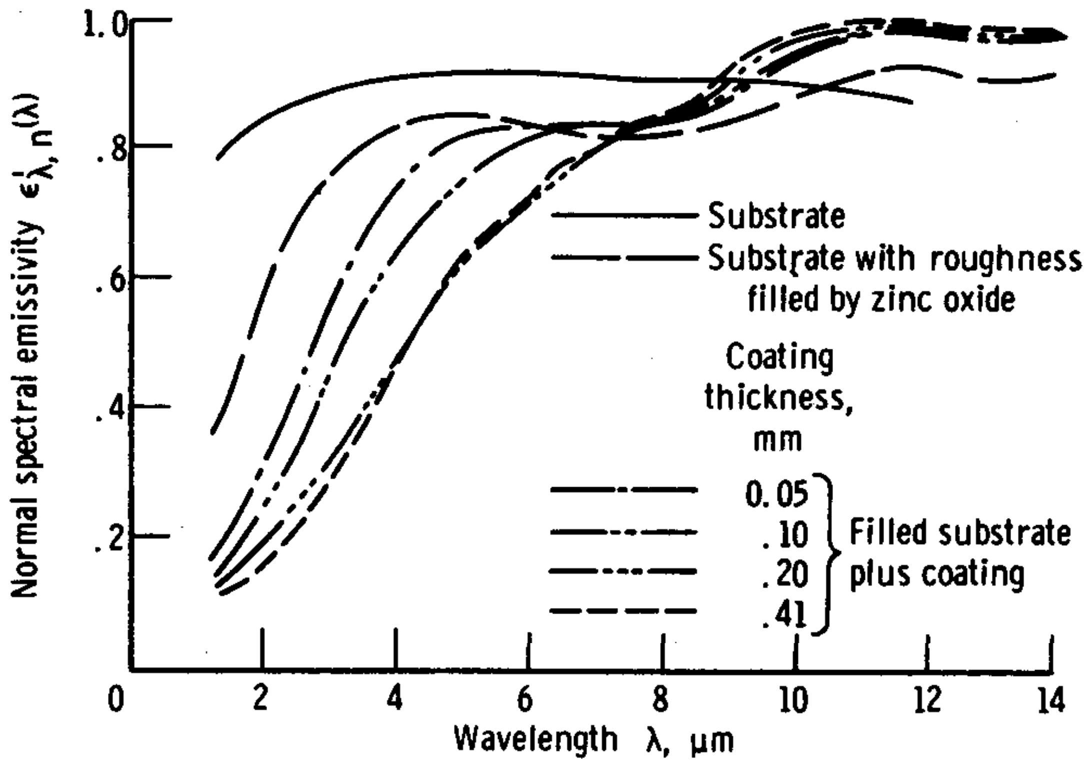
RADIATIVE PROPERTIES OF REAL MATERIALS

- **Electromagnetic Theory:**
  - **ideal, optically smooth surface**
  - **valid for spectral range larger than visible**
- **Real Materials: surface condition**
  - **contaminants or oxides**
  - **surface roughness**
  - **thin coating on substrate**

- **Material Dependence**
  - **opaque nonmetals**
  - **opaque metals**
  - **selective and directional opaque surfaces**
  - **selectively transparent materials**
- **Parameter Dependence**
  - **spectral and directional variations**
  - **variation with temperature**
  - **effect of surface roughness**
  - **effect of surface impurities**

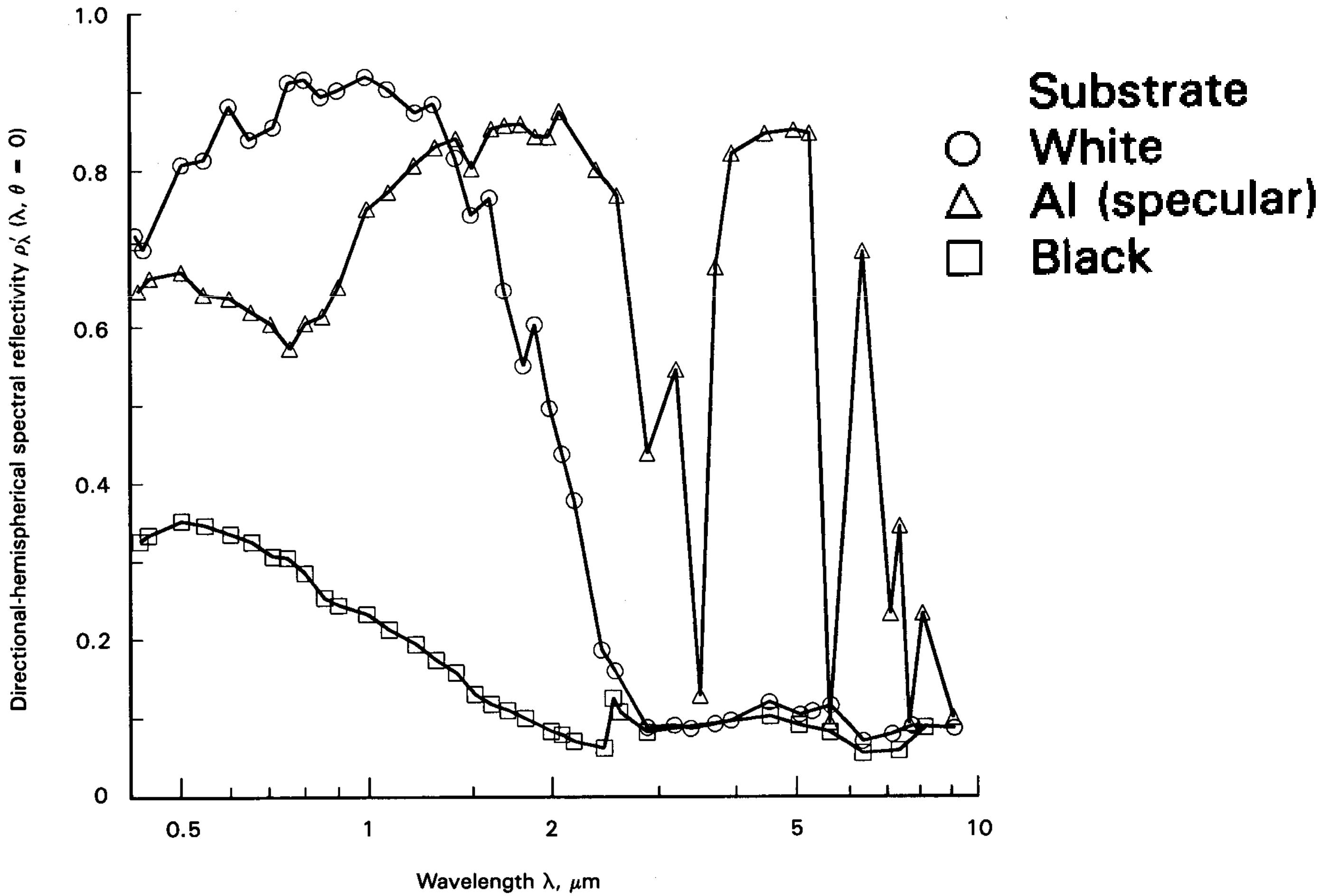
Radiative Properties of Opaque Nonmetals

Effect of Coating Thickness



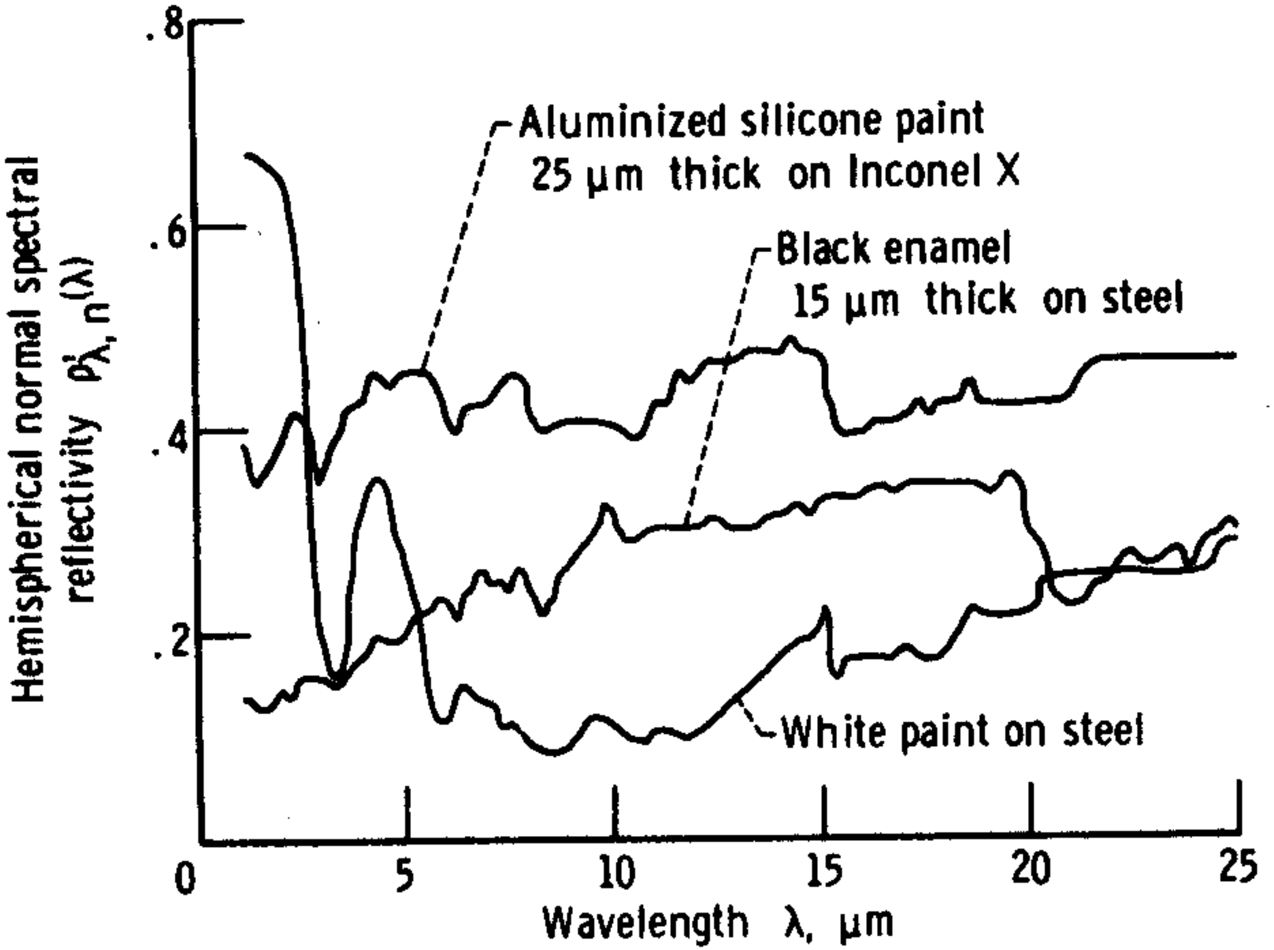
Emissivity of zinc oxide coatings on oxidized stainless steel substrate. Surface temperature, 880 ± 8 K

Effect of Substrates

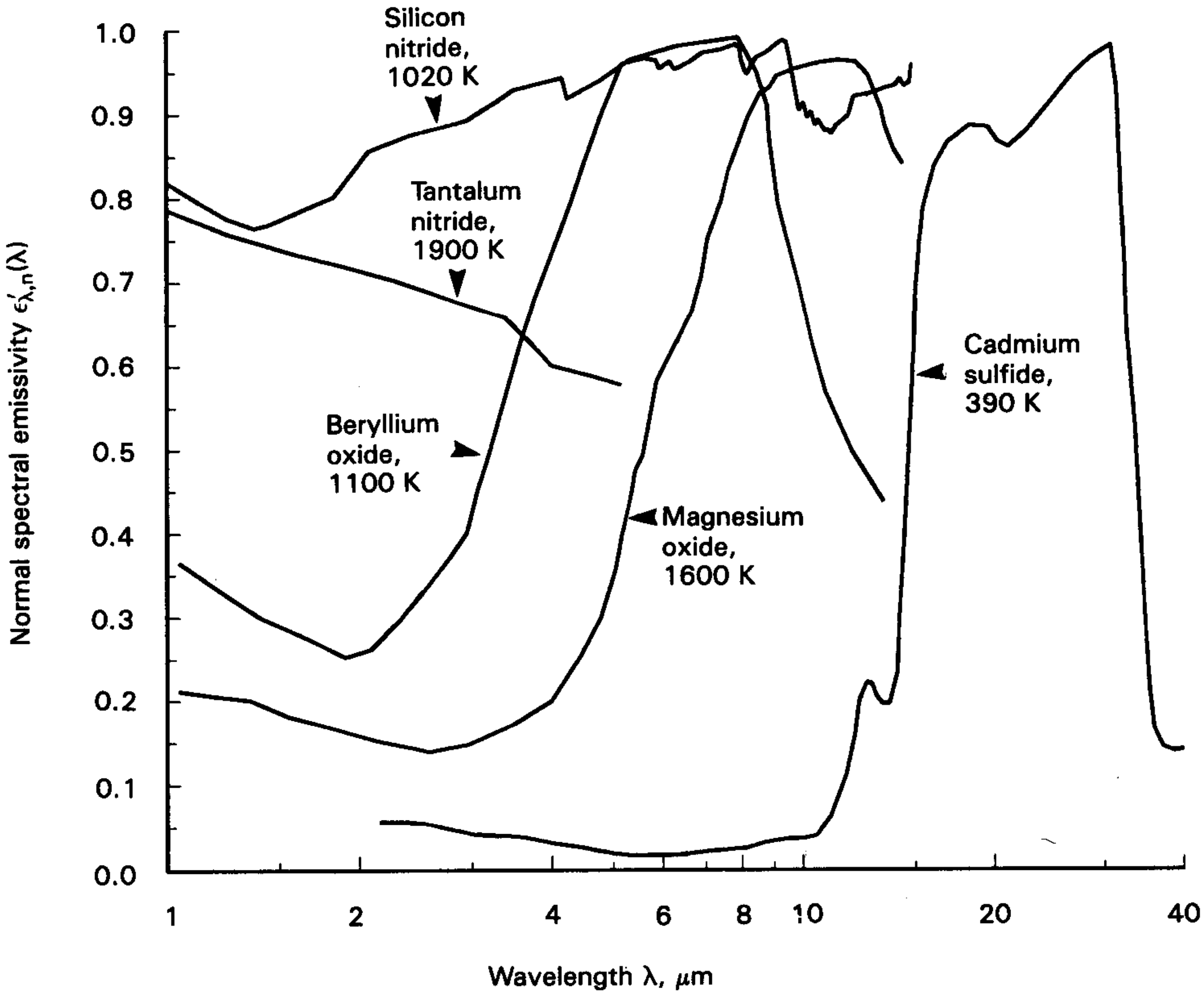


Effect of substrate reflection characteristics on the hemispherical characteristics of a TiO_2 paint film for normal incidence: Film thickness, 14.4 μm; volume concentration of pigment 0.017,

Spectral Dependence

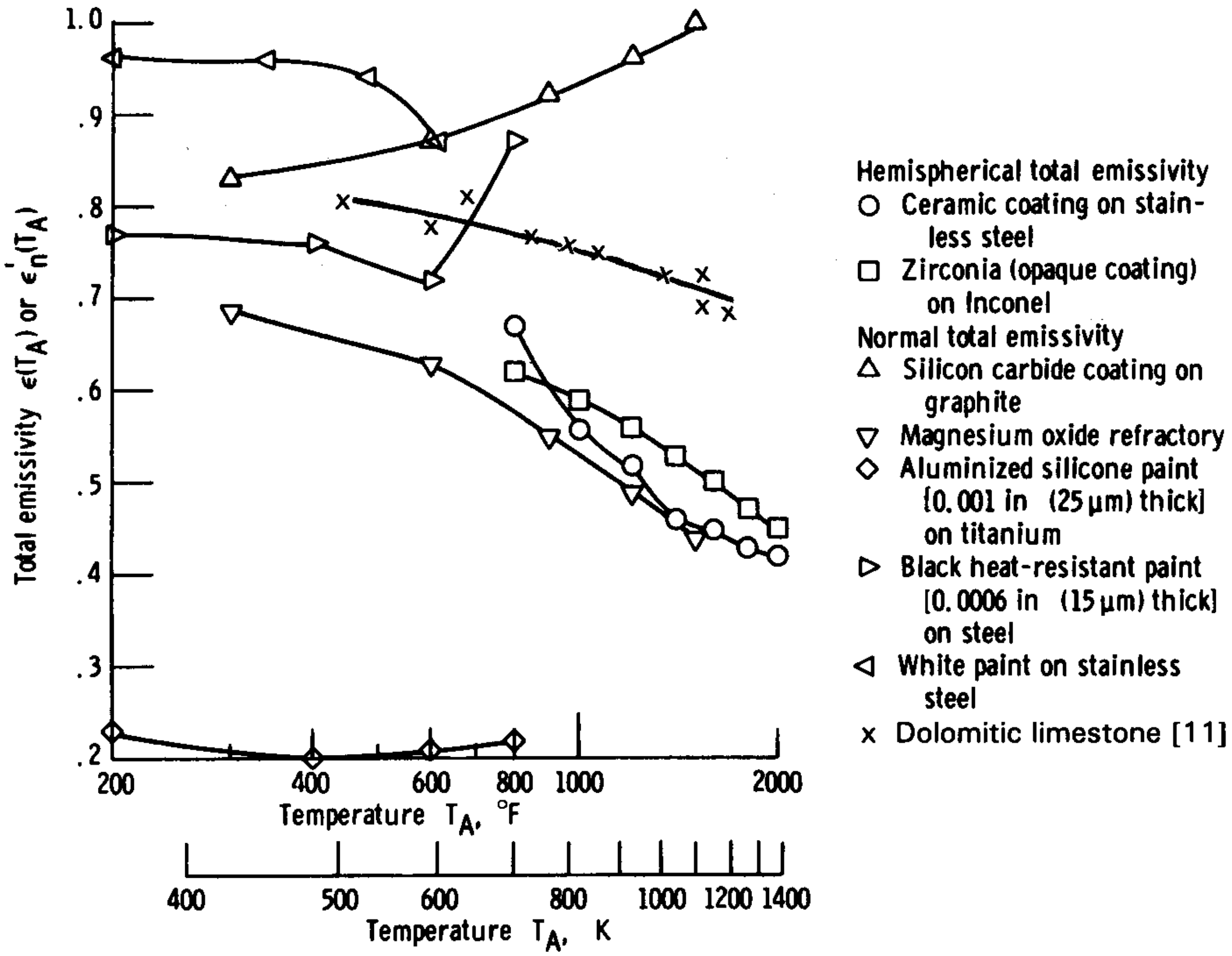


Spectral reflectivity of paint coatings. Specimens at room temperature

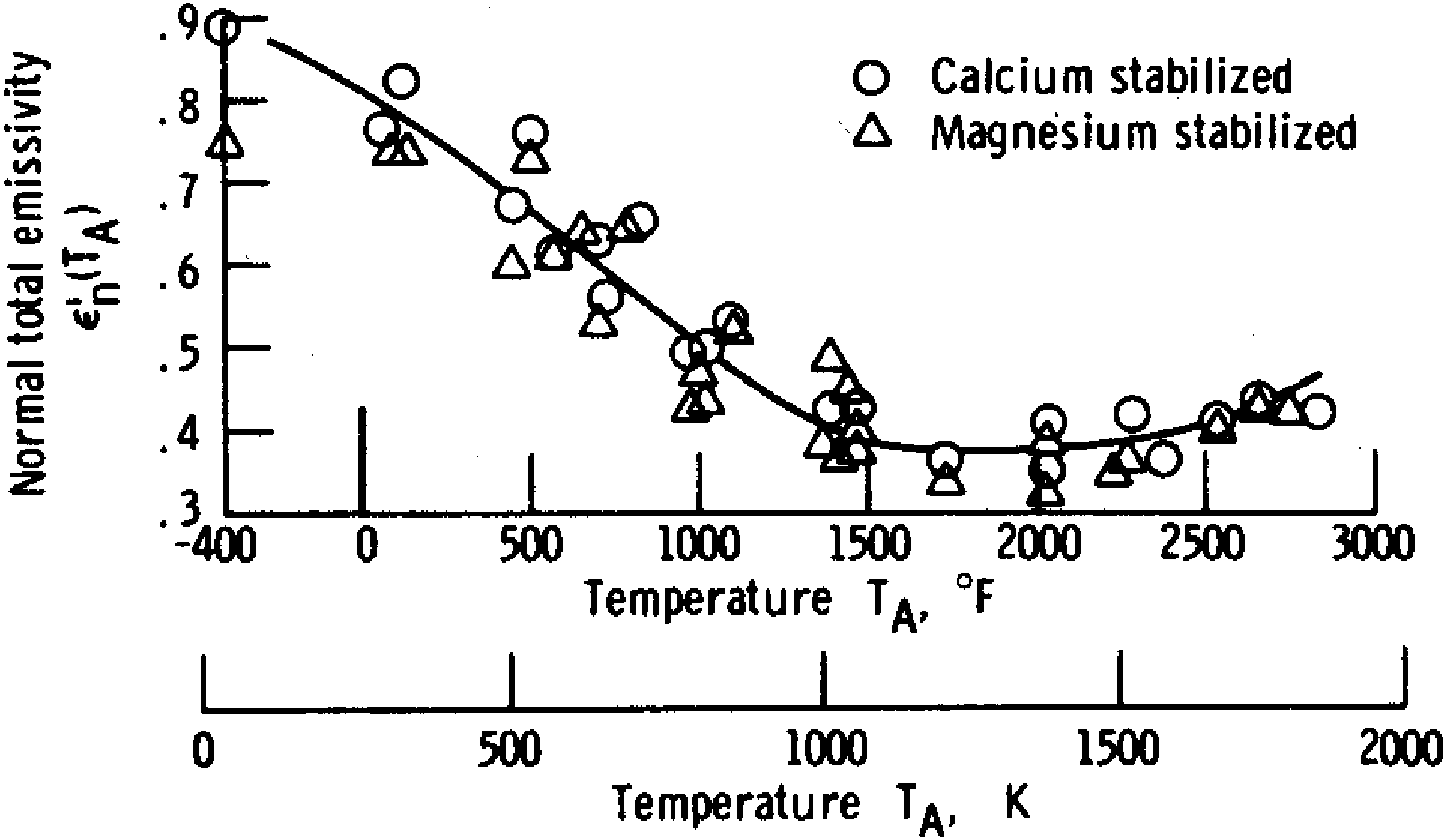


Normal spectral emissivity of some nonmetal samples.

Variation with Temperature

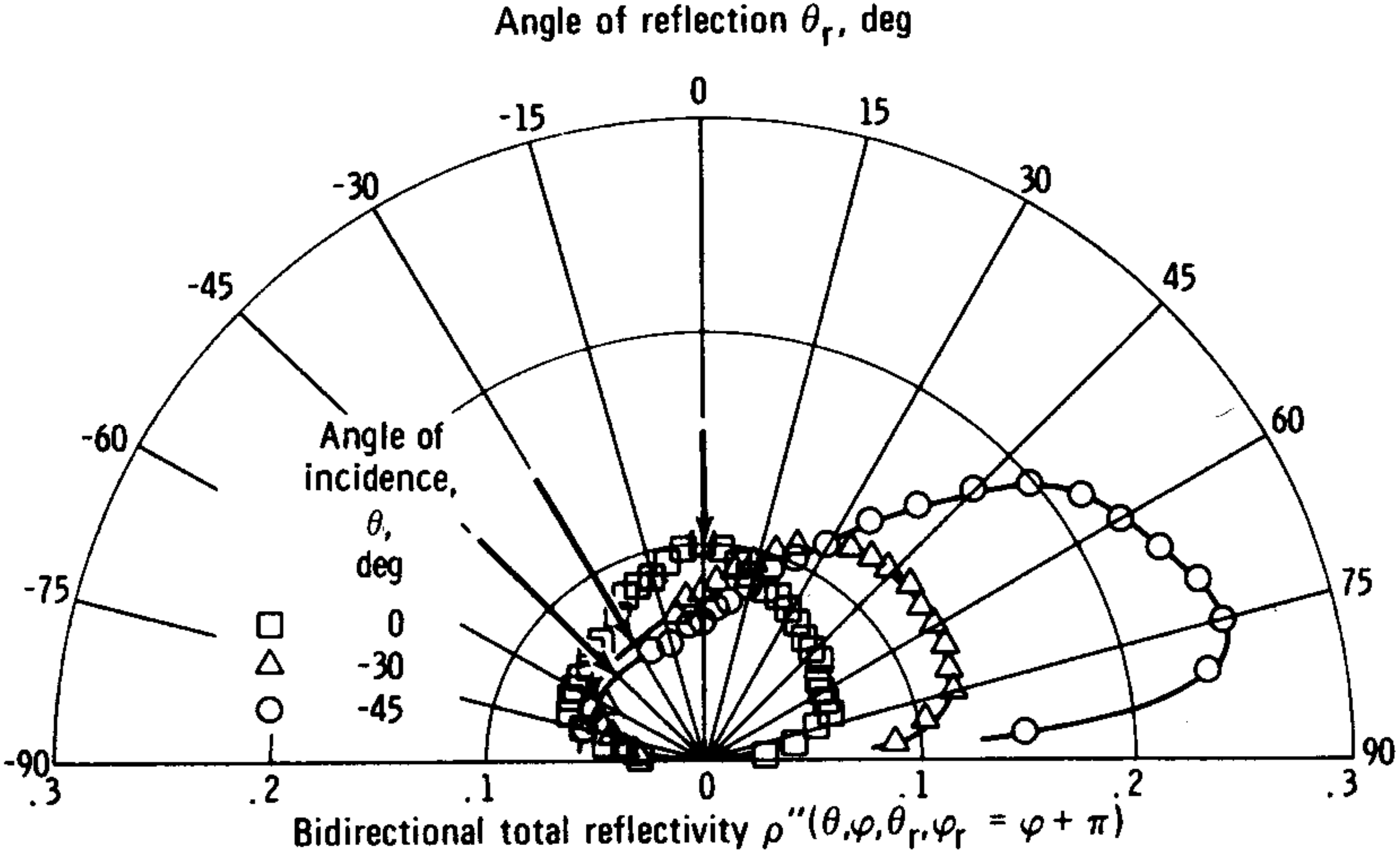


Effect of surface temperature on emissivity of dielectrics

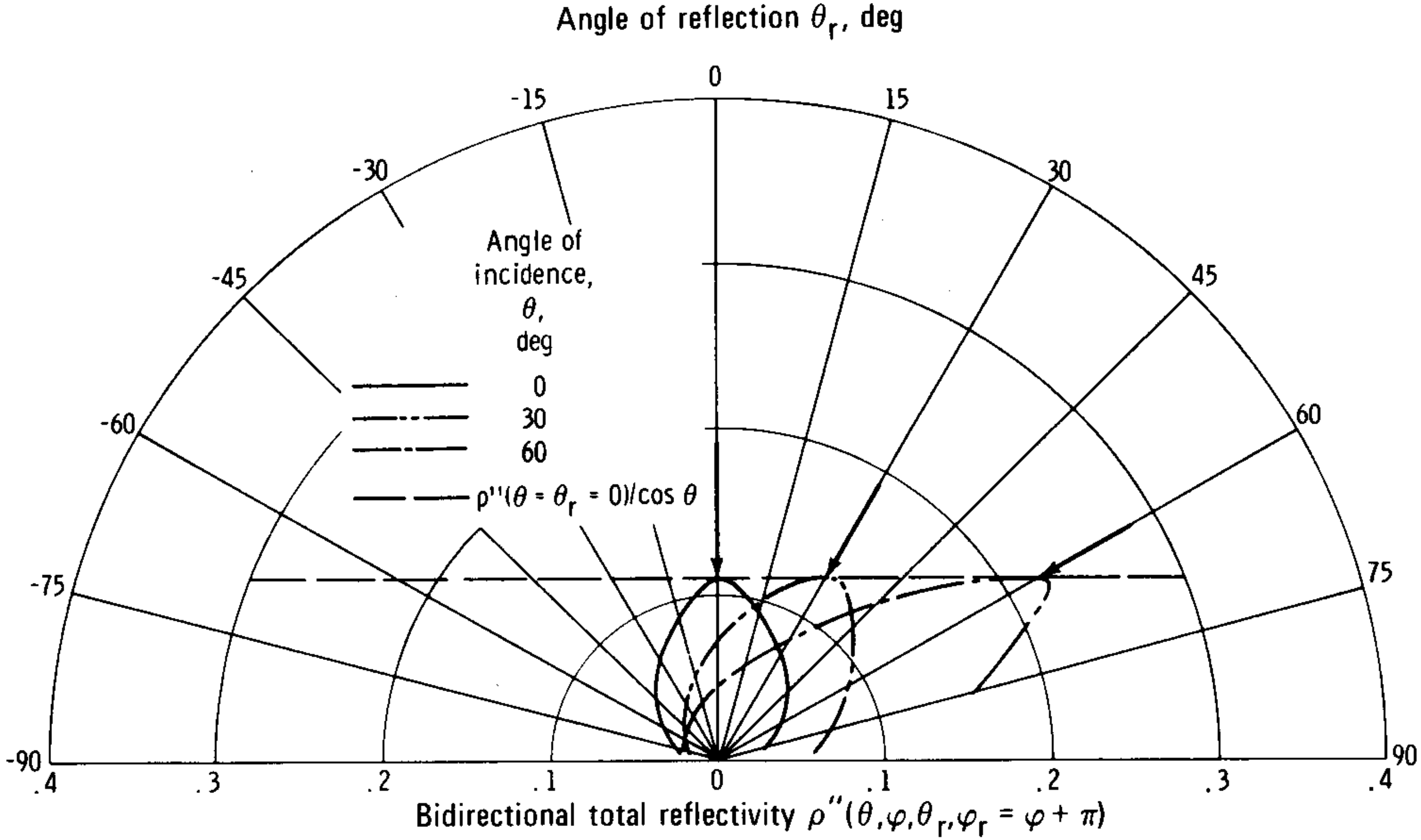


Effect of surface temperature on normal total emissivity of zirconium oxide

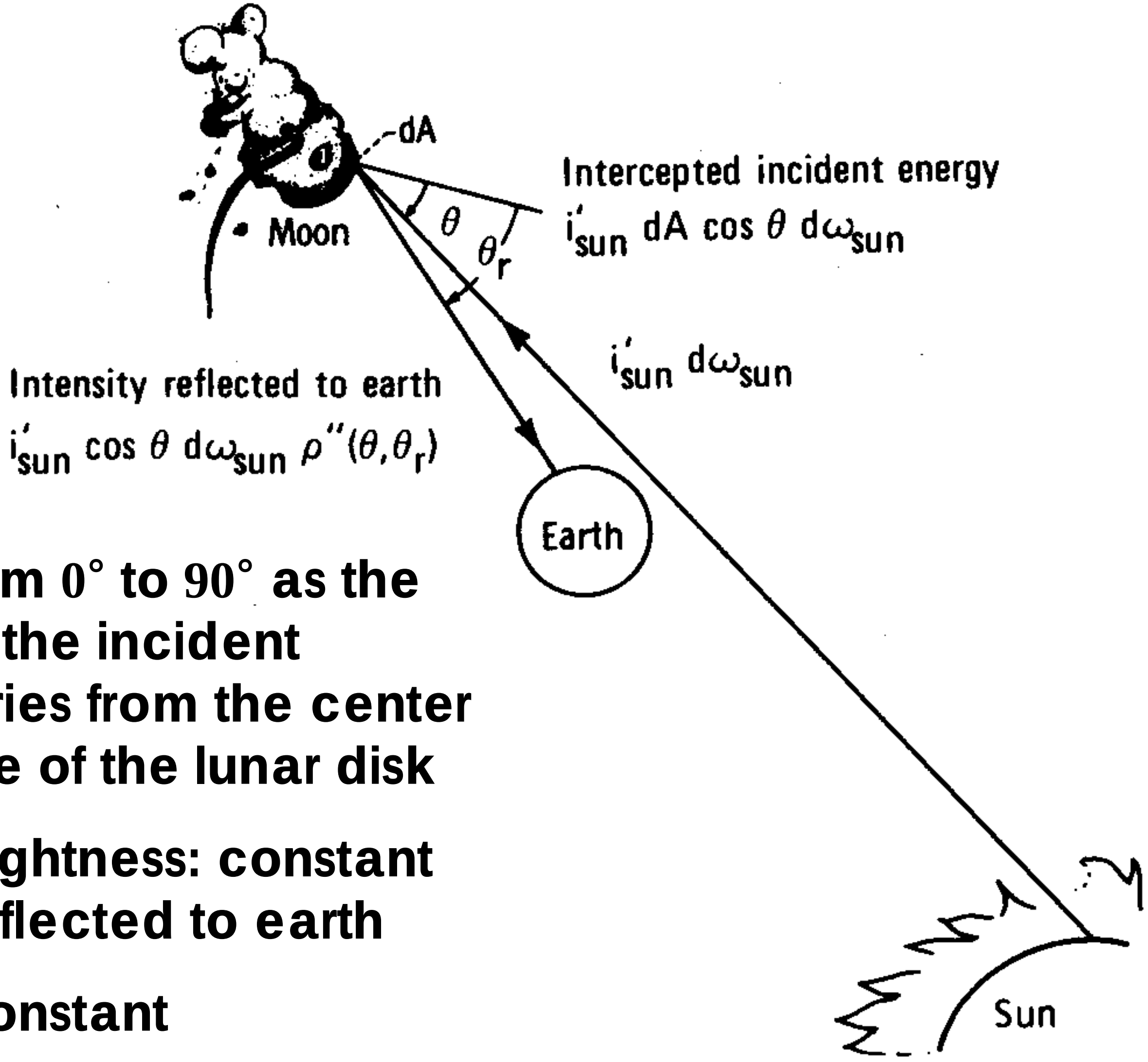
Effect of Surface Roughness



Bidirectional total reflectivity of typewriter paper in plane of incidence. Source temperature, 1178 K



Bidirectional total reflectivity for visible light in plane of incidence for mountainous regions of lunar surface



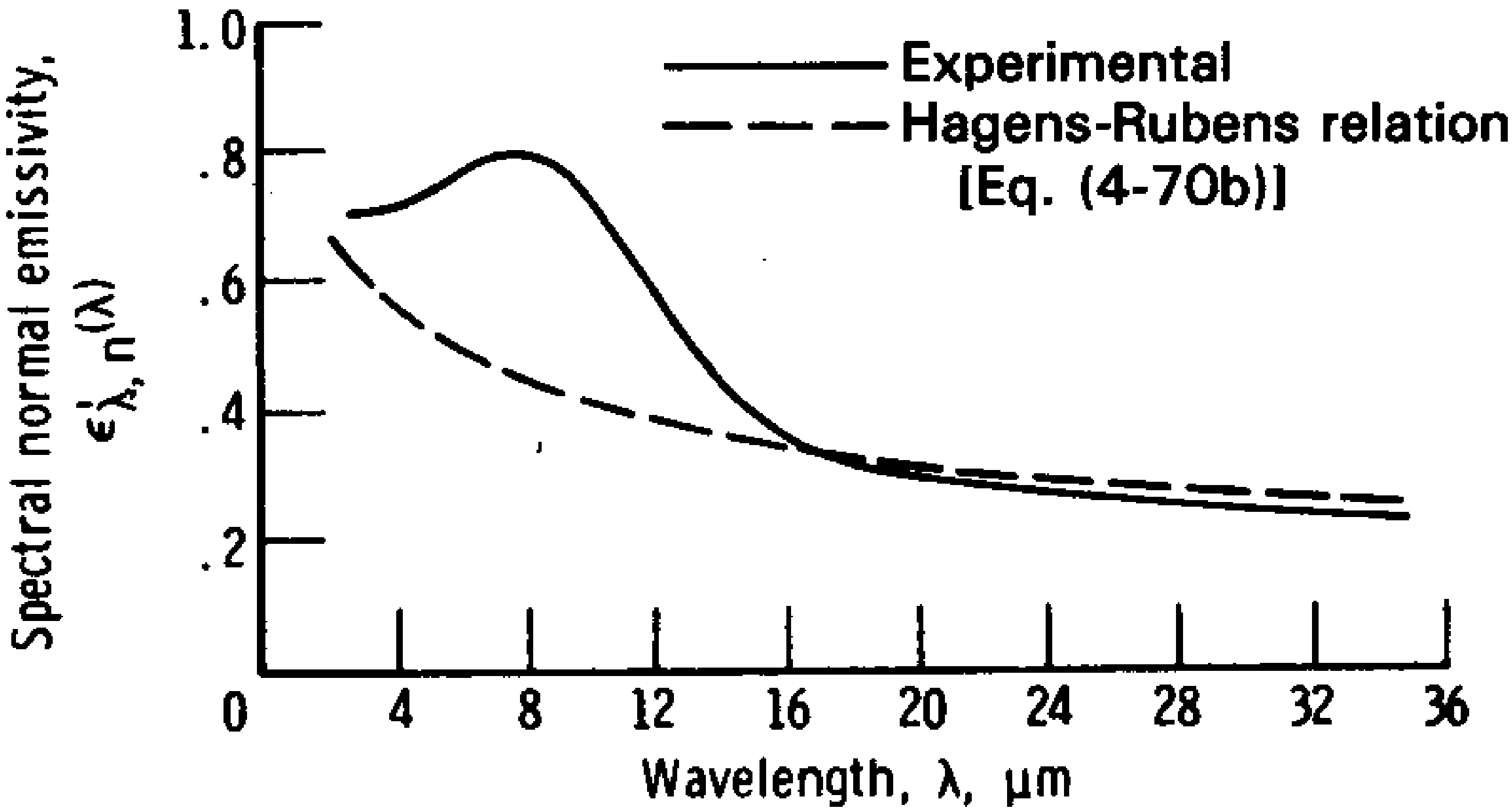
θ varies from $0°$ to $90°$ as the position of the incident energy varies from the center to the edge of the lunar disk

uniform brightness: constant intensity reflected to earth

$\rho'' \cos\theta =$ **constant**

Reflected energy at full moon

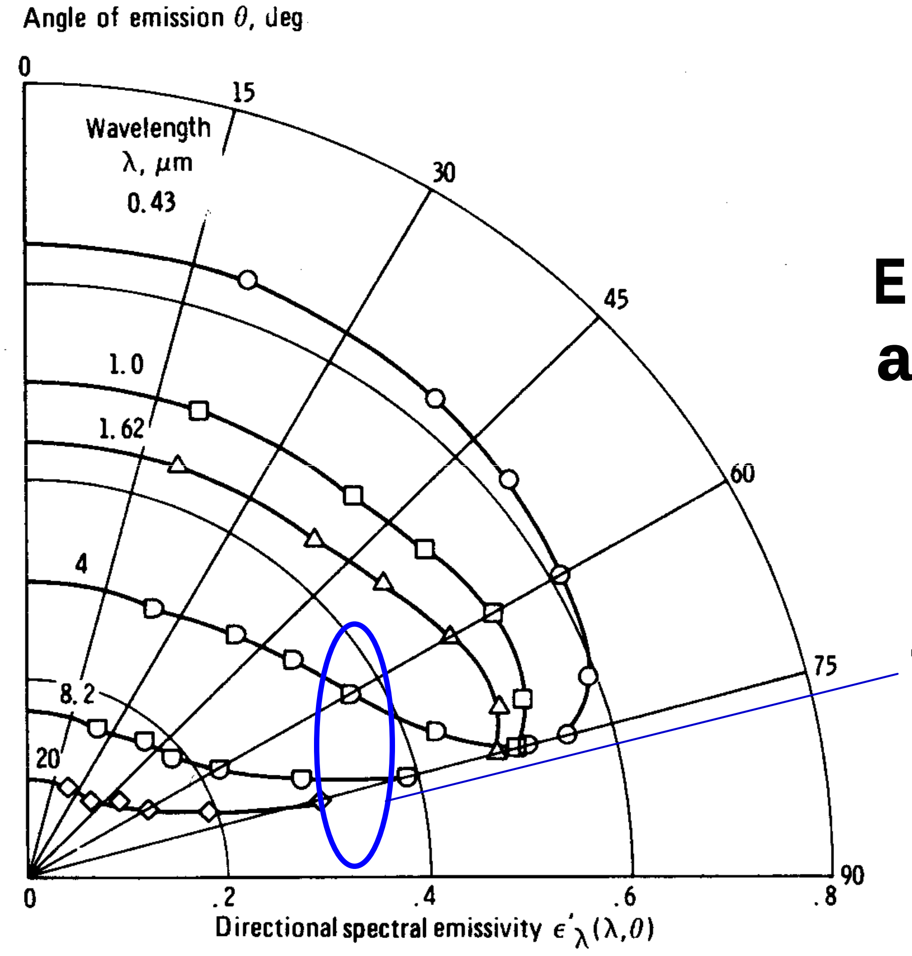
Semiconductor



Normal spectral emissivity of a highly doped silicon semiconductor at room temperature

Radiative Properties of Metals

Directional Dependence

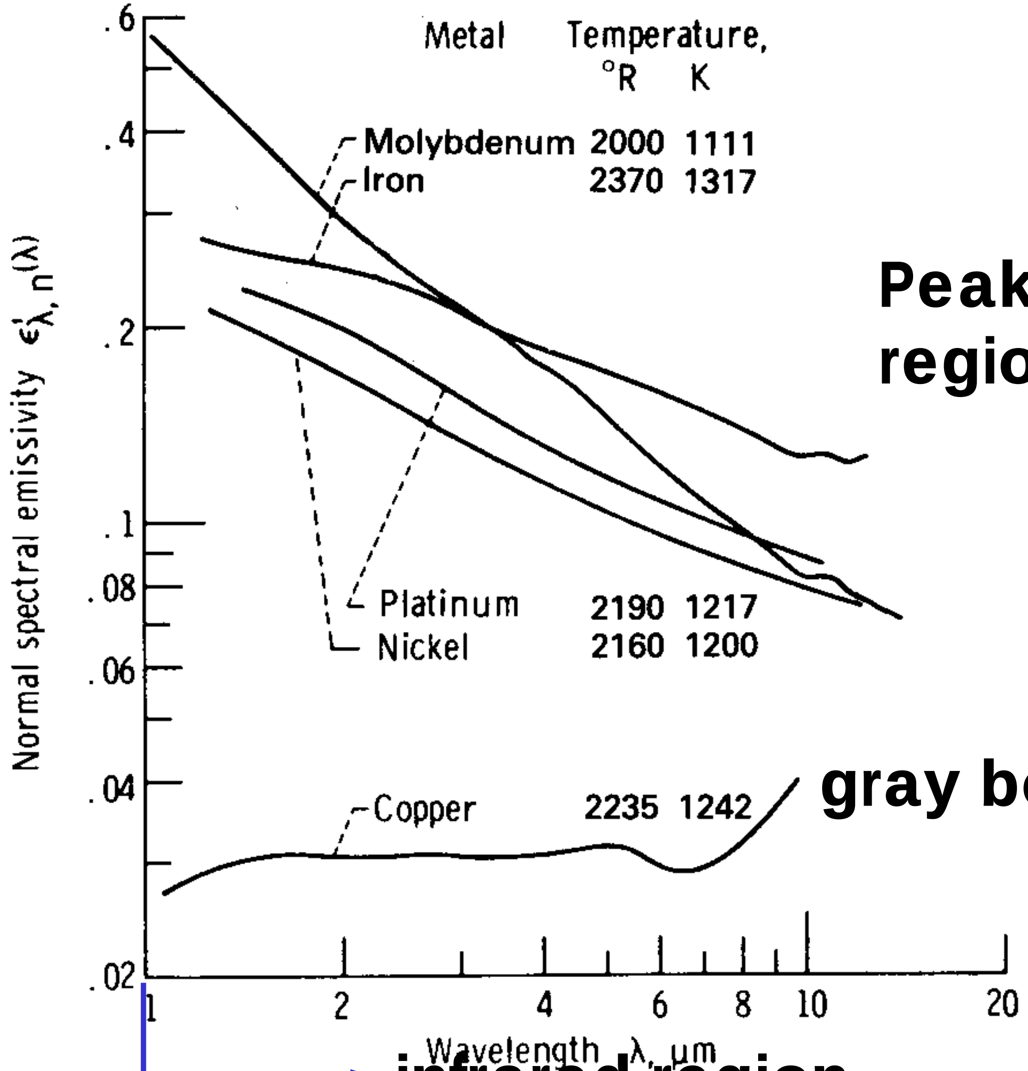


EM theory doesn't hold at shorter wavelengths.

follow theoretical trend

Effect of wavelength on directional spectral emissivity of pure titanium. Surface ground to 0.4 μm rms

Spectral Dependence

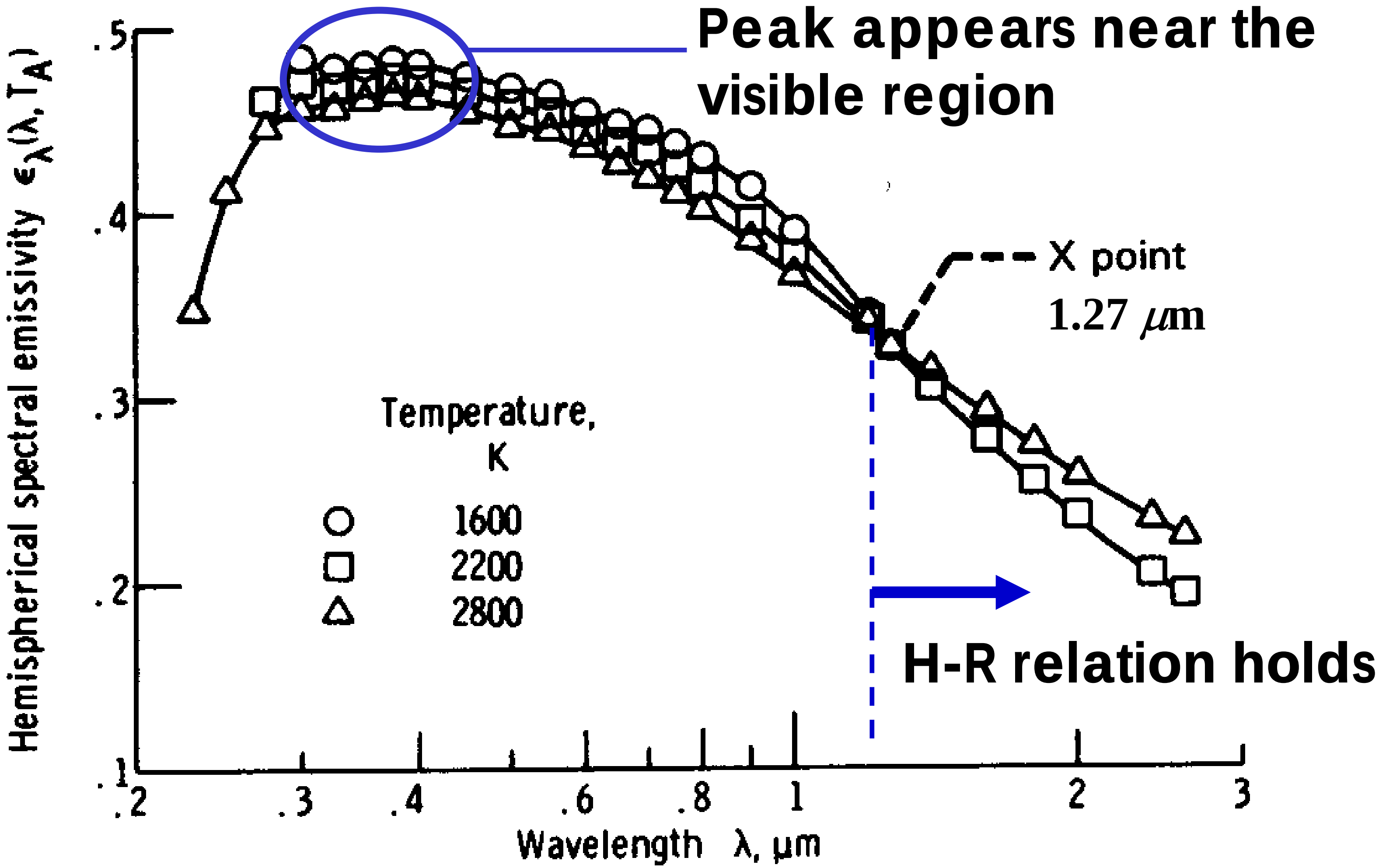


Peak ε near the visible region

gray body assumption

infrared region

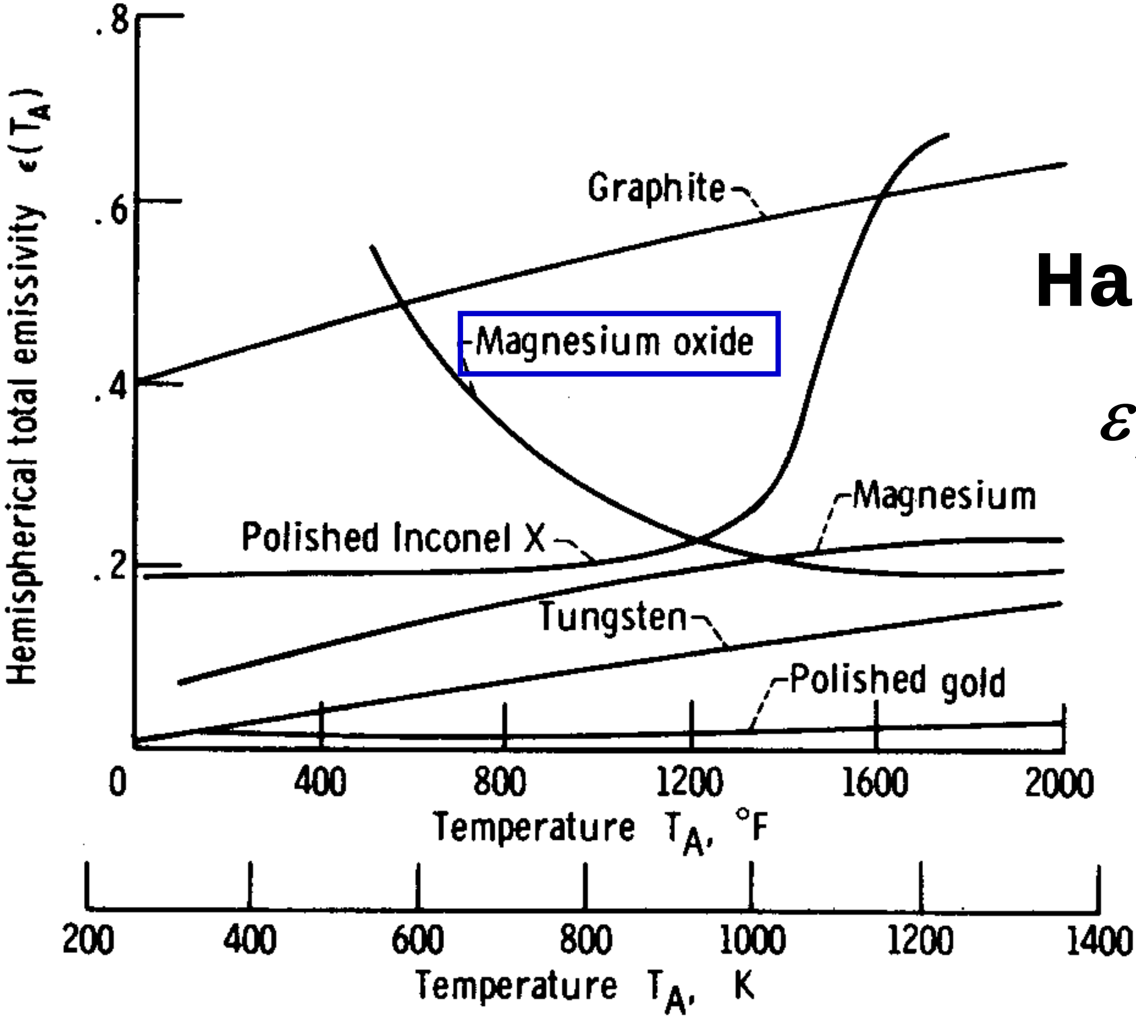
Variation with wavelength of normal spectral emissivity for polished metals



Effect of wavelength and surface temperature on hemispherical spectral emissivity of tungsten

X point: iron, 1.0 μm; nickel, 1.5 μm; copper, 1.7 μm; platinum, 0.7 μm

Variation with Temperature

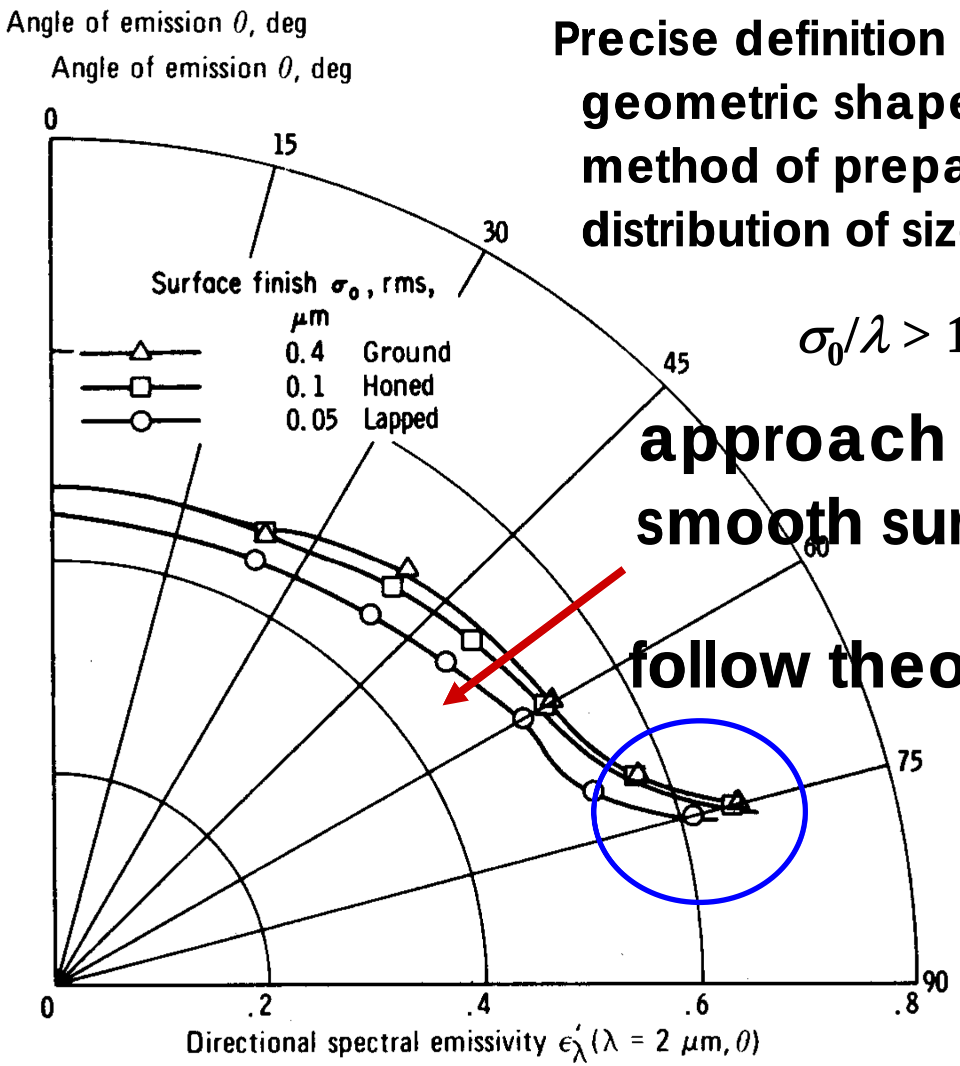


Hagen – Rubens

$$\varepsilon_\lambda \propto \sqrt{r_e} \propto \sqrt{T}$$

Effect of temperature on hemispherical total emissivity of several metals and one dielectric

Effect of Surface Roughness



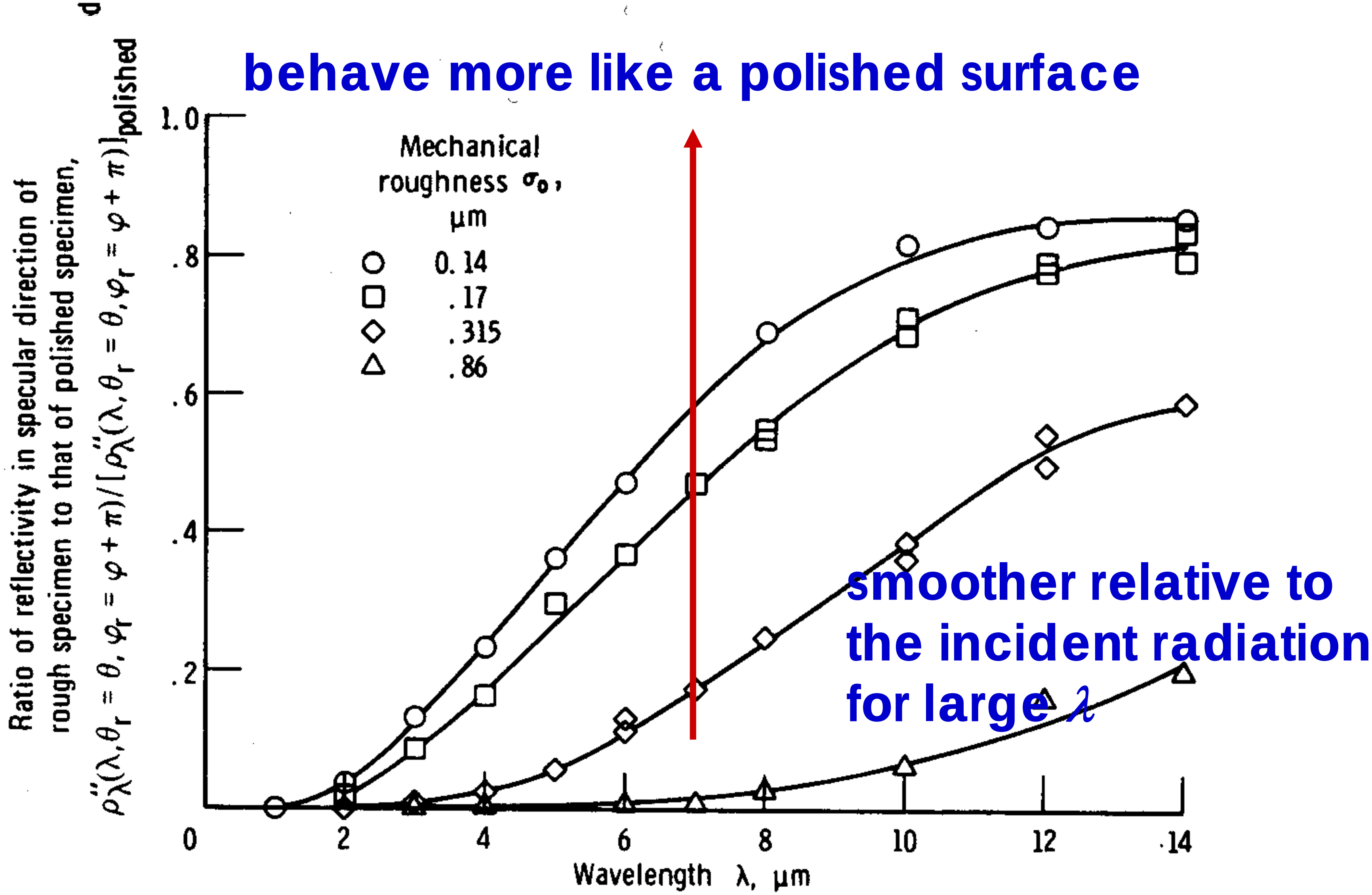
Precise definition of surface characteristics
- **geometric shape,**
- **method of preparation,**
- **distribution of size around rms**

$\sigma_0/\lambda > 1$**: multiple reflection**

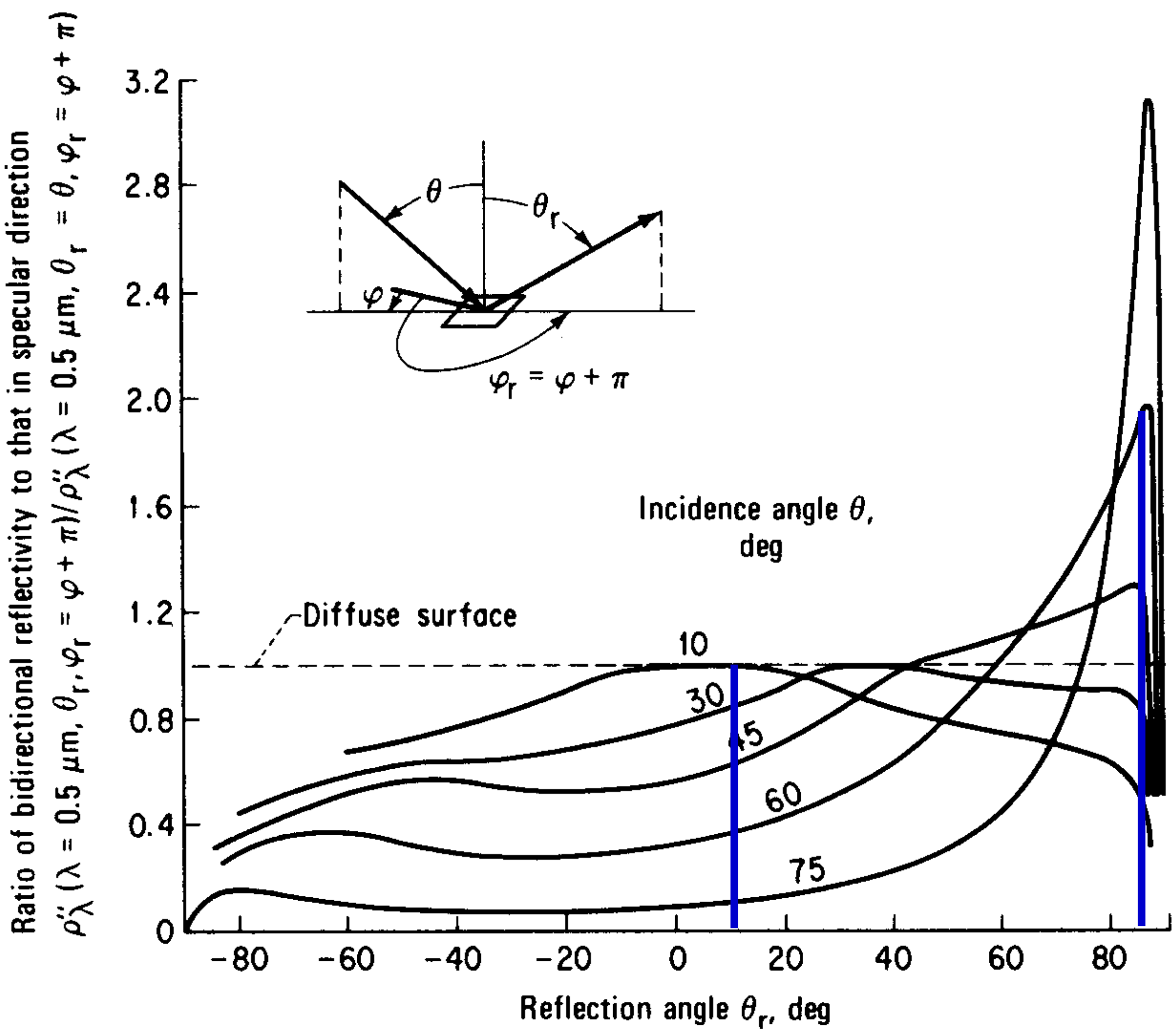
approach to optically smooth surface

follow theoretical trend

Roughness effects for small optical roughness, $\sigma_0/\lambda < 1$**; effect of surface finish on directional spectral emissivity of pure titanium. Wavelength,** $2\ \mu\text{m}$



Effects of roughness on bidirectional reflectivity in specular direction for ground nickel specimens. Mechanical roughness for polished specimen, 0.015 μm



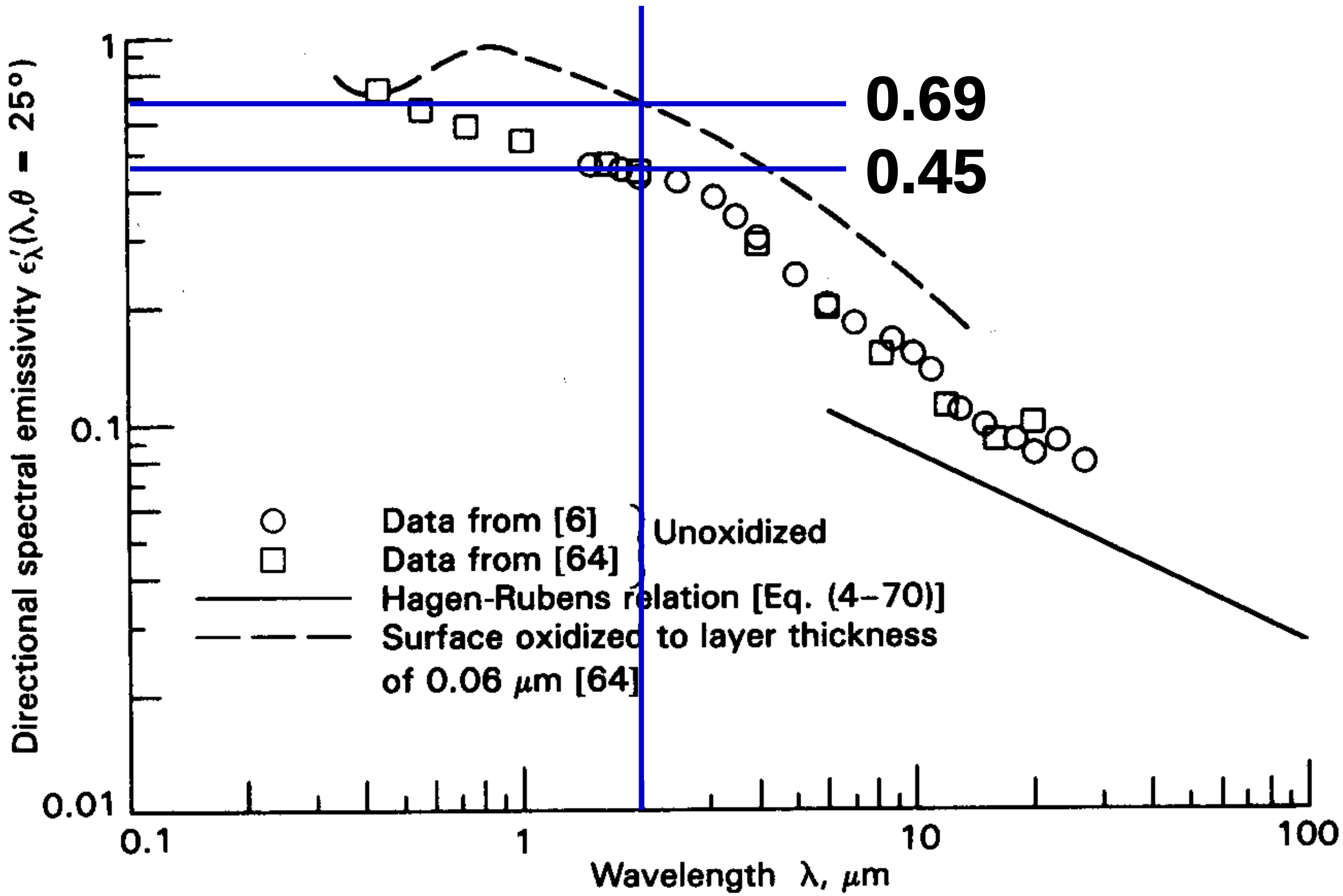
$\sigma_0/\lambda = 2.6$

For large θ, peak θ_r shifted to larger angles

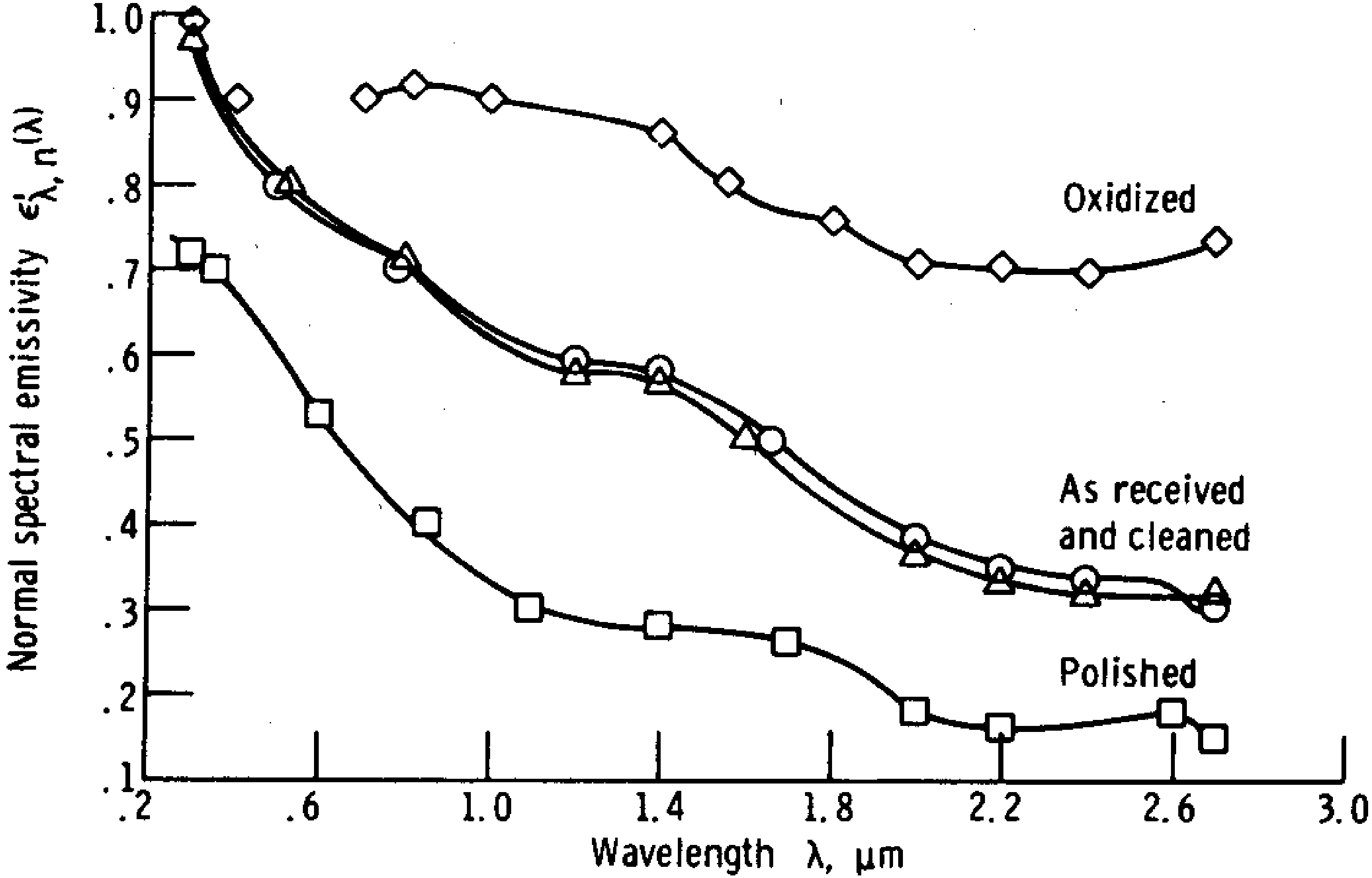
Off-specular reflection at larger roughness and incident angle

Bidirectional reflectivity in plane of incidence for various incidence angles; material, aluminum (2024-T4), aluminum coated; rms roughness $\sigma_0 = 1.3\ \mu m$; wavelength of incident radiation, $\lambda = 0.5\ \mu m$

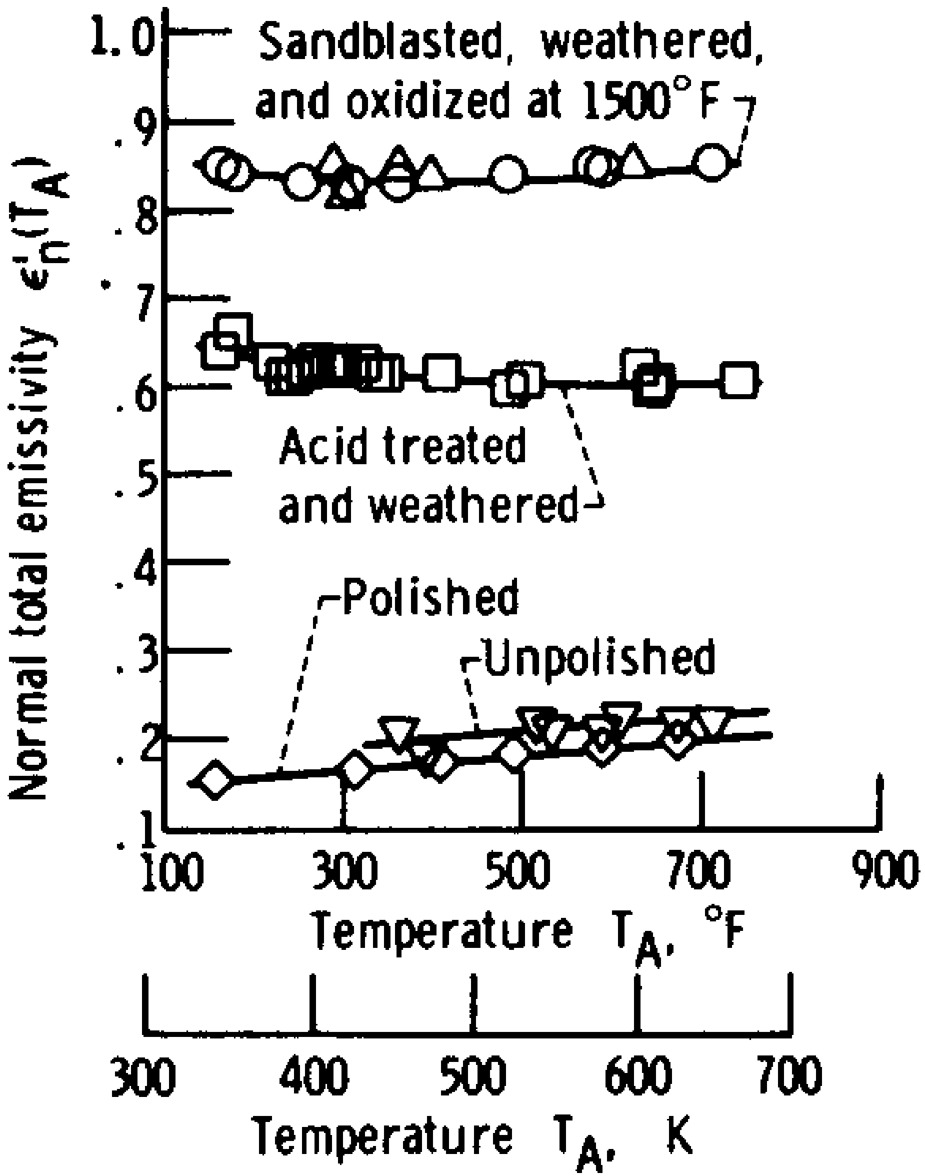
Effect of Surface Impurities



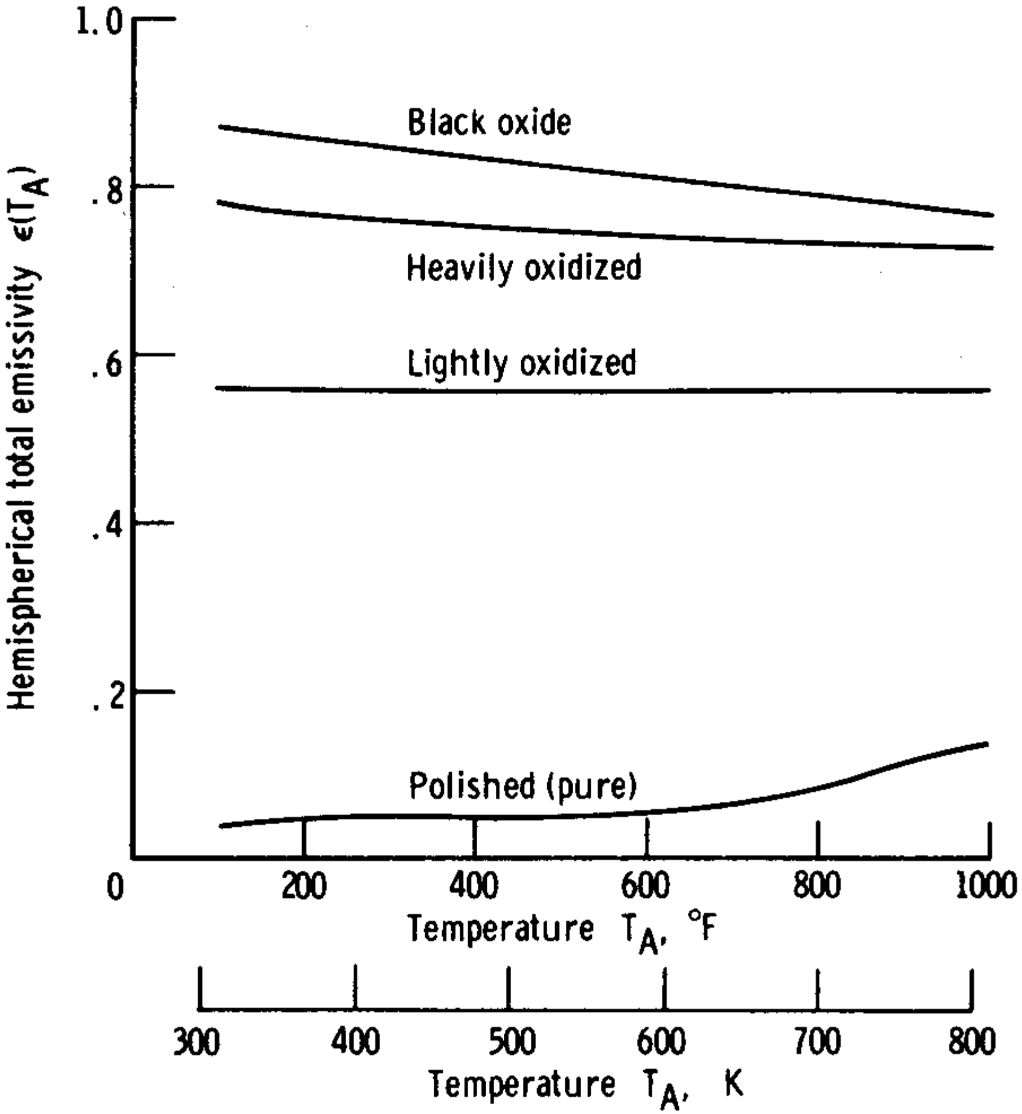
Effect of oxide layer on directional spectral emissivity of titanium. Emission angle, $\theta = 25°$; surface lapped to $0.05\ \mu m$ rms; temperature, 294 K.



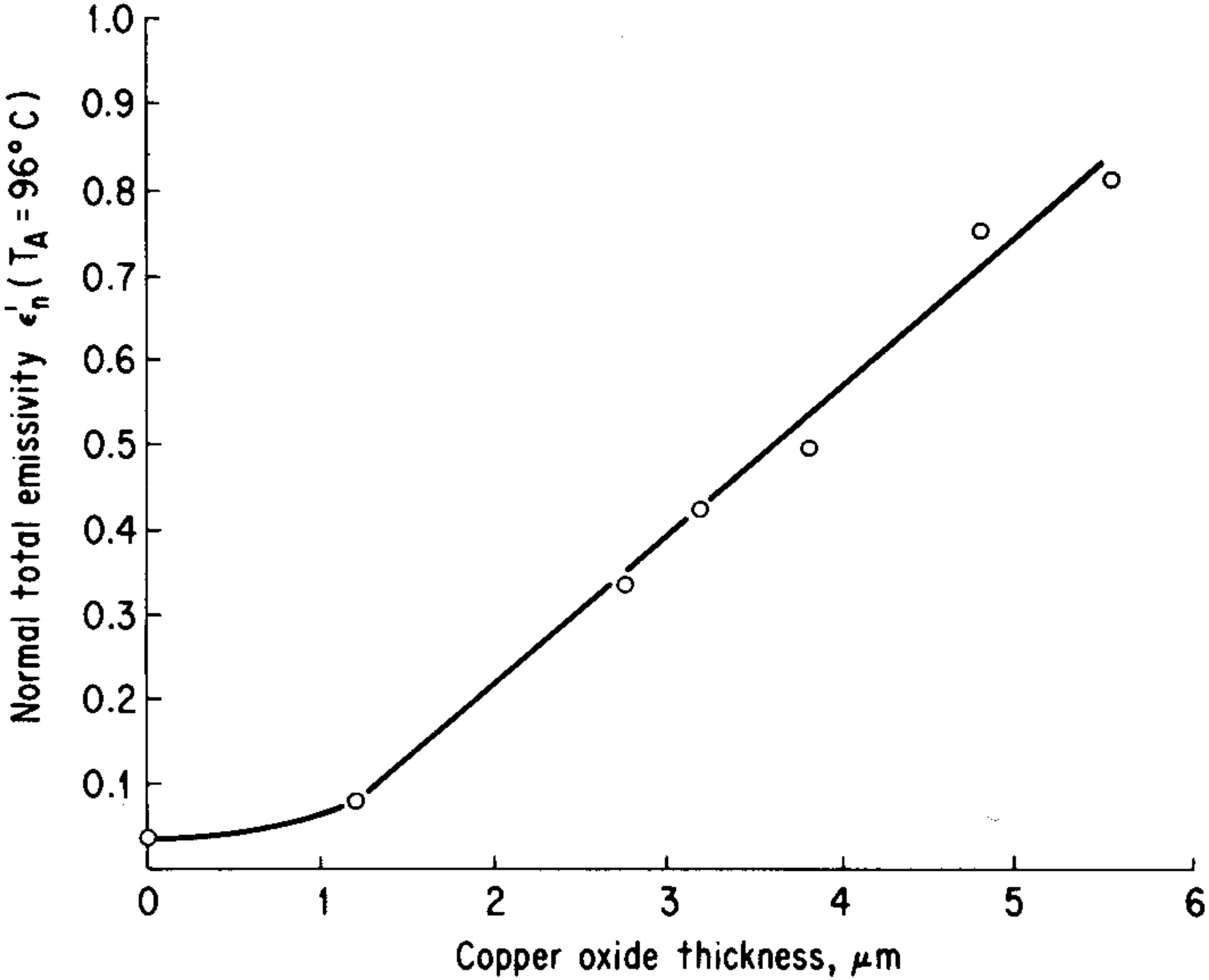
Effect of oxidation on normal spectral emissivity of Inconel X



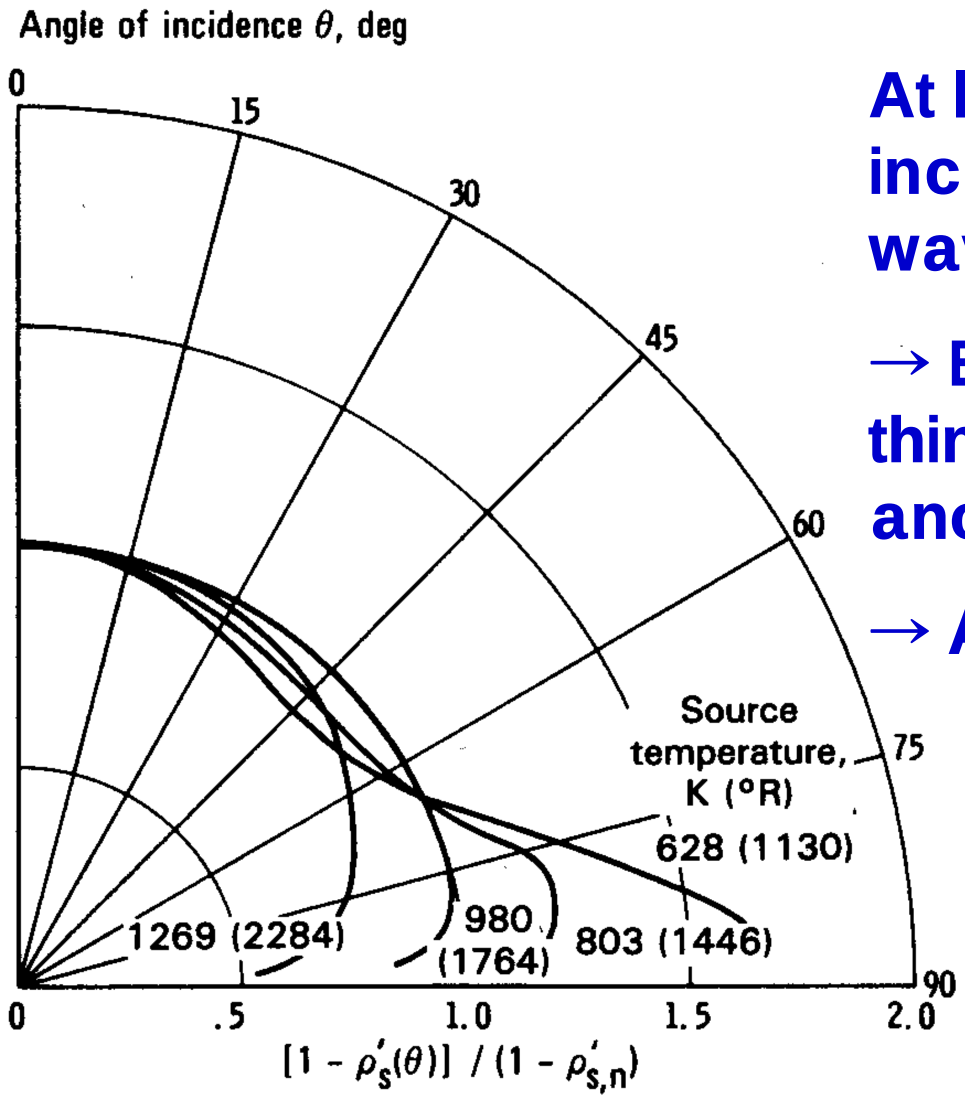
Effect of surface condition and oxidation on normal total emissivity of stainless steel type 18-8



Effect of oxide coating on hemispherical total emissivity of copper



Effect of oxide thickness on normal total emissivity of copper at 369 K

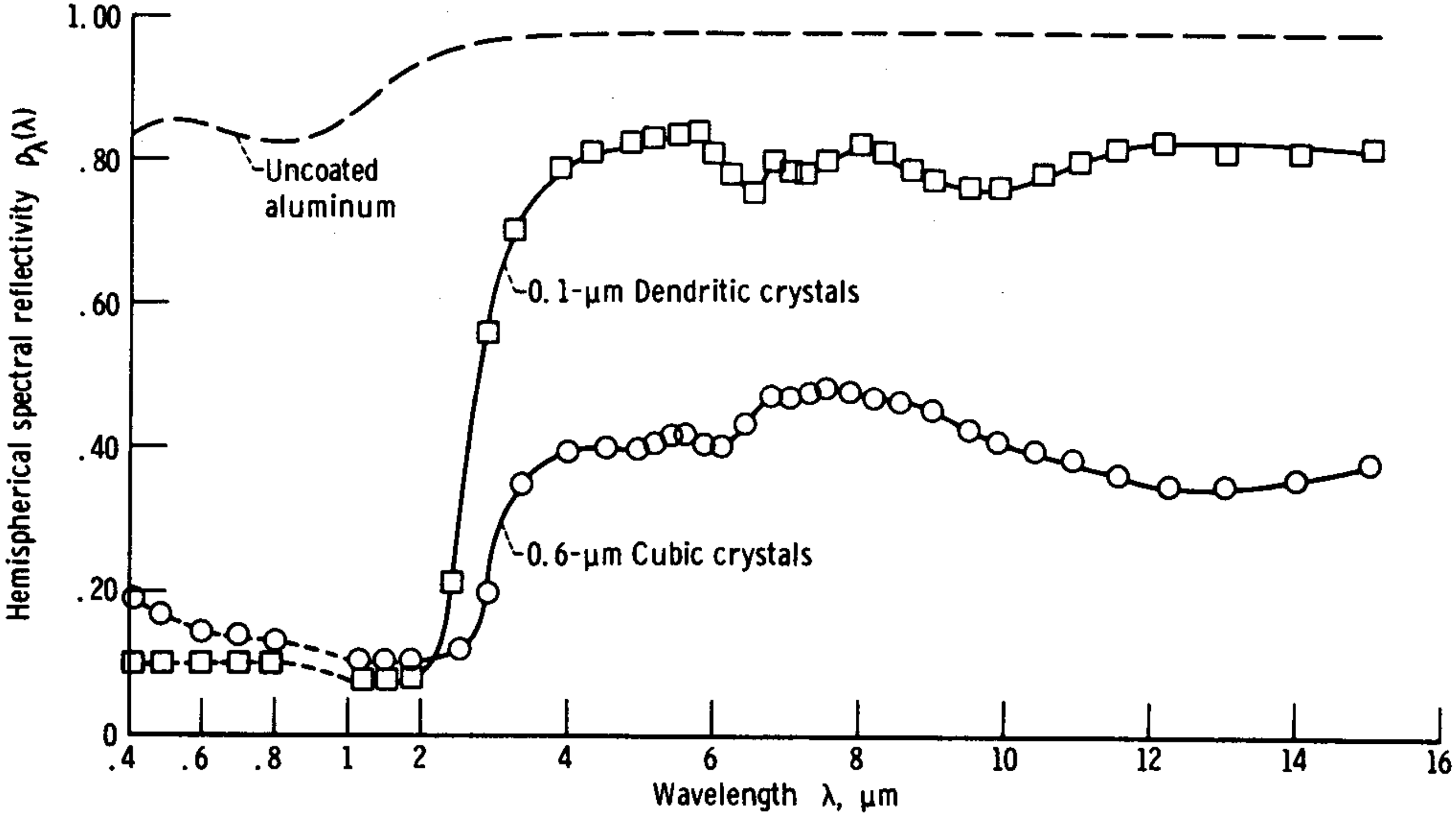


At low source temperature, incident radiation in long wavelength region

→ Barely influenced by the thin oxide layer on the anodized surface

→ Acts like a bare metal

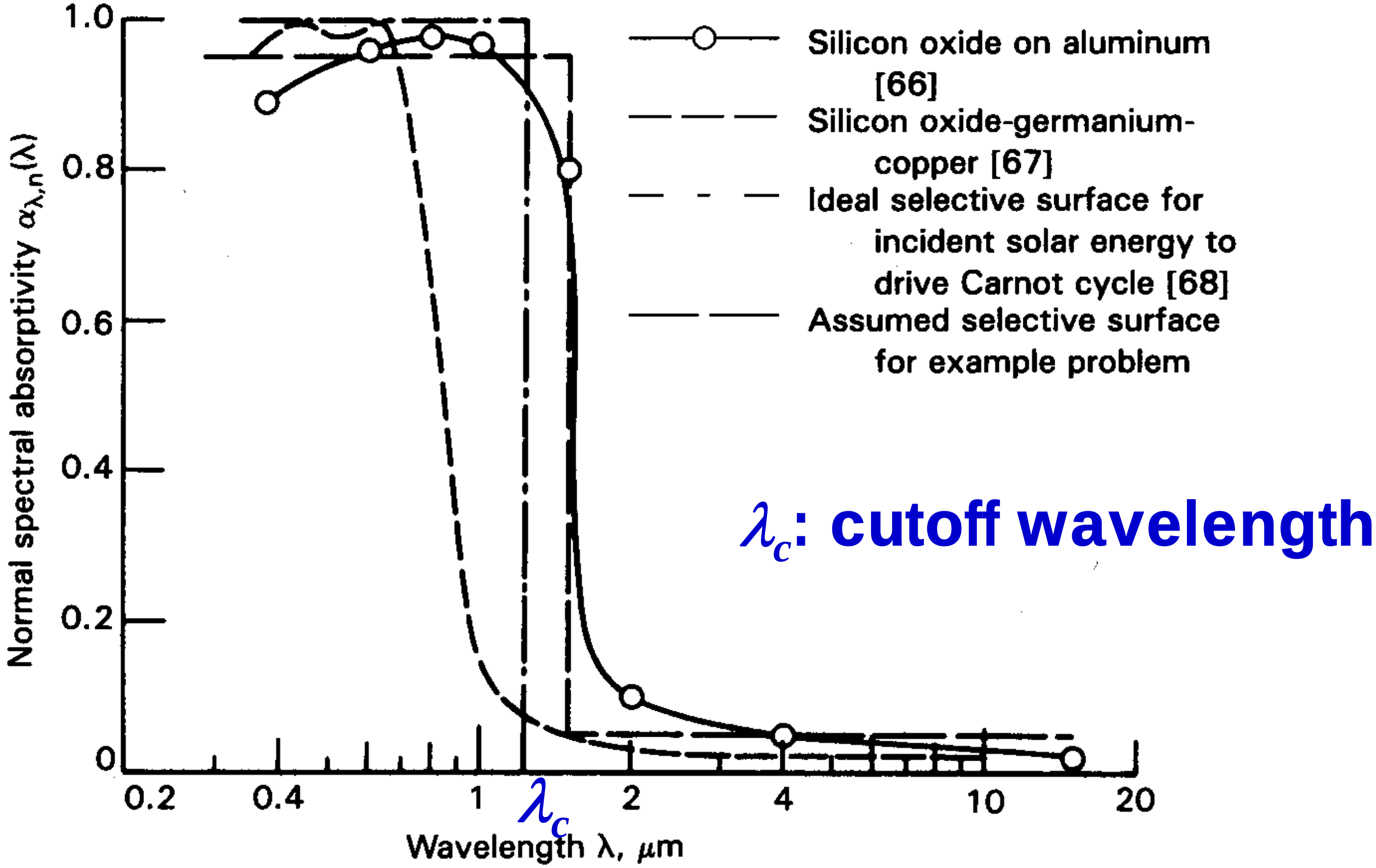
Approximate directional total absorptivity of anodized aluminum at room temperature relative to value for normal incidence



Hemispherical spectral reflectivity for normal incident beam on aluminum coated with lead sulfide. Coating mass per unit surface area, 0.68 mg/cm^2

Selective and Directional Opaque Surfaces

Modification of Surface Spectral Characteristics

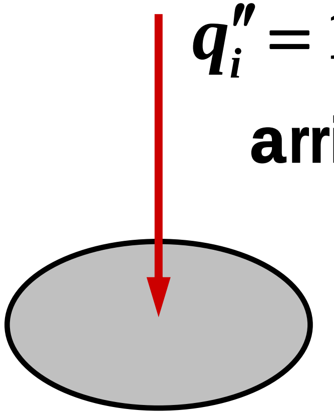


Characteristics of some spectrally selective surfaces

Ex 5-1

$q''_i = 1353\ \text{W/m}^2$

arriving from the sun at T_s = 5780 K



$T_{eq} = ?$

An ideal selective surface with a cutoff wavelength $\lambda_c = 1\ \mu\text{m}$

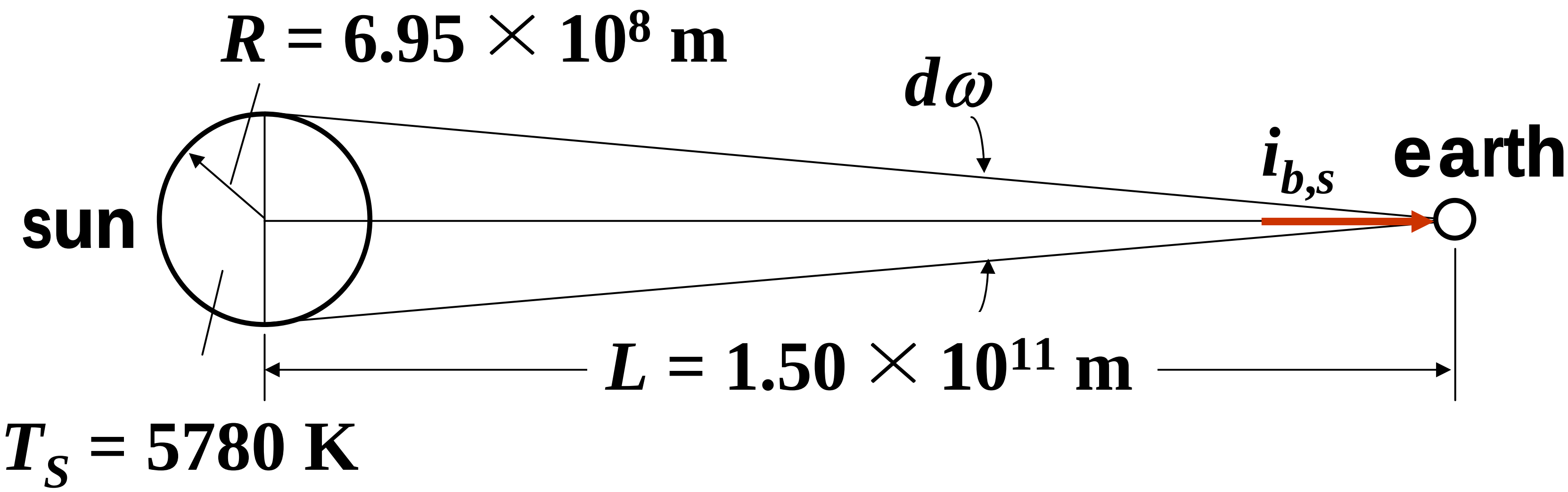
$$\alpha_\lambda = 1\ (0 \le \lambda < \lambda_c), \quad \alpha_\lambda = 0\ (\lambda \ge \lambda_c)$$

Energy balance

$$\dot{E}_{in} - \dot{E}_{out} + \cancel{\dot{E}_g} = \cancel{\dot{E}_{st}} \rightarrow \dot{E}_{in} = \dot{E}_{out}$$

$\dot{E}_{in}$ **: absorbed energy**

$\dot{E}_{out}$**: emitted energy**

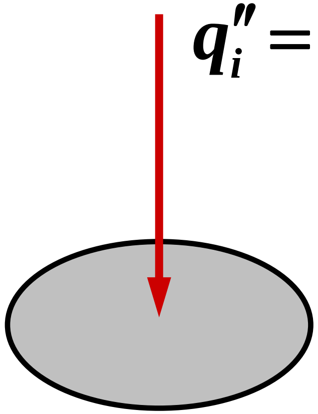


$$S_c = i_{b,s} \cos\theta \, d\omega = \frac{\sigma T_S^4}{\pi} \frac{\pi R^2}{L^2} \quad (\cos\theta \approx 1)$$

$$= \frac{5.67 \times (57.8)^4 (6.95)^2 \times 10^{16}}{(1.5)^2 \times 10^{22}} = 1358 \text{ W/m}^2$$

$q_i'' = 1353 \text{ W/m}^2$

arriving from the sun at T_s = 5780 K



An ideal selective surface with a cutoff wavelength λ_c = 1 μm

$T_{\mathrm{eq}} = ?$

$$q_i'' = \int_0^\infty \int_\cap C i_{\lambda b}(T_s) \cos\theta \, d\omega \, d\lambda = C\sigma T_s^4 = 1353 \text{ W/m}^2$$

$$\left[\sigma T_s^4 = 5.67 \times (57.8)^4 = 63,284,000 \text{ W/m}^2\right]$$

$$\dot{E}_{\mathrm{in}} = \int_0^\infty \int_\cap \alpha_\lambda'(T_{eq}) C i_{\lambda b}(T_s) \cos\theta \, d\omega \, d\lambda$$

$$= \int_0^\infty C i_{\lambda b}(T_s) \left[\int_\cap \alpha_\lambda'(T_{eq}) \cos\theta \, d\omega\right] d\lambda$$

$$\dot{E}_{\text{in}} = \int_0^\infty C i_{\lambda b}(T_s)\left[\int_\cap \alpha'_\lambda(T_{eq})\cos\theta d\omega\right] d\lambda$$

For diffuse irradiation

$$\alpha_\lambda = \frac{\int_\cap \alpha'_\lambda i_{\lambda,i}\cos\theta_i d\omega_i}{\int_\cap i_{\lambda,i}\cos\theta_i d\omega_i} \rightarrow \int_\cap \alpha'_\lambda(T_{\text{eq}})\cos\theta d\omega = \pi\alpha_\lambda$$

$$\dot{E}_{\text{in}} = \int_0^\infty C\pi\alpha_\lambda(T_{eq}) i_{\lambda b}(T_s) d\lambda$$

$$= C\int_0^\infty \alpha_\lambda(T_{eq}) e_{\lambda b}(T_s) d\lambda = C\int_0^{\lambda_c} e_{\lambda b}(T_s) d\lambda$$

$$= C\sigma T_s^4 \int_0^{\lambda_c} \frac{e_{\lambda b}(T_s)}{\sigma T_s^4} d\lambda = q''_i F_{0-\lambda_c T_s}$$

$$\dot{E}_{out} = \int_0^\infty \int_\cap \varepsilon'_\lambda(T_{eq}) i_{\lambda b}(T_{eq}) \cos\theta \, d\omega \, d\lambda$$

$$= \int_0^\infty i_{\lambda b}(T_{eq}) \left[\int_\cap \varepsilon'_\lambda(T_{eq}) \cos\theta \, d\omega \right] d\lambda$$

$$= \int_0^\infty \pi i_{\lambda b}(T_{eq}) \left[\frac{1}{\pi} \int_\cap \varepsilon'_\lambda(T_{eq}) \cos\theta \, d\omega \right] d\lambda$$

$$= \int_0^\infty \varepsilon_\lambda(T_{eq}) e_{\lambda b}(T_{eq}) \, d\lambda$$

For diffuse irradiation $\alpha_\lambda(T_{eq}) = \varepsilon_\lambda(T_{eq})$

$$\dot{E}_{out} = \int_0^{\lambda_c} e_{\lambda b}(T_{eq}) \, d\lambda = \sigma T_{eq}^4 F_{0-\lambda_c T_{eq}}$$

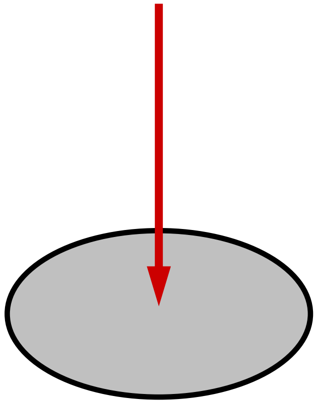
$$\sigma T_{eq}^4 F_{0-\lambda_c T_{eq}} = q''_i F_{0-\lambda_c T_s} \quad \text{or} \quad T_{eq}^4 F_{0-\lambda_c T_{eq}} = \frac{q''_i F_{0-\lambda_c T_s}}{\sigma}$$

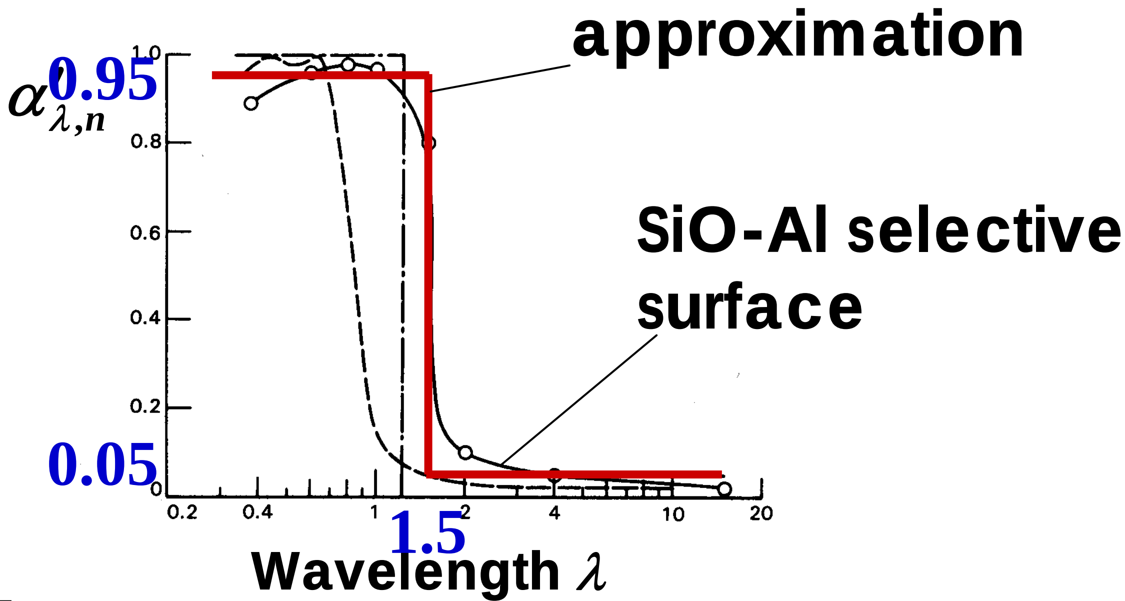
By trial and error $T_{eq} = 1334$ K

Cutoff wavelength λ_c, μm	Equilibrium temperature T_{eq}, K
0.6	1811
0.8	1523
1.0	1334
1.2	1210
1.5	1041
∞	393

Ex 5-3

$$q_i'' = 1353 \text{ W/m}^2$$





Solar energy absorber

at $T_A = 393$ K

1. **extracted energy for use in a power-generating cycle $q_p'' = ?$**

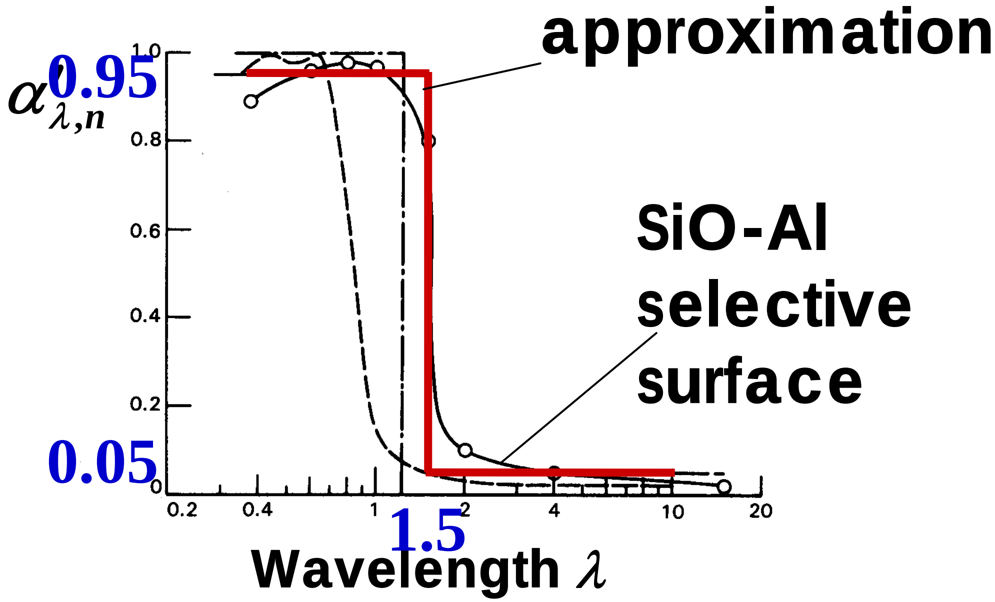
2. **q_p'' for the black surface at the same temperature**

Energy balance

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} + \dot{E}_{\text{g}} = \dot{E}_{\text{st}}$$

$$\dot{E}_{\text{in}} = q''_a, \qquad \dot{E}_{\text{out}} = q''_e + q''_p$$

$$q''_p = q''_a - q''_e$$



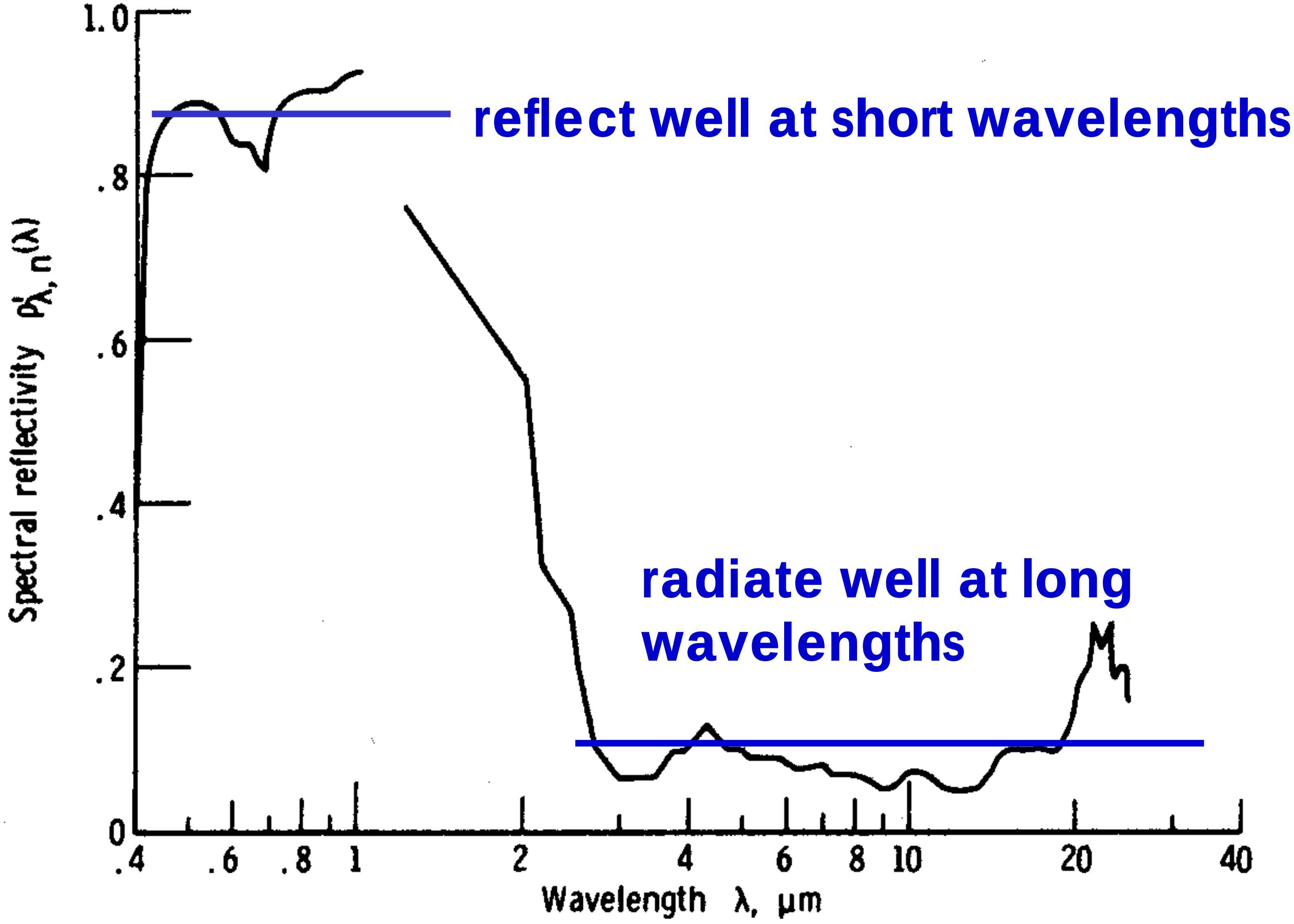
$$q''_a = q''_i\left[0.95F_{0-\lambda_c T_s} + 0.05\left(1 - F_{0-\lambda_c T_s}\right)\right] = 1139\ \mathrm{W/m^2}$$

$$q''_e = \sigma T_A^4\left[0.95F_{0-\lambda_c T_A} + 0.05\left(1 - F_{0-\lambda_c T_A}\right)\right] = 67.63\ \mathrm{W/m^2}$$

$$q''_p = 1139 - 68 = 1071\ \mathrm{W/m^2} \quad (79\%\ \text{of}\ q''_i)$$

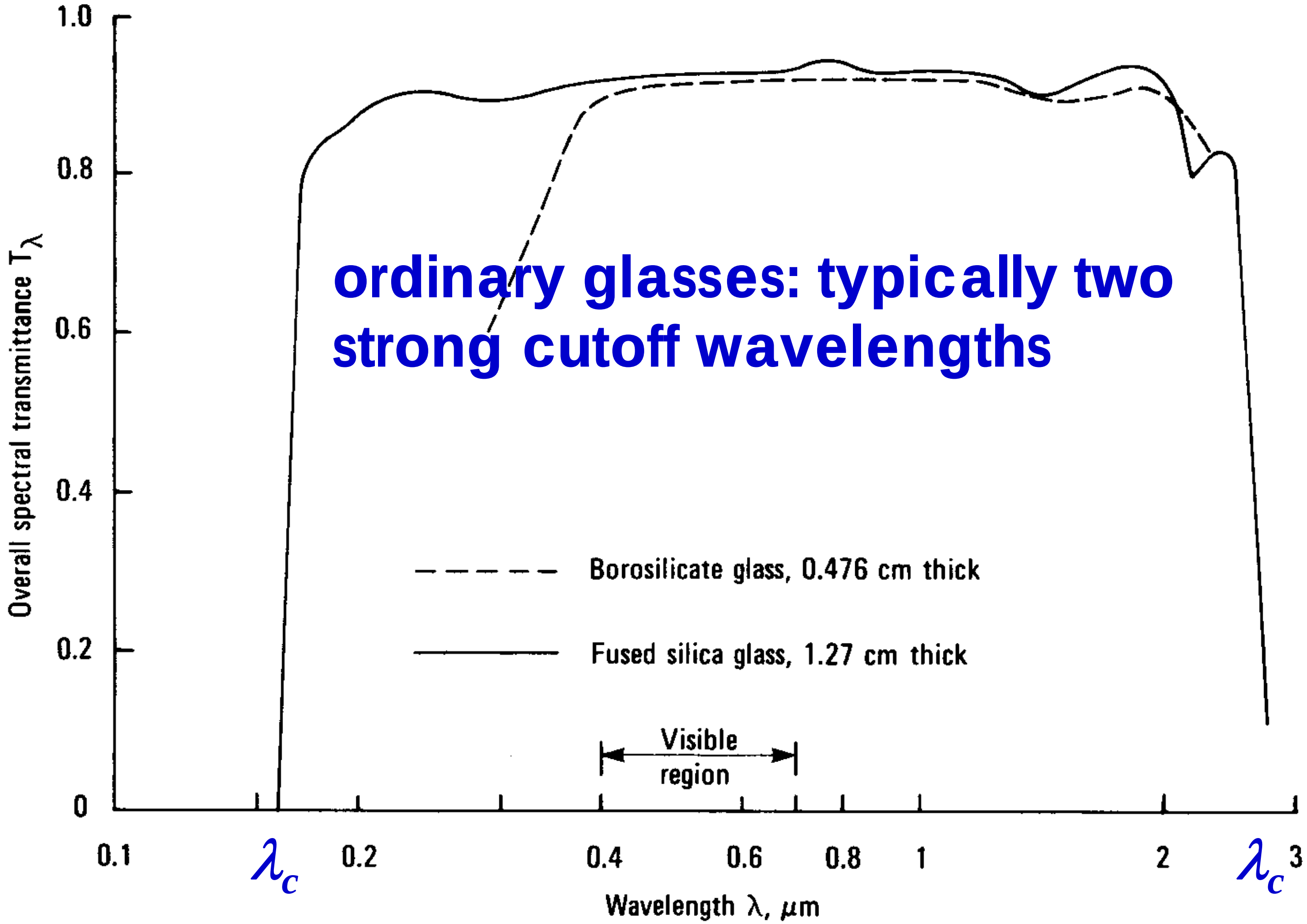
For black surface $q''_e = \sigma T_A^4 = 1353\ \mathrm{W/m^2} = q''_i$

No energy available



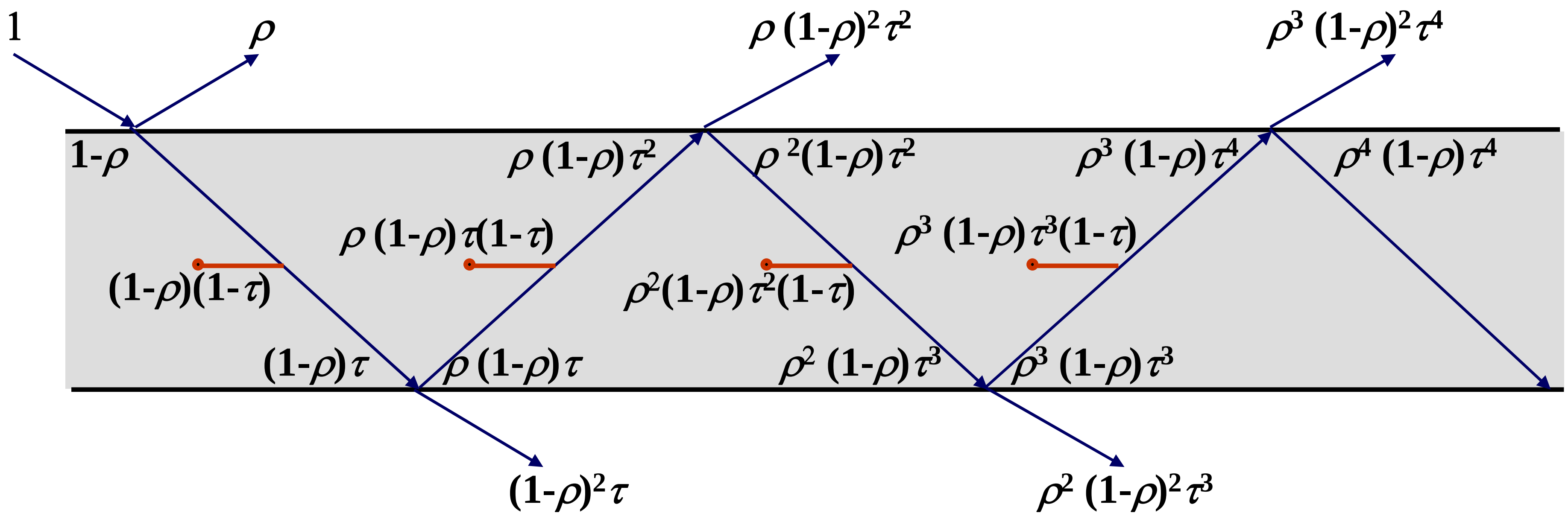
Reflectivity of white paint coating on aluminum

Selective Transmission



Normal overall spectral transmittance of glass plate (includes surface reflection) at 298 K

A transmitting Layer with Thickness $L > \lambda$



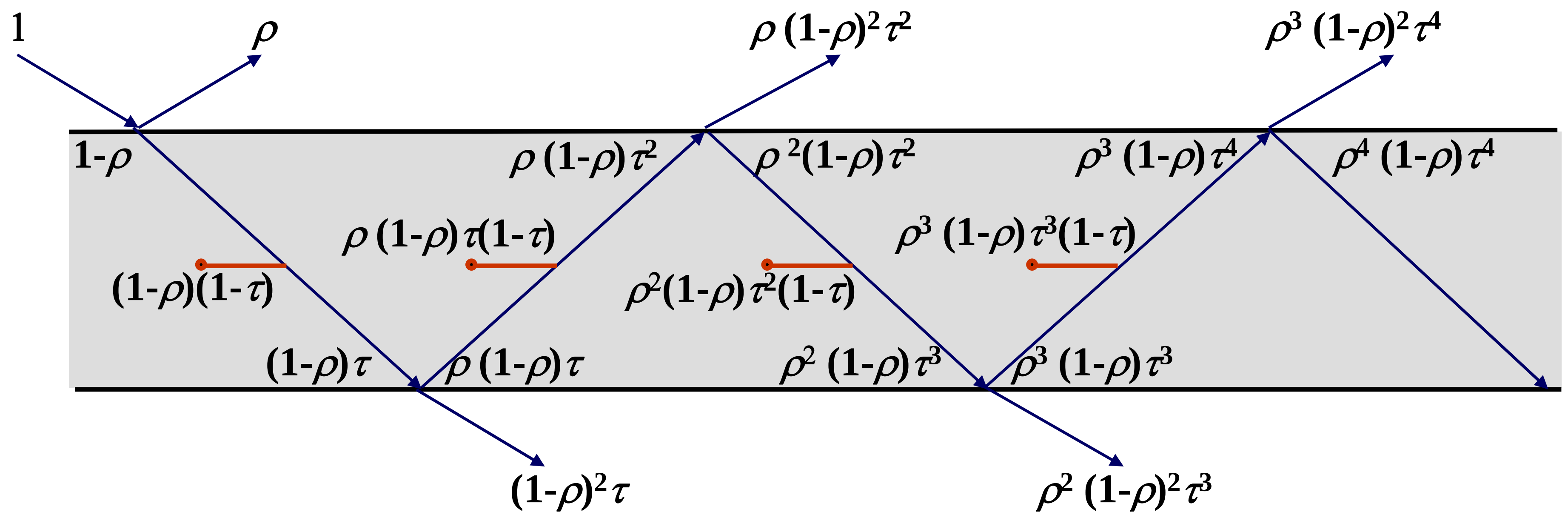
Reflectance

$$R = \rho\left[1+(1-\rho)^2\tau^2\left(1+\rho^2\tau^2+\rho^4\tau^4+\cdots\right)\right]$$

$$= \rho\left[1+(1-\rho)^2\tau^2\left(\frac{1}{1-\rho^2\tau^2}\right)\right] = \rho\left[1+\frac{(1-\rho)^2\tau^2}{1-\rho^2\tau^2}\right]$$

Transmittance

$$T = \tau(1-\rho)^2\left(1+\rho^2\tau^2+\rho^4\tau^4+\cdots\right) = \frac{\tau(1-\rho)^2}{1-\rho^2\tau^2}$$



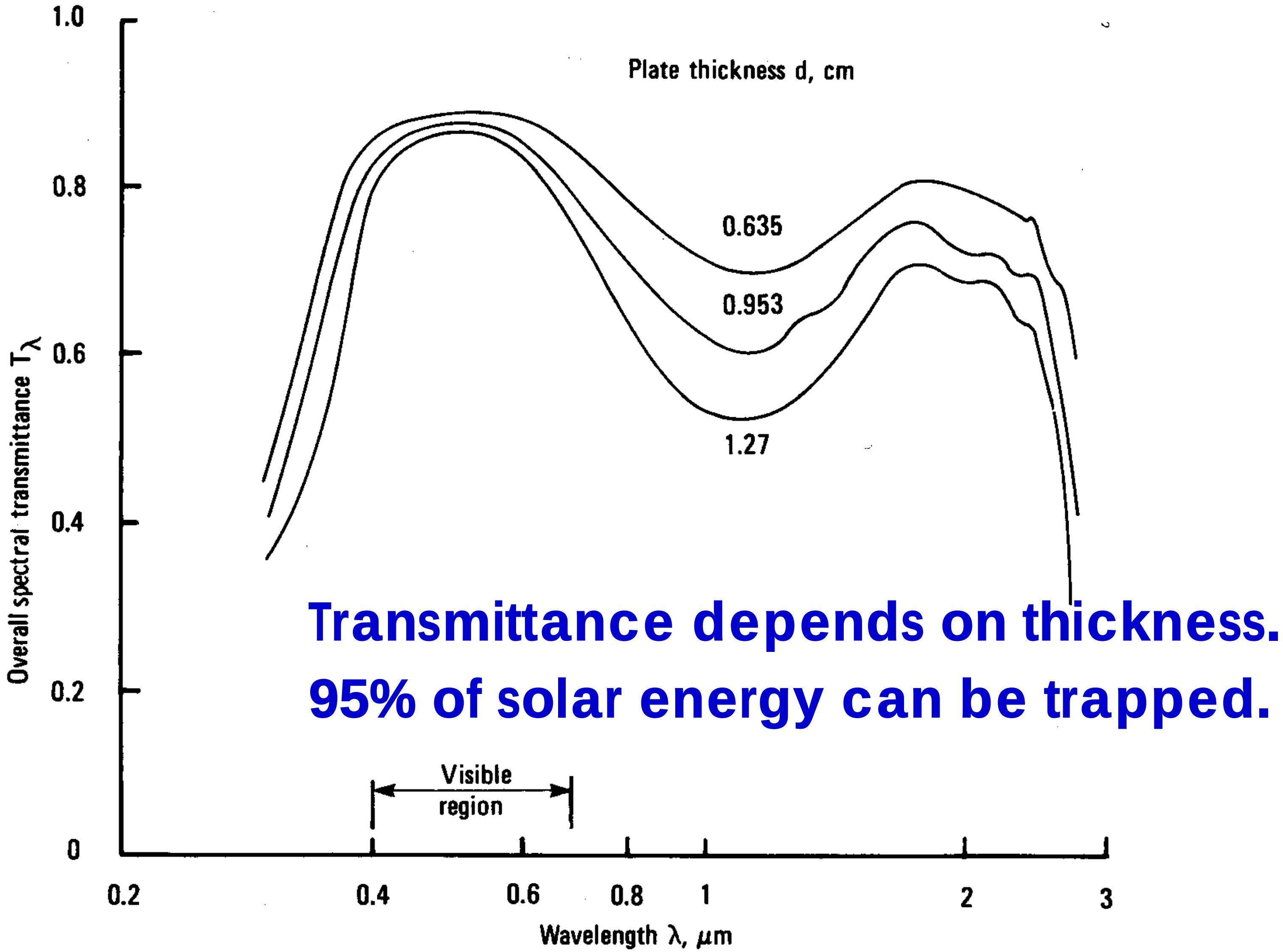
Absorptance

$$A=(1-\rho)(1-\tau)\left(1+\rho\tau+\rho^2\tau^2+\rho^3\tau^3+\cdots\right)=\frac{(1-\rho)(1-\tau)}{1-\rho\tau}$$

$$R+T+A=1$$

spectral transmittance $T_\lambda=\dfrac{\tau_\lambda(1-\rho_\lambda)^2}{1-\rho_\lambda^2\tau_\lambda^2}=\dfrac{G_{\lambda,\mathrm{tr}}}{G_\lambda},\ G_{\lambda,\mathrm{tr}}=T_\lambda G_\lambda$

total transmittance $T=\dfrac{\int_0^\infty G_{\lambda,\mathrm{tr}}d\lambda}{\int_0^\infty G_\lambda d\lambda}=\dfrac{\int_0^\infty T_\lambda G_\lambda d\lambda}{G}=\dfrac{\int_0^\infty \dfrac{\tau_\lambda(1-\rho_\lambda)^2}{1-\rho_\lambda^2\tau_\lambda^2}G_\lambda d\lambda}{G}$

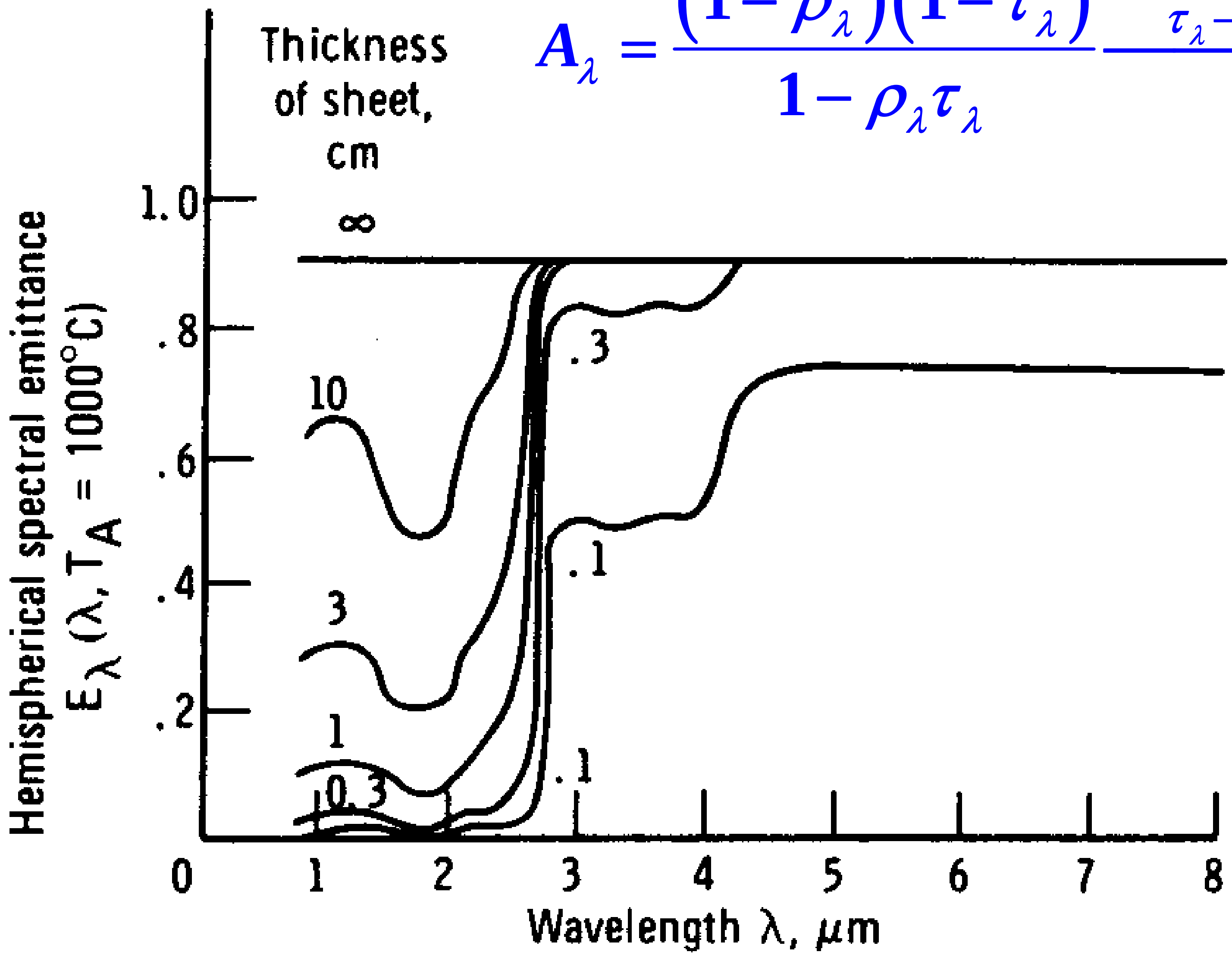


Transmittance depends on thickness.

95% of solar energy can be trapped.

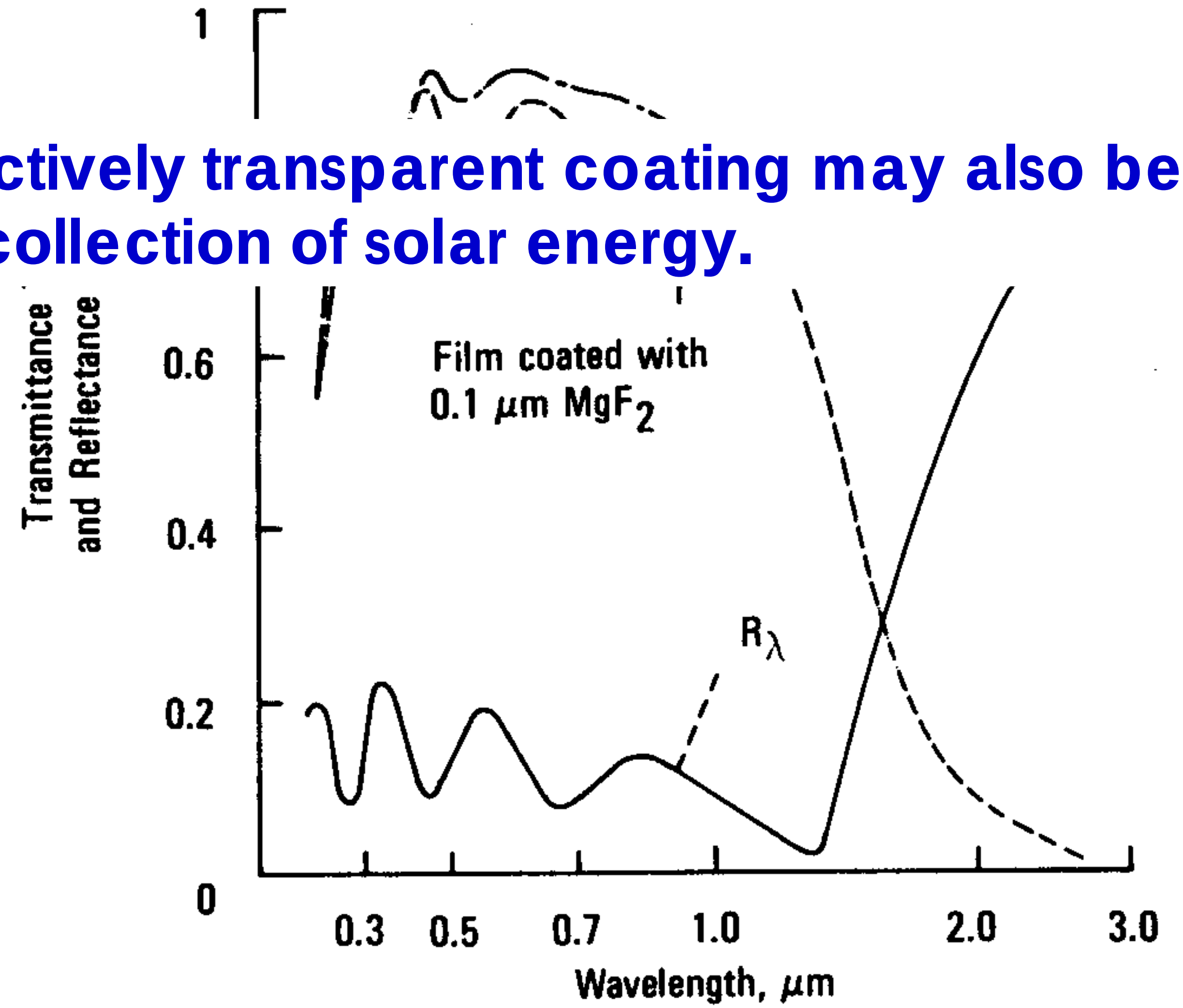
Effect of plate thickness on normal overall spectral transmittance of soda-lime glass (includes surface reflection) at 298 K

$$A_\lambda = \frac{(1-\rho_\lambda)(1-\tau_\lambda)}{1-\rho_\lambda \tau_\lambda} \xrightarrow{\tau_\lambda \to 0} 1-\rho_\lambda$$



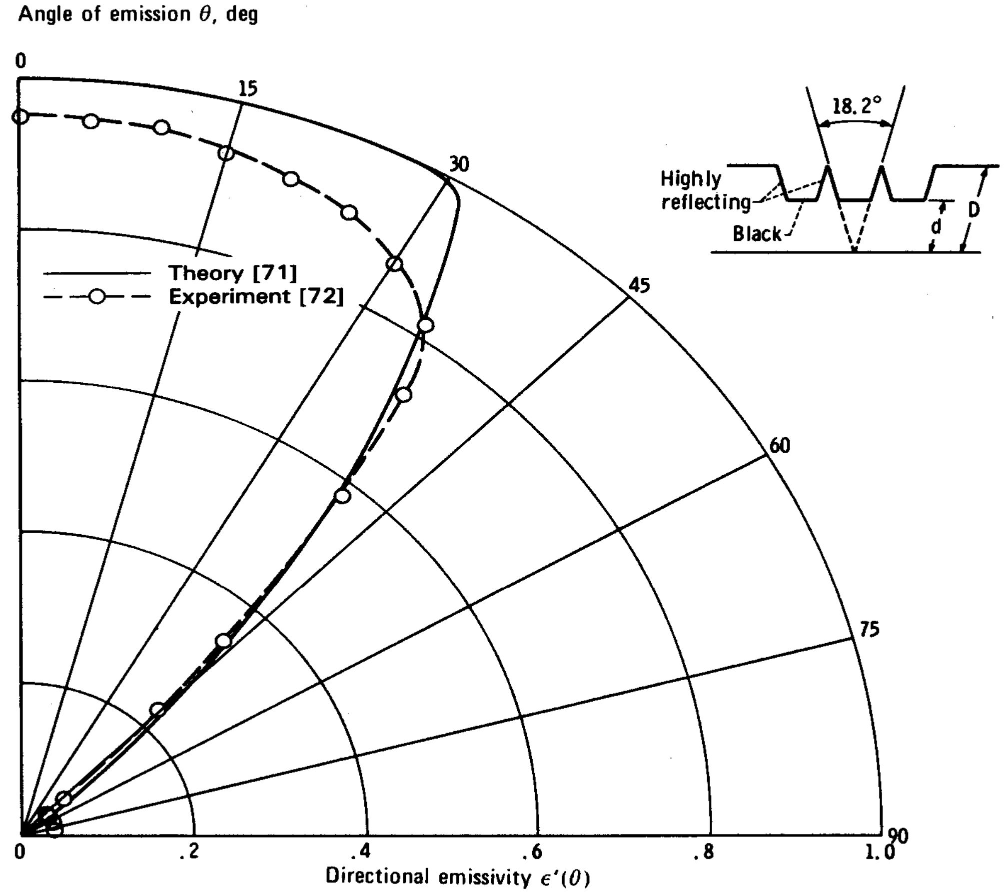
Emittance of sheets of window glass at 1000°C

Selectively transparent coating may also be useful in the collection of solar energy.



Transmittance and reflectance of 0.35-μm-thick film of Sn-doped In_2O_3 film on Corning 7059 glass. Also shown is the effect on T_λ of an antireflection coating of MgF_2

Modification of Surface Directional Characteristics



Directional emissivity of grooved surface with highly reflecting specular side walls and highly absorbing base; $d/D = 0.649$. Results in plane perpendicular to groove direction; data at 8 μm