OPTICAL PYROMETRY – RADIATIVE PROPERTIES

1. BASIC DEFINITIONS
   - Thermal radiation
   - Thermo-radiative properties
   - Optical Pyrometry
2. SOLAR BLIND MEASUREMENTS
   - Principles
   - Studies Exemples
3. TEMPERATURE MEASUREMENTS
   - Apparatus and methods
   - Two colour Pyroreflectometry
   - Studies Exemples

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ABOUT TEMPERATURE

Temperature is a one more measured parameter and most of other are depending …

Temperature is an intensive value

Temperature is a subjectif concept based on cold and hot sensation

Temperature is measured through a temperature scale : IST 90

ITS & THERMODYNAMIC TEMPERATURE

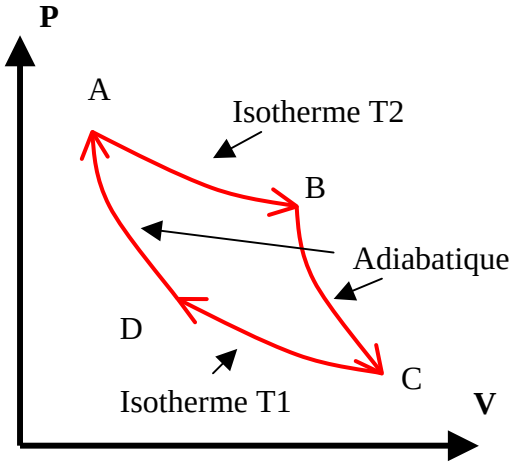
ITS 90

T (K)	Elem.	State	Inst.
.3 à 5	He	V	1 et 2
13.8033	e-H_2	T	2 et 3
17	e-H_2	V	2 et 3
20.3	e-H_2	V	2 et 3
24.5561	Ne	T	2 et 3
54.3584	O_2	T	3
83.8058	Ar	T	3
234.3156	Hg	T	3
273.16	H_2O	T	3
302.9146	Ga	F	3
429.7485	In	C	3
505.078	Sn	C	3
692.677	Zn	C	3
933.473	Al	C	3
1234.93	Ag	C	3 et 4
1337.33	Au	C	4
1357.77	Cu	C	4

°C = K –273.15 K

Sir W. Thomson -> Lord Kelvin 1852
FIRST DEFINITION OF MEASURABLE T

CARNOT CYCLE ON A PERFECT GAS



$$\frac{Q_2}{Q_1} = -\frac{f(T_2)}{f(T_1)}$$

$$f(T) = a\,T$$

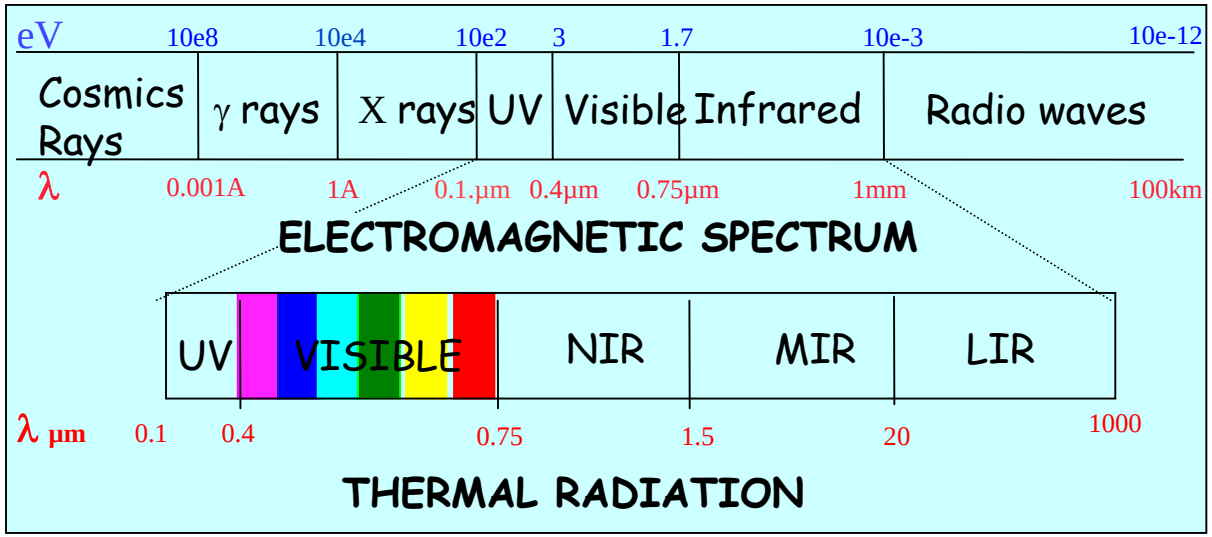
THEORY OF GAS KINETIC

Temperature is linked to molecule or particle movements

V : Pt. of vapor pression F : Fusion 1 : Ther. He vapor pression 2 : Ther. He gas pression
T : Pt. triple C : Freezing 3: Ther. Pt resistance 4 : Optical pyrometry

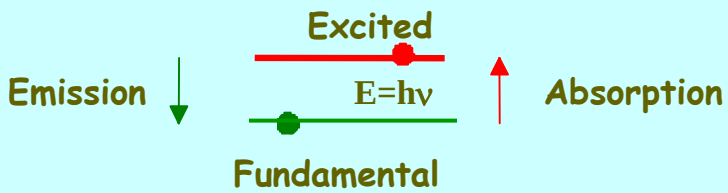
THERMAL RADIATION is ENERGY

Temperature is linked to thermal radiation



Max Planck 1858-1947

Quantum mechanics



- Quantum hν

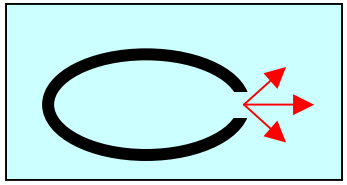
$$I^{O}(T,\lambda) = \left(\frac{C_1}{\pi}\right) \Big/ \left[\lambda^5\left(\exp^{\frac{C_2}{\lambda T}} - 1\right)\right]$$

$C_1 = 2hc^2$ = 3.7415.10^{-16} W.m^2 sr^{-1}

$C_2 = hc/k$ = 1.4388.10^{-2} mK

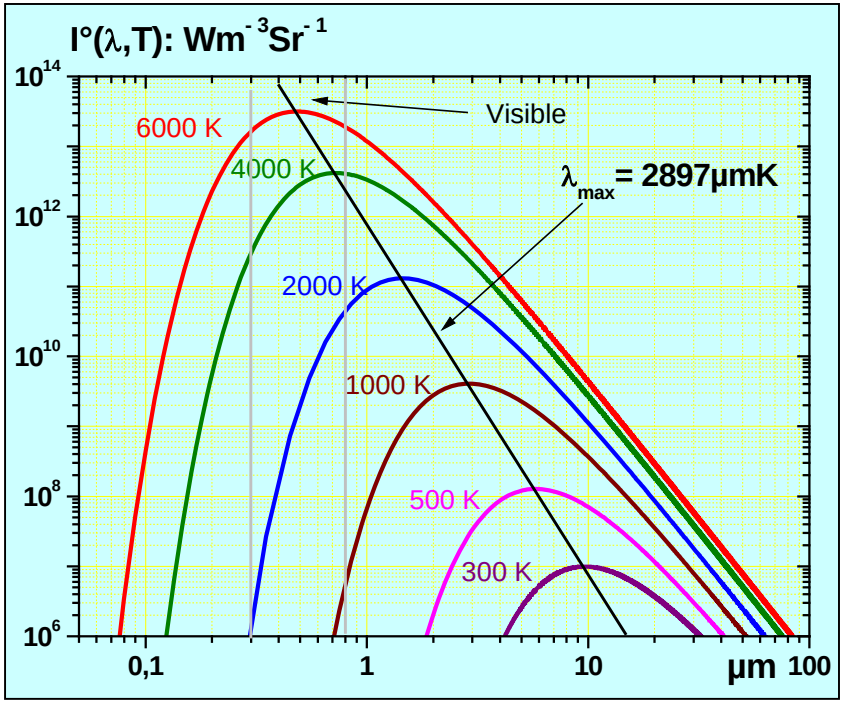
c : Ligth celerity in vacuum
h : Planck constant
k : Boltzmann constant

THERMAL RADIATION and BLACKBODY



The Blackbody is the reference source for Thermal Radiation

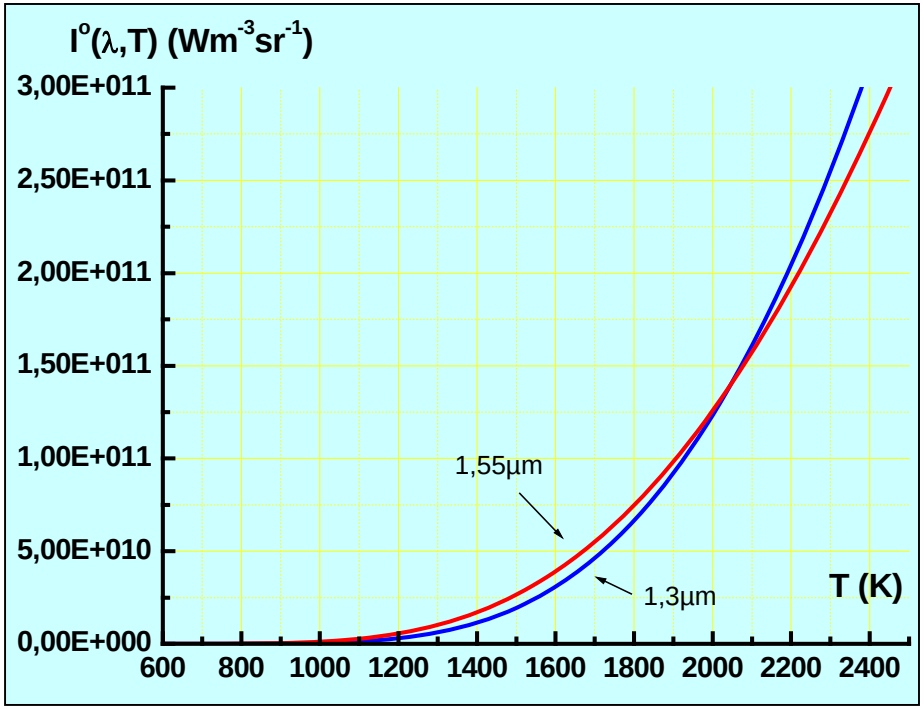
Definition: Total absorption of thermal radiation
Property: Emission follows Planck Law and it is isotropic



Isothermal Planck curves

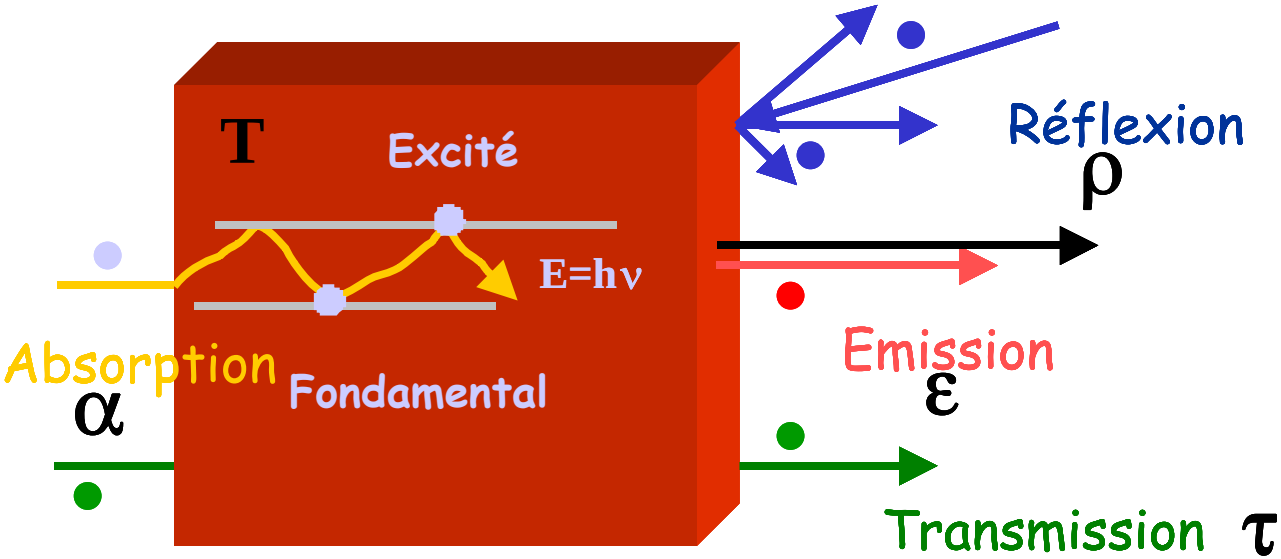
90% of energy emetted between

$$0{,}5\lambda_m < \lambda < 5\lambda_m$$



Isochromatic Planck curves

THERMAL RADIATION AND REAL BODY



Emission

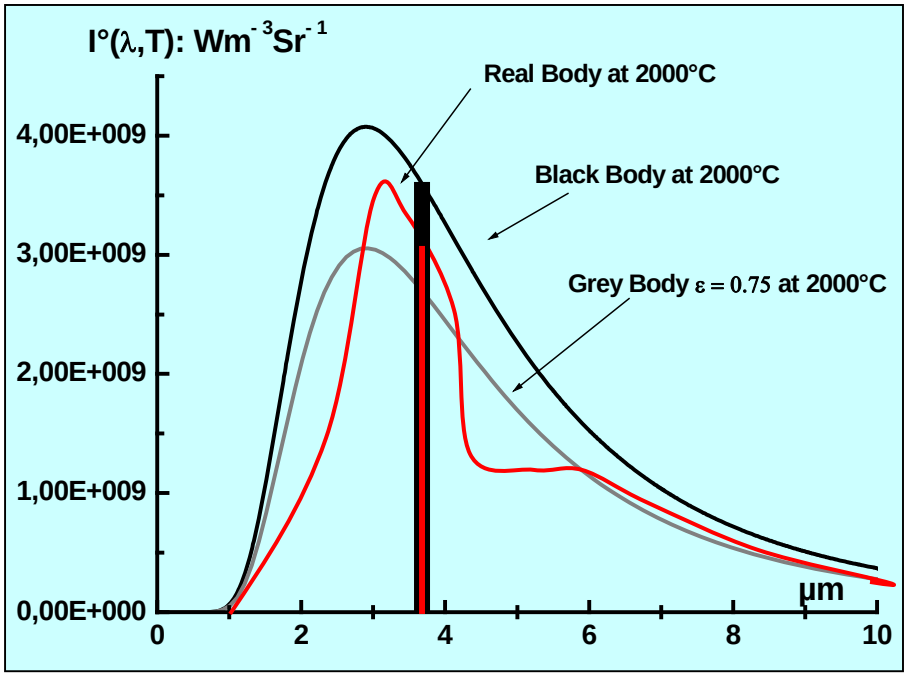
$$I^{\vec{j}} = \varepsilon^{\vec{j}} I^{o}$$

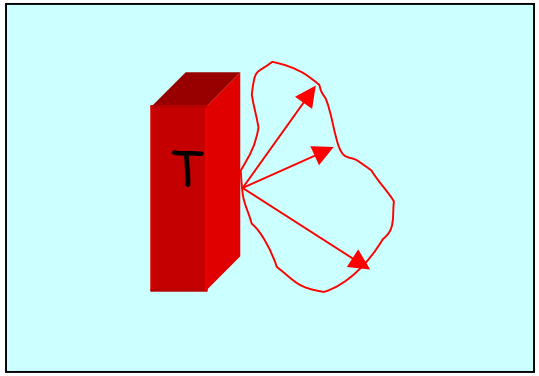
Interaction Material-Thermal Radiation

Energy Conservation

$$\alpha + \rho + \tau = 1$$

EMISSION of REAL BODY





EMISSION AND PROPERTIES

DIRECTIONAL DEPENDENT

$$\varepsilon^{\vec{j}}(T,\lambda)=\frac{I^{\vec{j}}(T,\lambda)}{I^{O}(T,\lambda)}$$

Emissivity <= 1

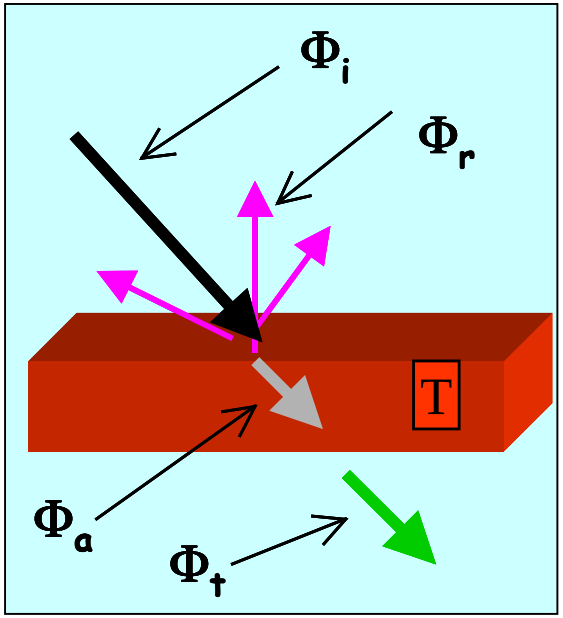
PARTICULAR PROPERTIES

$\varepsilon^{(T,\lambda)}$ isotropic

$\varepsilon^{\vec{j}}(T)$ grey body

INTERTACTION MAT. THER. RADIATION

Radiative Properties

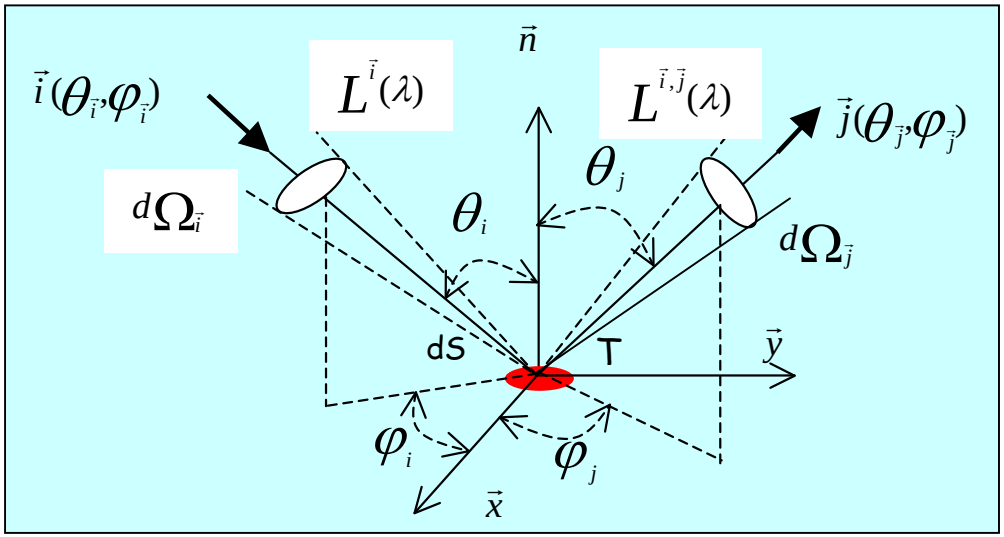


Absorptivity $\alpha^{\vec{j}}(T,\lambda)=\dfrac{d^2\Phi_{a,\lambda}}{d^2\Phi_{i,\lambda}}$

Reflectivity $\rho^{\vec{j},\cap}(T,\lambda)=\dfrac{d^2\Phi_{r,\lambda}}{d^2\Phi_{i,\lambda}}$

Transmitivity $\tau^{\vec{j}}(T,\lambda)=\dfrac{d^2\Phi_{t,\lambda}}{d^2\Phi_{i,\lambda}}$

Particularity of the reflection: directional hemispherical



Bidirectional reflectivity or B.R.D.F.

$$\rho^{\vec{i},\vec{j}}_{F.D.}(T,\lambda)=\frac{I^{\vec{i},\vec{j}}(\lambda)}{I^{\vec{i}}(\lambda)\cos(\theta_i)\,d\Omega_i}$$

$$\rho^{\vec{i},\cap}(T,\lambda)=\int_{\cap}\rho^{\vec{i},\vec{j}}_{F.D.}(T,\lambda)\cos(\theta_j)\,d\Omega_j$$

Sr^{-1}

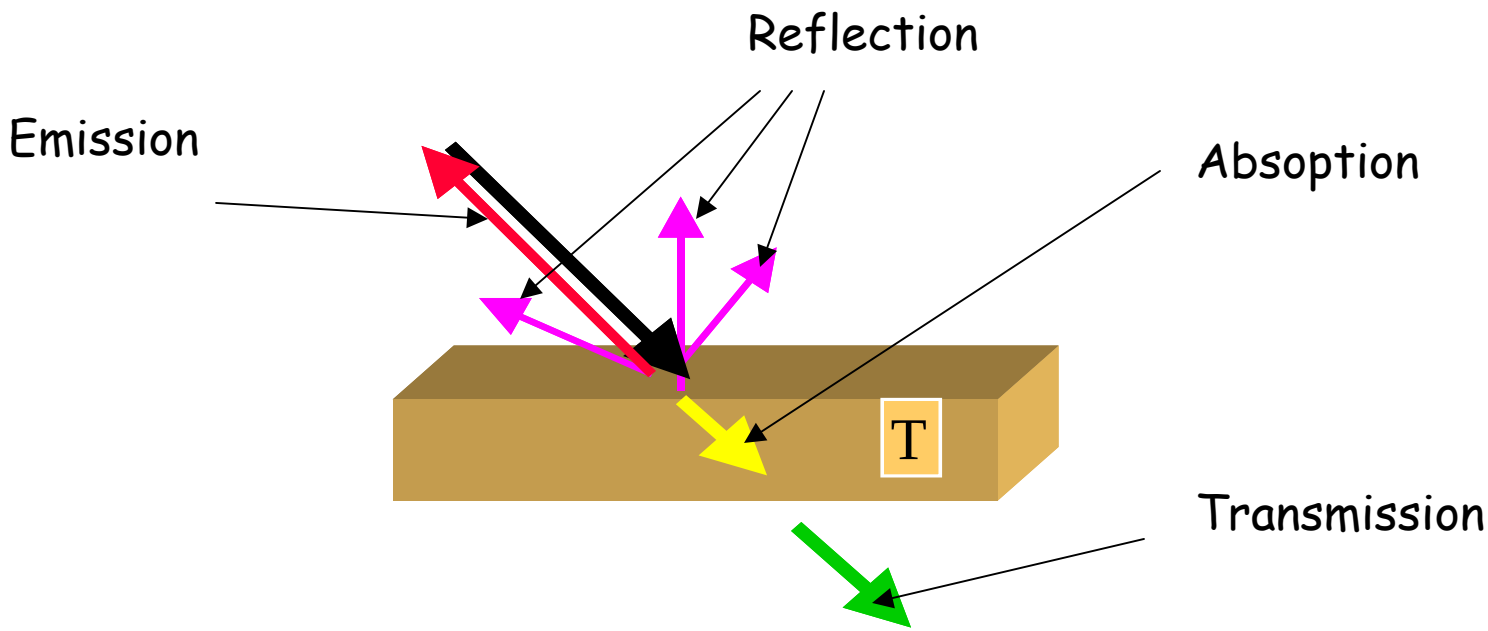
$$\rho^{\vec{i},\cap}(T,\lambda)=\pi\,\rho^{\vec{i},\vec{j}}_{F.D.}(T,\lambda)$$

Isotropic Reflexion

$$\rho^{\vec{i},\vec{j}}_{F.D.}(T,\lambda)\rightarrow+\infty$$

Specular Reflexion

RADIATIVE PROPERTIES RELATIONS



1st Kirchoff Law

$$\alpha^{\vec{j}}(T,\lambda)+\rho^{\vec{j},\cap}(T,\lambda)+\tau^{\vec{j}}(T,\lambda)=1$$

$$\alpha^{\vec{j}}(T,\lambda)+\rho^{\vec{j},\cap}(T,\lambda)=1$$

Opaque Material

2nd Kirchoff or Draper law

$$\alpha^{\vec{j}}(T,\lambda)=\varepsilon^{\vec{j}}(T,\lambda)$$

$$\alpha^{\vec{j}}(T,\lambda)=1-\rho^{\vec{j},\cap}(T,\lambda)$$

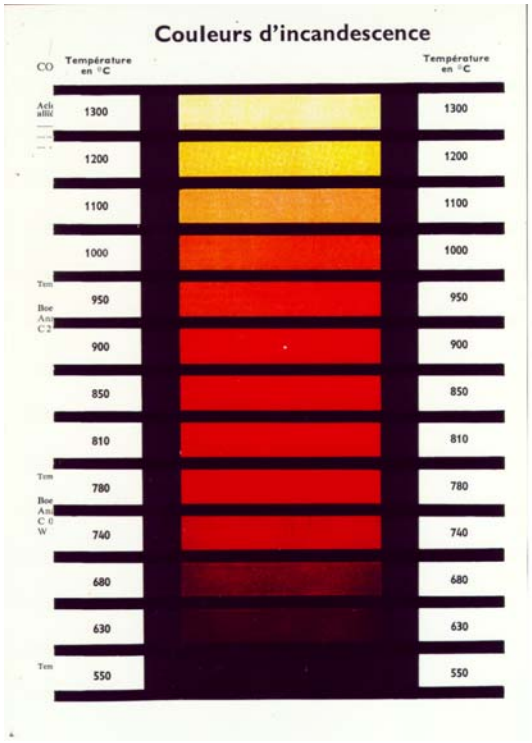
Opaque Material

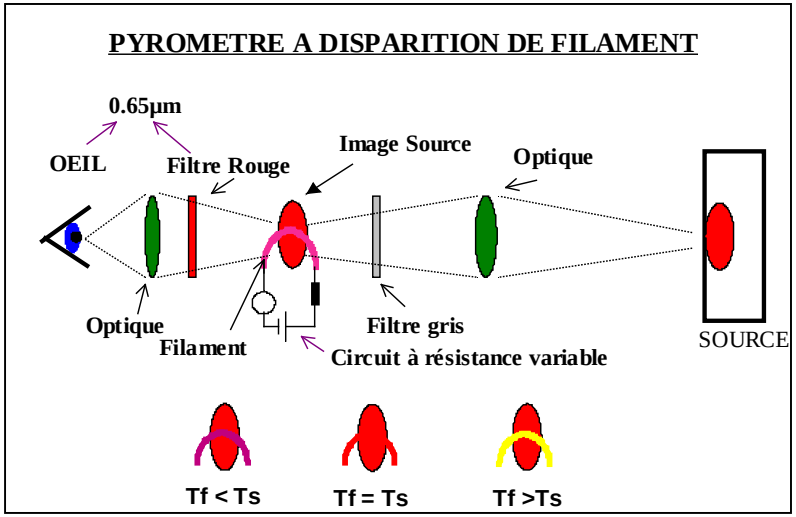
Helmholtz reciprocity

$$\rho_{F.D.}^{\vec{i},\vec{j}}(T,\lambda)=\rho_{F.D.}^{\vec{j},\vec{i}}(T,\lambda)$$

$$\rho^{\vec{i},\cap}(T,\lambda)=\rho^{\cap_{iso},\vec{i}}(T,\lambda)$$

PYROMETRY PRINCIPLE





Calibration

$$S(T,\lambda)=k\,I^{O}(T,\lambda)$$

Measure on a Real Body

$$S^{\vec{j}}(T,\lambda)=k\,I^{\vec{j}}(T,\lambda)=k\,I^{O}(T_{R,\lambda})=k\,\varepsilon^{\vec{j}}(T,\lambda)\,I^{O}(T,\lambda)$$

$$T \geq T_{R,\lambda}$$

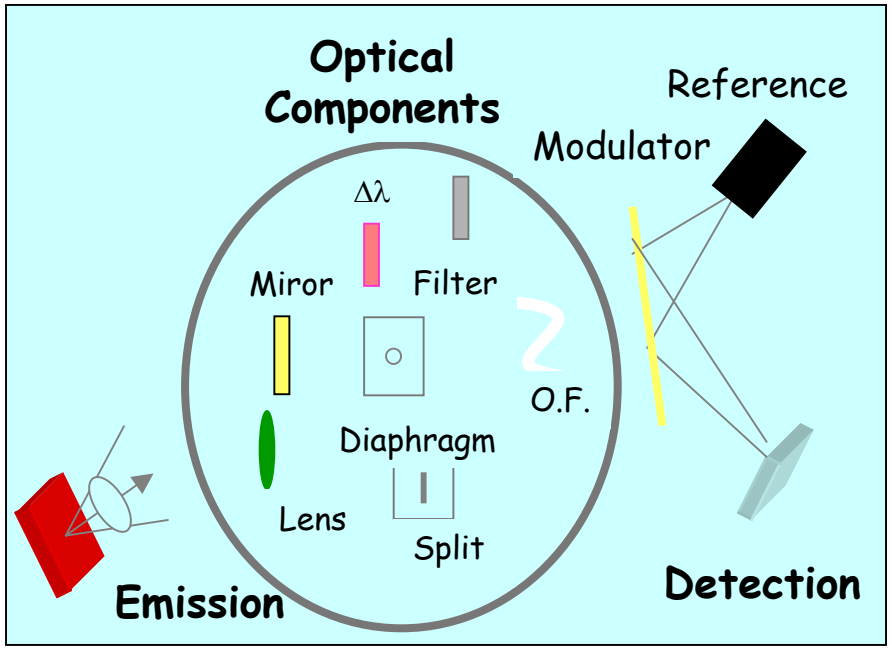
Wien Approximation

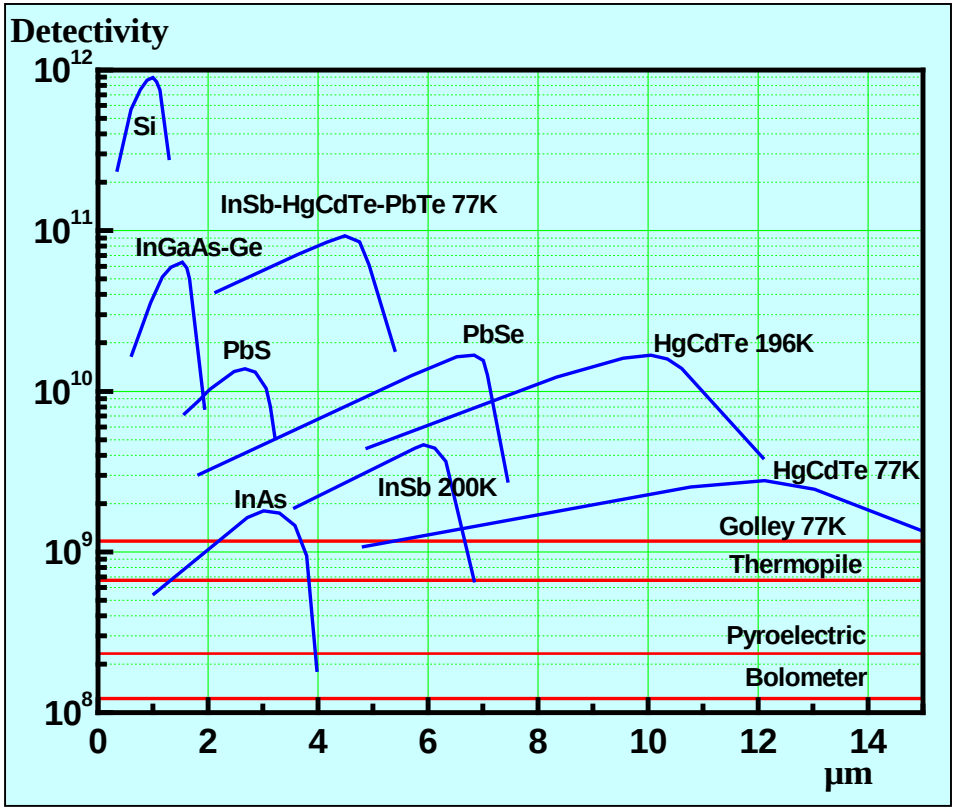
$$L^{O}(T,\lambda)=\left(\frac{C_1}{\pi}\right)\Big/\left[\lambda^{5}\left(\exp^{\frac{C_2}{\lambda T}}\right)\right]$$

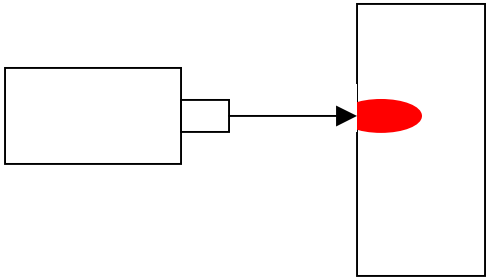
$$\lambda T << 14400\,\mu m K$$

$$\frac{1}{T}=\frac{1}{T_{R,\lambda}}+\frac{\lambda}{C_2}\ln(\varepsilon^{\vec{j}}(T,\lambda))$$

PYROMETER ARCHITECTURE







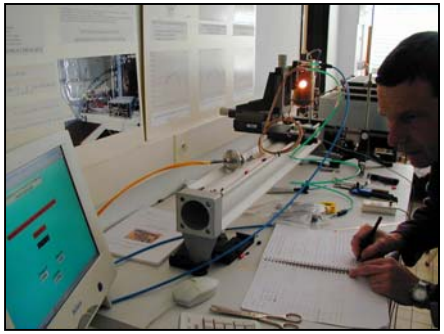
$$S(T,\lambda)=kI^{O}(T,\lambda)$$

$$S^{\vec{j}}(T,\lambda)=kI^{\vec{j}}(T,\lambda)=kI^{O}(T_{R,\lambda})=k\varepsilon^{\vec{j}}(T,\lambda)I^{O}(T,\lambda)$$

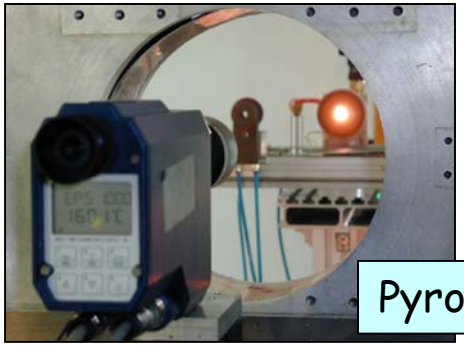
Calibration

$$T \geq T_{R,\lambda}$$

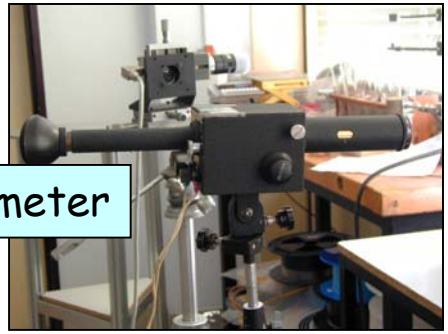
LAB APPARATUS- RADIANCE TEMP.



Blackbodies



Pyrometer



Spectro-radiometer

REALITY OF THE MEASURE

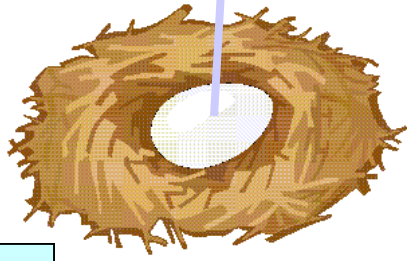
Losses

Emission

Reflection

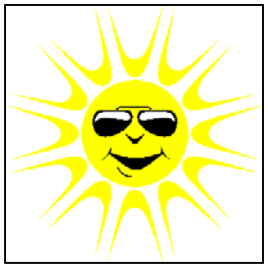
Transmission

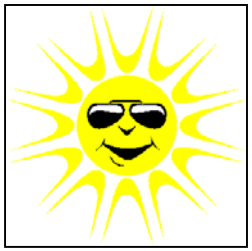
$$S^{\vec{j}}(\lambda,T)=a(\tau^{\vec{j}}_{o.t.}(\lambda))\left[\varepsilon^{\vec{j}}(\lambda,T)I^{o}(\lambda,T)+\iint_{\bigcap_{\vec{i}}}\rho^{\vec{i},\vec{j}}_{F.D.}(\lambda,T)I^{\vec{i}}\,Cos(\theta_i)d\bigcap_{\vec{i}}+\iint_{\bigcap_{\vec{i}}}\tau^{\vec{i}}(\lambda,T)\,I^{\vec{i}}\,d\bigcap_{\vec{i}}\right]$$



?

Dilemma





Hampering

REFLECTED RADIATION HAMPERING

Parabola geometrical parameter

Atmosphera transmission

Reflectance

Sun Intensity

Sun solid angle

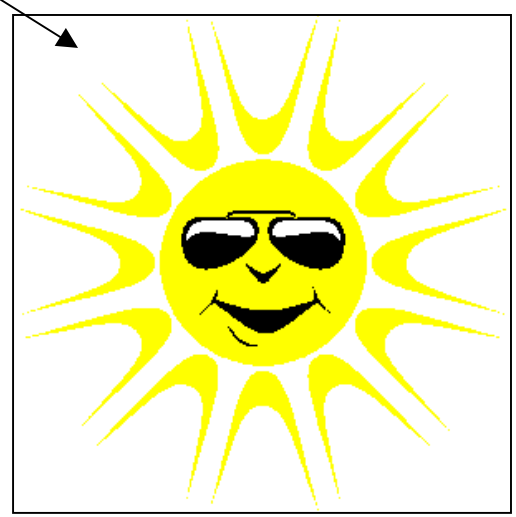
Sample Reflectivity

$$G_p \tau_a(\lambda) R^2(\lambda) C_p(\lambda) I_S(\lambda) \Omega_S \int_{\Omega_p} \rho^{\theta_i, \vec{j}}(T,\lambda,\theta) \cos(\theta_i) d\Omega_p$$

$$G_p = 1 / \left[\pi\left(\sin^2\theta_M - \sin^2\theta_0\right)\right]$$

Concentration

Parabola Solid angle



ANALYSIS AND EXPERIMENTAL RESULTS OF SOLAR-BLIND TEMPERATURE MEASUREMENTS IN SOLAR FURNACES
JSE 2004 Vol 126/645-653

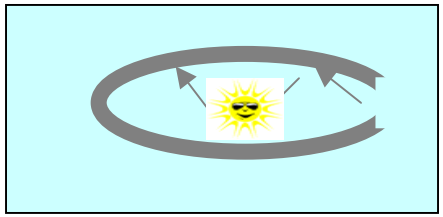
SOLAR BLIND TECHNICS

Chromatic occultation

$\tau_a(\lambda) = 0$ or $\tau_w(\lambda) = 0$

Temporary occultation

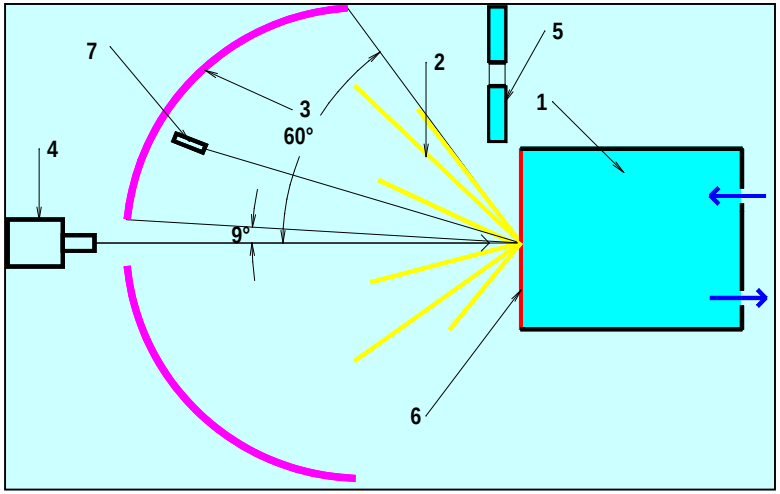
$I_s(\lambda) = 0$

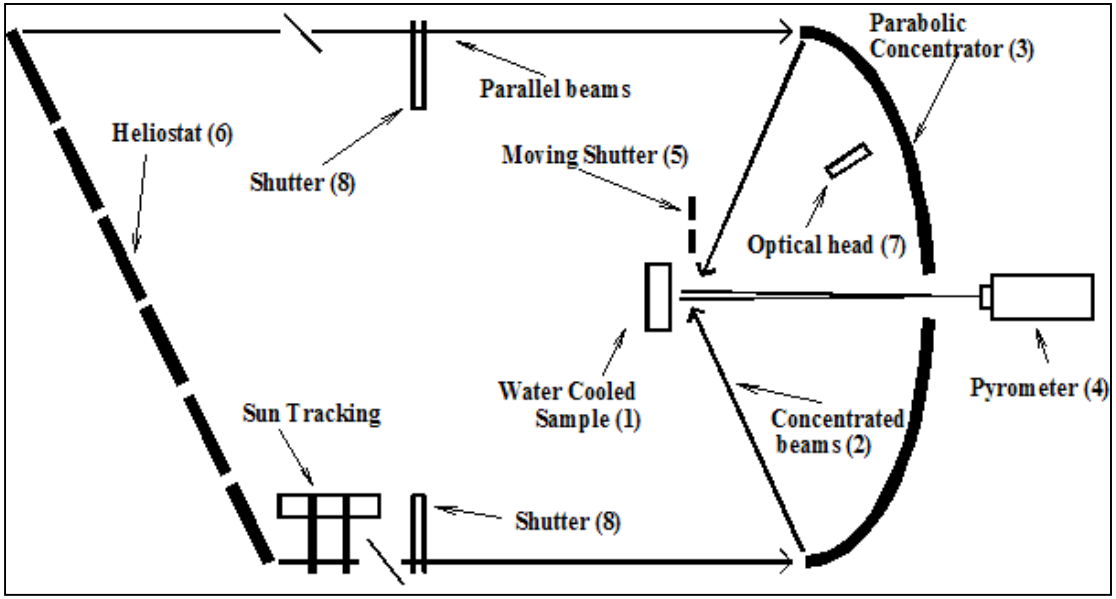


Blackbody condition

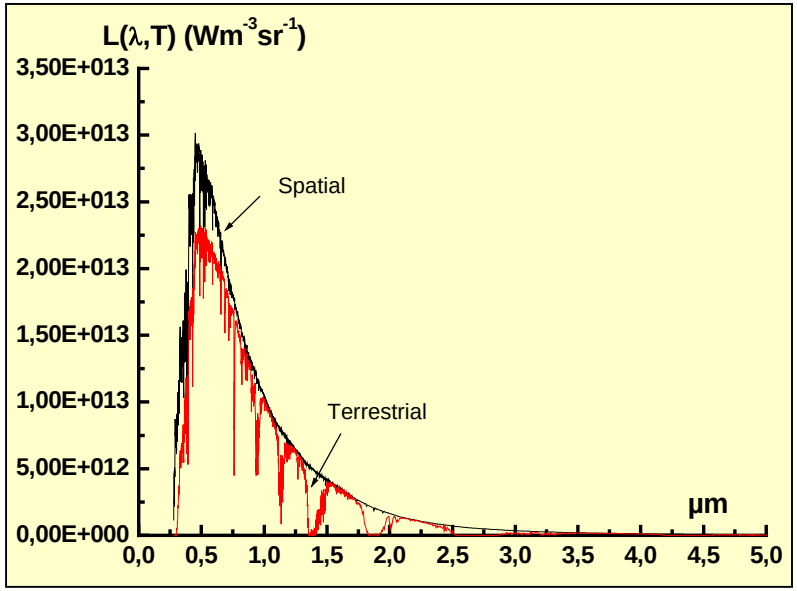
$\rho = 0$

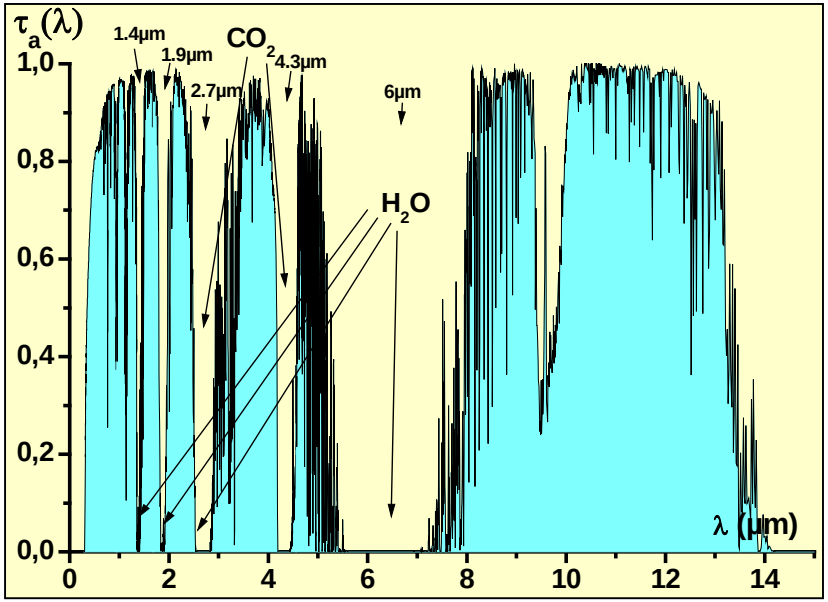
SOLAR BLIND EXPERIMENTS

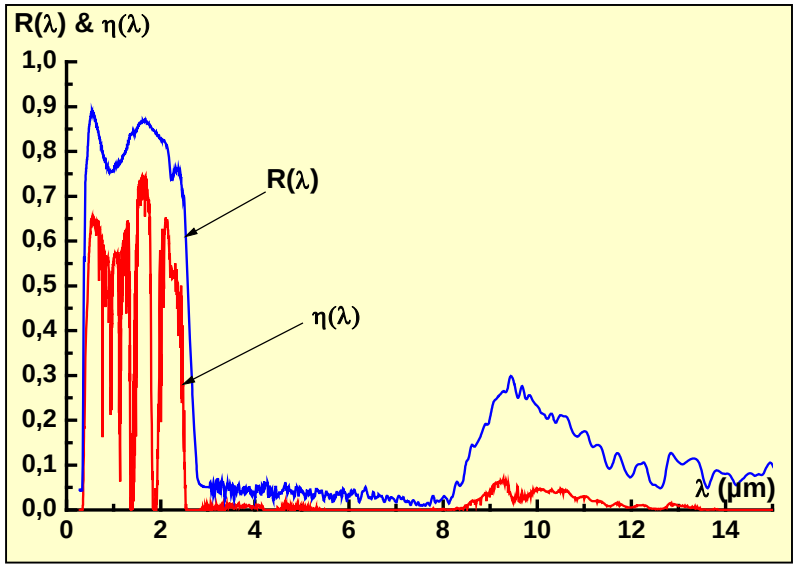




SPECTRAL SOLAR BLIND BANDS

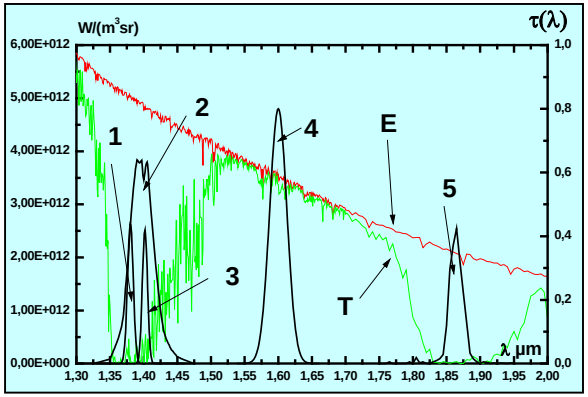


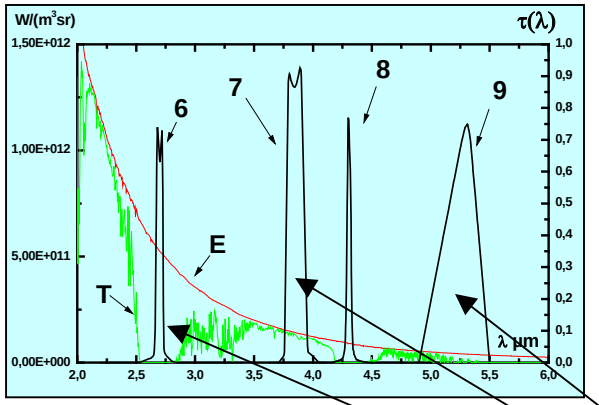


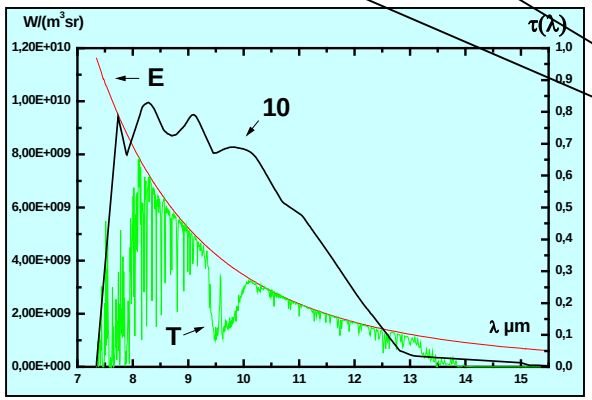


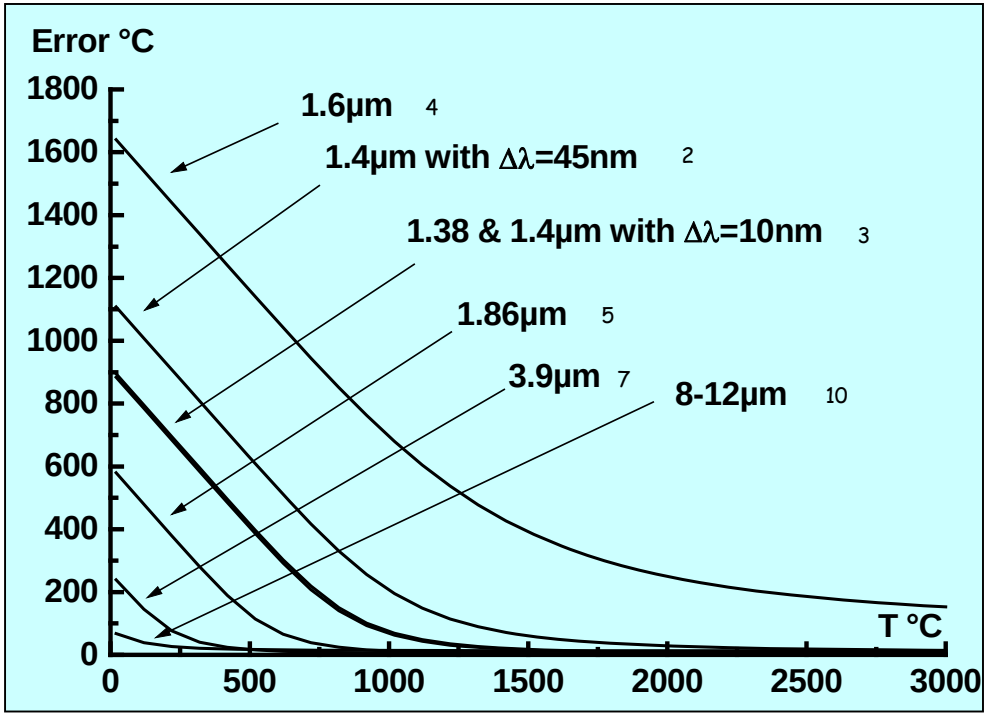
$$\eta(\lambda) = \tau_a(\lambda)\, R^2(\lambda)$$

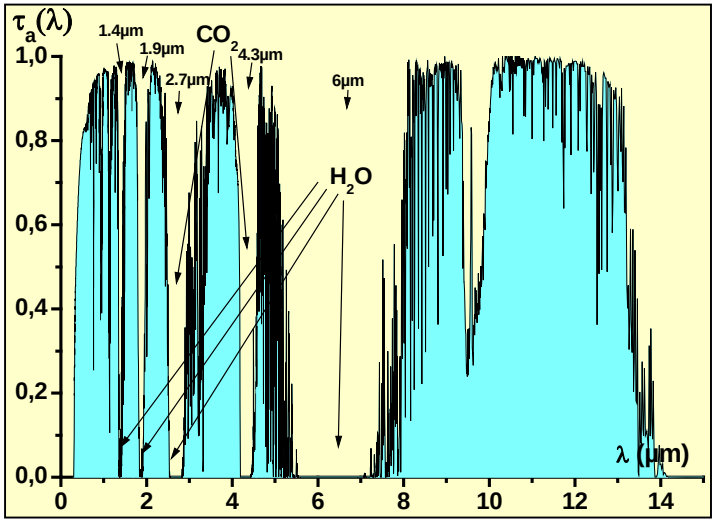
SPECTRAL SOLAR BLIND ERRORS



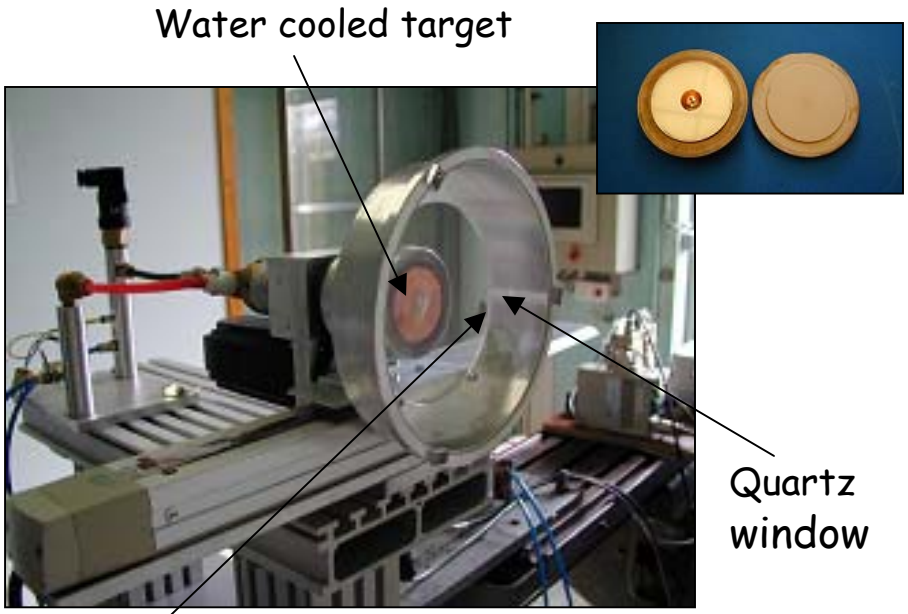


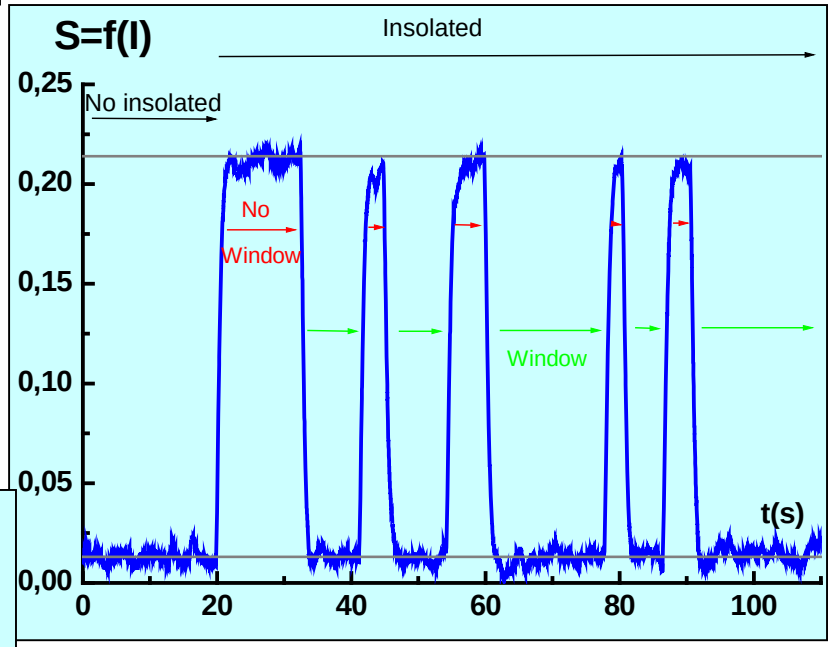


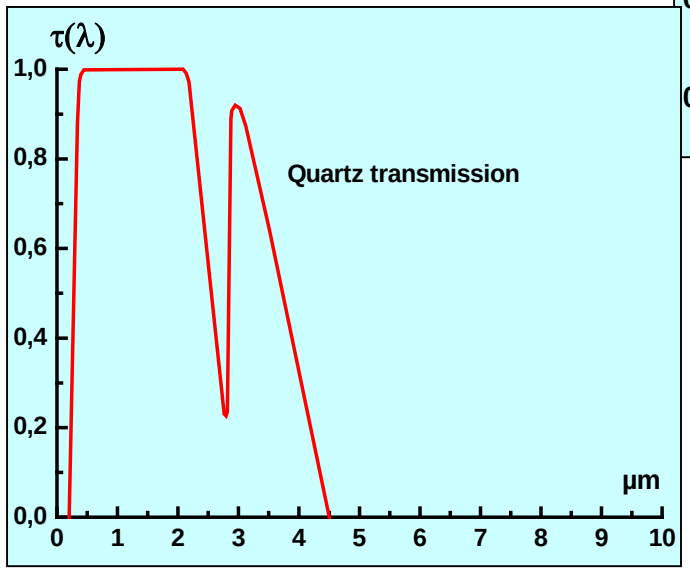




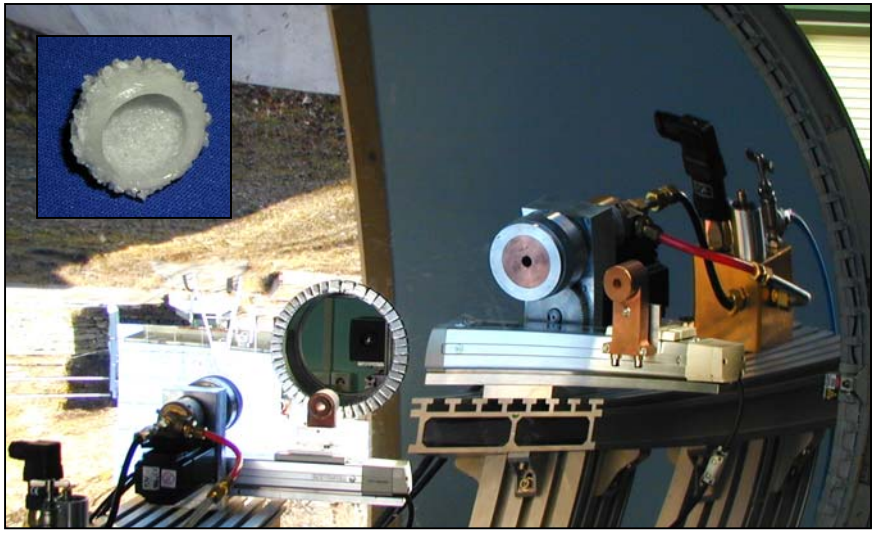
SOLAR BLIND WINDOWS



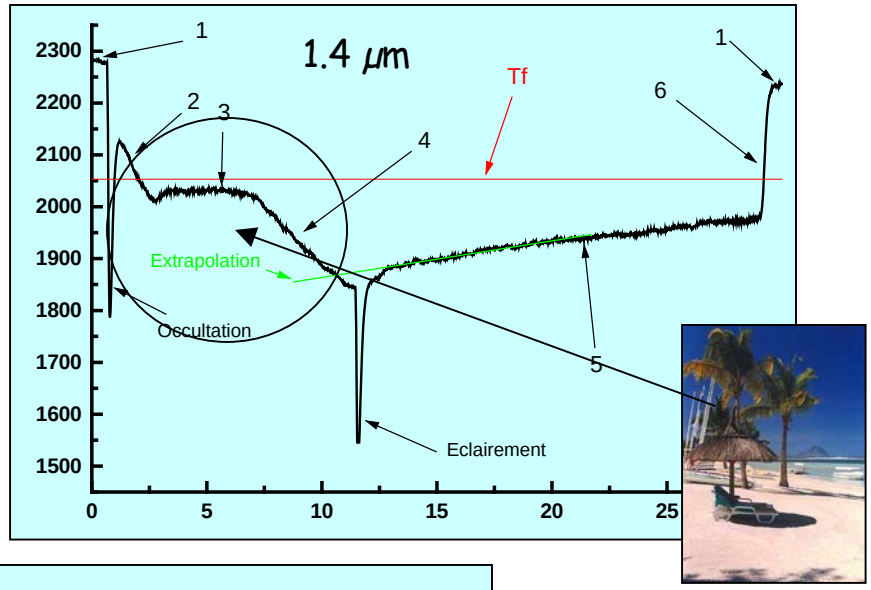


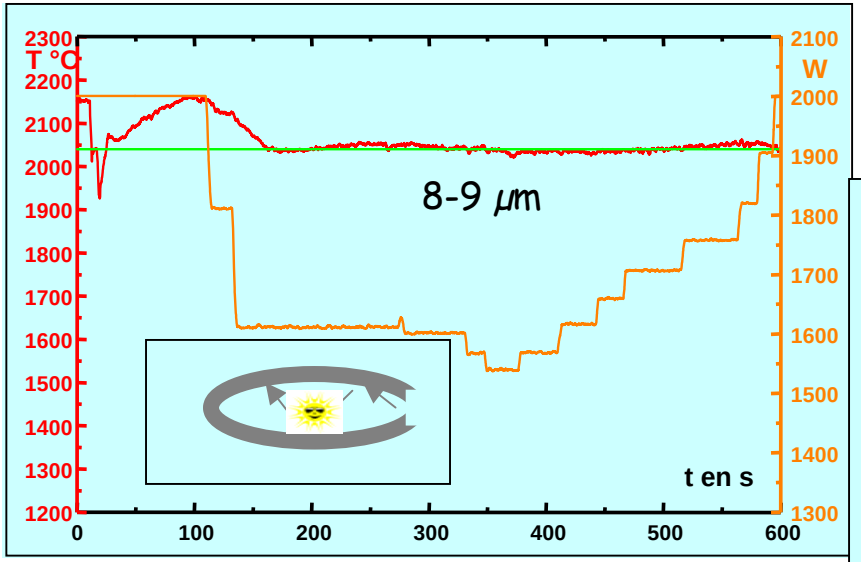


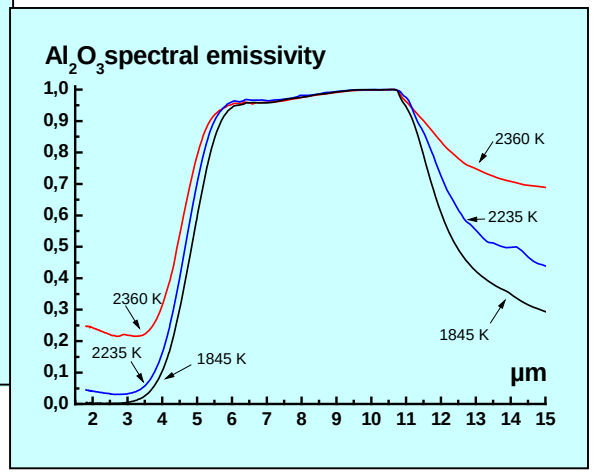
SOLAR BLIND CONDITIONS



Solar experimental methods for observing melting plateaux and associated temperature measurements for refractory oxides from 2000 to 3000 degrees C / JOURNAL OF THE EUROPEAN CERAMIC SOCIETY V:26 P: 1043-1049, 2006







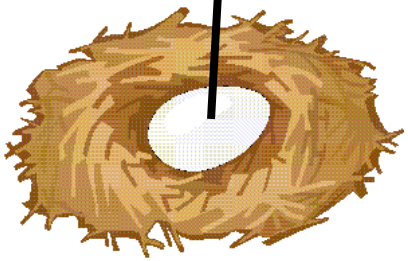
REALITY OF THE MEASURE

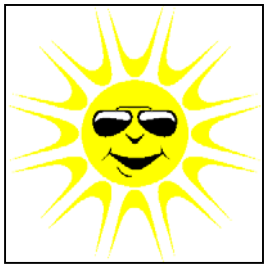
Emission

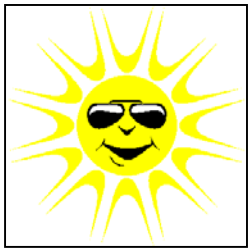
Reflexion

Transmission

$$S^{\vec{j}}(\lambda,T)=a(\tau^{\vec{j}}_{o.t.}(\lambda))\left[\varepsilon^{\vec{j}}(\lambda,T)I^{o}(\lambda,T)+\iint_{\bigcap_{\vec{i}}}\rho^{\vec{i},\vec{j}}_{F.D.}(\lambda,T)I^{\vec{i}}\,Cos(\theta_i)d\bigcap_{\vec{i}}+\iint_{\bigcap_{\vec{i}}}\tau^{\vec{i}}(\lambda,T)\,I^{\vec{i}}\,d\bigcap_{\vec{i}}\right]$$







?

Dilemma

APPARATUS AND METHODS

MONOCHOMATIC PYROMETER
BI CHROMATIC PYROMETER
SPECTRO RADIOMETER
INFRARED CAMERA

1 MONOCHROMATIC PYROMETRY
2 BICOLOR PYROMETRY
3 UV PYROMETRY
4 MULTI-COLOR PYROMETRY
5 ACTIVE PYROMETRY
6 CHRISTIANSEN POINT PYROMETRY
7 PYRO LASER
8 BICOLOR PYROREFLECTOMETRY

1 → $L^{\bar{j}}(T,\lambda)=L^{O}(T_{L,\lambda})=\varepsilon^{\bar{j}}(T,\lambda)L^{O}(T,\lambda)$ **Emissivity assumption**

Industrial

2 → $\frac{L^{\bar{j}}(T,\lambda_r)}{L^{\bar{j}}(T,\lambda_b)}=\frac{L^{O}(T_{C,\lambda_r,\lambda_b})}{L^{O}(T_{C,\lambda_r,\lambda_b})}=\frac{\varepsilon^{\bar{j}}(T,\lambda_r)L^{O}(T,\lambda_r)}{\varepsilon^{\bar{j}}(T,\lambda_b)L^{O}(T,\lambda_b)}$ **Grey Body assumption**

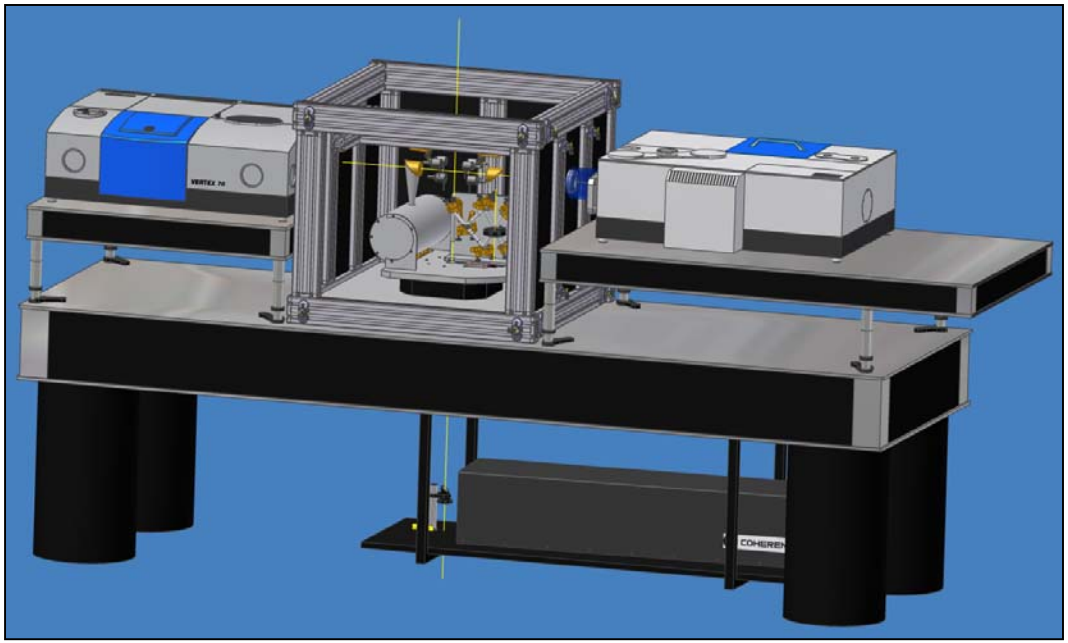
3 → $\frac{1}{T}=\frac{1}{T_{R,\lambda}}+\frac{\lambda}{C_2}\ln(\varepsilon^{\bar{j}}(T,\lambda))$ **Measurements at 0,3µm : photomultiplicators**

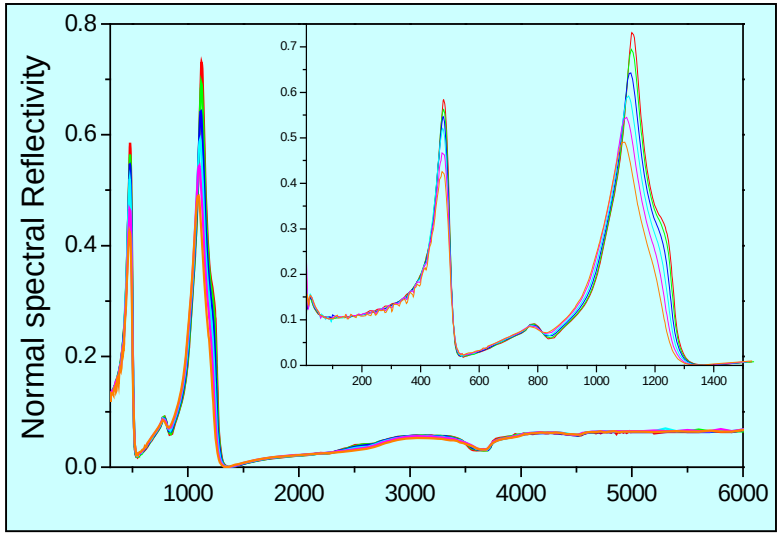
4 → $\varepsilon_\lambda = \exp(a_0 + a_1.\lambda)$ **Measurements at several wavelengths** Lab

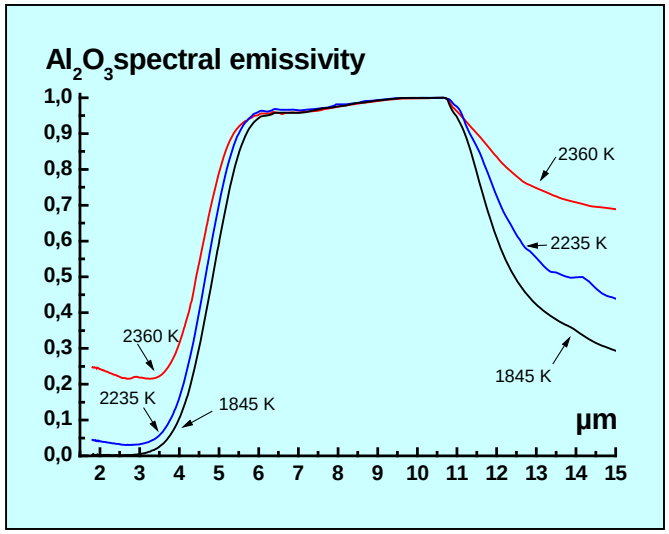
5 → **Determination of** $\alpha^{\bar{j}}(T,\lambda)$ **through T incrementation with controled laser flux**

CHRISTIANSEN METHOD

Lab method







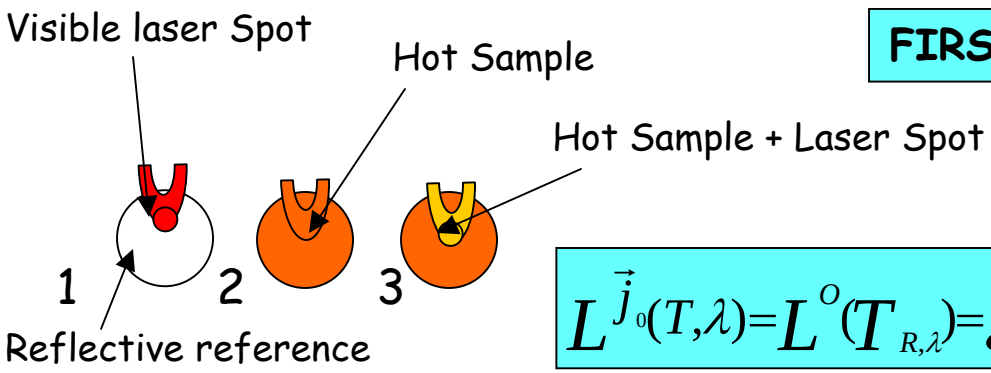
The method need a preliminary lab. studies

Limited to pure dielectrics materials

Choise of a pyrometer with adapted wavelength

7 PYROREFLECTOMETRY

Industrial



FIRST WORKS : OPTICAL DETECTION

Traverse,Foex, Badie : 1976

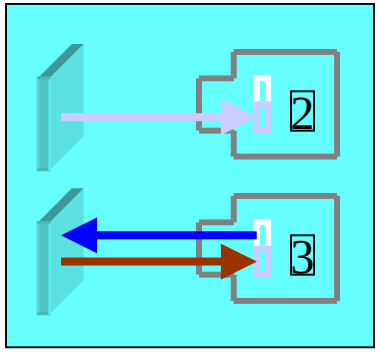
$$L^{\vec{j}_0}(T,\lambda)=L^{O}(T_{R,\lambda})=\varepsilon^{\vec{j}_0}(T,\lambda)L^{O}(T,\lambda)=(1-\rho^{\vec{j}_0,\cap}(T,\lambda))L^{O}(T,\lambda)$$

$$\rho^{\vec{j}_0,\cap}(T,\lambda)=\left[\left(D^{E+R}(T,\lambda)-D^{E}(T,\lambda)\right)/D_o^{R}(T_o,\lambda)\right]\rho_o^{\vec{j}_0,\cap}(T_o,\lambda)$$

1 MESURE ON Reflective Reference

2 MESURE OF EMISSION

3 MESURE OF EMISSION + REFLECTION

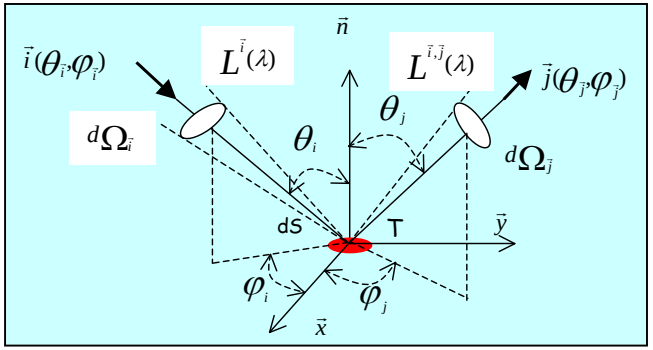


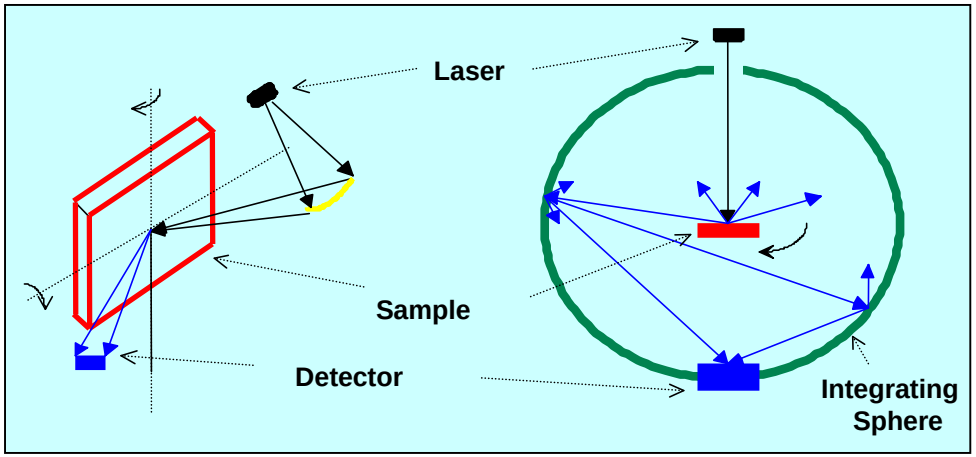
COMMERCIAL VERSION
'Pyrolaser'

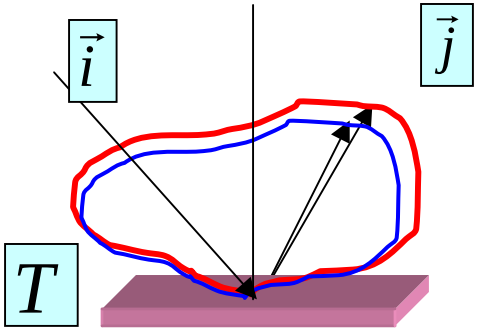
LIMITATED TO LAMBERTIAN SURFACE

TWO COLOR PYROREFLECTOMETRY

Industrial







Indicatrix of reflexion

FUNDAMENTAL ASSUMPTION

Same indicatrix of reflected fluxes for two near wavelengths λ_r and λ_b with :

$$\rho_{F.D.}^{\vec{i},\vec{j}}(T,\lambda_r) \neq \rho_{F.D.}^{\vec{i},\vec{j}}(T,\lambda_b)$$

Condition no so restrictive as grey or diffuse one

TWO COLOUR PYROREFLECTOMETRY

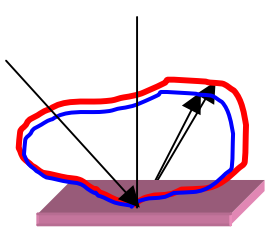
$$L^{\vec{j}_0}(T,\lambda)=L^O(T_{R,\lambda})=\varepsilon^{\vec{j}_0}(T,\lambda)L^O(T,\lambda)=(1-\rho^{\vec{j}_0,\cap}(T,\lambda))L^O(T,\lambda)$$

$$\rho^{\vec{j}_0,\cap}(T,\lambda)=\int_\cap \rho_{F.D.}^{\vec{j}_0,\vec{i}}(T,\lambda)\cos(\theta_i)d\Omega_i=\rho_{F.D.}^{\vec{i}_0,\vec{j}_0}(T,\lambda)\int_\cap \frac{\rho_{F.D.}^{\vec{j}_0,\vec{i}}}{\rho_{F.D.}^{\vec{j}_0,\vec{i}_0}}\cos(\theta_i)d\Omega_i$$

INTRODUCTION of THE DIFFUSION FACTOR

$$\eta_d^{\vec{i}_0,\vec{j}_0}(T,\lambda)=\int_\cap \frac{\rho_{F.D.}^{\vec{j}_0,\vec{i}}}{\rho_{F.D.}^{\vec{j}_0,\vec{i}_0}}\cos(\theta_i)d\Omega_i\Big/\int_\cap \cos(\theta_i)d\Omega_i=\left(\rho^{\vec{j}_0,\cap}(T,\lambda)\Big/\rho_{F.D.}^{\vec{i}_0,\vec{j}_0}(T,\lambda)\right)/\pi$$

$$L^O(T_{R,\lambda})=(1-\pi\eta_d^{\vec{i}_0,\vec{j}_0}(T,\lambda)\rho_{F.D.}^{\vec{i}_0,\vec{j}_0}(T,\lambda))L^O(T,\lambda)$$



$$L^O(T_{R,\lambda_r})=(1-\pi\eta_d^{\vec{i}_0,\vec{j}_0}(T)\rho_{F.D.}^{\vec{i}_0,\vec{j}_0}(T,\lambda_r))L^O(T,\lambda_r)$$

$$L^O(T_{R,\lambda_b})=(1-\pi\eta_d^{\vec{i}_0,\vec{j}_0}(T)\rho_{F.D.}^{\vec{i}_0,\vec{j}_0}(T,\lambda_b))L^O(T,\lambda_b)$$

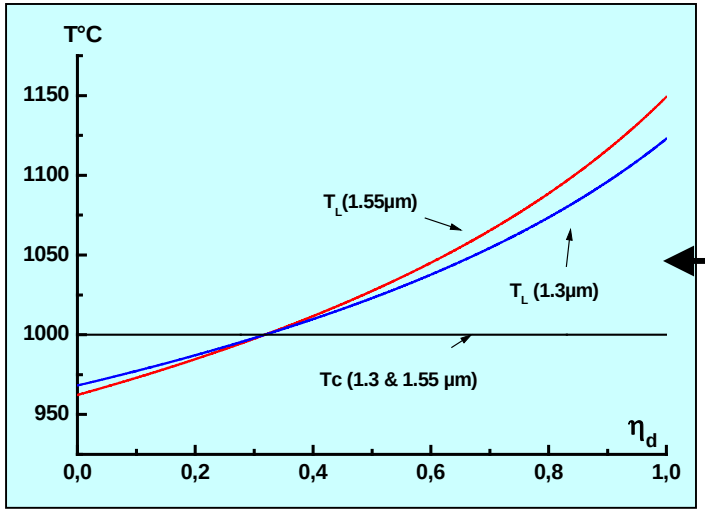
Solvable System measuring:

T_{R,λ_r} T_{R,λ_b}

$\rho_{F.D.}^{\vec{i}_0,\vec{j}_0}(T,\lambda_r)$ $\rho_{F.D.}^{\vec{i}_0,\vec{j}_0}(T,\lambda_b)$

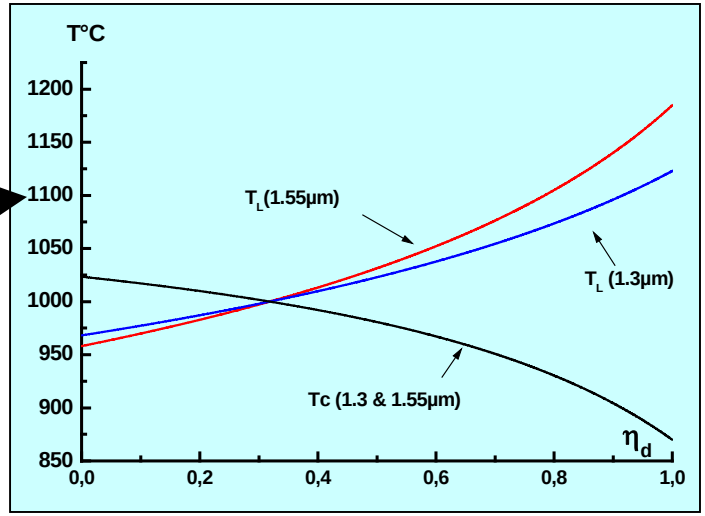
THREE DIFFERENT CASES

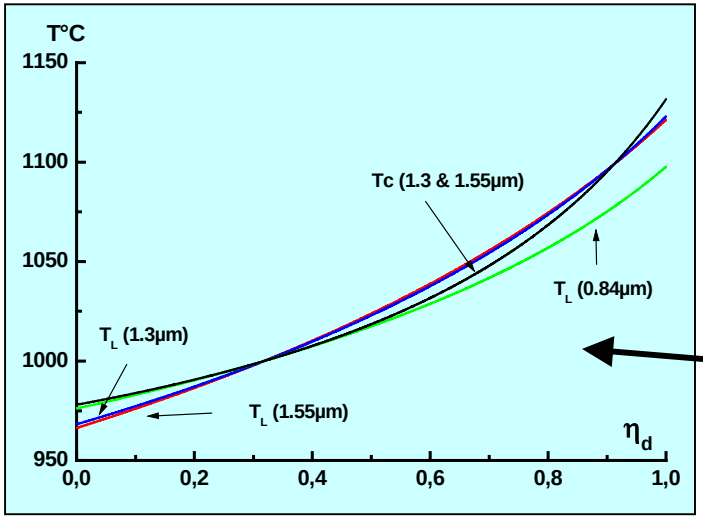
Simulation for T=1000 °C and $\eta = 1/\pi$



$\rho_r = \rho_b \rightarrow T_C = T$
Bicolor Pyrometry

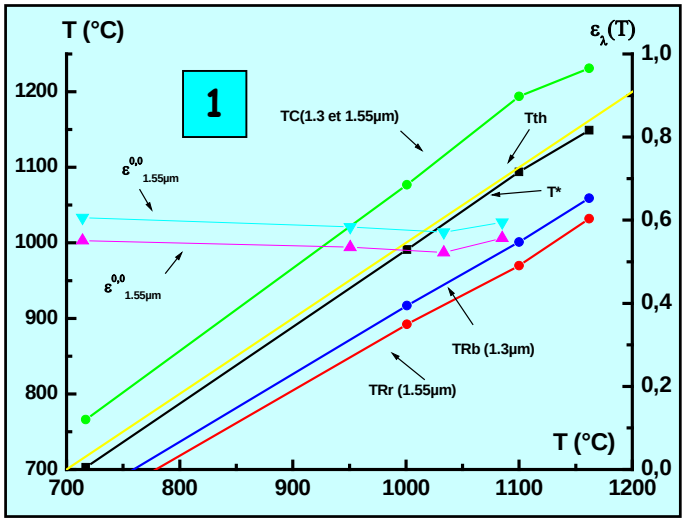
$\rho_r > \rho_b \rightarrow T_C > T$
Bicolor - Pyroreflectometry

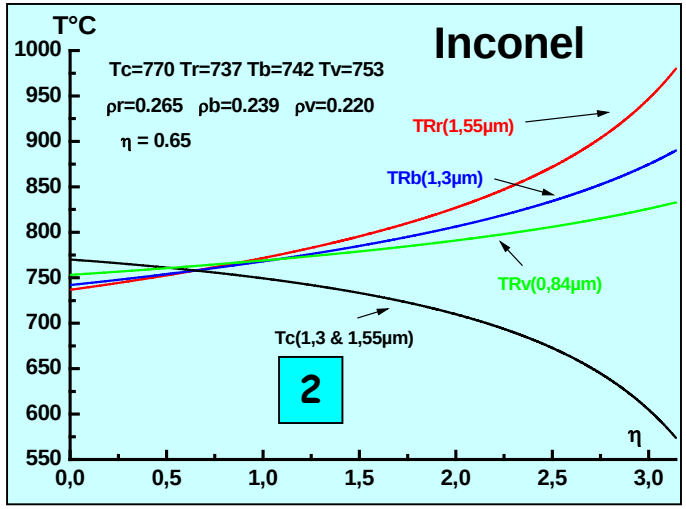


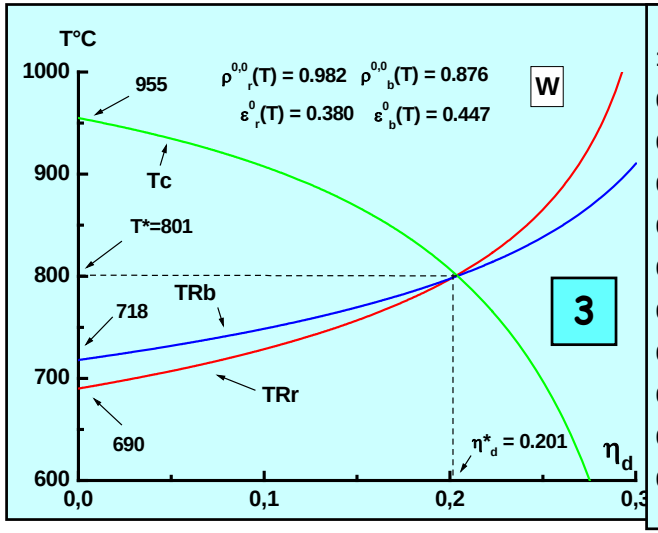


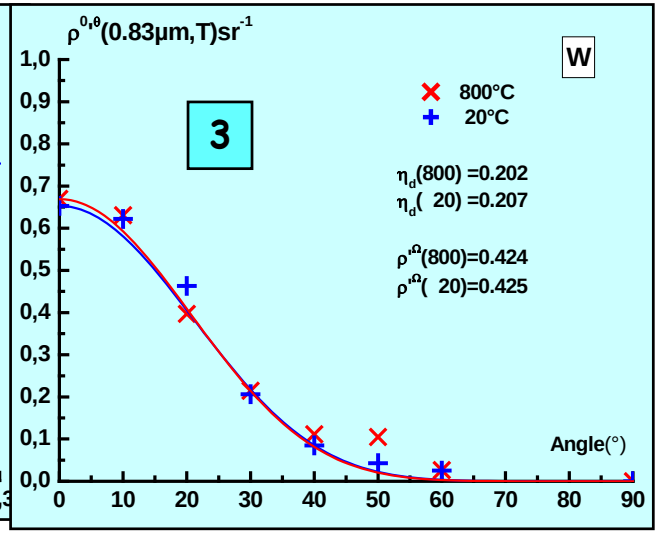
$\rho_r < \rho_b \rightarrow T_C < T$
Tricolor- Pyroreflectometry

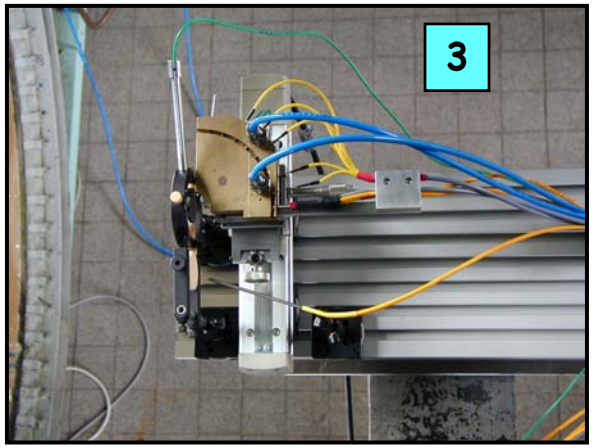
EXPERIMENTAL VALIDATION







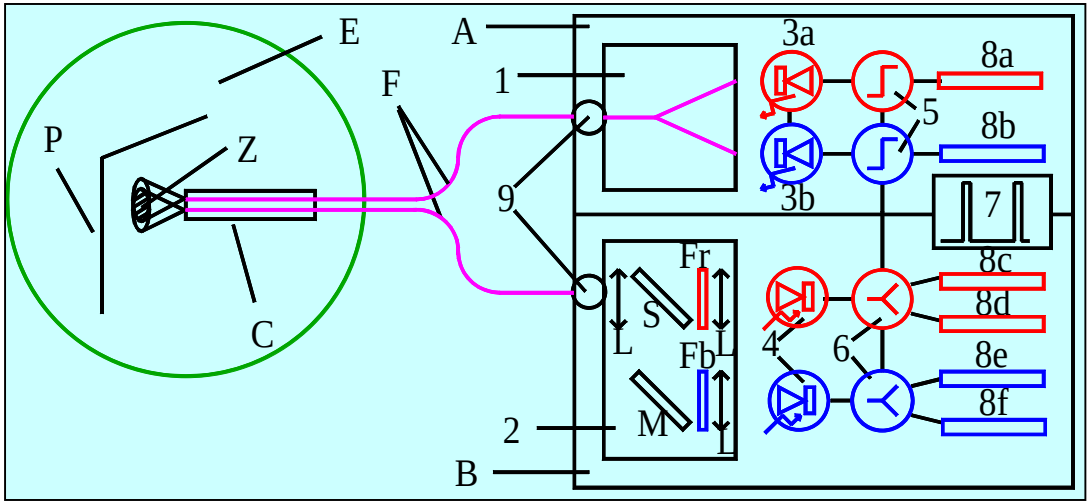




$\eta_d(800°C)=0.201$

$\eta_d(800°C)=0.202$

THE PYROREFLECTOMETER



A: Emission B: Detection F: Optical fibres
1: O.F. coupler 3: Laser diodes 4: Detectors 7: Delay generator

Diodes Characteristics

$\lambda r := 1.55\mu m$ - $\lambda b := 1.30\mu m$

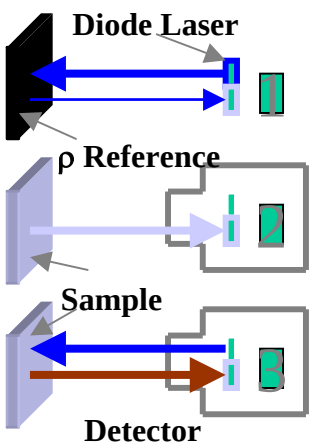
Frequency :10kHz (1µs & 99µs)

Outpout power :60mW

Optical Fiber Characteristics

Silica, Step index, N.A. = 0.22,

Core diam. 100,200,400,500µm

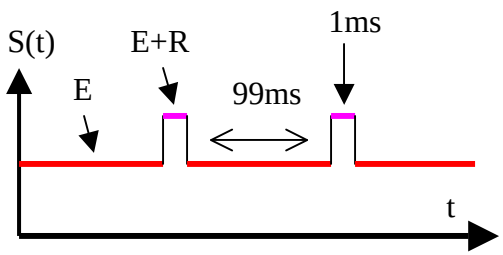


Measurement Principle

M1 ➔ $f(\rho^{i,j}(\lambda))$

M2 ➔ $f(L(\lambda, T_R))$

(M3-M2) / M1 ➔ $f(\rho^{i,j}(\lambda, T_R))$



Measured parameters

$Tr(\lambda_r)$, $Tr(\lambda_b)$, $Tc(\lambda_r, \lambda_b)$

$\rho^{i,j}(\lambda_r)$, $\rho^{i,j}(\lambda_b)$

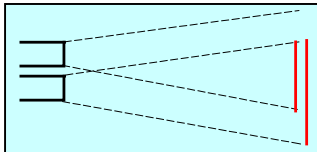
T min : 600°C

ΔT: +/- 5°

$\Delta\rho/\rho$: 2%

THE PROBES

PROXIMITY



PROBE WITHOUT LENSES

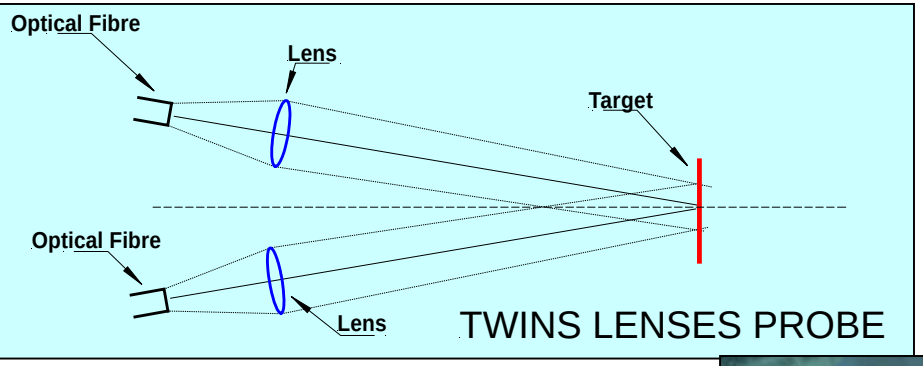
$$r_s = tg(\theta_{ouv})\, d$$

REMOTE

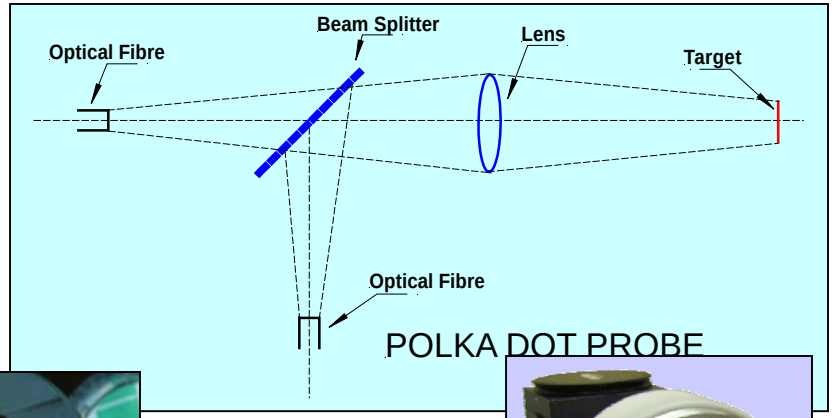
Typical size : 3-5mm diameter

$$\frac{1}{p} + \frac{1}{p'} = \frac{1}{f}$$

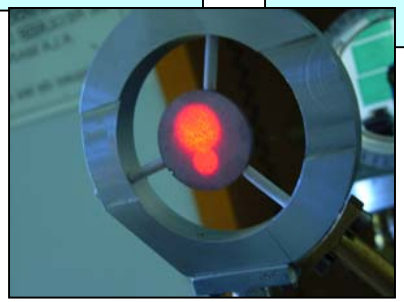
$$G = \frac{r_i}{r_f} = \frac{p'}{p}$$



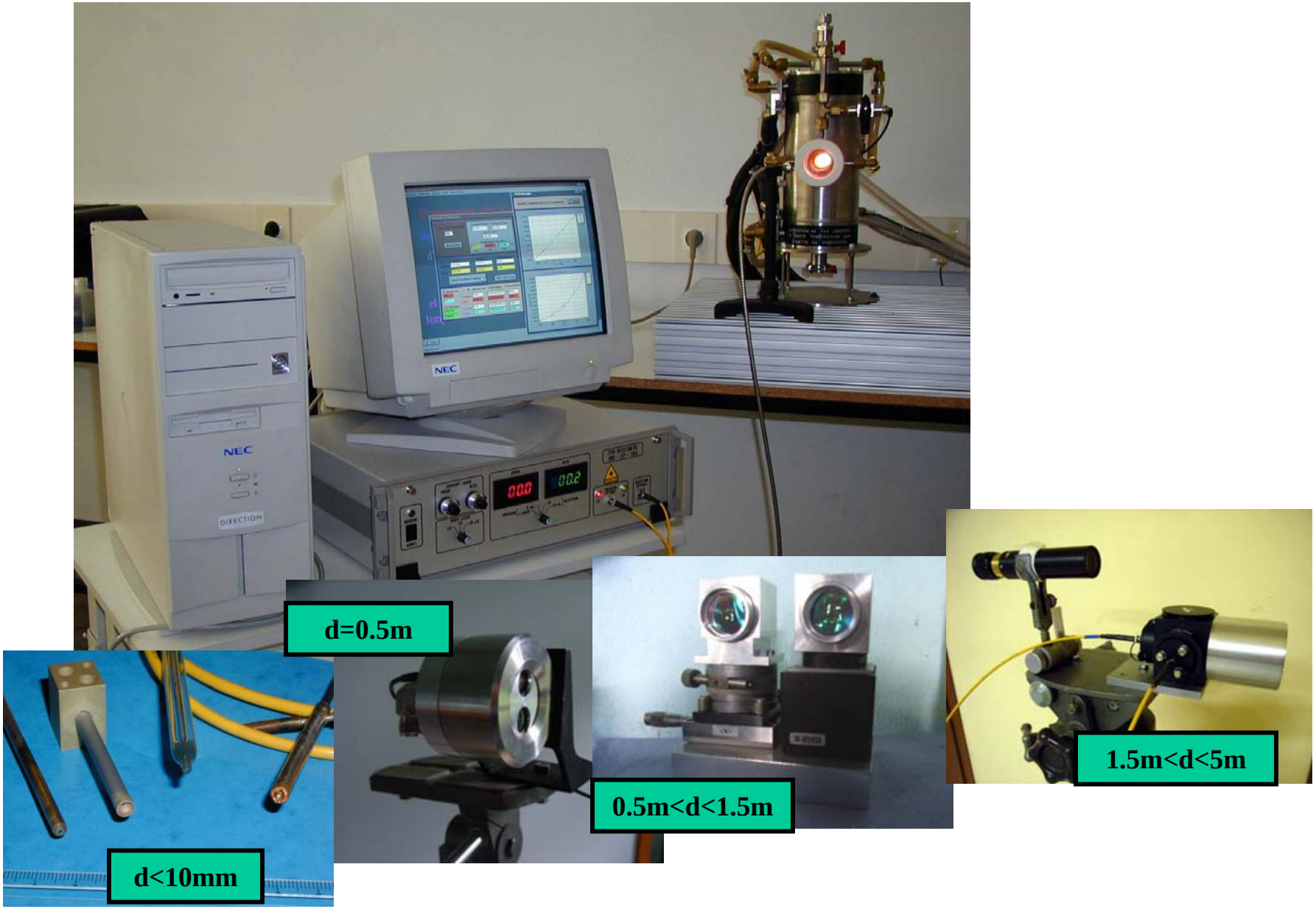
TWINS LENSES PROBE



POLKA DOT PROBE



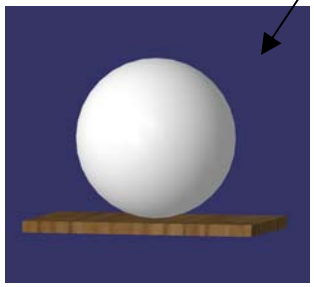
PYROREFLECTOMETER and PROBES



THE DIFFUSION FACTOR

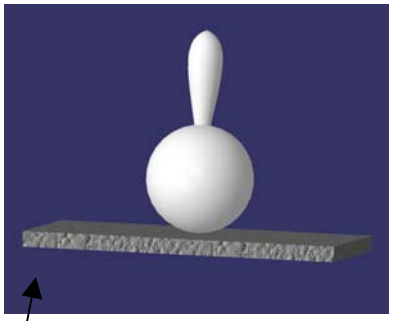
$$\eta_d^{\perp,\perp}(T,\lambda)\times\rho_{F.D.}^{\perp,\perp}(T,\lambda)\times\pi\leq 1$$

Lambertian

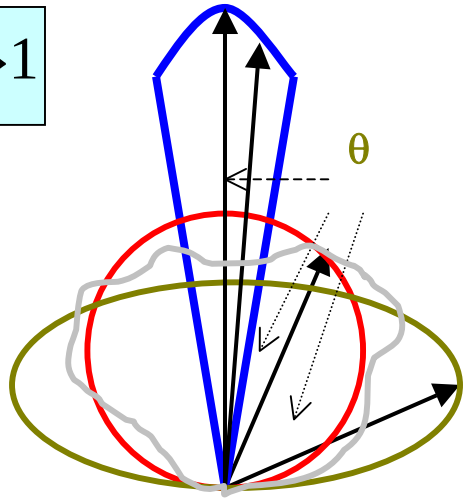


$\eta_d \rightarrow 1$

$0\leq\eta_d\leq 1$

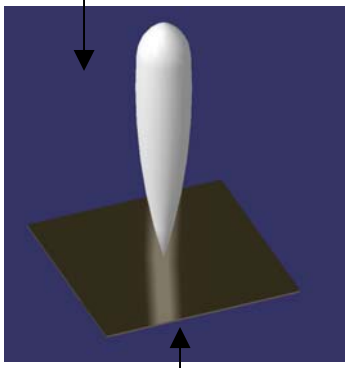


Diffuse & specular

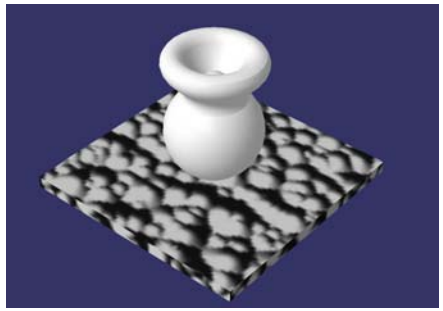


B.R.D.F. ➔ η_d

Specular



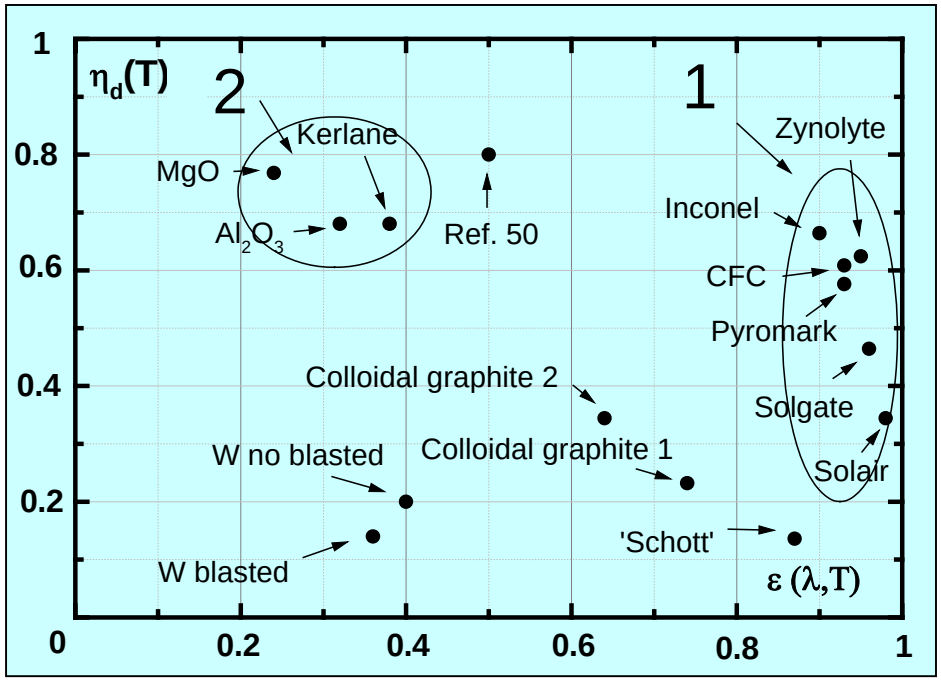
$\eta_d \rightarrow 0$



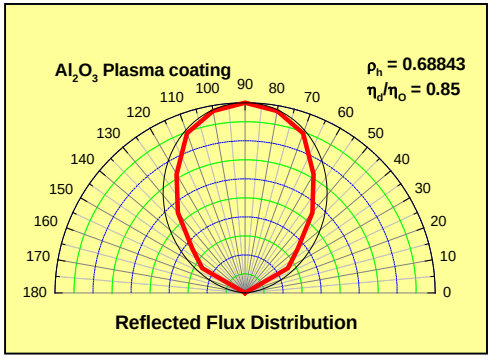
$\eta_d > 1$

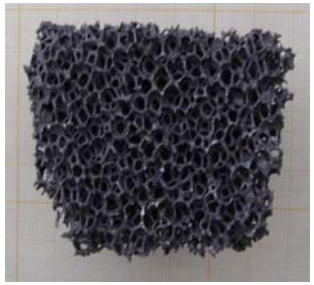
Oriented

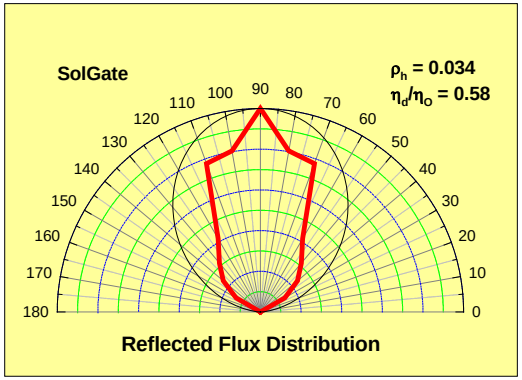
UTILITY OF DIFFUSION FACTOR

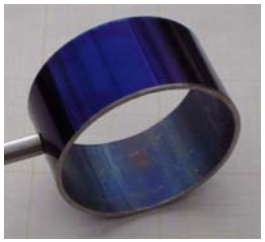


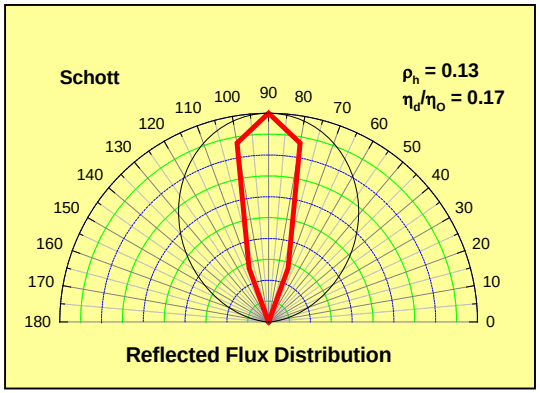
Surface Classification with ε and η





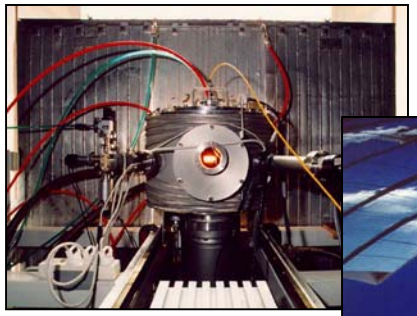


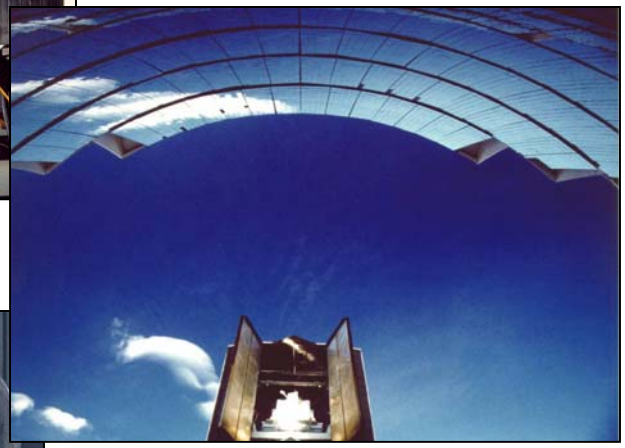




Pyroreflectometry to determine the true temperature and optical properties of surfaces J.S.E.Volume: 130 Issue: 3 Published: 2008

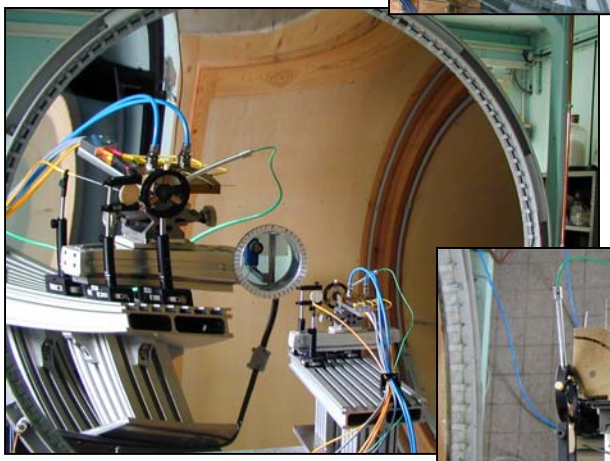
PYROREFLECTOMETRY AT PROMES

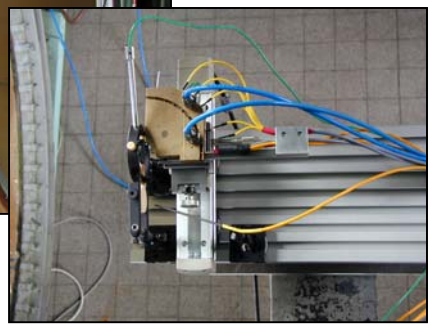




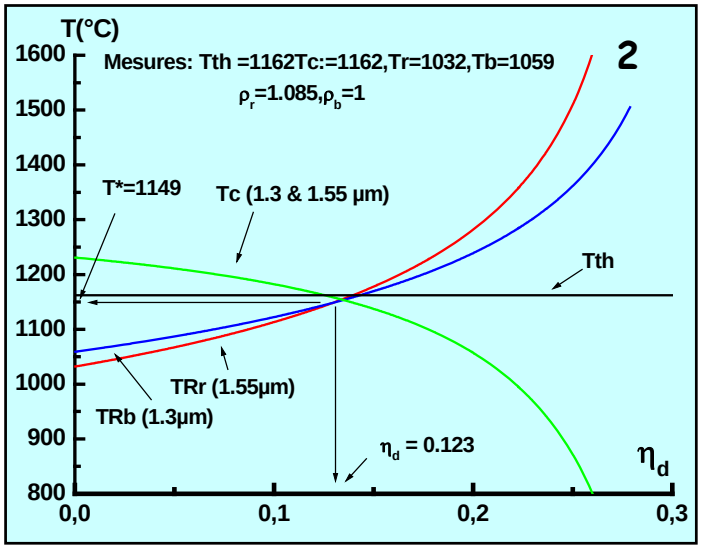
1 MW INSTALLATION
'GRAND FOUR'
MEDIASE

2 kW INSTALLATION
'BASTION'
DISCO

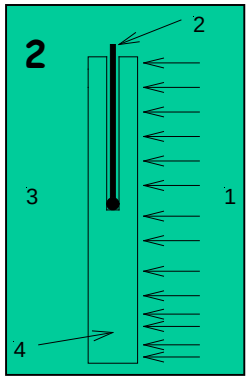


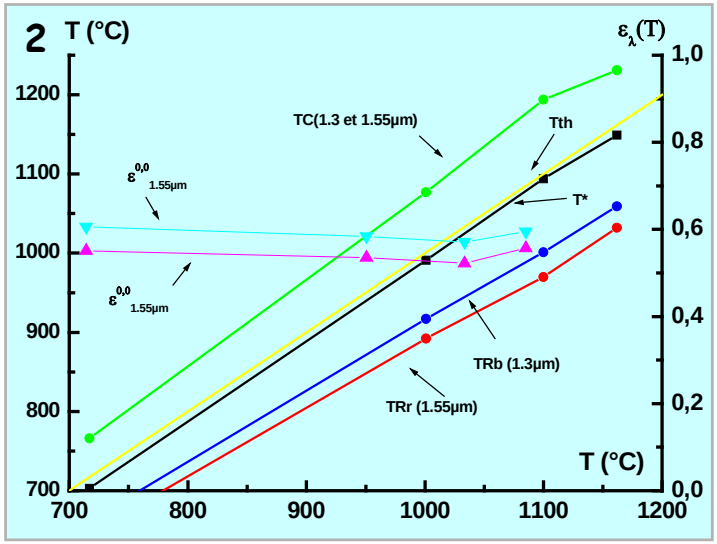


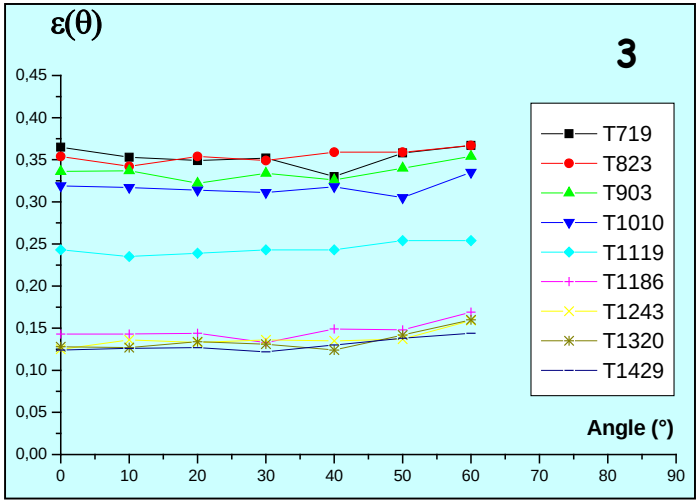
MEASUREMENTS ON TUNGSTEN

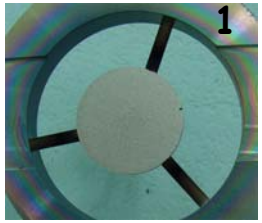


Validation









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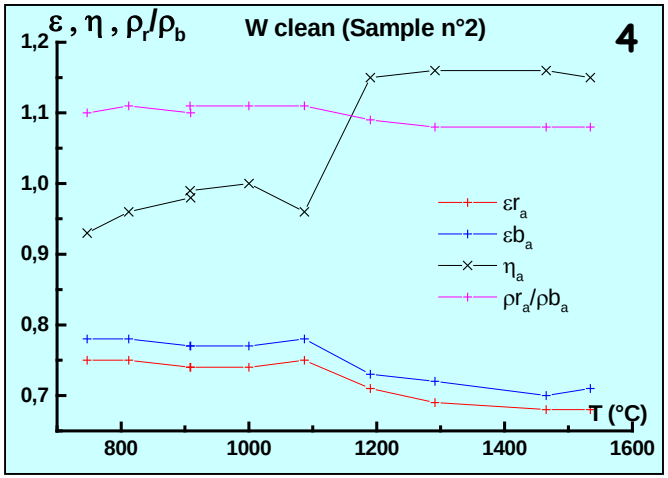
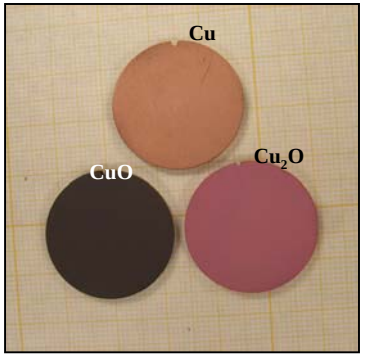
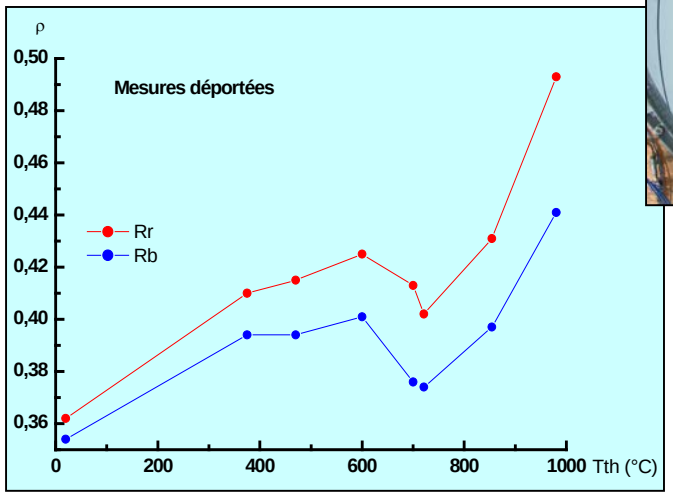
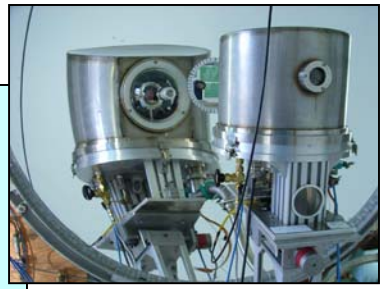
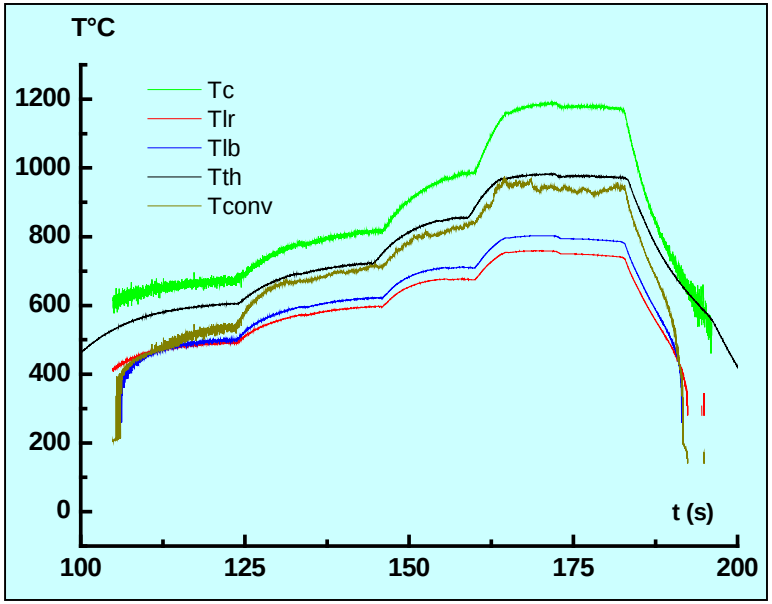


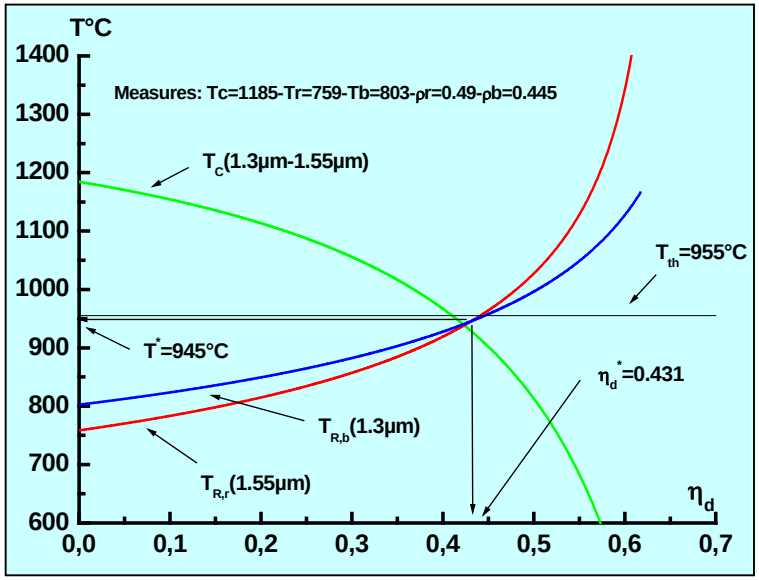
MEASUREMENTS ON COPPER











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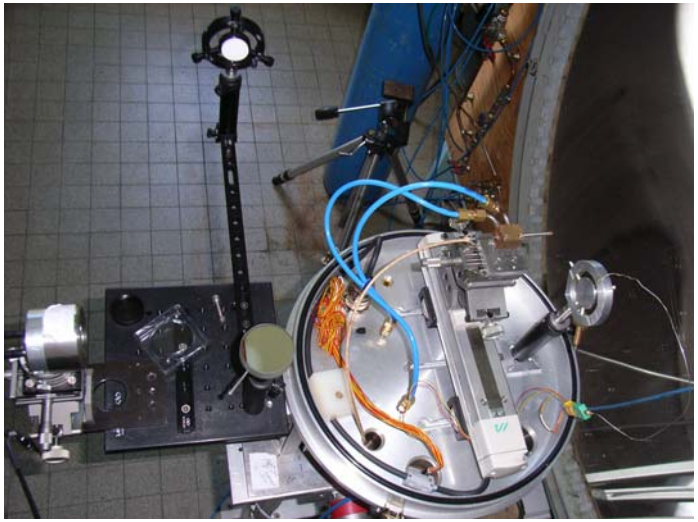
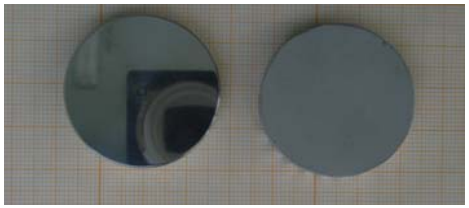
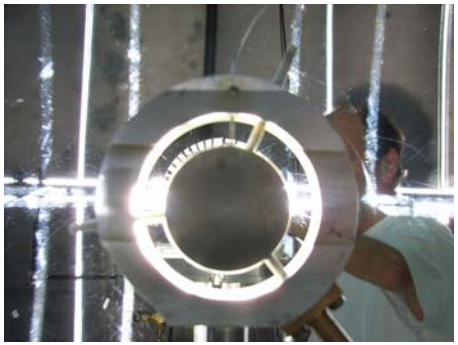
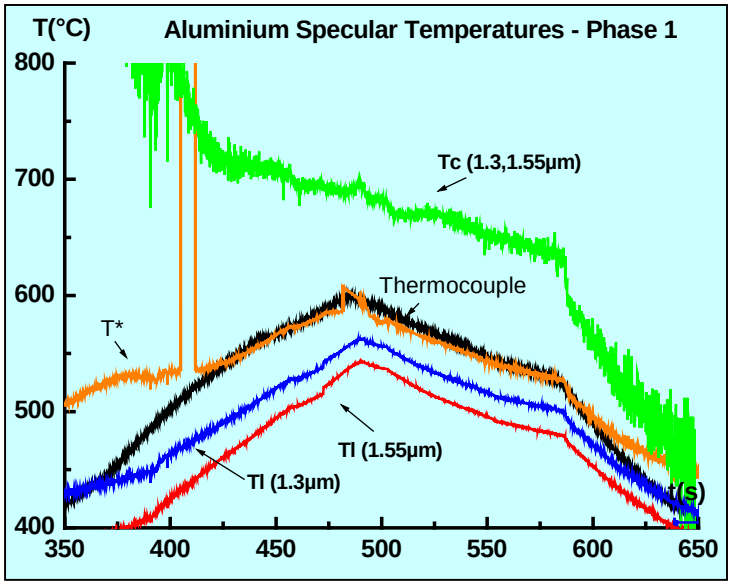
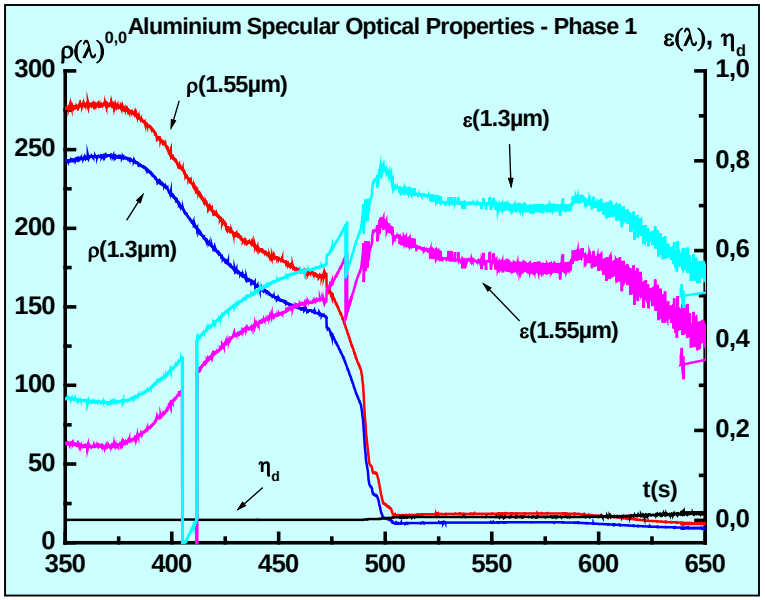


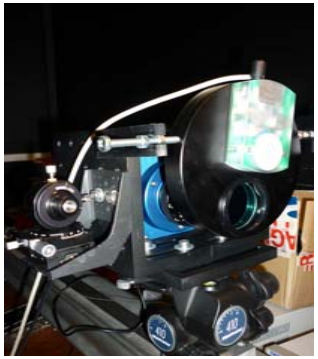


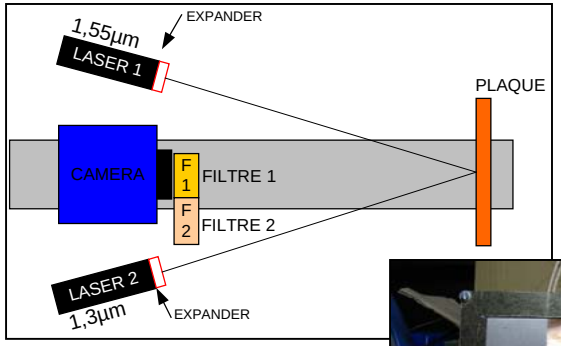


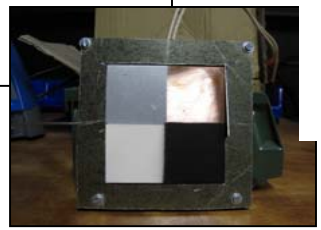




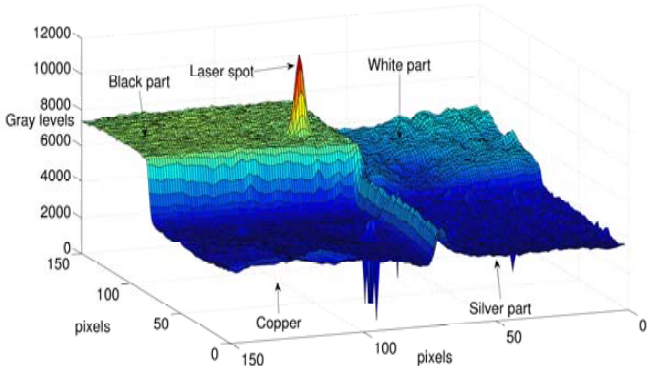
THERMOREFLECTOMETRY



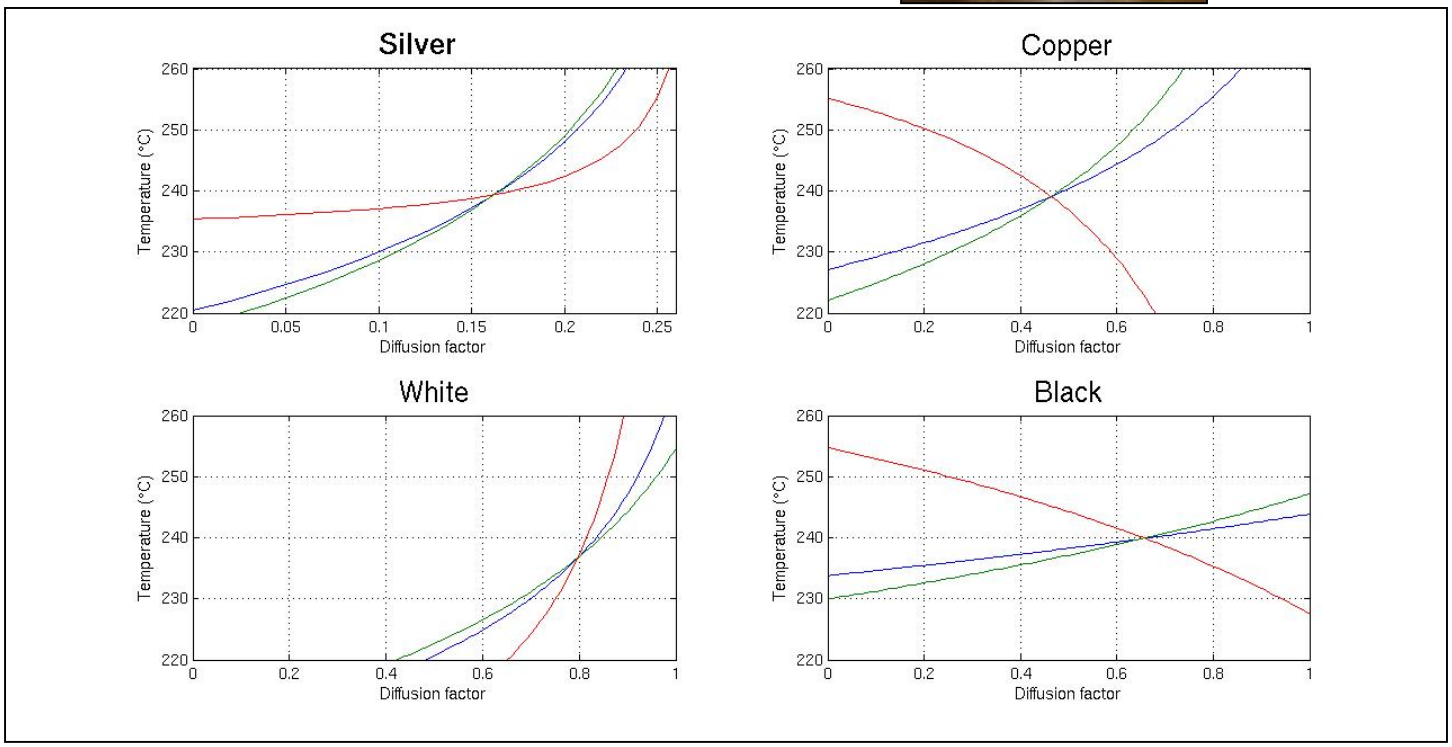


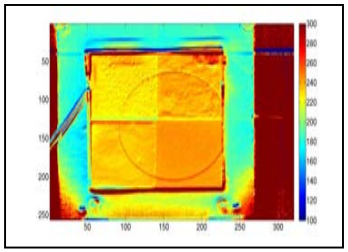


Sample with 4 areas



Pixel levels





Color temperature

ADVANTAGES OF PYROREFLECTOMETRY

- The less restrictive assumption
- In situ and on line measurements
- Permanent control of all the parameters
- Large experimental validation
- Large industrial application in rough conditions
- Surface control for non contact diagnostic
- Mature technique
- Possibility to be extended forward solar blind wavelengths
- Possibility to be extended for spatial measurements 'IR Camera'

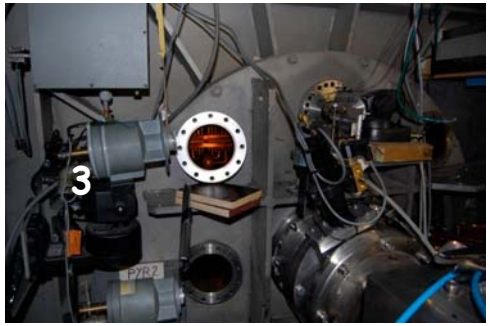
A concept to determine the true temperature of opaque materials using a tricolor pyroreflectometer REVIEW OF SCIENTIFIC INSTRUMENTS Volume: 76 Issue: 2 Published: 2005

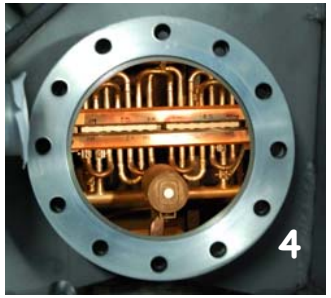
Development of two-colour pyroreflectometry technique for temperature monitoring of tungsten plasma facing components FUSION ENGINEERING AND DESIGN Volume: 83 Pages: 672-679 Published: 2008

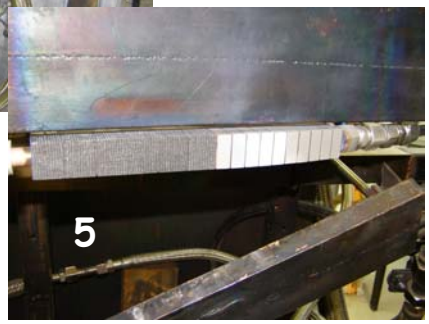
True temperature measurement on metallic surfaces using a two-color pyroreflectometer method REVIEW OF SCIENTIFIC INSTRUMENTS Volume: 80 Issue: 9 Published: 2009

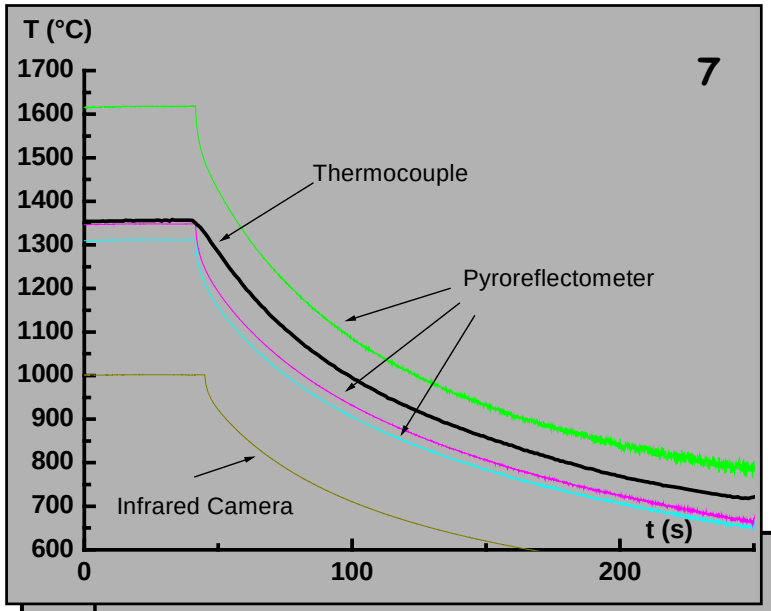
Experimental validation of a pyroreflectometric method to determine the true temperature on opaque surface without hampering reflections MEASUREMENT Volume: 42 Issue: 6 Pages: 836-843 Published: 2009

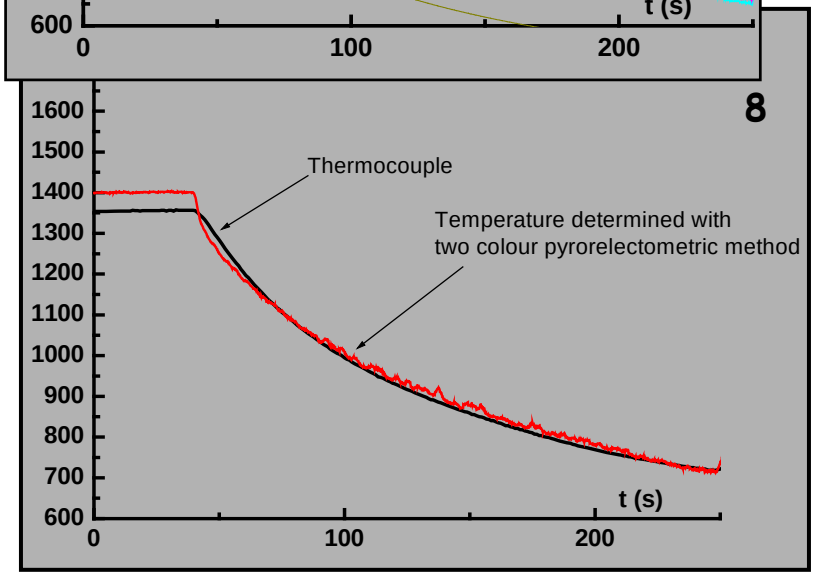
APPLICATION ON FUSION SIMULATOR (ITER)







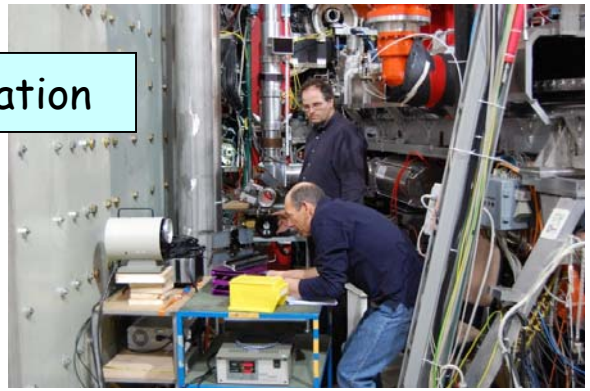


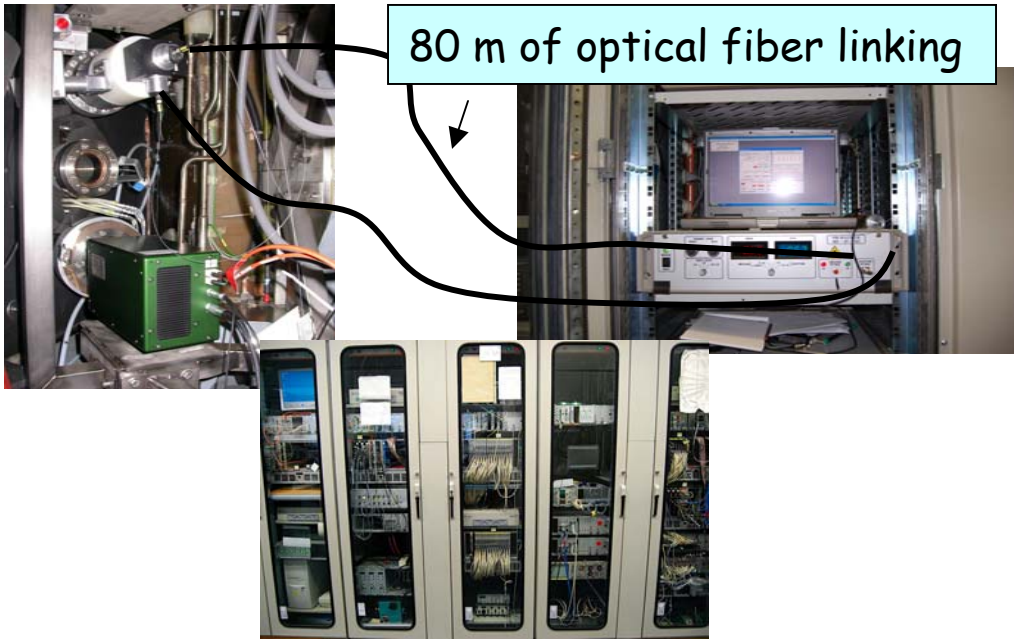


FE200 (CEA-AREVA)

APPLICATION ON FUSION REACTOR (ITER)

Calibration



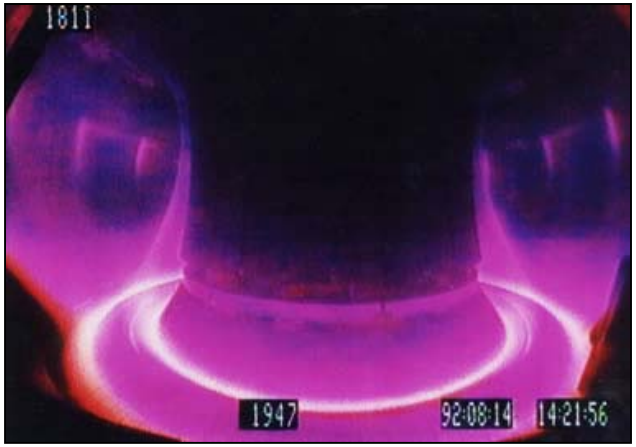


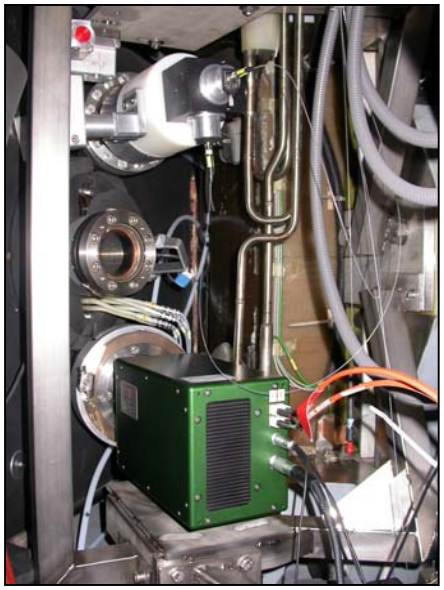
80 m of optical fiber linking

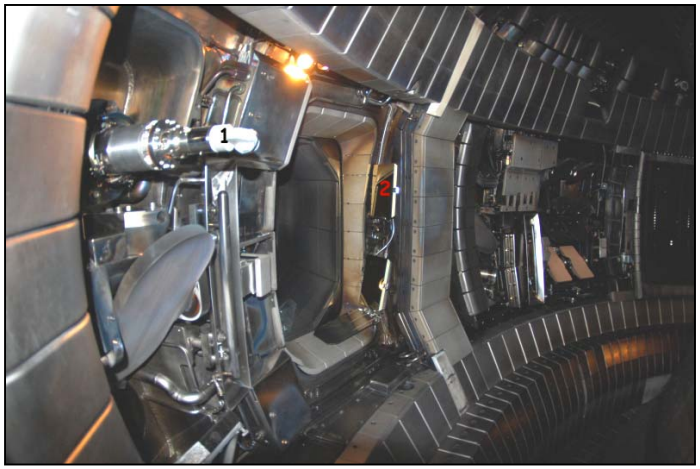
Control Room

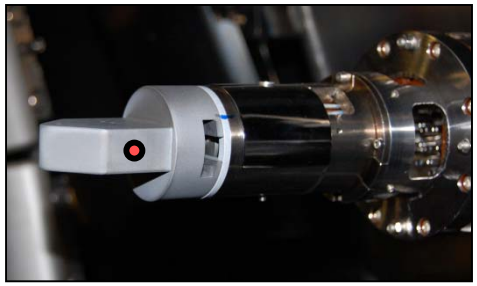
ASDEX-UPGRADE Max Planck Institute (Garching)

APPLICATION ON FUSION REACTOR (ITER)

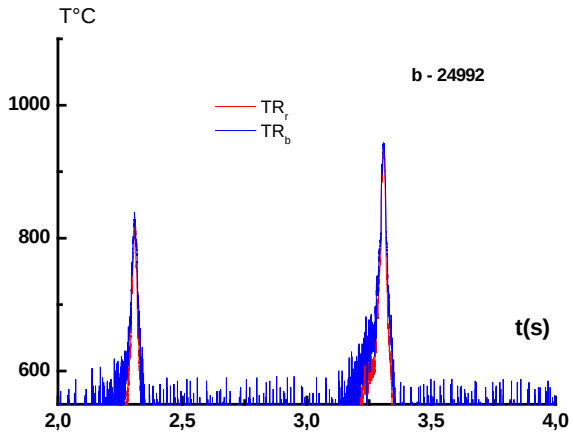


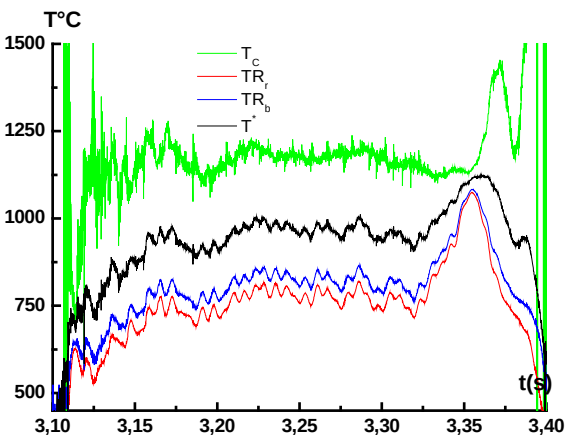


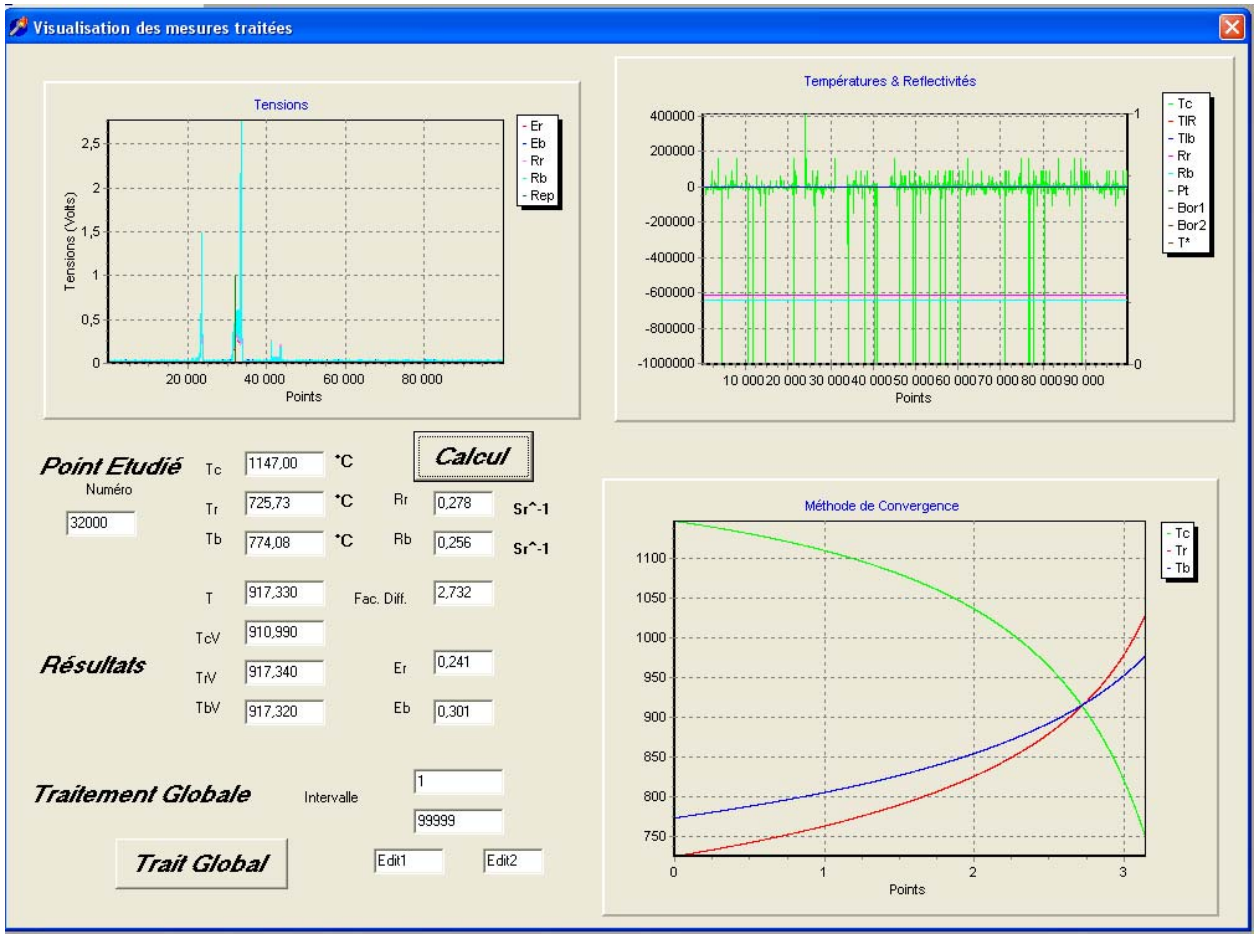




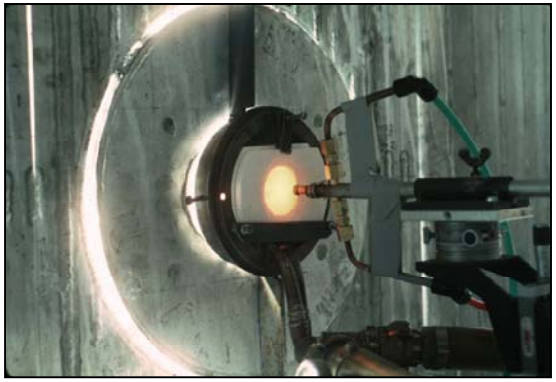
APPLICATION ON FUSION REACTOR (ITER)

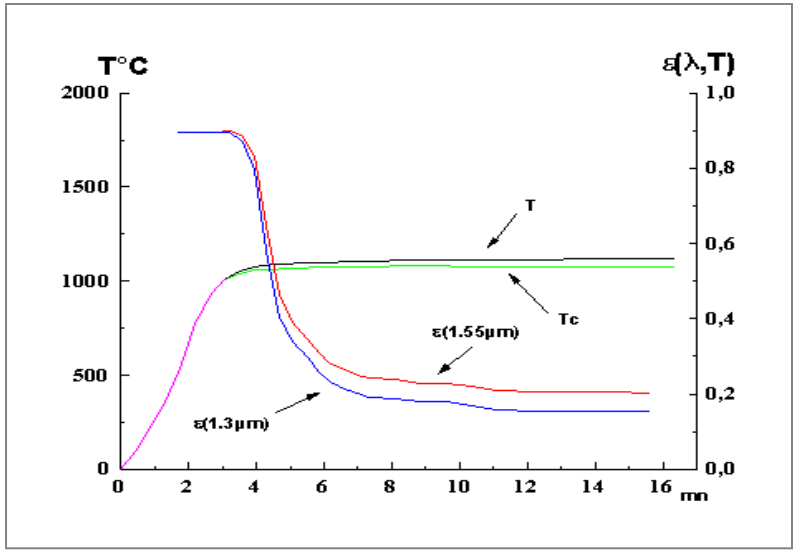


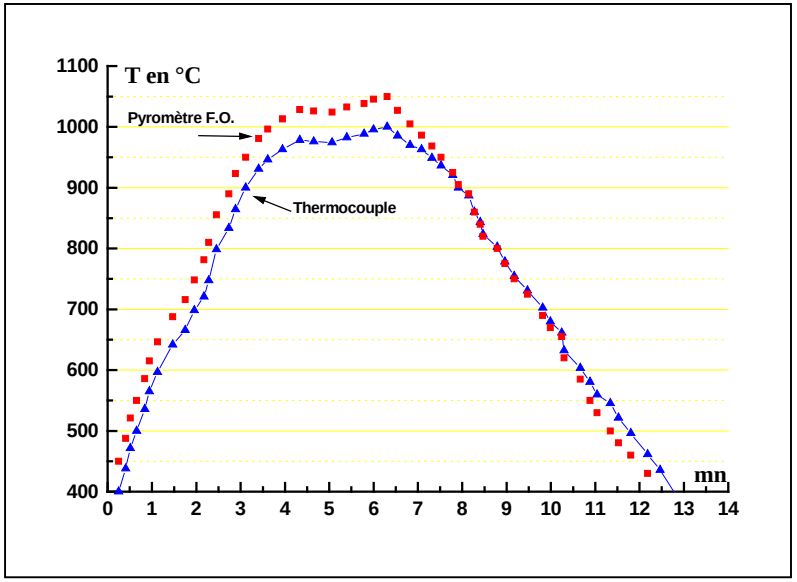




APPLCATION ON SOLAR INSTALLATIONS





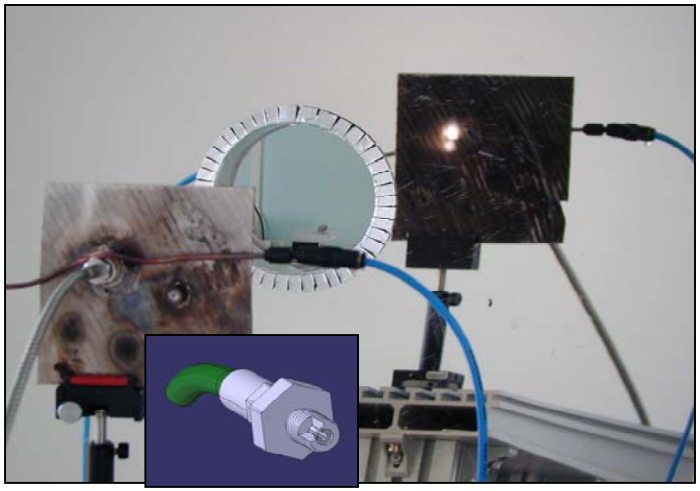


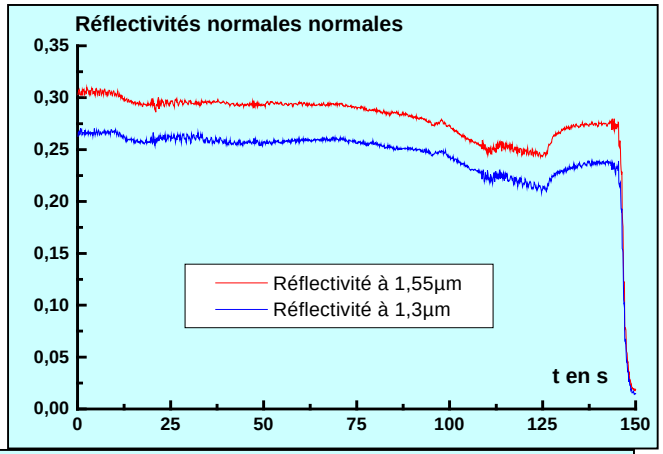
Oxidization of $ZrO_{(2-x)}$

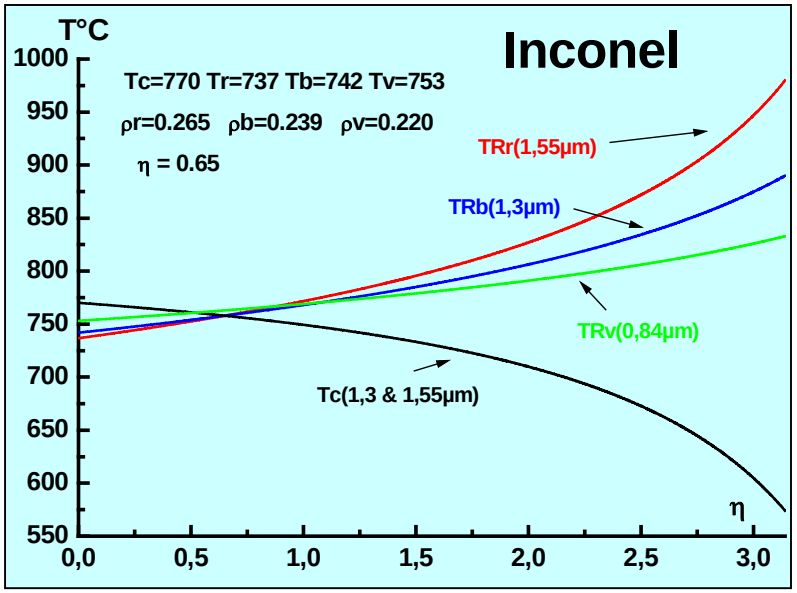
Hermes winging edge true temperature (Plata forma solar Almeria)

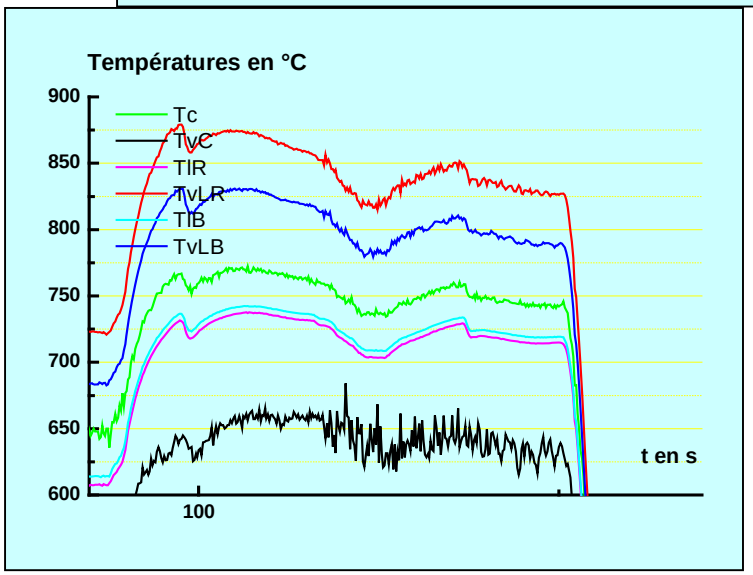
APPLICATION ON ROCKET MOTOR

Measurement inside 3mm cooling canal



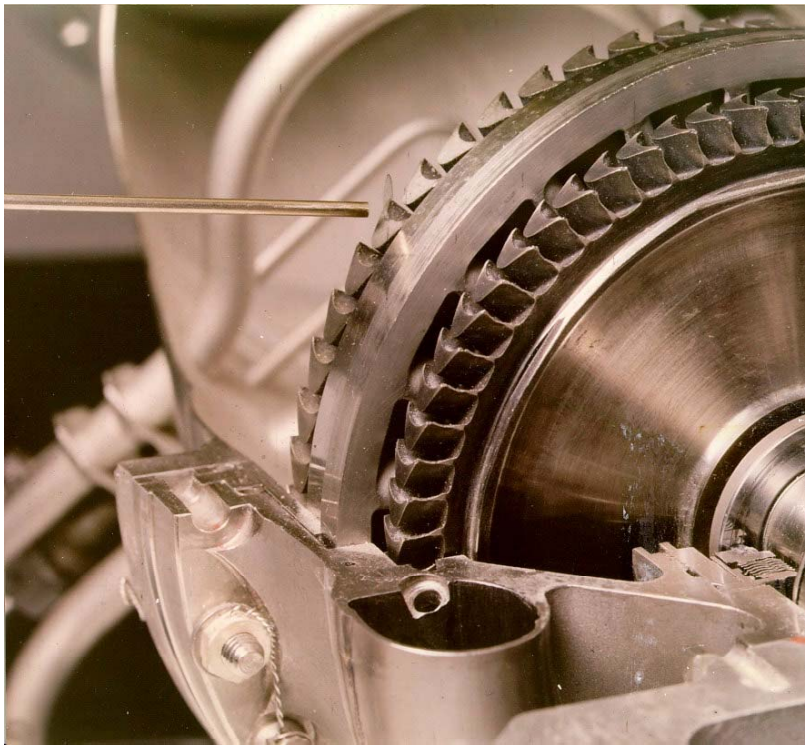




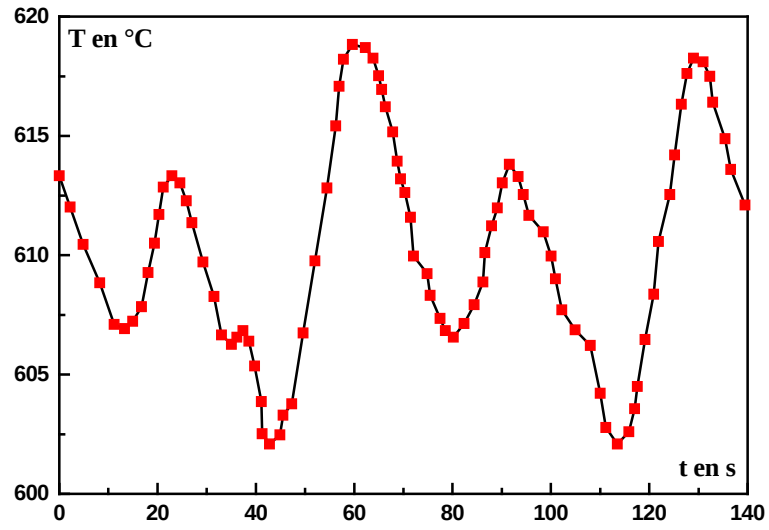


APPLICATION ON ROCKET MOTOR

MEASUREMENTS on TURBINES

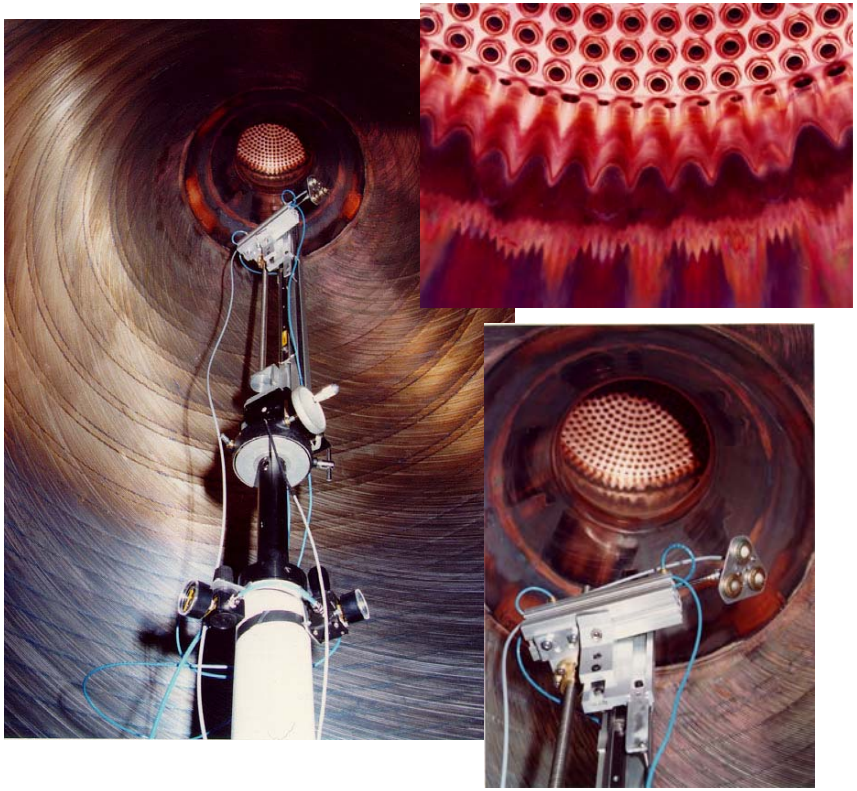


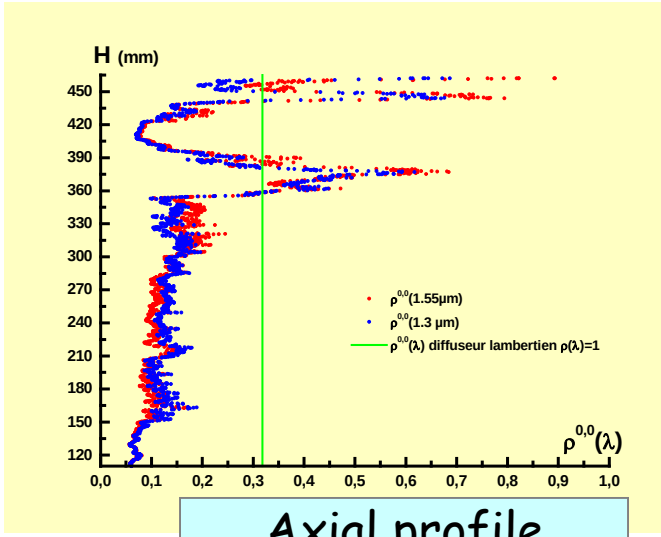
Measurements of T et ρ at 30 kHz



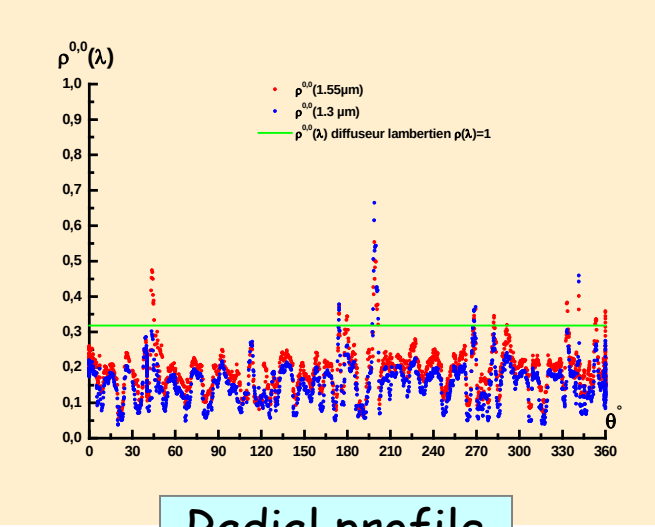
APPLICATION ON ROCKET MOTOR

Ageing diagnostic on motor divergent





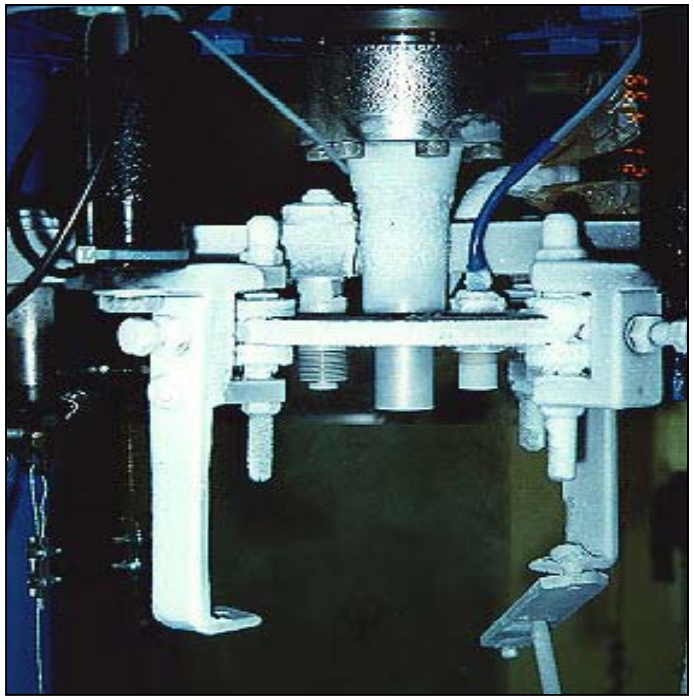
Axial profile

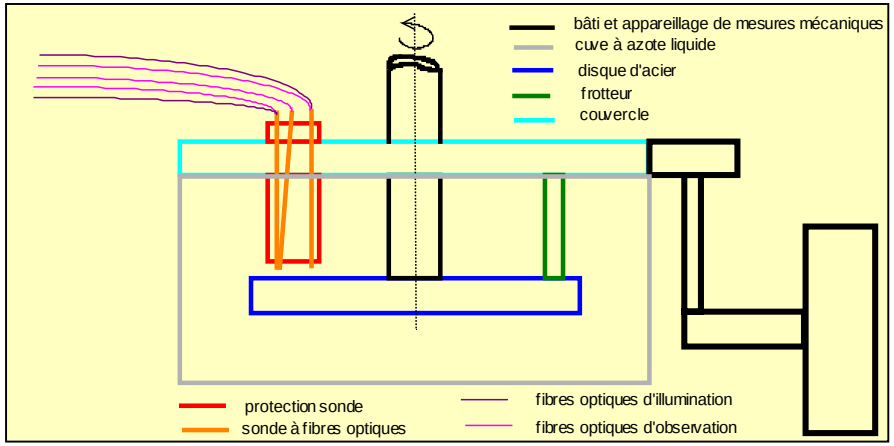


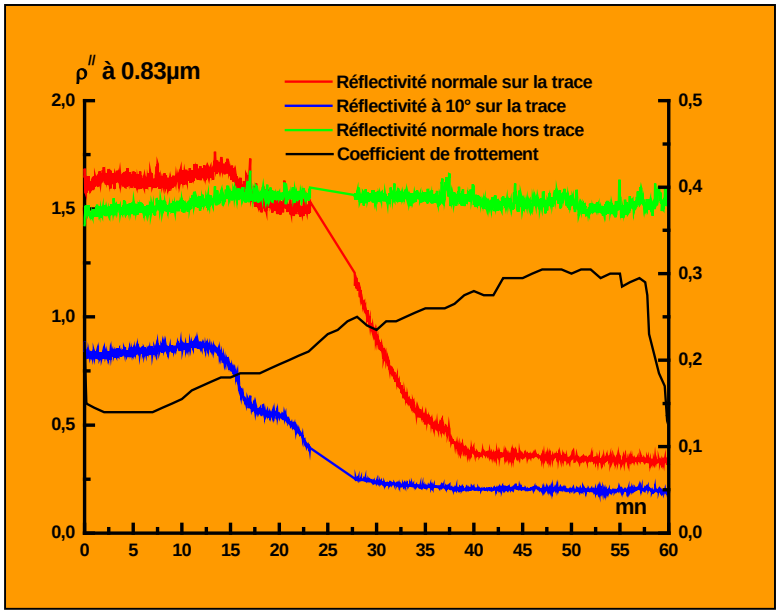
Radial profile

APPLICATION ON ROCKET MOTOR

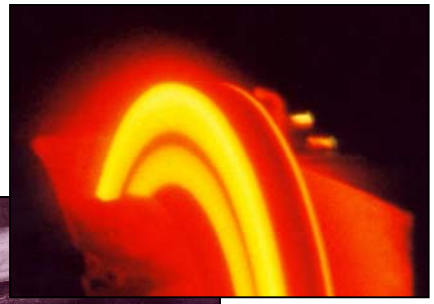
Ageing control of ball bearing surface in cryogenic conditions

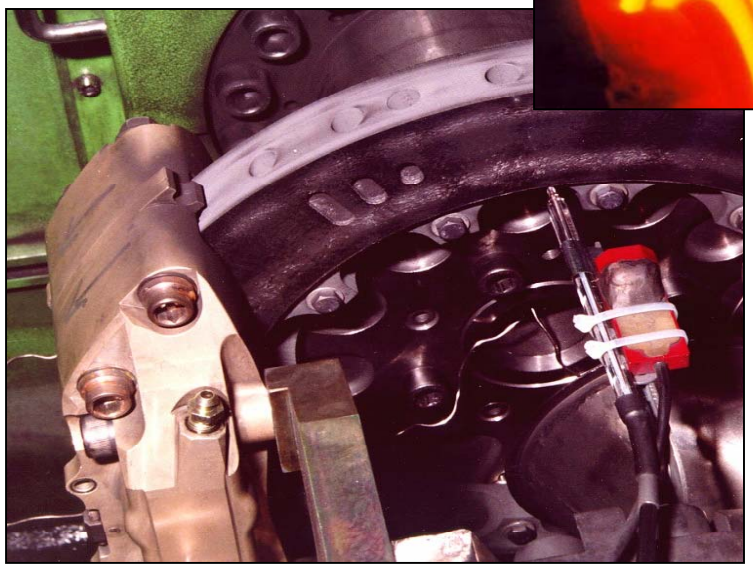


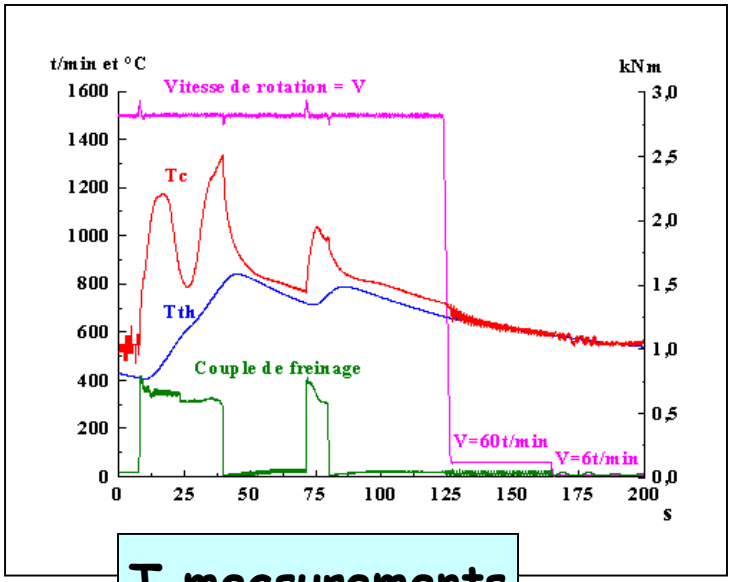




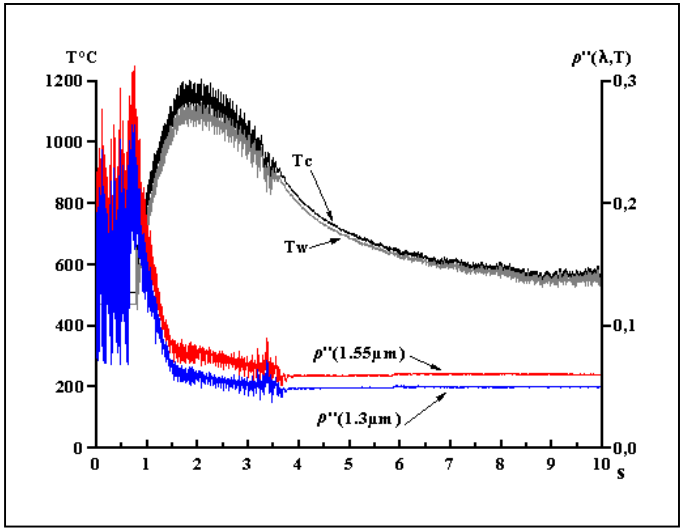
CONTROL for COMPOSITE BRAKE TESTS







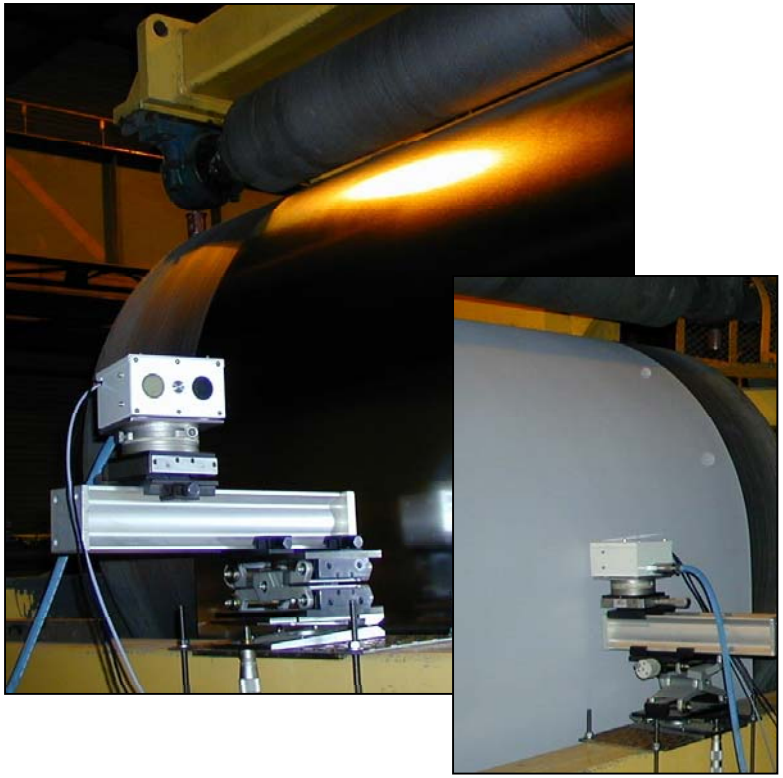
T measurements

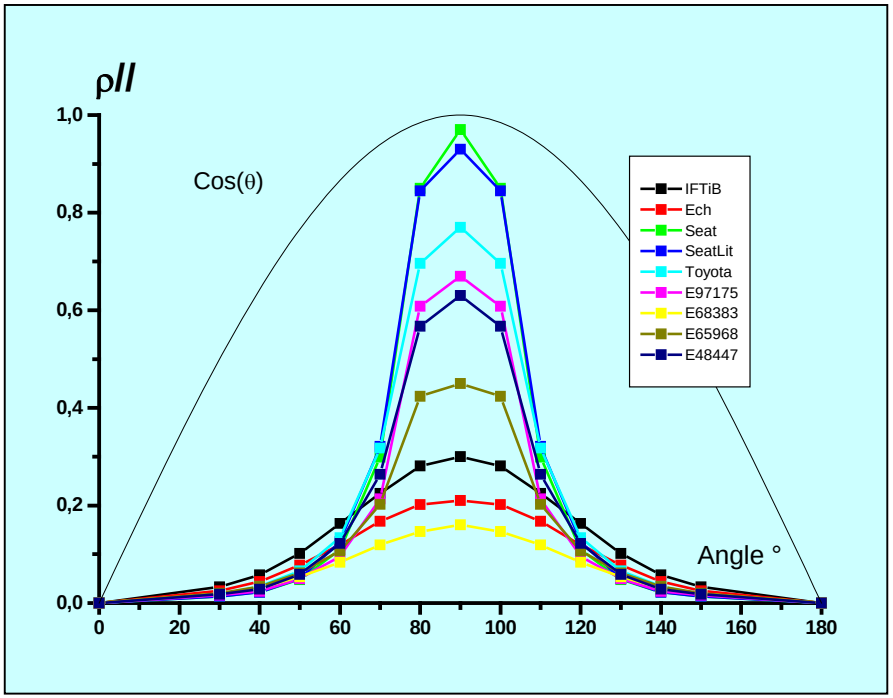


ρ measurements : surface state

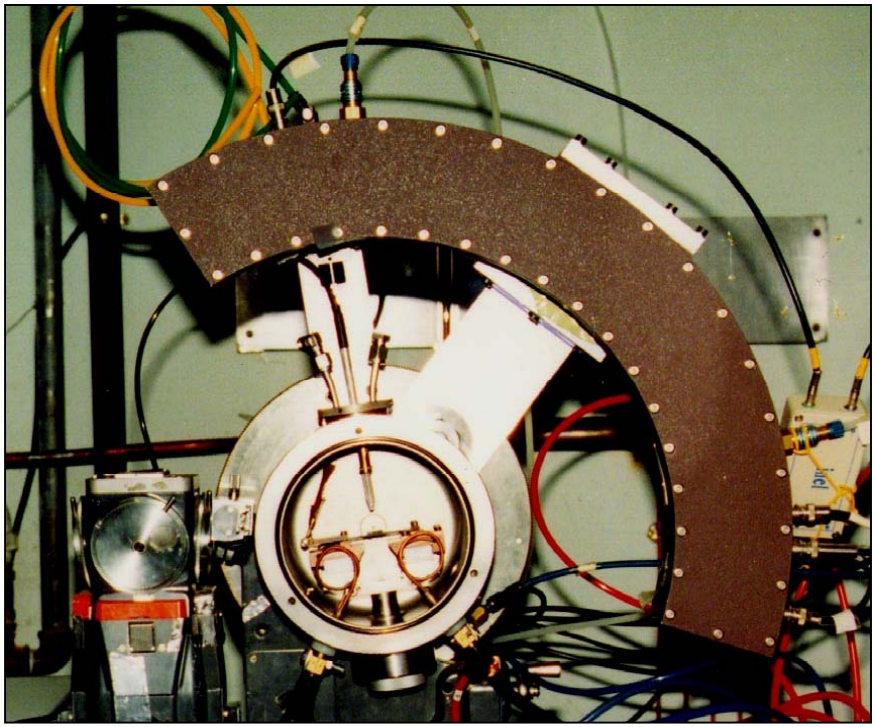
APPLICATION for CAR INDUSTRIE

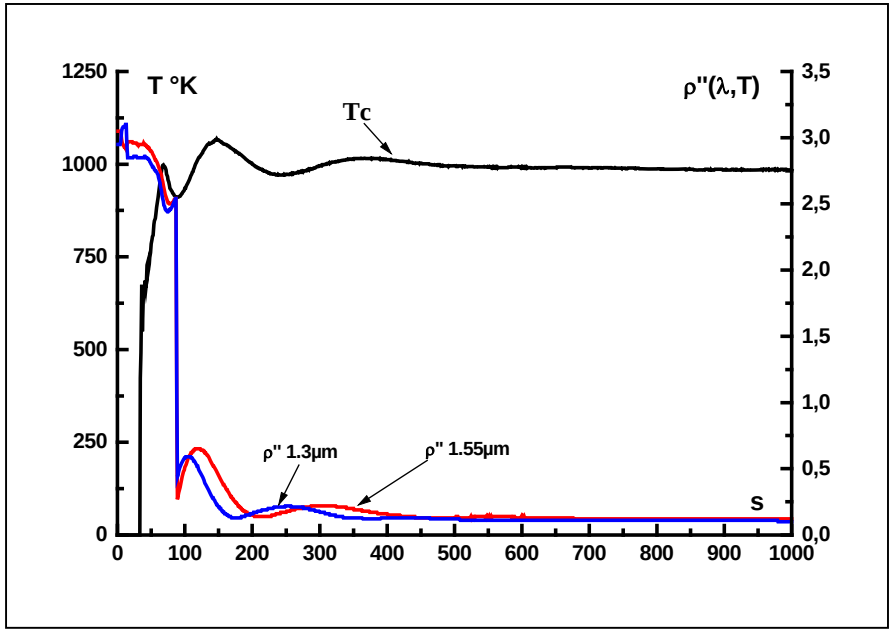
ON LINE MEASUREMENT OF SHEET IRON GALVANISATION





APPLICATION on H.T-X.R.D. CHAMBER





T and ρ measurements

Growing semi-transparent layer studies

In situ characterization of surface at high temperature by using simultaneously a pryroreflectometer and an diffractometer. Applied Surface Science, V135, p 91-96, 1998