ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Temperature Measurement

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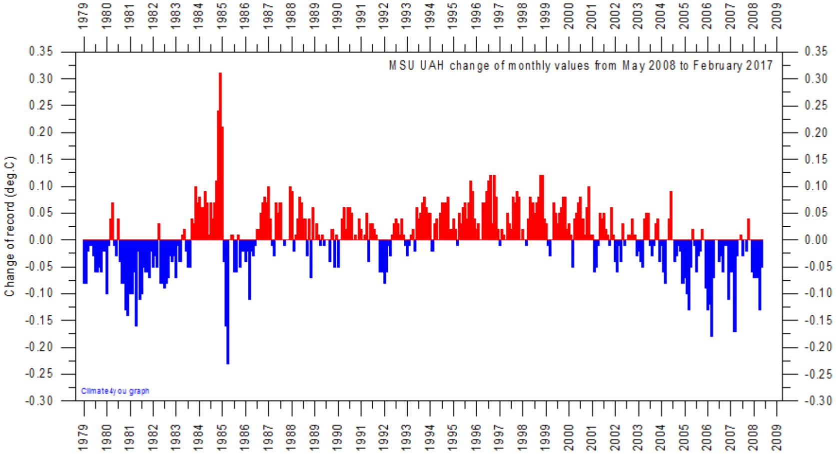
Laboratory of Renewable Energy Sciences and Engineering

Motivation


37.0 c


MSU UAH change of monthly values from May 2008 to February 2017
Change of record (deg.C)
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0.05
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Climate4you graph

Course structure

1. Temperature sensors
   1. Resistance Temperature Detectors (RTDs)
   2. Thermocouples
   3. Others
   4. Summary
2. Basics of radiation
   1. Electromagnetic spectrum
   2. The black body
   3. Various laws
3. IR thermography
   1. Principle of measurement
   2. IR detector
   3. Applications
   4. Summary
4. Other methods
5. Lab example

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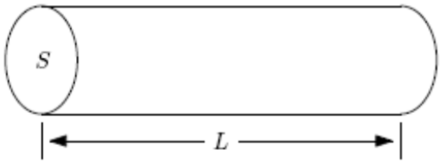
1.1 Resistance Temperature Detectors (RTDs)

- Principle:



$$R = \rho \cdot \frac{L}{S}$$

  - $R(\Delta T) = R_0 \cdot (1 + \alpha_R \cdot \Delta T)$
  - Measurement of electric resistance → Determination of temperature

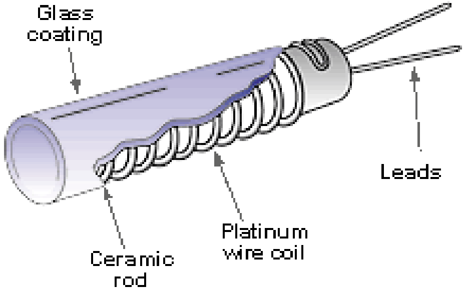
- General:
  - Based on the temperature dependent electric resistance of metals
  - Metals: platinum, tungsten, nickel
  - Types: positive/negative temperature coefficient

- Performance:
  - Measurement range: −200 °C – 850 °C
  - Response time: <10 ms (Ni on polymer film)
  - Linearity: depending on type, range from 0.1 to 5%

Source: Lecture «Technique de mesure: Mesure de température», spring 2016

1.1 Resistance Temperature Detectors (RTDs)

- Example: Pt100:
  - Platinum wire coil
  - Nominal resistance for 0°C: 100 Ω
  - Temperature range: -200°C – 850°C
  - Temp. coefficient: $\alpha_R \approx 4 \cdot 10^{-3}$ (1/K)
  - Accuracy (high quality sensors): $\Delta T = \pm (0.15 + 0.002 \times T)$



- Other platinum elements: Pt500, Pt1000, etc.
  - Higher accuracy, higher price
- Other temp. coefficient:

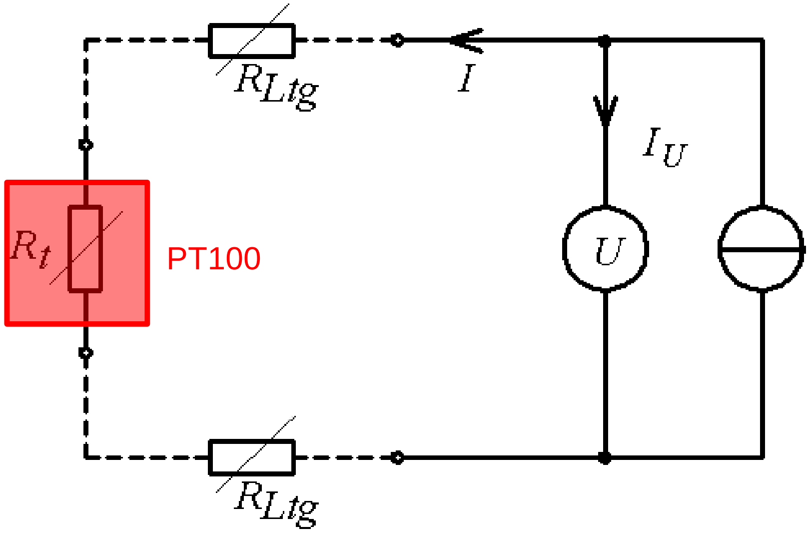
Material	Temperature Coefficient (1/K)
Platinum	0.00392
Tungsten	0.0048
Nickel	0.0067
Copper	0.0043
Gold	0.004
Silver	0.0041

Source: http://www.engineeringtoolbox.com/rtd-termal-resistive-d_498.html

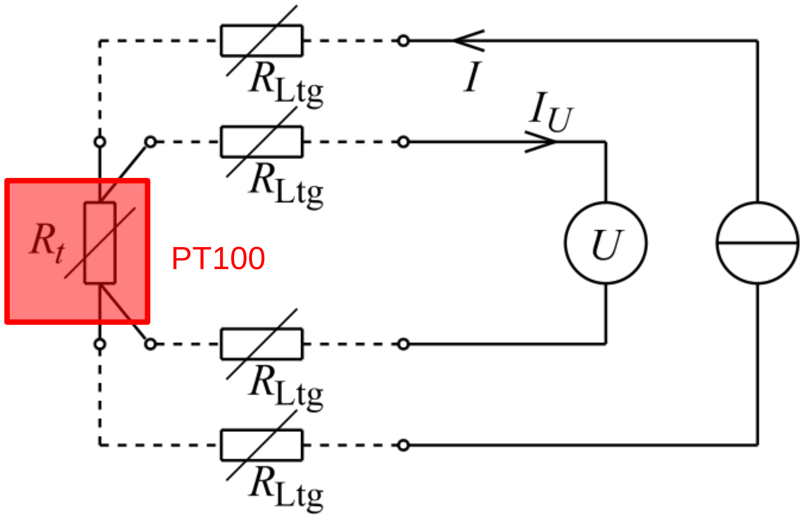
1.1 Resistance Temperature Detectors (RTDs)

- Measurement of R(ΔT): 2-wire vs. 4-wire configuration

2-wire configuration



4-wire configuration



$$U = I \cdot \left(R_t + 2 \cdot R_{Ltg}\right)$$

$$I_U \ll I$$

$$U \approx I \cdot R_t$$

→ Tradeoff between costs (wires) and accuracy

Schematics: https://de.wikipedia.org/wiki/Vierleitermessung

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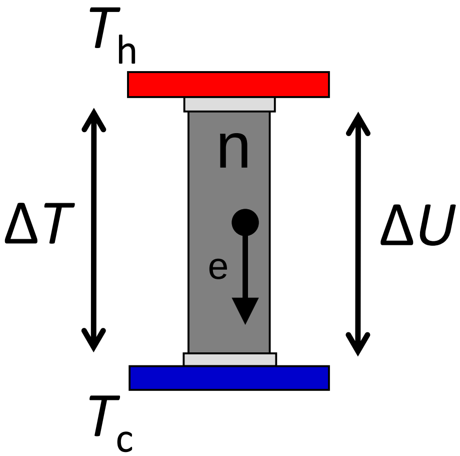
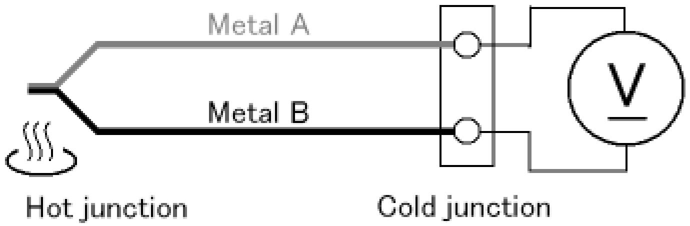
1.2 Thermocouples



- Seebeck effect:
  - Discovered by Th. Seebeck in 1821
  - Temperature difference induces electron gradient
  - Seebeck effect: $\Delta V = S \cdot \Delta T$



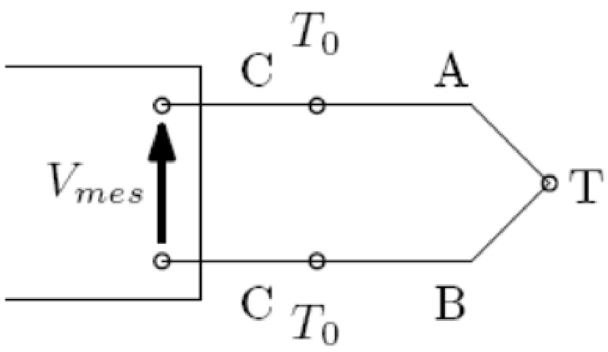
- Principle of thermocouple («junction»):
  - Based on Seebeck effect
  - Combination of two different metals

- Performance:
  - Precisions: 0.1 – 3°C
  - Response time: 0.05 s or higher

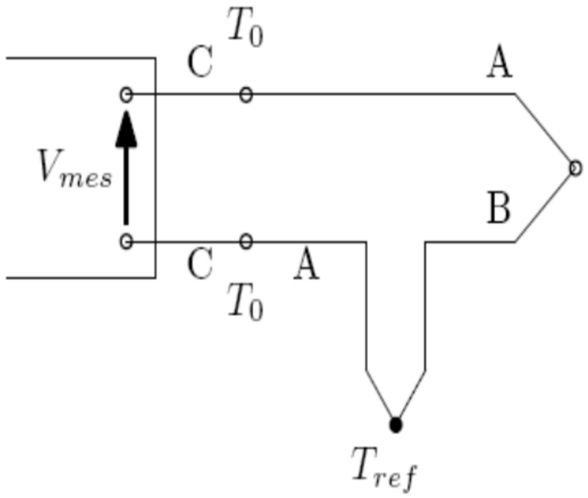
Source: Lecture «Technique de mesure: Mesure de température», spring 2016

1.2 Thermocouples

- Problem of cold junction compensation:
  - T_0 is unknown
  - Temperature difference only
  - $V_{mes} = S_C \cdot (T_0 - T_m) + S_A \cdot (T - T_0) + S_B \cdot (T_0 - T) + S_C \cdot (T_m - T_0)$
  - $V_{mes} = S_A \cdot (T - T_0) + S_B \cdot (T_0 - T)$



- Compensation by reference temperature T_{ref}
  - Known temperature T_{ref}
  - Two thermocouples of the same type
  - $V_{mes} = S_C \cdot (T_0 - T_m) + S_A \cdot (T - T_0) + S_B \cdot (T_{ref} - T) + S_A \cdot (T_0 - T_{ref}) + S_C \cdot (T_m - T_C)$
  - $V_{mes} = S_A \cdot (T - T_{ref}) + S_B \cdot (T_{ref} - T)$



- Compensation without reference temperature:
  - Measurement of T_0 by sensors
  - Integrated circuit with electronic compensation
  - Standard data acquisition has T_0 compensation on board

Source: Lecture «Technique de mesure: Mesure de température», spring 2016

1.2 Thermocouples

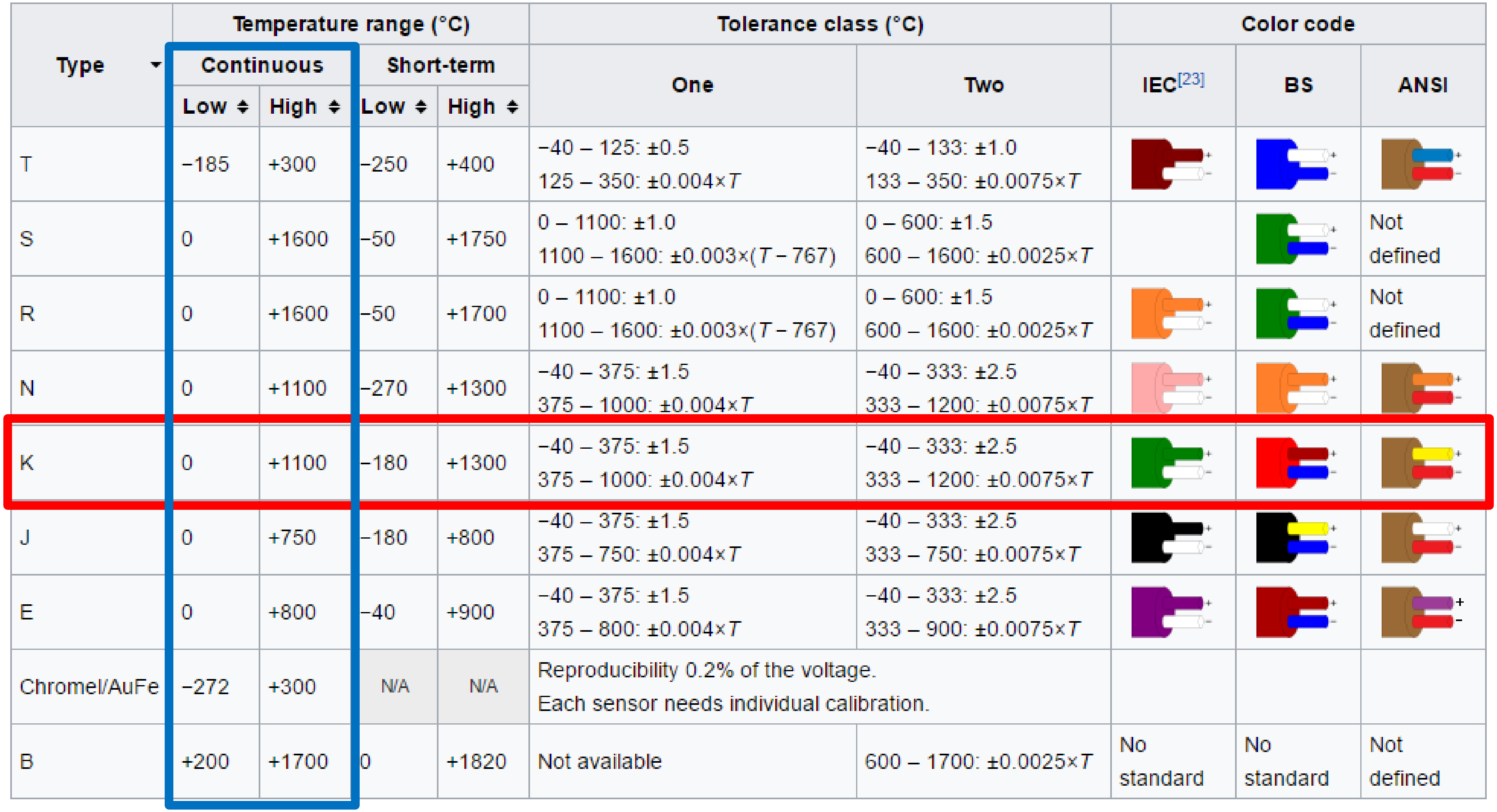
- Thermocouples types:

Type	Couples	Seebeck coeff (µV/K)
E	Chromel-Constantan	60
J	Iron-Constantan	51
T	Copper-Constantan	40
K	Chromel-Alumel	40
N	Nicrosil-Nisil	38
S	Pt (10% Rh)-Pt	11
B	Pt (30% Rh)-Pt (6% Rh)	8
R	Pt (13% Rh)-Pt	12

Source: https://www.electronics-cooling.com/2006/11/the-seebeck-coefficient/

1.2 Thermocouples

- Thermocouples types:



Type	Temperature range (°C)				Tolerance class (°C)		Color code		
	Continuous		Short-term		One	Two	IEC[23]	BS	ANSI
	Low	High	Low	High					
T	−185	+300	−250	+400	−40 – 125: ±0.5 125 – 350: ±0.004×*T*	−40 – 133: ±1.0 133 – 350: ±0.0075×*T*			
S	0	+1600	−50	+1750	0 – 1100: ±1.0 1100 – 1600: ±0.003×(*T* − 767)	0 – 600: ±1.5 600 – 1600: ±0.0025×*T*			Not defined
R	0	+1600	−50	+1700	0 – 1100: ±1.0 1100 – 1600: ±0.003×(*T* − 767)	0 – 600: ±1.5 600 – 1600: ±0.0025×*T*			Not defined
N	0	+1100	−270	+1300	−40 – 375: ±1.5 375 – 1000: ±0.004×*T*	−40 – 333: ±2.5 333 – 1200: ±0.0075×*T*			
K	0	+1100	−180	+1300	−40 – 375: ±1.5 375 – 1000: ±0.004×*T*	−40 – 333: ±2.5 333 – 1200: ±0.0075×*T*			
J	0	+750	−180	+800	−40 – 375: ±1.5 375 – 750: ±0.004×*T*	−40 – 333: ±2.5 333 – 750: ±0.0075×*T*			
E	0	+800	−40	+900	−40 – 375: ±1.5 375 – 800: ±0.004×*T*	−40 – 333: ±2.5 333 – 900: ±0.0075×*T*			
Chromel/AuFe	−272	+300	N/A	N/A	Reproducibility 0.2% of the voltage. Each sensor needs individual calibration.				
B	+200	+1700	0	+1820	Not available	600 – 1700: ±0.0025×*T*	No standard	No standard	Not defined

Source: https://en.wikipedia.org/wiki/Thermocouple

→ Check datasheet of manufacturer

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1.3 Others

- Thermistors
  - Similar to Resistance Temp Detectors
  - Material: metals, semiconductors etc.

- Silicon bandgap temperature sensors
  - Integrated circuits
  - Related to electrical engineering

- Quartz sensors
  - Quartz crystal
  - Temperature dependent frequency

Source: Lecture «Technique de mesure: Mesure de température», spring 2016

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1.4 Summary

	RTDs	Thermocouples
Price	High	Moderate
Temp. range	-200°C – 850°C	-270°C – 1700°C
Accuracy	Good (<2°C)	Moderate (~3°C)
Linearity	High	Moderate
Sensitivity	High	Moderate
Applications	Technical	Technical

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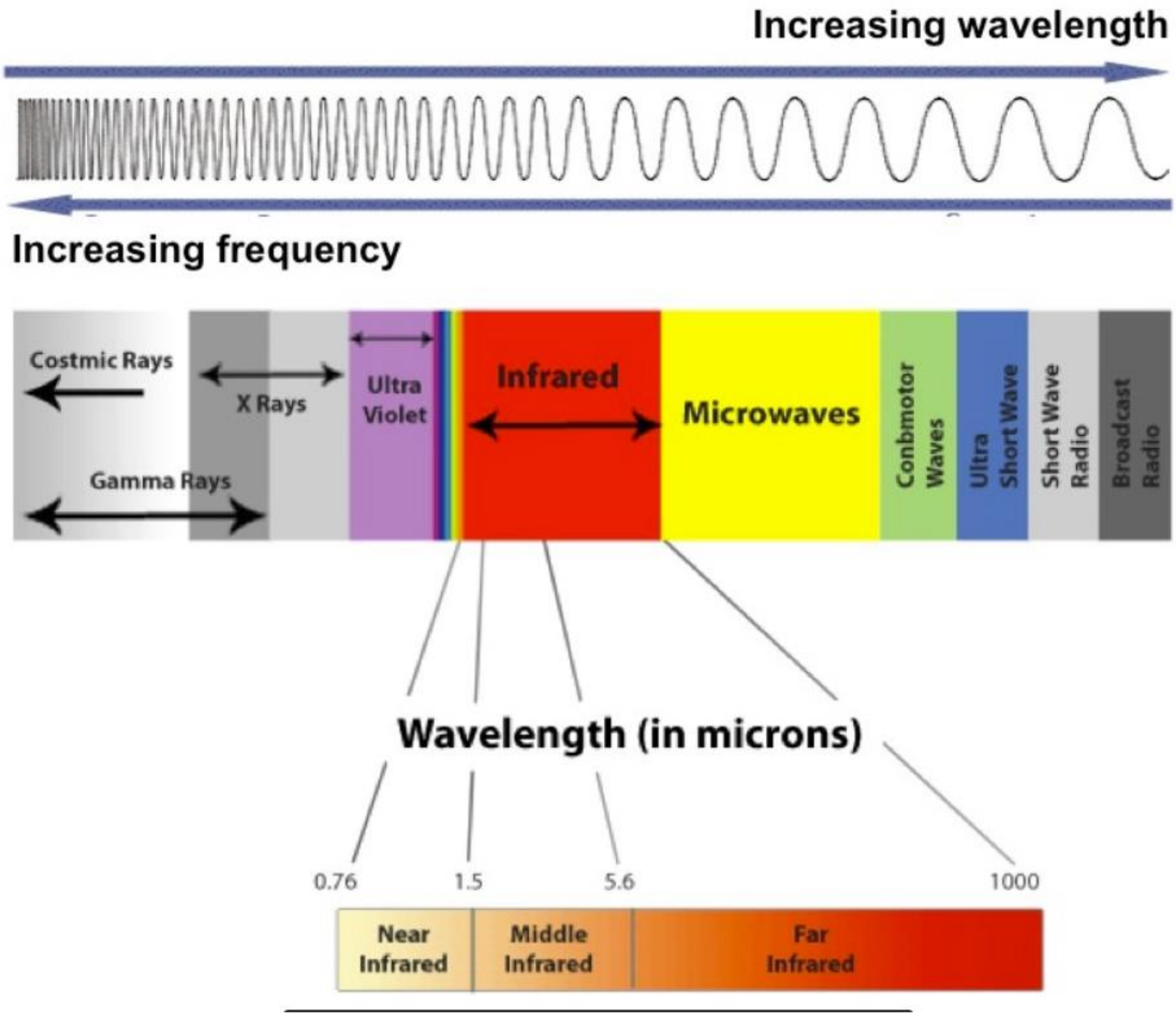
2.1 Electromagnetic spectrum



Source: Lecture «Technique de mesure: Mesure de température», spring 2016

2.1 Electromagnetic spectrum

- Matter emits and absorbs electromagnetic radiation permanently
- For temperature ranges as found on earth the emitted radiation of matter corresponds to the infrared spectrum
- The visible range corresponds to wave lengths from 0.4 – 0.8 µm
- The IR band spans from 0.8 – 1000 µm, with following subranges:
  - Near infrared (NIR): 0,8 à 1.5 µm
  - Mid infrared (MIR): 1.5 à 6 µm
  - Far infrared (FIR): 6 à 1000 µm
- In thermography normally the spectrum from 2 – 15 µm is used, in particular within the band **7 – 15 µm**.

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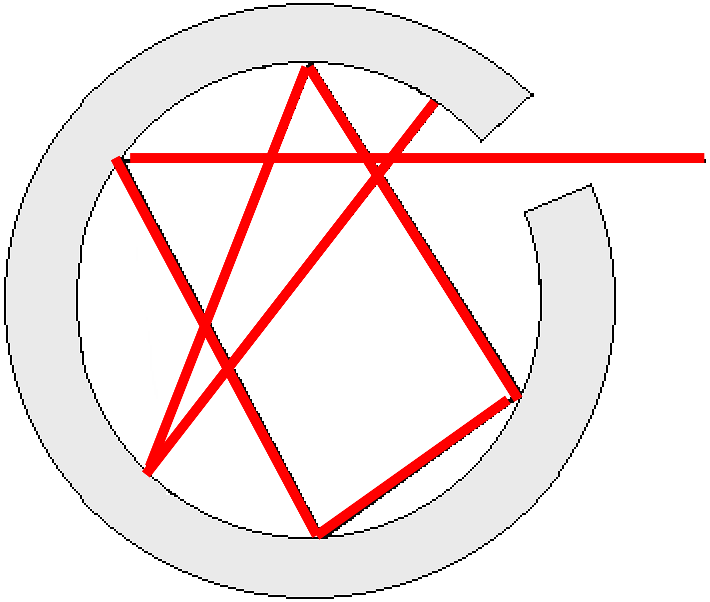
2.2 Black body

- A blackbody absorbs all incident radiation, regardless of wavelength and direction → **perfect absorber**
- For a prescribed temperature and wavelength, no surface can emit more energy than a blackbody → **perfect emitter**
- A blackbody is an idealized body, which does not exist in reality, but is used for the fundamentals of radiation



Source: Lecture «Advanced heat transfer», Prof. Sophia Haussener, Feb 2016

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2.3 Planck's law

$$E_{b\lambda}\left(T,\lambda\right)=\frac{C_1}{n^2\lambda^5\left[e^{C_2/(n\lambda T)}-1\right]},\qquad n=\text{const}\qquad \left(\mathrm{W\,m^{-2}\mu m^{-1}}\right)$$

$$\lambda=\frac{\lambda_0}{n}$$

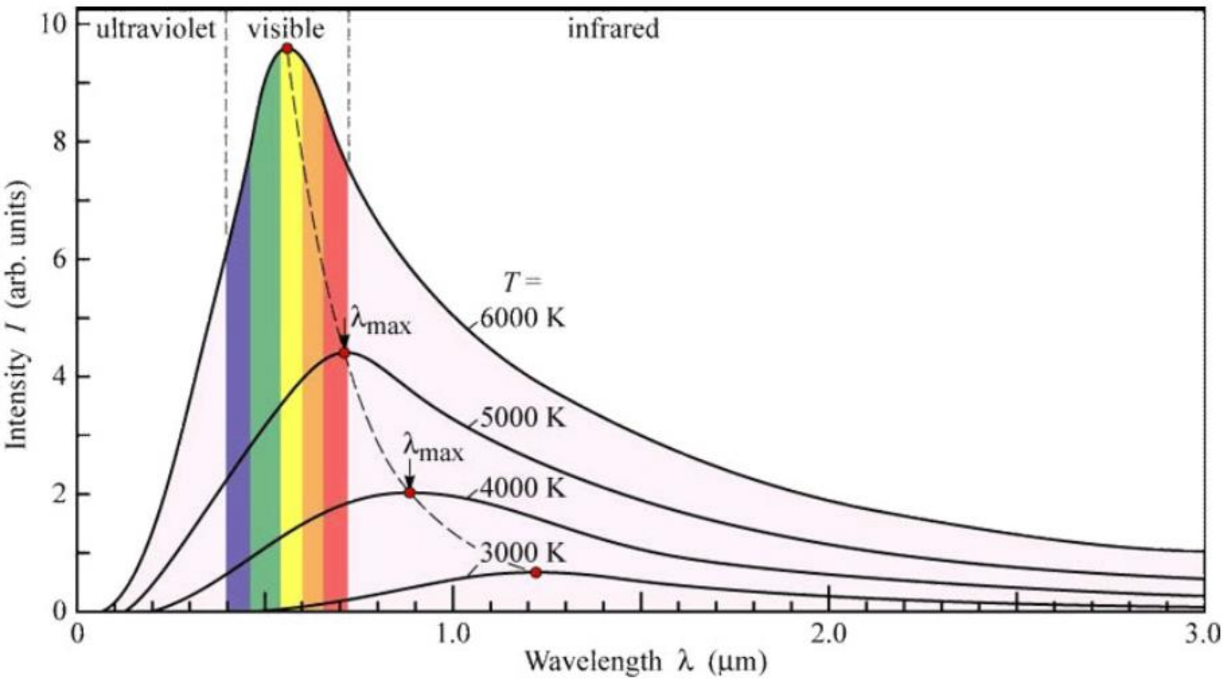
C_1 First radiation constant $\left(\begin{array}{l}=2\pi h c_0^2=3.7418\text{x}10^{-16}\ \mathrm{W\,m^2}\\ =3.7418\times10^{8}\ \mathrm{W\,\mu m^4 m^{-2}}\end{array}\right)$

C_2 Second radiation constant $\left(=hc_0/k=14{,}388.69\ \mathrm{\mu m K}\right)$

h Planck constant $\left(=6.6260755\times10^{-34}\ \mathrm{Js}\right)$

c_0 speed of light in vacuum $\left(=2.998\times10^{8}\ \mathrm{m\,s^{-1}}\right)$

k Boltzmann constant $\left(=1.380658\times10^{-23}\ \mathrm{JK^{-1}}\right)$



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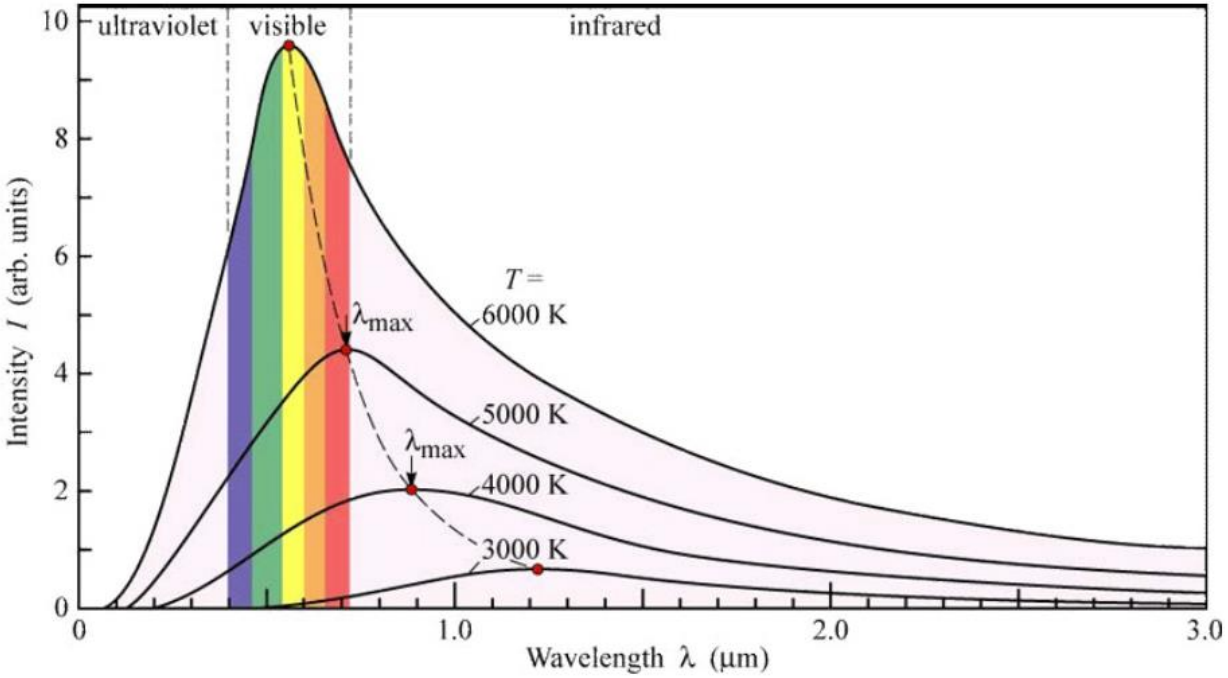
2.3 Wien's displacement law

- Idea: find maxima of emission as function of wave length
  - Derivative of Planck's law with respect to λ must equal zero



$$\left(n\lambda T\right)_{max} = C_3 = 2897.8\ \mu mK$$

«The higher the temperature the lower the max. wave length»

Source: Lecture «Advanced heat transfer», Prof. Sophia Haussener, Feb 2016

2.3 Stefan-Boltzmann law

- Total power emitted a blackbody (for all wave lengths):

$$E_b(T) = \int_{\lambda=0}^{\infty} E_{b\lambda}(T,\lambda)\,d\lambda$$

$$= C_1 n^2 T^4 \int_0^{\infty} \frac{d(n\lambda T)}{(n\lambda T)^5\left[e^{C_2/(n\lambda T)} - 1\right]}$$

$$= \left[\frac{C_1}{C_2^4}\int_0^{\infty}\frac{\xi^3\,d\xi}{e^{\xi}-1}\right] n^2 T^4$$

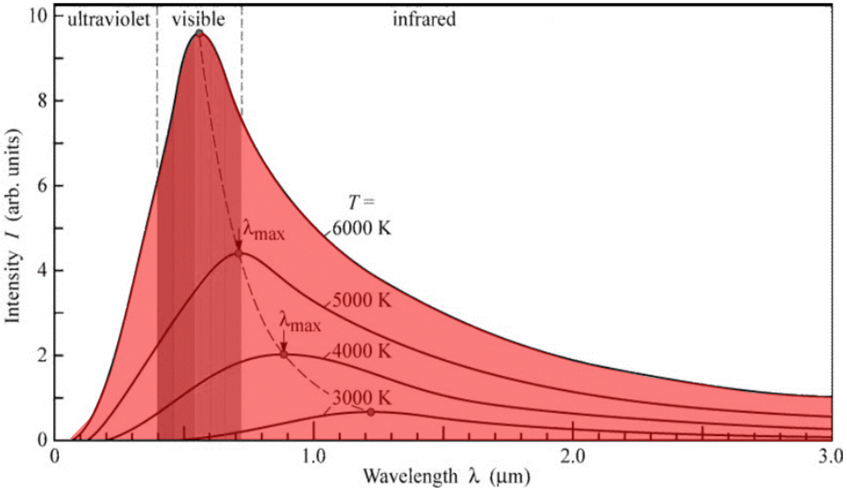
$$\xi = \frac{C_2}{n\lambda T}$$

$$= \frac{\pi^4 C_1}{15 C_2^4} n^2 T^4$$

$$= n^2 \sigma T^4$$

$\text{for } n = 1$

$$E_b(T) = \sigma T^4$$



Stefan-Boltzmann constant

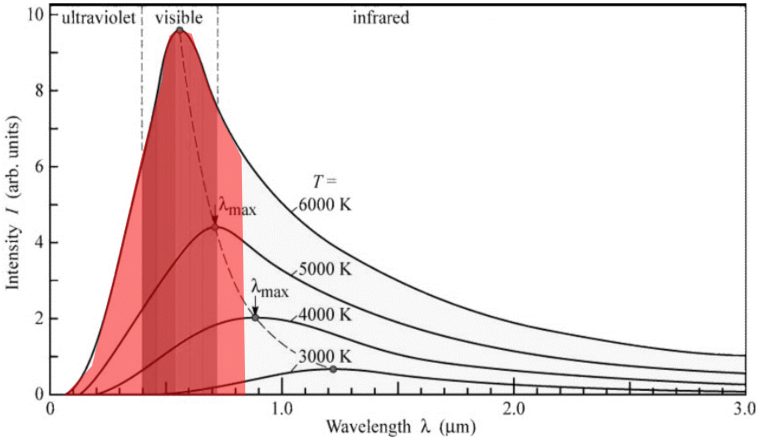
$$\sigma = 5.6704 \times 10^{-8}\left(\mathrm{W\,m^{-2}K^{-4}}\right)$$

Source: Lecture «Advanced heat transfer», Prof. Sophia Haussener, Feb 2016

2.3 Blackbody emission within a spectral band

- **Fraction of blackbody emissive power (blackbody fractional function)**

$$f\left(n\lambda T\right)=f_{0-n\lambda T}=\frac{\int_{0}^{\lambda}E_{b\lambda}\left(T,\lambda\right)d\lambda}{\int_{\lambda=0}^{\infty}E_{b\lambda}\left(T,\lambda\right)d\lambda}$$



$$=\frac{\int_{0}^{\lambda}E_{b\lambda}\left(T,\lambda\right)d\lambda}{n^2\sigma T^4}=\int_{0}^{n\lambda T}\frac{E_{b\lambda}\left(T,\lambda\right)}{n^3\sigma T^5}d\left(n\lambda T\right)=\frac{15}{\pi^4}\int_{\xi=C_2/(n\lambda T)}^{\infty}\frac{\xi^3\,d\xi}{e^{\xi}-1}=\frac{15}{\pi^4}\sum_{m=1}^{\infty}\left[\frac{e^{-m\xi}}{m}\left(\xi^3+\frac{3\xi^2}{m}+\frac{6\xi}{m^2}+\frac{6}{m^3}\right)\right]$$

$$\xi=\frac{C_2}{n\lambda T}\qquad\sigma=\frac{\pi^4 C_1}{15C_2^4}$$

↓

$$\left(e^{\xi}-1\right)^{-1}=e^{-\xi}+e^{-2\xi}+e^{-3\xi}+\dots$$

$$f_{n\lambda_1T-n\lambda_2T}=f_{0-n\lambda_2T}-f_{0-n\lambda_1T}=f\left(n\lambda_2T\right)-f\left(n\lambda_1T\right)$$

↓

$$E_{b,\lambda_1-\lambda_2}\left(T\right)=E_{b,n\lambda_1T-n\lambda_2T}=\int_{\lambda=\lambda_1}^{\lambda_2}E_{b\lambda}\left(T,\lambda\right)d\lambda$$

$$=\left[f\left(n\lambda_2T\right)-f\left(n\lambda_1T\right)\right]n^2\sigma T^4$$

$n\lambda T$ (μm·K)	$f(n\lambda T)$
1’448	0.01
2’898	0.25
4’107	0.50
6’148	0.75
22’890	0.99

Source: Lecture «Advanced heat transfer», Prof. Sophia Haussener, Feb 2016

2.3 Kirchhoff’s law

- A real body is « non-black » or « gray »

Emissivity $0 < \varepsilon < 1$	= Ratio of the flux emitted by a **real surface** to that emitted by a **blackbody**
Absorptivity $0 < \alpha < 1$	= Ratio of the flux absorbed by a surface to the incident flux (opaque materials)
Reflectivity $0 < \rho < 1$	= Ratio of the flux reflected by a surface to the incident flux
Transmissivity $0 < \tau < 1$	= Ratio of the flux transmitted through an interface of a semitransparent material to the incident flux

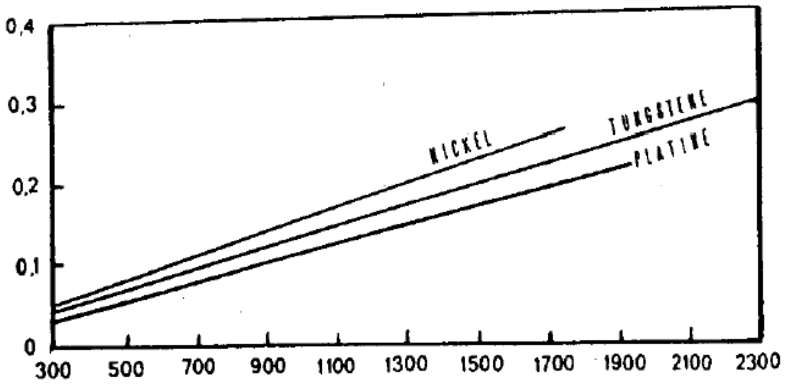
- Kirchhoff: $\alpha = \varepsilon$: «A good emitter is also a good absorber»
- Energy conservation: $\alpha + \rho + \tau = 1$
- The laws from the previous slides have to be extended, e.g.:
  - $E_\lambda(T,\lambda) = \varepsilon(T,\lambda) \cdot E_{b,\lambda}(T,\lambda)$

Source: Lecture «Advanced heat transfer», Prof. Sophia Haussener, Feb 2016

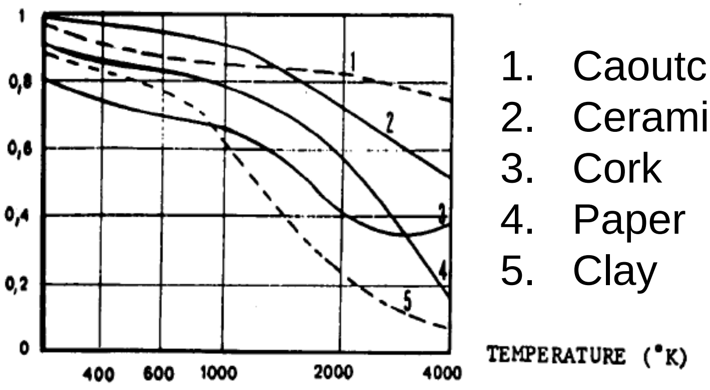
2.3 Emissivity dependencies

- **Material:**
  - Metals have generally low emissivities
  - Other, non-metallic materials have often $\varepsilon(\lambda) > 0.8$
  - Surfaces with high roughness have higher emissivities

- **Temperature:**
  - For metals: ε increases with the temperature
  - Other, non-metallic materials: ε decreases with the temperature



Emissivité totale ε (métaux)



1. Caoutchouc
2. Ceramics
3. Cork
4. Paper
5. Clay

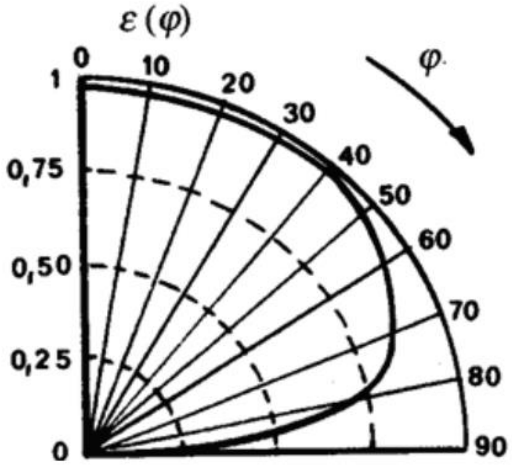
Emissivité totale ε (diélectriques)

Source: Lecture «Technique de mesure: Mesure de température», spring 2016

2.3 Emissivity dependencies

- **Wave length:**
  - The emissivities are selective, i.e. in some ranges the emissivity is high whereas in others it is low.
    Example: snow is in the IR spectrum a good absorber, in the visible spectrum a good reflector
  - Wave length dependent emissivities are often approximated as spectral bands where ε = const
    → Use of fractional functions!

- **Direction:**
  - The emissivity varies with angle of view
  - Often ε ≈ const for φ = 0 – 50°



Emissivity of water for λ = 10 µm as a function of angle of view

Source: Lecture «Technique de mesure: Mesure de température», spring 2016

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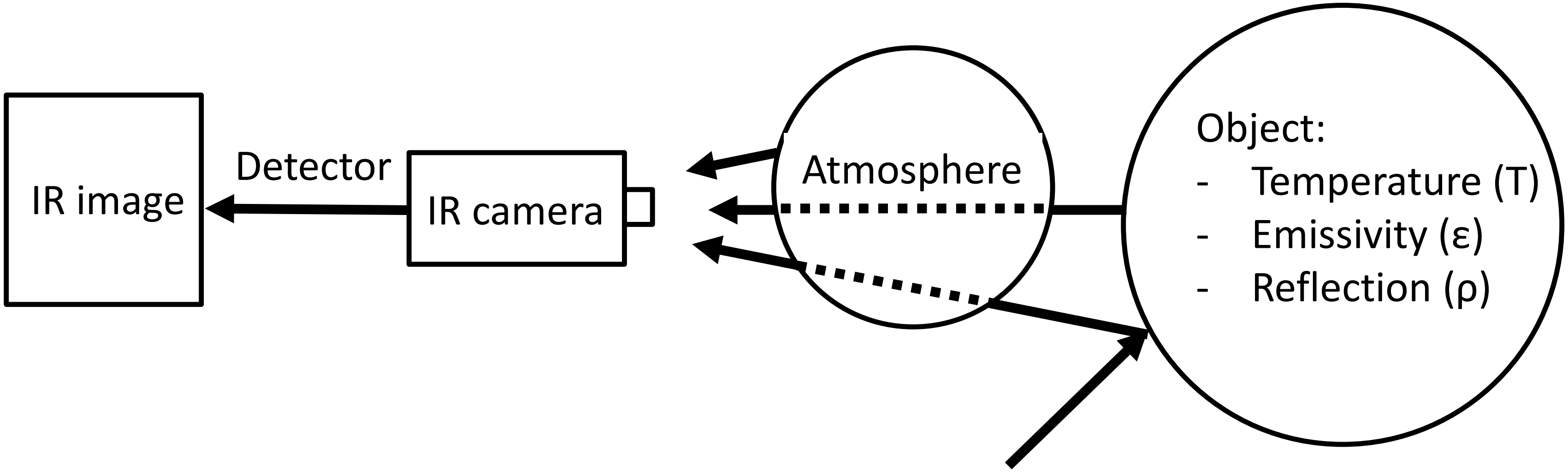
3.1 Measurement principle

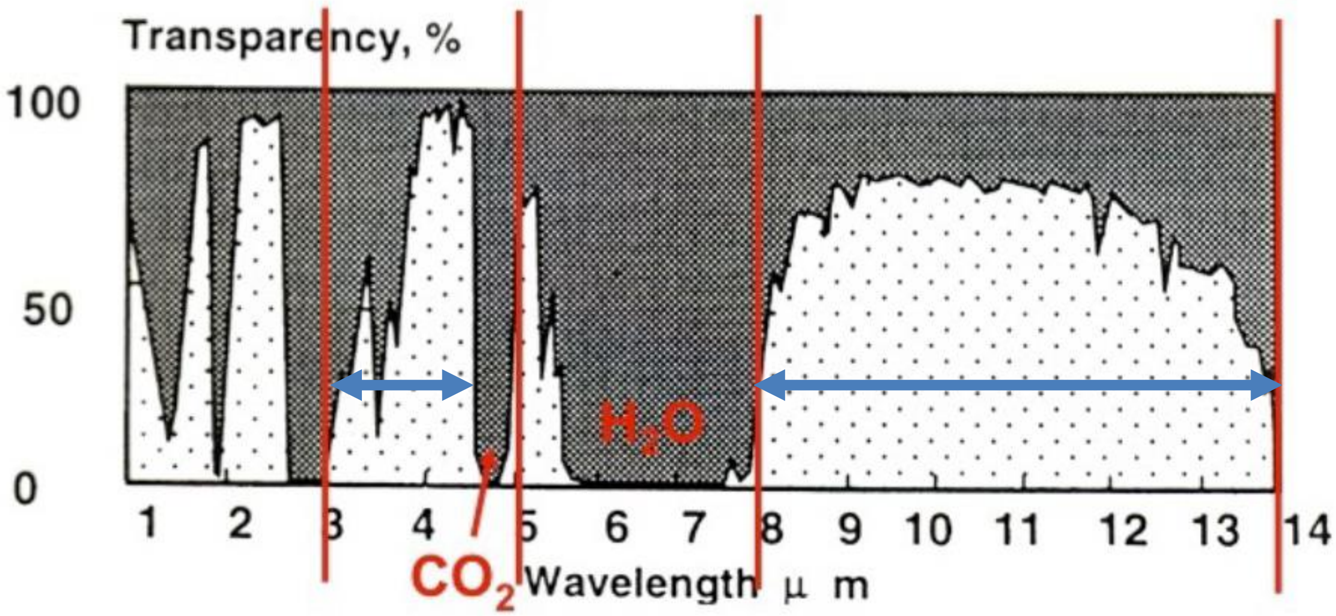


- Measurement of object with temperature T
- Interfering magnitudes:
  - Unknown emissivity of object
  - Reflection from object
  - Atmosphere

Source: Lecture «Technique de mesure: Mesure de température», spring 2016

3.1 Atmospheric Influence

- Water vapor and CO_2 attenuate radiation
  - CO_2 (4.5 – 5 µm) and H_2O (5.5 – 7.5 µm)
  - Two transmission bands: 3 – 4.5 µm and 8 – 14 µm
  - Depending on weather conditions



- In general, IR measurements are done in atmospheric conditions:
  - For technical applications negligible as only short distance

Source: Lecture «Technique de mesure: Mesure de température», spring 2016

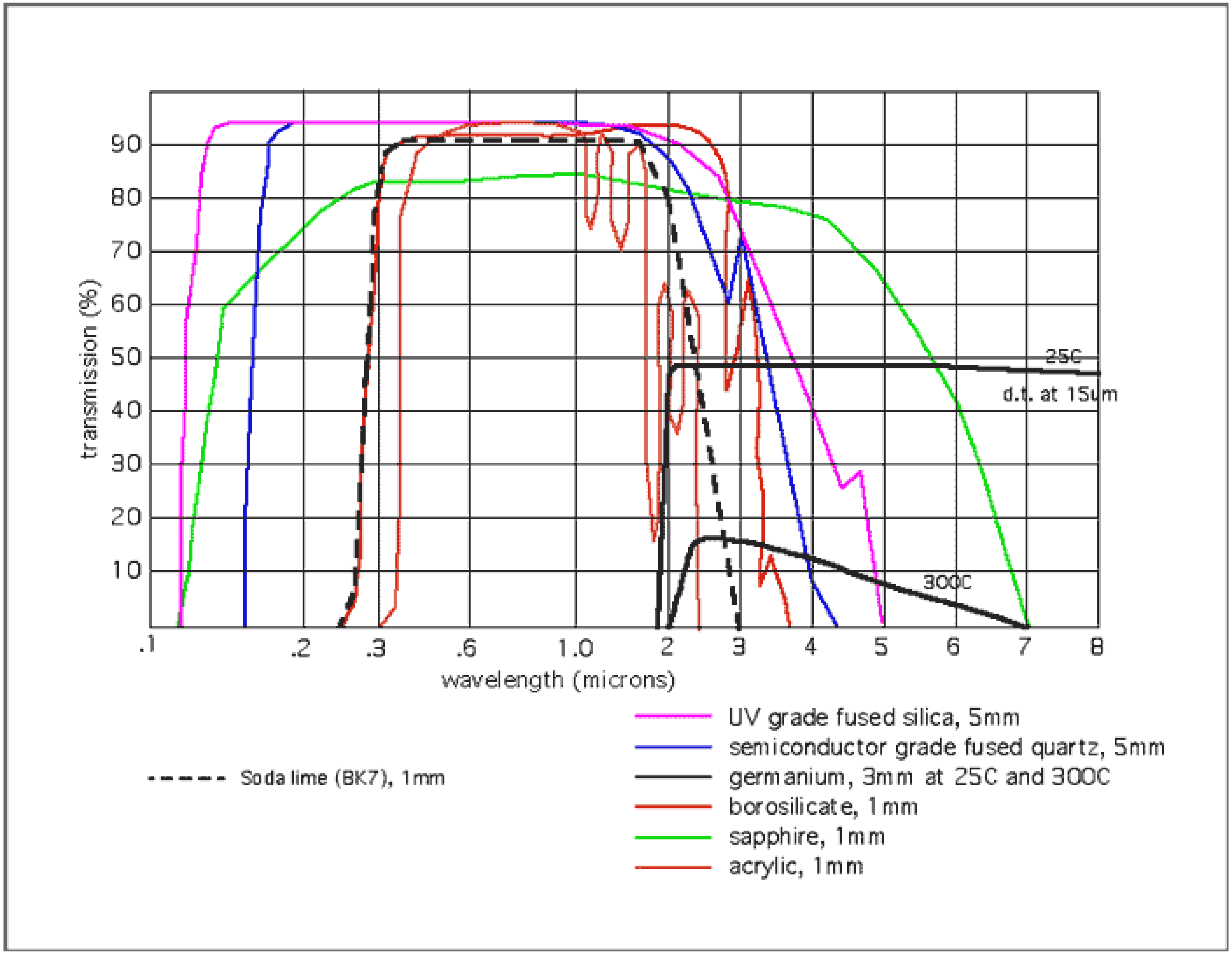
3.1 Emissivity of different materials

- Variety of materials:

Material	Temp (°C)	Range λ (µm)	Emissivity (-)
Aluminium, laminated foil	100	2 – 5	0.09
Concrete	20	2 – 5	0.94
Gold	30	8 – 12	0.01 / 0.10
Ice	<0	8 – 12	0.95
Skin, human	30	2 – 5	0.98
Soil, dry	20	2 – 5	0.90
Steel, oxidized	100	2 – 5	0.74
Steel, polished	100	2 – 5	0.07
Textile	30	8 – 12	0.95
Water	0 – 100	2 – 5, 8 – 12	0.93 – 0.95
Wood	20	2 – 5	0.83

Source: Lecture «Technique de mesure: Mesure de température», spring 2016

3.1 Transmissivity of various glasses



Source: https://www.encole.com/articles/about-sight-glass/

Course structure

1. Temperature sensors
    1. Resistance Temperature Detectors (RTDs)
    2. Thermocouples
    3. Others
    4. Summary
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5. Lab example

3.2 IR detector types

- Two type of detectors exist
- Thermal sensors:
  - Absorption of IR radiation induces temperature change, which is converted into an electric output signal
- Photon or quantum sensors:
  - The electric output signal is proportional to the number of photons of the absorbed IR radiation
- Qualitative overview:

	Thermal	Quantum
Price	Moderate	High
Cooled to ca. 80 K	No	Yes
Resolution	Low	High
Frame rate	Up to 100 Hz	Up to GHz
Sensitivity	Low	High

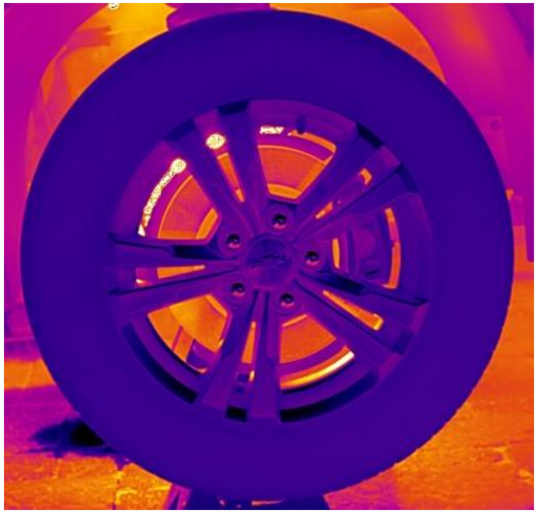
Source: http://www.flir.com/science/display/?id=65982

3.2 IR detector types

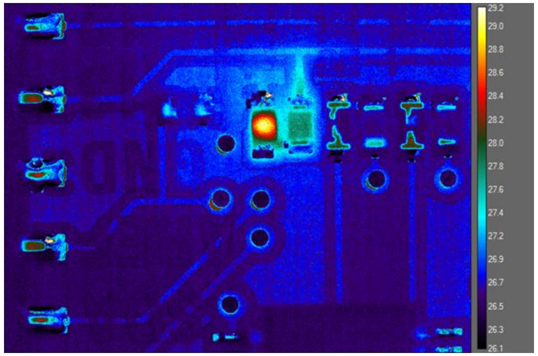
- Thermal vs. quantum detectors

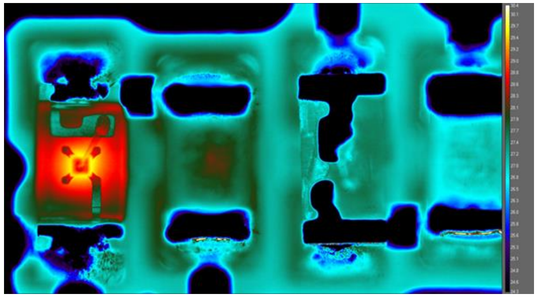
Speed


Rotating Tire at 20mph


Rotating Tire at 20mph

Spatial resolution



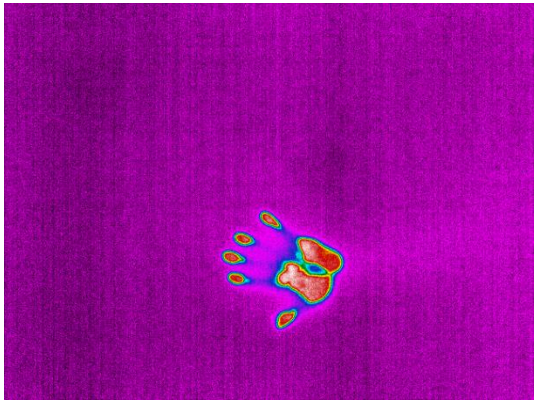

Close-up 4x

Source: http://www.flir.com/science/display/?id=65982

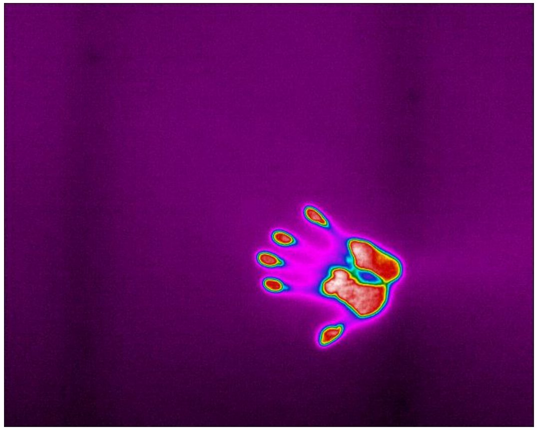
3.2 IR detector types

- Thermal vs. quantum detectors

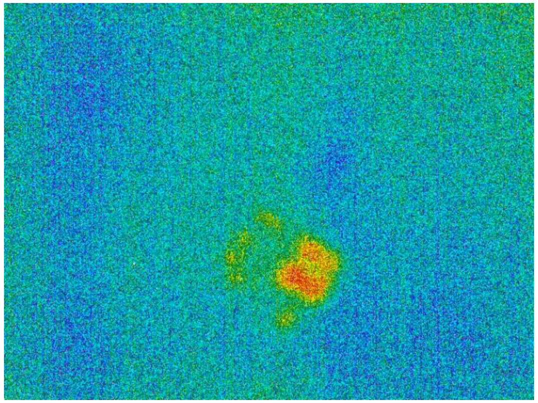
Sensitivity



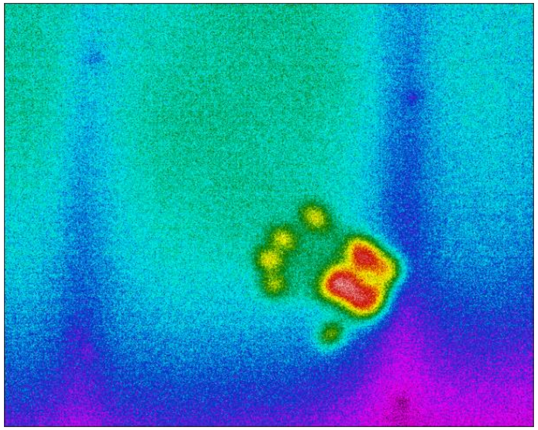
t = 0 min



t = 0 min



t = 2 min

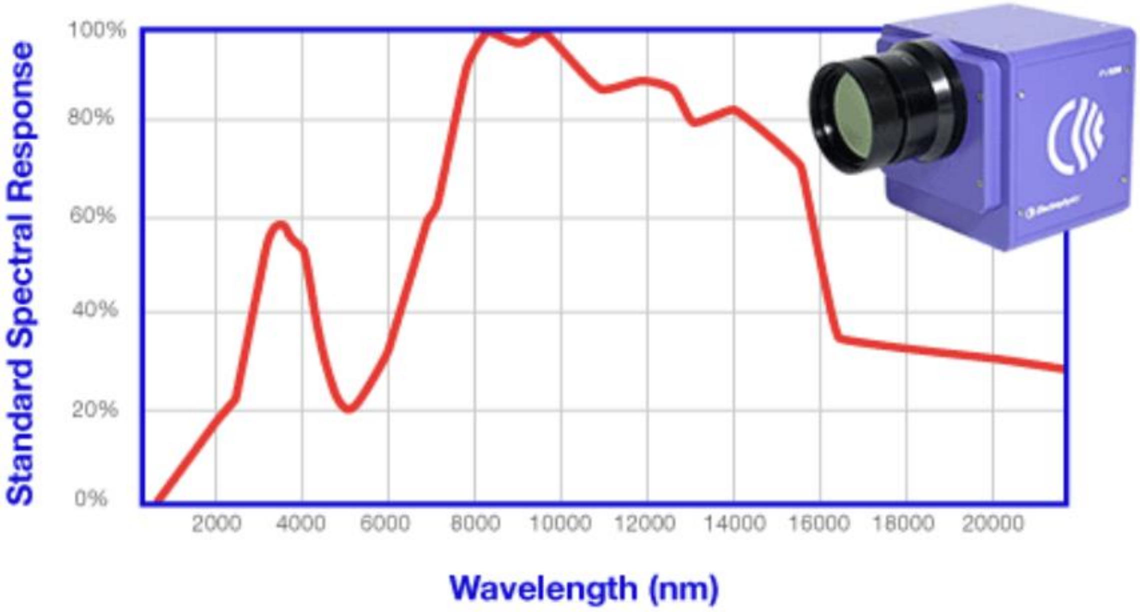


t = 2 min

Source: http://www.flir.com/science/display/?id=65982

3.2 IR detector sensitivity

- The spectral sensitivity s(λ) is the response *dV*(λ) to a flux *d*Φλ(λ)
- *s*(λ) depends on:
  - Wave length
  - Sensor type: quantum or thermal, material, temperature
- Best operation point for highest sensitivity



Source: Lecture «Technique de mesure: Mesure de température», spring 2016

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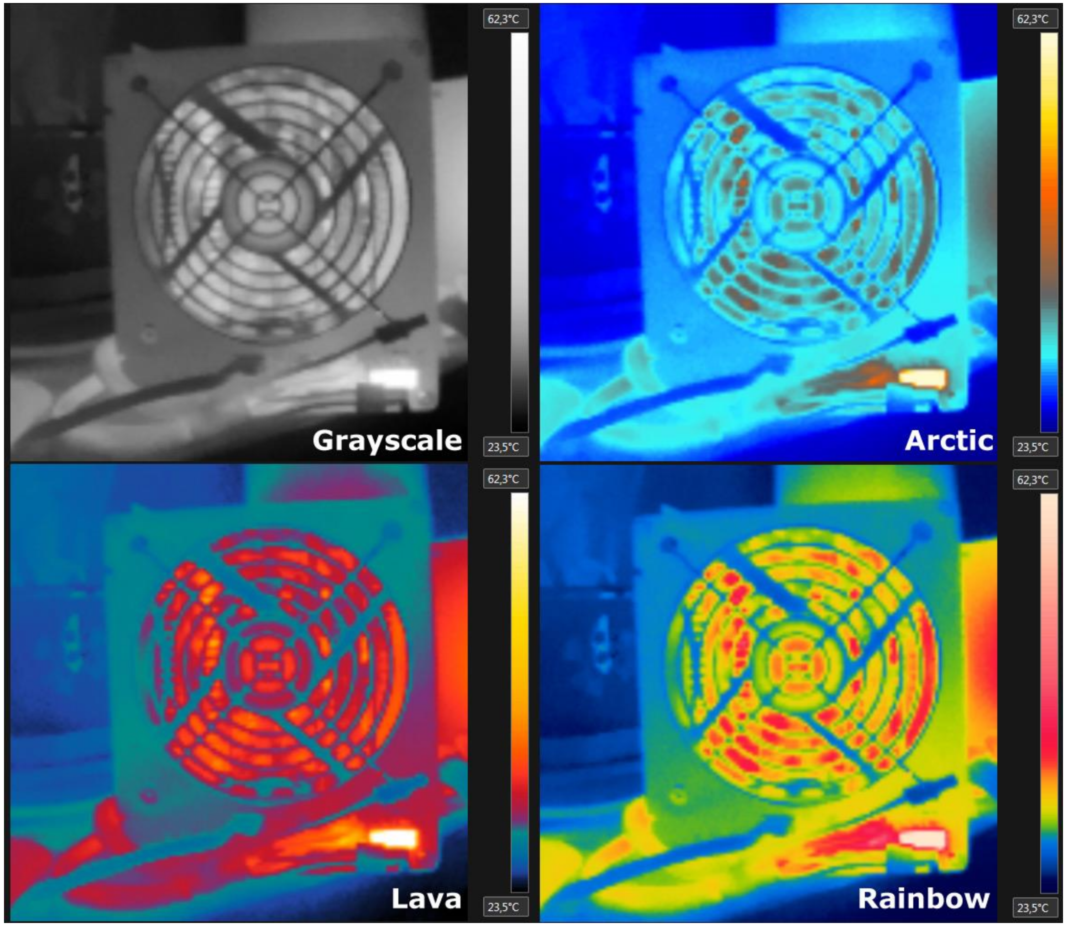
3.3 Live-Demo

- Model FLIR A35sc:
  - Sensor (thermal): Uncooled VoX micro bolometer (7.5 – 13 µm)
  - Spatial resolution: 320 x 256
  - Frame rate: 60 Hz
  - Focal length: f = 9mm
  - Field of view (lens): 48°×39°
  - Temperature range: -40°C to 550°C
  - Price: ~6’000 CHF

Source: http://www.flir.de/automation/display/?id=56341

3.3 False color images

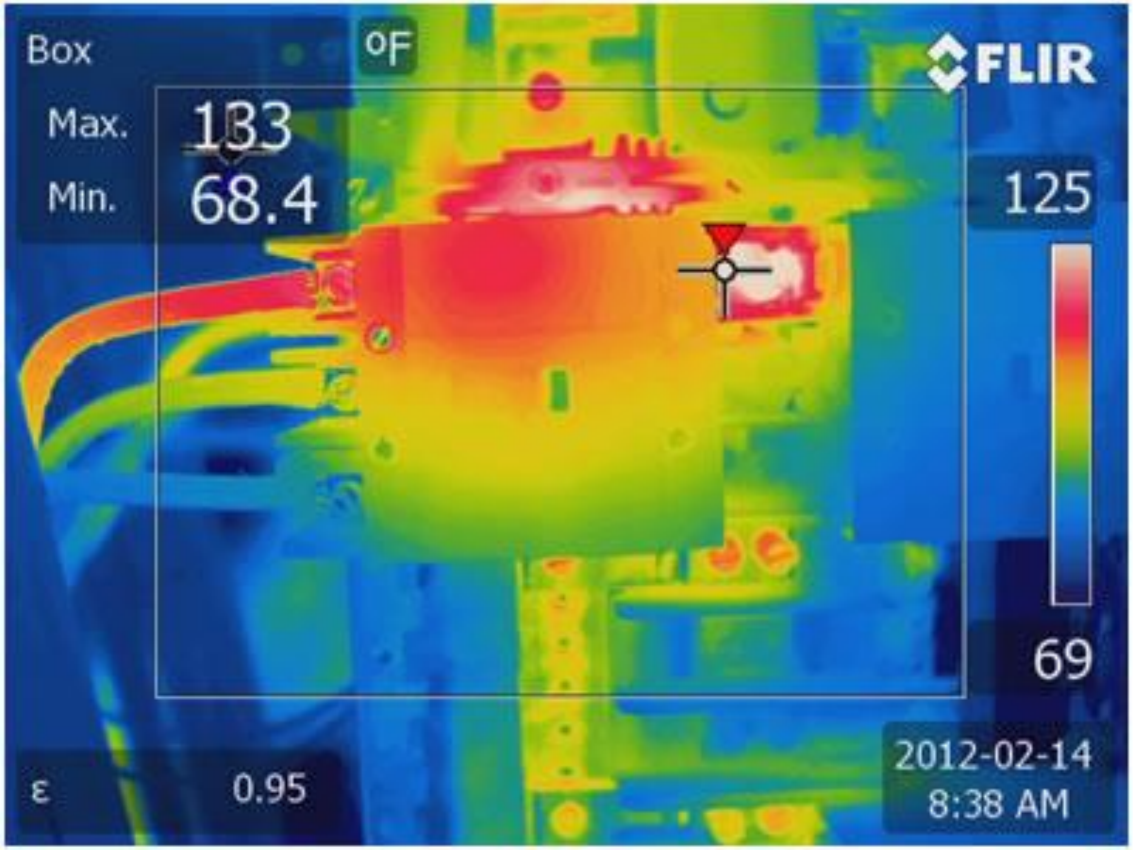
- IR images indicate temperature differences
- For easier distinction often «colored» images are used without any correspondence to true colors.



Source: http://thermalimaging-blog.com/tag/grayscale-palette/

3.3 Applications

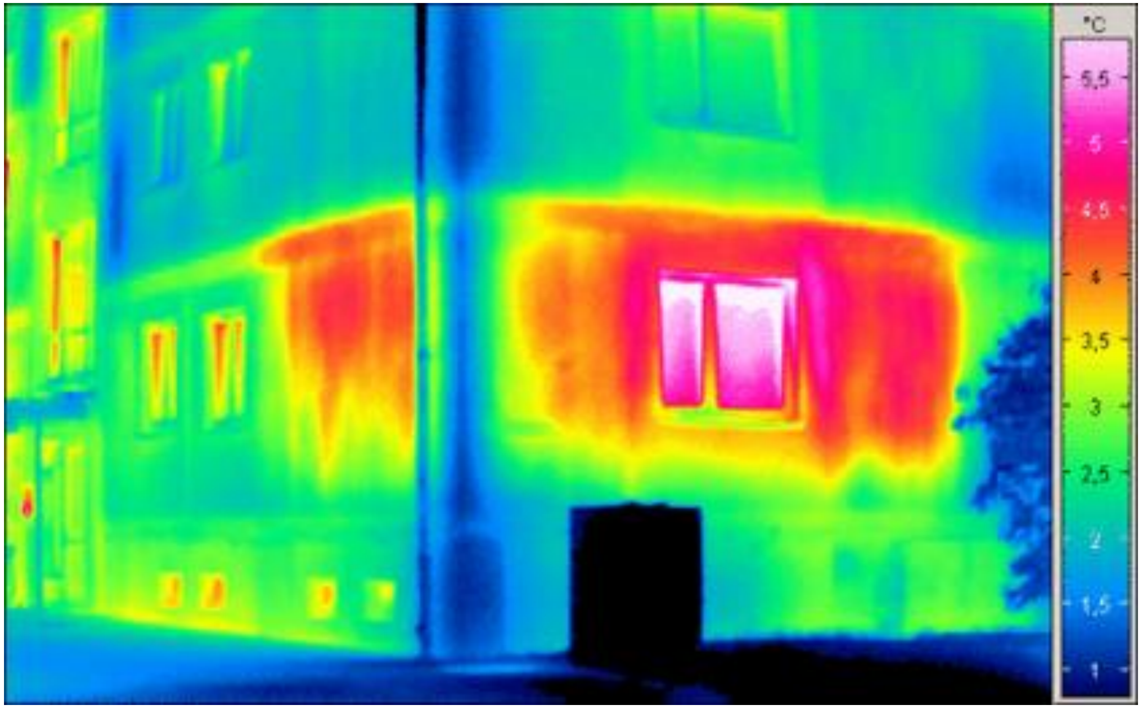
- **Electric inspections:**
  - Qualitative check of electric components during operation
  - Prevention of malfunctions



Source: http://www.tp-eur.com/thermography-electrical-inspection//

3.3 Applications

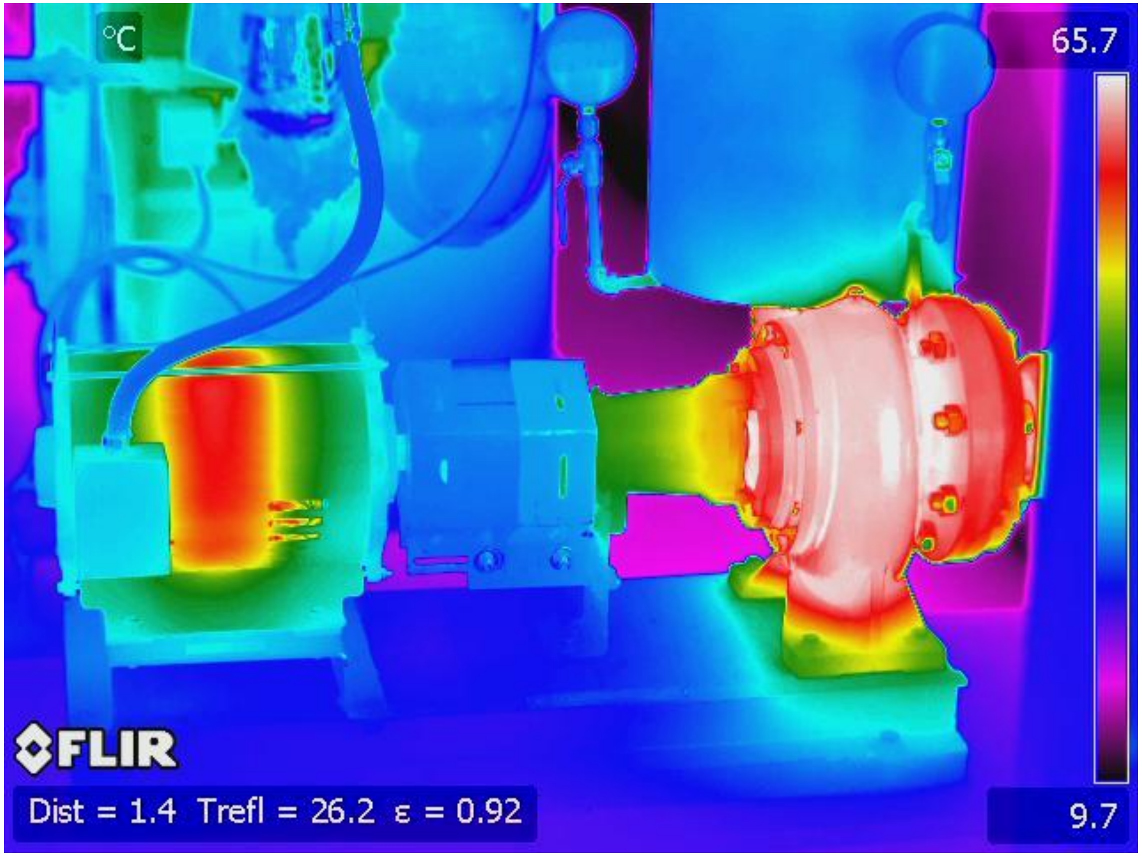
- **Inspections of buildings:**
  - Qualitative check of facade
  - «Hot spots» indicate high heat losses, e.g. windows



Source: http://www.infratec-infrared.com/thermography/application-area/building-thermography.html

3.3 Applications

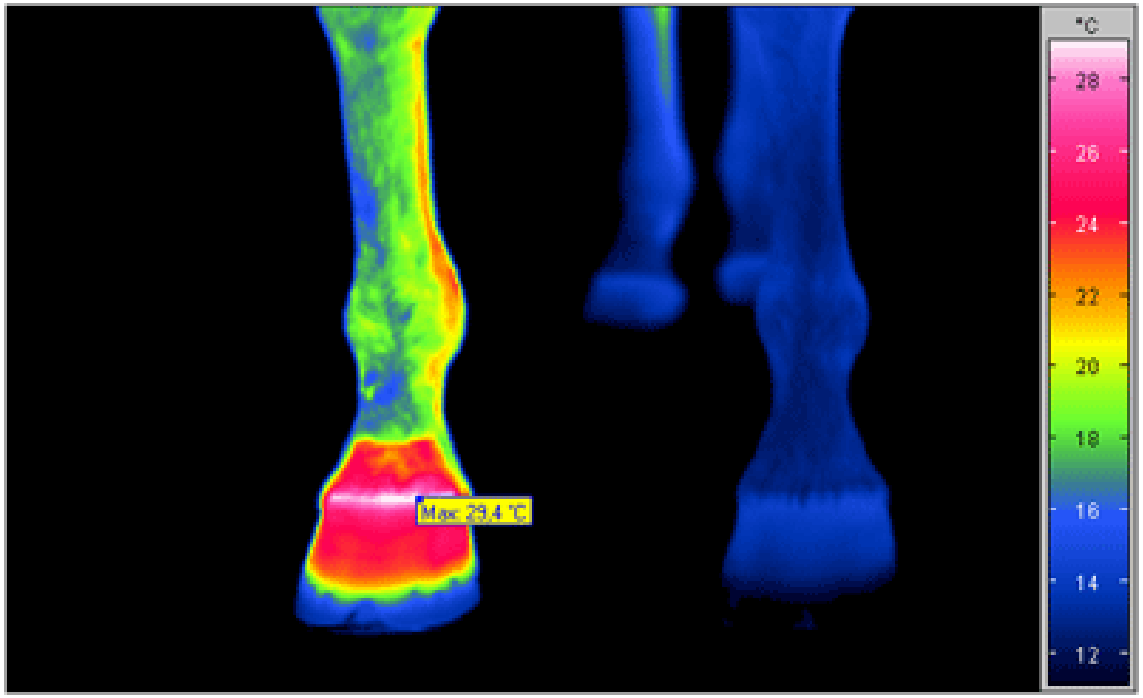
- **Inspections of mechanical systems:**
  - Qualitative check of mechanical components during operation
  - Prevention of malfunctions



Source: https://irispdm.com/infrared-thermography-for-mechanical-systems-and-motors/

3.3 Applications

- **Medical inspections:**
  - Check of body temperature
  - Detection of various desease patterns



Source: http://www.infratec.co.uk/thermography/application-area/medicine/veterinary-medicine.html/

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3.4 Summary

	Temperature sensors	IR thermography
Price	Low	High
Temp. range	High	High
Accuracy	High	Low
Sensitivity	High	High
Measurement	Selective point	Surface
Method	Invasive	Non-invasive
Applications	Technical	Technical, medical, etc.

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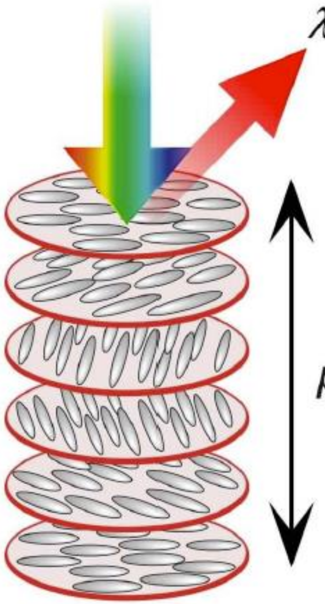
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

4. Others

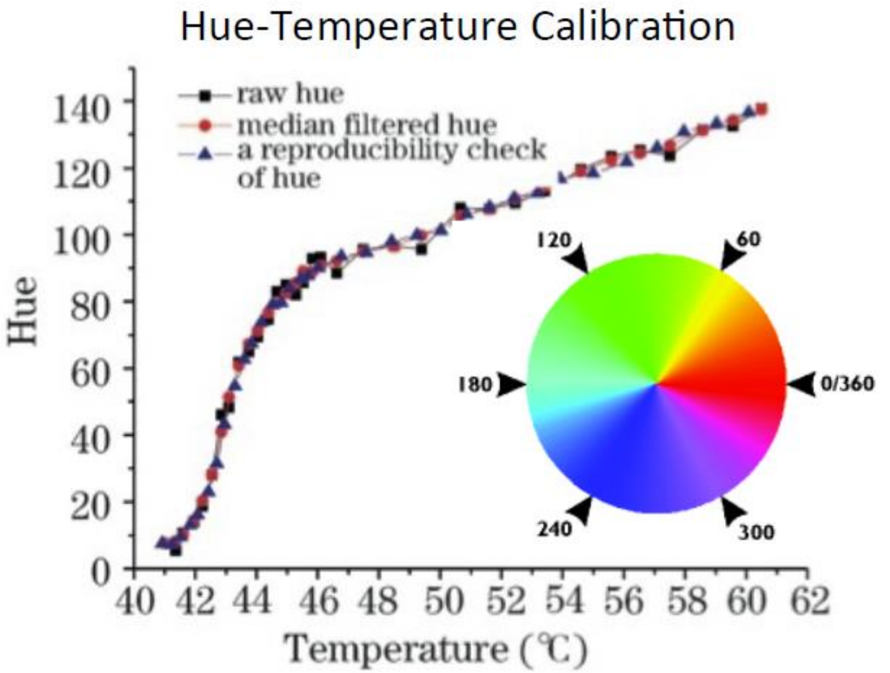
- Liquid Crystal Thermography (LCT)
  - Periodic layers with «rotating» orientation of crystals
  - Acts as 3D diffraction grating (Bragg type scattering)
  - Pitch length varies with temperature
  - → Reflected wave length (λ_{ref}) depends on temperature



$\lambda_{ref.}$: wavelength of the selectively reflected light

$$\lambda_{ref}(T) = p(T)\eta\sin\vartheta$$

$p/2$ = pitch / 2



Source: Lecture «Technique de mesure: Mesure de température», spring 2016

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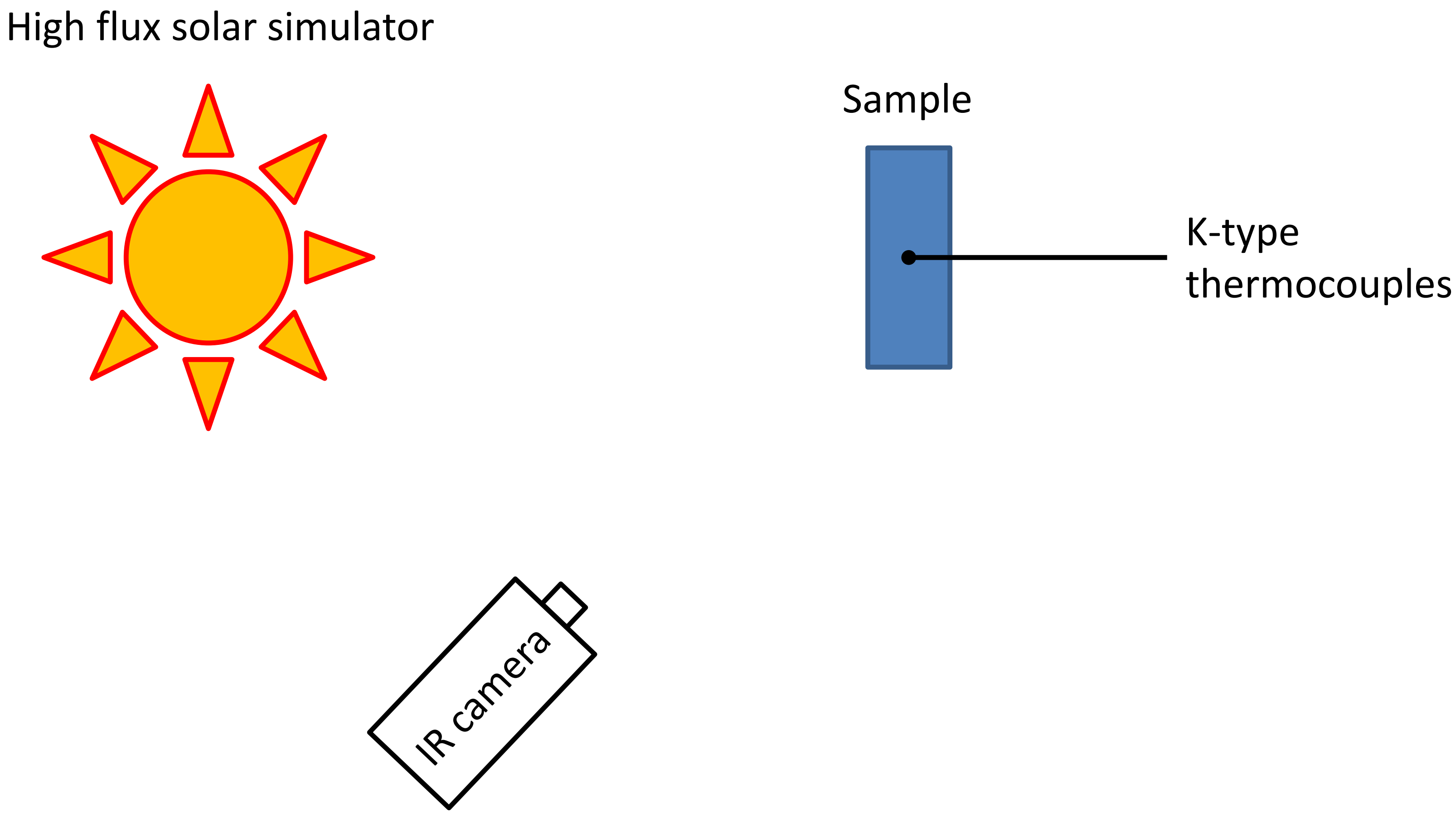
5. Lab example

- High temperature measurement of ceramic foam samples:



High flux solar simulator

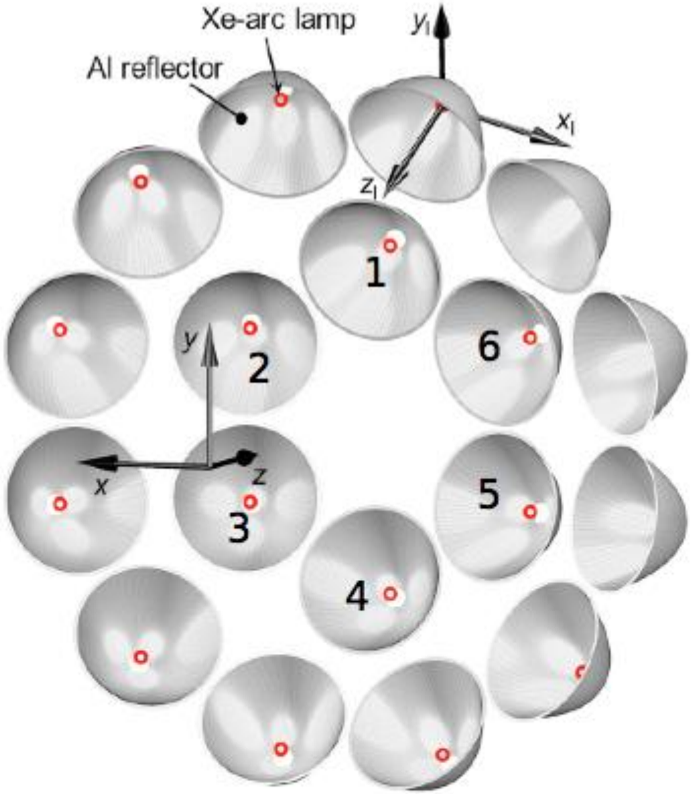
Sample

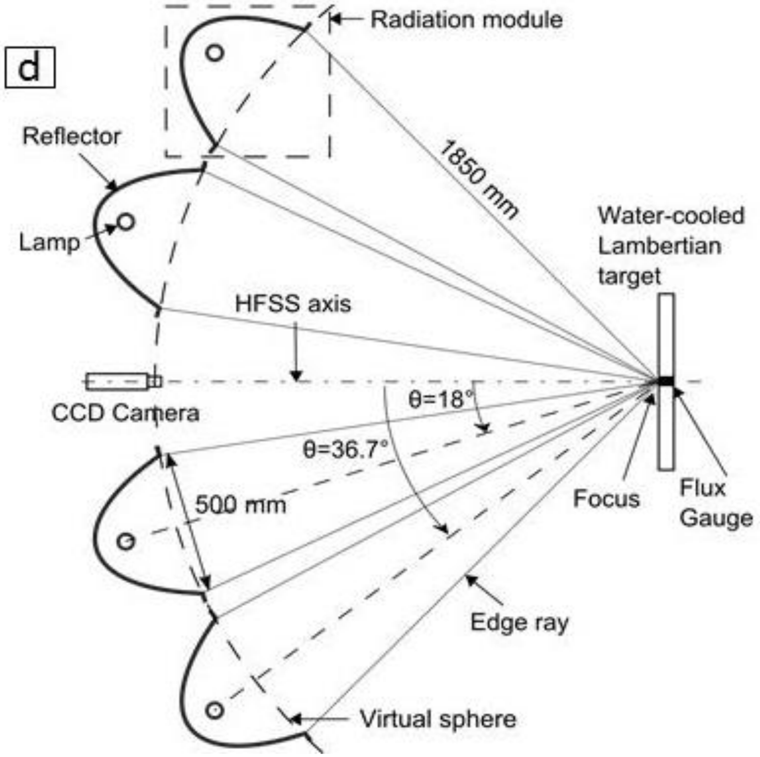
K-type thermocouples

IR camera

5. Lab example

- High flux solar simulator (HFSS):
  - 18 lamps
  - Power: 7.5 kW,
  - Peak flux: 20 MW m^{-2}

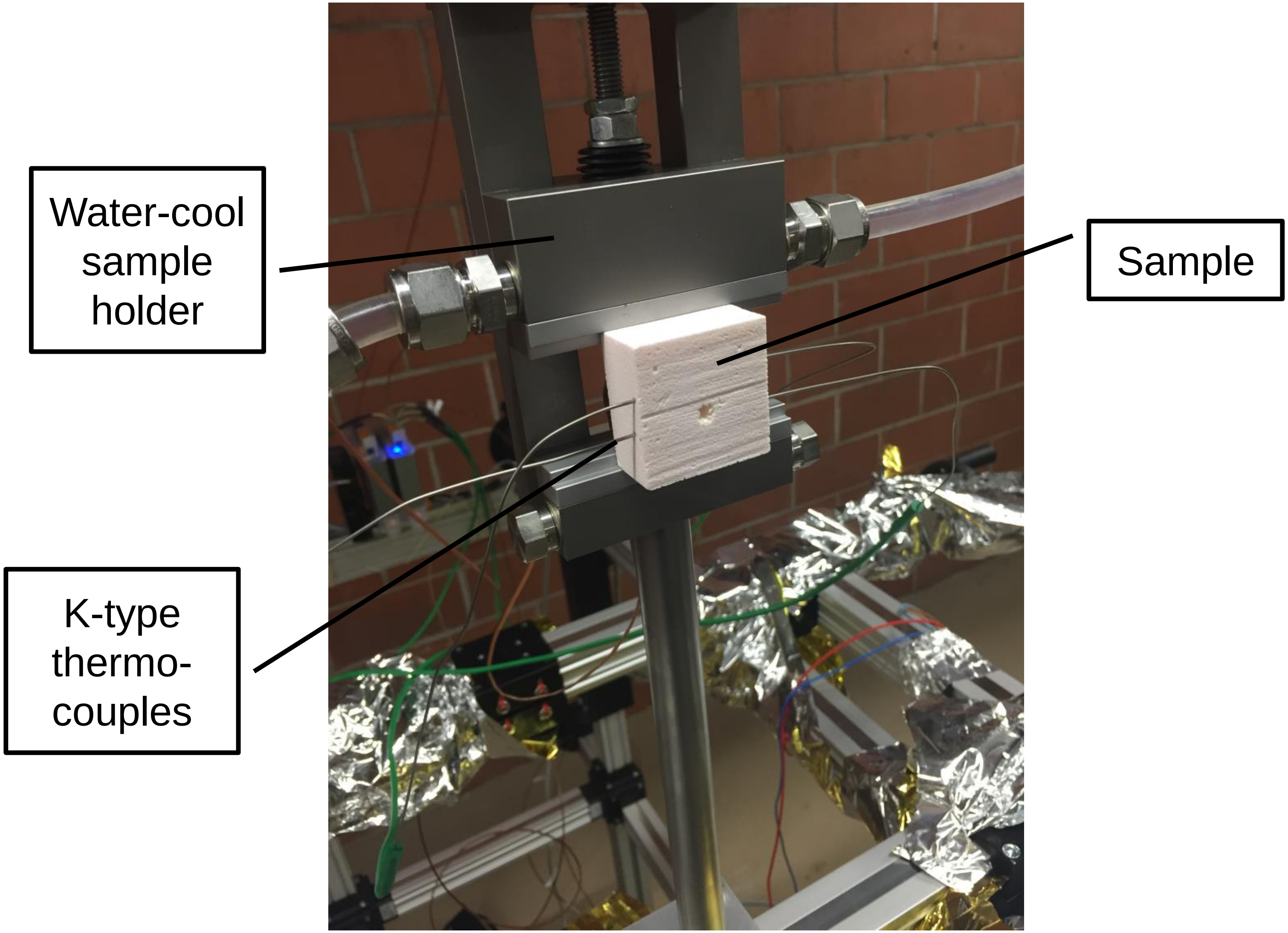




Source: lrese.epfl.ch

5. Lab example

- Experimental setup:



Water-cool sample holder

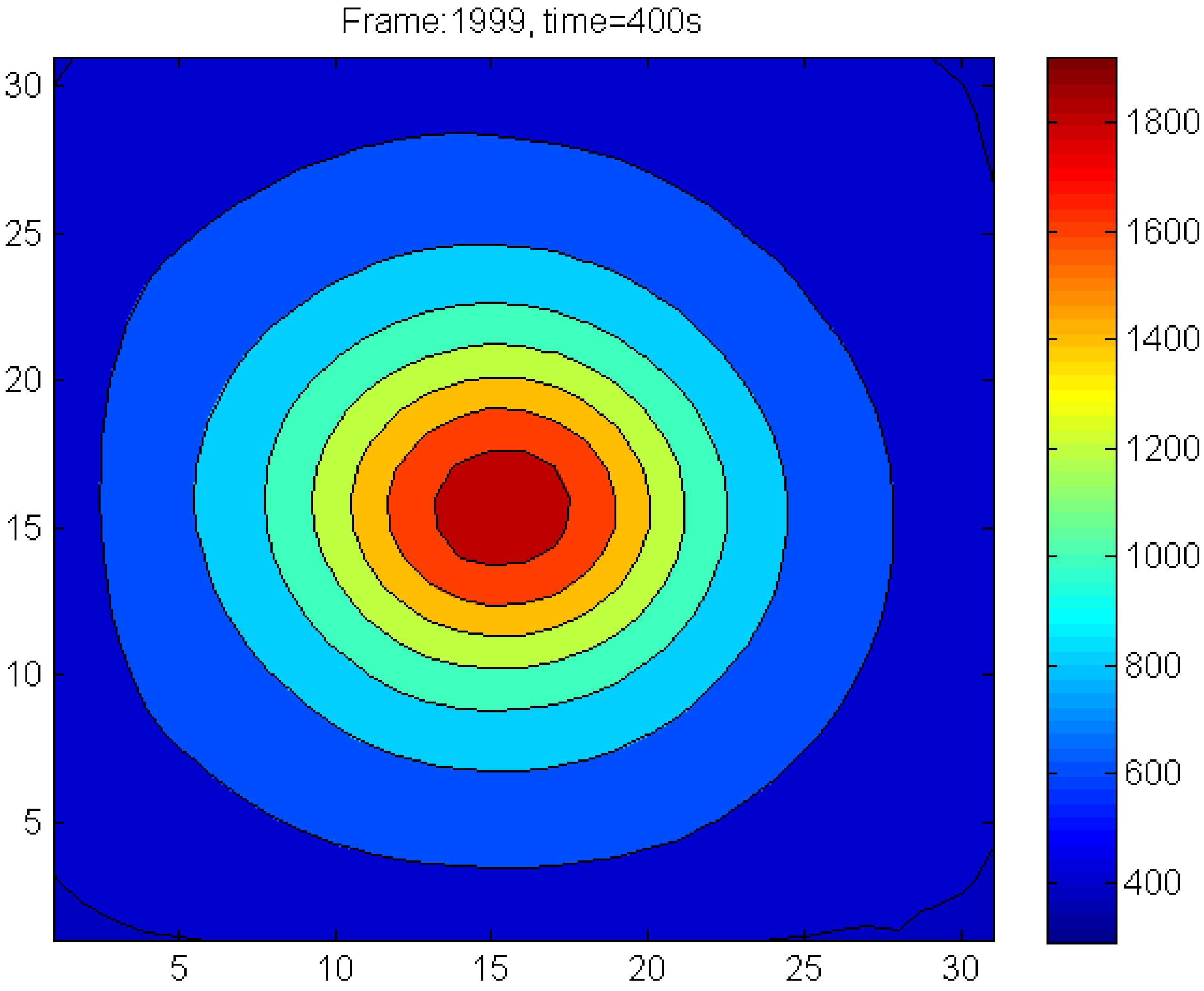
Sample

K-type thermo-couples

Source: lrese.epfl.ch

5. Lab example

- IR measurement of surface temperature

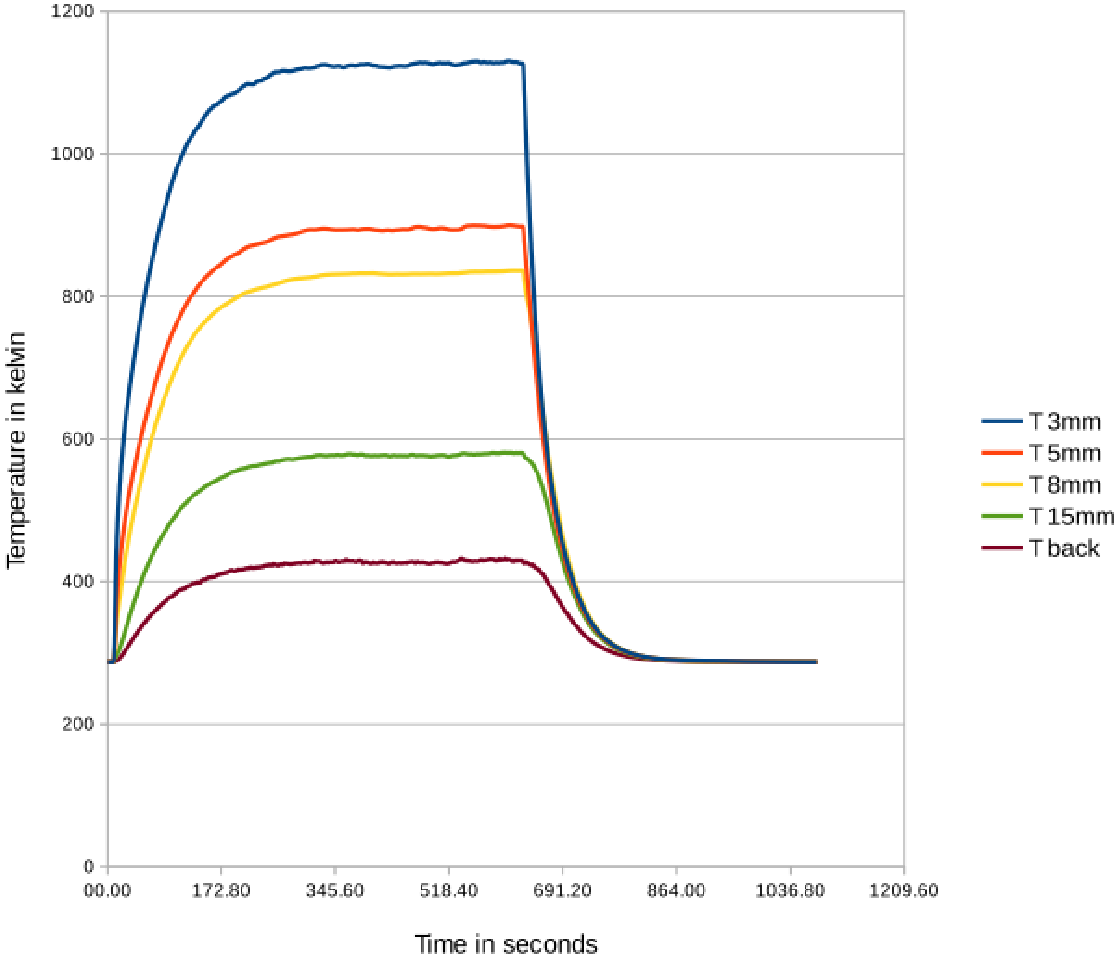


Lamps 3 and 6, 70A, heat flux approximately 1.5 MW/m2

Source: lrese.epfl.ch

5. Lab example

- Temperature measurement by k-type thermocouples



Source: lrese.epfl.ch

5. Lab example

- Goal of temperature measurement:
  - Material tests for finding max. allowed temperature
  - Better understanding of heat transfer coupling conduction, convection and radiation
  - Modelling of heat transfer in order to improve properties of ceramic foams, e.g. pore size


thank you
danke
рахмат
謝謝
ngiyabonga
teşekkür ederim
spas
Баярлалаа
mersi
kia ora
barka
welalin
tack
спасибо
faafetai lava
vinaka
спасибі
blagodaram
dank je
misaotra
matondo
paldies
grazzi
mahalo
tapadh leat
gracias
kiitos
dankie
nanni
nandri
dhanyavad
mauruuru
köszönöm
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manana
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terima kasih
tanemirt
rahmet
grazie
arigatô
takk
dakujem
trugarez
ευχαριστώ
diolch
dhanyavadagalu
shukriya
mercé
мерси
তোমাকে ধন্যবাদ
감사합니다
xièxie
merci