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Space Engineering — Thermal design handbook

Part 5: Structural Materials: Metallic and Composite

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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).

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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

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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**.

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3 Terms, definitions and symbols

3.1 Terms and definitions

For the purpose of this Standard, the terms and definitions given in ECSS-S-ST-00-01 apply.

3.2 Symbols

B	magnetic induction, [T]
E	modulus of elasticity, [Pa]
H	magnetic field strength, [A.m^{-1}]
R	reflectance factor
c	specific heat, [J.kg^{-1}.K^{-1}]
k	thermal conductivity, [W.m^{-1}.K^{-1}]
$\Delta L/L$	thermal expansion
α	thermal diffusivity, [m^2.s^{-1}] $\alpha = k/\rho c$
α	temperature coefficient of electrical resistivity, [K^{-1}]
α	hemispherical total absorptance
$\alpha'(\beta,\theta)$	directional total absorptance
α_s	normal solar absorptance
$\alpha_\lambda(\lambda)$	hemispherical spectral absorptance
$\alpha'_\lambda(\lambda,\beta,\theta)$	directional spectral absorptance
β	mean coefficient of linear thermal expansion, [K^{-1}]
	angle between surface normal and direction of incident flux, [angular degrees]
β'	angle between surface normal and direction of emitted, reflected or transmitted flux, [angular

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	degrees]
ε	hemispherical total emittance
$\varepsilon'(\beta',\theta')$	directional total emittance
$\varepsilon_\lambda(\lambda)$	hemispherical spectral emittance
$\varepsilon'_\lambda(\lambda,\beta',\theta')$	directional spectral emittance
θ	azimuthal angle of incident flux, [angular degrees]
θ'	azimuthal angle of emitted, reflected or transmitted flux, [angular degrees]
λ	wavelength, [m]
μ/μ_0	relative magnetic permeability
ρ	density, [kg.m^{-3}]
	hemispherical total reflectance
$\rho_\lambda(\lambda)$	hemispherical spectral reflectance
$\rho'(\beta,\theta)$	directional-hemispherical total reflectance
$\rho'(\beta',\theta')$	hemispherical-directional total reflectance
ρ'_s	normal-hemispherical solar reflectance
$\rho'_\lambda(\lambda,\beta,\theta)$	directional-hemispherical spectral reflectance
$\rho'_\lambda(\lambda,\beta',\theta')$	hemispherical-directional spectral reflectance
$\rho''(\beta,\theta,\beta',\theta')$	bidirectional total reflectance.
$\rho''_\lambda(\lambda,\beta,\theta,\beta',\theta')$	bidirectional spectral reflectance
$\rho''_s(\beta,\theta,\beta',\theta')$	bidirectional solar reflectance
σ	electrical conductivity, [Ω^{-}1.m] $\sigma 1$, electrical resistivity [Ω.m]
σ_{ult}	ultimate tensile strength, [Pa]
$\tau'_\lambda(\lambda,\beta,\theta,\beta',\theta')$	bidirectional spectral transmittance
ω	solid angle of incident radiation beam [steradians]
ω'	solid angle of emitted, reflected or transmitted radiation beam, [steradians]

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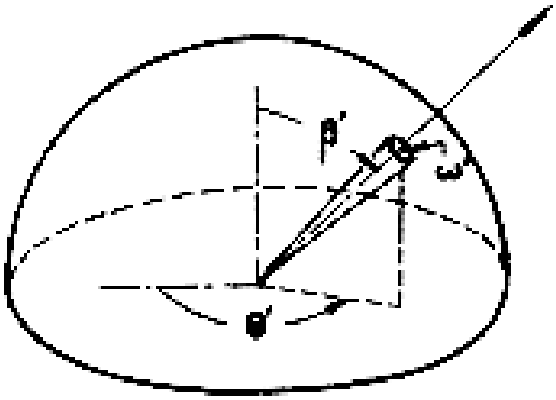
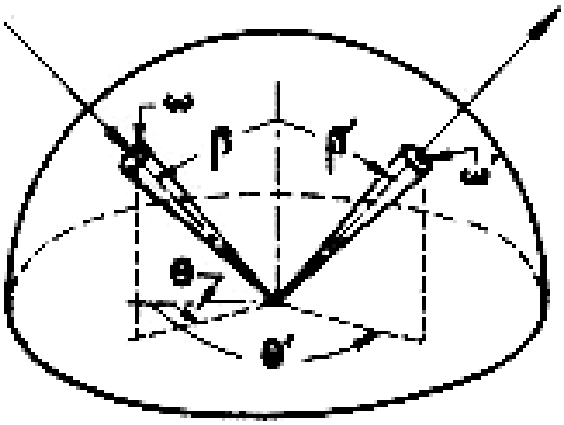
The sketches below show the angles used to characterize the radiative fluxes arriving at or leaving a surface element.

Angles used to define directional emittance



Angles used to define bidirectional reflectance



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4 Metallic materials

4.1 General

Data for each alloy are arranged as indicated below. When no data on some property are available the heading is omitted.

1. TYPICAL COMPOSITION, PERCENT

2. OFFICIAL DESIGNATIONS

3. PHYSICAL PROPERTIES

3.1. Density

3.2. Thermal properties

3.2.1. Specific heat

3.2.2. Thermal conductivity

3.2.3. Thermal diffusivity

3.2.4. Thermal expansion

3.2.5. Melting range

3.3. Thermal radiation properties

3.3.1. Emittance

3.3.1.1. Directional spectral emittance

3.3.1.1.1. Normal spectral emittance

3.3.1.1.2. Angular spectral emittance

3.3.1.2. Directional total emittance

3.3.1.2.1. Normal total emittance

3.3.1.3. Hemispherical spectral emittance

3.3.1.4. Hemispherical total emittance

3.3.2. Absorptance

3.3.2.1. Directional spectral absorptance

3.3.2.1.1. Normal spectral absorptance

3.3.2.2. Directional total absorptance

3.3.2.2.1. Normal total absorptance

3.3.2.3. Hemispherical spectral absorptance

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3.3.2.4. Hemispherical total absorptance

3.3.2.5. Solar absorptance

3.3.2.5.1. Normal solar absorptance

3.3.2.5.2. Angular solar absorptance

3.3.2.6. Absorptance to emittance ratio

3.3.3. Reflectance

3.3.3.1. Bidirectional spectral reflectance

3.3.3.1.1. Normal-normal spectral reflectance

3.3.3.1.2. Angular (non-normal) spectral reflectance

3.3.3.2. Directional-hemispherical spectral reflectance

3.3.3.2.1. Normal-hemispherical spectral reflectance

3.3.3.2.2. Angular-hemispherical spectral reflectance

3.3.3.3. Hemispherical-directional spectral reflectance

3.3.3.3.1. Hemispherical-normal spectral reflectance

3.3.3.4. Hemispherical spectral reflectance

3.3.3.5. Bidirectional total reflectance

3.3.3.5.1. Normal-normal total reflectance

3.3.3.5.2. Angular (non-normal) total reflectance

3.3.3.6. Directional-hemispherical total reflectance

3.3.3.6.1. Normal-hemispherical total reflectance

3.3.3.7. Hemispherical-directional total reflectance

3.3.3.7.1. Hemispherical-normal total reflectance

3.3.3.8. Bidirectional solar reflectance

3.3.3.8.1. Normal-normal solar reflectance

3.3.3.9. Directional-hemispherical solar reflectance

3.3.3.9.1. Normal-hemispherical solar reflectance

3.3.4. Transmittance

3.3.4.1. Bidirectional spectral transmittance

3.3.4.1.1. Normal-normal spectral transmittance

3.3.4.1.2. Angular (non-normal) spectral transmittance

3.4. Other physical properties

3.4.1. Electrical resistivity

3.4.2. Magnetic properties

4. ENVIRONMENTAL BEHAVIOR

4.1. Prelaunch

4.2. Postlaunch

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5. CHEMICAL PROPERTIES

5.1. Solution potential

5.2. Corrosion resistance

6. FABRICATION

6.1. Casting

6.2. Forming

6.3. Welding

6.4. Machining

6.5. Heat treatment

6.6. Anodizing

7. AVAILABLE FORMS AND CONDITIONS

8. USEFUL TEMPERATURE RANGE

9. APPLICATIONS

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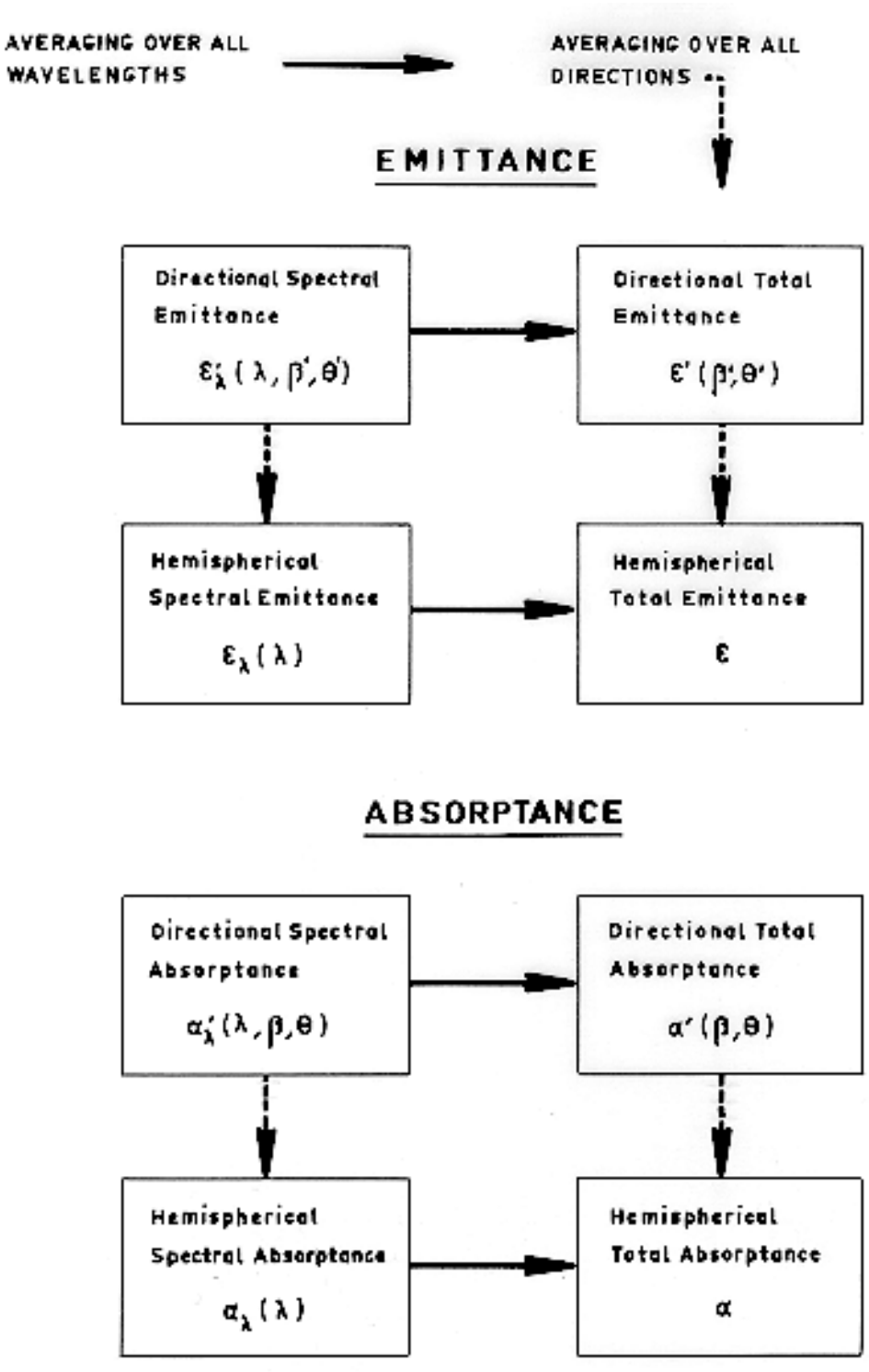
4.1.1 Modifiers of thermal radiative properties



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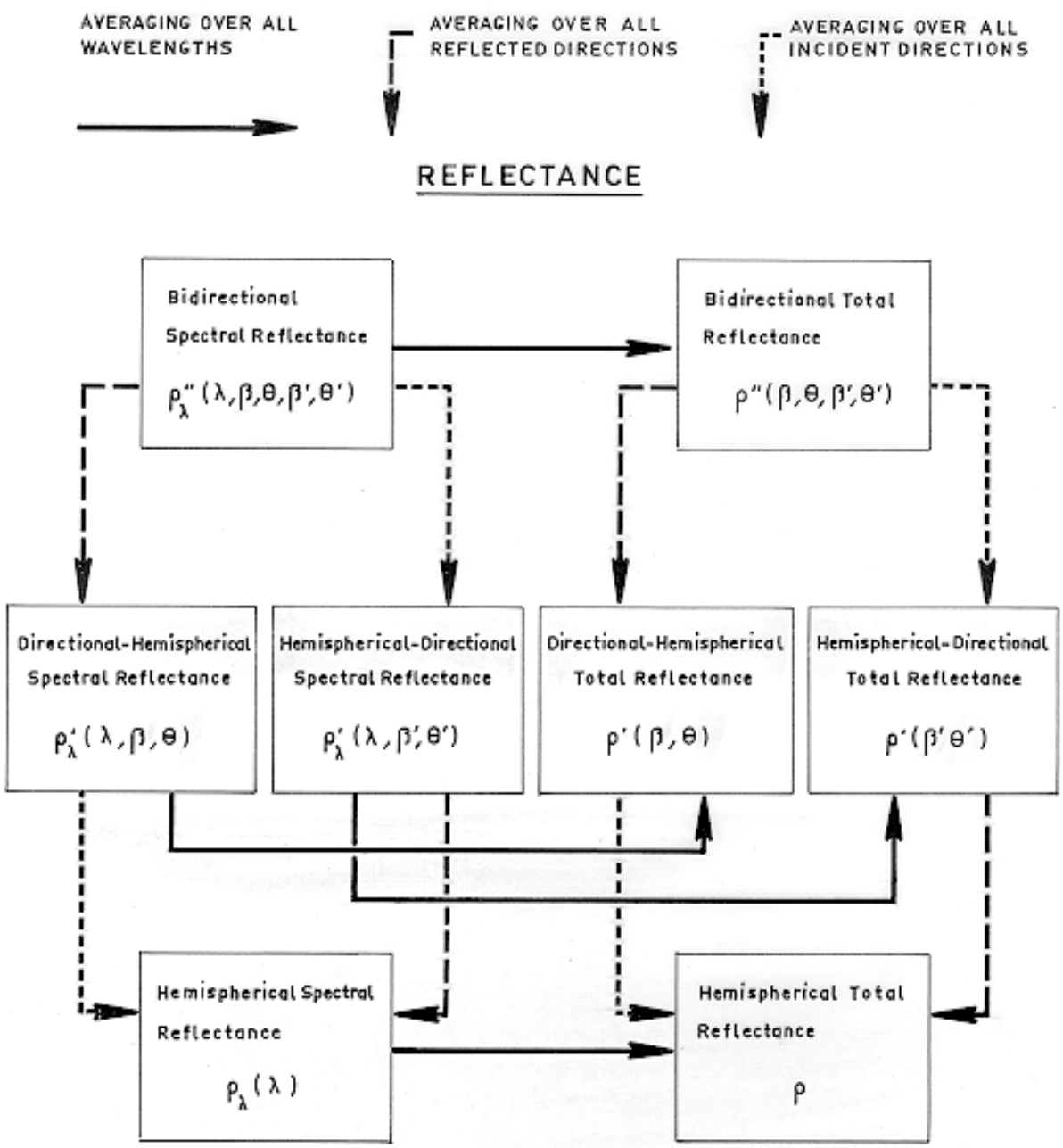

4.1.2 Cladding definitions

Clad. A composite metallic material containing two or three layers that have been bonded together. Bonding may be achieved by co-rolling, welding, casting, heavy chemical deposition or heavy electroplating.

Alclad. Clad produced by bonding either a corrosion-resistant aluminium alloy or high purity aluminium to a base of a structurally stronger aluminium alloy.

Nonclad. Metallic material to which no other alloy has been bonded by cladding.

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4.1.3 Temper designation for heat treatable aluminium alloys

F Condition: As fabricated.

O Condition: Annealed (wrought products only).

W Condition: Solution heat treated.

T1 Condition: Naturally aged to a stable condition.

T2 Condition: Annealed (cast products only).

T3 Condition: Solution heat treated, cold worked, and naturally aged to a substantially stable condition.

T4 Condition: Solution heat treated and naturally aged to a substantially stable condition.

T5 Condition: Artificially aged only.

T6 Condition: Solution heat treated and artificially aged.

T7 Condition: Solution heat treated and over aged.

T8 Condition: Solution heat treated, cold worked, and artificially aged. Different amounts of cold working are denoted by a second digit.

T9 Condition: Solution heat treated, artificially aged and cold worked.

T10 Condition: Artificially aged and cold worked.

4.2 Aluminium alloys

ALLOYS Al - 99,99. Al - 99,9. Al - 99,8. Al - 99,7. Al - 99,5. Al - 99,3. Al - 99.

This data item concerns all aluminium alloys whose aluminium content is above 99%.

1. TYPICAL COMPOSITION, PERCENT. Maximum values are given except for Aluminium.

	Al	Cu	Fe	Mn	Si	Zn	Others	
							Each	Total
Al - 99,99	>99,99	-	-	-	-	-	-	0,01
Al - 99,9	>99,9	0,02	0,07	0,01	0,07	0,03	0,01	-
Al - 99,8	>99,8	0,03	0,15	0,03	0,15	0,06	0,02	-
Al - 99,7	>99,7	0,03	0,25	0,03	0,20	0,07	0,03	-
Al - 99,5	>99,5	0,05	0,40	0,05	0,30	0,10	0,03	-
Al - 99,3	>99,3	0,10	0,60	0,05	0,30	0,10	0,05	-
Al - 99,0	>99,0	0,20	0,80	0,05	0,50	0,10	0,05	-

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2. OFFICIAL DESIGNATIONS

	AECMA	ISO	AFNOR	AMS	BS	DIN
Al - 99,99					1	Al 99,98R S - Al 99,98R 3,0385
Al - 99,9						Al 99,9 3,0305
Al - 99,8		Al 99,8	A8		1A	Al 99,8 S - Al 99,8 3,0285
Al - 99,7		Al 99,7	A7	~4000		Al 99,7 3,0275
Al - 99,5	Al P 99,5	Al 99,5	A5	~4000	1B ~1E	Al 99,5 S - Al 99,5 3,0255 ~E - Al ~3,0257
Al - 99,3			~A45	4040 4041 4042		~S - Al 99,5Ti ~3,0805
Al - 99,0		Al 99,0 ~Al 99,0Cu	A4	~1100 4001 4003 4062 4102 4180 7220	1C	Al 99 3,0205

NOTE ~ Can be approximately included with those alloys having the indicated aluminium content.

3. PHYSICAL PROPERTIES

3.1. Density.

Al - 99,99, $\rho = 2699$ kg.m^{-3}. (Pennington (1961) [29]).

Al - 99,5 $\rho = 2700$ kg.m^{-3}. (Kappelt (1961) [23]).

Al - 99,0 $\rho = 2710$ kg.m^{-3}. (Kappelt (1961) [23]).

3.2. Thermal properties

3.2.1. Specific heat

Effect of temperature on specific heat: Figure 4-1.

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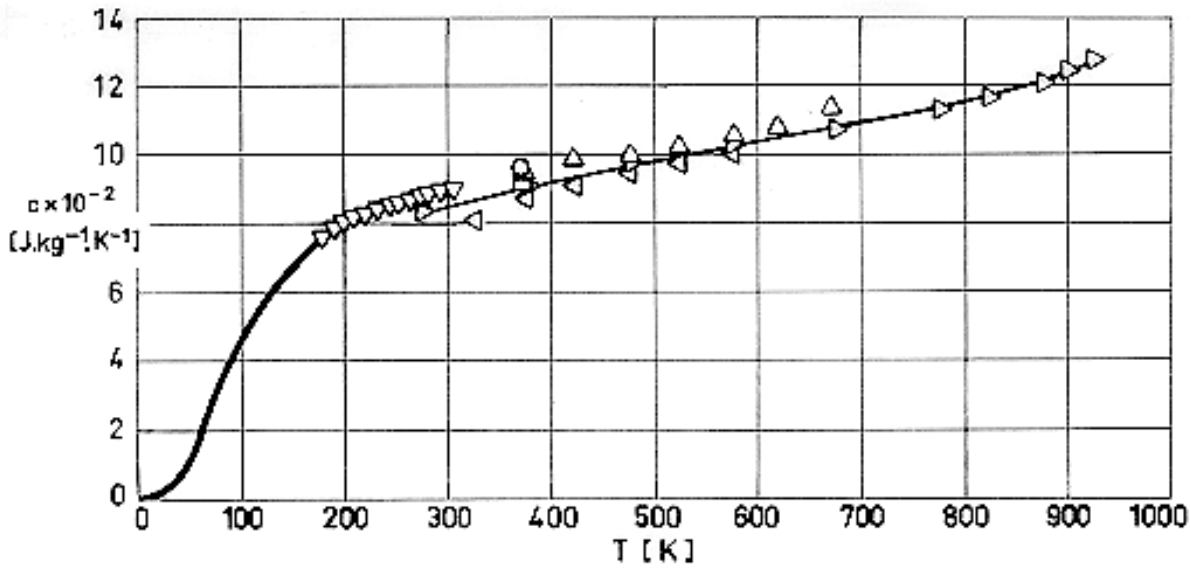

Figure 4-1: Specific heat, *c*, of Aluminium as a function of temperature, *T*.

Explanation

Key	Description	Comments	References
○	Al - 99,0		Kappelt (1961) [23].
□	Al - 99,99		Pennington (1961) [29].
△	Al - 99,99 Average of 2 samples 1) Water quenched from 873 K; annealed 100 h at 403 K. 2) Cooled from 873 K at 5 K.min^{-1}	Reported error ≤ 1%	Touloukian (1967)a [38]
▽	Al 99,9 Single crystal. Melted and cooled 2 d in vacuum.		
▷	Al - 99,9	Reported error ± 5%	
◁		Reported error ± 5%	
▬			Coston (1967) [18].

3.2.2. Thermal conductivity

Effect of temperature on thermal conductivity: Figure 4-2.

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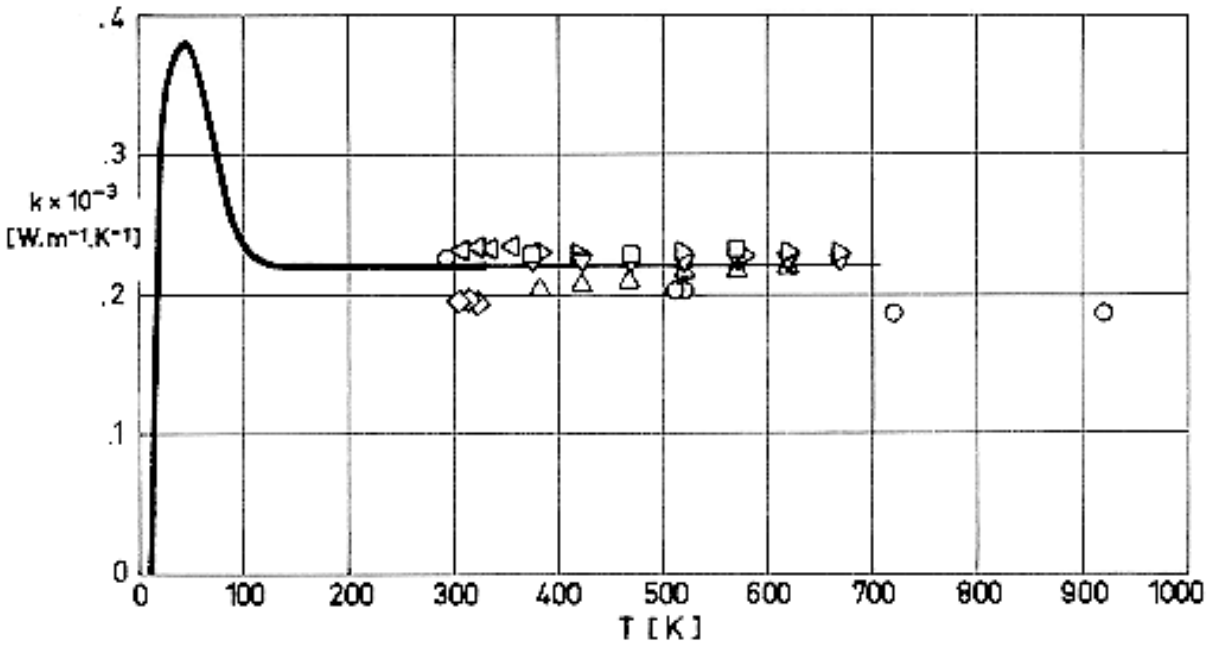

Note: non-si units are used in this figure

Figure 4-2: Thermal conductivity, κ, of Aluminium as a function of temperature, T.

Explanation

Key	Description	Comments	References
○	Al - 99,9	Losses evaluated by measuring unsteady state cooling of rod initially at uniform temperature.	Touloukian (1967)a [38].
□	0,04 Si - 0,03 Fe - 0,006 Cu - 0,005 Ti, and traces of Mn and Mg. Annealed 1 h at 723 K and cooled slowly.	Reported error ± 3%.	
△	Al - 99,5 Cast at 973 K into molds at 473 K; rolled and drawn, then turn into rods.		
▽	Al - 99,9 Same treatment as above.		
▷	Al - 99,9 Same treatment as above.		
◁	Al 99,99	Reported error ± 1%.	
◊	Commercially pure.	Reported error ± 3%.	

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Key	Description	Comments	References
	Sample $2x10^{-2}$m in diameter and $1,8x10^{-2}$ m length.		
▬▬			Coston (1967) [18].

Thermal conductivity integrals: Figure 4-3.

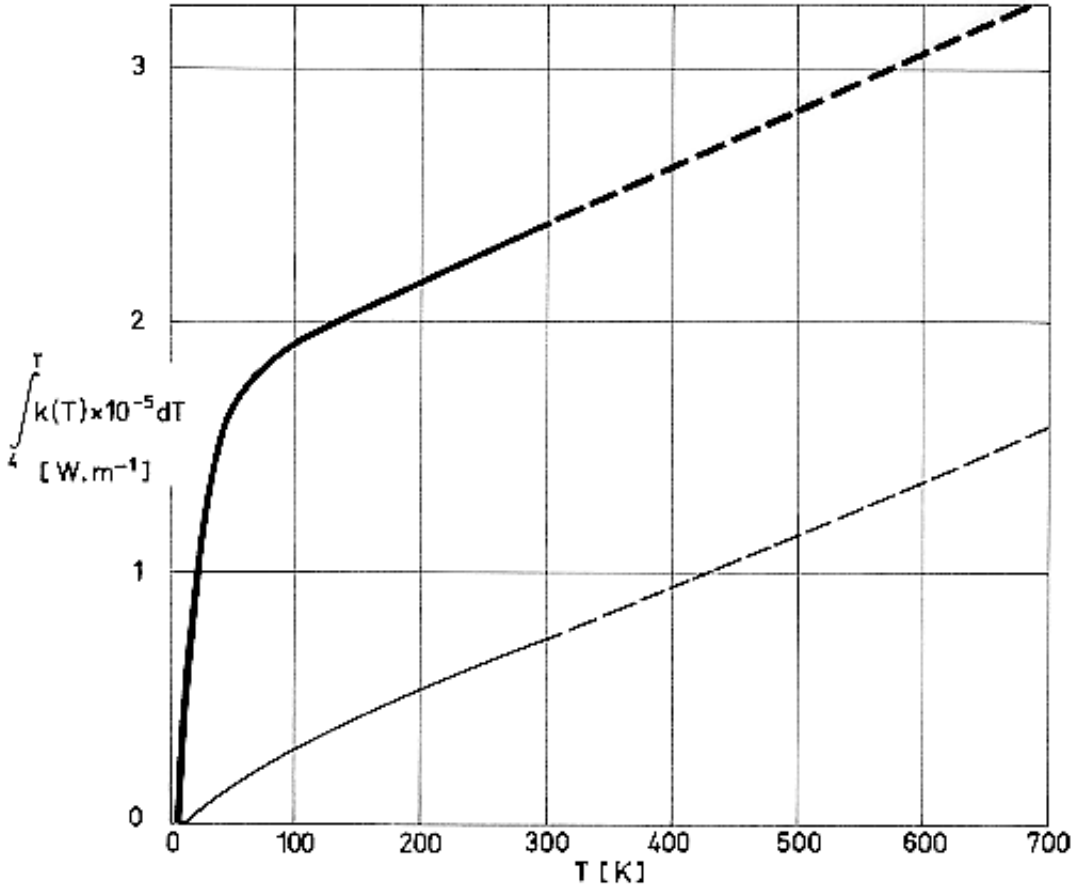

Figure 4-3: Thermal conductivity integrals of Aluminium as a function of temperature, *T*.

Explanation

▬▬▬: Al - 99,99. From Coston (1967) [18].

▬▬▬: Al - 99,0. From Coston (1967) [18].

▬ ▬: Straight line whose slope has been calculated by the compiler by fitting the experimental data points ▷ and ◁ of Figure 4-2 with the least-squares method.

▬ ▬: Calculated by the compiler from data points ◇ of Figure 4-2

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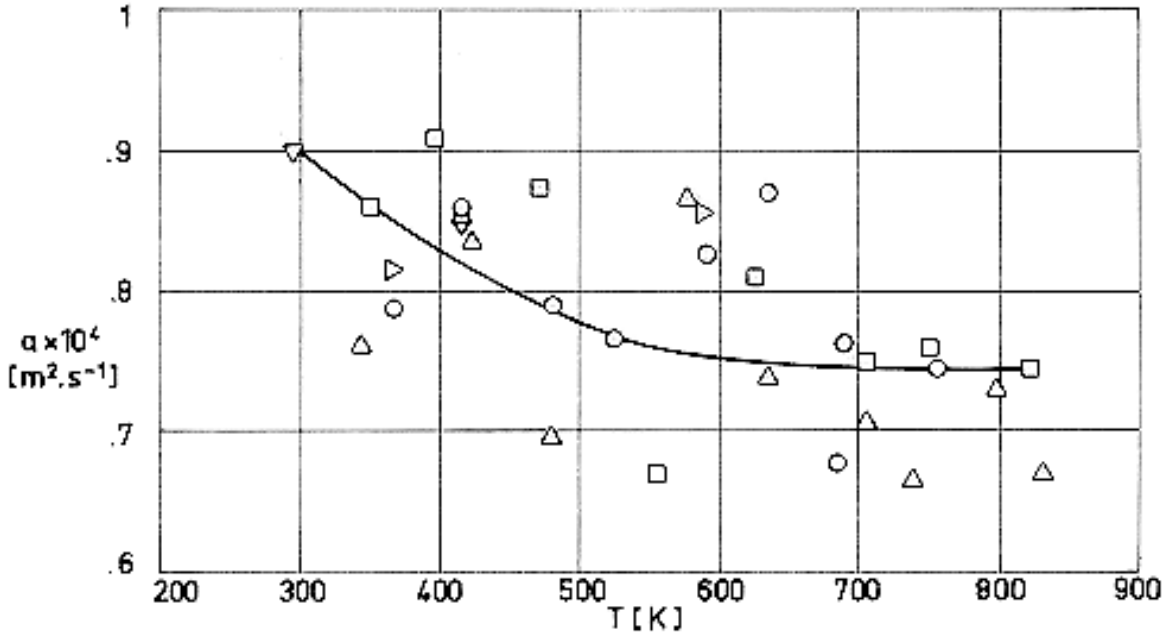
3.2.3. Thermal diffusivity.

Effect of temperature on thermal diffusivity: Figure 4-4.



Note: non-si units are used in this figure

Figure 4-4: Thermal diffusivity, α, of Aluminium as a function of temperature, T.

Explanation

Key	Description	Comments	References
○	Al - 99,9	Reported error ± 11%.	Touloukian (1967)a [38].
□	Same as above.	Second run of the above specimen. Reported error ± 11%.	
△	Same as above.	Third run of the above specimen. Reported error ± 11%.	
▽	Pure. 1.9×10^{-3} m² square cross-section and 3.52×10^{-3} m length.	Reported error ± 5%.	
▷	Pure.		

3.2.4. Thermal expansion.

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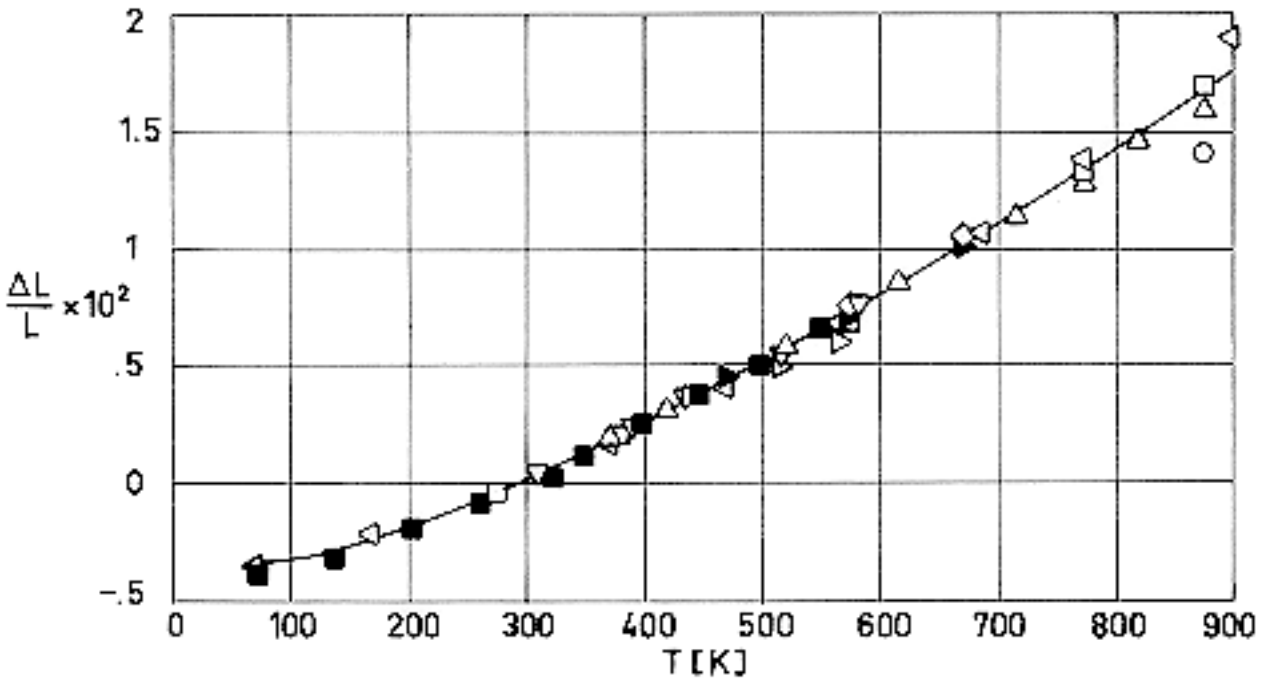
Effect of temperature on thermal expansion: Figure 4-5.



Note: non-si units are used in this figure

Figure 4-5: Linear thermal expansion, ΔL / L, of Aluminium as a function of temperature, T.

Explanation

Key	Description	Comments	References
○			Touloukian (1967)a [38].
□	Al - 99,99 Annealed above 873 K.		
■	Al - 99,99		
△	Al - 99,9 Annealed 2 h at 893 K and cooled slowly.		
▽	99,952 Al - 0,019 Cu - 0,015 Fe - 0,014 Si. Cast in graphite mold.		
▷	Chemically pure.	X-ray diffraction method.	

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Key	Description	Comments	References
◁	99,989 Al - 0,004 each Si, Cu - 0,003 Fe.		
▶	Pure. Pressed rod made of sintered aluminium powder.		
◇	Al - 99,5		

Mean coefficient of linear thermal expansion, β.

The available information concerning thermal expansion coefficients of these alloys seems to indicate that there is no noticeable influence of the aluminium content on β. Values given below correspond to Al - 99,99.

T [K]	73-293	123-293	173-293	223-293	293-373	293-473	293-573	293-673	293-773
$\beta x10^6$ [K^{-1}]	18,0	19,9	21,0	21,8	23,6	24,5	25,5	26,4	27,4

From Pennington (1961) [29].

3.2.5. Melting range

Al - 99,99: 933 K. (Pennington (1961) [29]).

Al - 99,5: 919 K - 930 K. (Kappelt (1961) [23]).

Al - 99,0: 916 K -930 K. (Kappelt (1961) [23]).

3.3. Thermal radiation properties

3.3.1. Emittance

Data concerning emittance have been arranged as indicated in the following Table.

3.3.1.1. Directional spectral emittance.				
Clause	**Heading**	**Data presented**	**Fig.**	**Table**
3.3.1.1.1.	Normal $\beta' = 0$	Al - 99,7	Figure 4-6	
		Aluminium conversion coatings.	Figure 4-7	
3.3.1.1.2.	Angular (non-normal) $\beta' \neq 0$	Al - 99,0	Figure 4-7	
3.3.1.2. Directional total emittance.				

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3.3.1.2.1.	Normal $\beta' = 0$	Aluminium.		Table 4-1
		Aluminium. Effect of temperature.	Figure 4-9	
		Aluminium contact coatings.		Table 4-2[a]
		Aluminium conversion coatings.		Table 4-3[a]
		Aluminium conversion coatings. Effect of anodizing thickness.	Figure 4-10	
3.3.1.4. Hemispherical total emittance.				
	$\omega' = 2\pi$	Aluminium. Effect of temperature.	Figure 4-11	
		Aluminium contact coatings.		Table 4-4
		Aluminium conversion coatings. Effect of anodizing thickness.	Figure 4-12	

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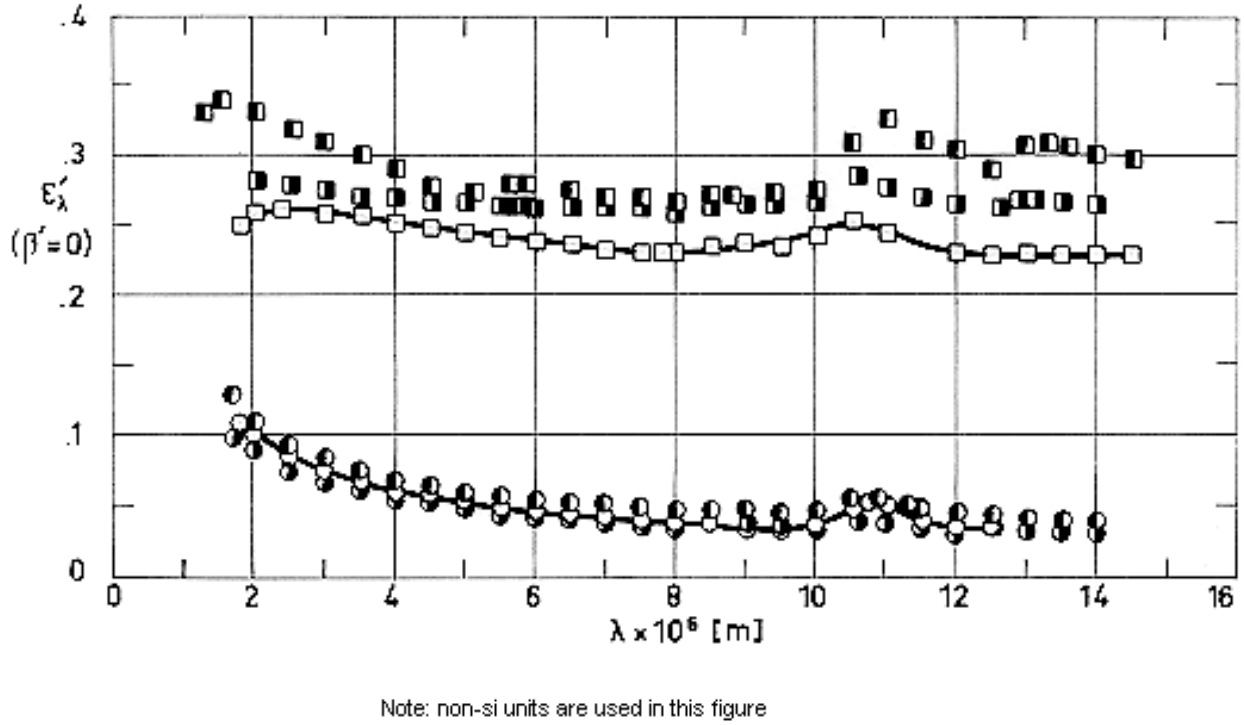
[a] Solar absorptance, α_s, has been also included in this Table in order to save space.



Note: non-si units are used in this figure

Figure 4-6: Normal spectral emittance, ε_λ', of Aluminium as a function of wavelength, λ.

Explanation

Key	Description	Comments	References
○	99,7 Al - 0,11 Fe - 0,11 Si - 0,01 Cu - 0,01 Mg - <0,01 Mn, Ni, Zn. Cylindrical tube. Heated at 467 K for 15 h. Polished. Surface roughness: $7{,}62 \times 10^{-8}$ m (center line average).	Sample temperature: T = 599 K. Data from smooth curve. Reported error ± 20% (in the wavelength range 2×10^{-6} to 10^{-5} m).	Touloukian & DeWitt (1970) [42].
◑	Same as ○ except heated at 697 K for 20 h.	Same as ○ except T = 697 K.	
◐	Same as ○ except heated at 805 K for 15 h.	Same as ○ except T = 805 K.	
□	Same specimen as ○ except heated at 462 K for 25 h. Roughness and knurled with grade 180 silicon carbide paper. Surface roughness: $2{,}92 \times 10^{-6}$ m (centre line average).	T = 462 K. Data from smooth curve. Reported error ± 10% (in the wavelength range 2×10^{-6} to 10^{-5} m).	

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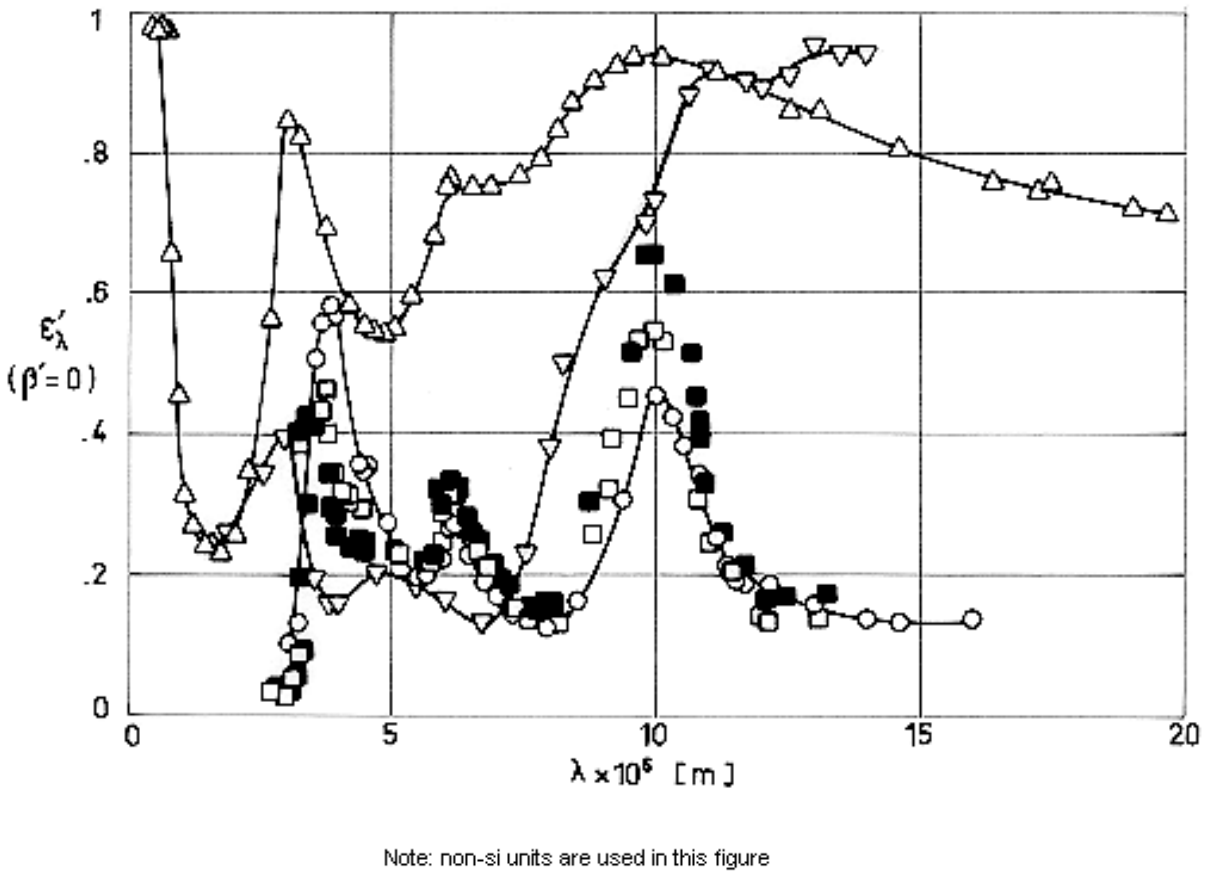
Key	Description	Comments	References
◨	Same as □ except heated at 598 K for 22 h.	Same as □ except T = 599 K.	
◧	Same as □ except heated at 715 K for 27 h.	Same as □ except T = 715 K.	



Note: non-si units are used in this figure

Figure 4-7: Normal spectral emittance, $\varepsilon\lambda'$, of Aluminium conversion coatings as a function of wavelength, λ.

Explanation

Key	Description	Comments	References
○	Alodine 401.45. Reaction of an aluminium surface with an aqueous solution of chromic, phosphoric, and hydrofluoric acid. Substrate: Al - 99,8 (Echo II).	Sample temperature: T = 295 K. Data from smooth curve. Converted from $R(2\pi,0)$.	Touloukian, DeWitt & Hernicz (1972) [43].
□	Same as ○ except reacted for 20 s in a 1 N		

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Key	Description	Comments	References
	sodium hydroxide solution at 298 K, then washed in water and dried in air.		
■	Same as □. Reacted for 40 s.		
△	Black anodized.	T = 323 K. Data from smooth curve. Converted from $R(2\pi,0)$.	
▽	Al - 99.7. Anodized 30 min at 10^{-2} A.m^{-2} in 4 N analar sulphuric acid at 293 K, sealed for 30 min in boiling distilled water. Anodizing thickness 2,54x10^{-6} m. Heated at 456 K for 15 h.	T = 461 K. Data from smooth curve. Reported error ± 10%.	

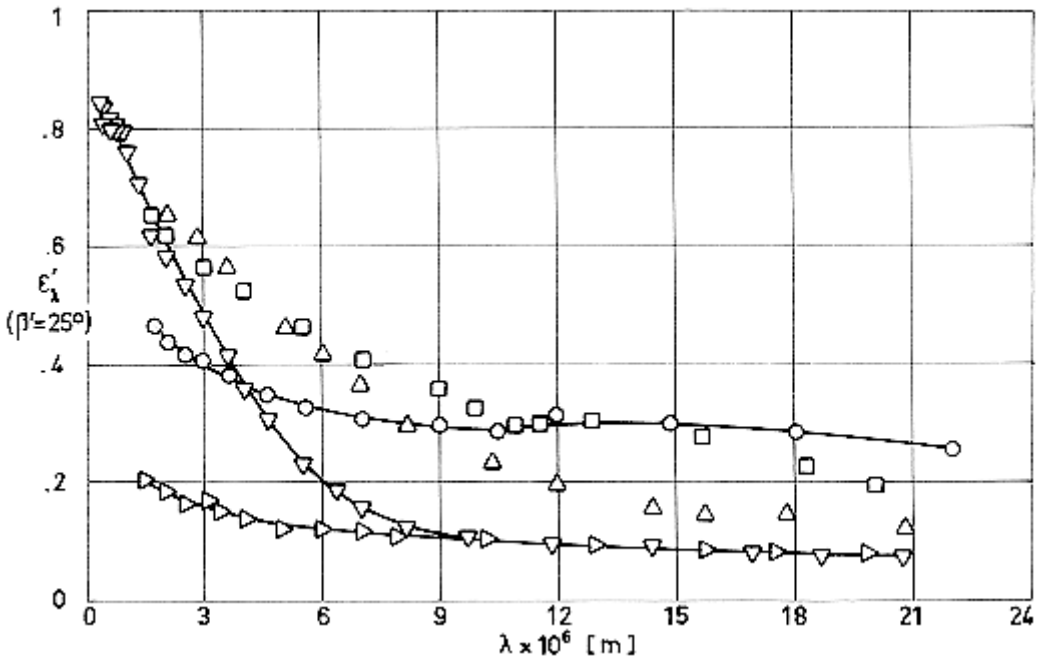

Figure 4-8: Angular spectral emittance, $\varepsilon\lambda'$, of Aluminium as a function of wavelength, λ.

Explanation

Key	Description	Comments	References
○	Al - 99.0. Nominal composition. Sandblasted with 120 mesh alumina (mesh opening 1,25x10^{-4} m).	Sample temperature:	Touloukian & DeWitt (1970) [42].

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Key	Description	Comments	References
□	Same as ○ except sandblasted with 320 mesh alumina (mesh opening 4,6x10^{-5} m).	T = 306 K. Authors assumed $\alpha=\varepsilon=1-\rho$. ρ (25°, 2π).	
△	Same as ○ except sandblasted with 600 mesh alumina (mesh opening 2,4x10^{-5}m).		
▽	Same as ○ except sandblasted with 1000 mesh alumina (mesh opening 1,4x10^{-5} m).		
▷	Same as ○ except sanded with 280 mesh silicon carbide paper.		

Table 4-1: Normal Total Emittance of Aluminium

Alloy	T [K]	ε' ($\beta' = 0$)	Comments	References
Al - 99,99	298	0,03		Pennington (1961) [29]
Al - 99,0		0,05	Polished	Zerlaut, Carrol & Gates (1966) [47].
Al -		0,21	Foil, vapor blasted, wet.	
Al - 99,0		0,33	Sandblasted.	
Al -	311	0,065	Bright foil roughened with abrasive cloth.	Touloukian (1967)a [38].
Al -	373	0,18	Sheet, rough polished.	
Al - 99,99		0,02	Foil (1,27x10^{-4} m thick) GMC Bright dip for 10 min at 350 K.	Bevans (1969) [14].
Al -	296	0,04	Polished.	TRW (1970) [44].
Al -	298	0,055 to 0,070	Rough plate.	
Al -		0,04	Bare metal.	Scollon & Carpitella (1970) [33].
Al - 99,0	370	0,022	Polished with Mg0 and water, measured in vacuum (2,1x10^{-2} Pa).	Touloukian & DeWitt (1970) [42].
Al - 99,99	425,4	0,037	Rolled, polished.	

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Alloy	T [K]	ε' ($\beta' = 0$)	Comments	References
Al - 99,99	647	0,045	Same as above.	
Al - 99,99	780	0,0497	Same as above.	
Al - 99,99	414	0,0486	Highly polished.	
Al - 99,99	610	0,0576	Same as above.	
Al - 99,99	733	0,065	Same as above.	
Al -	366	0,028	Foil.	
Al -	311	0,045	Foil, embossed (Pattern No. 1).	
Al -	311	0,056	Foil, embossed (Pattern No. 2).	
Al -	311	0,047	Foil, embossed (Pattern No. 3).	
Al -	311	0,056	Foil, embossed (Pattern No. 4).	
Al -	311	0,061	Foil, embossed (Pattern No. 5).	
Al - 99,9	311	0,045	0,002 Si, 0,0001 Fe, 0,001 Cu, 0,0003 Na, 0,0003 Ca, 0,0003 Mg. Electrolytically brightened, density 2698 $kg.m^{-3}$ at 298 K. aluminium foil reference ($\varepsilon = 0,05$).	
Al -	311	0,035 to 0,050	Foil, bright; etched in hot sodium hydroxide solution 0,5 to 2 min, and dipped in nitric acid.	
Al -	311	0,044	Foil, bright; roughened with abrasive cloth (No. 120 Aloxite cloth).	
Al -	311	0,063	Foil, bright; roughened with abrasive cloth (No. 120 Aloxite cloth).	
Al -	311	0,066	Foil, bright; roughened with abrasive cloth (No. 120 Aloxite cloth).	
Al -	311	0,04	Foil, surface film formed by means of exposure to corrosive attack; foil-covered cardboard taken from foil-insulated dry-ice cabinet	

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Alloy	T [K]	ε' ($\beta' = 0$)	Comments	References
			exposed to weather on beach during 8 months.	
Al -	311	0,05	Foil; suspended vertically in the laboratory for 3 years and measured with the accumulated dust and fume.	
Al -	311	0,09	Foil; chemically oxidized by treating with hot solution of sodium carbonate and chromate.	
Al -	311	0,10	Foil; lacquer coated; heated to partially decompose lacquer and color in brown.	
Al -	311	0,10	Foil after 2 years exposure to salt spray and moisture at seashore.	
Al -	373	0,09	Commercial sheet.	
Al -	373	0,095	Sheet, polished.	

Table 4-2: Normal Total Emittance and Normal Solar Absorptance of Aluminium Contact Coatings

Alloy	T [K]	ε' ($\beta' = 0$)	α_s ($\beta = 0$)	Comments	References
Al -		0,03	0,10	Vacuum deposited (opaque thickness) on aluminium sheet with resin undercoat.	Bevans (1969) [14].
Al -		0,03	0,09	Vacuum deposited (opaque thickness) on aluminium foil, Reynolds Wrapp.	
Al -		0,04	0,21	Vacuum deposited (opaque thickness) on Beryllium foil.	
Al -		0,03	0,09	Vacuum deposited (opaque thickness) on Mylar film $2{,}5 \times 10^{-5}$ m thick.	
Al -		0,014	0,08	10^{-7} to 2×10^{-7} m thick aluminium	Scollon & Carpitella

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Alloy	T [K]	ε' ($\beta' = 0$)	α_s ($\beta = 0$)	Comments	References
				vapor deposited on unspecified surface. Polished surface. Measured in vacuum.	(1970) [33].
Al -		0,051	0,15	Same as above. Measured in air.	
Al -		0,024	0,13	Vapor deposited aluminium on Mylar.	
Al -		≤ 0,05	≤ 0,13	Vapor deposited aluminium on $1{,}2 \times 10^{-5}$ m thick Kapton. Data for metallic side. Silicone pressure sensitive adhesive. Schjeldahl.	
Al -		≤ 0,06	0,10 to 0,14	Vapor deposited aluminium on Kapton . Data for metallic side. Silicone pressure sensitive tape. Schjeldahl G-103500 tape.	
Al -		0,13 to 0,17	0,12 to 0,16	Vapor deposited aluminium on $1{,}2 \times 10^{-5}$ m thick Kapton plus nylon tulle. Data for metallic surface. Acrylic pressure sensitive adhesive. Second surface reflector. Schjeldahl G-102000 tape.	
Al -		0,025	0,11	$1{,}5 \times 10^{-7}$ m thick evaporated aluminium on Quartz.	McCargo, Spradley, Greenberg & McDonald (1971) [26].

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Table 4-3: Normal Total Emittance and Normal Solar Absorptance of Aluminium Conversion Coatings

Alloy	T [K]	ε' ($\beta' = 0$)	α_s ($\beta = 0$)	Comments	References
Al - 99,99		0,77	0,20	Hard anodized, $8x10^{-6}$ m thick, with sulphuric acid electrolyte 11% by weight, at 270 K.	Bevans (1969) [14].
Al - 99,99		0,79	0,14	Soft anodized, $1,3x10^{-5}$ m thick, with sulphuric acid electrolyte 15% by weight, at 270 K.	
Al - 99,7		0,82	0,24	Soft anodized, $1,3x10^{-5}$ m thick, with sulphuric acid electrolyte 16% by weight, at 294 K.	
Al - 99,7		0,74	0,40	Anodized, $8x10^{-6}$ m thick, with chromic acid electrolyte 5% by weight, at 308 K, anodizing voltage 40V DC, 120 min.	
Al - 99,99		0,08	0,27	Anodized, citric acid electrolyte 1 $kg.m^{-3}$ ammonium citrate, at 295 K, anodizing voltage: 300V DC, 60 min.	
Al - 99,7		0,86	0,31	Anodized, $2x10^{-5}$ m thick, oxalic acid solution 3% by weight, at 311 K, anodizing voltage: 30V DC, 60 min.	
Al - 99,99		0,39	0,33	Anodized, sulphamic acid electrolyte 100 $kg.m^{-3}$, at 294 K, anodizing voltage: 45V DC, 30 min.	
Al - 99,99		0,77	0,64	Anodized, sulphamic acid electrolyte 100 $kg.m^{-3}$, at 294 K, anodizing voltage: 15V DC, 30 min.	
Al - 99,99		0,03	0,27	Anodized, sulphamic acid electrolyte 100 $kg.m^{-3}$, at 294 K, anodizing voltage: 5,5V DC, 15 min.	
Al -		0,73	0,70	Chromic acid anodized. Chemical surface finish. Degradation caused by deposition of outside contaminants (73 h in low earth orbit on board Apollo 9).	Scollon & Carpitella (1970) [33].
Al -		0,90		Carbon black impregnated anodized coating. Chemical surface finish.	

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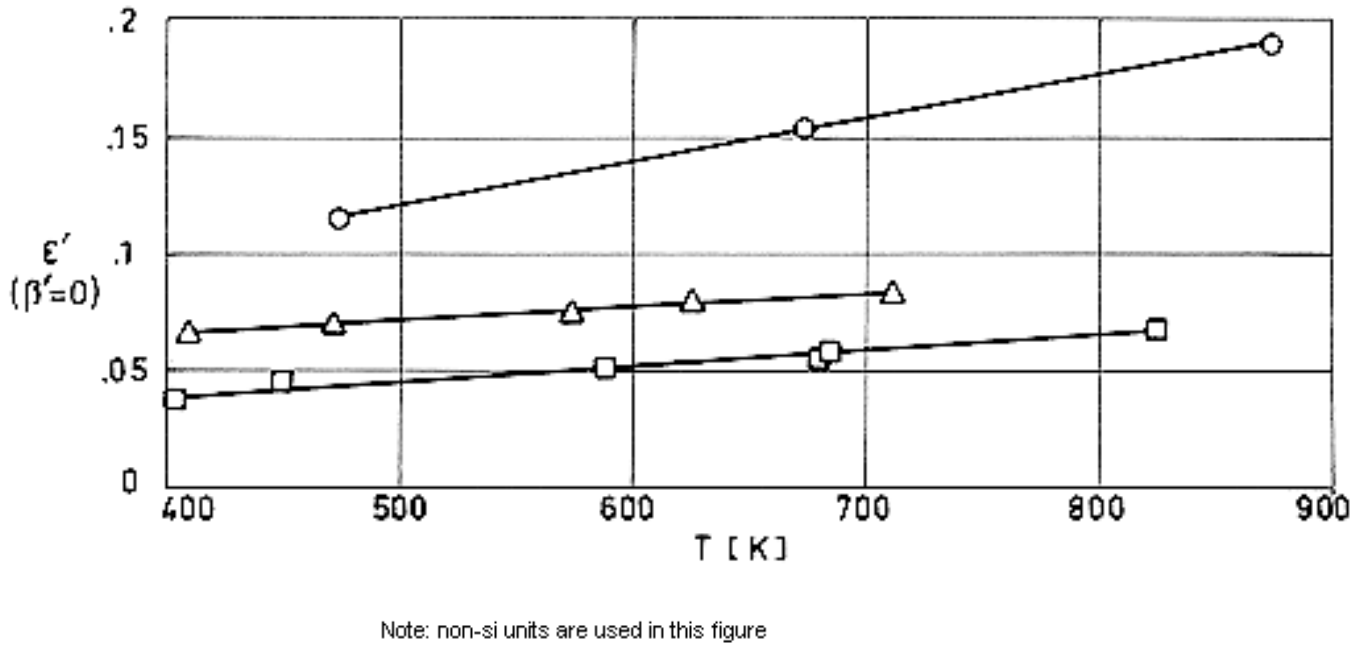

Note: non-si units are used in this figure

Figure 4-9: Normal total emittance, ε', of Aluminium as a function of temperature, T.

Explanation

Key	Description	Comments	References
○	Cleaned, polished, and oxidized.		Touloukian & DeWitt (1972) [158].
□	Pure. Highly polished.	Reported error 2%.	
△	Pure. Rolled, as received.		

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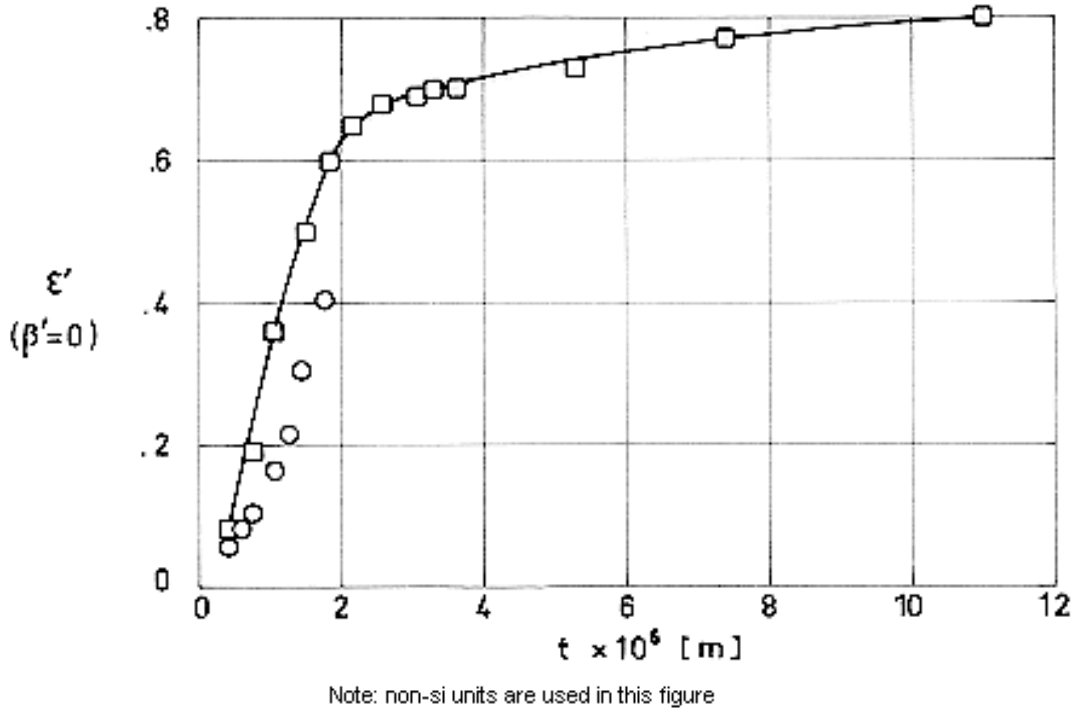

Figure 4-10: Normal total emittance, ε', of Aluminium anodized as a function of anodizing thickness, t_c .

Explanation

Key	Description	Comments	References
○	Barrier-layer anodic coating on a high aluminium substrate. Substrate cleaned, electropolished in a flouboric acid solution, anodized in aqueous ammonium tartrate solution, then immersed in a phosphoric acid solution.	Sample temperature T~298 K. Measured in vacuum (~1,33x10^{-4} Pa).	Touloukian, DeWitt & Hernicz (1972) [43].
□	Foil oxidized electrolytically in 15% sulphuric acid.	T = 311 K. Measured relative to Aluminium.	

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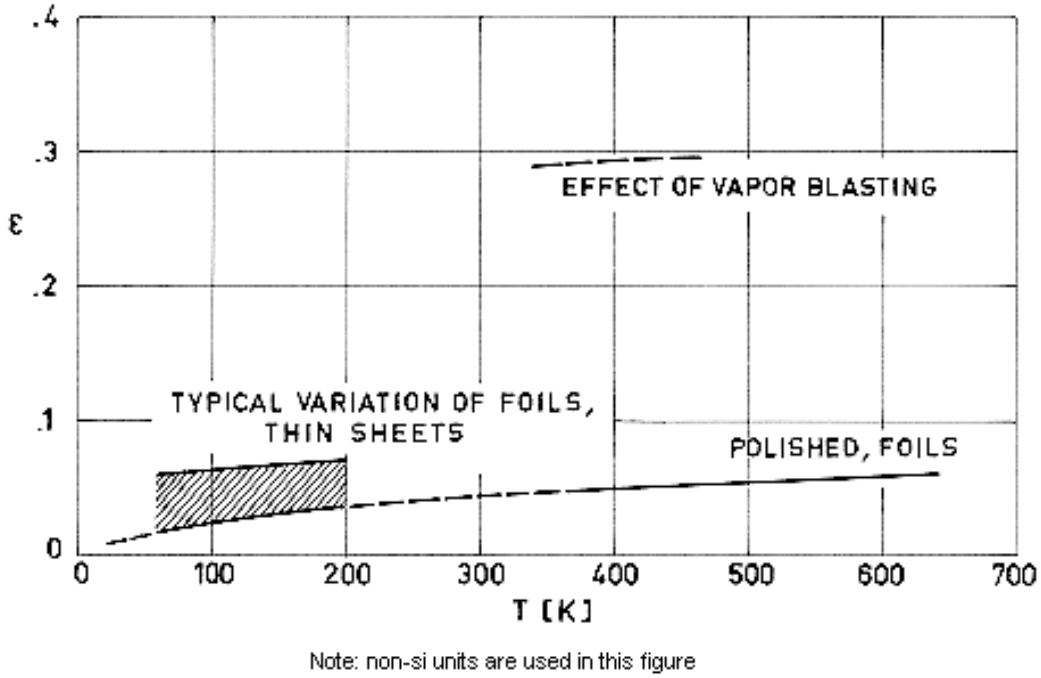

Figure 4-11: Summary of data concerning the hemispherical total emittance, ε, of Aluminium as a function of temperature, T. From Touloukian & DeWitt (1970) [42].

Table 4-4: Hemispherical Total Emittance of Aluminium Contact Coatings.

T [K]	ε	Comments
76	0,04	Aluminium; plastic Mylar (1,27x10^{-5} m thick) and aluminium substrates; produced by vaporizing aluminium on both sides of Mylar. Measured in vacuum (1,3x10^{-4} to 1,3x10^{-5} Pa). Authors assumed $\alpha=\varepsilon$ for 300 K blackbody incident radiation. Reported error 5%.
76	0,07	Aluminium; stainless steel substrate; Al sprayed on substrate. Measured in vacuum (1,3x10^{-4} to 1,3x10^{-5} Pa). Authors assumed $\alpha=\varepsilon$ for 300 K blackbody incident radiation. Reported error 5%.
76	0,06	Aluminium; stainless steel substrate; Al sprayed on substrate; wire brushed. Measured in vacuum (1,3x10^{-4} to 1,3x10^{-5} Pa). Authors assumed $\alpha=\varepsilon$ for 300 K blackbody incident radiation. Reported error 5%.
76	0,04	Aluminium plastic Mylar (1,27x10^{-5} m thick) and aluminium substrate; Al vapor deposited on both sides of Mylar. Measured in vacuum (1,3x10^{-4} Pa). Authors assumed $\alpha=\varepsilon$ for 294 K blackbody radiation.

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T [K]	ε	Comments
76	0,043	Similar to above specimen and conditions.
773-1273	0,69-0,78	Aluminium; iron substrate; substrate sandblasted and degreased; coated to a surface density of 75 kg.m^{-2} with aluminium powder suspension; sintered at 1223 K in vacuum. Measured in vacuum (6,7x10^{-4} Pa). Data extracted from smooth curve. Reported error 2,5%.
378-486	0,33-0,27	Aluminium (1,27x10^{-4} to 2,03x10^{-4} m thick); Al substrate; sprayed. Measured in vacuum (0,13 Pa). Reported error 3%.
333	0,047	Aluminium; Mylar substrate. Measured in vacuum (6,7x10^{-4} Pa). Reported error <3,5%.
300-415	0,06	Aluminium (10^{-6} m thick); Mylar (1,2x10^{-5} m thick) and stainless steel (2,5x10^{-4} m thick) substrates; Mylar cemented to stainless steel; Al vapor deposited. Measured in vacuum (1,3x10^{-5} Pa). Reported error 5%.
258-348	0,0428-0,0454	Aluminium (2x10^{-7} m thick); stainless steel substrate; Al vapor deposited on hand-polished substrate; property measured by steady-state calorimetric method. Mentioned below as specimen 1.
248-348	0,0293-0,0311	Same specimen and conditions as 1 except property measured by transient calorimetric method; property of second side of sample assumed.
303	0,024	Same specimen and conditions as 1 except property calculated from ρ (10°, 10°) measured by specular method relative to a front surface aluminized mirror.
300	0,0482	Same specimen and conditions as 1 except property calculated from ρ (7,5°, 2π) measured by ellipsoid method.
200-400	0,0224-0,0237	Same specimen and conditions as 1 except property calculated from ρ (2π-75°, 15°). Specimen placed at the center of a heated cavity, so that the angle of viewing can be varied from 15° to 75°. (Millard & Streed (1969) [27]).
295	0,0279	Same specimen and conditions as 1 except property measured by a portable Quick Emittance Device.
295	0,041	Same specimen and conditions as 1 except property measured by a portable emissometer.
~298	0,0334	Polyester film (6,35x10^{-6} m thick) double aluminized. Coating thickness of emitting surface t_{c1}= 4,55x10^{-8} m. Coating thickness of second surface t_{c2} = 3,78x10^{-8} m.

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