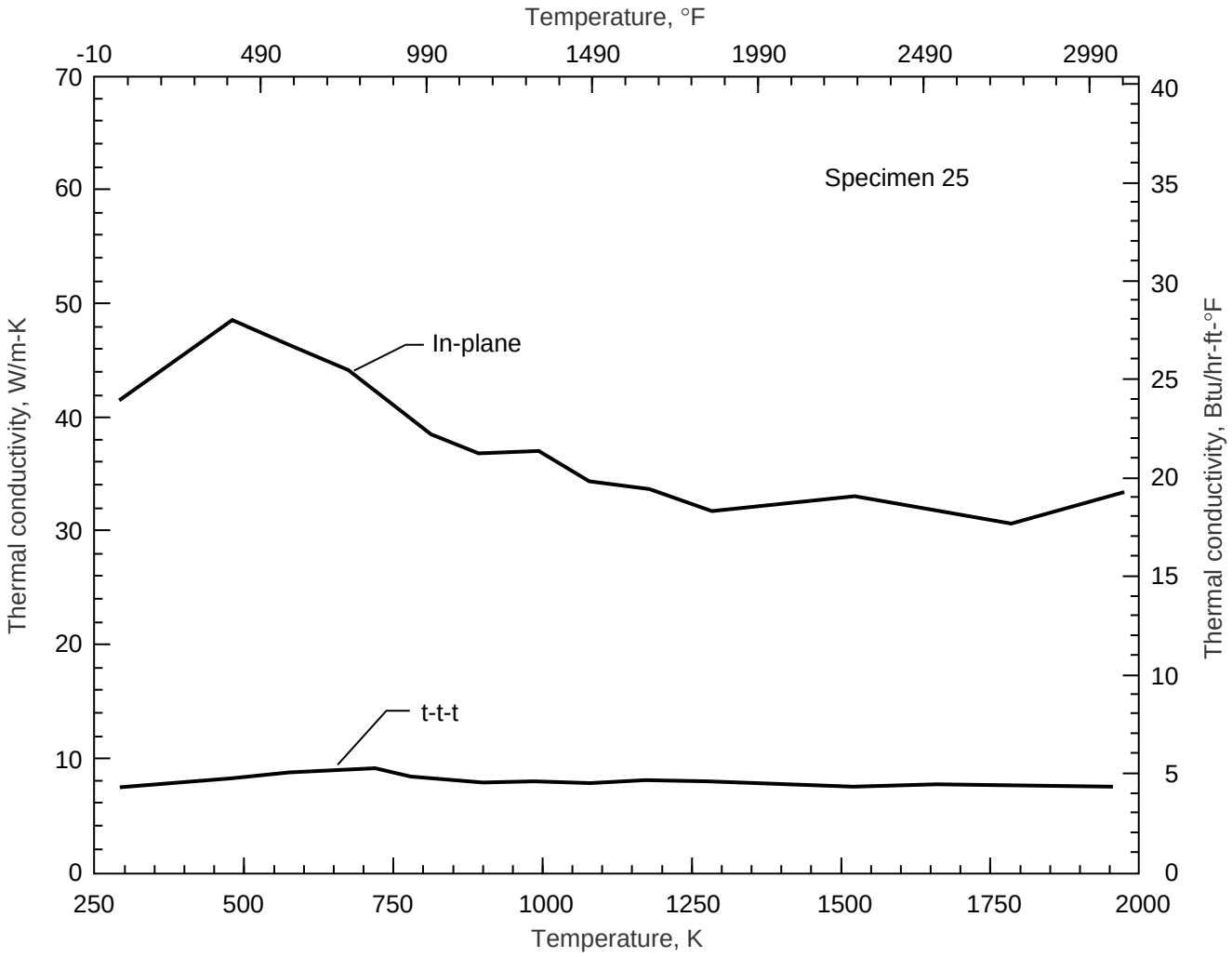

Figure 53. Thermal conductivity versus temperature for LaRC J7, which is T-300 3k CVI densified material.

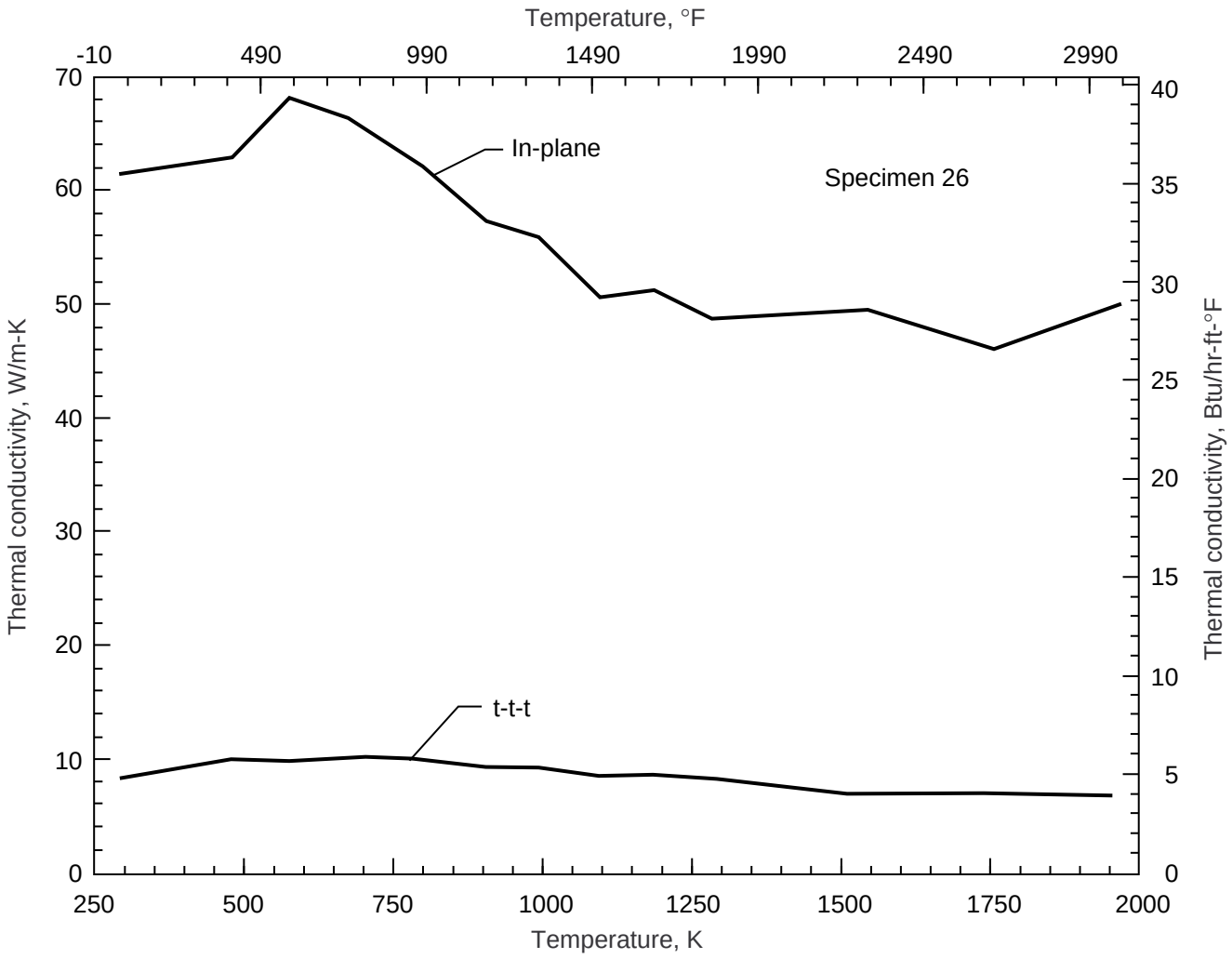

Figure 54. Thermal conductivity versus temperature for LaRC J8, which is T-300 3k CVI densified material.

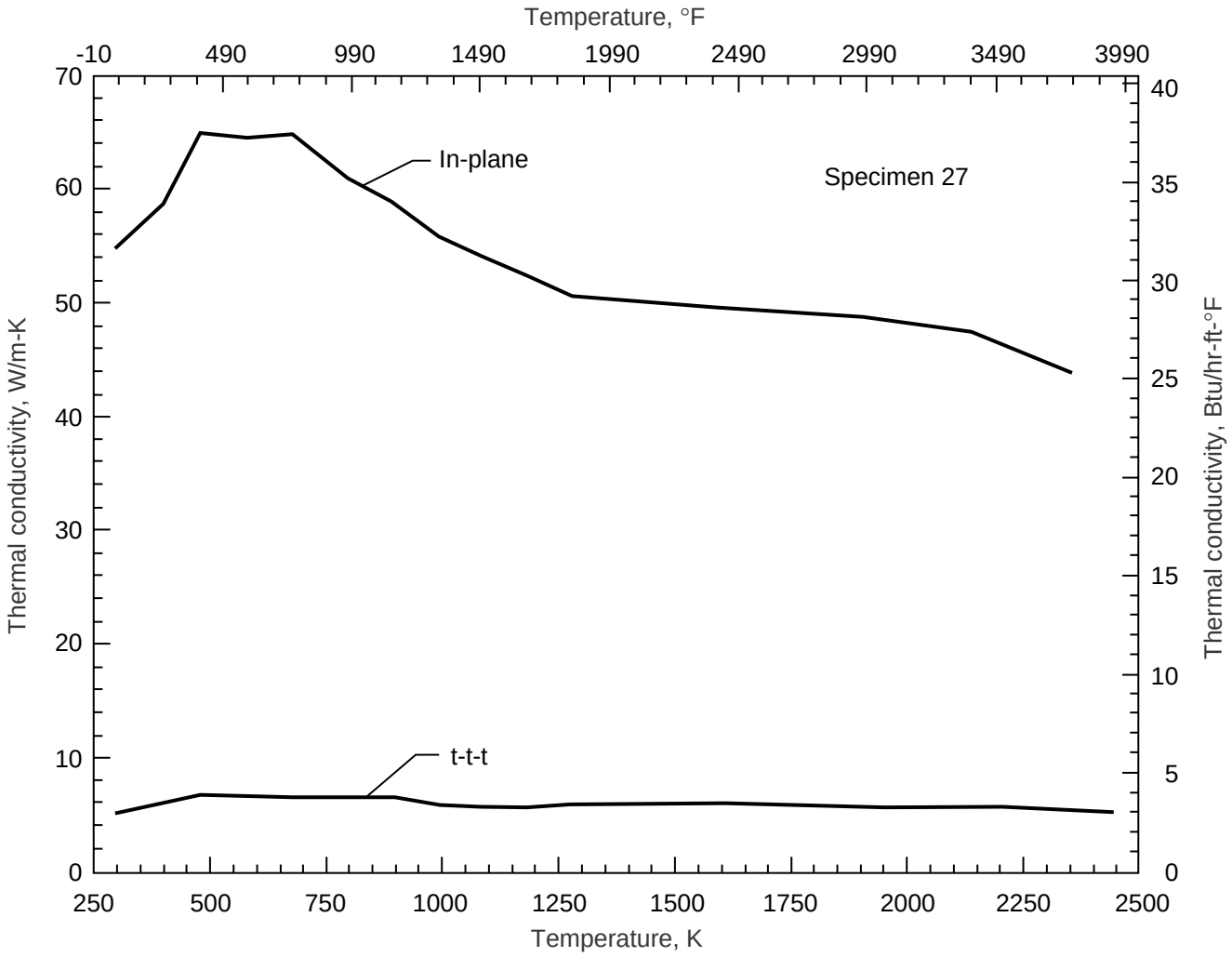

Figure 55. Thermal conductivity versus temperature for LaRC F1, which is K321 2k phenolic densified material.

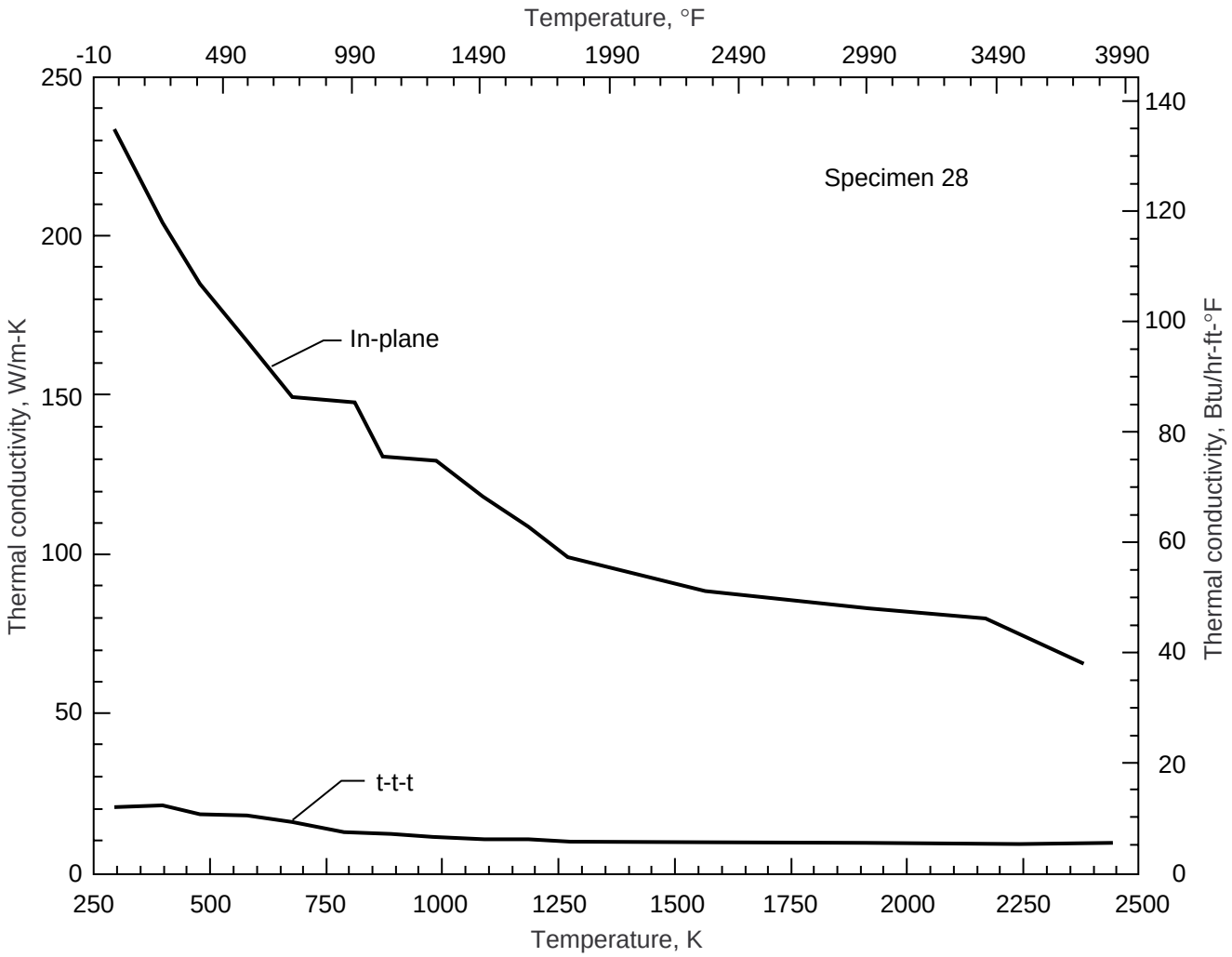

Figure 56. Thermal conductivity versus temperature for LaRC P1, which is K321 2k AR pitch densified material.

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13. ABSTRACT *(Maximum 200 words)*

Advanced thermal protection materials envisioned for use on future hypersonic vehicles will likely be subjected to temperatures in excess of 1811 K (2800°F) and, therefore, will require the rapid conduction of heat away from the stagnation regions of wing leading edges, the nose cap area, and from engine inlet and exhaust areas. Carbon-carbon composite materials are candidates for use in advanced thermal protection systems. For design purposes, high temperature thermophysical property data are required, but a search of the literature found little thermal conductivity data for carbon-carbon materials above 1255 K (1800°F). Because a need was recognized for in-plane and through-the-thickness thermal conductivity data for carbon-carbon composite materials over a wide temperature range, Langley Research Center (LaRC) embarked on an effort to compile a consistent set of thermal conductivity values from room temperature to 1922 K (3000°F) for carbon-carbon composite materials on hand at LaRC for which the precursor materials and thermal processing history were known. This report documents the thermal conductivity data generated for these materials. In-plane thermal conductivity values range from 10 to 233 W/m-K, whereas through-the-thickness values range from 2 to 21 W/m-K.

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