# Introduction to Radiation Thermometry and Thermography.

# Radiation Thermometry

When the source is too hot to touch
(or too far away!)

# Thermal Radiation

- All matter at finite temperature emits electromagnetic radiation.
- The emitted power, and the wavelength, depend on the temperature.
- It is possible to work out the maximum amount of radiation emitted per unit area of surface for a perfect emitter, a so called ‘Blackbody’.

# Newton and his prism

# Colour perception

- Colour perception is a physiological phenomenon.
- Visible light ranges from 400 nm (red) to 700 nm (blue)
- The eye has receptor cells sensitive to different wavelengths
- If all the receptors fire at once then the brain perceives ‘white’ light.
- The colour of an object is the wavelength(s) reflected from its surface.
- A red surface reflects 650-700 nm and absorbs other wavelengths
- A yellow surface reflects around 590 nm
- A white surface reflects all visible wavelengths

# Colour perception

- A black surface is a good absorber at all wavelengths.
- No real surface can be perfectly ‘black’ (zero reflection) but you can get close.
- This can be generalised to other wavelengths, especially the infra red ( longer than 700 nm)
- We perceive IR not as an optical effect but as heat.

# Infra Red Radiation

- IR radiation transports heat.
- Objects emit, reflect and absorb heat via IR radiation
- A perfect absorber turns out to be a perfect emitter as well
- It is called a Black Body.
- No real surface is a perfect BB, but they can be close…

# Blackbody Radiation

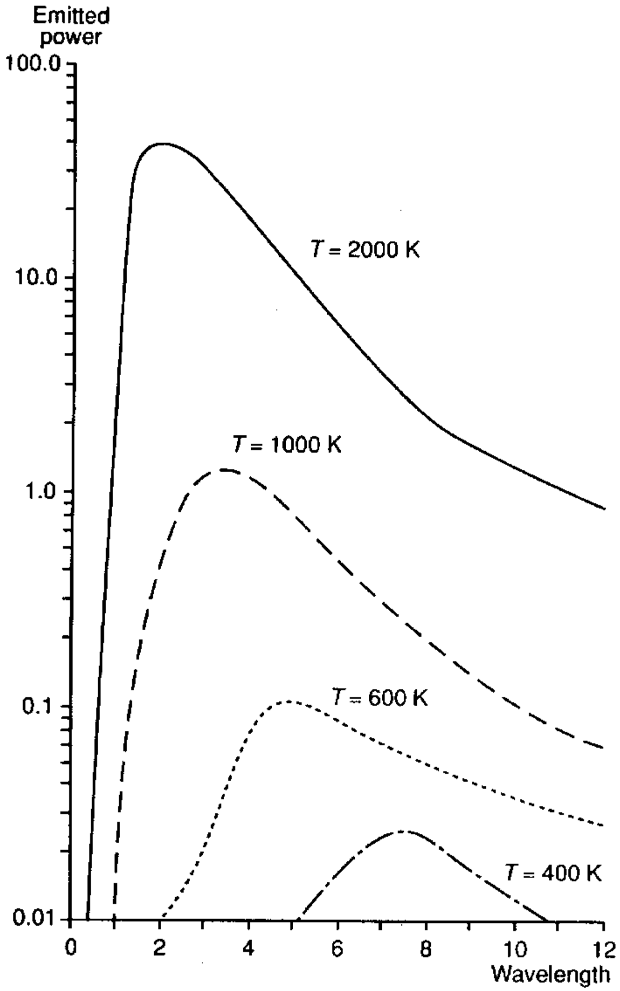
The spectrum of the electromagnetic radiation produced by a 'black body' i.e. a perfect emitter, at an absolute temperature of $T$ degrees K is described by the following expression.

$$W_{BB}(T,\lambda) = \frac{C_1}{\lambda^5\left(e^{C_2/\lambda T} - 1\right)} \quad \text{Watts cm}^{-2}\mu\text{m}^{-1}$$

where:

$W_{BB}$ = power emitted per unit wavelength (at $\lambda$) per unit area of emitter.
$T$ = absolute temperature (degrees Kelvin)
$\lambda$ = wavelength ($\mu$m)
$C_1$ = 37413 W $\mu$m$^4$ cm$^{-2}$
$C_2$ = 14388 $\mu$m K

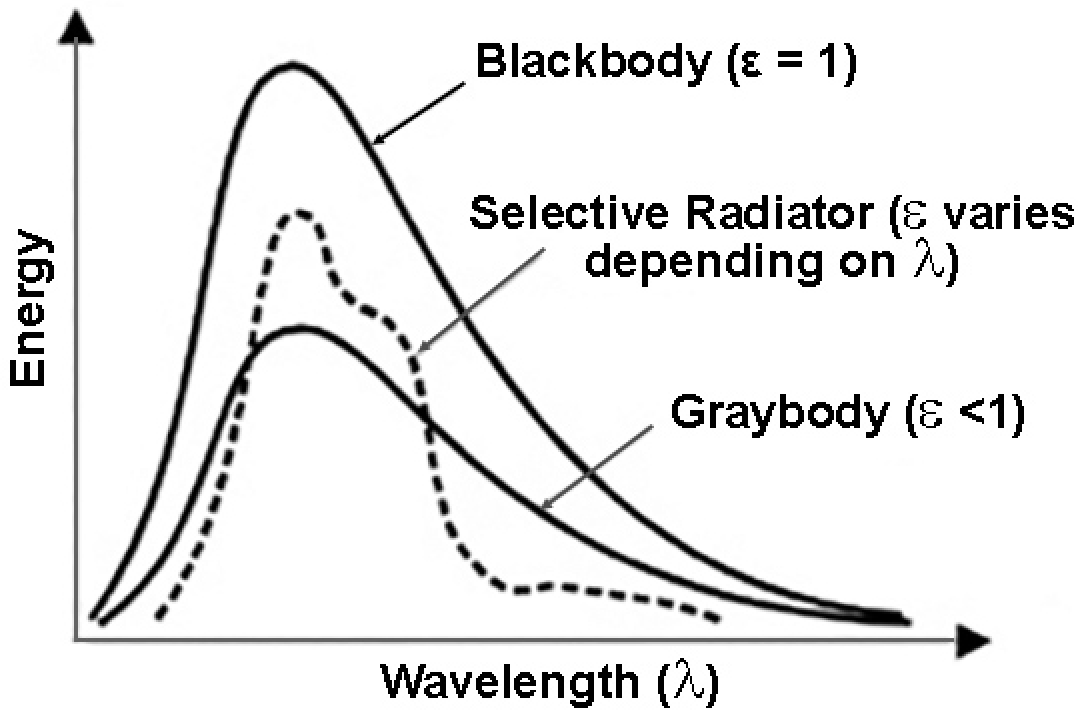
# Blackbody Radiation Spectra




$$W_{BB}(T,\lambda) = \frac{C_1}{\lambda^5\left(e^{C_2/\lambda T} - 1\right)} \quad \text{Watts cm}^{-2}\mu\text{m}^{-1}$$

$$W_{BB} = \sigma T^4$$

# Emissivity




- A ‘graybody’ would have a constant ε<1.
- Real surfaces will have emissivity less than 1 which varies with λ
- Maybe use 0.85 as a first guess for typical matt surface.

# Optical Pyrometer

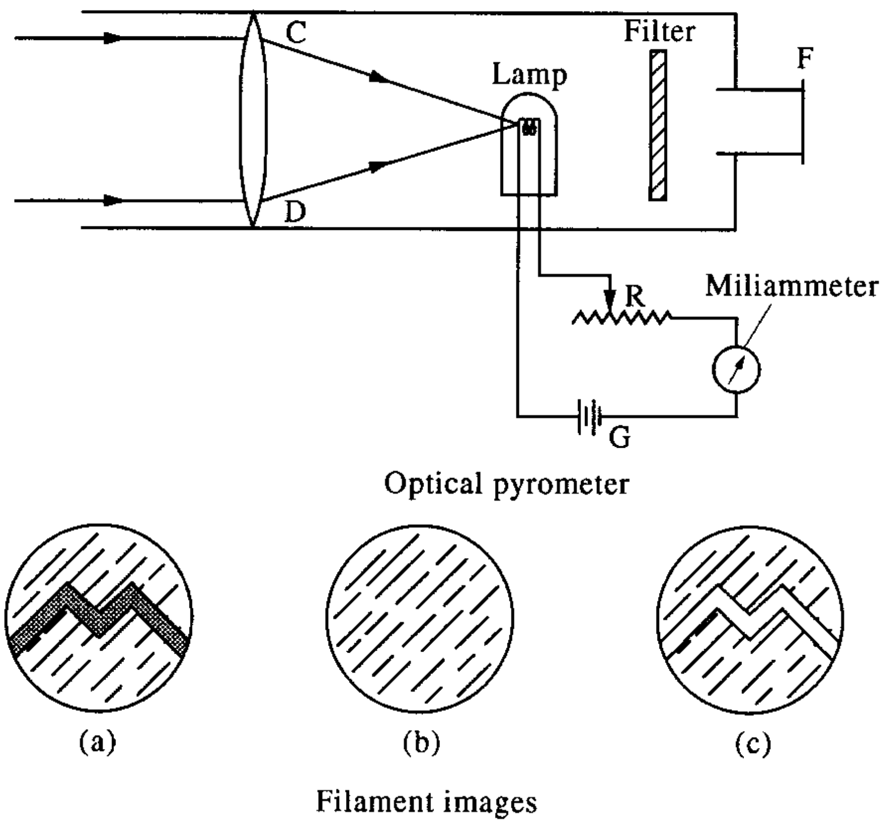
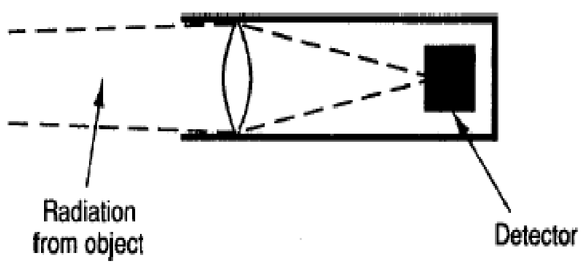



**FIGURE 18** – The Schematic of an Optical (Brightness) Pyrometer.

# Radiation Pyrometer

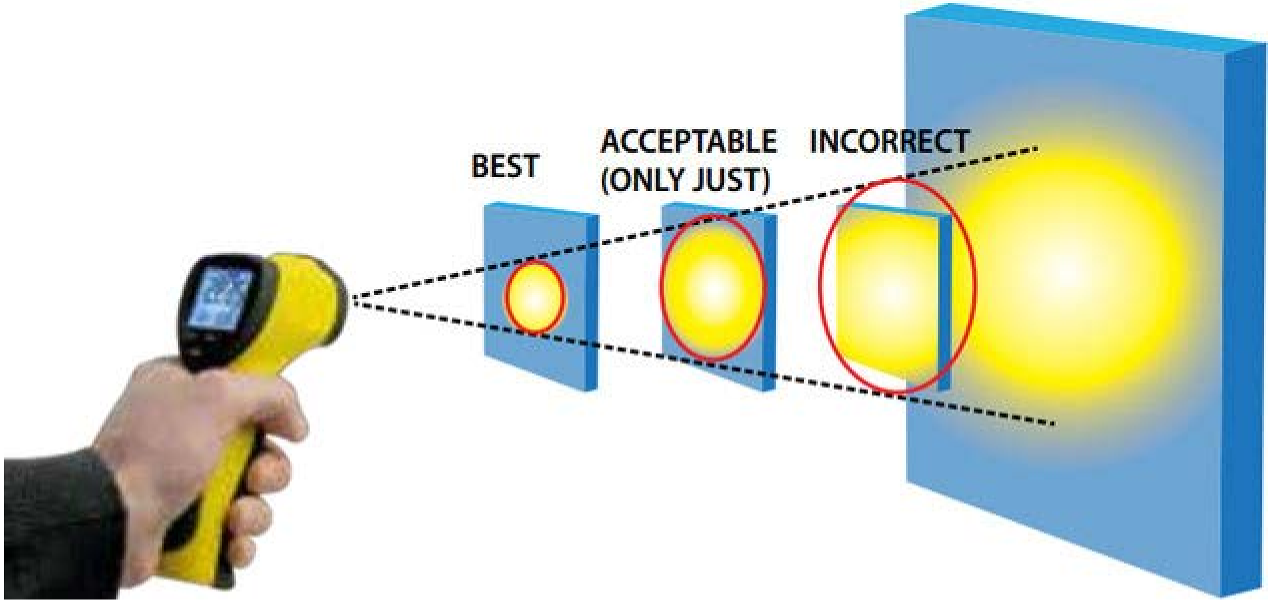



- Radiation from hot object impinges on detector.
- Use thermal detector to measure temperature rise or,
- Use photon detector to count radiation quanta.

# Typical IR thermometer


- Convenient but easily misused.
- Watch out for emissivity setting!
- You are NOT measuring the temperature at the laser aiming dot!

# IR thermometer doesn’t make spot measurements.



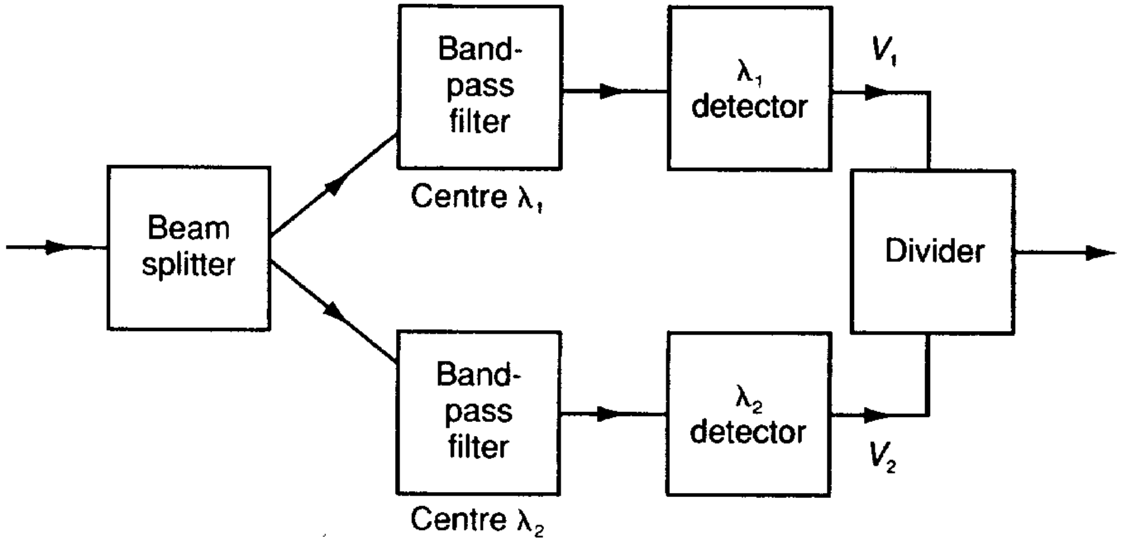
# Radiation Pyrometer

- Broad band
- Narrow Band
- Chopped
- Two Colour

# Two Colour Pyrometer

- Hard to make measurements based on absolute radiation intensity.
- Better to use the ratio of intensities at two wavelengths.
- It the wavelengths are quite close together then there will not be a significant difference in the emissivities so this effect will cancel too.

# Two Colour Pyrometer




$$R_T = \left(\frac{\lambda_2}{\lambda_1}\right)^5 e^{\frac{c_2}{T}\left\{\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right\}}$$

# How does the thermal detector work?

- A tiny fraction of the radiation from the hot source is focused onto the detector element

- The detector element temperature increases proportionally to the incident power

- NB temp rise is small – nothing like the sourse temperature!

- A heat balance equation applies.

*The Heat Balance Equation:*

[Power incident on detector] – [Power conducted away from detector]
= [Power absorbed by detector]

or

$$P_D - UA(T_D - T_S) = Mc\frac{dT_D}{dt}$$

where:

| | | |
|---|---|---|
| $P_D$ | = | Total power incident on detector |
| $U$ | = | Heat transfer coefficient W m$^{-2}$ °C$^{-1}$ |
| $A$ | = | Area of detector |
| $M$ | = | Mass of detector |
| $c$ | = | specific heat capacity of detector |
| $T_S$ | = | Temperature of surroundings |

therefore:

$$T_D + \tau\frac{dT_D}{dt} = \frac{1}{UA}P_D + T_S$$

where $\tau = Mc/UA$ is the time constant of the detector. To obtain the steady state solution we set $dT_D/dt = 0$,

$$T_D = \frac{1}{UA}P_D + T_S$$

This result is intuitively reasonable since it says that $T_D$ is proportional to $P_D$, the rate of heat influx and inversely proportional to $UA$, which governs the rate of heat loss.

**Detector Output**

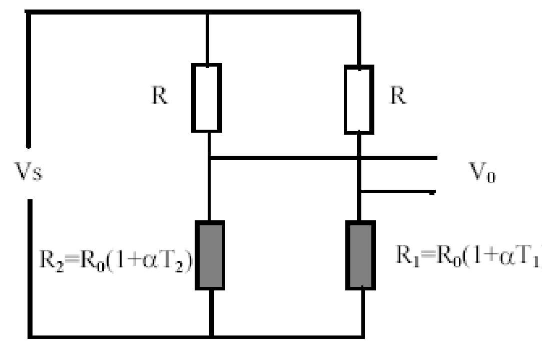
1) Thermopile:

$E_{T_D,T_S} = na(T_D - T_S)$ where $n$ is the number of junctions and $a$ is the thermocouple sensitivity. From the previous result, $T_D = \frac{1}{UA} P_D + T_S$ we can express the output voltage as:

$$E_{T_D,T_S} = P_D \frac{na}{UA}$$

2) Bolometer:

This is a passive resistive device so we use a bridge circuit to produce an output voltage proportional to temperature. Two sensors, labelled $R_1$ and $R_2$ in the diagram are the measuring and reference elements.




The bridge output is:

$$V_0 = V_S\left\{\frac{R_0(1+\alpha T_1)}{R+R_0(1+\alpha T_1)} - \frac{R_0(1+\alpha T_2)}{R+R_0(1+\alpha T_2)}\right\}$$

NB $V_0 = 0$ for $T_1 - T_2$

rearranging this expression we have:

$$V_0 = V_S\left\{\frac{1}{1+\dfrac{R1}{R_0(1+\alpha T_1)}} - \frac{1}{1+\dfrac{R1}{R_0(1+\alpha T_2)}}\right\}$$

by setting $R >> R_0$ we can linearise the output at the expense of a smaller sensitivity. In this limit the output becomes

$$V_0 \approx V_S \left\{ \frac{(1+\alpha T_1)}{R/R_0} - \frac{(1+\alpha T_2)}{R/R_0} \right\} \text{ which simplifies to } V_0 \approx V_S \alpha \frac{R_0}{R}(T_1 - T_2)$$

3) Pyroelectric Detector

Pyroelectric detectors are man-made ferroelectric ceramics. The ceramic is composed of a mass of minute crystalites; provided the ceramic is below the Curie temperature, then each crystalite behaves as a small electric dipole. Normally the material is unpoled, i.e. the dipoles are randomly orientated with respect to each other. The material can be poled by placing it in an electric field and heating it to just below the Curie temperature. After the ceramic has cooled and the applied field has been removed, the dipoles remain aligned with a residual polarisation $P$. The pyroelectric effect arises because $P$ diminishes as $T$ increases. The reduction in polarisation produces an excess of induced charge on the electrodes. If $\Delta q$ is the excess charge caused by If $\Delta T$ then

$$\Delta q = \left( \frac{dP}{pT} \right) A \Delta T$$

where $A$ is the area of the electrodes. The electrodes and the block of dielectric ceramic form a parallel plate capacitor $C$. The ceramic can be thought of as a current source $i$ in parallel with $C$.

$$i = \frac{dq}{dt} = A \frac{dP}{dT} \frac{dT}{dt}$$

A typical pyroelectric detector has a diameter of 2 mm, a responsivity of 250 V W $^{-1}$ and a noise equivalent power of $2 \times 10^{-9}$ W Hz$^{-1}$ at 25 °C. When used with a silicon window its wavelength response is limited to between 1 and 15 μm.

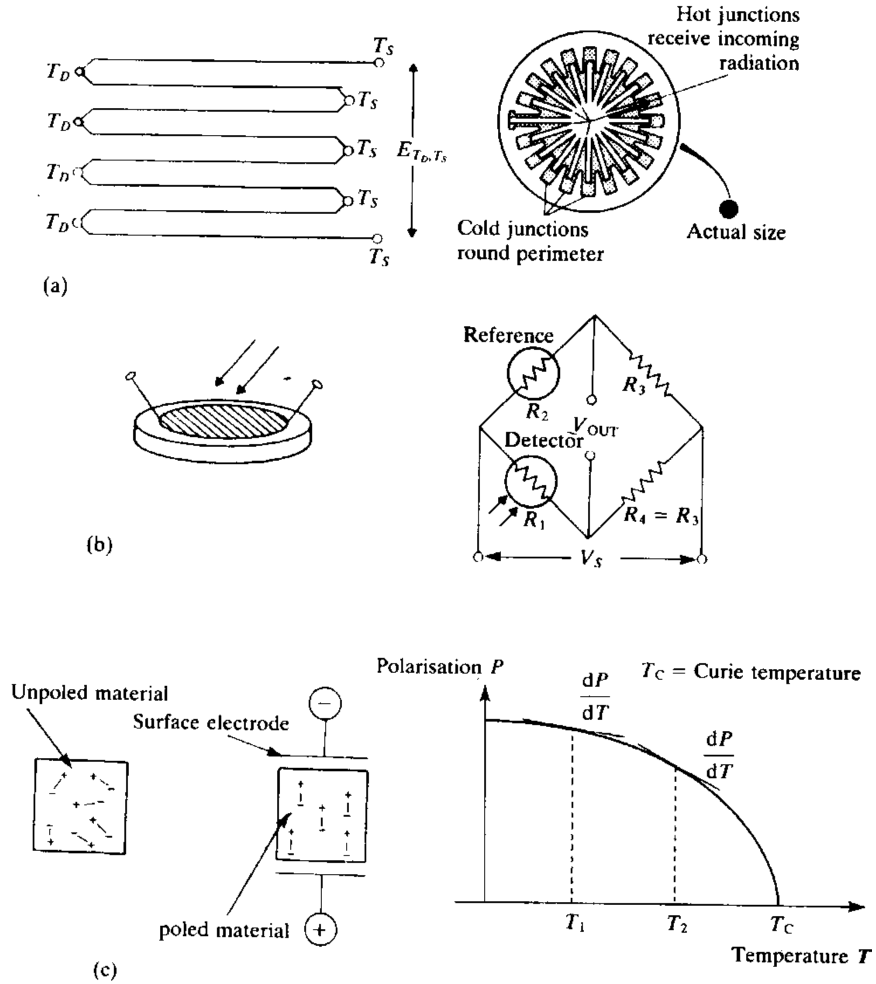



*Fig. 15.14* Thermal detectors
(a) Thermopile
(b) Bolometer
(c) Pyroelectric

# Thermography

- False colour image constructed from thermal radiation.
- Can produce map of temperature (thermography)

# Optical Materials for Radiation Thermometers

- Glass wont work in the IR region
- Can use intrinsic Si (3-5 $\mu$m) or n-type Ge (8-13.5 $\mu$m) for lenses. Si/Ge doublets for colour correction.
- $PbF_2$, $MgF_2$ used for coatings.
- Note that these wavelengths are 10-20 times longer than visible light.

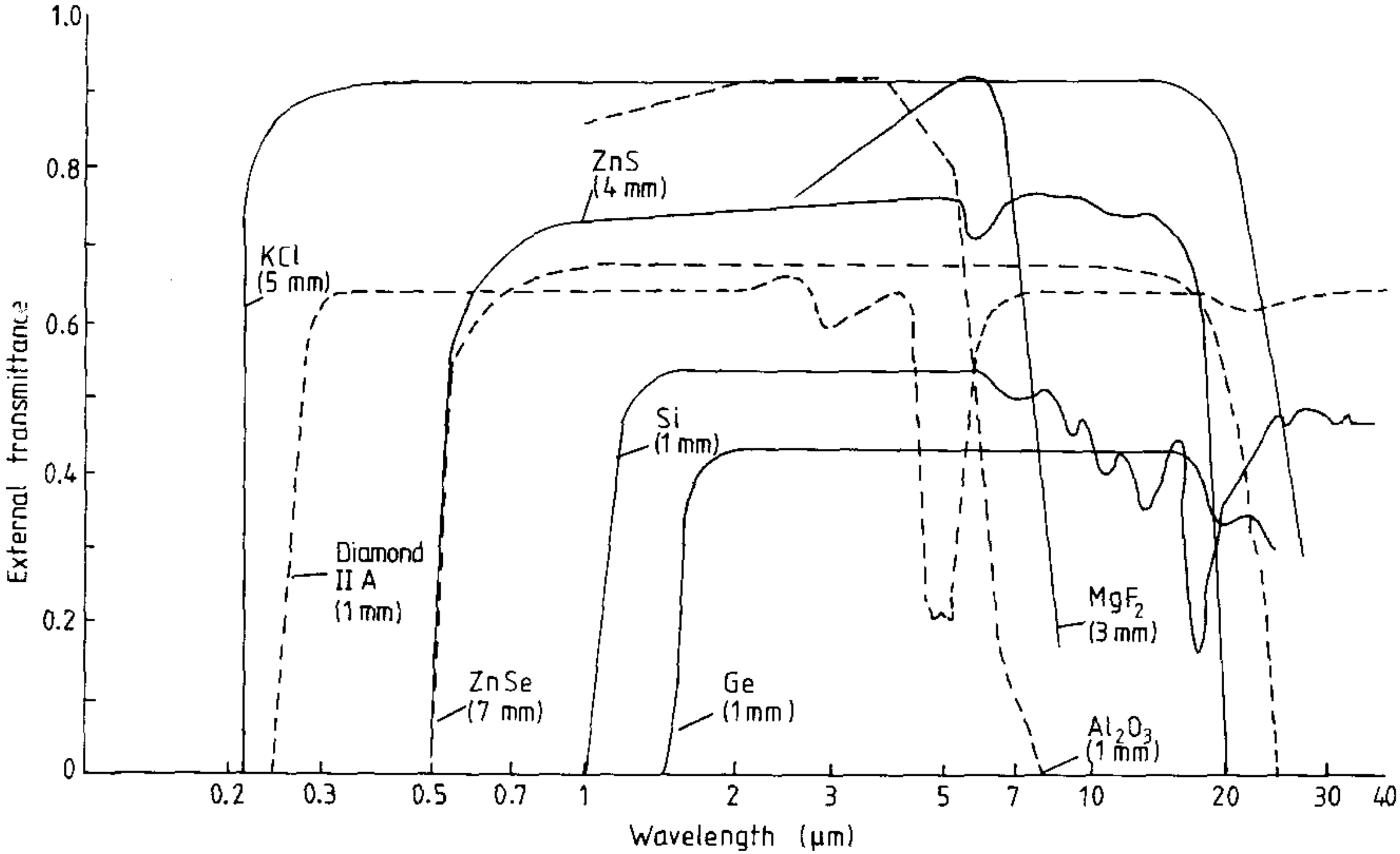



**Figure 1.10** Infrared transmission of optical materials.

# Thermal Imaging Systems

- Use 2-6 μm or 8-14μm.
- Use scanning system or (more recently) a focal plane array (FPA).
- Can map absolute temperatures to 1%.

# Focal Plane Arrays

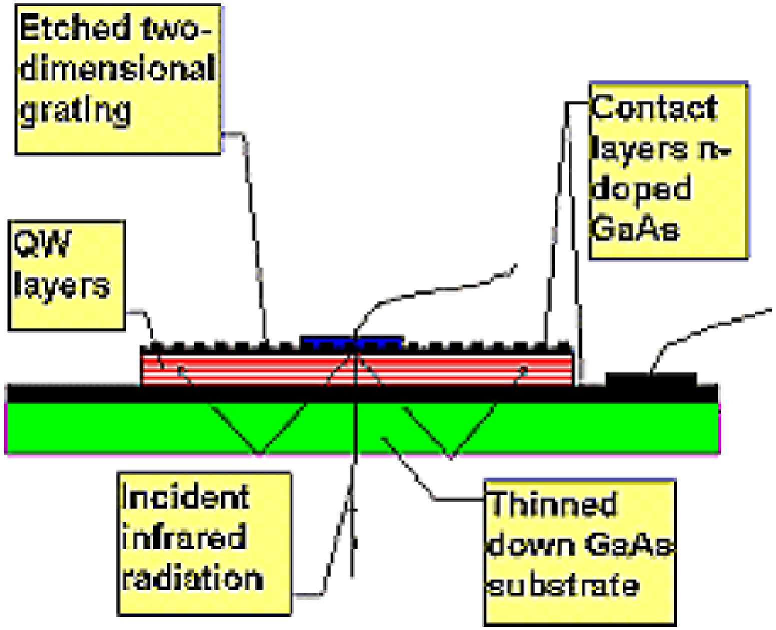
- Can't just use digital camera technology – IR photons are 10-20 times less energetic than visible light photons.
- different wavelength photons need different detectors.
- Two types
  - Photon detectors: e.g. QWIP
  - Thermal detectors: e.g. microbolometer array

# Quantum Well Infrared Photodetector QWIP

- Very thin layers (1-10 nm) of GaAs semiconductor material trap electrons which can be liberated by absorption of IR photons.

- Can make an array of pixels on wafer.

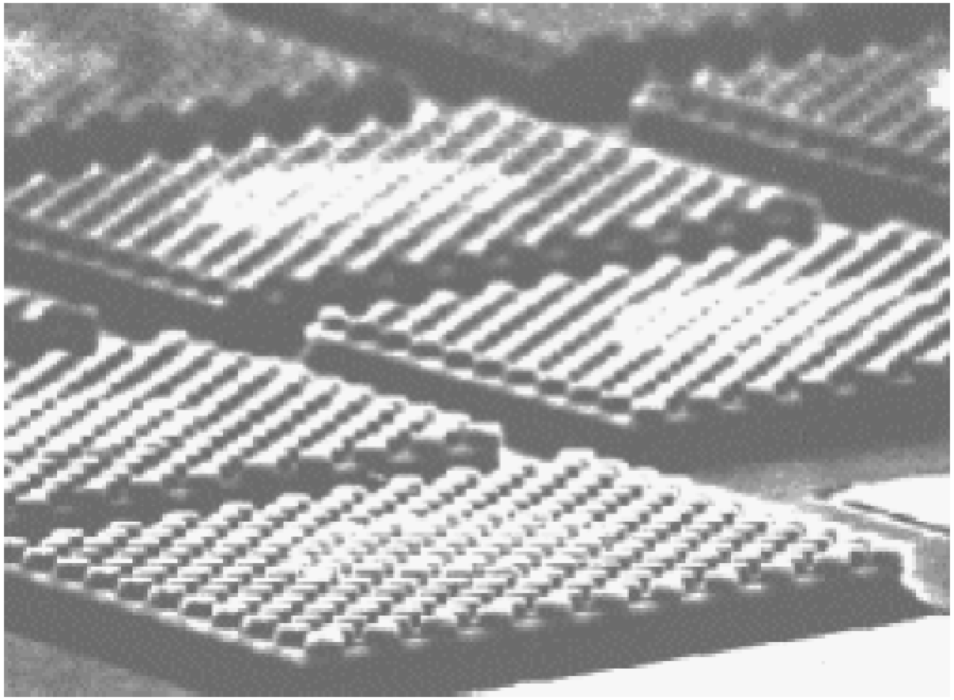
# Quantum Well Infrared Photodetector QWIP



# Quantum Well Infrared Photodetector QWIP

- IR radiation entering from the bottom of the picture is multiply reflected in the quantum well structure.
- Grating helps to reflect light an so increase efficiency of the detector.

# Quantum Well Infrared Photodetector QWIP



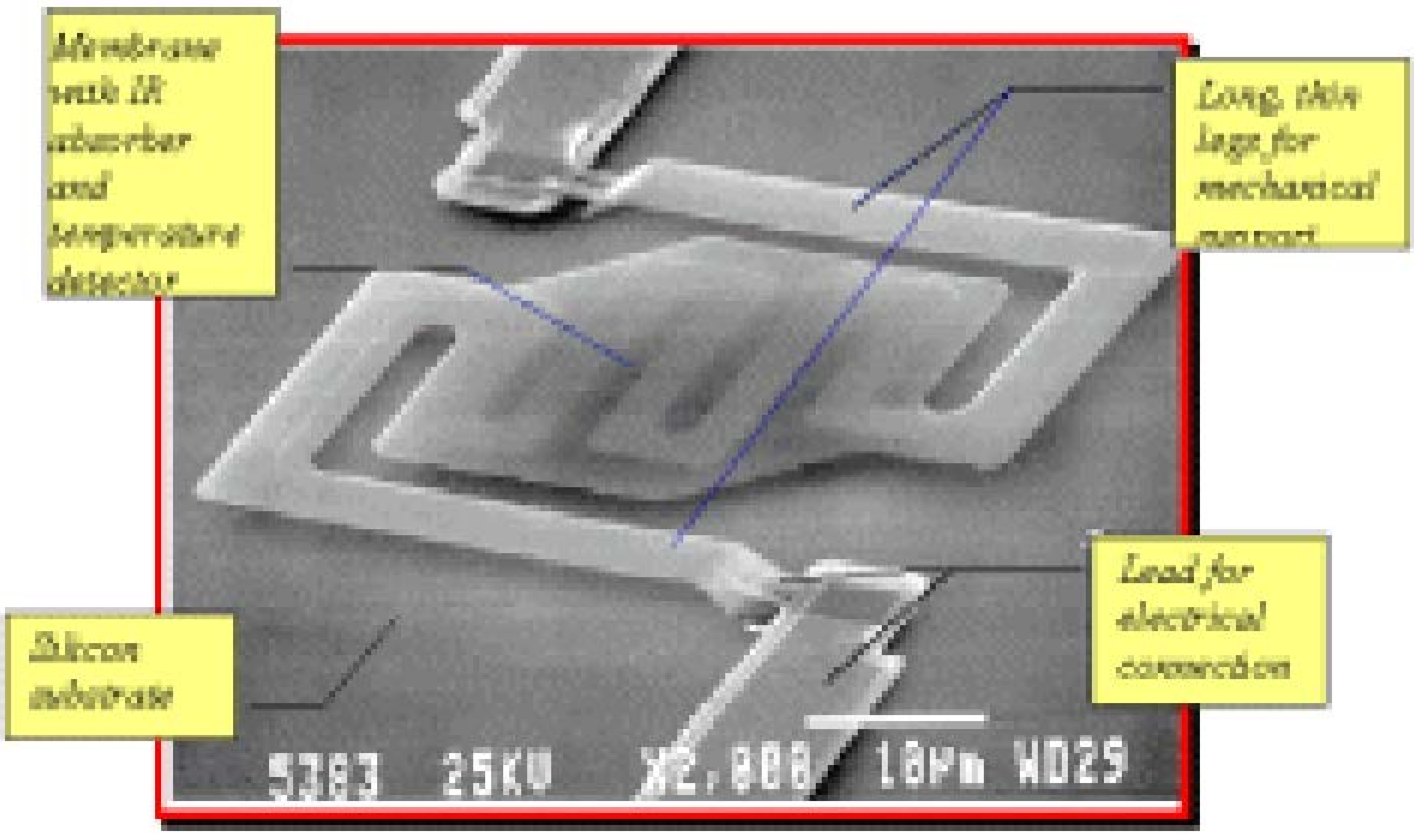
Electron micrograph of QWIP pixel detectors showing two dimensional grating on the underside.

IR image acquired with a 320 x 240 element QWIP matrix

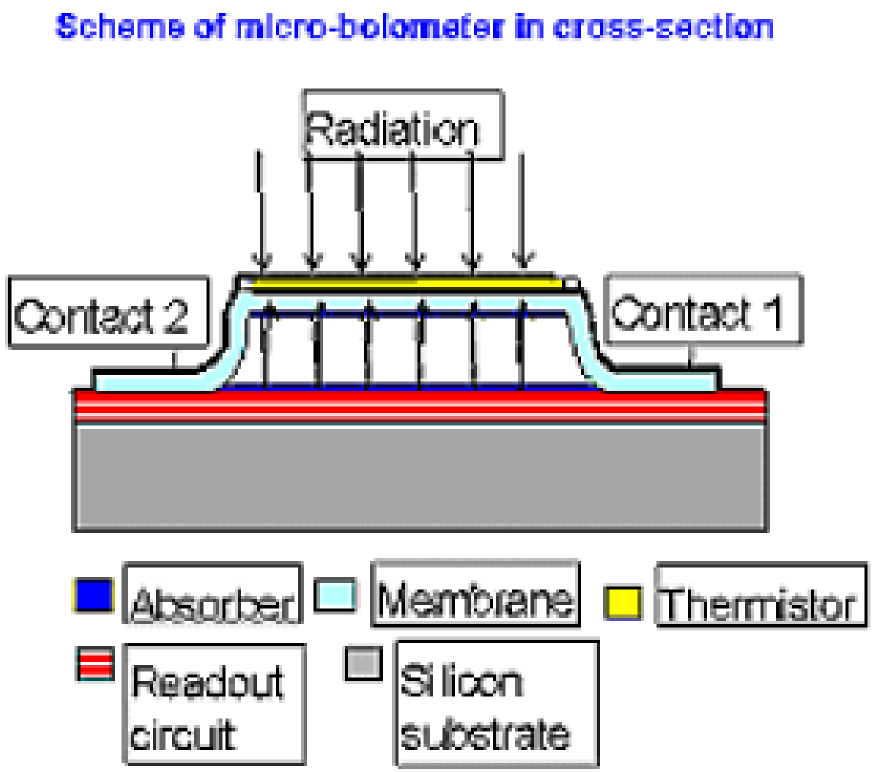
# Micro Bolometer Array

- Array of thermal detector pixel elements
- Silicon Nitride membrane absorbs IR
- Platinum resistor or thermistor detects temperature rise.

# Micro Bolometer



# Micro Bolometer



# Thermography Examples

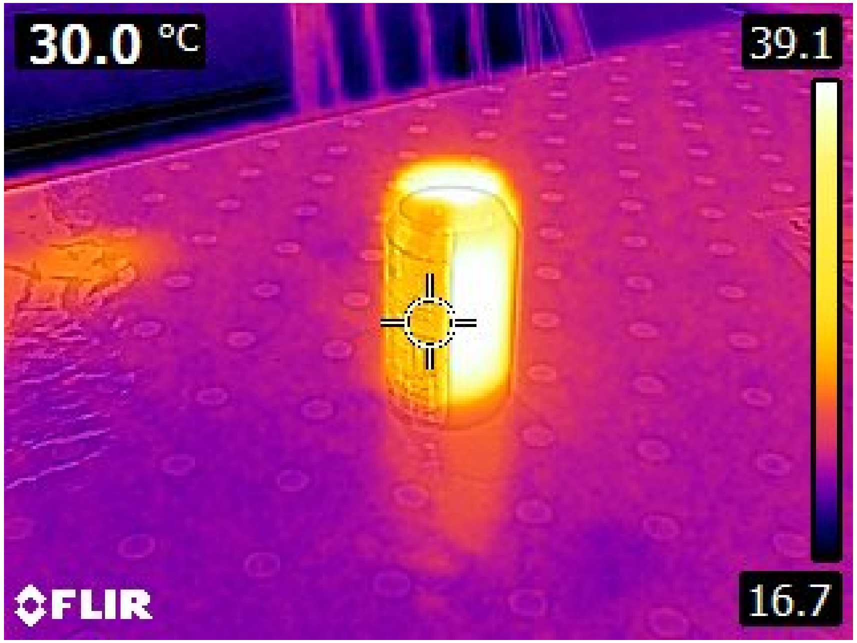
# FLIR E4 thermal imaging camera

# Effect of Emissivity

## half polished/half blackened drinks can

**Normal image**

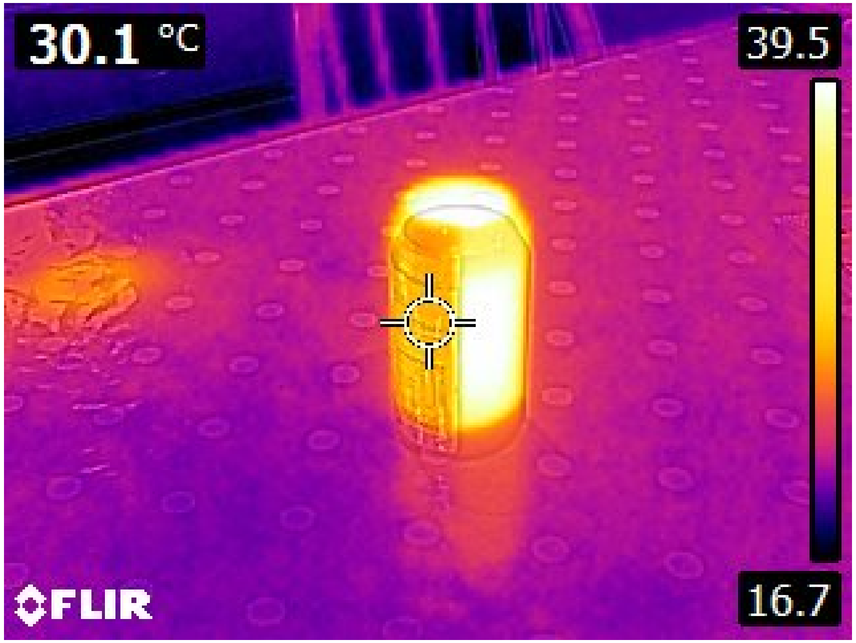

**Thermal image**



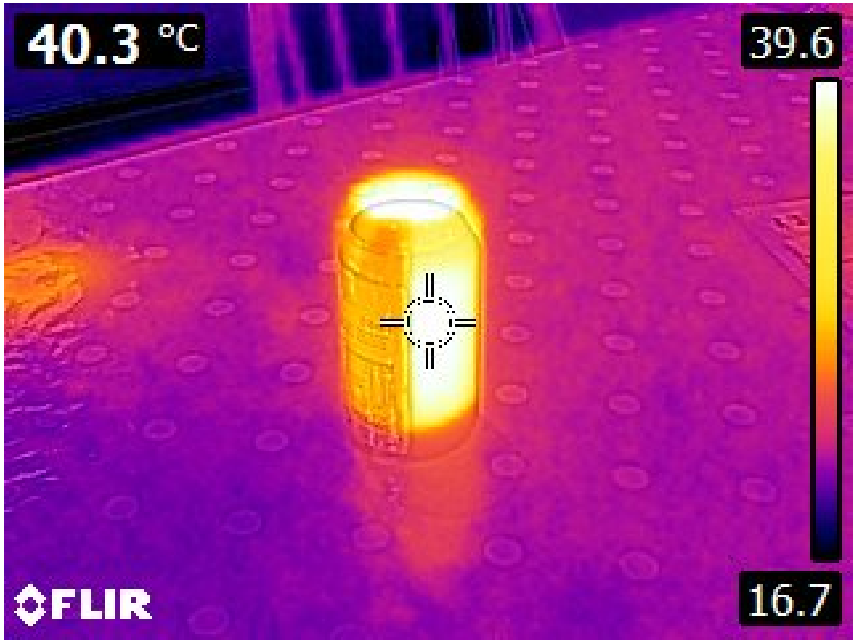
# Effect of Emissivity

**half polished/half blackened drinks can**

**Low emissivity (polished) side**



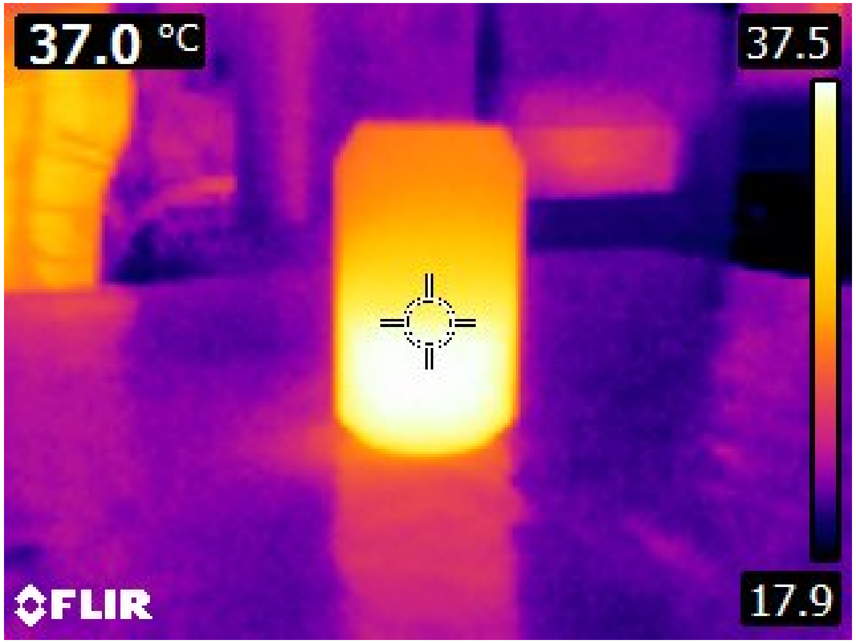

**High emissivity (black) side**



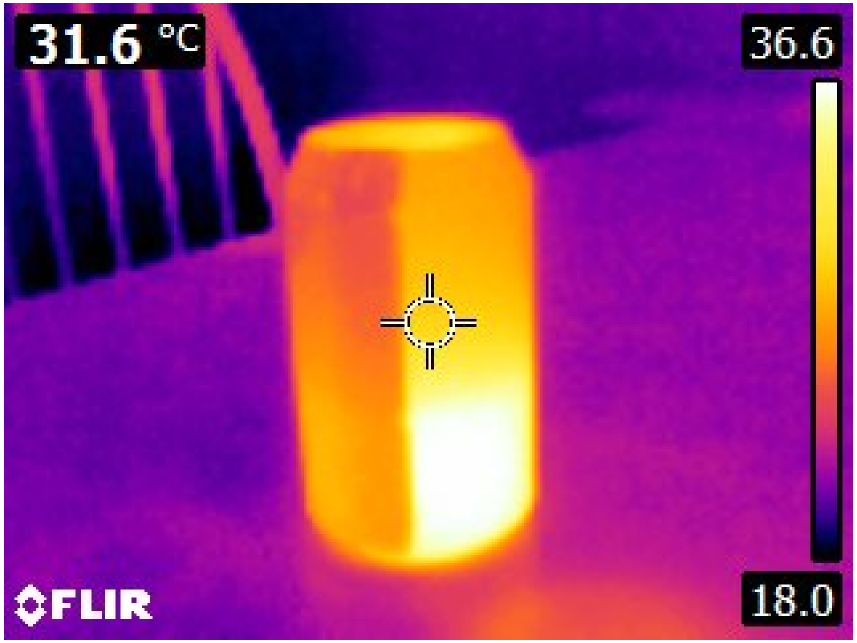
# Effect of Emissivity

## half polished/half blackened drinks can

**Can half full (black side)**



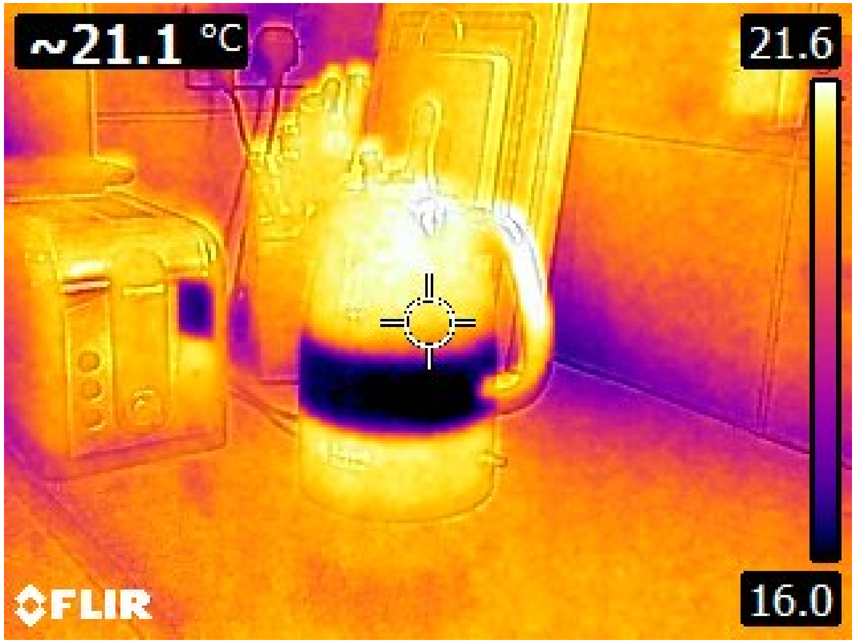

**Emissivity Comparison**



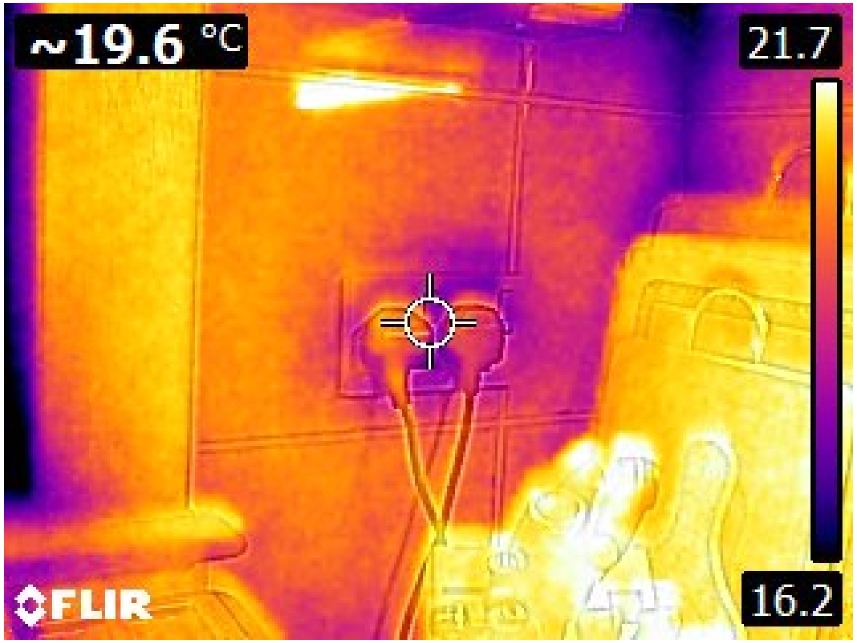
# Boiling Kettle

time evolution of image

**Half full of cold water**



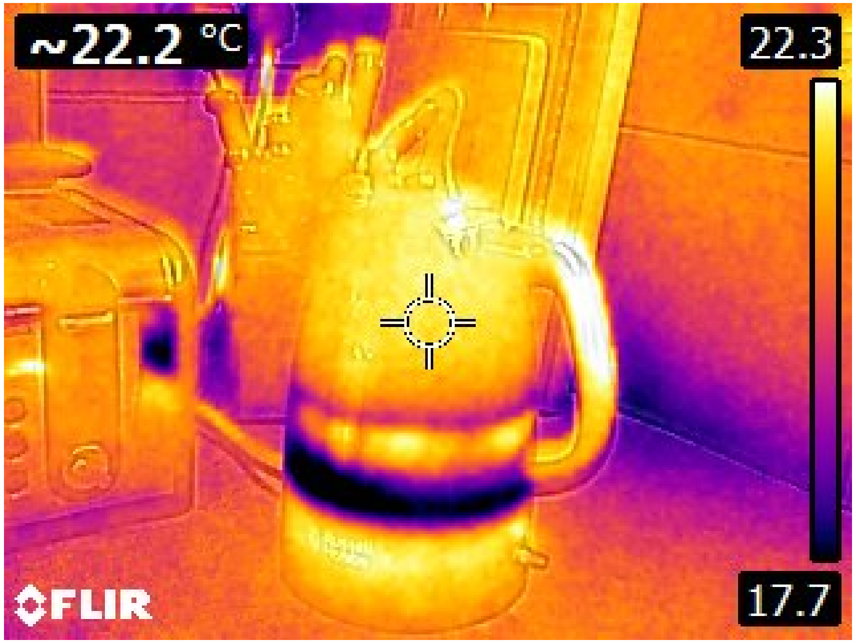

**Power cable - cold**



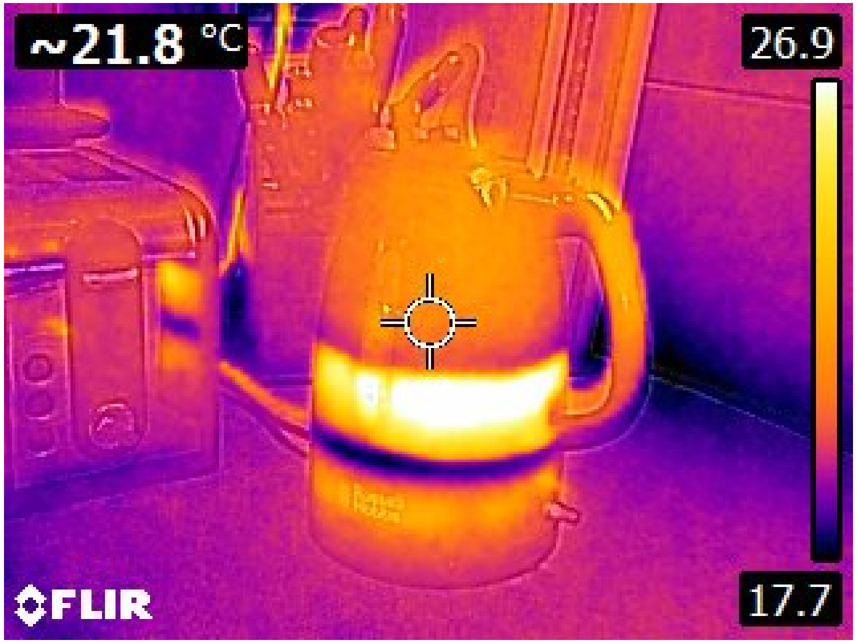
# Boiling Kettle

time evolution of image

**Heating begins – note effect of convection.**



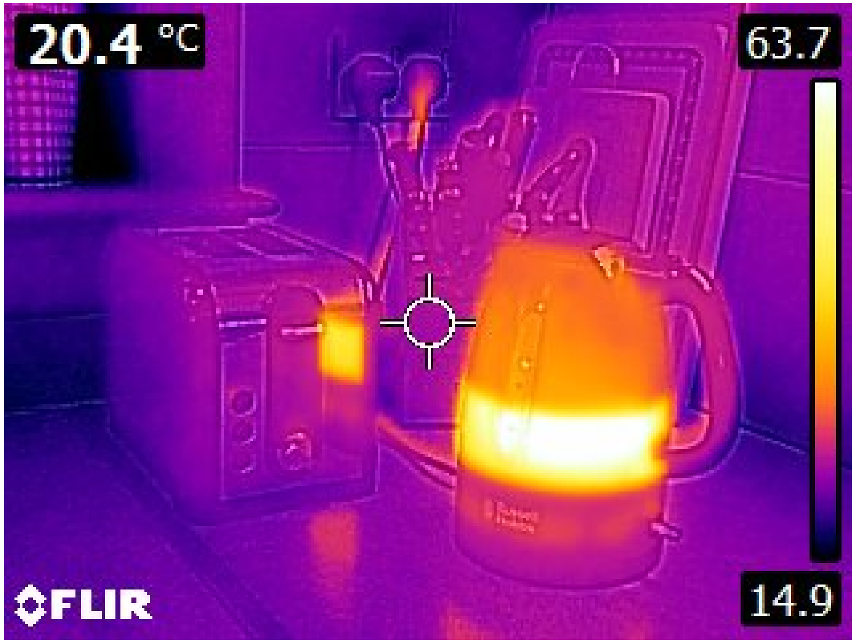

**Heating continues**



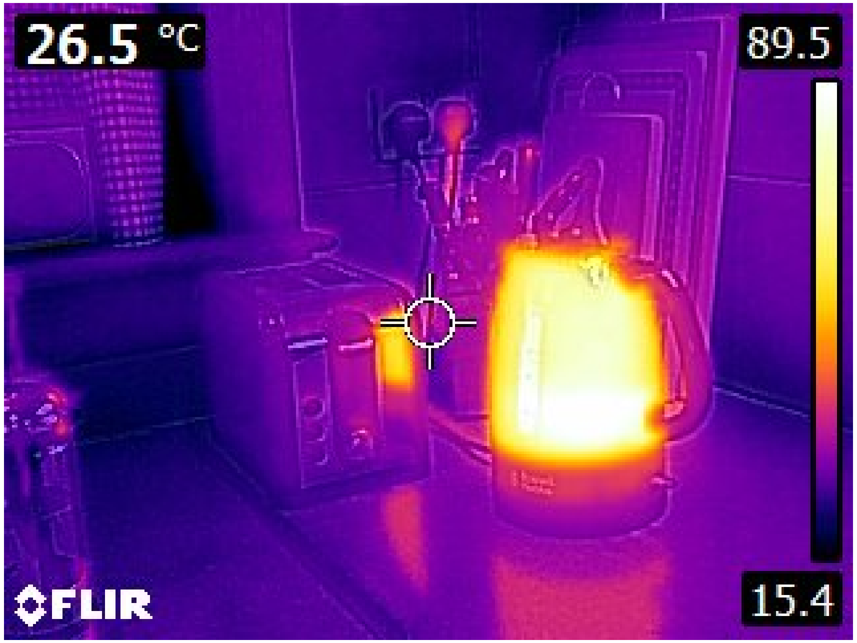
# Boiling Kettle

time evolution of image

**Can see hot water level inside.**



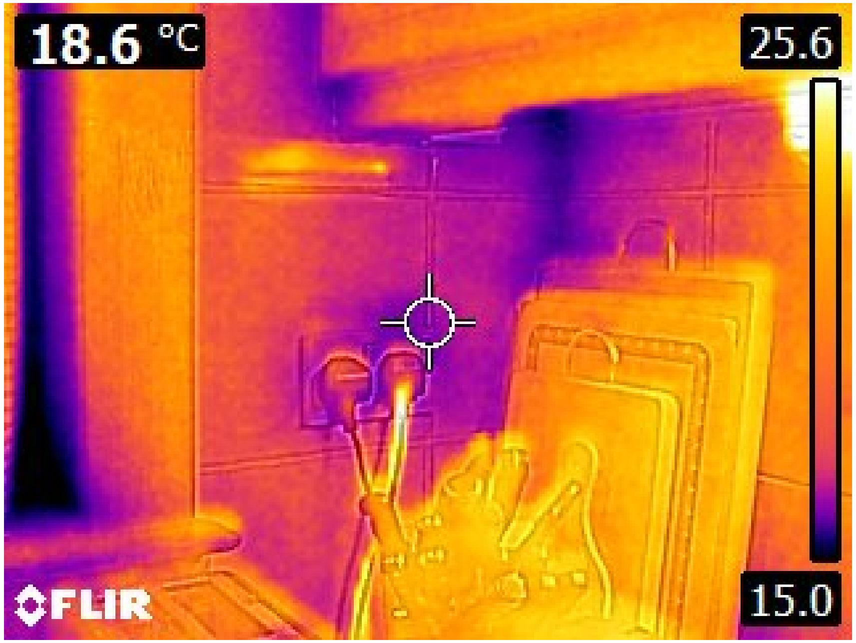

**Boiling! Steam is a good conductor of heat.**



# Boiling Kettle

time evolution of image

**Power cable warming**




**Power cable fully warm**

# Industrial Examples of Thermography

# Oil Pipeline

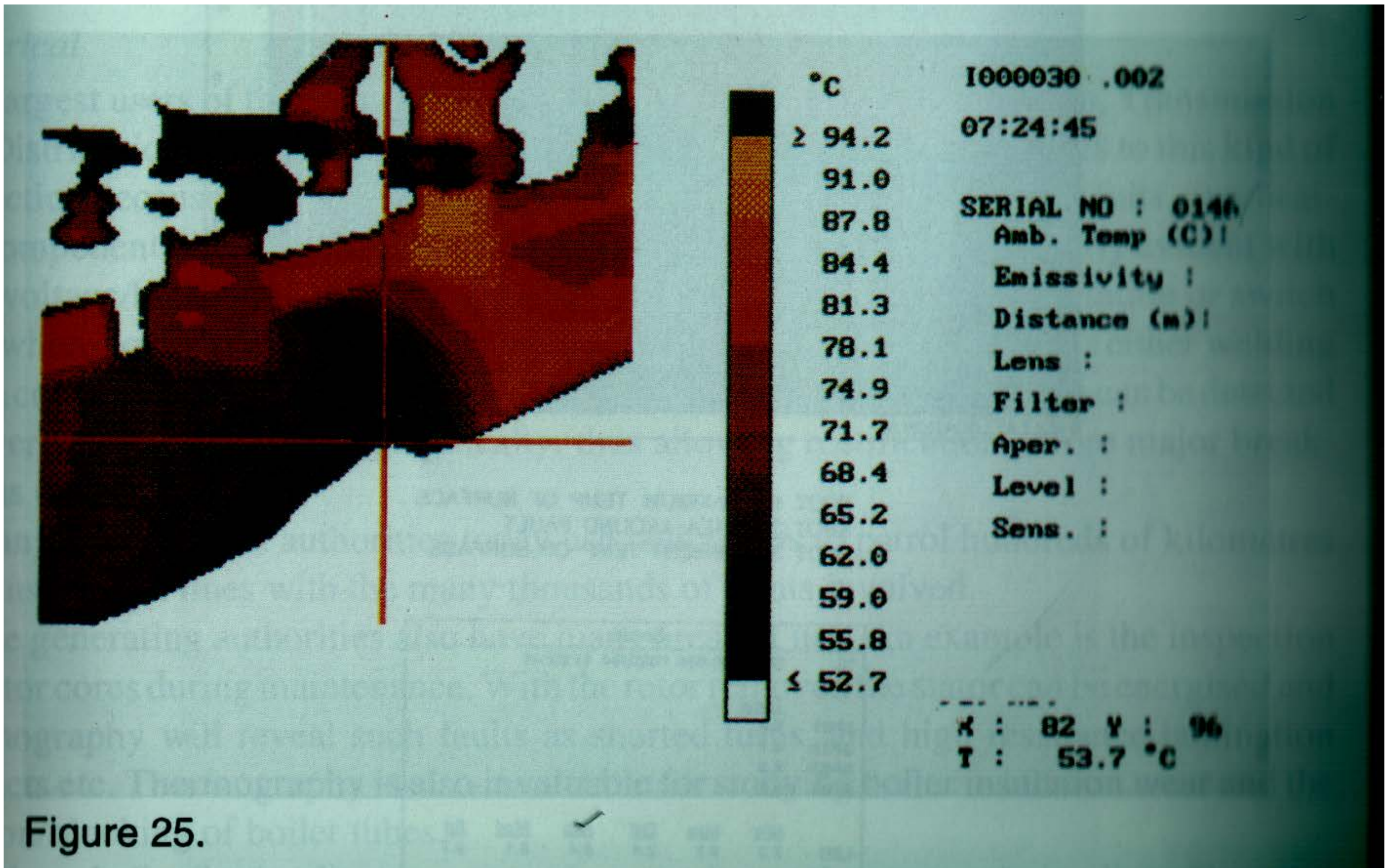



Figure 25.

# Oil Pipeline

- Crude oil is a mixture of oil, gas, water,sand etc. It is quite warm when extracted from deep underground.
- This picture shows a cool portion of pipe, internally insulated by a build up of solid matter which threatens to block the pipe.

Figure 22.

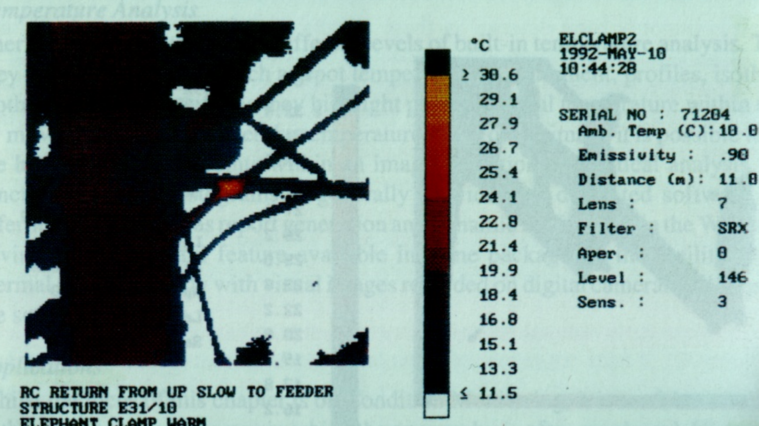
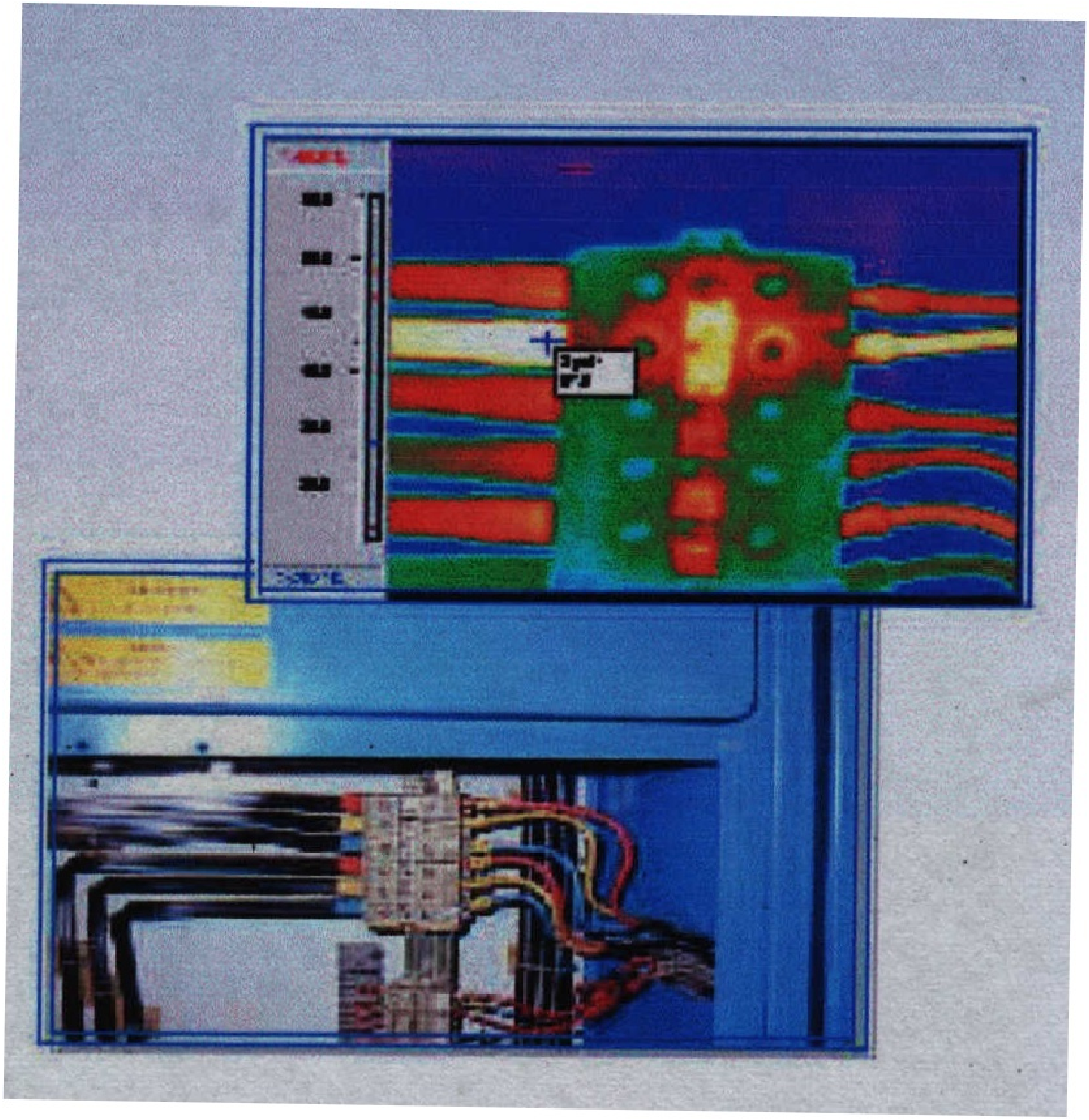



Figure 23.

- 'Elephant Clamp' from railway overhead power lines showing spark erosion.

The thermal image below could have been recorded by engineer on foot or by camera mounted on train.



Ohmic heating fault in electrical junction box.

# Plastic Film Laminator

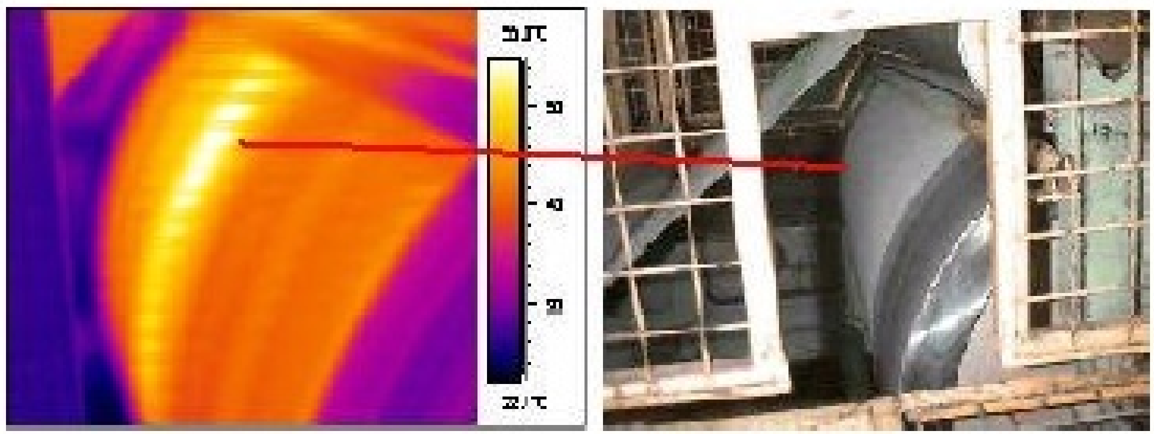


Figure 2 - Indicated hot area on the cooling drum of the 150 machine.

# Plastic Film Laminator

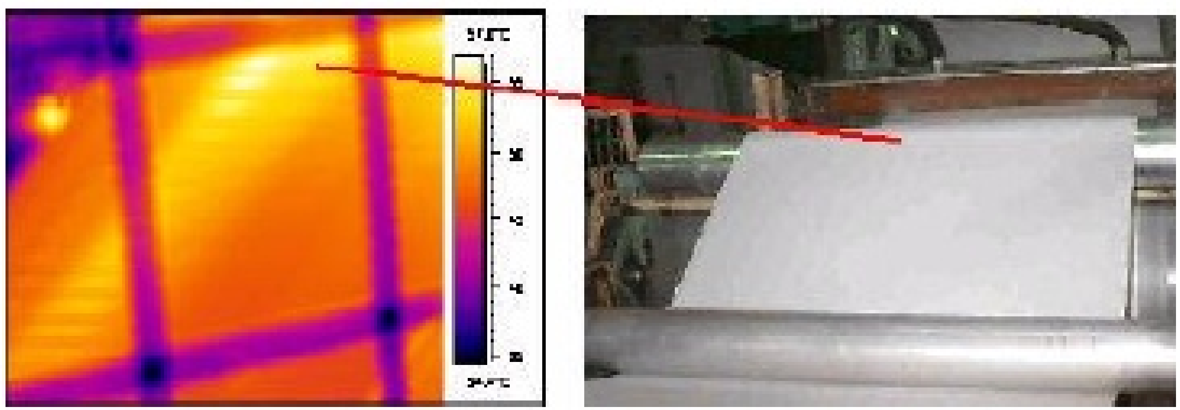


Figure 3 - Hot spot evident on finished product.

# Plastic Film Laminator

- In this example  two sheets of plastic film are being laminated together while hot and then cooled on a rotating drum.
- The drum has a section of blocked cooling ducts and so has a hot strip in its face.
- The roll of plastic film has a delaminated blister running down the middle.