IAEA
International Atomic Energy Agency
*Atoms for Peace and Development*

# Assessment of Occupational Exposure due to External Radiation Sources

## Passive Dosimetry Techniques

# Passive integrating dosimeters

- Photographic film
- Luminescence
  - Thermoluminescence
  - Optically stimulated luminescence
  - Radiophotoluminescence
- Semiconductors: direct ion storage

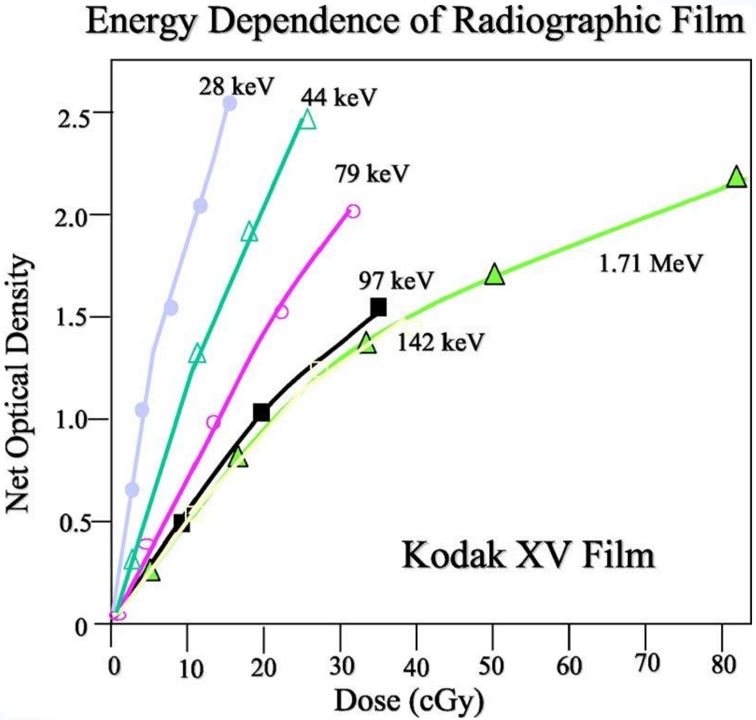
# A wide range of passive dosimeter designs have been developed…

# Photographic Film Dosimetry

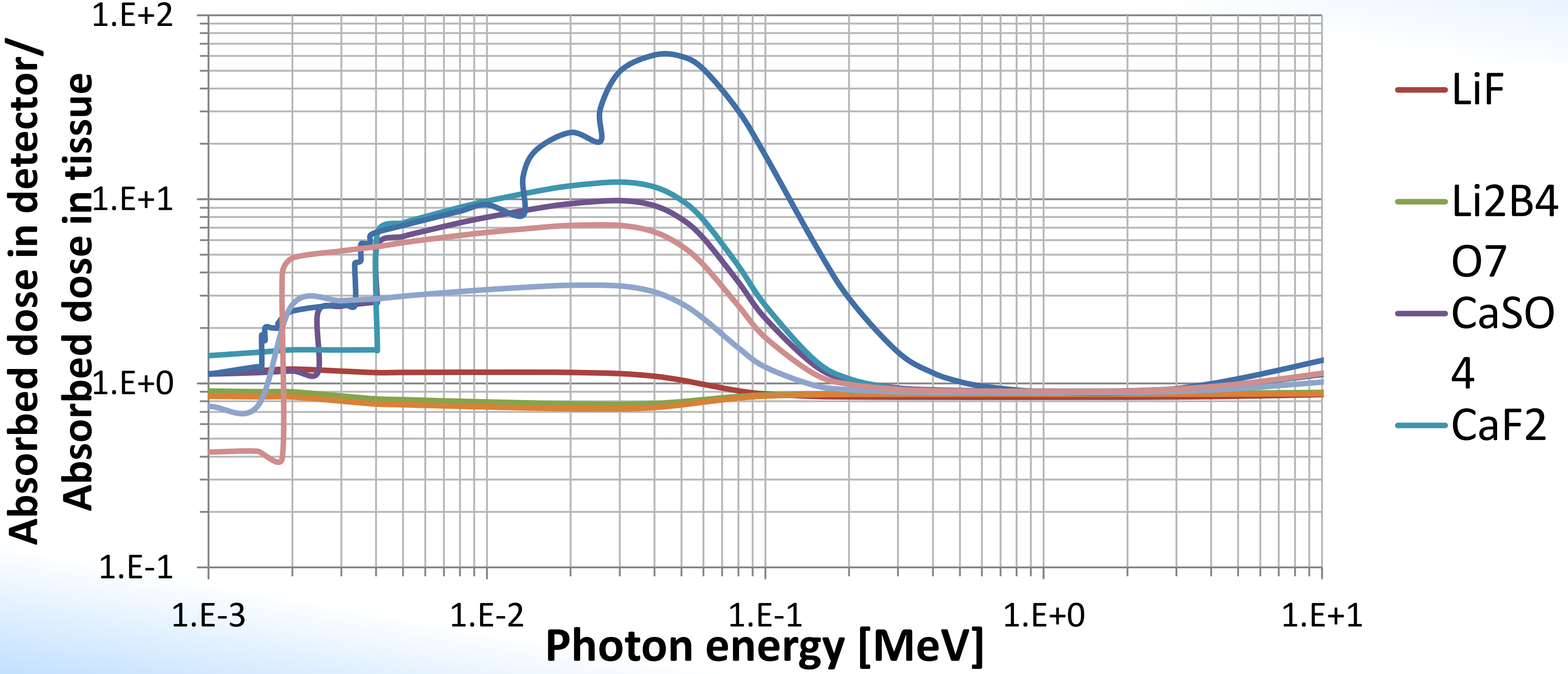
# Photographic film: basic principles

- Film emulsion is made of AgBr crystals suspended in a gelatinous medium
- A thin emulsion layer is coated on a plastic base
- Ionizing radiation interacts with emulsion grains to produce a latent image
- In development, silver ions in the latent image produce permanent blackening
- Blackening is measured with a densitometer
- Degree of blackening is a function of film type, developing process, temperature, and radiation type and energy

# Film has a strong photon energy dependence



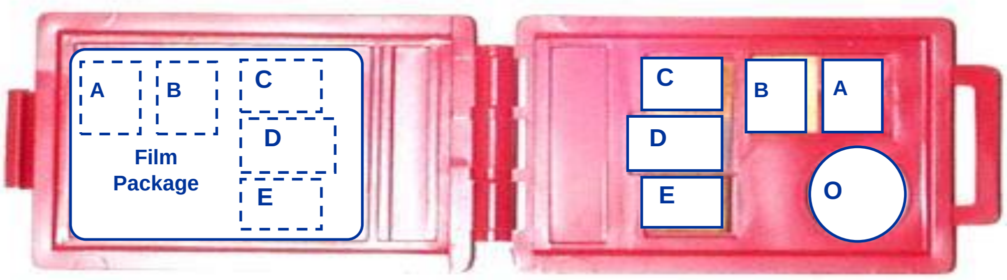
# Film has a strong photon energy dependence

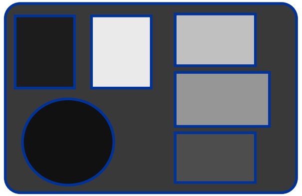


# Photographic film: energy dependence

- Film badges are not tissue equivalent:
  - Need for multiple element dosimeters
  - Need for algorithm
- Compensation for energy dependence of the film dosimeter is achieved either by the use of one or more filters
- Especially lower energy overresponse needs to be compensated by introducing filters:
  - Multiple filters (e.g. Cu, plastic and open window) are used for lower energy photons
- Multiple element dosimeter can have advantages:
  - Type and dose of incident radiation can be estimated from the ratio of responses behind different filters

# Typical design of film dosimeter

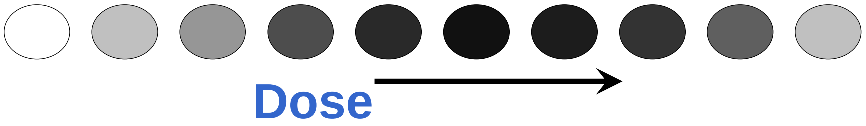


A - Plastic filter
B to E - Metallic filters
O - Open window

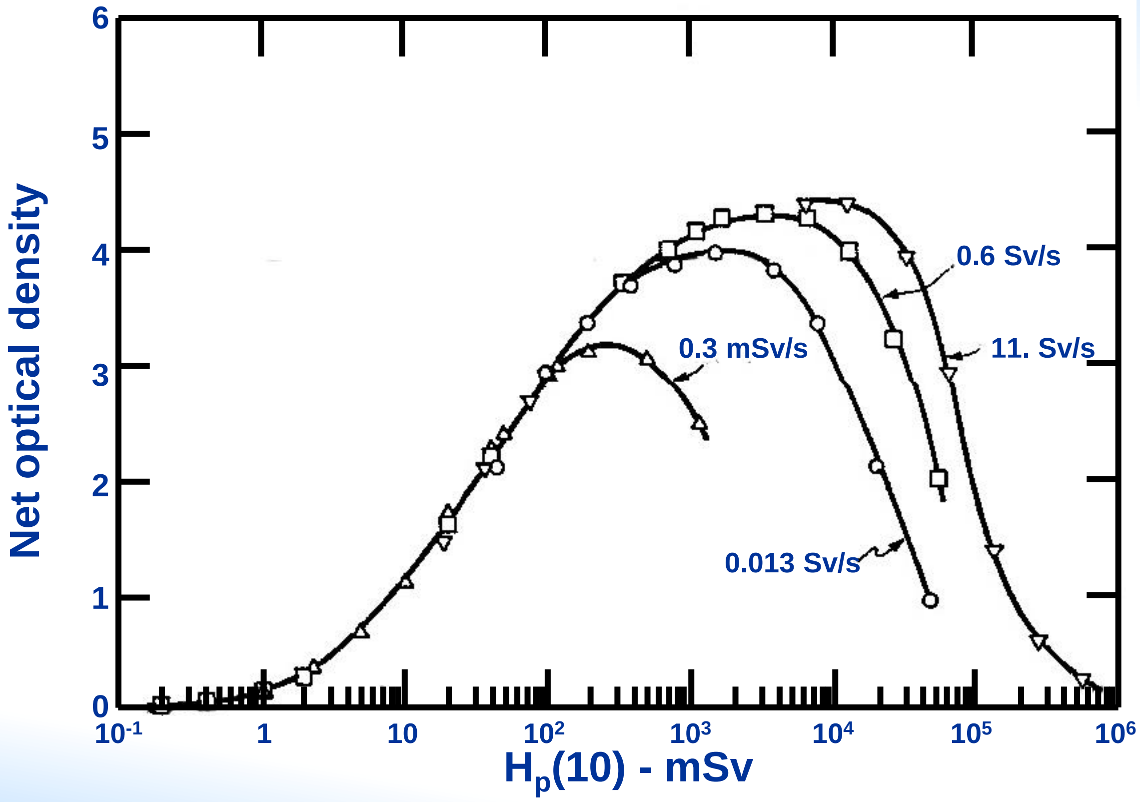
# Photographic film: not linear

- Optical density does not vary linearly with dose
- At higher doses, a reversal of optical density - solarization - takes place

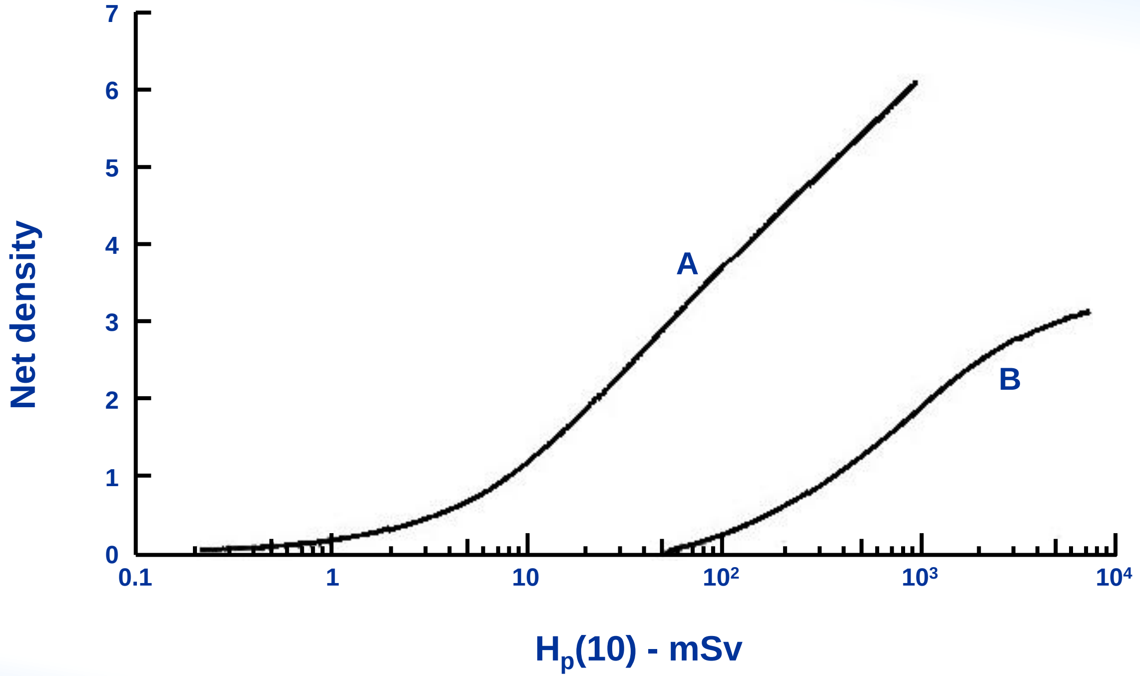



- Linear combination of the responses behind suitable filters can be used to determine the dose

# Typical photographic film calibration curve



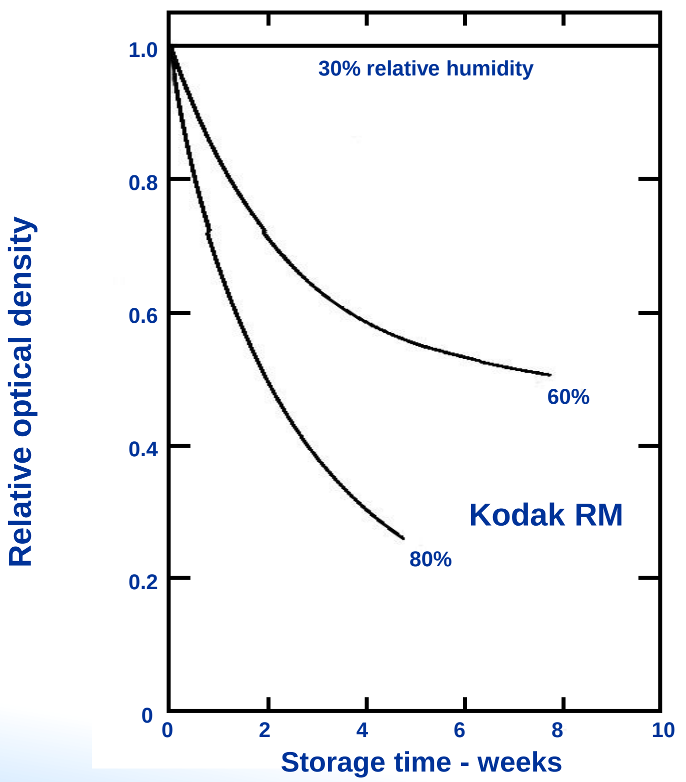
# Films with different sensitivities extend the measurable dose range of the film badge



# Photographic film: calibration

- New calibrations are necessary for each new film batch, or when the developing process changes
- Operational films are often calibrated by using identical standard films irradiated to known doses and processing them simultaneously with the operational dosimeters
- Calibrations at doses that cover the full range for which the dosimeter is used
- Film badges are used for issue periods up to one month
  - For longer periods, fading is a problem
- Important influence of temperature and humidity

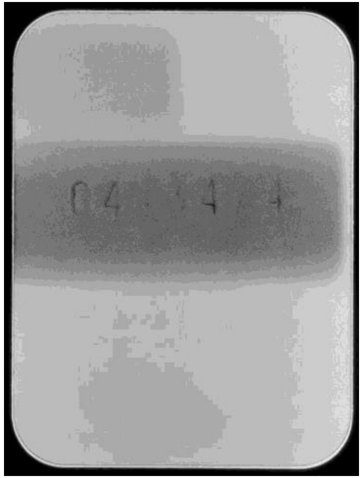
# For longer periods, fading is a problem



# Film dosimeters are less and less used

- Film dosimetry can be economical depending upon the degree of automation
- Now on rapid decline
  - Less manufacturers
  - Competition of novel dosimetry techniques

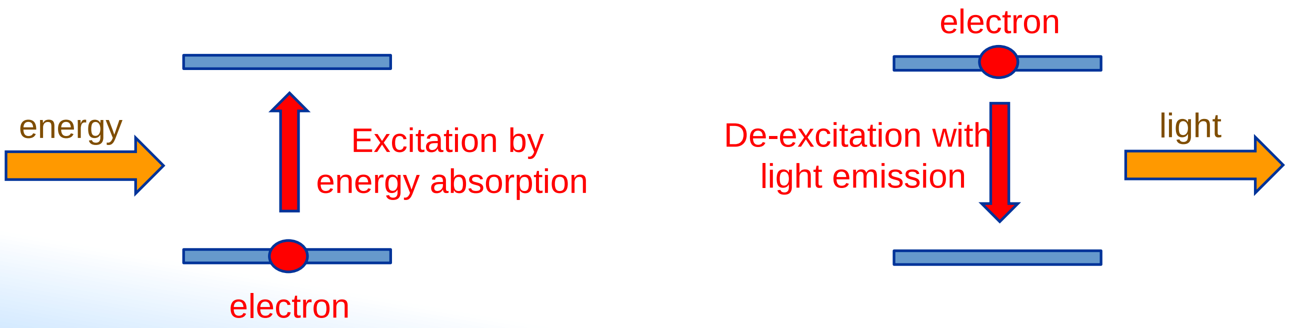




# Luminescence

# Luminescence: creation of light

- Electrons in a material have a specific energy level
  - Only discrete energy levels or energy band are possible, dependent on material
- By energy absorption they can jump to a higher energy level
- After that, they can fall down to a lower level
- Going to lower level can be accompanied by light emission



# Different types of luminescence:

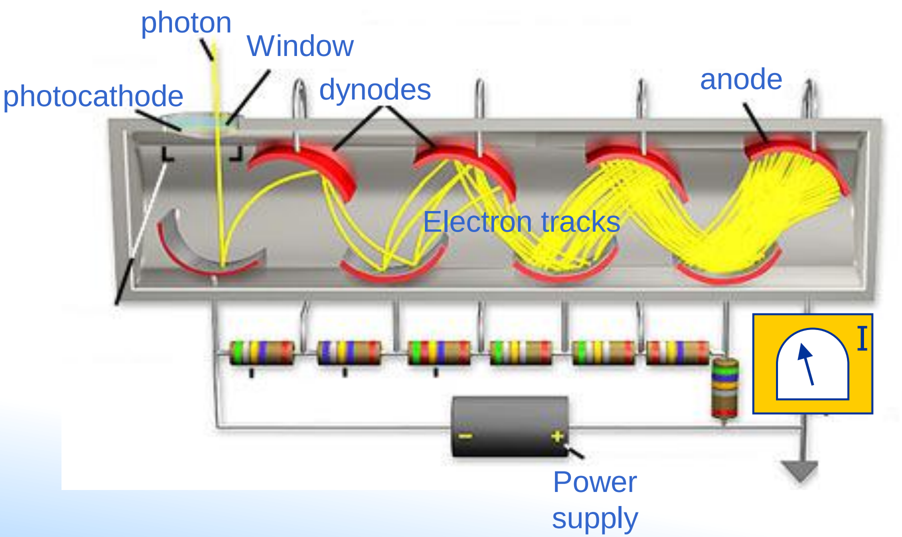
- Chemiluminescence, the emission of light as a result of a chemical reaction
  - Bioluminescence, electrochemiluminescence, lyoluminescence, candoluminescence
- Crystalloluminescence, produced during crystallization
- Electroluminescence, a result of an electric current passed through a substance
- Mechanoluminescence, a result of a mechanical action on a solid
  - Triboluminescence, fractoluminescence, piezoluminescence, sonoluminescence

# Different types of luminescence:

- Photoluminescence, a result of absorption of photons
  - Fluorescence: typical lifetime: nanoseconds
  - Phosphorescence: typical lifetime: milliseconds to hours
- Radioluminescence, a result of bombardment by ionizing radiation
- Thermoluminescence, the re-emission of absorbed energy when a substance is heated
  - Cryoluminescence (when it is cooled)

# Conversion of light to electrical current/pulses: photomultiplier

- Photon is converted to electron at the photocathode
- One electron creates an electron avalanche in the dynodes
- Leads to measurable pulse or current at the anode

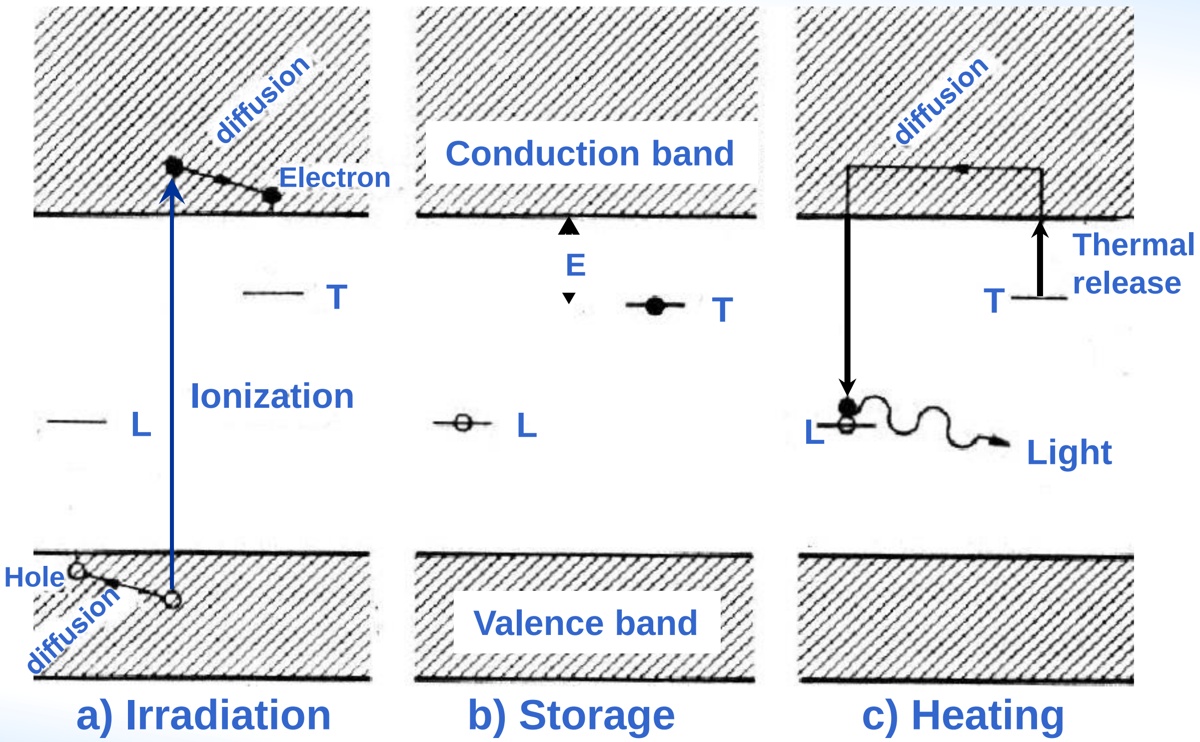



# Detecting radiation with luminescence

- Radiation can be converted to light through radioluminescence
- Light can easly be converted to electrical current/pulses
- Electrical current gives information on radiation field
- 4 types of luminescent radiation detectors
  - Scintillation detectors (not for passive dosimeters)
  - Thermoluminescent detectors (TL)
  - Optically stimulated luminescent detectors (OSL)
  - Radiophotoluminescent detectors (RPL)

# Thermoluminescence

# Simplified thermoluminescent process

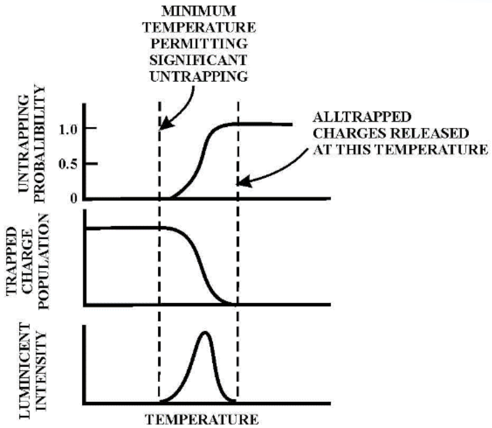


# Glow curves

- The result of a thermoluminescent measurement is a glow curve
- Physical process can be simplistically modelled for one trap by:

$$I(t) = -dn/dt = n \, . \, s \exp(-E/k\,T)$$

- Where:
  - n= number of captured electrons
  - s= probability of electron escape
  - E= energy needed for thermal “untrapping“
  - T= temperature in K
  - k= Boltzmann constant




- This formula leads to a specific shape of the signal with increasing temperature
- In reality: much more complicated because of many traps and recombination centres
  - Glow curve will show different peaks

# Process of thermoluminescent dosimetry

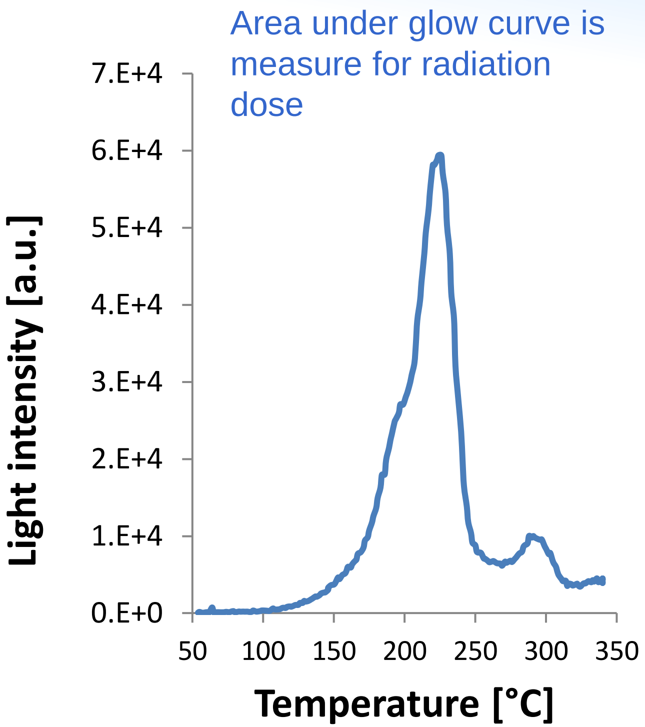
- Annealing (=heating) of detector to remove all previous signals
- Expose dosimeter to ionising radiation
- Read out of dosimeter by heating the detector and measuring the light output in the form of a glow curve
- Analyse the measurement result, taking into account the calibration, background, fading, etc…
- Possibility to reuse the detector by annealing the detector

# Process of thermoluminescent dosimetry

### 1) Anneal in oven

### 2) Irradiation

### 3) Read-out

# Thermoluminescent reader

- Heating system: to heat the detectors
- Heating can be done with different methods:
  - Planchet heating
  - Hot anvil
  - Hot gas (mostly inert nitrogen)
  - Infrared
  - Laser heating
- Light detection system: mostly photomultiplier tube (PMT)
- Read-out unit: to integrate the current from the PMT

# TLD is attractive for radiation protection dosimetry

- Easy process of read-out
- Some TL materials are nearly tissue-equivalent
- TL offers high sensitivity, accuracy, low detection limit and linearity over a wide dose range
- Many TL materials are commercially available as small solid detectors adaptable for automatic processing
- Particularly suited to eye lens and extremity dosimetry

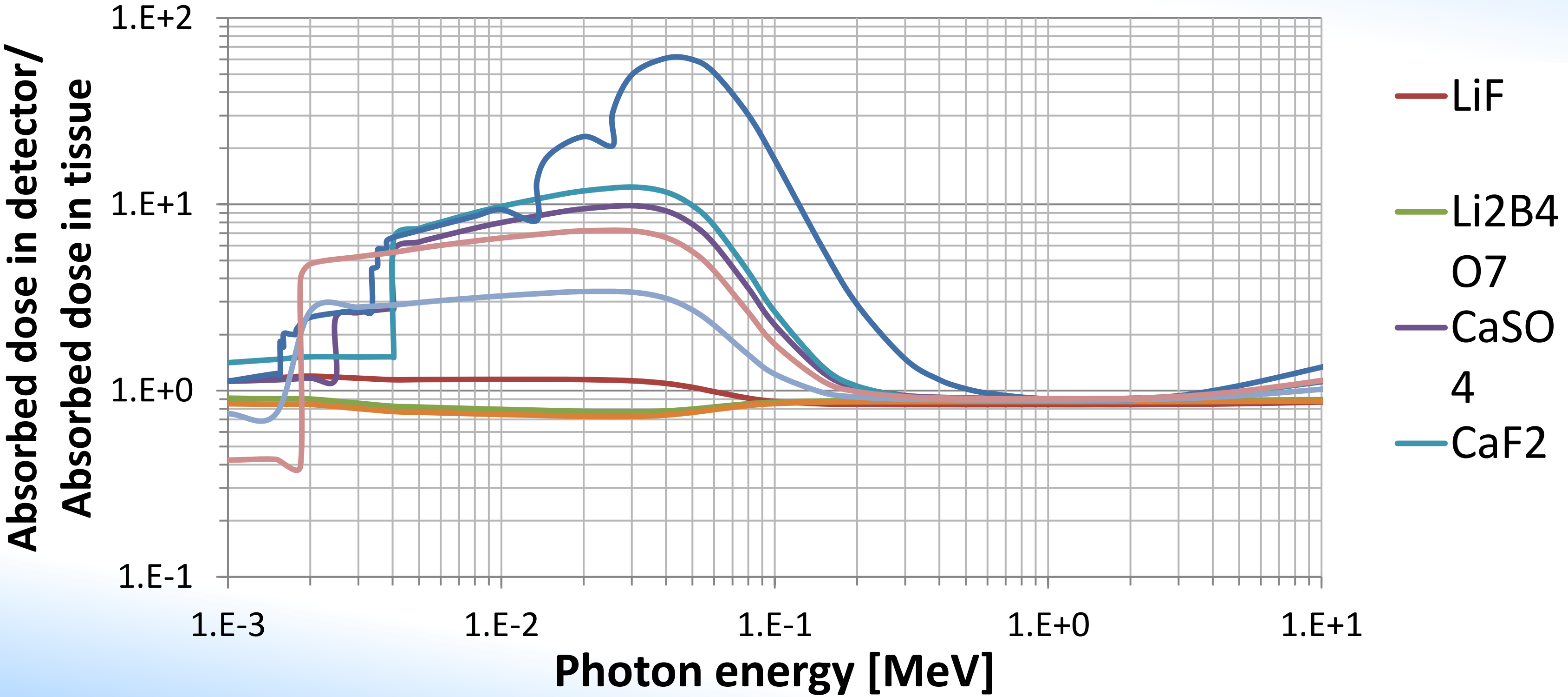
# TLD materials

- Needed to be a good dosimetric TL material:
  - Many capture centres
  - Low fading (thermal nor optical)
  - Tissue equivalent
  - Suitable emission wave length
  - Constant sensitivity
  - Independence of dose rate
- Examples: LiF: Mg,Ti; LiF: Mg,Cu,P; $Li_2B_4O_7$:Mn; $CaSO_4$: Dy; $CaF_2$:Tm; BeO
- Li-based TLD’s most used because of their near tissue equivalence

# General characteristics of commercially available TLDs

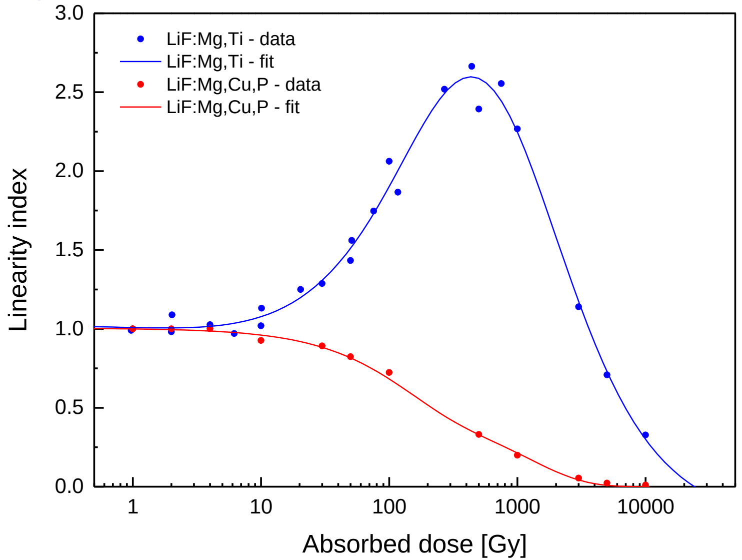
| TLD type | Effective atomic number $Z_{eff}$ | Main peak (°C) | Emission maximum (nm) | Relative sensitivity | Fading (at 25 °C) |
|---|---|---|---|---|---|
| LiF:Ti,Mg | 8.3 | 200 | 400 | 1 | 5%/year |
| LiF:Na,Mg | 8.3 | 200 | 400 | 1 | 5%/year |
| LiF:Mg,Cu,P | 8.3 | 210 | 400 | 25 | 5%/year |
| $Li_2B_4O_7$:Mn | 7.3 | 220 | 605 | 0.20 | 4%/month |
| $Li_2B_4O_7$:Cu | 7.3 | 205 | 368 | 2 | 10%/2 months |
| $MgB_4O_7$:Dy | 8.4 | 190 | 490 | 10 | 4%/month |
| BeO | 7.1 | 190 | 200-400 | 0.20 | 8%/2 months |
| $CaSO_4$:Dy | 14.5 | 220 | 480-570 | 30 | 1%/2 months |
| $CaSO_4$:Tm | 14.5 | 220 | 452 | 30 | 1-2%/2 months |
| $CaF_2$:Mn | 16.3 | 260 | 500 | 5 | 16%/2 weeks |
| $CaF_2$ (natural) | 16.3 | 260 | 380 | 23 | very slight |
| $CaF_2$:Dy | 16.3 | 215 | 480-570 | 15 | 8%/ months |
| $Al_2O_3$ | 10.2 | 360 | 699 | 4 | 5%/2 weeks |

# Energy dependence of TL materials



# Supralinearity

- Some TL materials show a specific feature at high doses: supralinearity
  - If dose doubles, signal more than doubles
  - Complex phenomena of competing traps
- Important for frequently used material LiF:Mg,Ti
  - Only for doses above several Gy/Sv
  - Need to correct in case of accidents



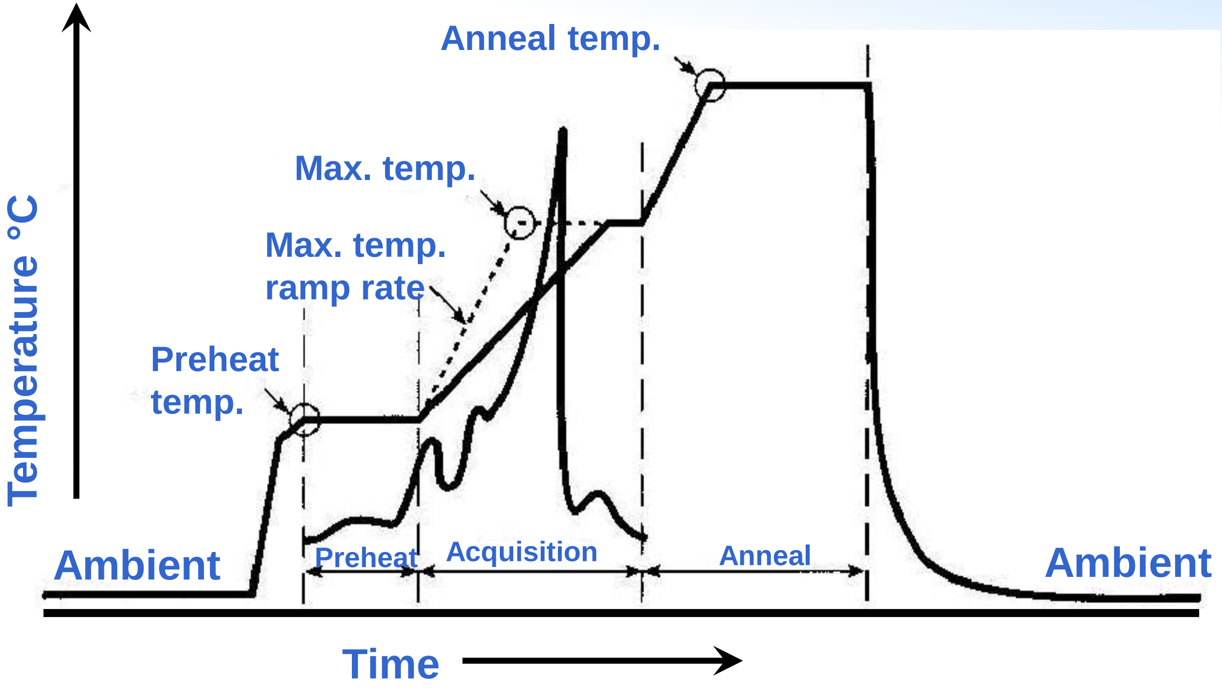
# Thermoluminescent fading

- Unintentional release of trapped electrons before readout is called fading
- Any storage of detectors leads to fading
- There is fading before and after the irradiation
  - Before irradiation there is fading of electron traps
  - After irradiation there is fading of electrons in traps
- Probability is function of temperature: fading is higher at higher temperatures
- Low temperature peaks show more fading, high temperature peaks are more stable
- Fading depends on detector material
- Fading needs to be limited for occupational dosimetry:
  - Possibly also need to correct for fading

# Glowcurve deconvolution

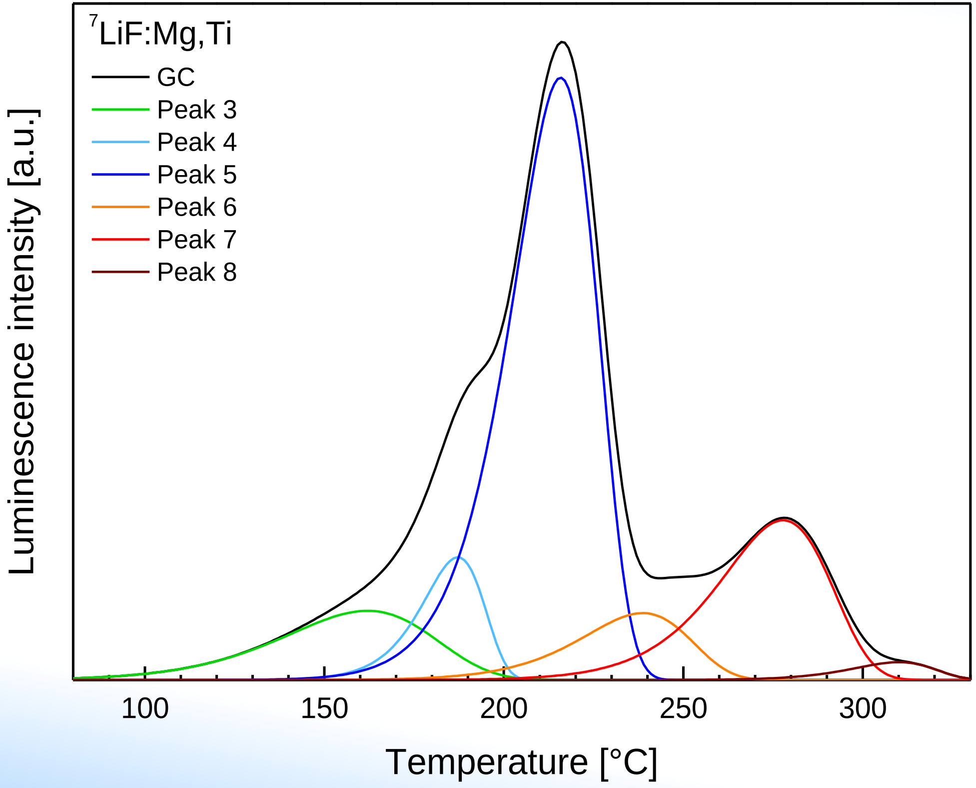
- Glowcurve consists of different peaks
  - From different trap centres
  - Each peak has different characteristics
- Glowcurve deconvolution = splitting up the different peaks
  - Can help to improve dosimetric characteristics
    - Improve precision at low dose: better discrimination with inherent background
    - Fading correction: removal of less stable peaks through preheat (=heating at lower temperatures before actual reading)

# Time-temperature profile (TTP)

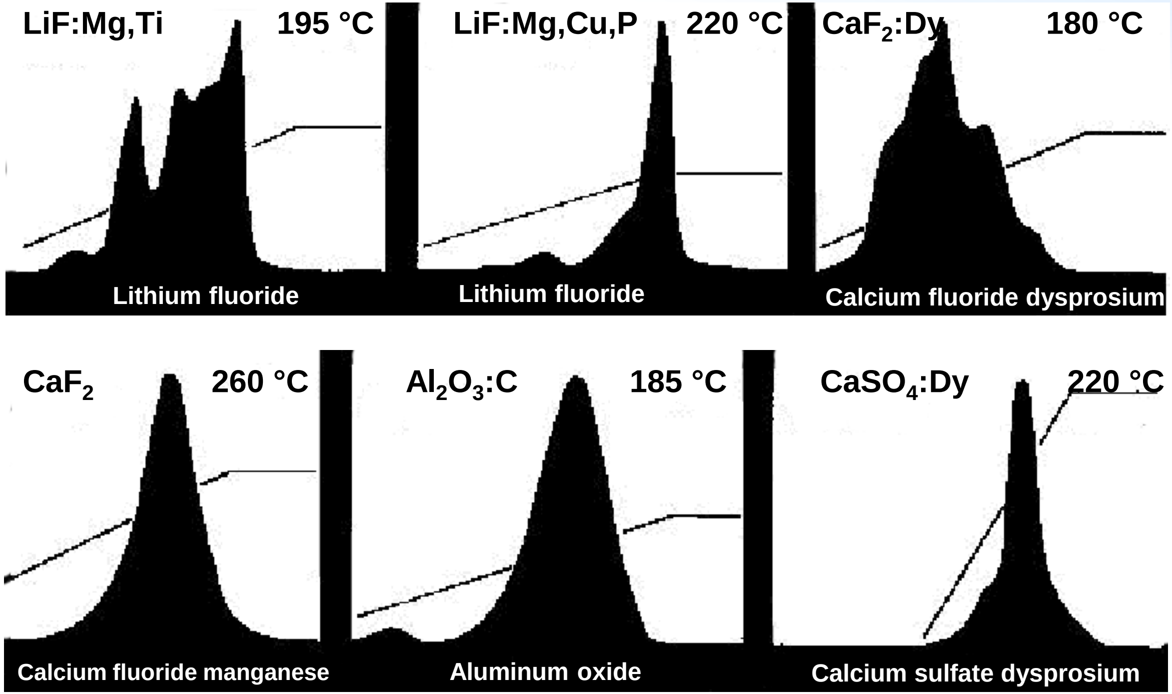



Time-temperature profile and glow curve for LiF:Mg,Ti freshly exposed to 1 Gy

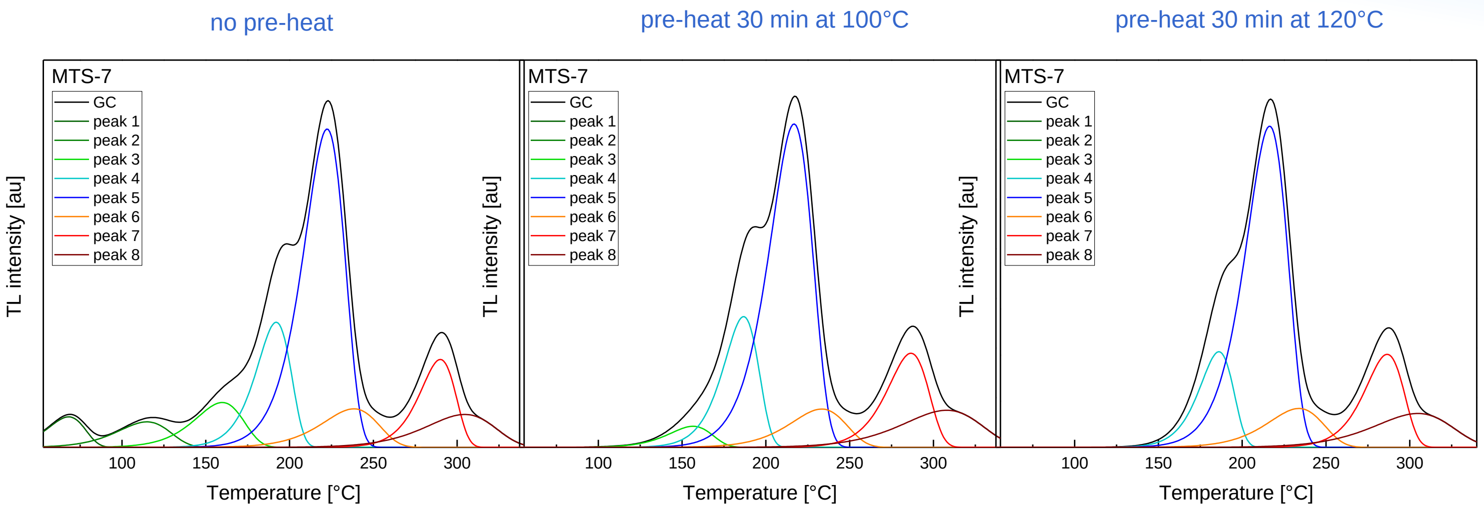
# Example: glowcurve deconvolution of LiF:Mg,Ti



# Glow curves for various TL phosphors



# Result of preheat on low temperature peaks



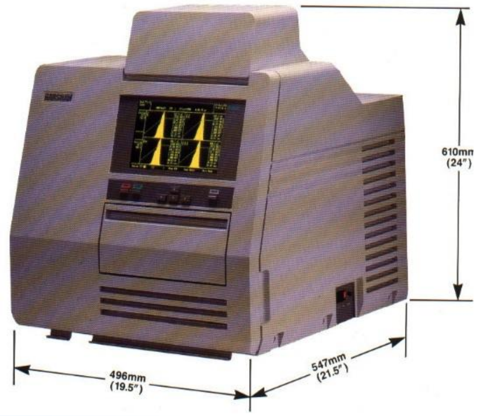
# Pros and cons: thermoluminescent dosimetry

- Advantages
  - Very compact
  - Reusable
  - High sensitivity
  - Near tissue equivalence
- Disadvantages
  - Only one read out is possible
  - Reproducible and controlled heating is a challenge
  - Fading (depending on material and preheat)

- Often used in occupational dosimetry: different commercial systems available

# Harshaw TL system

- Different configurations in badge possible (2 or 4 elements)
- LiF:Mg,Ti detectors (also possible with LiF:Mg,Cu,P)
- Readers of different size and capacity




# Panasonic TL system

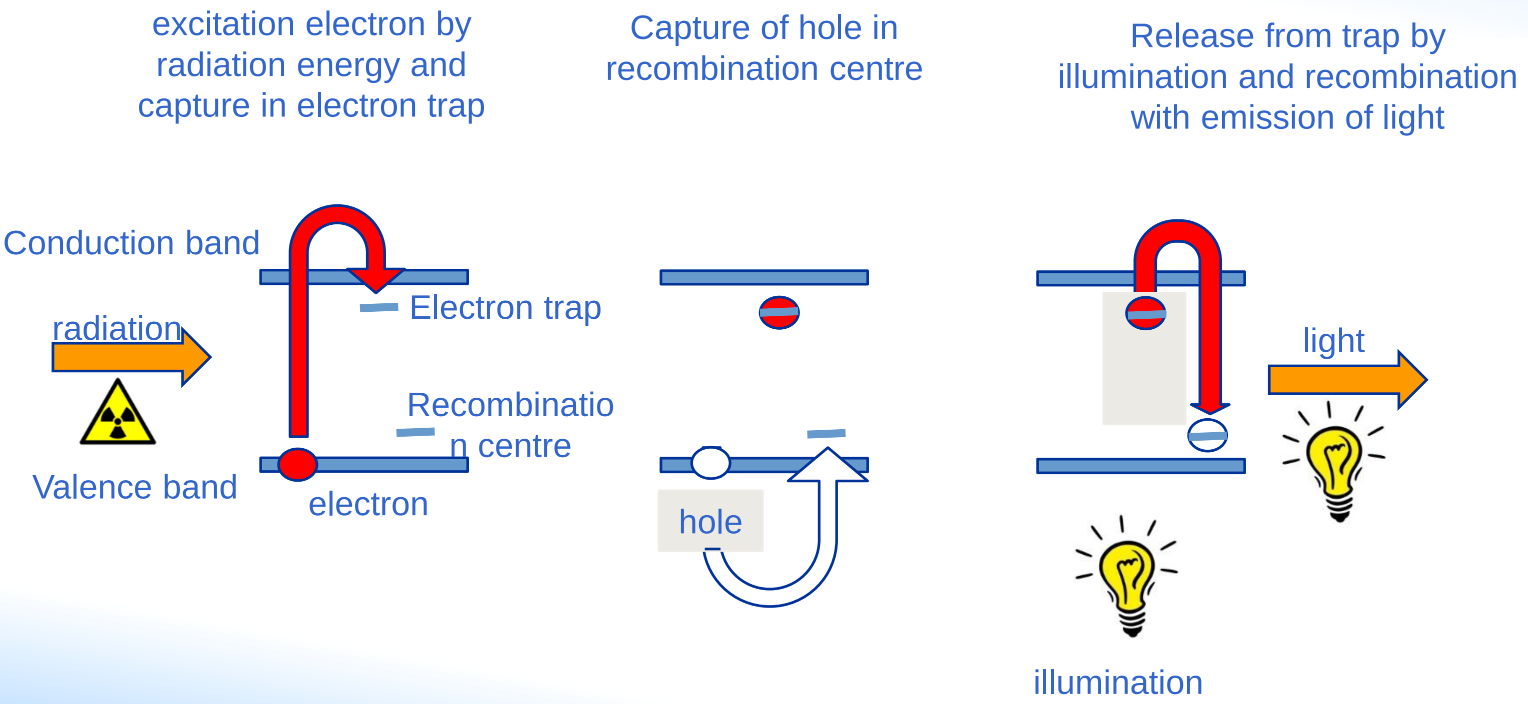
- Badge consists of
  - 2 $CaSO_4$:Tm detectors
    - High sensitivity but not tissue equivalent
  - 2 $Li_2B_4O_7$:Cu detectors
    - Near tissue equivalent
- Branching algorithm to calculate $H_p(10)$


# Rados TL system

- Badge consists of 2 or 4 elements
- LiF:Mg,Ti or LiF:Mg,Cu,P detectors
- Different filters possible

# Optically Stimulated Luminescence

# Simplified optically stimulated luminescence process



# Process of optically stimulated luminescent (OSL) dosimetry

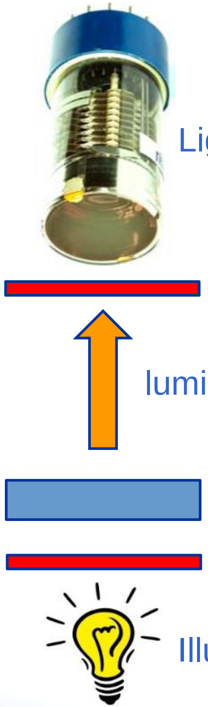
- Reset/annealing (=illumination) of detector to remove all previous signals
- Expose dosimeter to ionising radiation
- Read out of dosimeter by illuminating the detector and measuring the light output
  - Stimulation wavelength is different from emission wavelength
- Analyse the measurement result, taking into account the calibration, background, etc…
- Possibility of multiple reads of detector
  - If only part of the signal is removed by illumination
- Possibility to reuse the detector by resetting the detector

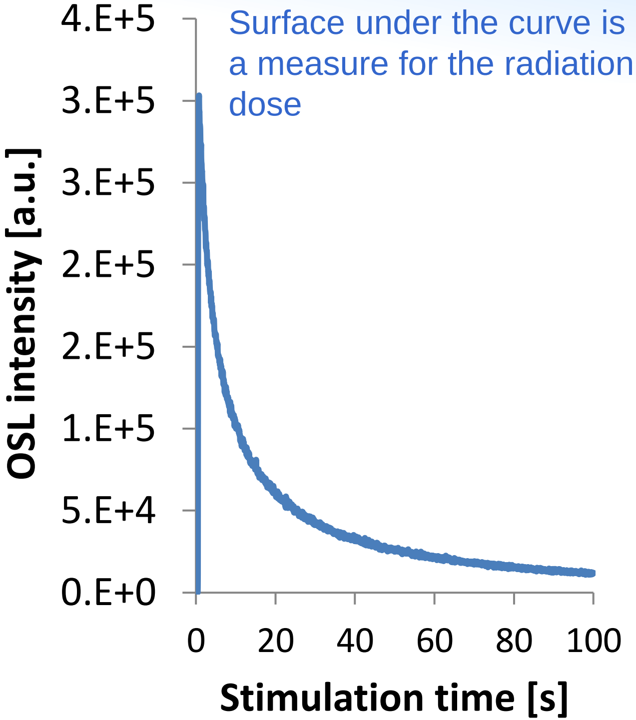
# Process of OSL dosimetry

**1) reset OSLD by illumination**

**2) Irradiation OSLD**

**3) Read out OSLD**



# OSLD reader

- No heating system needed
- Illumination can be done with LED’s
  - Wavelengths dependent on material and trap centre
  - Most OSL is done with pulsed stimulation
  - Each luminescence accumulation period ranges from 25 msec to 100 msec
  - Different accumulation periods per dose measurement
- Series of filters to discriminate between stimulation and emission light
- Light detection system: mostly photomultiplier tube (PMT)
- Read-out unit: to integrate the current from the PMT
- Optical energy releases a small fraction of the trapped charge carriers created during exposure

# OSLD materials

- Examples:
  - $Al_2O_3$:C
  - Halides: KCl, KBr, NaCl, RbI, $CaF_2$
  - Sulfates: MgSO4, CaSO4
  - Sulfides: MgS, SrS, CaS, BaS
  - Oxides: BeO, $SiO_2$
- Only $Al_2O_3$:C and BeO have been developed into commercial systems

# OSLD materials

- $Al_2O_3$:C : commercialized by Landauer
  - $Al_2O_3$:C  powder is mixed with a polyester binder and coated onto a roll of clear polystyrene film (Luxel)
  - Not tissue equivalent: multiple element dosimeter needed + algorithm
- The wavelength of the stimulation beam is 532 nm
- Blue luminescence has a peak wavelength of 420 nm

# OSLD materials

- BeO : commercialized by Dosimetrics
  - Near tissue equivalent
  - Toxic
- The wavelength of the stimulation beam is around 450 nm
- The wavelength of the emission is around 270 nm

# OSL fading and bleaching

- Any storage of detectors leads to fading
  - Unintentional release of trapped electrons before readout
- Bleaching occurs by unintended exposure to light
- Probability is function of temperature: fading is higher at higher temperatures
- Fading depends on detector material
- Fading needs to be limited for occupational dosimetry:
  - Possibly also need to correct for fading

# Pros and cons: optically stimulated luminescent dosimetry

- Advantages
  - Very compact
  - Reusable
  - High sensitivity
  - Fast and controllable read out
  - Multiple read outs are possible
  - Near tissue equivalent (BeO)
- Disadvantages
  - Not tissue equivalent ($Al_2O_3$:C)
  - Need to be shielded from environmental light
- Increasingly used in occupational dosimetry

# Landauer OSL system

- Badge consists of 4 elements of $Al_2O_3$:C behind different filters
- Algorithm to calculate $H_p(0.07)$ and $H_p(10)$
- Readers of different sizes and capacities


# Dosimetrics OSL system

- Badge consists of BeO material
- Different badge layout and number of elements possible

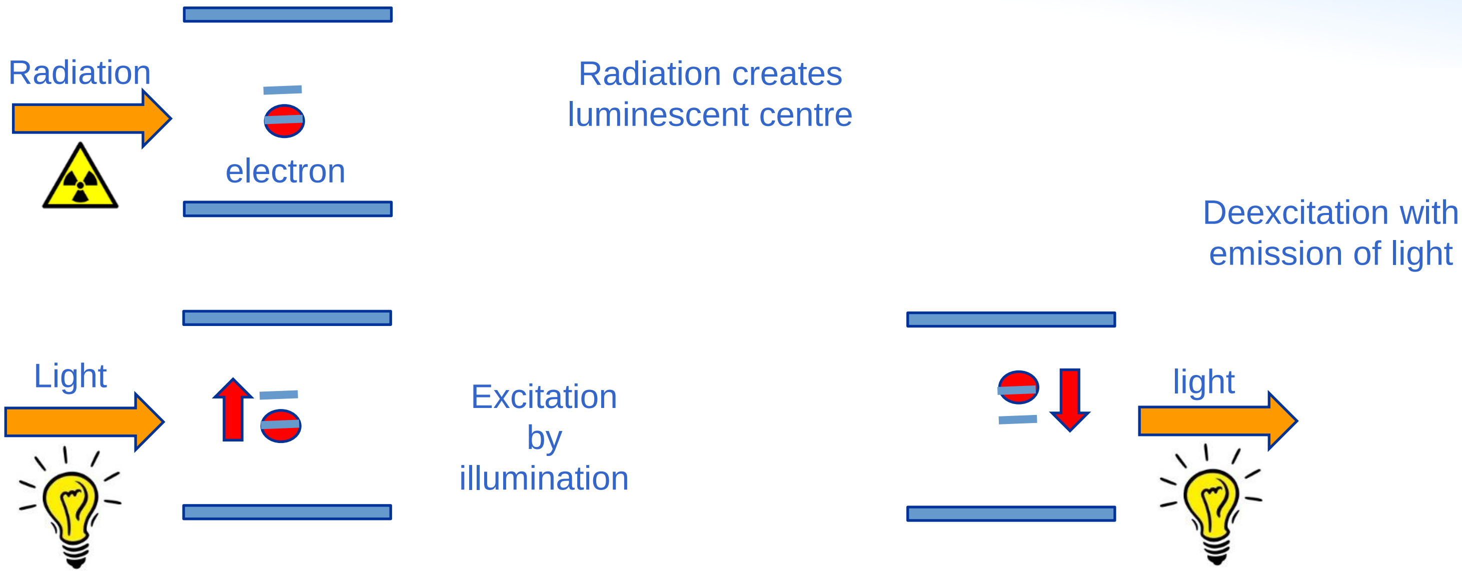


# Combined TL/OSL system

- Systems that give combined TL and OSL read-out possibilities have also been developed: Riso, Freiburg instruments

# Radiophotoluminescence

# Simplified radiophotoluminescent process

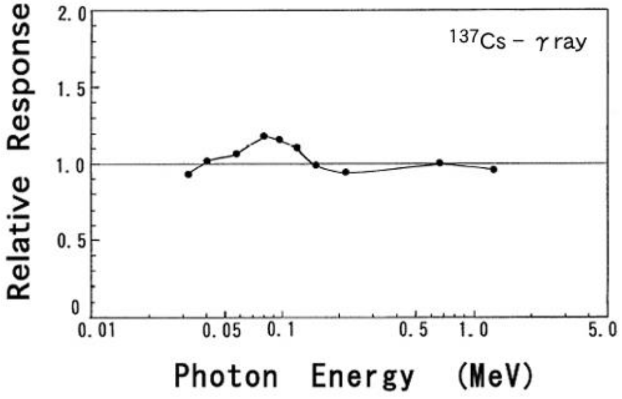


# Occupational dosimetry with radiophotoluminescent (RPL) dosimetry

- Photoluminescence is based on formation of induced luminescent centers in silver doped phosphate glass
  - Electrons can be excited to these luminescent centres by ionizing radiation
  - Trapped electrons can be excited within the luminescent centers by UV light
- When exposed to UV light, fluorescent light of a larger wave length is emitted with intensity linearly related to absorbed dose
- Centers are not destroyed by normal read-out and are stable
- Dose information can be obtained at any time during long-term dose accumulation
- Because of the high Z value of the glass materials, energy compensation filters are required
- Annealing (heating) is needed to reuse detector

# RPL is attractive for radiation protection dosimetry

- Commercial system with silver doped phosphate glass
- Easy and fast process of read-out
- With suitable filters and algorithm: flat energy response
- Good accuracy
- Negligible fading
- Can be remeasured
- Good reproducibility and constant sensitivity



# Pros and cons: radiophotoluminescent dosimetry

- Advantages
  - Compact
  - Reusable
  - Fast and controllable read out
  - Multiple read outs are possible, no signal loss
  - No need to shield from environmental light
- Disadvantages
  - Not tissue equivalent
  - High temperature anneal needed for reuse

# Chiyoda Technology RPL system

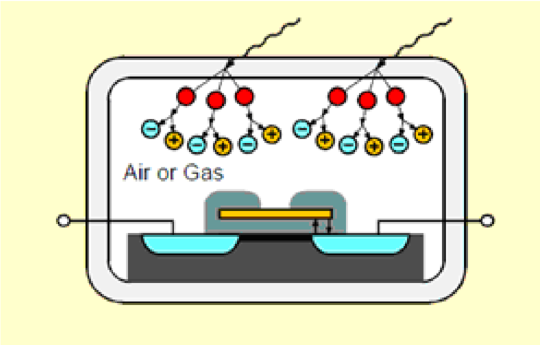
- Badge consists of phosphate glass material
- Different elements behind different filters with an algorithm

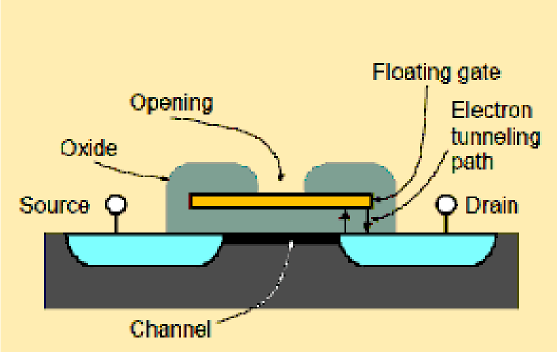

# Semi conductor: direct ion storage

# Basic features of Direct Ion Storage (DIS) systems

- Based on semiconductor materials
- Passive system:
  - no direct reading
  - no alarm function
- Commercially available as DIS dosimeter
  - Read-out with DBR reader
  - Exchange through dosimetry service
- Commercially available as Instadose dosimeter
  - No more monthly exchange
  - Wireless transfer of read-out data

# Principle of operation




- Radiation creates charges in small ionisation chamber above the detector
- Charges are collected on floating gate of Mosfet
- Measurement of voltage gives indication of dose
- Measurement is non destructive

# DIS dosimeter

- Passive electronic system with Direct Ion Storage (DIS)
- Small and rugged devices for personal dosimetry
- Several chambers to measure $H_p(10)$ and $H_p(0.07)$ for photon and beta radiation
- High sensitivity chamber for low doses
- Low and medium sensitivity chambers for high doses

# Basic features of DIS dosimeter

- Nondestructive readout: can be read out several times
- Hard reset is possible by reverse current and annealing
  - When sensitive chamber is saturated
- Passive operation
- Small dimensions
- Works in specific temperature range
  - Not suited for high or low temperatures

# DIS reader


- Reader is small and easy in use
- Several read-outs possible
- In use in several countries as official dosimeter
- Suitable for data networks

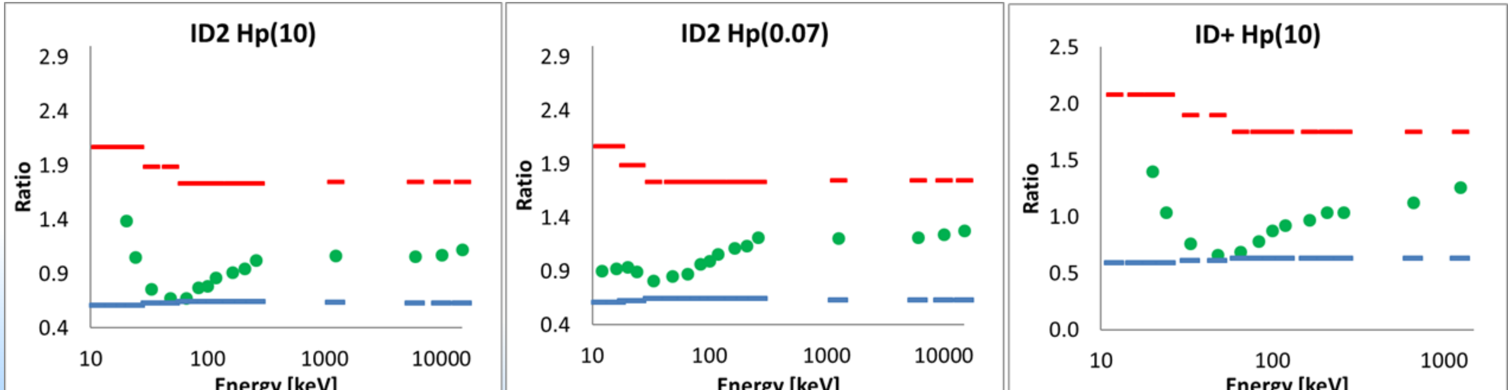
# Instadose dosimeter ID




- Newest development based on DIS technology: several DIS chambers incorporated in dosimeter
- Exclusively distributed by Mirion
- Several versions:
  - ID, ID+: only $H_p(10)$
  - ID2: includes also $H_p(0,07)$ chamber

# Basic features of Instadose

- Voltage measurement is done in dosimeter
- Measurement results are sent by bluetooth to receptor device and transfered to dosimetry service database for processing
  - Receptor device can be mobile phone, instalink station (internet), …
- Same radiological characteristics as DIS
  - Sufficient energy and angular dependence
  - Operational in specific temperature range (15-30°C)



# Specificities of Instadose

- No more monthly exchange:
  - dosimeter can stay with wearer
  - Exchange when dosimeter is full (100 mSv)
  - Exchange when recalibration is needed
- Read out is automatic
- Read-out frequency can be programmed
- Extra read outs are possible by push on button
- Dose measurements stored in dosimeter, even without transfer possibilities
- Change of wearer is possible at any time
- Background still needs to be subtracted
- Detection limit can be higher than other techniques