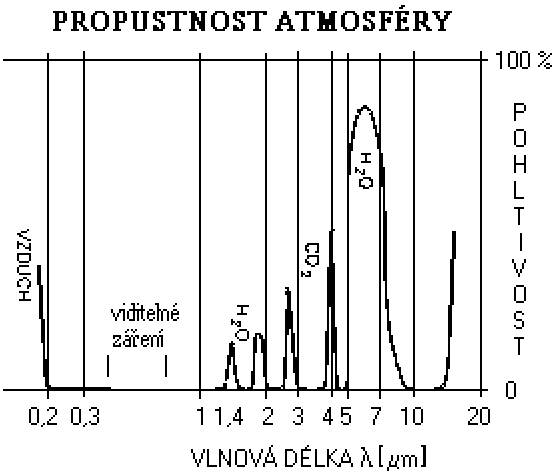
Infrared radiation and history

History

British astronomer William Frederic Herschel is the discoverer of infrared radiation in 1800. His discovery of infrared rays was aided by the discovery of an enormous rise in temperature in the red band of visible light when sunlight was spread through a glass prism, which signalled the presence of yet another radiation that was no longer visible to the human eye. Infrared radiation (so called after its original designation as ultraviolet) is technologically divided according to its wavelength range into bands A, B, C. Band A includes a wavelength range of 0.76-1.4 µm, mid-band B 1.4-3 µm and long-wave band C a section above 3 µm (this then passes without a sharp boundary, approximately in the band around 100 m, into the radio wave region). In the IR-A band, few rays of the solar spectrum pass through vapours in the Earth's atmosphere and few are absorbed by water. The IR-B band is almost completely absorbed by water, passing through glass and the Earth's atmosphere, and this effect is amplified in the IR-C band, where the source may be incandescent spirals or perhaps electrically heated bodies.



Year 1900 Planck's law

The

$$dI = \frac{\hbar}{\pi^2 c^2} \, \frac{\omega^3}{e^{\frac{\hbar\omega}{kT}} - 1} \, d\omega,$$

ω je úhlová frekvence záření,

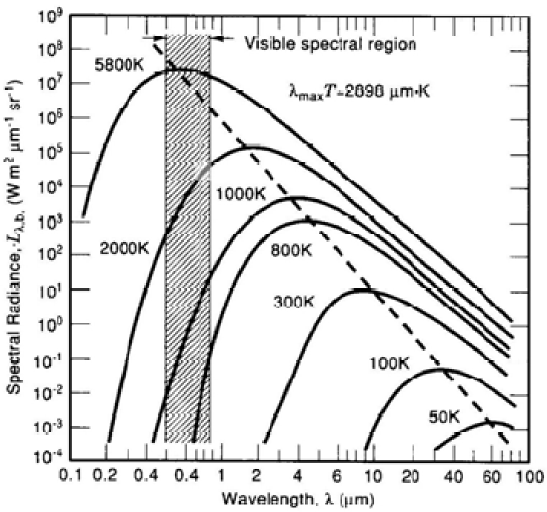
I je intenzita záření,

T je teplota absolutně černého tělesa,

$\hbar$ je redukovaná Planckova konstanta,

c je rychlost světla ve vakuu a

k Boltzmannova konstanta.



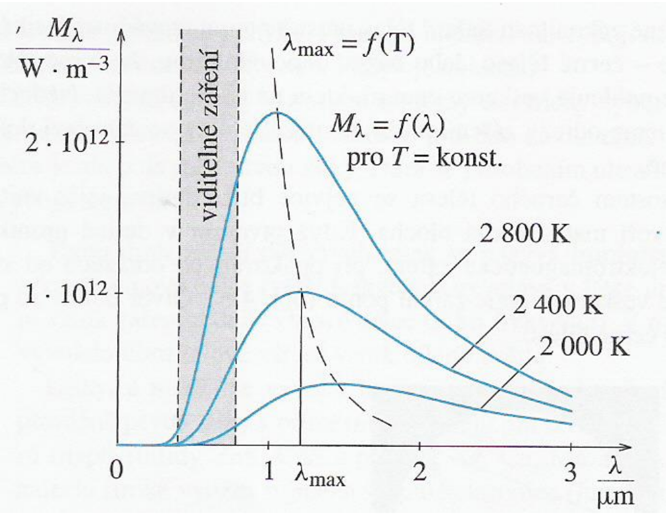
- intenzita vyzařování klesá výrazně s klesající teplotou

Planck curves show that the amount of radiation emitted depends even on the 4th power of the absolute temperature, and that the spectral distribution of radiation shifts to longer wavelengths for cooler objects. If the surface of the Sun at 5700 K emits maximum energy in the yellow-green optical part of the spectrum for wavelengths faintly above 500 nm, a person at 310 K shines most in the band faintly above 9 micrometers - that is, just in the infrared spectral region.

Wien's Law

$$\lambda_{\max} = \frac{b}{T}, \quad b = 2{,}897\,768\;5(51) \cdot 10^{-3}\ \mathrm{m \cdot K}$$

Wien's law shows us how the radiation maximum shifts with temperature. It gives the value of the wavelength at which maximum emission occurs at a given temperature.

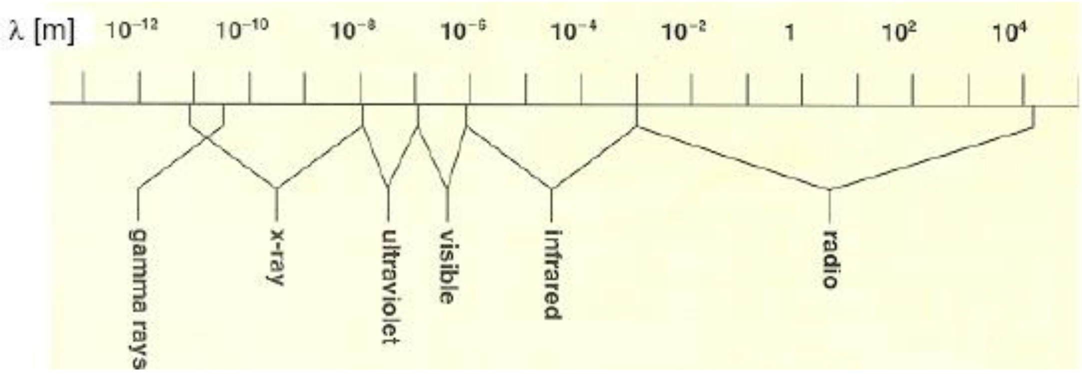


Stefan-Boltzmann law

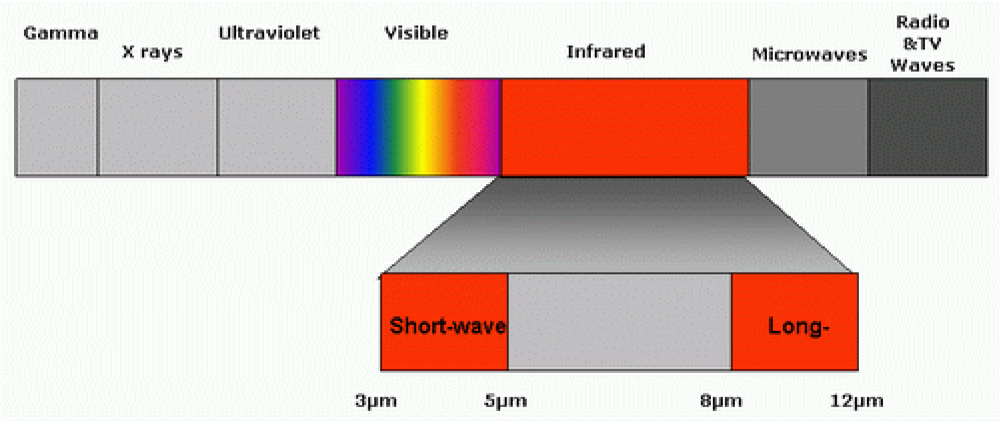
Any body with a temperature above 0 K (-273,15 °C = absolute zero) emits energy in the form of electromagnetic radiation at various wavelengths. The part of the radiation that is produced by the thermal motion of particles of solids, liquids or even gases and plasmas is called thermal radiation, and the energy radiated is proportional to the fourth power of the temperature of the body, which is expressed by the Stefan-Boltzmann law for the total intensity of radiation radiated per unit area into half-space.

$I = \sigma$-T^4 whereσ = 5.67-10^{-8} W-$m^{(-2)}$)-K^{-4}.

Spectrum



λ [m]
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
gamma rays
x-ray
ultraviolet
visible
infrared
radio



Other variables

- Radiant flux (radiant power) Φ (W)
  Radiation intensity M (W-m^{-2}) - sometimes referred to as I and H

- Radiant flux ratios
- Absorption α (absorbed/impacted)
- Accessibility τ (permeating/influencing) $\alpha + \tau + \rho = 1$ resp. $\varepsilon + \tau + \rho = 1$
- Reflectivity ρ (reflected/impacted) $\alpha_\lambda + \tau_\lambda + \rho_\lambda = 1$ resp. $\varepsilon_\lambda + \tau_\lambda + \rho_\lambda = 1$

Emissivity and blackbody

Black body
A black body is a body that absorbs all incident radiant energy (regardless of wavelength) and then emits it only as thermal radiation.

- there is no such body in nature
- in practice, it can be realized by a cavity with blackened inner walls and a small opening
- the incident radiation transfers its energy in multiple reflections to the walls of the black body, which radiate it as thermal radiation

Selective emitters
These are bodies that have different emissivity ε_λ for different wavelengths.
Grey body
The emissivity ε *of* the gray body can be considered constant over a fairly wide range of wavelengths.
The colour of the body changes with

- t <525 °C - infrared radiation (we can't see)
- t =700 °C - dark red
- t =900 °C - red
- t =1100 °C - orange red
- t =1300 °C - white
- t =3000 °C - blue and white

Emissivity

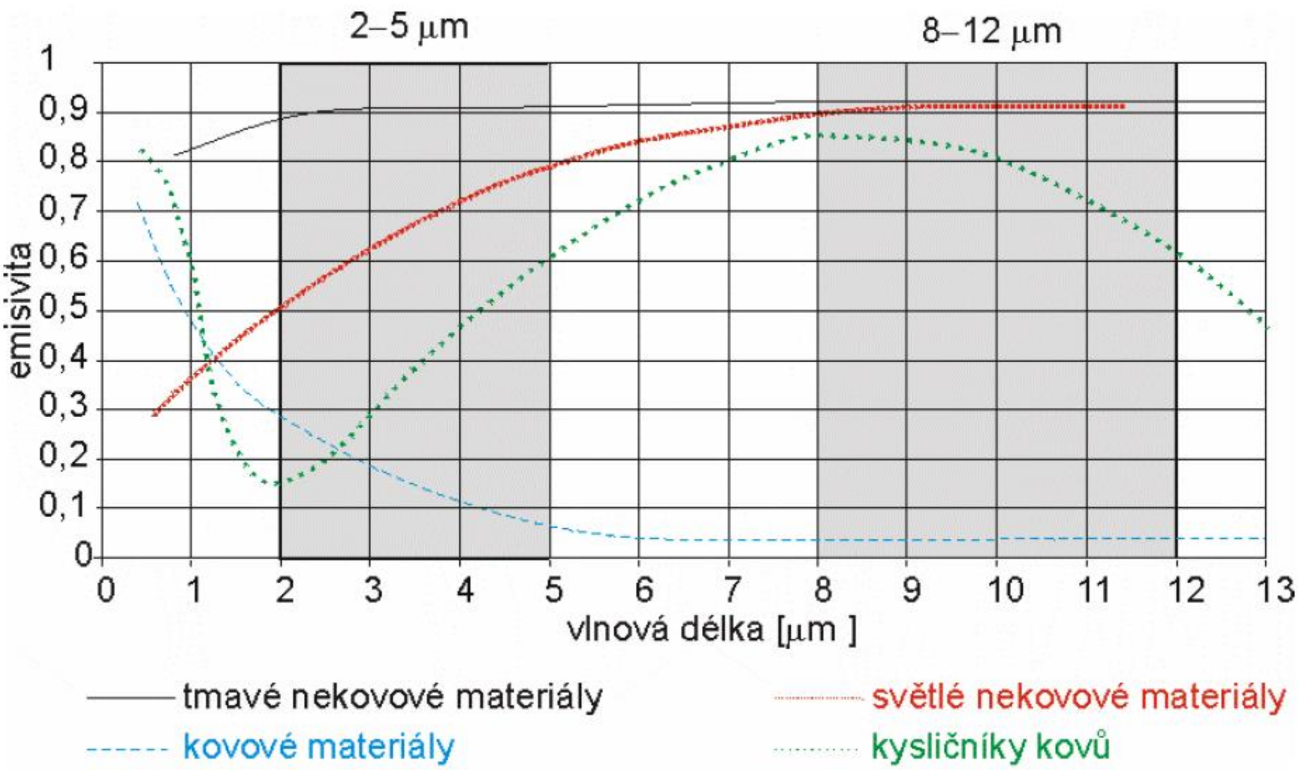
The emissivity of each body is called the emissivity of the surface of that body and is denoted by ε. The emissivity is numerically equal to the ratio of the energies radiated by the real surface and the absolute blackbody:

$$\varepsilon = \frac{H_{\mathrm{m}}(T)}{H_{\mathrm{c}}(T)} \qquad \varepsilon = \frac{M}{M_0} = \frac{\int_0^\infty \varepsilon(\lambda, T) \cdot M_{0\lambda} \mathrm{d}\lambda}{\int_0^\infty M_{0\lambda} \mathrm{d}\lambda}$$

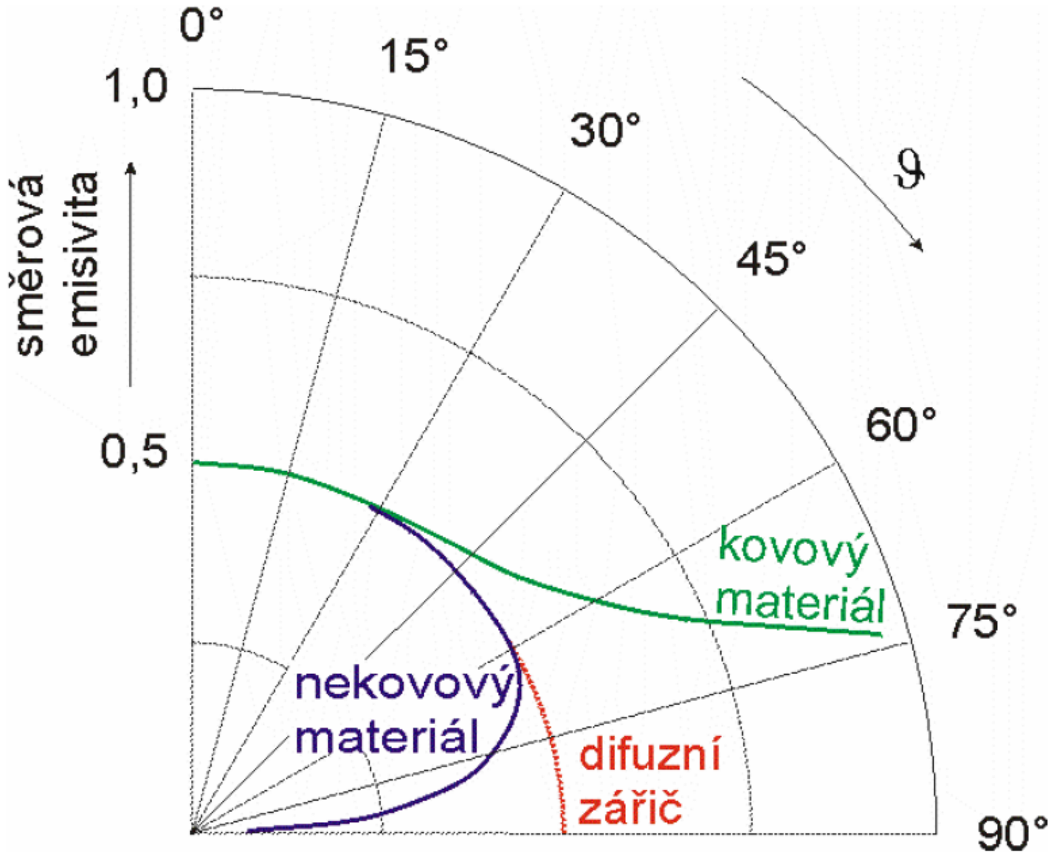
where $H_{\mathrm{m}}(T)$ is the energy radiated by the measured object at temperature T
$H_{\mathrm{c}}(T)$ is the energy radiated by a black body with temperature T

The definition of emissivity expresses the total emissivity. In practice, we work with instruments that measure the energy of radiation only in a limited spectral range. Therefore, it is convenient to consider spectral emissivity, where emissivity is a function of wavelength ($\varepsilon = \varepsilon\lambda$). Since total radiation pyrometers are not very common in practice, we will further understand the concept of emissivity in terms of spectral emissivity. Determining emissivity by calculation is difficult, so emissivity is rather determined by measurement. We must also consider that the emissivity also depends on the direction of the emitter from the pyrometer and varies with temperature. For some materials this dependence is stronger, for others weaker. The greatest changes are observed when the material changes the structure of its crystal lattice. Surface oxidation also has a large effect on the surface properties of a material.

Emissivity versus wavelength...selected types of materials



Emissivity versus direction



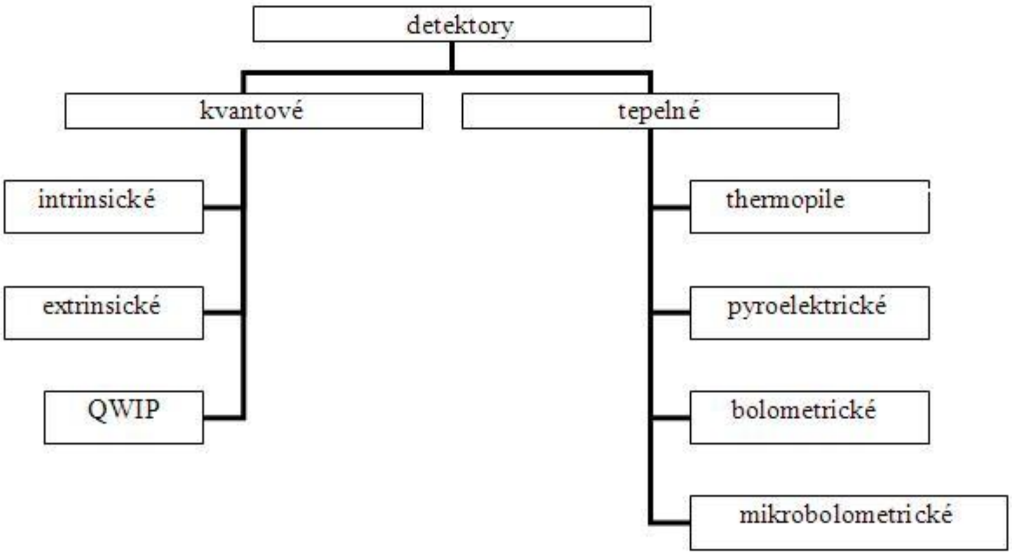
Emissivity values for selected surfaces:

Body	emissivity
black body 1	
black matt lacquer 0,99	
water 0,95	
bricks 0,85	
oxidized steel plate 0,75	
oxidised aluminium 0,55	
Glossy steel sheet 0,25	

Detectors

We will continue to look at detectors that are used for non-contact temperature measurement. For the purpose of sensing infrared radiation, two types of detectors are used, which use two different approaches to convert it into an electrical signal suitable for electronic processing:

- Thermal Detectors - use changes in a material property based on the absorption of infrared energy.
- Quantum Detectors - use direct conversion of incident radiation into charge or electric current.



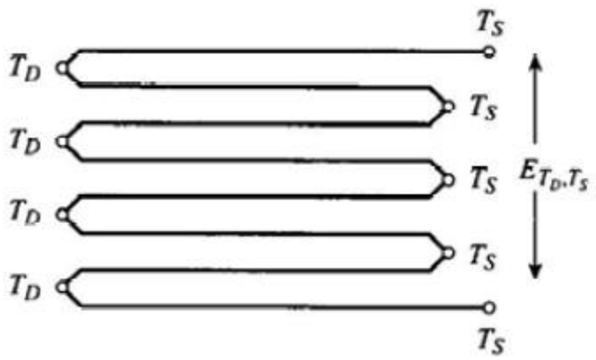
Heat detectors

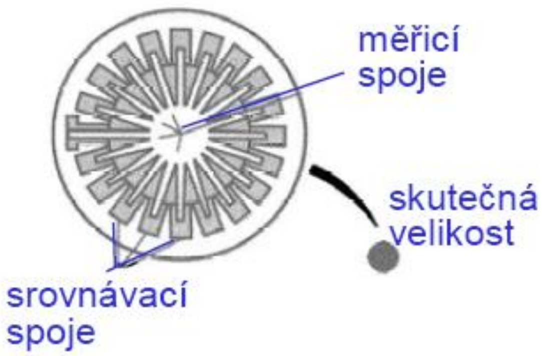
Comparison of thermal radiation pyrometry detectors

Type of temperature detector	Spectral sensitivity	Conversion constant (according to the processing output)	NEP - Noise Equivalent Power	Frequency response
Thermopile	0.2 to 35 µm	approx. up to 100 V/W	0.1 to 10 nW/√Hz	up to 100 Hz
Si bolometer	1.6 to 5000 µm	up to 100 kV/W	1 pW/√Hz to 1 fW/√Hz	up to 1 kHz
Pyroelectric (LiTaO3)	0.01 to 1000 µm	up to 3.0 µA/W	10 nW/√Hz to 10 µW/√Hz	up to 100 kHz (1MHz)
Calorimeter	0.25 to 35 µm	0.1 V/W	10 µW/√Hz to 10 mW/√Hz	0.001 to 0.2 Hz

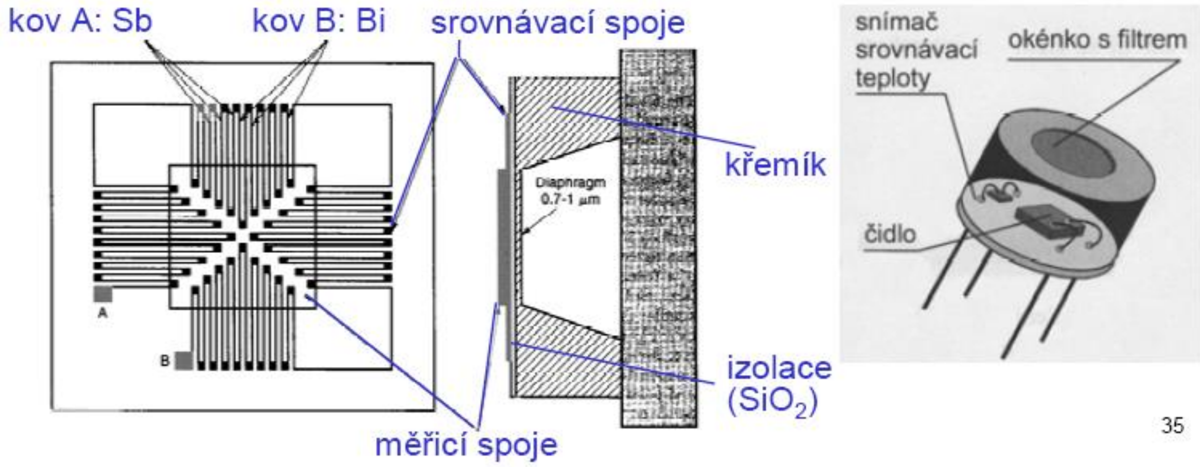
Thermopile

Thermopile sensors, generally referred to as radiation pyrometers or infrared thermocouples, are sensors for non-contact measurement of the surface temperature of objects. As the quite apt name of infrared thermocouples suggests, it is the heating of thermocouples by infrared radiation emitted by any object of a certain temperature. However, not to be confused with pyroelectric sensors, which work on a similar principle but use the pyroelectric effect.





On the left we see the actual design of the infrared cells. The lower part shows us the possible design and encapsulation of the sensor.

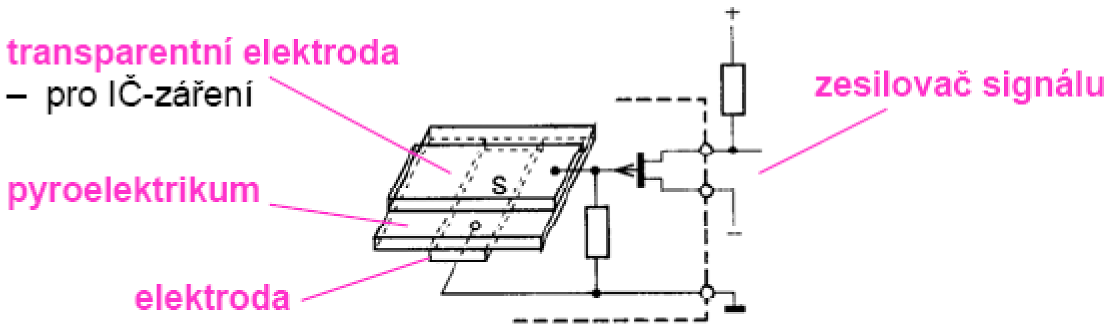


Pyroelectric sensors

- based on the pyroelectric phenomenon, the change of spontaneous polarization of the pyroelectric when the temperature changes
- pyroelectrics: e.g. ceramics based on titanium and lead zirconate

<u>The principle of pyroelectric sensor :</u>

- the sensor is a capacitor, on whose electrodes a charge is induced when the polarization changes in the pyroelectric
- when applying the pyroelectric sensor, the thermal radiation must be cyclically interrupted

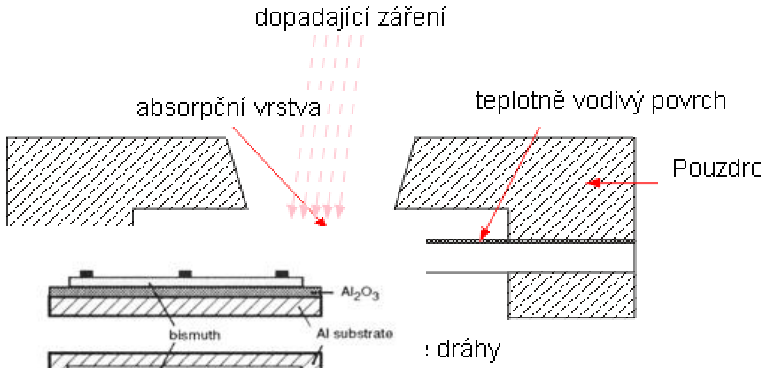


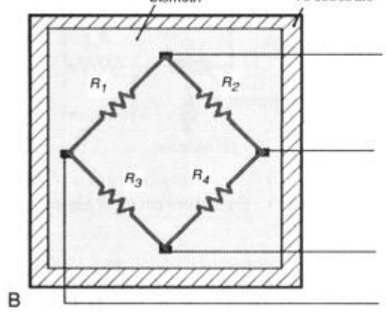
<u>Pyroelectric sensor arrangement</u>

- before each measurement it is necessary to shield the radiation falling on the detector and shield it again
- pyroelectric materials exhibit a parasitic piezoelectric effect (e.g. when the pyroelectric is shaken and deformed), which compensated for in some instruments by a second opposite-pole detector that is shielded from the thermal radiation

Bolometers and microbolometers as the most commonly used

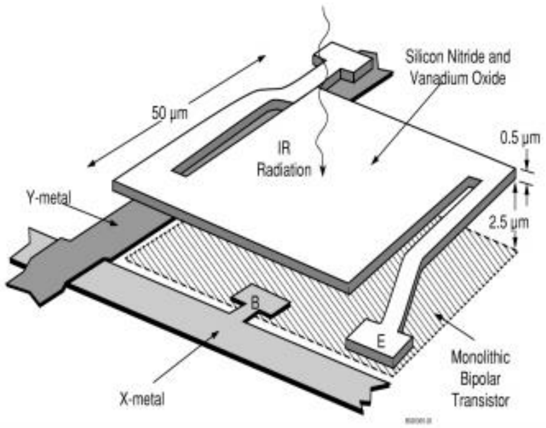
The current most used sensor is the bolometer and its microstructure, the microbolometer. It is a thermal sensor where the temperature changes with the absorption of IR radiation and thus its resistance. The principle is similar to metal temperature sensors.

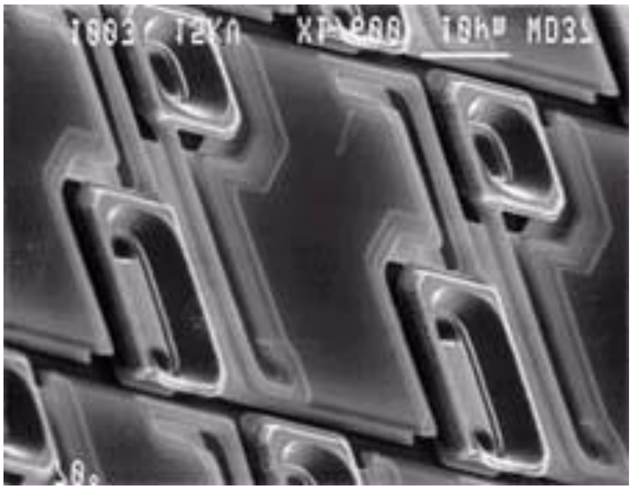


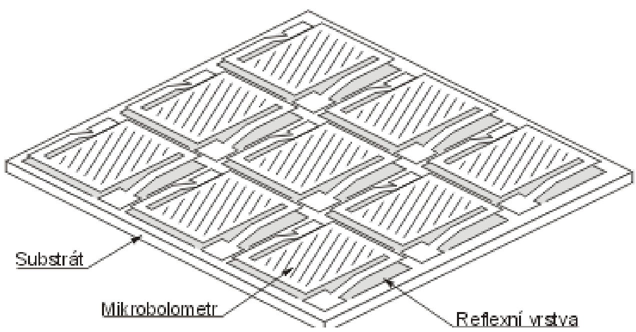


Classic bolometers, simple layout and bridge circuitry to compensate for ambient effects

Microbolometers are made using nanotechnology, here you can see the FPA detector. The top photo is a model of one element, showing the implementation of the sensor and the wiring to the transistor that provides the transmission of the incident radiation information. The photographs show the actual sensor and a view of the structure under magnification. The lower image shows the model of the element arrangement. A Peltier cell is sometimes used to thermally stabilize the detector environment.







Development

1st Generation - includes the first thermal imaging cameras created in the70. a 80s, which were mainly developed and designed for military purposes. These cameras used simple discrete detectors that consisted of non-multiplexed photoconductive linear arrays with up to 100 elements (the last high-end 1st generation cameras had up to 180), typically made from InSb, PbSe and later HgCdTe. The invention of SPRITE detectors and the deployment of scanning technology in the 1980s brought a significant shift in quality. Typically, these cameras operated in the 8 - 12 micrometer band with F/2 - F/4 optics and a typical NETD temperature resolution of 0.2 Kelvin. Some 1st generation thermal imagers are still in service in the military.

Generation 2 - characterized by the use of a scanning system in conjunction with linear or 2D FPA (Focal Plane Arrays) detectors with 100 to 1000 elements or, alternatively, multi-element SPRITE detectors. The temperature resolution of NETDs is thus typically reduced to about 0.1 K. These cameras were already characterized by acceptably small size and weight and started to be sold in commercial versions. This was achieved by the art of fully integrating the sensing elements and the basic readout logic onto one common chip. The deployment of these thermal cameras in the military started in the second half of the 1980s and lasted until about the mid-1990s, and even today they still represent the major share of these devices in the armament of armies. Thermal imagers using improved multilinear FPA detectors are sometimes referred to as Generation 2+ with improved temperature resolution down to 0.05 K. At the core are 288x4 element HgCdTe detectors for the 3-5 micrometer and 8-10.5 micrometer bands with full signal processing (photocurrent integration, fast readout, splitting, TDI, output preamplification, etc.).

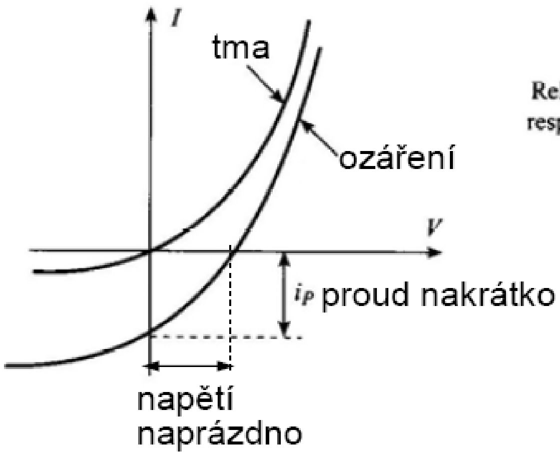
Generation 3 - includes non-scanning thermal cameras using either 2D cooled FPA detectors made of HgCdTe, InSb or more recently QWIP technology, or uncooled FPA based on microbolometer or ferroelectric technology. The number of elements reaches1 a more millions. These staring arrays, as they are also referred to, already include full digital signal processing on a common chip, fast integrated readout circuitry ROIC, pixel selection, antiblooming of each pixel, preamplification, block editing and filtering, etc. The "cancellation" of the scanning drive has greatly simplified the optics, which now only has the task of focusing the infrared image on the FPA. The first 3rd generation cameras were available in the 1990s, and since the beginning of the 21st cooled cameras with QWIP technology or uncooled cameras with microbolometer detectors have been freely available. The latter are characterized by significantly lower image quality than the cooled types, but again they are 2 to 4 times cheaper.

Quantum sensors

When photons interact with the sensor structure, electron-hole pairs are generated. Intrinsic detectors are those that use only their own semiconductor, extrinsic detectors are those that use doped structures,

Photodiode

The photodiode exploits the phenomena that occur at the PN junction of the Si diode.



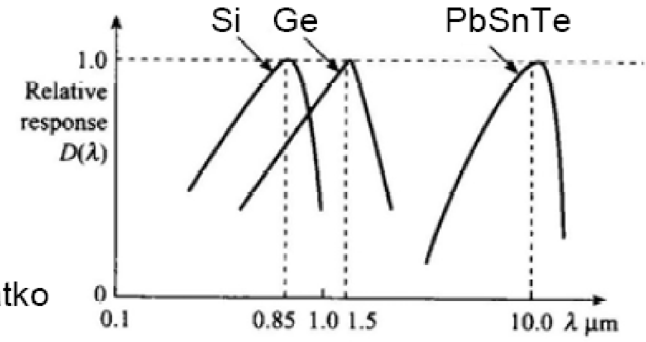
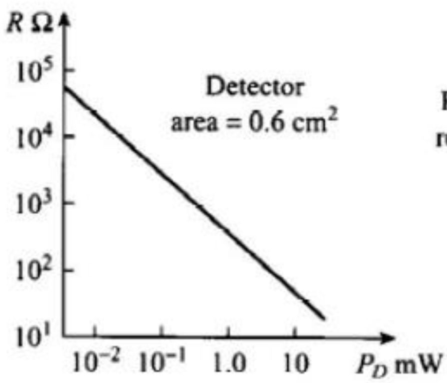
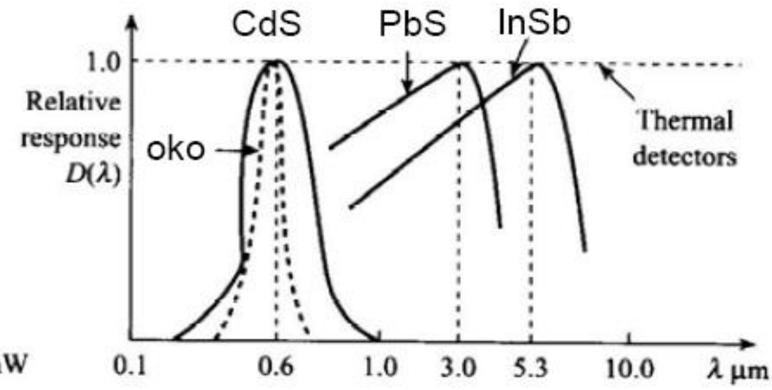


Photo support

- change in charge carrier mobility when photons hit the semiconductor layer
- conductivity is a function of photon flux
- the detector requires an electric field created by connecting an external voltage
- photoresists based on CdS, PbS, InSb, PbSe





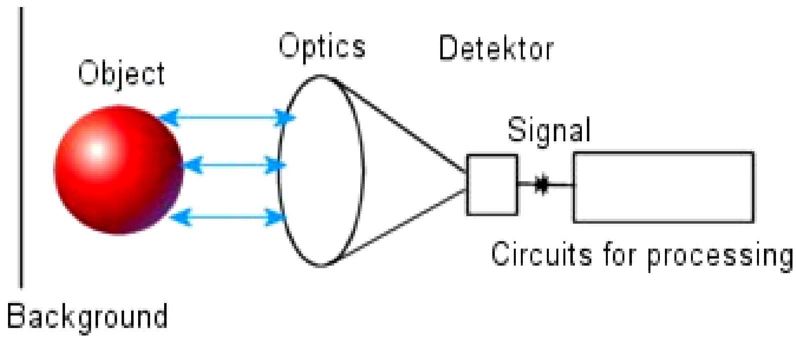
QWIP detectors

These are modern detectors that work on the quantum principle. Classical infrared detectors work on the same principle as conventional digital video cameras, but the pixels of their sensing chip do not convert photons of visible light into electric current, but infrared radiation. The more pixels, the greater the resolution. In contrast, the QWIP detector is made up of more than 100 layers of GaAs (gallium arsenide) semiconductor, each of which is extremely thin -

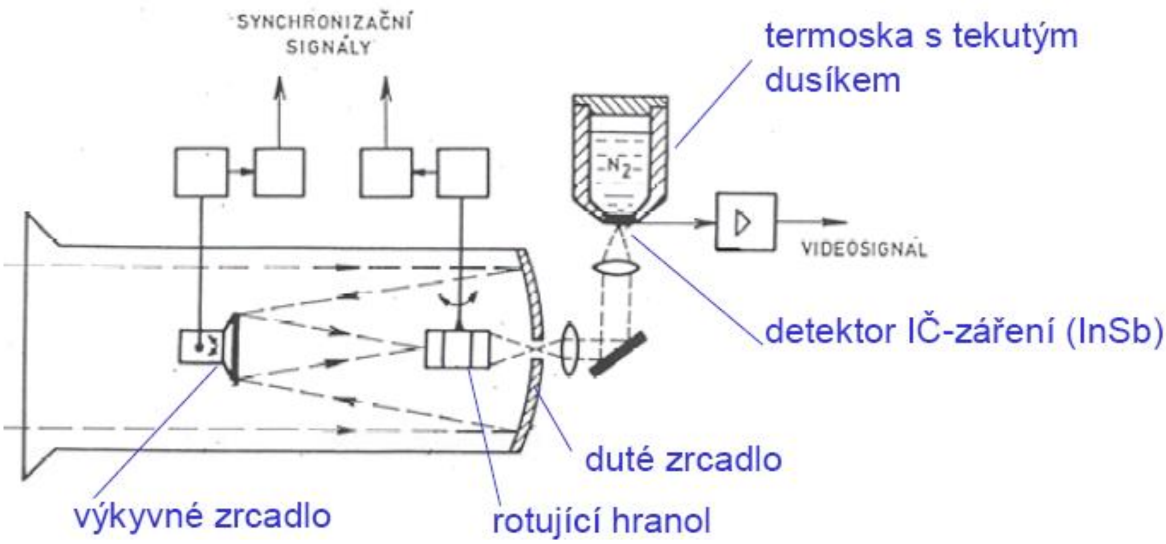
between 10 and 700 atoms thick. Each layer operates as a quantum well, meaning it will only release an electron when a light beam of precisely defined energy hits it, and each layer is "tuned" to incident photons of different energy. As a result, the latest version of the QWIP detector can process IR radiation in the wavelength range of 8 to 12 micrometres. The released electrons are then detected by a special chip, which transmits the information to a computer. It then uses the data to produce a final image. The resolution of an IR device with a QWIP detector corresponds to a conventional detector with a million pixels. At the same time, the new technology is relatively inexpensive, as it can use processes common in the production of semiconductor chips. Thus, blocks of gallium arsenide can be "grown" as cheaply and in the same sizes as silicon single crystals for the computer industry.

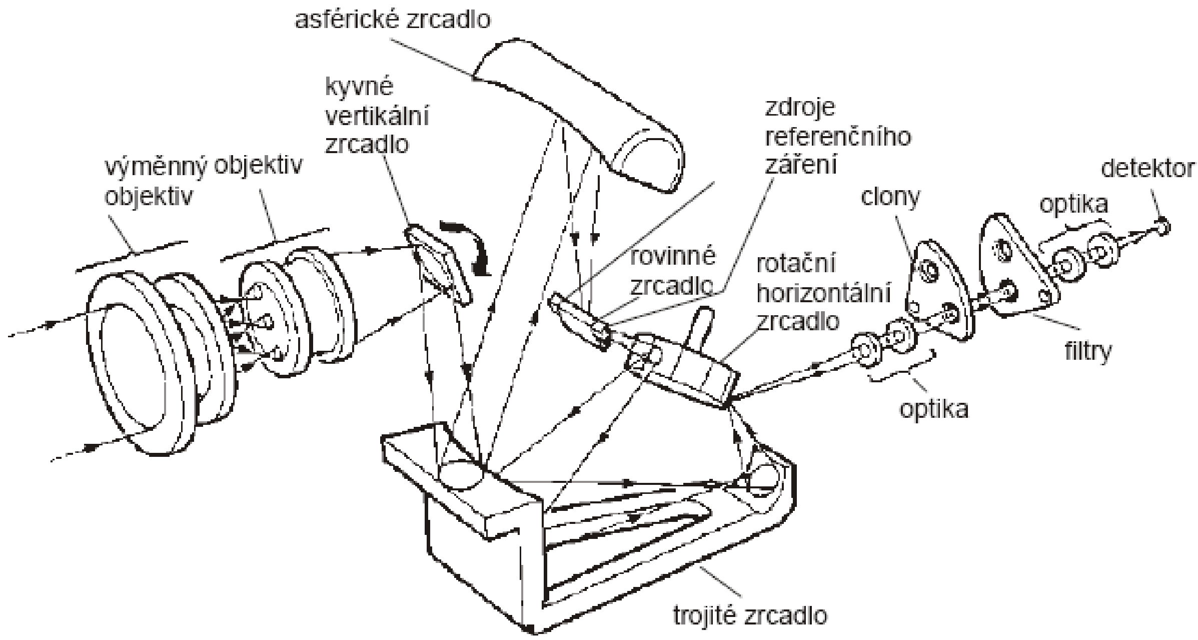
Cameras for thermal diagnostics

These are devices that implement detector and signal processing circuitry. The whole system obviously needs a power source and means of isolation from the surrounding environment to minimize the impact on the sensor.
Simple camera wiring diagram.



The principle of thermal imaging camera with electromechanical image decomposition. It is an older type of cameras that required cooling. Mechanical decomposition of the image by means of rotating elements was used. The image is decomposed into lines and points by a vertically oscillating mirror and a horizontally rotating prism or mirror. The detectors were cooled to a temperature of less than 80 K.

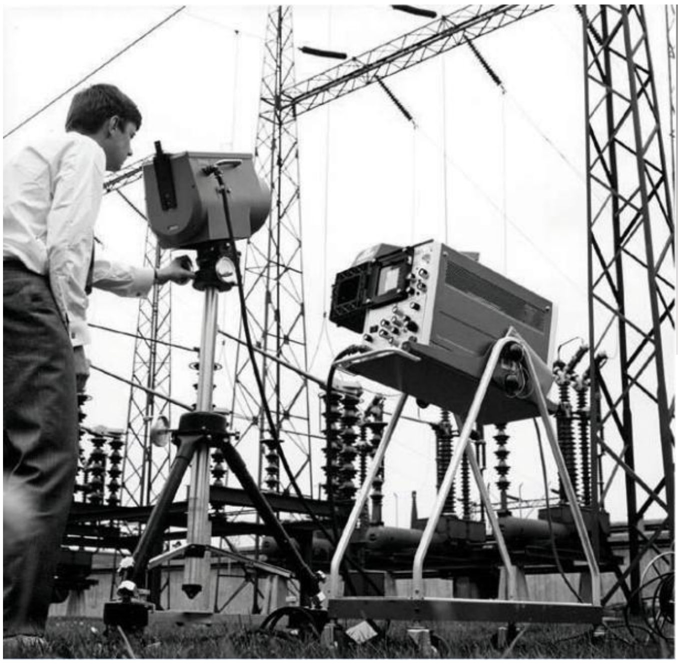




The actual arrangement of an element in a system with mechanical decomposition of the image.

<u>Thermal imaging cameras with matrix detectors.</u> This is a simpler method but requires higher resolution detectors. The arrangement of the camera is as shown at the beginning of the chapter. The system consists of optics, sensor and circuitry. Both cooled and uncooled detectors are used, usually microbolometers. A new step is QWIP detectors, which have much higher resolution and thus provide more accurate images.

Cameras history and present



Camera 0,55 kg

Camera 25 kg
Oscilloscope 20 kg
Tripod 15 kg
Polaroid 6 kg
Nitrogen 10 l
TOTAL approx. 70 kg

The photographs show how the cameras have changed over some 40 years.

Examples of cameras

Their parameters vary according to the application. The smaller ones are for quick diagnostics in operation, the larger ones for detailed analysis and applications in technology. They have different sensitivities, sensor sizes, body designs, temperature ranges...

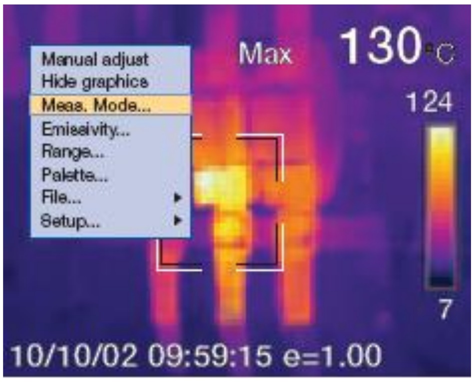
FLIR E45 camera

It's a camera used for measurements in our department. It is a small compact camera with a roughened handle for a firm grip designed for industrial measurements with IP 54 protection.

This instrument is described by the manufacturer as a type for quick measurements in fault diagnosis. The spectral range is 7.5 - 13 μm. Measured temperature range -20 ÷ 100 °C, 0 ÷ 250 °C, 120 ÷ 900 °C. It can image objects at a frequency of 50 Hz and at the time of purchase was the lightest camera on the market (0,7 kg). Images are displayed on a two and a half inch colour display on the top of the body. Control is via a set of buttons located below the display. The resolution of the sensor is 160 x 120 pixels. The internal memory allows storage of up to 200 images. The instrument start-up time is about 15 seconds, for measurement the manufacturer recommends to let the instrument temperature stabilize for 5 minutes, then it guarantees the given accuracy of measurement. It is possible to use it in an environment with temperatures - 15 to50 °C . Accuracy ±2°C of the sensed temperature and sensitivity0,1 °C . For data transmission we can use RS - 232 / USB or CVBS (S-Video out) interface.

Screen and settings

Parameter settings are made via the graphic display. The menu is in multiple languages, supports Czech. The basic menu includes settings - measurement mode (point, area - max, min,



average), range selection (automatic, manual), emissivity (0.1 - 1.0), color palette (rainbow, gray, iron), temperature ranges, hide menu, file (image management), settings (date, time, localization...).

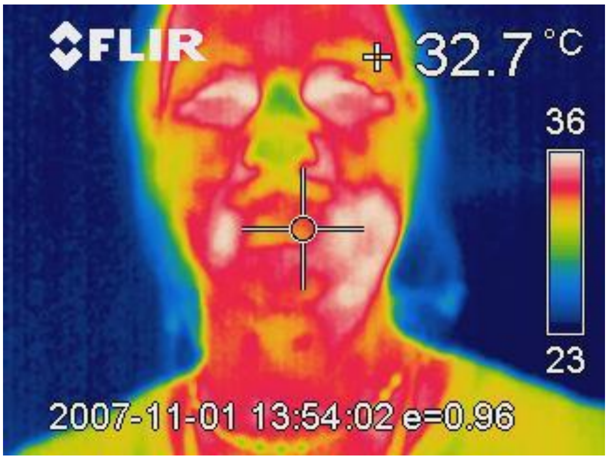
The previous picture shows an example of a camera screen containing a menu in English, then the date, time and emissivity at the bottom, a temperature colour palette on the right, the maximum measured temperature at the top and the centre indicates the area measurement, with the maximum in the marked area.

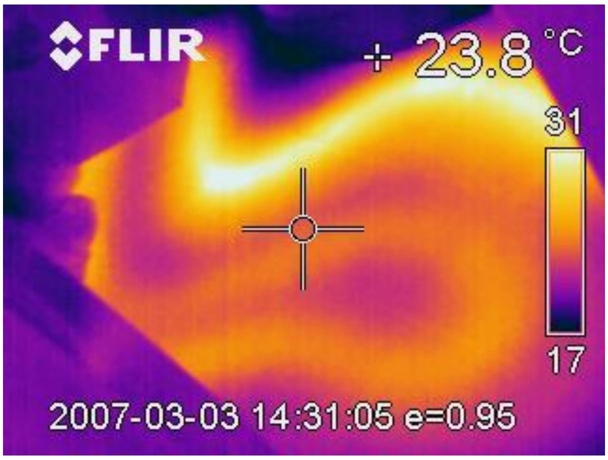
Data export and software usage

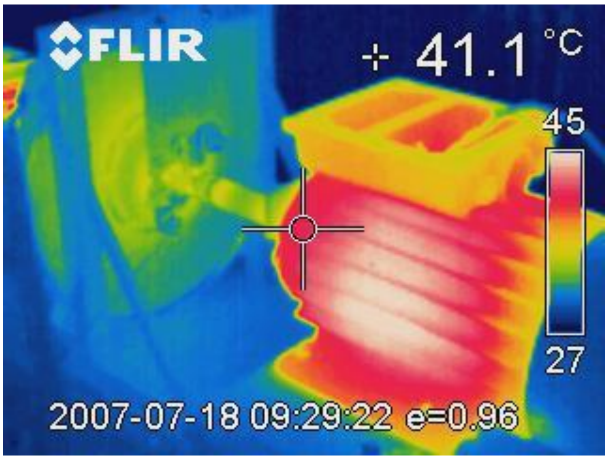
The camera continuously captures the object to be measured, and the image can be stored in the internal memory if the composition is suitable. The sensor has a resolution of 160x120 pixels, the images are stored in interpolated resolution of 320x240 in JPG format.

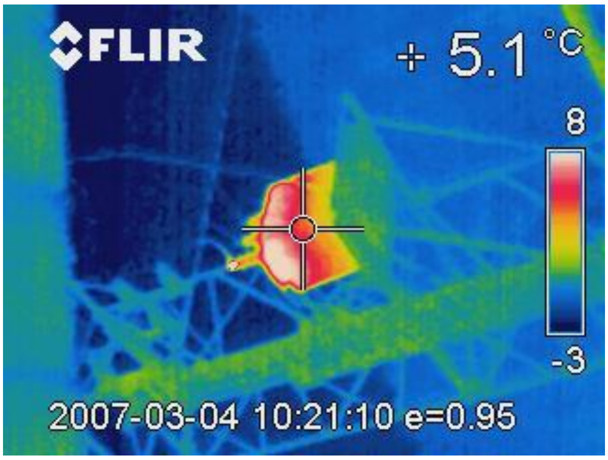
Examples of images

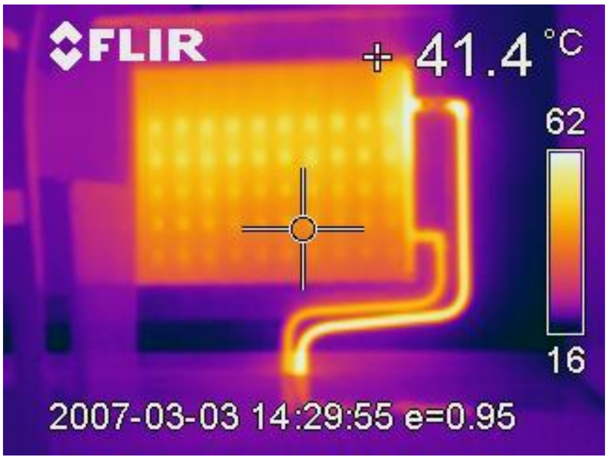
The possibility of using thermodiagnostics in practice, followed by several snapshots from different sectors.

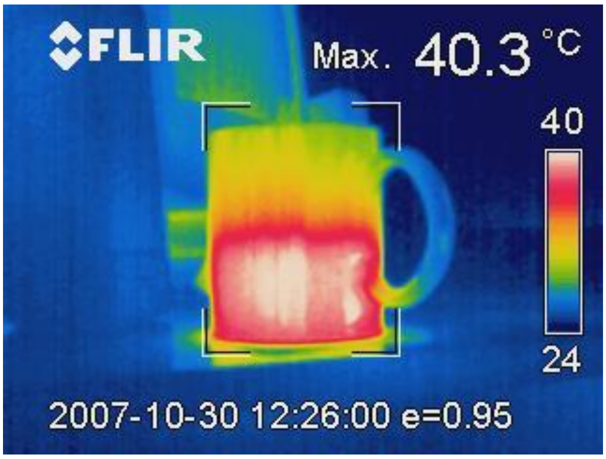






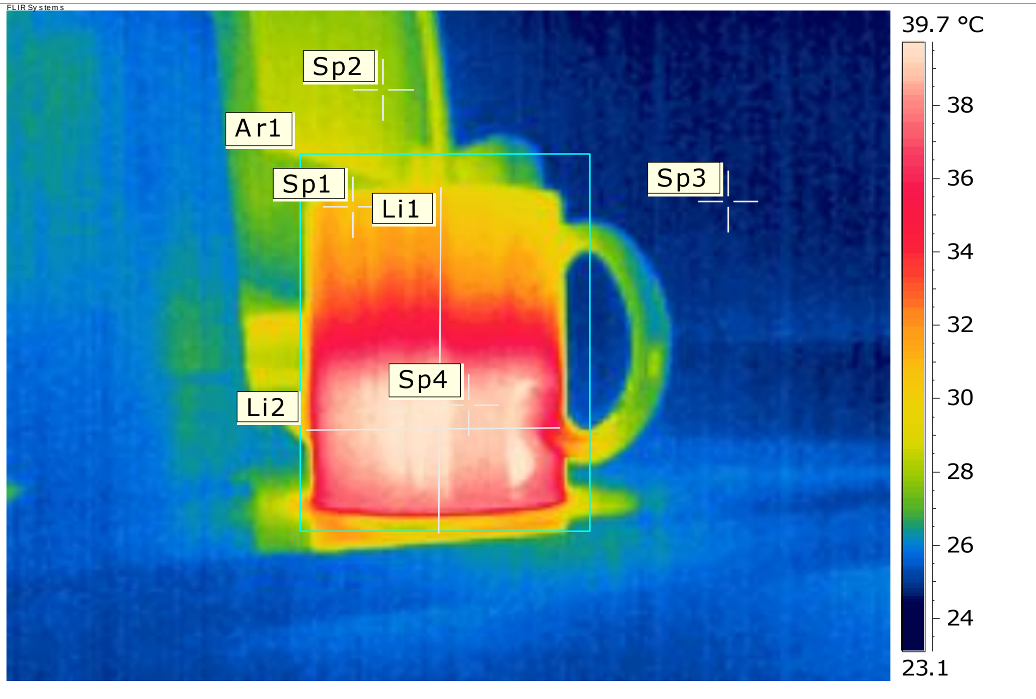




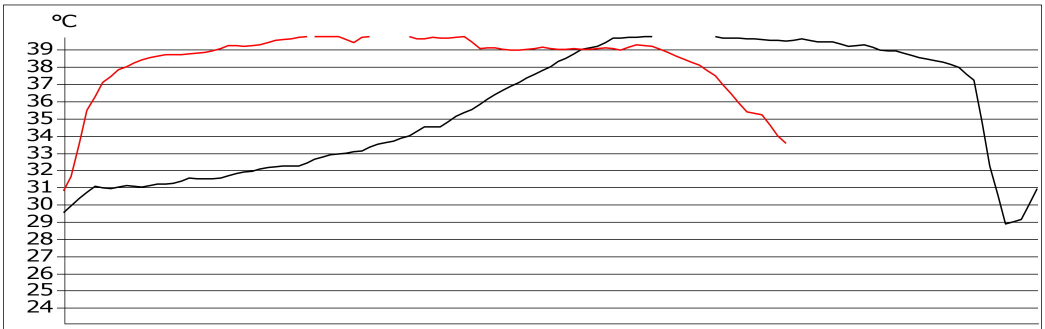


All the previous images were taken with the Flir E45 camera under different conditions, most of them are set to spot temperature, only the last image shows a flat measurement with maximum.

Rozložení teploty na keramickém hrnku naplněném tekutinou



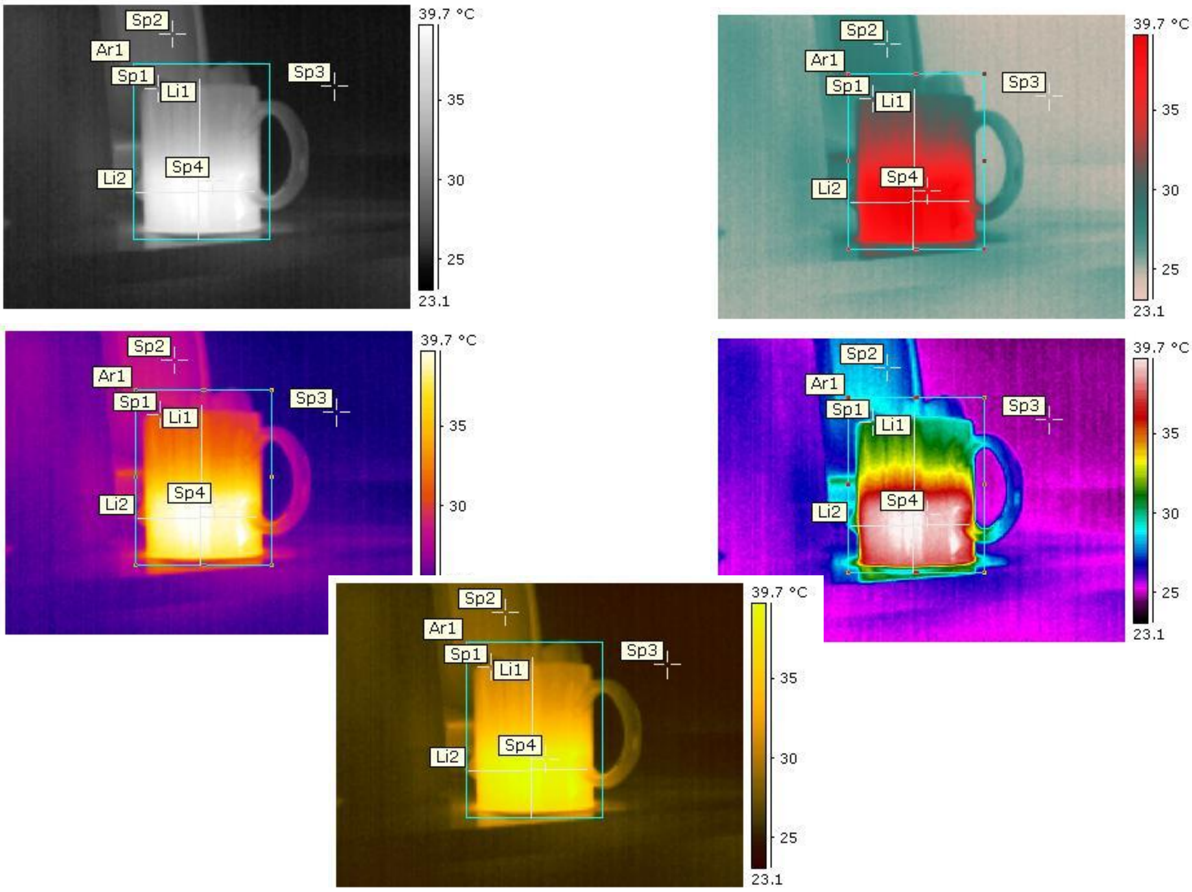
Průběh teploty na liniích Li1 a Li2



Název	Kurzor	Min	Max
Li1	-	28.8	39.9
Li2	-	30.7	40.1

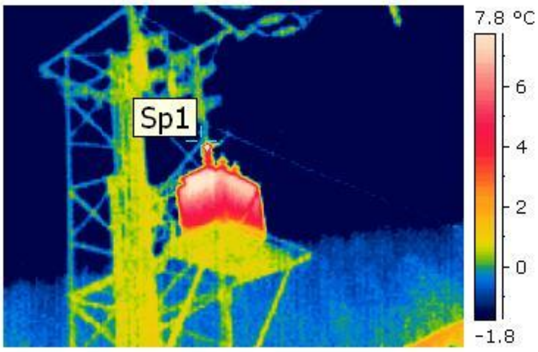
Parametry objektu	**Hodnota**	Sp1	30.5 °C
Emisivita	0.95	Sp2	27.8 °C
Vzdálenost objektu	2.0 m	Sp3	24.6 °C
Odražená teplota	20.0 °C	Sp4	39.0 °C
Teplota atmosféry	20.0 °C	Li1: Max	39.9 °C
Propustnost atmosféry	0.99	Li2: Max	40.1 °C
Podrobnosti	**Hodnota**	Ar1: Max	40.3 °C

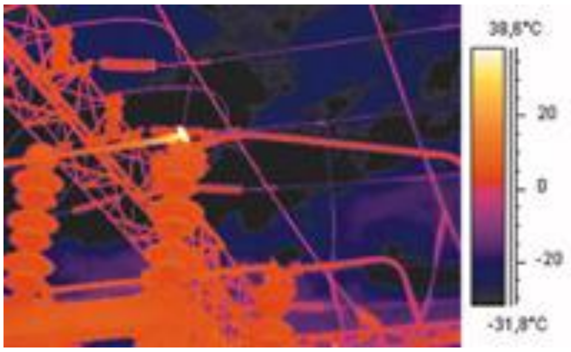
Sample logs created with Thermal Reporter. The heat traces along the Li1 and Li2 lines are shown, showing the change in temperature with change in spatial coordinate.

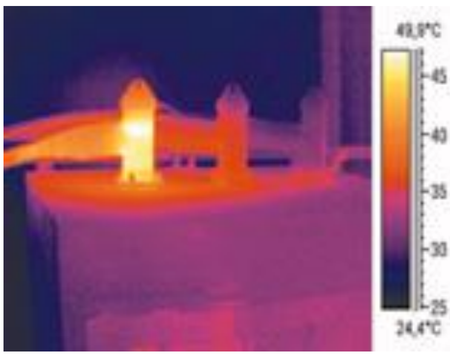


Color rendering options that are switchable. There are transitions between two, three, five and eight colours.

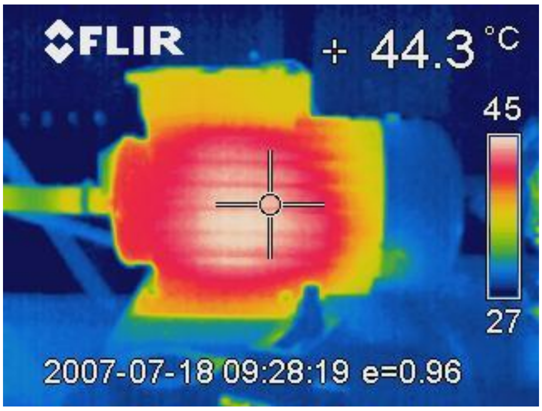
Energy - faults on interconnections

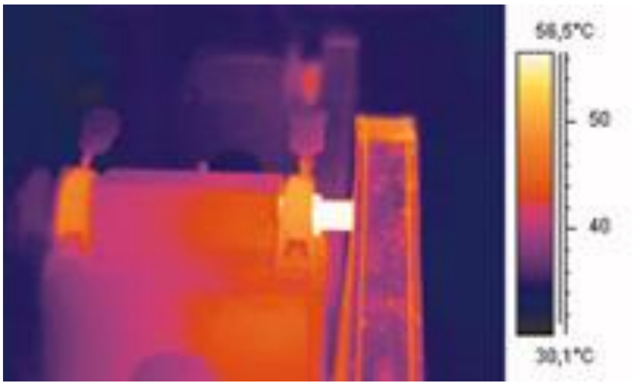


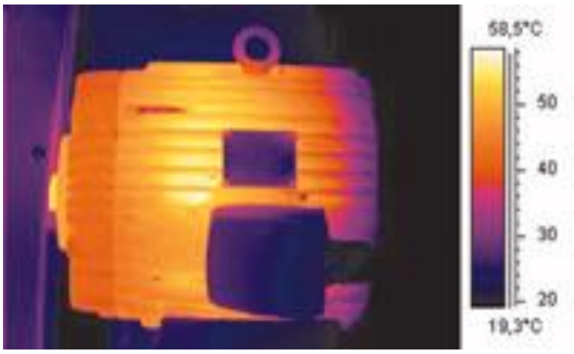


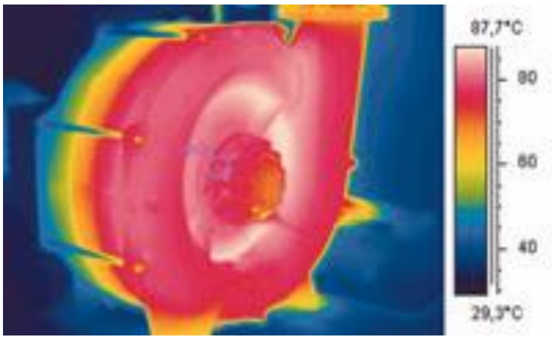


Rotating machines - overheating

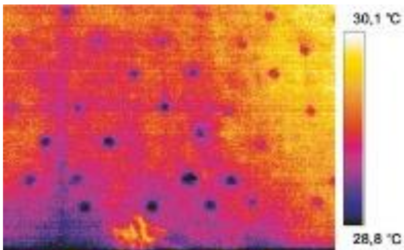


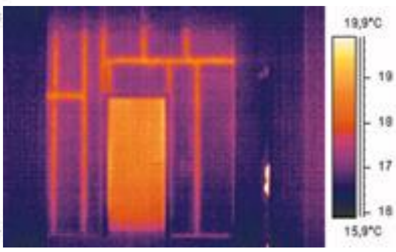




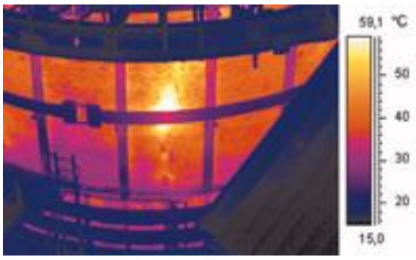


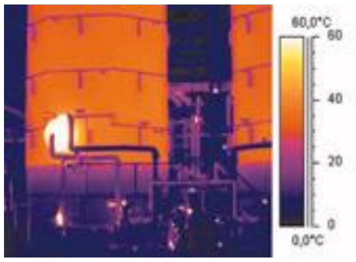
Construction

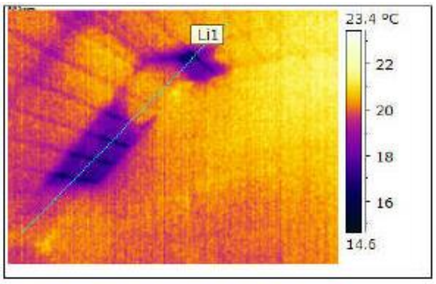


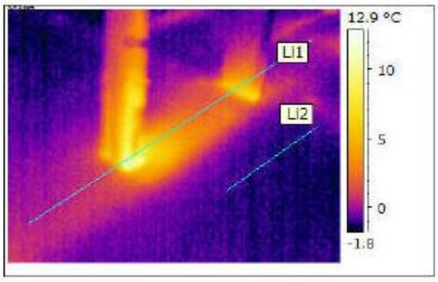


Technology









Medicine