

TECHNICAL REPORT  
RAPPORT TECHNIQUE  
TECHNISCHER BERICHT

CEN/CLC/TR 17603-31-  
05

August 2021

ICS 49.140

English version

Space Engineering - Thermal design handbook - Part 5:  
Structural Materials: Metallic and Composite

Ingénierie spatiale - Manuel de conception thermique -  
Partie 5 : Matériaux de structure : métalliques et  
composites

Raumfahrttechnik - Handbuch für thermisches Design -  
Teil 5: Strukturmaterialien: Metalle und Verbundstoffe

This Technical Report was approved by CEN on 14 June 2021. It has been drawn up by the Technical Committee CEN/CLC/JTC 5.

CEN and CENELEC members are the national standards bodies and national electrotechnical committees of Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom.



CEN-CENELEC Management Centre:  
Rue de la Science 23, B-1040 Brussels

## Table of contents

<b>European Foreword.....</b>	<b>17</b>
<b>1 Scope.....</b>	<b>18</b>
<b>2 References .....</b>	<b>19</b>
<b>3 Terms, definitions and symbols .....</b>	<b>20</b>
3.1    Terms and definitions .....	20
3.2    Symbols.....	20
<b>4 Metallic materials.....</b>	<b>23</b>
4.1    General.....	23
4.1.1    Modifiers of thermal radiative properties.....	26
4.1.2    Cladding definitions.....	27
4.1.3    Temper designation for heat treatable aluminium alloys.....	28
4.2    Aluminium alloys.....	28
4.3    Aluminium-Copper alloys .....	85
4.4    Aluminium-Magnesium alloys .....	104
4.5    Aluminium-Zinc alloys.....	114
4.6    Magnesium-Zink-Thorium alloys .....	131
4.7    Titanium-Aluminium-Tin alloys .....	133
4.8    Titanium-Aluminium-Tin alloys .....	144
4.9    Titanium-Aluminium-Vanadium alloys .....	151
4.10    Nickel-Chrome-Cobalt-Molybdenum alloys .....	165
4.11    Iron-Nickel alloys .....	175
<b>5 Composite materials .....</b>	<b>182</b>
5.1    List of symbols .....	182
5.2    List of matrices, preprints and laminates quoted in this clause .....	187
5.2.1    Matrices, adhesives, potting, moulding compounds .....	188
5.2.2    Preprints, laminates and films .....	193
5.2.3    Code list of manufacturers (or developers).....	195
5.3    General introduction .....	197
5.3.2    Composition .....	198

5.3.3	Commercial fiber product names, descriptions and manufacturers .....	200
5.3.4	Geometry of fiber reinforcement. fabrics. abridged designation .....	205
5.4	Physical properties .....	210
5.4.1	Density.....	210
5.5	Thermal properties.....	216
5.5.1	Specific heat .....	216
5.5.2	Thermal conductivity .....	222
5.5.3	Thermal diffusivity .....	247
5.6	Thermo-elastic properties .....	256
5.6.1	Coefficient of linear thermal expansion.....	256
5.7	Thermal radiation properties of bare high strength fibers .....	319
5.7.1	Sample characterization.....	319
5.7.2	Emittance.....	319
5.7.3	Absorptance.....	321
5.8	Thermal radiation properties of bare composite materials.....	324
5.8.1	Tabulated data .....	324
5.9	Thermal radiation properties of coated composite materials .....	326
5.9.1	White painted composite materials.....	327
5.9.2	Sputtered Aluminium on graphite-epoxy composite material .....	331
5.10	Operating temperature range.....	334
5.10.1	Temperatures related to the maximum service temperature.....	335
5.11	Electrical properties .....	341
5.11.1	Electrical resistance and electrical resistivity .....	341
5.12	Prelaunch environmental effects.....	348
5.12.1	Moisture absorption and desorption .....	348
5.13	Postlaunch environmental effects .....	355
5.13.1	Ascent.....	355
5.13.2	Orbital effects.....	357
5.13.3	Re-entry effects.....	367
5.14	Thermal vacuum cycling .....	371
5.14.1	Test facilities .....	371
5.14.2	Measurement methods .....	372
5.14.3	Thermal vacuum cycling effects on the coefficient of linear thermal expansion .....	373
5.14.4	Trends in the variation of mechanical properties .....	378
5.15	Coating application .....	378
5.15.1	Pcbz conductive white paint .....	378
5.15.2	APA-2474 (TiO <sub>2</sub> white paint) .....	378

5.15.3	Wiederhold's Z-12321 .....	379
5.16	Past spatial uses .....	380
5.16.1	Intelsat v .....	380
5.16.2	Spelda (structure porteuse externe de lancement double ariane).....	381
5.16.3	CS-3A Japanese satellite .....	384
<b>Bibliography</b>	<b>metallic materials.....</b>	<b>387</b>
<b>References</b>	<b>composite materials.....</b>	<b>391</b>

## Figures

Figure 4-1:	Specific heat, $c$ , of Aluminium as a function of temperature, $T$ .....	30
Figure 4-2:	Thermal conductivity, $\kappa$ , of Aluminium as a function of temperature, $T$ .....	31
Figure 4-3:	Thermal conductivity integrals of Aluminium as a function of temperature, $T$ .....	32
Figure 4-4:	Thermal diffusivity, $\alpha$ , of Aluminium as a function of temperature, $T$ .....	33
Figure 4-5:	Linear thermal expansion, $\Delta L / L$ , of Aluminium as a function of temperature, $T$ .....	34
Figure 4-6:	Normal spectral emittance, $\varepsilon_\lambda'$ , of Aluminium as a function of wavelength, $\lambda$ .....	37
Figure 4-7:	Normal spectral emittance, $\varepsilon_\lambda'$ , of Aluminium conversion coatings as a function of wavelength, $\lambda$ .....	38
Figure 4-8:	Angular spectral emittance, $\varepsilon_\lambda'$ , of Aluminium as a function of wavelength, $\lambda$ .....	39
Figure 4-9:	Normal total emittance, $\varepsilon'$ , of Aluminium as a function of temperature, $T$ .....	45
Figure 4-10:	Normal total emittance, $\varepsilon'$ , of Aluminium anodized as a function of anodizing thickness, $t_c$ .....	46
Figure 4-11:	Summary of data concerning the hemispherical total emittance, $\varepsilon$ , of Aluminium as a function of temperature, $T$ . From Touloukian & DeWitt (1970) [42].....	47
Figure 4-12:	Summary of data concerning the hemispherical total emittance, $\varepsilon$ , of Aluminium conversion coatings vs. temperature, $T$ . From Touloukian, DeWitt & Hernicz (1972) [43].....	52
Figure 4-13:	Directional spectral absorptance, $\alpha_\lambda'$ , of Aluminium as a function of wavelength, $\lambda$ . Data points $\nabla$ correspond to $\beta = 25^\circ$ .....	54
Figure 4-14:	Absorptance to emittance ratio, $\alpha/\varepsilon$ , of Aluminium conversion coatings as a function of the exposure time, $t$ .....	60
Figure 4-15:	Normal - normal spectral reflectance, $\rho_\lambda''$ , of Aluminium as a function of wavelength, $\lambda$ .....	62
Figure 4-16:	Normal - normal spectral reflectance, $\rho_\lambda''$ , of Aluminium contact coatings as a function of wavelength, $\lambda$ .....	64
Figure 4-17:	Effect of coating thickness on normal - normal spectral reflectance, $\rho_\lambda''$ , of Aluminium conversion coatings as a function of wavelength, $\lambda$ .....	65
Figure 4-18:	Bidirectional reflectance, $\rho_\lambda''$ , of Aluminium contact coatings as a function of wavelength, $\lambda$ .....	66

Figure 4-19: Bidirectional spectral reflectance, $\rho_\lambda''$ , of Aluminium conversion coatings as a function of zenith angles, $\beta$ and $\beta'$ , of incident and reflected radiations.....	68
Figure 4-20: Summary of data concerning normal - hemispherical spectral reflectance, $\rho_\lambda'$ , of Aluminium vs. wavelength, $\lambda$ . From Touloukian & DeWitt (1970) [42] .....	69
Figure 4-21: Normal - hemispherical spectral reflectance, $\rho_\lambda'$ , of Aluminium conversion coatings as a function of wavelength, $\lambda$ .....	70
Figure 4-22: Effect of UV exposure on normal - hemispherical spectral reflectance, $\rho_\lambda'$ , of Aluminium conversion coatings as a function of wavelength, $\lambda$ .....	71
Figure 4-23: Effect of electron exposure on normal - hemispherical spectral reflectance of Aluminium conversion coatings as a function of wavelength, $\lambda$ .....	72
Figure 4-24: Effect of simultaneous UV - electron exposure on normal - hemispherical spectral reflectance, $\rho_\lambda'$ , of Aluminium conversion coatings as a function of wavelength, $\lambda$ .....	73
Figure 4-25: Effect of proton exposure on normal - hemispherical spectral reflectance, $\rho_\lambda'$ , of Aluminium conversion coatings as a function of wavelength, $\lambda$ .....	74
Figure 4-26: Directional - hemispherical spectral reflectance, $\rho_\lambda'$ , of Aluminium conversion coatings as a function of wavelength, $\lambda$ .....	75
Figure 4-27: Hemispherical - normal spectral reflectance, $\rho_\lambda'$ , of Aluminium contact coatings as a function of wavelength, $\lambda$ .....	76
Figure 4-28: Bidirectional total reflectance, $\rho''$ , of Aluminium as a function of the viewing zenith angles, $\beta'$ .....	77
Figure 4-29: Normal - normal spectral transmittance, $\tau_\lambda''$ , of Aluminium as a function of wavelength, $\lambda$ .....	80
Figure 4-30: Angular spectral transmittance, $\tau_\lambda''$ , of Aluminium as a function of wavelength, $\lambda$ .....	81
Figure 4-31: Electrical resistivity, $\sigma^{-1}$ , of Aluminium as a function of temperature, $T$ .....	83
Figure 4-32: Specific heat, $c$ , of Al - 4,3 Cu - 1,5 Mg - 0,6 Mn as a function of temperature, $T$ .....	86
Figure 4-33: Thermal conductivity, $k$ , of Al - 4,3 Cu - 1,5 Mg - 0,6 Mn as a function of temperature, $T$ .....	87
Figure 4-34: Thermal conductivity integrals of Al - 4,3 Cu - 1,5 Mg - 0,6 Mn as a function of temperature, $T$ .....	88
Figure 4-35: Thermal diffusivity, $\alpha$ , of Al - 4,3 Cu - 1,5 Mg - 0,6 Mn as a function of temperature, $T$ .....	89
Figure 4-36: Linear thermal expansion, $\Delta L / L$ , of Al - 4,3 Cu - 1,5 Mg - 0,6 Mn as a function of temperature, $T$ .....	90
Figure 4-37: Normal - spectral emittance, $\varepsilon_\lambda'$ , of Al - 4,3 Cu - 1,5 Mg - 0,6 Mn as a function of wavelength, $\lambda$ .....	91
Figure 4-38: Normal total emittance, $\varepsilon'$ , of Al - 4,3 Cu - 1,5 Mg - 0,6 Mn as a function of temperature, $T$ .....	93
Figure 4-39: Normal-normal spectral reflectance, $\rho_\lambda''$ , of Al-4,3 Cu-1,5 Mg-0,6 Mn, anodized, as a function of wavelength, $\lambda$ .....	98

Figure 4-40: Normal - hemispherical spectral reflectance, $\rho_\lambda'$ , of Al - 4,3 Cu - 1,5 Mg - 0,6 Mn as a function of wavelength, $\lambda$ .....	99
Figure 4-41: Normal - hemispherical spectral reflectance, $\rho_\lambda'$ , of Al - 4,3 Cu - 1,5 Mg - 0,6 Mn, anodized, as a function of wavelength, $\lambda$ .....	100
Figure 4-42: Normal-hemispherical spectral reflectance, $\rho_\lambda'$ , of Al-1 Mg-0,6 Si, as received, as a function of wavelength, $\lambda$ .....	108
Figure 4-43: Normal-hemispherical spectral reflectance, $\rho_\lambda'$ , of Al-1 Mg-0,6 Si, grit blasted, as a function of wavelength, $\lambda$ .....	109
Figure 4-44: Normal-hemispherical spectral reflectance, $\rho_\lambda'$ , of Al-1 Mg-0,6 Si, chemically polished, as a function of wavelength, $\lambda$ .....	111
Figure 4-45: Normal - hemispherical spectral reflectance, $\rho_\lambda'$ , of Al - 1 Mg - 0,6 Si, chemically milled, as a function of wavelength, $\lambda$ .....	112
Figure 4-46: Specific heat, $c$ , of Al - 5,7 Zn - 2,5 Mg - 1,6 Cu as a function of temperature, $T$ .....	115
Figure 4-47: Thermal conductivity, $k$ , of Al - 5,7 Zn - 2,5 Mg - 1,6 Cu as a function of temperature, $T$ .....	116
Figure 4-48: Thermal conductivity integral of Al – 5,7 Zn – 2,5 Mg – 1,6 Cu as a function of temperature, $T$ .....	117
Figure 4-49: Thermal diffusivity, $\alpha$ , of Al - 5,7 Zn - 2,5 Mg - 1,6 Cu as a function of temperature, $T$ .....	118
Figure 4-50: Linear thermal expansion, $\Delta L / L$ , of Al - 5,7 Zn - 2,5 Mg - 1,6 Cu as a function of temperature, $T$ .....	119
Figure 4-51: Normal spectral emittance, $\varepsilon_\lambda'$ , of Al - 5,7 Zn - 2,5 Mg - 1,6 Cu as a function of wavelength, $\lambda$ .....	120
Figure 4-52: Angular spectral emittance, $\varepsilon_\lambda'$ , of Al - 5,7 Zn - 2,5 Mg - 1,6 Cu as a function of wavelength, $\lambda$ .....	121
Figure 4-53: Normal total emittance, $\varepsilon'$ , of Al - 5,7 Zn - 2,5 Mg - 1,6 Cu as a function of temperature, $T$ .....	122
Figure 4-54: Normal-hemispherical spectral reflectance, $\rho'_\lambda$ , of Al - 5,7 Zn - 2,5 Mg - 1,6 Cu conversion coatings, as a function of wavelngth, $\lambda$ .....	126
Figure 4-55: Specific heat, $c$ , of Ti - 5 Al - 2,5 Sn as a function of temperature, $T$ .....	134
Figure 4-56: Thermal conductivity, $k$ , of Ti - 5 Al - 2,5 Sn as a function of temperature, $T$ .....	135
Figure 4-57: Thermal linear expansion, $\Delta L/L$ , of Ti - 5 Al - 2,5 Sn as a function of temperature, $T$ .....	136
Figure 4-58: Normal spectral emittance, $\varepsilon_\lambda'$ , of Ti - 5 Al - 2,5 Sn as a function of temperature, $T$ , for $\lambda = 6,65 \times 10^{-7}$ m.....	137
Figure 4-59: Normal total emittance, $\varepsilon'$ , of Ti - 5 Al - 2,5 Sn as a function of temperature, $T$ .....	138
Figure 4-60: Normal-normal spectral reflectance, $\rho_\lambda''$ , of Ti - 5 Al - 2,5 Sn as a function of wavelength, $\lambda$ .....	140
Figure 4-61: Normal - hemispherical spectral reflectance, $\rho_\lambda'$ , of Ti - 5 Al - 2,5 Sn as a function of wavelength, $\lambda$ .....	141

Figure 4-62: Normal - hemispherical spectral reflectance, $\rho_\lambda'$ , of Ti - 5 Al - 2,5 Sn, anodized, as a function of wavelength, $\lambda$ .....	142
Figure 4-63: Electrical resistivity, $\sigma^{-1}$ , of Ti - 5 Al - 2,5 Sn as a function of temperature, $T$ .....	143
Figure 4-64: Specific heat, $c$ , of Ti - 6 Al - 2 Sn - 4 Zr - 2 Mo as a function of temperature, $T$ .....	145
Figure 4-65: Thermal conductivity, $k$ , of Ti - 6 Al - 2 Sn - 4 Zr - 2 Mo as a function of temperature, $T$ .....	146
Figure 4-66: Mean coefficient of linear thermal expansion, $\beta$ , of Ti - 6 Al - 2 Sn - 4 Zr - 2 Mo from room temperature to temperature $T$ .....	147
Figure 4-67: Electrical resistivity, $\sigma^{-1}$ , of Ti - 6 Al - 2 Sn - 4 Zr - 2 Mo as a function of temperature, $T$ .....	149
Figure 4-68: Specific heat, $c$ , of Ti - 6 Al - 4 V as a function of temperature, $T$ .....	152
Figure 4-69: Thermal conductivity, $k$ , of Ti - 6 Al - 4 V as a function of temperature, $T$ .....	153
Figure 4-70: Thermal conductivity integrals of Ti - 6 Al - 4 V as a function of temperature, $T$ .....	154
Figure 4-71: Thermal diffusivity, $\alpha$ , of Ti - 6 Al - 4 V as a function of temperature, $T$ .....	155
Figure 4-72: Thermal linear expansion, $\Delta L/L$ , of Ti - 6 Al - 4 V as a function of temperature, $T$ .....	156
Figure 4-73: Normal spectral emittance, $\varepsilon_\lambda'$ , of Ti - 6 Al - 4 V as a function of temperature, $T$ .....	157
Figure 4-74: Normal total emittance, $\varepsilon'$ , of Ti - 6 Al - 4 V as a function of temperature, $T$ ....	158
Figure 4-75: Hemispherical total emittance, $\varepsilon$ , of Ti - 6 Al - 4 V as a function of temperature, $T$ .....	160
Figure 4-76: Normal - hemispherical spectral reflectance, $\rho_\lambda'$ , of Ti - 6 Al - 4 V as a function of wavelength, $\lambda$ .....	162
Figure 4-77: Electrical resistivity, $\sigma^{-1}$ , of Ti - 6 Al - 4 V as a function of temperature, $T$ .....	163
Figure 4-78: Specific heat, $c$ , of Ni - 19 Cr - 11 Co - 10 Mo - 3 Ti as a function of temperature, $T$ .....	166
Figure 4-79: Thermal conductivity, $k$ , of Ni - 19 Cr - 11 Co - 10 Mo - 3 Ti as a function of temperature, $T$ .....	167
Figure 4-80: Thermal linear expansion, $\Delta L/L$ , of Ni - 19 Cr - 11 Co - 10 Mo - 3 Ti as a function of temperature, $T$ .....	168
Figure 4-81: Normal spectral emittance, $\varepsilon_\lambda'$ , of Ni - 19 Cr - 11 Co - 10 Mo - 3 Ti as a function of wavelength, $\lambda$ .....	169
Figure 4-82: Normal total emittance, $\varepsilon'$ , of Ni - 19 Cr - 11 Co - 10 Mo - 3 Ti as a function of temperature, $T$ .....	170
Figure 4-83: Normal-normal spectral reflectance, $\rho''_\lambda$ , of Ni - 19 Cr - 11 Co - 10 Mo - 3 Ti as a function of wavelength, $\lambda$ . Data points ▷ correspond to normal-hemispherical reflectance while ▶, ◀, ◁ correspond to hemispherical-normal reflectance. ....	172
Figure 4-84: Specific heat, $c$ , of Fe - 36 Ni (Invar) as a function of temperature, $T$ .....	176

Figure 4-85: Linear thermal expansion, $\Delta L/L$ , of Fe - 36 Ni (Invar) as a function of temperature, $T$ .....	177
Figure 4-86: Effect of the concentration of alloying elements, $c$ , on the value of the coefficient of linear expansion, $\beta$ . From MOND NICKEL Co. ....	178
Figure 4-87: Normal emittance, $\varepsilon_\lambda'$ , of Fe - 36 Ni (Invar), for $\lambda = 6,7 \times 10^{-7}$ as a function of temperature, $T$ .....	179
Figure 5-1: International ties between Carbon Fiber manufactures. From SENER (1984) [147].....	205
Figure 5-2: Schematic of an angle plied laminate. From Chamis (1987) [67]. ....	206
Figure 5-3: Schematic of a tri-orthogonally fiber reinforced composite. a) Straight filaments. From Domínguez (1987) [82]. b) Tapes. From Aboudi (1984) [49].....	206
Figure 5-4: Main types of woven fabrics. Lengthwise (warp) yarns and crosswise (fill) yarns can be interlaced to produce woven fabrics. A fabric construction of 16 x 14 means 16 warp ends per inch and 14 fill ends per inch. a) Plain weave. Very stable. Small yarn slippage. b) Leno weave. Minimizes distortion with few yarns. c) Twill. The fabric has a broken diagonal line and, consequently, greater pliability than a plain weave. d) Crowfoot satin. Pliable and comfortable to contoured surfaces. From Domínguez (1987) [82], Weeton, Peters & Thomas (1987) [164]. .....	207
Figure 5-5: Longitudinal (to fibers) and transverse directions for the measurement of composite properties. From Chamis (1987) [67].....	209
Figure 5-6: Cryostat assemblies for measuring the thermal conductivity, $k$ . a) High- $k$ samples. b) Low- $k$ samples. From Pilling, Yates, Black & Tattersall (1979) [137]. For explanation see text. ....	222
Figure 5-7: Facility used to measure the thermal conductivity, $k$ , of a sample as a function of temperature in the range 90 K to 410 K. Temperature changes continuously. From Ott (1981) [132]. .....	224
Figure 5-8: Hypodermic probe to measure the thermal conductivity of polymer melts. All the dimensions are in mm. From Lobo & Cohen (1990) [120].....	225
Figure 5-9: Thermal conductivity, $k_m$ , of different matrices as a function of temperature, $T$ . Numerical values are given in Table 5-10. ....	236
Figure 5-10: Longitudinal thermal conductivity, $k_f1$ , of several advanced pitch graphite fibers vs. temperature, $T$ . The fiber designation is from Amoco Performance Products; the number stands for the fiber elasticity modulus in millions of lbs.in $^{-2}$ . All the data, unless otherwise stated, are from LMSC. Pitch precursor graphite fibers have a structure which approaches that of a single crystal of graphite and, thus, their thermal conductivity is very large. From McGuire & Vollerin (1990) [127]. .....	237
Figure 5-11: Typical assembly for measuring the thermal diffusivity, $\alpha$ , of a long slender bar by use of the Angström method. From Landis (1964) [116]. ....	247
Figure 5-12: Typical assembly for measuring the thermal diffusivity, $\alpha$ , of a disc shaped sample. From Lachi, Legrand & Degiovanni (1988) [115]. ....	248
Figure 5-13: Thermal diffusivity, $\alpha_f$ , of different fiber cloths as a function of temperature, $T$ . Numerical values are given in Table 5-33 From Touloukian (1967) [157]. ....	251

Figure 5-14: Experimental arrangement for the interferometric measurement of the thermal expansion. a) Specimen chamber assembly. b) Optical system. From James & Yates (1965) [108]. For explanation see text.	256
Figure 5-15: The ESTEC CTE 1000 facility for the measurement of the linear thermal expansion of structure up to 0,7 m long. All the dimensions are in mm. From Aalders (1989) [48].	258
Figure 5-16: Linear thermal expansion, $\beta_m$ , as a function of temperature, $T$ , for four different epoxy matrices. Numerical values are given in Table 5-41.	269
Figure 5-17: Linear thermal expansion coefficient measured parallel to fibers, $\beta_1$ , as a function of temperature, $T$ , for some composite materials formed by the same matrix, DER 332/T403, and two different glass fiber reinforcements. Upper and lower limits of the shadowed regions are for 95% confidence.	278
Figure 5-18: Linear thermal expansion coefficient measured perpendicular to fibers, $\beta_2$ , as a function of temperature, $T$ , for some composite materials formed by the same matrix, DER 332/T403, and two different glass fiber reinforcements.	280
Figure 5-19: Linear thermal expansion coefficient measured in different directions, $\beta$ , as a function of temperature, $T$ , for similar carbon fiber reinforced composite materials. The matrix is ERLA 4617/mPDA. From Rogers, Phillips, Kingston, Lee, Yates, Overy, Sargent & McCalla (1977) [144].	281
Figure 5-20: Linear thermal expansion coefficient measured parallel to fibers, $\beta_1$ , as a function of temperature, $T$ , for different fiber volume ratios, $\varphi_f$ . Fiber: Courtaulds HTS PT112/21Z; Matrix: DLS 351/BF <sub>3</sub> 400.	290
Figure 5-21: Linear thermal expansion coefficient measured perpendicular to fibers, $\beta_2$ , as a function of temperature, $T$ , for different fiber volume ratios, $\varphi_f$ . Fiber: Courtaulds HTS PT112/21Z; Matrix: DLS 351/BF <sub>3</sub> 400.	291
Figure 5-22: Linear thermal expansion coefficient measured either in plane of laminate, $\beta_1$ , or perpendicular to it, $\beta_3$ , as a function of temperature, $T$ , for similar carbon fibers reinforced composite materials. The fiber is carbon HTS PT112/21Z. From Yates, McCalla, Sargent, Rogers, Phillips & Kingston-Lee (1978)b [169].	292
Figure 5-23: Linear thermal expansion coefficient, $\beta$ , of a carbon fiber reinforced unidirectional composite material, measured in plane of laminate, as a function of the direction of the measurement, $\theta$ . Matrix is Epikote 828/BF <sub>3</sub> MEA. Fibers are Torayca T300A. Temperature range is 290 K to 340 K. From Isikawa, Koyama & Kobayashi (1977, 1978) [106] & [107].	299
Figure 5-24: Linear thermal expansion coefficient measured parallel to fibers, $\beta_1$ , as a function of temperature, $T$ , for two nominally identical carbon fiber reinforced composite materials produced on separate occasions and having slightly different fiber volume ratios, $\varphi_f$ . Fiber: HTSCarbon; Matrix: Fibredex 914C.	300
Figure 5-25: Linear thermal expansion coefficient measured perpendicular to fibers, $\beta_2$ , as a function of temperature, $T$ , for two nominally identical carbon fiber reinforced composite materials produced on separate occasions and having slightly different fiber volume ratios, $\varphi_f$ . Fiber: HTSCarbon; Matrix: Fibredex 914C.	301
Figure 5-26: Linear thermal expansion coefficient measured in 0° direction, $\beta_0$ , as a function of temperature, $T$ , for some carbon fiber reinforced composite	

materials with various amounts of fibers in different directions. Fiber: Courtaulds HTS, Type II; Matrix: Fibredex 914C. ....	306
Figure 5-27: Linear thermal expansion coefficient, $\beta_0$ , of a two-ply ( $\pm \theta$ ) carbon fiber reinforced composite material, measured in direction $0^\circ$ of the plane of laminate, as a function of the angle ply, $\theta$ . Matrix is Hercules 3002, fibers are Hercules HT (Hercules 3002T prepreg). Temperature range is 80 K to 450 K. From Friend, Poesch & Leslie (1972) [90]. ....	308
Figure 5-28: Linear thermal expansion coefficient, $\beta$ , measured in several directions of the plane of laminate for an unidirectional and an angle plied carbon fiber reinforced composite material, as a function of temperature, $T$ . Matrix is Narmco 5208, fibers are Narmco T300. From Karlsson (1983) [111]. ....	309
Figure 5-29: Linear thermal expansion coefficient measured either parallel, $\beta_1$ , or perpendicular, $\beta_2$ , to fibers of two composites with similar epoxy matrices, but with carbon fiber or Kevlar 49 reinforcements. ....	316
Figure 5-30: Linear thermal expansion coefficient measured parallel to fibers, $\beta_1$ , as a function of temperature, $T$ , for two graphite fiber-metal and one carbon fiber-epoxy composite materials. ....	317
Figure 5-31: Linear thermal expansion coefficient measured perpendicular to fibers, $\beta_2$ , as a function of temperature, $T$ , for graphite fiber-metal and carbon fiber-epoxy composite materials. ....	318
Figure 5-32: Normal spectral absorptance, $\alpha'_\lambda$ , of SiO <sub>2</sub> Fabric at 310 K vs. wavelength, $\lambda$ . Sample is described in the text. From Eagles, Babjak & Weaver (1975) [85]. ....	320
Figure 5-33: Normal-hemispherical spectral reflectance, $\rho'_\lambda$ , of SiO <sub>2</sub> Fabric vs. wavelength, $\lambda$ . Sample is described in the text. From Eagles, Babjak & Weaver (1975) [85]. ....	321
Figure 5-34: Solar absorptance, $\alpha_s$ , of SiO <sub>2</sub> Fabric-Substrate composite as a function of the solar absorptance, $\alpha_{ss}$ , of the substrate. Sample: 16 Harness Satin Weave 0,38x10 <sup>-3</sup> m thick, on different substrates. From Eagles, Babjak & Weaver (1975) [85]. ....	322
Figure 5-35: Absorptance/Emitatnce ratio, $\alpha_s/\varepsilon$ , solar absorptance, $\alpha_s$ , and hemispherical total emittance, $\varepsilon$ , of various mosaics of silica and carbon yarn as functions of the exposed black to total area fraction, $A_B/A$ . From Eagles, Babjak & Weaver (1975) [85]. ....	322
Figure 5-36: Normal spectral emittance, $\varepsilon'_\lambda$ , of PV 100 coating on different substrates and with different thicknesses (see Table 5-67) vs. wavelength, $\lambda$ , at 393 K. From Giommi, Marchetti, Salza & Testa (1985) [92]. ....	327
Figure 5-37: Normal-hemispherical spectral reflectance factor, $R'_\lambda$ , of PV 100 coating on different substrates and with different thicknesses vs. wavelength, $\lambda$ . From Giommi, Marchetti, Salza & Testa (1985) [92]. ....	329
Figure 5-38: Normal total emittance, $\varepsilon'(0)$ , of sputtered aluminium on T300/5209 graphite-epoxy composite material as a function of sputtered coating thickness, $t_c$ , and for two different textures of the supporting material. From Witte & Teichman (1989) [166]. ....	332
Figure 5-39: Normal solar absorptance, $\alpha_s$ , of sputtered aluminium on T300/5209 graphite-epoxy composite material as a function of sputtered coating	

thickness, $t_c$ , and for two different textures of the supporting material. From Witte & Teichman (1989) [166].....	333
Figure 5-40: Solar absorptance to emittance ratio of sputtered aluminium on T300/5209 graphite-epoxy composite material as a function of sputtered coating thickness, $t_c$ , and for two different textures of the supporting material. From Witte & Teichman (1989) [166].....	334
Figure 5-41: Tensile strength, $\sigma_t$ , vs. temperature, $T$ , of structural materials. Inert atmospheres. From DeMario (1985) [81].....	335
Figure 5-42: Electrical resistivity, $\rho$ , as a function of frequency, $f$ , for a carbon-epoxy composite material. Fiber: Super A, Matrix: Fibredux 914C. Layup ( $0^\circ \pm 45^\circ$ ) 16 plies. Sample size: $\textcircled{O} :> 1,98 \times 10^{-3} \text{ m}, 10 \times 10^{-3} \text{ m}, 25 \times 10^{-3} \text{ m}$ . $\square :> 1,98 \times 10^{-3} \text{ m}, 5,5 \times 10^{-3} \text{ m}, 25 \times 10^{-3} \text{ m}$ . From Thomson (1982) [156].....	345
Figure 5-43: One-dimensional and radial models of laminar diffusion through homogeneous-isotropic media. ....	350
Figure 5-44: Moisture content, $M$ , as a function of ambient temperature, $T$ , after 100 h of exposure to distilled water at that temperature, for several carbon fiber reinforced composites. The specimens are infinitely large rods of $6 \times 10^{-3} \text{ m}$ diameter. $M_0 = 0,002$ assumed.....	351
Figure 5-45: Effect of UV radiation on linear thermal expansion, $\beta$ , of Graphite/epoxy T300/SP 288 laminates. a) $\theta = 90^\circ$ , b) $\theta = (\pm 43^\circ)_s$ , c) $\theta = 0^\circ$ . Ambient pressure $10^{-4} \text{ Pa}$ to $10^{-5} \text{ Pa}$ . From Tennyson & Zimcik (1982) [107], Hansen & Tennyson (1983) [153].....	361
Figure 5-46: Effect of UV radiation on linear thermal expansion, $\beta$ , of Kevlar/epoxy 3M SP 306 laminates. a) $\theta = 90^\circ$ , b) $\theta = (\pm 43^\circ)_s$ , c) $\theta = 0^\circ$ . Ambient pressure $10^{-4} \text{ Pa}$ to $10^{-5} \text{ Pa}$ . From Tennyson & Zimcik (1982) [154], Hansen & Tennyson (1983) [95] .....	361
Figure 5-47: Effect of electron radiation with (thick solid line) and without (thin solid line) UV exposure, on linear thermal expansion, $\beta_0$ , of graphite/epoxy and Kevlar/epoxy, $\theta = (\pm 43^\circ)_s$ . Ambient pressure $10^{-4} \text{ Pa}$ to $10^{-5} \text{ Pa}$ . Exposure > 1 year and 300 ESD of UV. From Hansen & Tennyson (1983) [95].....	362
Figure 5-48: Linear thermal expansion, $\beta_0$ , as a function of temperature, $T$ , of T50(PAN)/F263 (0/90) <sub>2s</sub> HM graphite/epoxy laminates exposed to electron radiation. Calculated by the compiler by numerical derivation ( $\beta = d(\Delta L/L)/dT$ ) of data from Mauri & Crossman (1983) [125].....	362
Figure 5-49: Graphs for estimating the depletion by atomic oxygen of a material of known Reaction Efficiency, $R_e$ . From Leger & Visentine (1986) [118].....	367
Figure 5-50: Effect of the number of thermal cycles, $N$ , on the linear thermal expansion, $\beta_0$ , of $(\pm 22^\circ)_s$ T300/3M SP288 Graphite/Epoxy laminates. $300 \text{ K} \leq T \leq 370 \text{ K}$ , $p = 1,33 \times 10^{-4} \text{ Pa}$ to $1,33 \times 10^{-5} \text{ Pa}$ . From Tennyson & Zimcik (1982) [154], Hansen & Tennyson (1983) [95].....	375
Figure 5-51: Effect of the number of thermal cycles, $N$ , on the linear thermal expansion, $\beta_0$ , of $(\pm 43^\circ)_s$ T300/3M SP288 Graphite/Epoxy laminates. $300 \text{ K} \leq T \leq 370 \text{ K}$ , $p = 1,33 \times 10^{-4} \text{ Pa}$ to $1,33 \times 10^{-5} \text{ Pa}$ . From Tennyson (1980) [153], Tennyson & Zimcik (1982) [154], Hansen & Tennyson (1983) [95].....	375
Figure 5-52: Effect of the number of thermal vacuum cycles, $N$ , on the linear thermal expansion, $\beta_0$ , of $(\pm \theta^\circ)_s$ T300/3M SP288 Graphite/Epoxy laminates. $300 \text{ K} \leq T \leq 370 \text{ K}$ , $p = 1,33 \times 10^{-4} \text{ Pa}$ to $1,33 \times 10^{-5} \text{ Pa}$ . 50 cycles $\approx 220$ days in	

vacuum. From Tennyson & Zimcik (1982) [154], Hansen & Tennyson (1983) [95].....	376
Figure 5-53: Effect of the number of thermal vacuum cycles, $N$ , on the linear thermal expansion, $\beta_0$ , of $(\pm \theta^\circ)_S$ 3M SP306 Kevlar/Epoxy laminates. $300 \text{ K} \leq T \leq 370 \text{ K}$ , $p = 1,33 \times 10^{-4} \text{ Pa}$ to $1,33 \times 10^{-5} \text{ Pa}$ . 50 cycles $\approx 220$ days in vacuum. From Tennyson & Zimcik (1982) [154], Hansen & Tennyson (1983) [95].....	376
Figure 5-54: Comparison of predicted (-) and experimental (o) values of the linear thermal expansion, $\beta_0$ , vs. fiber angle, $\theta$ , for $(\pm \theta^\circ)_S$ 3M SP306 Kevlar/Epoxy laminates. 48 cycles $\approx 220$ days in vacuum. $300 \text{ K} \leq T \leq 370 \text{ K}$ , $p = 1,33 \times 10^{-4} \text{ Pa}$ to $1,33 \times 10^{-5} \text{ Pa}$ . From Tennyson & Zimcik (1982) [171], Hansen & Tennyson (1983) [95]. Results for Graphite/Epoxy are given in Tennyson (1980) [153]. Compare also with Figure 5-27. ....	377
Figure 5-55: Effect of the number of thermal vacuum cycles, $N$ , on the linear thermal expansion, $\beta_0$ , of $(\pm \theta^\circ)_S$ 3M SP290 Boron/Epoxy laminates. $300 \text{ K} \leq T \leq 370 \text{ K}$ , $p = 1,33 \times 10^{-4} \text{ Pa}$ to $1,33 \times 10^{-5} \text{ Pa}$ . 50 cycles $\approx 220$ days in vacuum. From Tennyson & Zimcik (1982) [154], Hansen & Tennyson (1983) [95].....	377
Figure 5-56: Coefficient of the linear thermal expansion, $\beta_0$ , as a function of temperature, $T$ , for Graphite/Epoxy circular hybrid tubes, identified as Spec. No. 12 in Table 5-84 and Table 5-85, before (solid line) and after (dashed line) thermal vacuum cycling. 3000 cycles. $98 \text{ K} \leq T \leq 370 \text{ K}$ , $p = 1,33 \times 10^{-3} \text{ Pa}$ . From Reibaldi (1985) [141]. ....	378
Figure 5-57: Outline of INTELSAT V communication satellite.....	380
Figure 5-58: Sketch of the ARIANE 4 upper part. From Thomas & Oliver (1985) [155].....	382
Figure 5-59: Exploded view of SPELDA. From Thomas & Oliver (1985) [155].....	383
Figure 5-60: Sketch of the CS-3a structure. From Kawashima, Inoue & Seko (1985) [112].....	384
Figure 5-61: Exploded view of CS-3a Central Thrust Tube. Prepared by the compiler after Kawashima, Inoue & Seko (1985) [112]. .....	385

## Tables

Table 4-1: Normal Total Emittance of Aluminium.....	40
Table 4-2: Normal Total Emittance and Normal Solar Absorptance of Aluminium Contact Coatings.....	42
Table 4-3: Normal Total Emittance and Normal Solar Absorptance of Aluminium Conversion Coatings.....	44
Table 4-4: Hemispherical Total Emittance of Aluminium Contact Coatings.....	47
Table 4-5: Hemispherical total Absorptance of Aluminium.....	55
Table 4-6: Normal Solar Absorptance of Aluminium .....	57
Table 4-7: Normal Solar Absorptance of Aluminium Conversion Coatings.....	58
Table 4-8: Angular Solar absorptance of Aluminium.....	60
Table 4-9: Normal-Normal Solar Reflectance of Aluminium Conversion Coatings .....	78
Table 4-10: Normal-Hemispherical Solar Reflectance of Both Bulk Aluminium and Contact Coatings.....	79
Table 4-11: Normal Total Emittance of Al – 4,3 Cu – 1,5 Mg – 0,6 Mn, Anodized .....	95

Table 4-12: Hemispherical Total Emittance of Al – 4,3 Cu – 1,5 Mg – 0,6 Mn .....	95
Table 4-13: Normal Solar Absorptance of Al – 4,3 Cu – 1,5 Mg – 0,6 Mn .....	96
Table 4-14: Normal Solar Absorptance of Al – 4,3 Cu – 1,5 Mg – 0,6 Mn, Anodized .....	97
Table 4-15: Normal Hemispherical Solar Reflectance of Al – 4,3 Cu – 1,5 Mg – 0,6 Mn, Anodized .....	102
Table 4-16: Normal Total Emittance of Al – 1 Mg – 0,6 Si .....	105
Table 4-17: Hemispherical Total Emittance of Al – 1 Mg – 0,6 Si .....	106
Table 4-18: Normal Solar Absorptance of Al – 1 Mg – 0,6 Si.....	107
Table 4-19: Hemispherical Total Emittance of Al – 5,7 Zn – 2,5 Mg – 1,6 Cu Conversion Coatings.....	124
Table 4-20: Normal Solar Absorptance and Normal-Hemispherical Solar Reflectance of Al – 5,6 Zn – 2,5 Mg 1,6 Cu.....	125
Table 4-21: Normal Solar Absorptance of Ti – 5 Al – 2,5 Sn.....	139
Table 4-22: Normal Solar Absorptance of Ti – Al – 4 V.....	161
Table 4-23: Cost of Ti – 6 Al – 4 – V compared with those of other structural metallic materials.....	164
Table 4-24: Electrical Resistivity of Ni – 19Cr – 11Co – 10Mo – 3Ti <sup>a</sup> .....	173
Table 4-25: Linear thermal expansion coefficient of Fe – 36 Ni under different temper conditions.....	178
Table 4-26: Magnetic Properties of Fe – 36 Ni under different temper conditions.....	180
Table 4-27: Relative Permeability of Fe – 36 Ni, measured at 400 A.m <sup>-1</sup> .....	180
Table 5-1: Abridged Designation of Single Reinforcement Laminates .....	208
Table 5-2: Density, $\rho_f$ [kg.m <sup>-3</sup> ], of High-Strength Fibers .....	210
Table 5-3: Density, $\rho_m$ [kg.m <sup>-3</sup> ], of Matrices .....	215
Table 5-4: Specific Heat, $c_f$ [J.kg <sup>-1</sup> .K <sup>-1</sup> ], of High-Strength Fibers.....	217
Table 5-5: Fussed Silicia .....	218
Table 5-6: Kevlar <sup>d</sup> .....	219
Table 5-7: Specific Heat, $c_m$ [J.kg <sup>-1</sup> .K <sup>-1</sup> ], of Matrices .....	220
Table 5-8: Specific Heat, $c$ [J.kg <sup>-1</sup> .K <sup>-1</sup> ], of Composite Materials .....	221
Table 5-9: Longitudinal (1) and Transverse (2) Thermal Conductivity, of High-Strength Fibers. Tabulated Data are $k_{f1}$ [W.m <sup>-1</sup> .K <sup>-1</sup> ]/ $k_{f2}$ [W.m <sup>-1</sup> .K <sup>-1</sup> ], of Fibers .....	226
Table 5-10: Thermal Conductivity, $k_m$ [W.m <sup>-1</sup> .K <sup>-1</sup> ], of Matrices.....	228
Table 5-11: Araldite LY556 .....	229
Table 5-12: DER 332/T403 (100:36) <sup>c</sup> .....	229
Table 5-13: Epitoke 210/BF <sub>3</sub> 400 <sup>b</sup> .....	230
Table 5-14: Epoxin 162 <sup>a</sup> .....	230
Table 5-15: Palatal P51 <sup>a</sup> .....	231
Table 5-16: Nylon 6 <sup>a</sup> .....	232
Table 5-17: Comco, Nylon 6/6 <sup>g,h</sup> .....	233

Table 5-18: Polypenco 101, Nylon 6/6 <sup>g,h</sup> .....	234
Table 5-19: Polypropylene <sup>a</sup> .....	235
Table 5-20: Characteristics of Composite Materials (Thermal Conductivity can be found following the links).....	237
Table 5-21: Smoothed values of the Thermal conductivity, $k$ [W.m <sup>-1</sup> .K <sup>-1</sup> ], of the Composite Specimens Characterized in Table 5-9.....	241
Table 5-22: Smoothed values of the Thermal conductivity, $k$ [W.m <sup>-1</sup> .K <sup>-1</sup> ], of the Composite Specimens Characterized in Table 5-9.....	241
Table 5-23: Smoothed values of the Thermal conductivity, $k$ [W.m <sup>-1</sup> .K <sup>-1</sup> ], of the Composite Specimens Characterized in Table 5-9.....	242
Table 5-24: Smoothed values of the Thermal conductivity, $k$ [W.m <sup>-1</sup> .K <sup>-1</sup> ], of the Composite Specimens Characterized in Table 5-9.....	242
Table 5-25: Smoothed values of the Thermal conductivity, $k$ [W.m <sup>-1</sup> .K <sup>-1</sup> ], of the Composite Specimens Characterized in Table 5-9.....	242
Table 5-26: Smoothed values of the Thermal conductivity, $k$ [W.m <sup>-1</sup> .K <sup>-1</sup> ], of the Composite Specimens Characterized in Table 5-9.....	243
Table 5-27: Smoothed values of the Thermal conductivity, $k$ [W.m <sup>-1</sup> .K <sup>-1</sup> ], of the Composite Specimens Characterized in Table 5-9.....	243
Table 5-28: Smoothed values of the Thermal conductivity, $k$ [W.m <sup>-1</sup> .K <sup>-1</sup> ], of the Composite Specimens Characterized in Table 5-9.....	244
Table 5-29: Smoothed values of the Thermal conductivity, $k$ [W.m <sup>-1</sup> .K <sup>-1</sup> ], of the Composite Specimens Characterized in Table 5-9.....	245
Table 5-30: Smoothed values of the Thermal conductivity, $k$ [W.m <sup>-1</sup> .K <sup>-1</sup> ], of the Composite Specimens Characterized in Table 5-9.....	245
Table 5-31: Smoothed values of the Thermal conductivity, $k$ [W.m <sup>-1</sup> .K <sup>-1</sup> ], of the Composite Specimens Characterized in Table 5-9.....	246
Table 5-32: Smoothed values of the Thermal conductivity, $k$ [W.m <sup>-1</sup> .K <sup>-1</sup> ], of the Composite Specimens Characterized in Table 5-9.....	246
Table 5-33: Thermal diffusivity, $\alpha_f \times 10^6$ [m <sup>2</sup> .s <sup>-1</sup> ], of High-Strength Fibers.....	249
Table 5-34: Thermal diffusivity, $\alpha_f \times 10^6$ [m <sup>2</sup> .s <sup>-1</sup> ], of High-Strength Fibers.....	250
Table 5-35: Thermal diffusivity, $\alpha_m$ [m <sup>2</sup> .s <sup>-1</sup> ], of Matrices .....	252
Table 5-36: Thermal diffusivity, $\alpha_x \times 10^6$ [m <sup>2</sup> .s <sup>-1</sup> ], of Composite Materials .....	253
Table 5-37: Thermal diffusivity, $\alpha_x \times 10^6$ [m <sup>2</sup> .s <sup>-1</sup> ], of Composite Materials .....	254
Table 5-38: Thermal diffusivity, $\square \times 10^6$ [m <sup>2</sup> .s <sup>-1</sup> ], of Composite Materials.....	255
Table 5-39: Linear thermal expansion, $\beta_f$ [K <sup>-1</sup> ], and elasticity modulus, $E_f$ [Pa], of high-strength fibers .....	260
Table 5-40: Linear thermal expansion, $\beta_m$ [K <sup>-1</sup> ], elasticity modulus, $E_m$ [Pa] and Poisson's ratio, $\nu_m$ , of matrices .....	264
Table 5-41: Arrangements of the Data on Linear Thermal Expansion, $\beta$ , of Composite Materials Compiled in Table 5-42 to Table 5-60 .....	270
Table 5-42: Characterization of Composite Materials (Linear Thermal Expansion is given following the links). .....	271

Table 5-43: Smoothed values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens characterized in Table 5-85.....	274
Table 5-44: Smoothed values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens characterized in Table 5-85.....	274
Table 5-45: Smoothed values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens characterized in Table 5-85.....	275
Table 5-46: Smoothed values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens characterized in Table 5-85.....	275
Table 5-47: Smoothed values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens characterized in Table 5-85.....	276
Table 5-48: Smoothed values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens characterized in Table 5-85.....	277
Table 5-49: Characterization of Composite Materials (Linear Thermal Expansion is given following the links).....	282
Table 5-50: Smoothed Values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens Characterized in Table 5-49.....	285
Table 5-51: Smoothed Values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens Characterized in Table 5-49.....	286
Table 5-52: Smoothed Values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens Characterized in Table 5-49.....	288
Table 5-53: Smoothed Values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens Characterized in Table 5-49.....	289
Table 5-54: Characterization of Composite Materials (Linear Thermal Expansion is given following the links).....	293
Table 5-55: Smoothed Values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens Characterized in Table 5-54.....	295
Table 5-56: Smoothed Values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens Characterized in Table 5-54.....	296
Table 5-57: Characterization of Composite Materials (Linear Thermal Expansion is given following the links).....	302
Table 5-58: Smoothed Values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens Characterized in Table 5-57.....	304
Table 5-59: Smoothed Values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens Characterized in Table 5-57.....	305
Table 5-60: Characterization of Composite Materials (Linear Thermal Expansion is given following the links).....	310
Table 5-61: Smoothed Values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens Characterized in Table 5-60.....	312
Table 5-62: Smoothed Values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens Characterized in Table 5-60.....	313
Table 5-63: Smoothed Values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens Characterized in Table 5-60.....	314
Table 5-64: Smoothed Values of the Linear Thermal Expansion Coefficient, $\beta \times 10^6$ [K <sup>-1</sup> ], of the Specimens Characterized in Table 5-60.....	315

Table 5-65: Effect of the Space Environment on Solar Absorptance, $\alpha_s$ , of Silica Fabrics .....	323
Table 5-66: Normal Total Emittance, $\varepsilon' (\beta=0)$ , and Solar Absorptance, $\alpha_s$ , of Uncoated Plastic Materials .....	324
Table 5-67: Coated Composite Materials the Thermal Radiation Properties of Which Are Given in This Clause .....	326
Table 5-68: Normal Total Emittance, $\varepsilon' (\beta=0)$ , of PV 100 Coating on Different Substrates and with Different Thicknesses .....	328
Table 5-69: Normal Solar Reflectance, $\rho_s (\beta=0)$ , of PV 100 Coating on Different Substrates and with Different Thicknesses .....	330
Table 5-70: Characteristic Temperatures of Neat and Reinforced Resins .....	336
Table 5-71: Electrical Resistivity, $\rho_f [\Omega \cdot m]$ , of High-Strength Fibers .....	342
Table 5-72: Electrical Resistivity, $\rho [\Omega \cdot m]$ , of Carbon-Epoxy Composite Materials .....	344
Table 5-73: Drill Bit Costs and Standard Drilling Hourse .....	346
Table 5-74: Characterization of Composite Materials, the Maximum Moisture Content and Diffusion Constants of which are given in Table 5-75 and Table 5-76 respectively .....	352
Table 5-75: Maximum Moisture Content, $M_m$ , of the Specimens Characterized in Table 5-74 .....	353
Table 5-76: Constants $D_o$ and C for the Arrhenius Expression, of the Transverse Diffusion Coefficient, $D_2$ , of the Specimens Characterized in Table 5-74 .....	353
Table 5-77: Outgassing Data for Typical Composite Materials .....	355
Table 5-78: Characterization of Materials Tested under a Vacuum Radiation Environment .....	357
Table 5-79: Summary of the Data Regarding Radiation Effects on the Coefficient of Linear Thermal Expansion for the Specimens Characterized in Table 5-78 .....	360
Table 5-80: Average Values of Linear Thermal Expansion, $\beta$ , for 75S(Pitch)/948A1(0/90) <sub>2S</sub> Graphite/Epoxy Laminates in the Temperature Range 280 K - 370 K .....	363
Table 5-81: Atomic Oxygen Reaction Efficiency Data from Reported LEO Flights and Ground Testing .....	365
Table 5-82: Weight Loss, WL (%), of Carbon Fibers After Isothermal Aging in Flowing Air .....	368
Table 5-83: Chemical Composition, Atom (%), of both T40R and Hercules AS4 Carbon Fibers, as received and oxidized, ESCA .....	370
Table 5-84: Characterization of Materials Tested under or after Thermal Vacuum Cycling .....	371
Table 5-85: Thermal Vacuum Cycling Effects on the Coefficient of Linear Thermal Expansion of the Specimens Characterized in Table 5-84 .....	373
Table 5-86: Effect of Storage on the Linear Thermal Expansion, $\beta_o$ , of the Hybrid Tubes Identified as Spec. No. 1, in Table 5-84 and Table 5-85 .....	374
Table 5-87: Effect of Thermal Cycling (either Ambient or Vacuum) on the Linear Thermal Expansion, $\beta_o$ , of the Hybrid Tubes Identified as Spec. No. 1 in Table 5-84 and Table 5-85 <sup>a</sup> .....	374

## European Foreword

This document (CEN/CLC/TR 17603-31-05:2021) has been prepared by Technical Committee CEN/CLC/JTC 5 "Space", the secretariat of which is held by DIN.

It is highlighted that this technical report does not contain any requirement but only collection of data or descriptions and guidelines about how to organize and perform the work in support of EN 16603-31.

This Technical report (TR 17603-31-05:2021) originates from ECSS-E-HB-31-01 Part 5A.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN [and/or CENELEC] shall not be held responsible for identifying any or all such patent rights.

This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association.

This document has been developed to cover specifically space systems and has therefore precedence over any TR covering the same scope but with a wider domain of applicability (e.g.: aerospace).

# 1

## Scope

In this Part 5 of the spacecraft thermal control and design data handbooks, clause 4 contains technical data on the metallic alloys used in spacecrafts is given: composition, application areas, properties and behaviour from a thermal and thermo-optics point of view, degeneration and aging. All other properties of the metallic alloys are outside the scope of this document.

Properties of composite materials combined to form heterogeneous structures are given in clause 5.

The Thermal design handbook is published in 16 Parts

TR 17603-31-01	Thermal design handbook – Part 1: View factors
TR 17603-31-02	Thermal design handbook – Part 2: Holes, Grooves and Cavities
TR 17603-31-03	Thermal design handbook – Part 3: Spacecraft Surface Temperature
TR 17603-31-04	Thermal design handbook – Part 4: Conductive Heat Transfer
TR 17603-31-05	Thermal design handbook – Part 5: Structural Materials: Metallic and Composite
TR 17603-31-06	Thermal design handbook – Part 6: Thermal Control Surfaces
TR 17603-31-07	Thermal design handbook – Part 7: Insulations
TR 17603-31-08	Thermal design handbook – Part 8: Heat Pipes
TR 17603-31-09	Thermal design handbook – Part 9: Radiators
TR 17603-31-10	Thermal design handbook – Part 10: Phase – Change Capacitors
TR 17603-31-11	Thermal design handbook – Part 11: Electrical Heating
TR 17603-31-12	Thermal design handbook – Part 12: Louvers
TR 17603-31-13	Thermal design handbook – Part 13: Fluid Loops
TR 17603-31-14	Thermal design handbook – Part 14: Cryogenic Cooling
TR 17603-31-15	Thermal design handbook – Part 15: Existing Satellites
TR 17603-31-16	Thermal design handbook – Part 16: Thermal Protection System

**2****References**

EN Reference	Reference in text	Title
EN 16601-00-01	ECSS-S-ST-00-01	ECSS System - Glossary of terms
TR 17603-31-04	ECSS-E-HB-31-01 Part 4	Thermal design handbook – Part 4: Conductive Heat Transfer
TR 17603-31-12	ECSS-E-HB-31-01 Part 12	Thermal design handbook – Part 12: Louvers
TR 17603-31-13	ECSS-E-HB-31-01 Part 14	Thermal design handbook – Part 14: Cryogenic Cooling

All other references made to publications in this Part are listed, alphabetically, in the **Bibliography**.