# *Chapter 6*
# *Temperature measurements*

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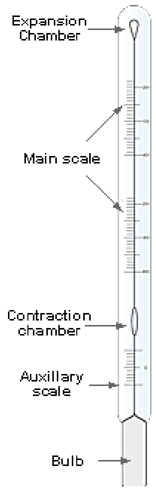
## *Lecture Contents*

- Introduction
- Temperature Sensor Classification
- The International Practical Temperature Scale
- Evolution of Noncontact Temperature sensors
- Thermal Radiation Theory
- Infrared Radiometry
- Temperature Measurement by Radiant Techniques
- Applications of Infrared Sensing
- Practical Operation

*Modern Measuring Techniques of Thermo-fluids Mechanics* *By An-Bang Wang* *National Taiwan University Institute of Applied Mechanics*

# *Introduction*

- One of the differences between temperature and other physical concepts, such as mass or length, is that it is subjective: different people will have different perceptions of what is hot and what is cold. To make objective measurements, we must use a thermometer in which some physical property of a substance changes with temperature in a reliable and reproducible way.(NPL)
- All material which is sensitive to temperature could be used as thermometer.




# The Early History of Temperature Sensing

| Year | Events | | |
|---|---|---|---|
| 1592 | The first instrument to measure temperature – The barothermoscope | Galilei, Italy | Contact measurement |
| 1611 | Temperature scale was added (but uncalibrated). | Galen | |
| 1613 | Using a thermoscope to record "degrees of heat" of winter snow, summer heat… | Sagredo | |
| 1624 | "Thermometer" appeared in the literature. | Leurechon | |
| 1654 | The first sealed thermometer filled with spirits of alcohol – The Florentian Thermometer that sensing temperature independent of pressure. | Ferdinand II, Italy | |
| 1661 | The Florentian thermometer was exported to Rome, Paris, England. | | |
| 1663 | Attempted to calibrate and standardize thermometers – using ice point. | Hooke | |
| 1694 | Suggested ice point and boiling point as two fixed points and scale 12. | Renaldini, Italy | |
| 1701 | Defined two fixed points: ice point and armpit temperature (labeled as also 12). | Newton, British | |
| 1708 | Modified Romer (a Danish astronomer) scale to a Fahrenheit scale, substitute mercury for spirits, used a mixture of sea salt, ice, and water to produce the zero point. Ice point = 32, boiling point = 212. | Fahrenheit, Netherland | |
| 1742 | Invented a scale with 0 at the steam point and 100 at the ice point. | Celsius, Sweden | |
| 1743 | Inverted Celsius scale and named "centigrade" to indicate a scale divided into 100 parts. | Christin, France | |
| 1821 | Discover the existence of thermoelectric current | Seeback, Estonia | |
| 1848 | Define a thermodynamic (absolute) temperature scale with ideal gas ($H_2$). | Kelvin, British | |

(from Lee (2001) with some modifications)

# What is Temperature?

**❑ Qualitative Definitions:**

1. The degree of hotness or coldness of a body.
2. All bodies have the same temperature if they are in thermal equilibrium.
3. The level of thermal energy. (cf. Electrical energy; Mechanical potential energy.)

**❑ Units of temperature (one of System International units, SI) :**

| Unit | | Symbol | Quantity measured |
|---|---|---|---|
| Dimensional | 1. Meter | m | Length |
| | 2. Kilogram | kg | Mass |
| | 3. Second | s | Time |
| | 4. Ampere | A | Electric current |
| | 5. Kelvin | K | Temperature |
| | 6. Mole | mol | Amount of substance |
| | 7. Candela | cd | Luminous intensity |
| Dimensionless | 8. Radian | rad | Plane angle |
| | 9. Steradian | sr | Solid angle |

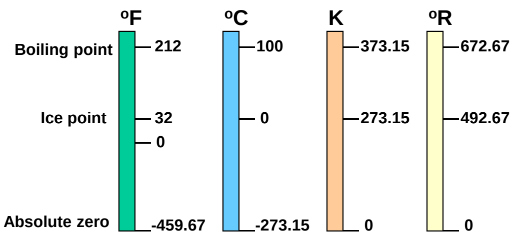
(from Lee (2001))



# How to Quantify the temperature?

**❑ Four common temperature scales:**

Fahrenheit(1708), Celsius(1740), Kelvin(1848), Rankine(1730)




$$^{o}F = \frac{9}{5}(^{o}C) + 32$$

$$^{o}C = \frac{5}{9}(^{o}F - 32)$$

$$K = 273.15 + {}^{o}C$$

$$^{o}R = 459.67 + {}^{o}F$$

**❑ Fundamental temperature scales:**

The relationship of measured variable to temperature depends only on fundamental physical constants, not on arbitrary calibrating constants.

Examples:

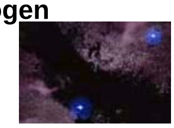
1.Thermodynamic, PV=PV(T, $\underline{N_A}$, $\underline{k}$)

2.Thermal radiance, W=W(T, $\underline{k}$, $\underline{c}$, $\underline{h}$)

(from Lee (2001))

# Temperature spectrum

| | |
|---|---|
| 200,000,000 ˚C : | The Joint European Torus (JET) nuclear fushion project |
| 15,000,000 ˚C : | Temperature of the centre of the Sun |
| 6000 ˚C : | Temperature of the surface of the Sun |
| 1,200 ~ 1,500 ˚C : | Molten glass / steel |
| 1064 ˚C : | Melting point of gold |
| 100 ˚C : | Boiling point (at 1 atm-pressure ) |
| 0 ˚C : | Freezing point of pure water |
| - 89.2 ˚C : | All time coldest point on earth |
| - 196 ˚C : | Cryogenic storage in liquid nitrogen |
| - 270 ˚C : | Cosmic background radiation |



(http://www.npl.co.uk/npl/publications/temperature/spectrum.html)



# Temperature Sensor Classification

| | Principle | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Sensor** | Thermo-electric | Electrical Resistance | Carrier Mobility | Thermal Radiation | Electrical Capacitance | Thermal Expansion | Resonant Frequency | Others |
| Thermocouple | ■ | | | | | | | |
| Thermopile | ■ | | | | | | | |
| RTD(PTC, NTC) | | ■ | | | | | | |
| Thermistor | | ■ | ■ | | | | | |
| P-N junction | | | ■ | | | | | |
| Optical pyrometer | | | | ■ | | | | |
| Pyro-electric | | | | ■ | ■ | | | |
| Quantum | | | ■ | ■ | | | | |
| Spectroradiometer | | | ■ | ■ | | | | |
| Cooling IR imager | | | ■ | ■ | | | | |
| Uncooled IR imager | ■ | ■ | ■ | ■ | ■ | ■ | | |
| Gas | | | | | | ■ | | |
| Liquid | | | | | | ■ | | |
| Bi-metal | | | | | | ■ | | |
| Quartz | | | | | | | ■ | |
| Liquid Crystal | | | | | | | | 1 |
| Others | | | | | | | | 2,3,4,5 |
| [Remark]: 1.Reflectance, 2.Index of Refraction, 3.Ultrasonic, 4.Microwave, 5.Acoustic | | | | | | | | |

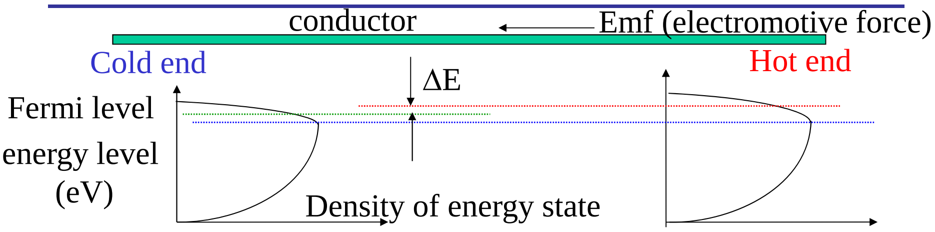
(from Lee (2001))

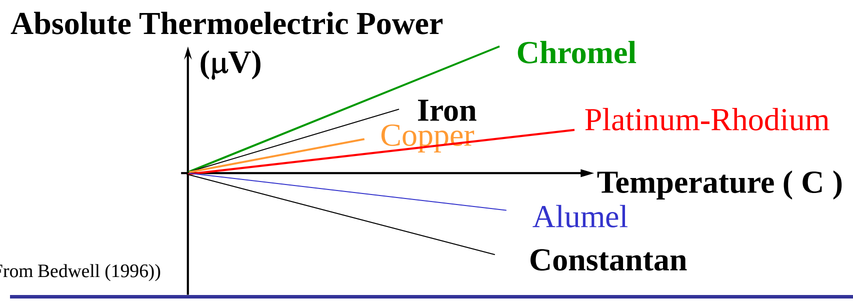
# Temperature Sensor Classification

| Transducer or probe | Temperature sensitive parameter | Contact method | Remarks |
|---|---|---|---|
| Resistor | Electrical resistance or voltage at constant current | Direct contact | Usually calibrated against a thermocouple. However Pt RTDs are one of the most accurate temperature sensors available. |
| Thermocouple | Open circuit voltage | Direct contact | Useful as a "point"sensor. |
| Diode or transistor | Voltage, usually with constant forward bias current | Direct contact | Usually employed to measure an active device or IC temperature. |
| Infrared or radiation | Detector voltage | Line-of-site or optical contact | Can yield either a point temperature or a thermal map or image. Not strictly quantitative unless sample emittance is known at the image points. |
| Fluorescent detector | Detector voltage | Direct contact (proximity) | Approximate point detector, contact resistance a problem. |
| Liquid crystal | Color | Direct contact | Yields a temperature map, semiquantitative unless a detailed calibration is performed to quantify color vs. temperature relation. |



# Thermocouple Sensor (I)



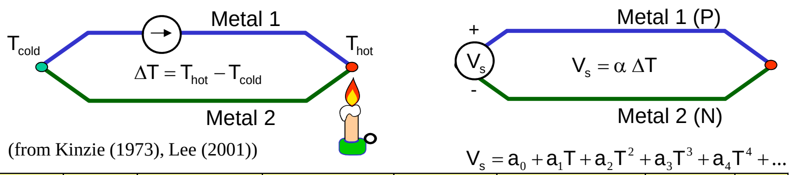




(From Bedwell (1996))

# Thermocouple Sensor (II)

❑ **Thermoelectric Effect (Thomas Seebeck, Germany, 1821):**

Two wires composed of dissimilar metals are connected at both ends, to make a complete electrical circuit, an electrical current will flow in the circuit if one of the ends is heated.




(from Kinzie (1973), Lee (2001))

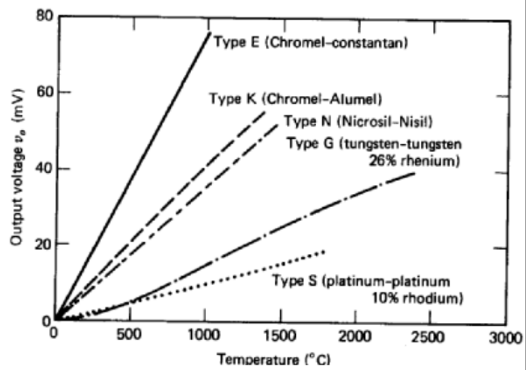
$$V_s = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4 + ...$$

| Letter | P wire | N wire | Range | Accuracy | Output(μV/°C) | Stability | Cost |
|---|---|---|---|---|---|---|---|
| T | Cu | $Ni_{45}Cu_{55}$ | -160~400℃ | 0.5℃ | 46 | ? | low |
| J | Fe | $Ni_{45}Cu_{55}$ | 0~760℃ | 0.1℃ | 46 | ? | low |
| E | $Ni_{90}Cr_{10}$ | $Ni_{45}Cu_{55}$ | -100~1000℃ | 0.5℃ | 68 | Low-mid | low |
| K | $Ni_{90}Cr_{10}$ | $Ni_{95}Mn_2Al_2Si_1$ | 0~1370℃ | 0.7℃ | 42 | low | low |
| N | Nicrosil | Nisil | 0~1300℃ | | 38 | mid-high | low |
| S | $Pt_{90}Rh_{10}$ | Pt | 0~1750℃ | 1.0℃ | | | |
| R | $Pt_{87}Rh_{13}$ | Pt | 0~1400℃ | 0.5℃ | 10 | high | high |
| B | $Pt_{70}Rh_{30}$ | $Pt_{94}Rh_6$ | 100~1750℃ | | 5 | high | high |

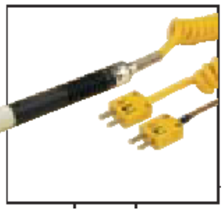


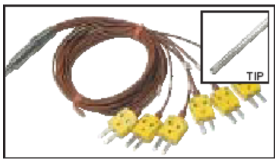
# Thermocouple Sensor (III)

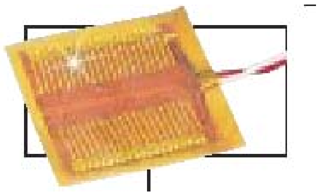
- ❑ **Thermocouples rank only behind the clinical thermometer for popularity for temperature measurement.**
- ❑ **Advantages:**
  **- smaller and cheaper than resistance devices (allow for high number of individual measurements).**
  **- simpler to condition than oscillating sensors, e.g., quartz crystals.**
  **- wider operating range than thermistors or liquid crystals.**



# Thermocouple Sensor (IV)





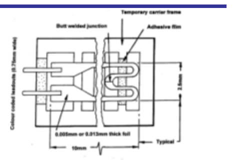



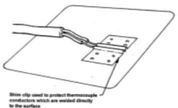


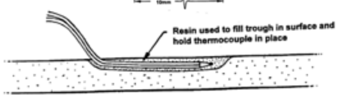
# Thermocouple installation

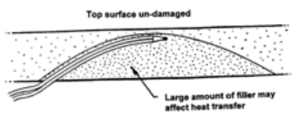
Installation methods:

- Bonding the substrate mounted TC by adhesive or braze.
- direct welding
- Being recessed (cable and junction) under the surface.







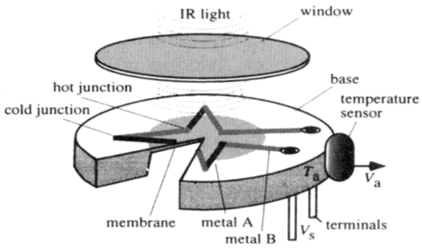



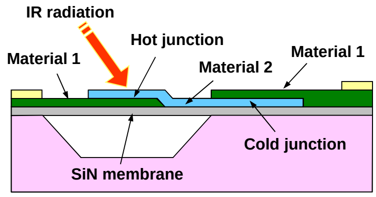

Some restrictions:

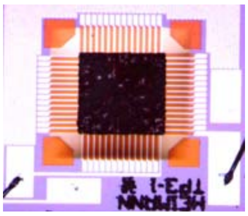
- the adhesives and substrate materials are limited to around 300°C.
- The TC earths to the surface might cause problems
- The accuracy of TC bead position is the prime concern and the filled resin should have similar conductivity.

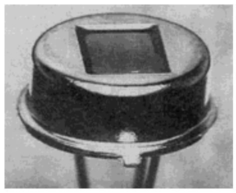
# Thermopile Sensor

❑ **Thermopile (Melloni,1833):** A thermopile is serially connected thermocouples.





(from Lee (2001))



# RTD

❑ **Resistance Temperature Detector (RTD)**

For general metal or alloy (Pt, Ni, Balco (Ni-Cu alloy)),

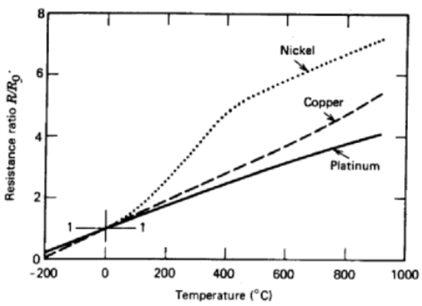
PTCR : Positive Temperature Coefficient of Resistance

$$R(T) = R_0[1 + \alpha_0(T - T_0) + \alpha_1(T - T_0)^2 + \ldots]$$

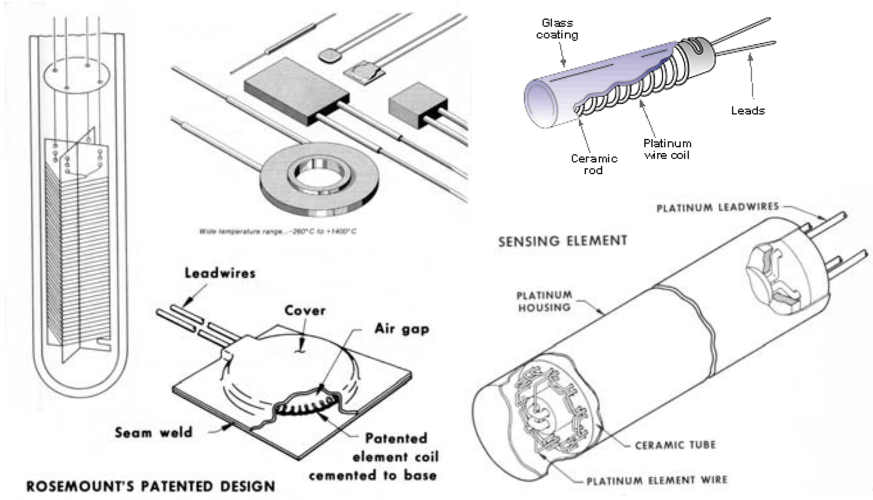
$$\alpha = \frac{1}{R}\frac{dR}{dT}\bigg|_{T=T_0}$$ good linearity for a limited temperature range

$R_0$: resistance at 0°C

$\alpha$ : 0.0035/K for Pt



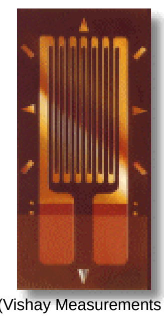
# RTD Sensors






# RTD surface sensors

- Foil sensor (Polyimide or epoxy) : Easy to Install
- Compact, Flexible and Thin
- Fast Response Time
- High Output
- Capable of Measuring Temperatures from -200° to +370° C
- Excellent Accuracy and Repeatability
- Metal Foils: Nickel, Balco, Platinum



(Vishay Measurements Group)

# Thermistor

## ❑ Thermal Sensitive Resistor (Thermistor)

For Semiconducting materials,

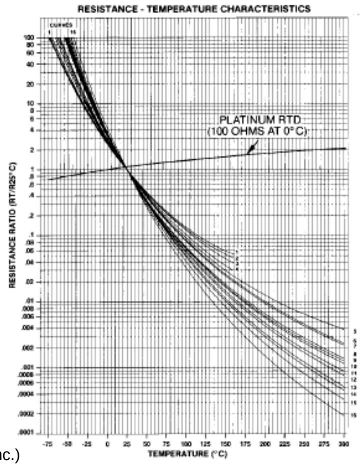
NTCR/PTCR : Negative/Positive Temperature Coefficient of Resistance

$$R(T) = R_0 \, e^{B(\frac{1}{T} - \frac{1}{T_0})} \qquad (T \text{ in } K)$$

$$\text{Sensitivity: } \alpha = \frac{1}{R}\frac{dR}{dT}\bigg|_{T=T_0} \approx -\frac{\beta}{T^2}$$

In general, higher sensitivity, lower cost, smaller size, faster response, in comparison with RTD

Measuring range: -200 ~ 1000ºC

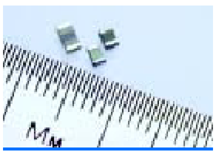



(Thermometrics Inc.)



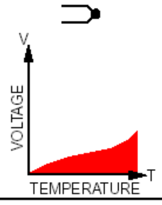
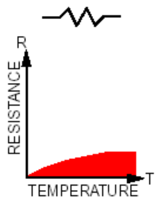
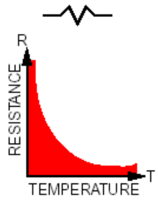
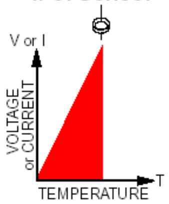
# Thermistor

NTC


PTC


# Analysis of common temperature sensors

| | Thermocouple | RTD | Thermistor | I. C. Sensor |
|---|---|---|---|---|
| |  |  |  |  |
| Advantages | ☐ Self-powered<br>☐ Simple<br>☐ Rugged<br>☐ Inexpensive<br>☐ Wide variety<br>☐ Wide temperature range | ☐ Most stable<br>☐ Most accurate<br>☐ More linear than thermocouple | ☐ High output<br>☐ Fast<br>☐ Two-wire ohms measurement | ☐ Most linear<br>☐ Highest output<br>☐ Inexpensive |
| Disadvantages | ☐ Non-linear<br>☐ Low voltage<br>☐ Reference required<br>☐ Least stable<br>☐ Least sensitive | ☐ Expensive<br>☐ Current source required<br>☐ Small ΔR<br>☐ Low absolute resistance<br>☐ Self-heating | ☐ Non-linear<br>☐ Limited temperature range<br>☐ Fragile<br>☐ Current source required<br>☐ Self-heating | ☐ T<200°C<br>☐ Power supply required<br>☐ Slow<br>☐ Self-heating<br>☐ Limited configurations |

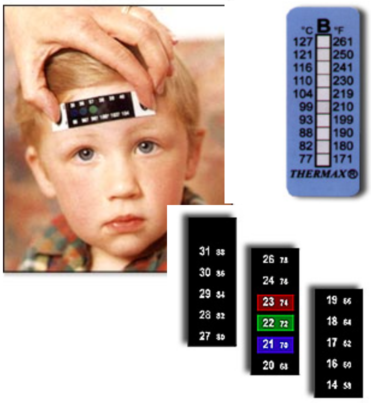
(Omega)



# Liquid crystal Thermometer

**Forehead Thermometer**
**Fish box thermometer**

- **Safe**
- **convenient**
- **accurate**
- **Time constant: some seconds**
- **Mirror or observer is needed.**




From: Taiwah Charts Corp.

# Remote temperature sensing

- Too far to measure
- Too hot/dangerous
- Too small to access
- Moving body

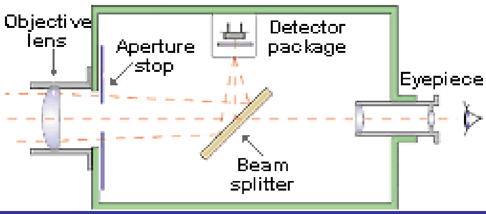
Advantages of IR-sensing

- Fast response
- High accuracy available (1~3%)
- Wide measuring range (~3000°C)

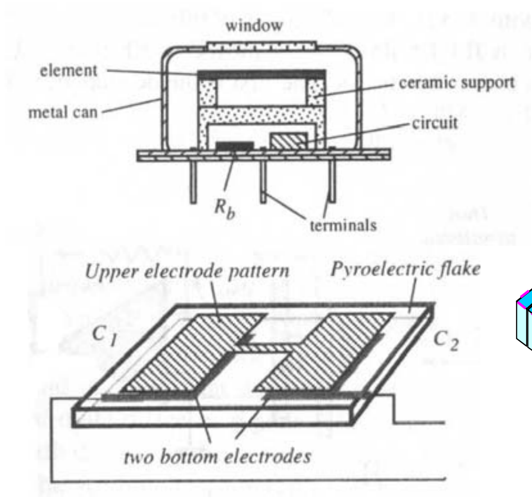


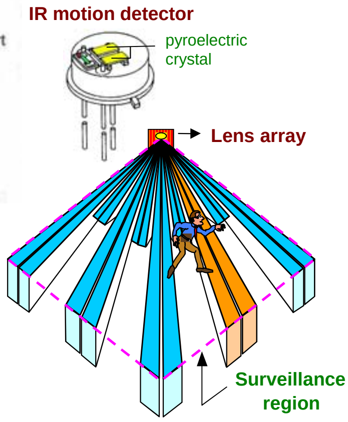
# Radiation (Pyrometer)

Radiation thermometers, or pyrometers, make use of the fact that all objects emit thermal radiation, as seen when looking at the bars of an electric fire or a light bulb. The amount of radiation emitted can be measured and related to temperature using the Planck law of radiation. Temperatures can be measured remotely using this technique, with the sensor situated some distance away from the object. Hence it is useful for objects that are very hot, moving or in hazardous environments.



# Pyro-electric Sensor



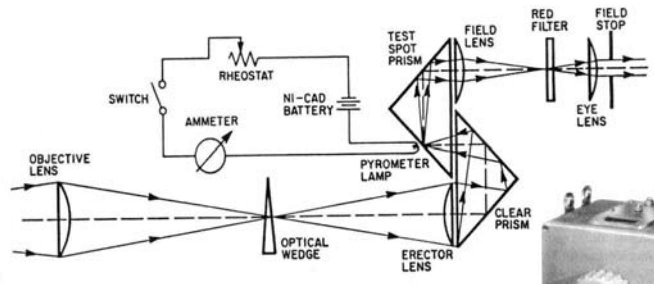




(from Lee (2001))



# Optical Pyrometer

❑ **The disappearing filament optical pyrometer**




(from Lee (2001))

# Spectroradiometer/Radiometer

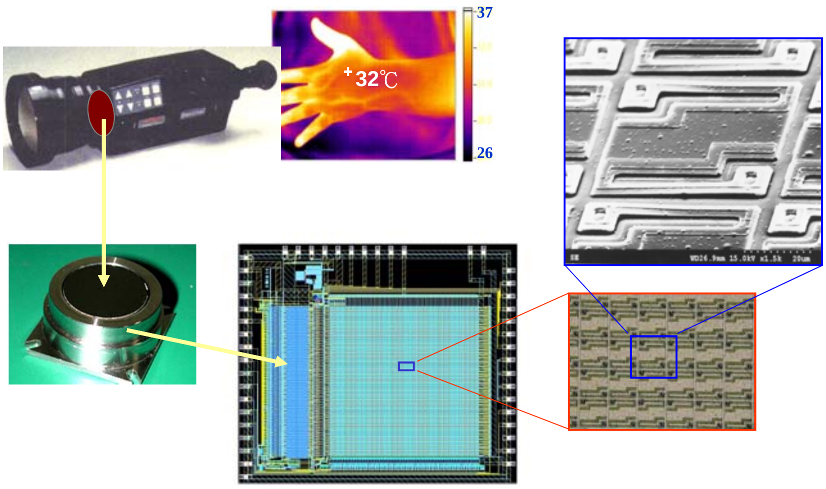

Blackbody radiation spectrum fitting

| Items | Specifications |
|---|---|
| **Spectral range** | 0.2 to 25 microns |
| **FOV** | 0.3 mrad - 100 mrad |
| **Focusing range** | 2.5m to infinity |
| **Scan rates** | 0.015 to 30 scans/sec |
| **Chopping Frequency** | 100 to 1800 Hz. |


(from Lee (2001))



# Infrared Imager




(from Lee (2001))

# Temperature Scales

❑ **Requirements for establishing a temperature scale:**

1. Set the fixed points and given the temperature value.
2. Choosing an appropriate instrument to interpolate scale.
3. Determine the relationship between the measurement variable and the temperature.

❑ **The International Practical Temperature Scale:**

The International Committee of Weights and Measures(1927,.. 1960,.. 1968,.. 1990)
Fixed points: 6(ITS-27), 13(IPTS-68), 17(ITS-90)

**Defining fixed points of the ITS-27 ℃**

| Number | ℃ | Substance | State |
|---|---|---|---|
| 1 | -182.97 | $O_2$ | Boiling Point |
| 2 | 0.000 | $H_2O$ | Freezing Point |
| 3 | 100.000 | $H_2O$ | Boiling Point |
| 4 | 444.60 | S | Boiling Point |
| 5 | 960.5 | Ag | Freezing Point |
| 6 | 1063.0 | Au | Freezing Point |

| Range | ℃ | Interpolating Instrument |
|---|---|---|
| I | -182.97 ~ 0 | Platinum resistance |
| II | 0 ~ 660 | Platinum resistance |
| III | 660 ~ 1063.0 | S-type thermocouple |
| IV | >1063.0 | Optical pyrometer |

(from Lee (2001))



# ITS-90(1)

❑ **The International Temperature Scale of 1990 (ITS-90)**
[Ref]:http://www.omega.com/techref/intltemp.html

**1. Units of Temperature**

The unit of the fundamental physical quantity known as thermodynamic temperature, symbol T, is the kelvin symbol K, defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
Because of the way earlier temperature scales were defined, it remains common practice to express a temperature in terms of its difference from 273.15 K, the ice point. A thermodynamic temperature, T, expressed in this way is known as a Celsius temperature, symbol t, defined by:

$t / ℃ = T / K - 273.15$

The unit of Celsius temperature is the degree Celsius, symbol ℃, which is by definition equal in magnitude to the kelvin. A difference of temperature may be expressed in kelvins or degrees Celsius.
The International Temperature Scale of 1990 (ITS-90) defines both International Kelvin Temperatures, symbol T90, and International Celsius Temperatures, symbol t90. The relation between T90 and t90 is the same as that between T and t, i.e.:

$t_{90} / ℃ = T_{90} / K - 273.15$

The unit of the physical quantity T90 is the kelvin, symbol K, and the unit of the physical quantity T90 is the degree Celsius, symbol ℃, as is the case for the thermodynamic temperature T and the Celsius temperature t.

(from Lee (2001))

# ITS-90(2)

**2. Principles of the International Temperature Scale of 1990 (ITS-90)**

**The ITS-90 extends upwards from 0.65 K to the highest temperature practicably measurable in terms of the Planck radiation law using monochromatic radiation.** The ITS-90 comprises a number of ranges and sub-ranges throughout each of which temperatures T90 are defined. Several of these ranges or sub-ranges overlap, and where such overlapping occurs, differing definitions of T90 exist: these differing definitions have equal status.

**3. Definition of the International Temperature Scale of 1990**

Between 0.65 K and 5.0 K T90 is defined in terms of **the vapour-pressure temperature relations 3He and 4He**.

Between 3.0 K and the triple point of neon (24.5561 K) T90 is defined by means of **a helium gas thermometer** calibrated at three experimentally realizable temperatures having assigned numerical values (defining fixed points) and using specified interpolation procedures.

Between the triple point of equilibrium hydrogen (13.8033 K) and the freezing point of silver (961.78℃) T90 is defined by means of **platinum resistance thermometers** calibrated at specified sets of defining fixed points and using specified interpolation procedures.

Above the freezing point of silver (961.78℃) T90 is defined in terms of a defining fixed point and **the Planck radiation law**.

(from Lee (2001))



# Defining Fixed Points of the ITS-90

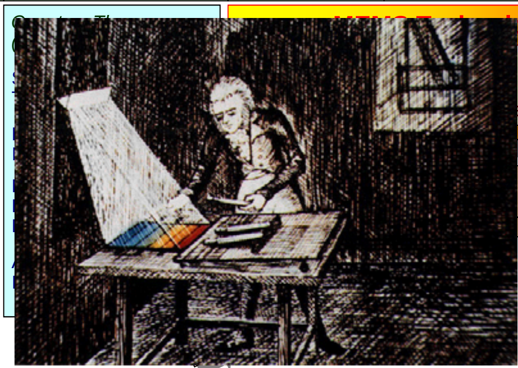
| | Temperature | | | |
|---|---|---|---|---|
| **Number** | **$T_{90}$/K** | **$t_{90}$/°C** | **Substance** | **State** |
| 1 | 3 to 5 | -270.15 to -268.15 | He | V |
| 2 | 13.8033 | -259.3467 | e-$H_2$ | T |
| 3 | ~17 | ~-256.15 | e-$H_2$ (or He) | V (or G) |
| 4 | ~20.3 | ~-252.85 | e-$H_2$ (or He) | V (or G) |
| 5 | 24.5561 | -248.5939 | Ne | T |
| 6 | 54.3584 | -218.7916 | $O_2$ | T |
| 7 | 83.8058 | -189.3442 | Ar | T |
| 8 | 234.3156 | -38.8344 | Hg | T |
| 9 | 273.16 | 0.01 | $H_2O$ | T |
| 10 | 302.9146 | 29.7646 | Ga | M |
| 11 | 429.7485 | 156.5985 | In | F |
| 12 | 505.078 | 231.928 | Sn | F |
| 13 | 692.677 | 419.527 | Zn | F |
| 14 | 933.473 | 660.323 | Al | F |
| 15 | 1234.93 | 961.78 | Ag | F |
| 16 | 1337.33 | 1064.18 | Au | F |
| 17 | 1357.77 | 1084.62 | Cu | F |

V: vapor pressure point; T: triple point; G: Gas thermometer point;
M: melting point; F: Freezing point

(from Lee (2001))

# Evolution of IR Sensor Technologies

| 1800 ~ 1899 | 1900 ~ 1979 | 1980 ~ 1989 | 1990 ~ 1995 | 1996 ~ 2001... |
|---|---|---|---|---|
| *IR discovery (Herschel, 1800)*<br>*Thermo-electric effect (Seebeck,1821)*<br>Thermocouple (Nobili,1829)<br>Thermopile (Melloni,1833)<br>Bolometer (Langley,1880)<br>*Radiation theory (1884)* | | | | Uncooled IRFPA electronic scan<br>Microbolometer Micro-pyroelectric<br>**Low cost Thermal Imager** |



Single detector

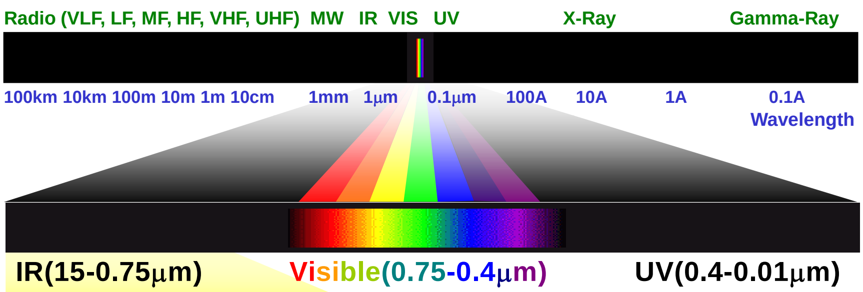
Single / Linear / Area array detector
$LN_2$, $n_2$/ argon gas cooling, mechanical scan

(from Lee (2001))

**Thermal-type** **Quantum-type** **Thermal-type**



# The Electromagnetic Spectrum



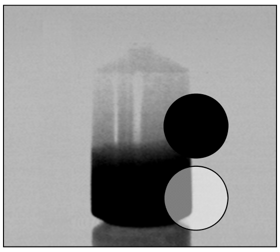

| | | | |
|---|---|---|---|
| Near IR | (NIR) | : | 0.75 - 3μm |
| Middle IR | (MIR) | : | 3 - 6μm |
| Far IR | (FIR) | : | 6 - 15μm |
| Extreme IR | (XIR) | : | 15 - 1000μm |


(from Lee (2001) & K.L. Lin(2006))

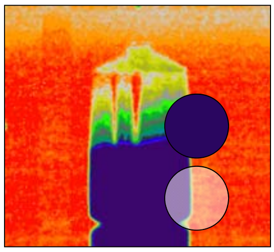
# Visible cf. Thermal Radiation (1)

❑ **Target signature (Spatial Distribution)**

Visible(0.4-0.75μm)



FIR(8-12μm)



FIR(8-12μm)

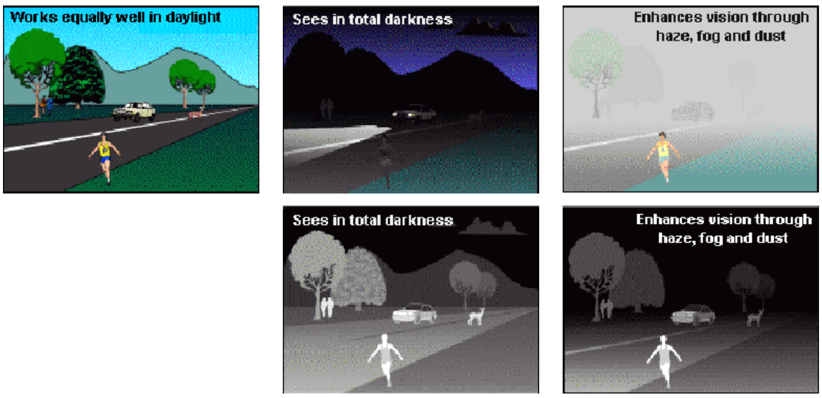
- Active sensing：Visible, NIR
- Passive Sensing：Visible, NIR, MIR, FIR

(from Lee (2001))



# Visible cf. Thermal Radiation(2)

❑ **Background signature (Spatial Distribution)**




Ref. "Thermal imaging solutions", TI NIGHTSIGHT interactive explorer.

(from Lee (2001))

# Gas Thermometer

- Developed in the first half of 19th century.
- Least liable to uncertain variation and generally accepted as the standard for comparing all types of thermometers.
- Boyle-Mariotte law:

  $(PV)_t = K$ for ideal gases
- Charles-Gay-Lussac Law:

$$\frac{1}{V_0}\left(\frac{V-V_0}{T-T_0}\right)_p = \alpha_{0p} \quad \text{or} \quad \frac{1}{P_0}\left(\frac{P-P_0}{T-T_0}\right)_V = \alpha_{0V}$$

- Clapeyron's equation of state:

$$PV = R_p\left(T - T_0 + \frac{1}{\alpha_{0p}}\right) \quad \text{or} \quad PV = R_V\left(T - T_0 + \frac{1}{\alpha_{0V}}\right)$$

- Regnault's



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