Dosimetric materials applications – TSL and OSL

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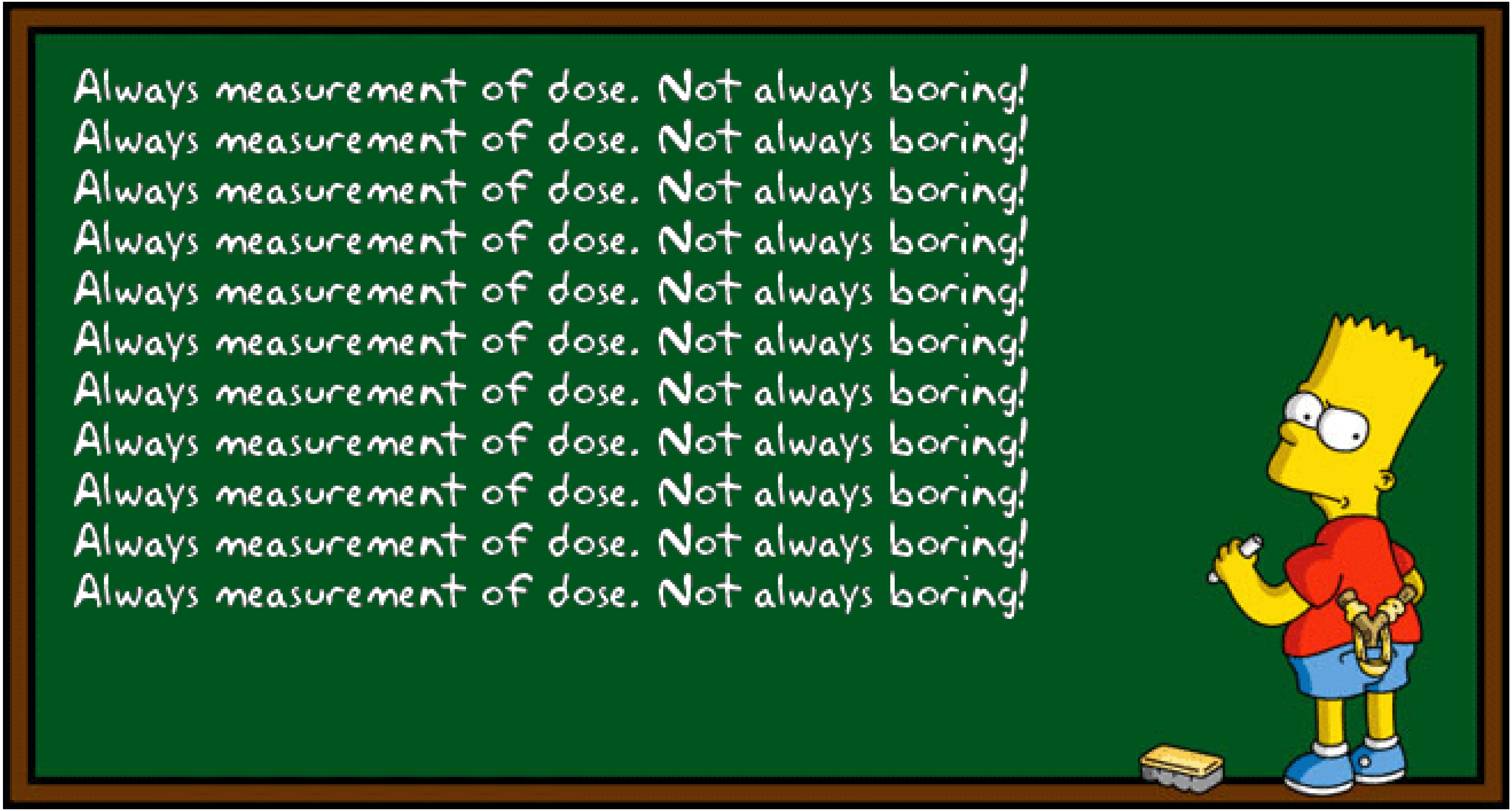
LUMDETR 2018 Summer School


Always measurement of dose. Not always boring!
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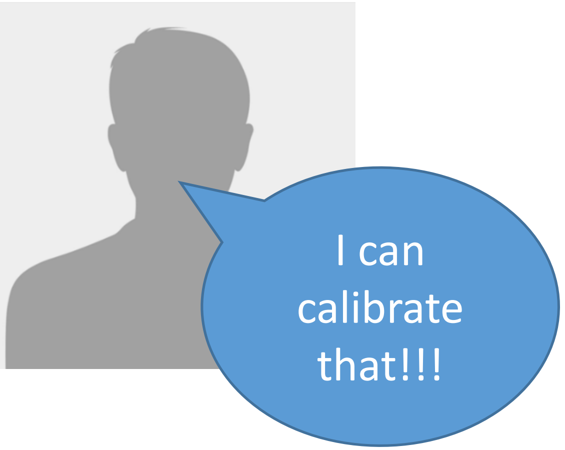
List of (selected) applications

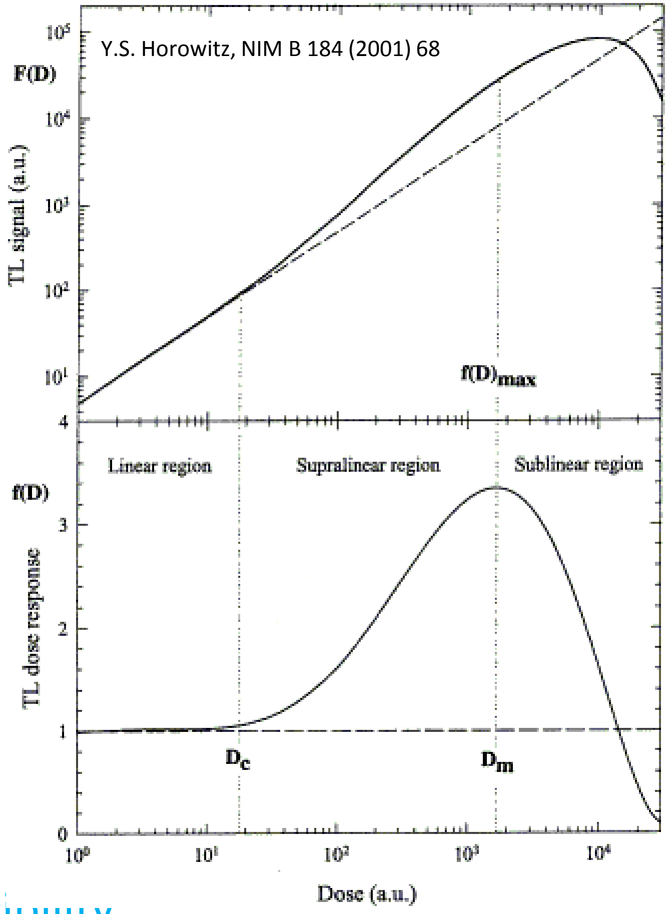
- Personal dosimetry
    - Dosimetry in space
  - Neutron dosimetry
- Emergency dosimetry
- Enviromental monitoring
- Dosimetry in medicine
  - Radiotherapy
  - Radiodiagnostics
- Thermoluminescence dating
- Aplications in biology, reactor engineering, industry…
  - High dose measurement – exploit OSL/TSL materials – but use alternative means of evaluation
    - Optical absorption
    - Different TSL peaks
    - Radiophotoluminescence
- Military applications (Dr. Janda)
- Education
  - Lectures on thermolumiscence materials especially

Personal dosimetry

- Task
  - Measurement of a dose obtained by individual worker
- Requirements and their reasons
  - Small dosimeter
    - Wearable
    - Finger dosimeter (extremity dosimetry)
    - Eye dosimeter
  - Measurement range at least 0.1 mSv – 1 Sv (10 Sv for extremities]
    - Natural background
      - Very roughly 1 mSv/year (radon not included) → 0.25 mSv/evaluation period
    - Worker limit
      - 20 mSv/year (whole body, eye)
      - 500 mSv/year (skin, extremities)
    - Death
      - Approximately 4 Gy

Personal dosimetry





- Requirements and their reasons
  - Low fading
    - Maximally 5 % during evaluation period (1 or 3 months)
    - Possibility of one-time irradiation (anytime)
  - Cheap, re-usable, fast reading, simple evaluation
    - High number of radiation workers (e.g. 12 000 in Czech hospitals, 1 000 000 in EU)
  - Linear dose response
    - Supralinearity and sublinearity complicates calibration, limits reproducibility
  - Response independent of (survivable) temperature, humidity, angle, energy, dose rate…
  - Acceptable precision
    - Approximately ±30(40) %
    - Low precision is mostly due to complex relation of $H_p(10)$ and dosimeter dose

Personal dosimetry

- Limits are given in effective dose E

$$E = \sum_T W_T \cdot H_T = \sum_T W_T \sum_R W_R \cdot \bar{D}_{T,R}$$

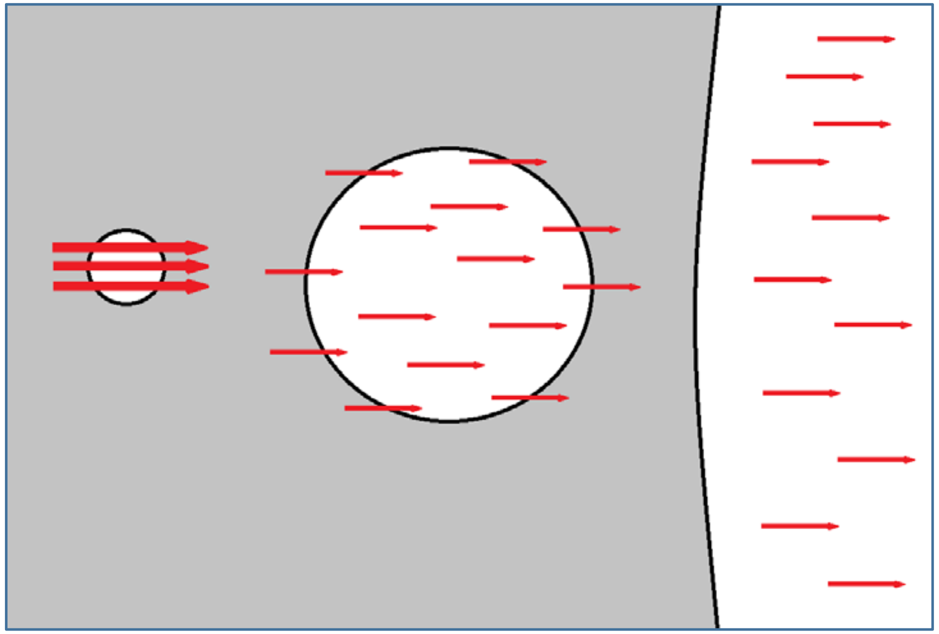
- $D_{T,R}$ – dose in organ T from radiation R
- W_R – radiation weighting factor
- W_T – tissue weighting factor
- → Should we measure $D_{T,R}$ for all organs and radiation type?
- Unrealistic!!!
- We measure Personal dose equivalent $H_p(10)$, $H_p(0.07)$ or $H_p(3)$
- Realistic assumption: $H_p(10) > E$

Personal dosimetry (energy dependence)

- For photon radiation and homogeneous irradiation
  - $E = H_p(10) = D$
- Approximation: $R = c\ D$
  - c – calibration constant
  - D – dose
  - R – response
- So simple? Not at all…
- Dose
  - Absorbed energy / mass (Gy = J/kg)
- We measure D_{dos} – dose in dosimeter
- We are interested in personal dose (in tissue) D_T
- We require $D_T = f\ D_{dos}$
  - Fortunately true
  - f (cavity correction factor) could be calculated or measured (calibration)

Personal dosimetry (energy dependence)

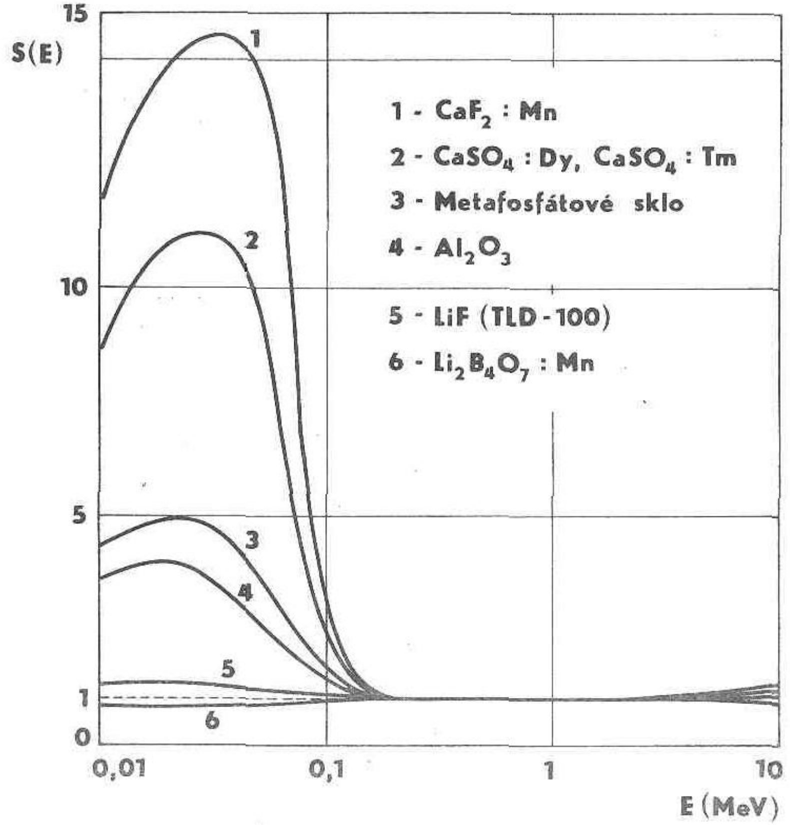
- Cavity theory (W wall = tissue; C cavity = dosimeter)
  - Assumption: photon beam / field is not attenuated
    - Otherwise – detector irradiation is inhomogenous
      - Extreme: only shallow layer below surface is irradiated
        - High angular dependence
  - Small
    - $f = f_{small} = {}_mS_C / {}_mS_W$
  - Large
    - $f = f_{large} = (\mu_{En}/\rho)_C / (\mu_{En}/\rho)_W$
  - Intermediate (according to Burlin)
    - $f = d\, f_{small} + (1-d)\, f_{large}$
    - $d = [1 - \exp(-Bx)] / Bx$
      - B – effective mass attenuation factor for electrons
      - x – mean electron path in C



- Quantities dependent on photon energy
  - ${}_mS_C$, ${}_mS_W$, $(\mu_E/\rho)_C$, $(\mu_E/\rho)_W$, B, x
  - → f depends on energy

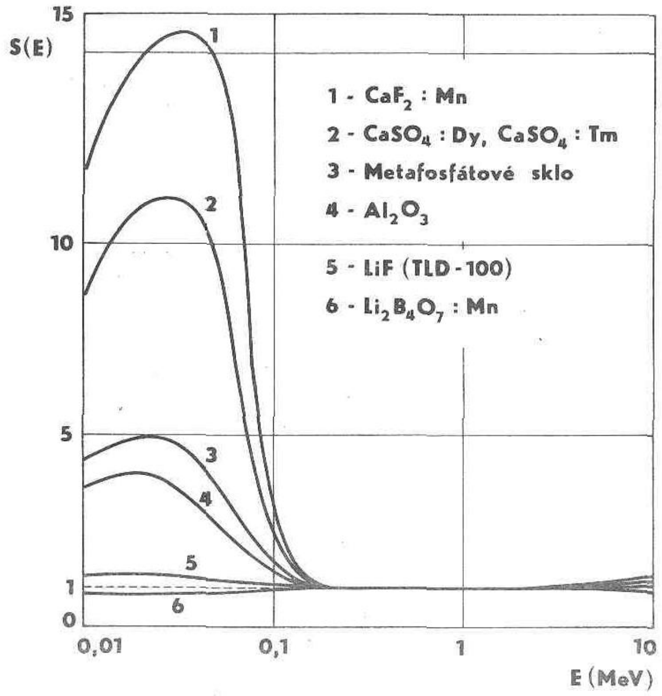
Personal dosimetry (energy dependence)

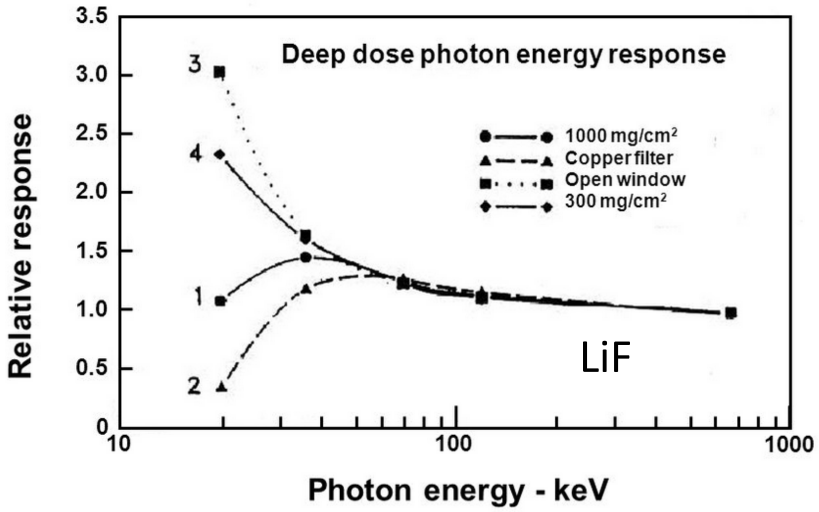
- Real TSL/OSL dosimeter could be considered small, intermediate or large cavity, depends on photon energy
- $D_T = f(E)\ D_{dos}$
- ☹ Energy E is generally unknown
- Solutions
  - Somehow make f constant
  - Compensate for the energetic spectrum
    - „Measure energy“



Personal dosimetry ("making f constant")

- $f = d\, f_{small} + (1-d)\, f_{large}$
- f = 1 if
  - $f_{small} = {}_mS_C/{}_mS_W = 1$
  - $f_{large} = (\mu_{En}/\rho)_C/(\mu_{En}/\rho)_W = 1$
  - $d \neq 1$
  - Could be achieved for limited E interval
- So-called tissue equivalent materials
  - Close to tissue equivalence: LiF, $Li_2B_4O_7$
  - Far: far to many, e.g. CaF_2, $CaSO_4$
- Filtering methods

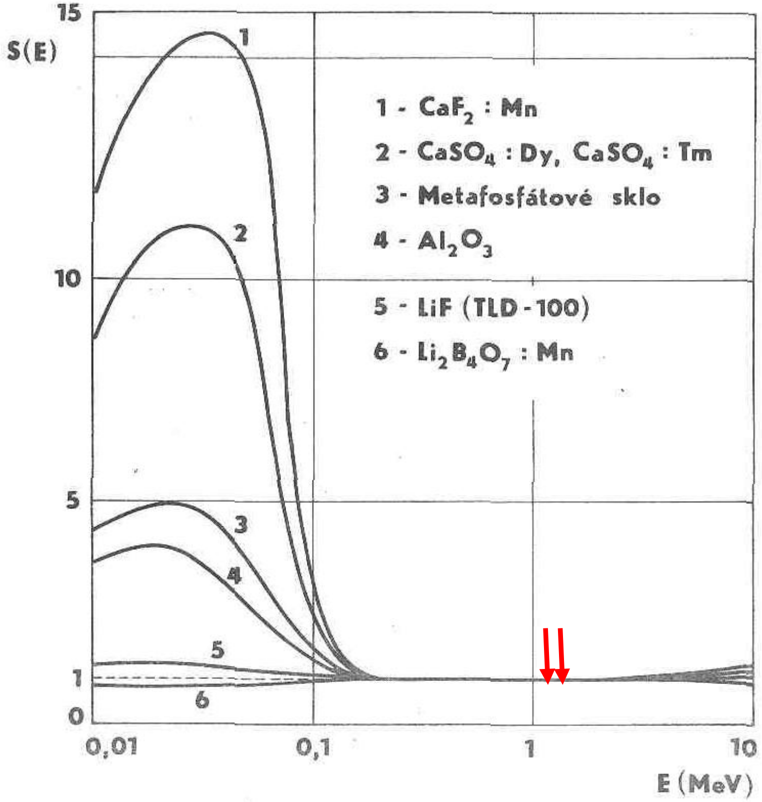




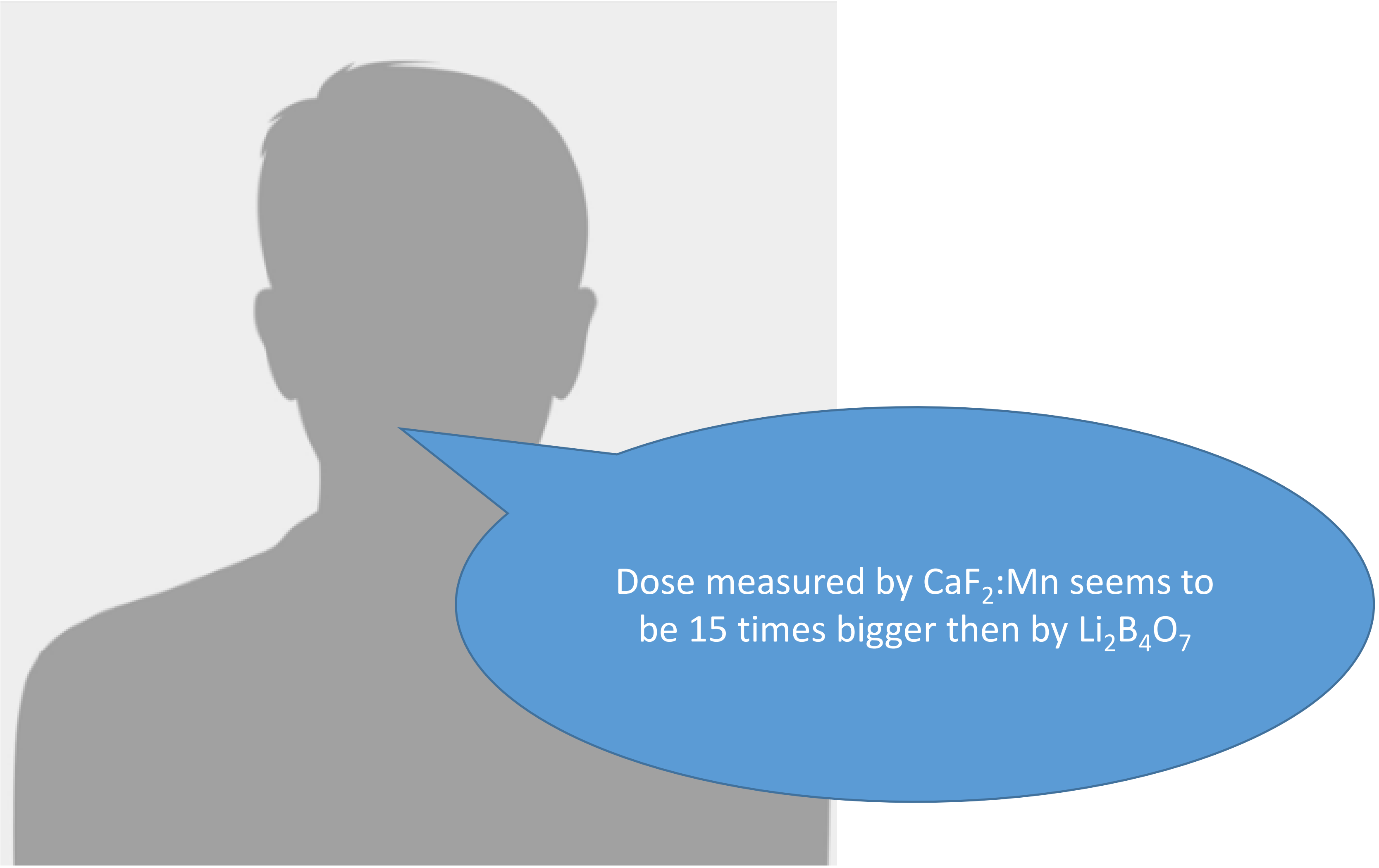
J. Anderson, ASSESSMENT OF OCCUPATIONAL EXPOSURE DUE TO EXTERNAL RADIATION SOURCES AND INTAKES OF RADIONUCLIDES Personal Dosimeters, IAEA

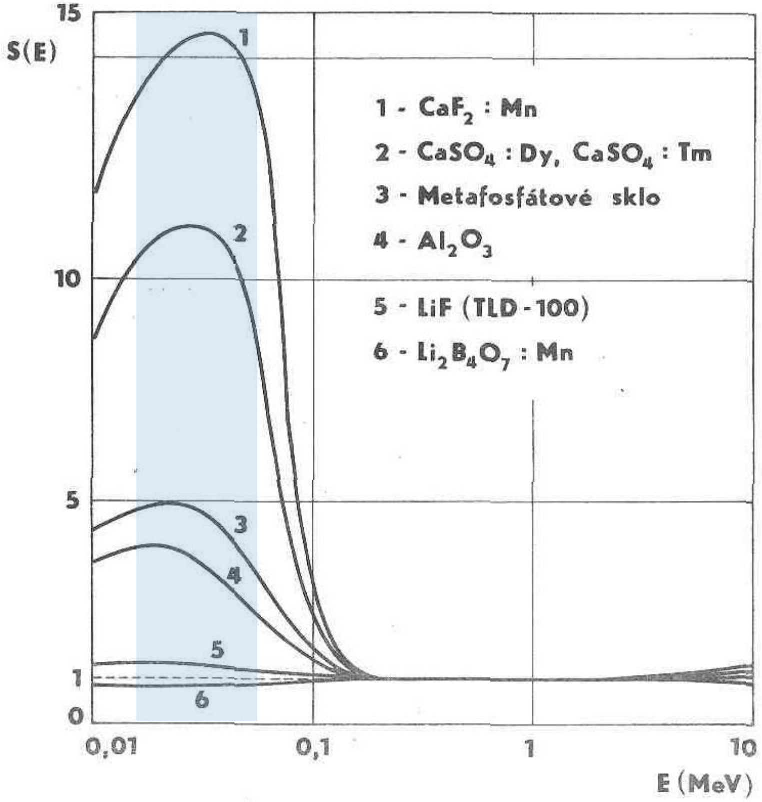
Personal dosimetry ("energy measurement")

There is CaF_2:Mn, $CaSO_4$:Dy, Al_2O_3 and $Li_2B_4O_7$ in my dosimetric cassette. I have calibrated it using ^{60}Co irradiator.



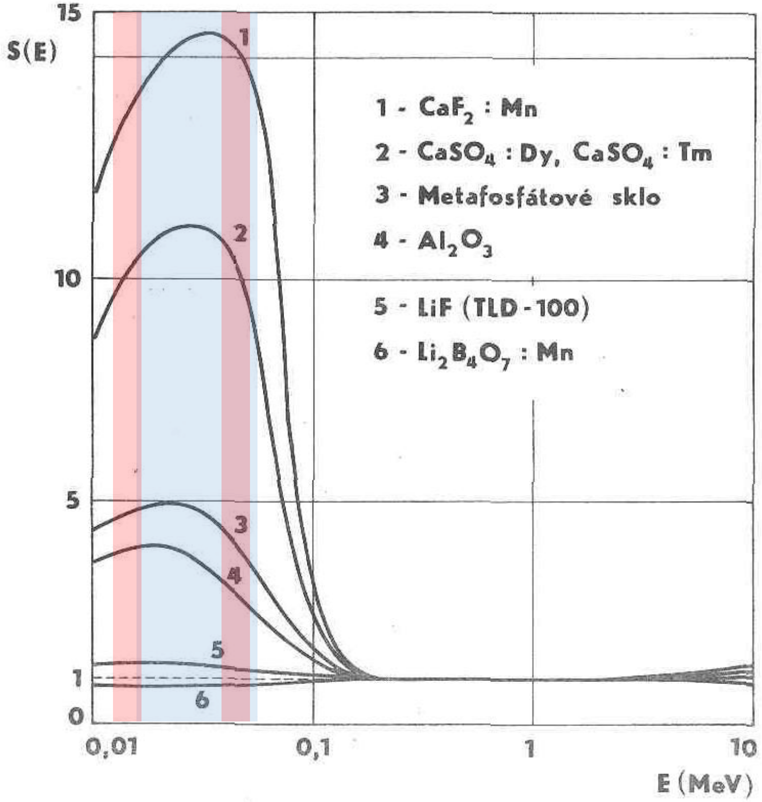
Personal dosimetry ("energy measurement")





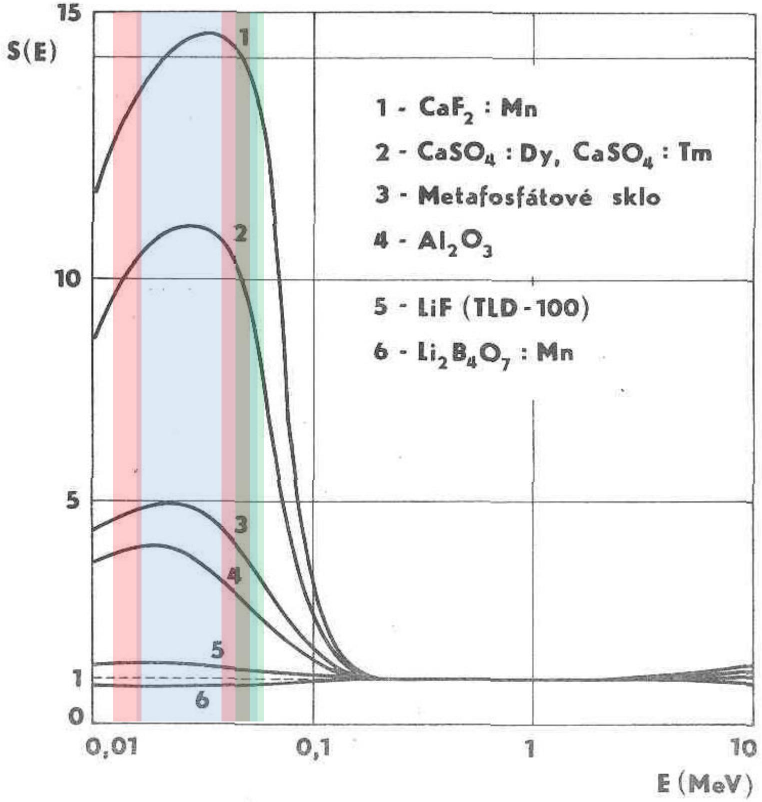
Personal dosimetry ("energy measurement")

Dose measured by $CaSO_4$:Dy seems to be 10 times bigger then by $Li_2B_4O_7$

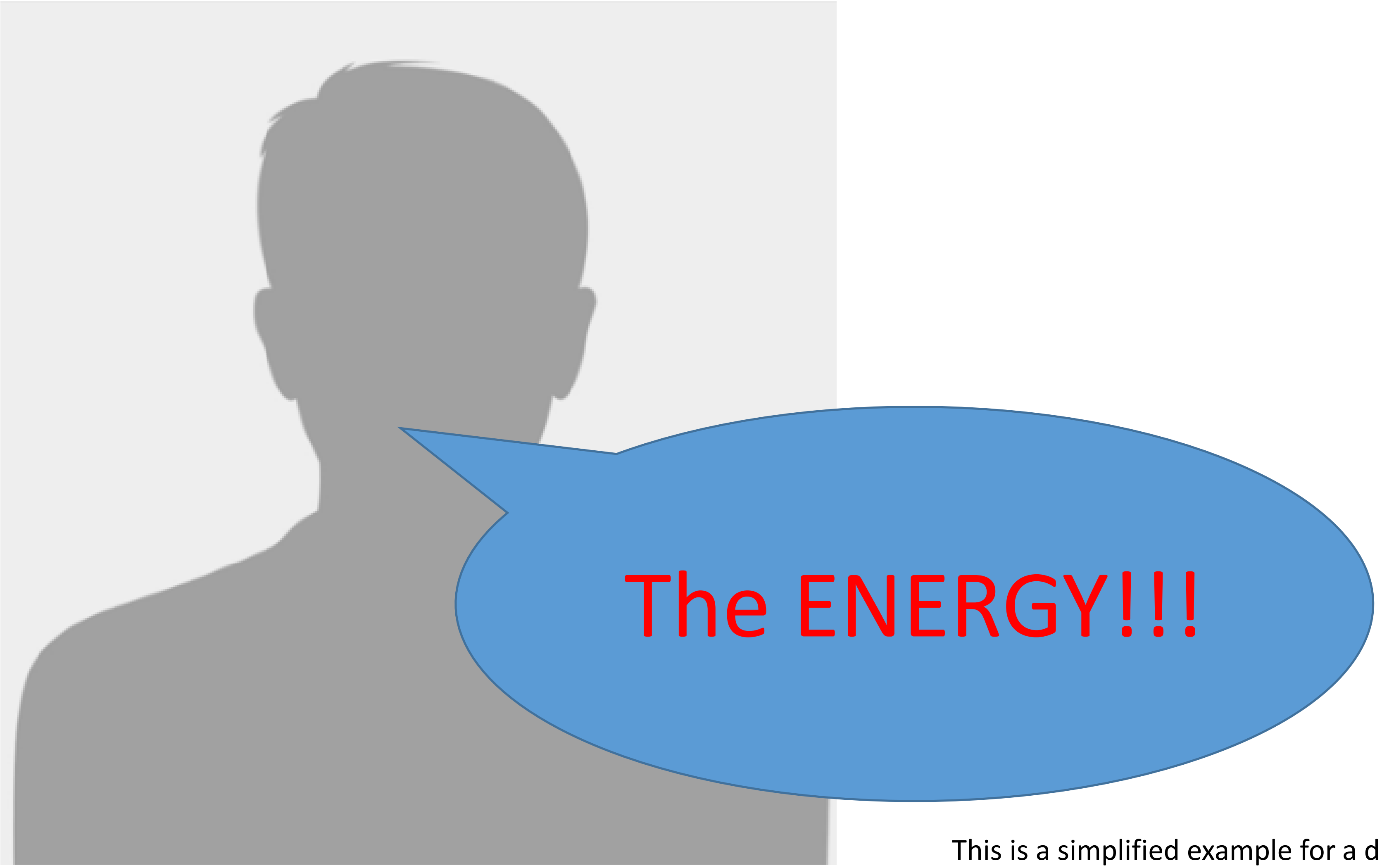


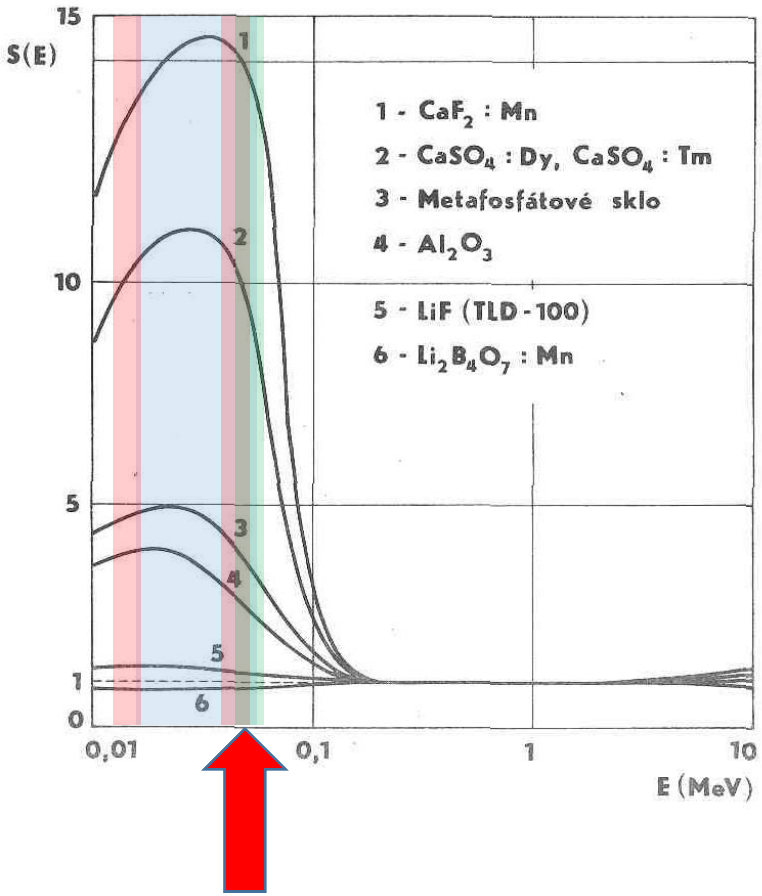
Personal dosimetry ("energy measurement")

Dose measured by Al_2O_3 seems to be 2.8 times bigger then by $Li_2B_4O_7$



Personal dosimetry ("energy measurement")

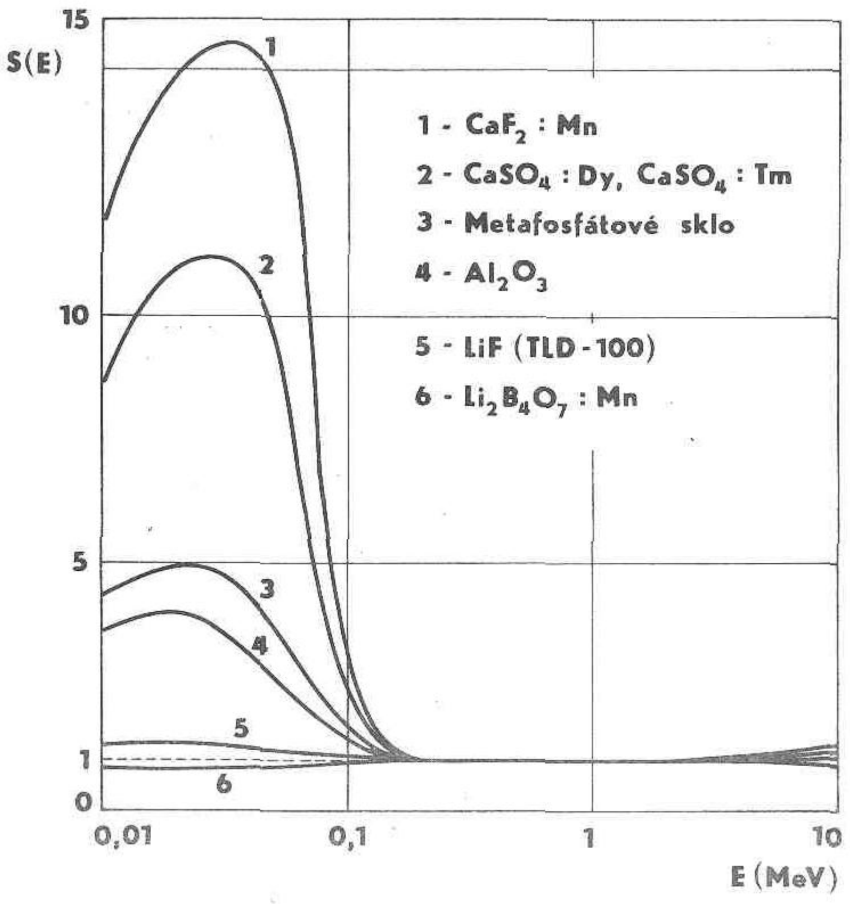




This is a simplified example for a discrete energy spectrum. However, such analysis is in principle applicable for complex spectra as well (in a slightly more complicated form)

Personal dosimetry (energy dependence)

- Constant f
  - More simple
  - Faster evaluation (1 dosimeter)
  - Cheaper
- “energy measurement”
  - Rough information on energy available
  - Complicated evaluation if two or more materials are used
    - instead: one material, several dosimeters with different filters (probably most common method)
      - E.g., plastic, **plastic**, Al+plastic, Cu+plastic
  - Higher Z materials could be involved



Personal dosimetry (materials used)

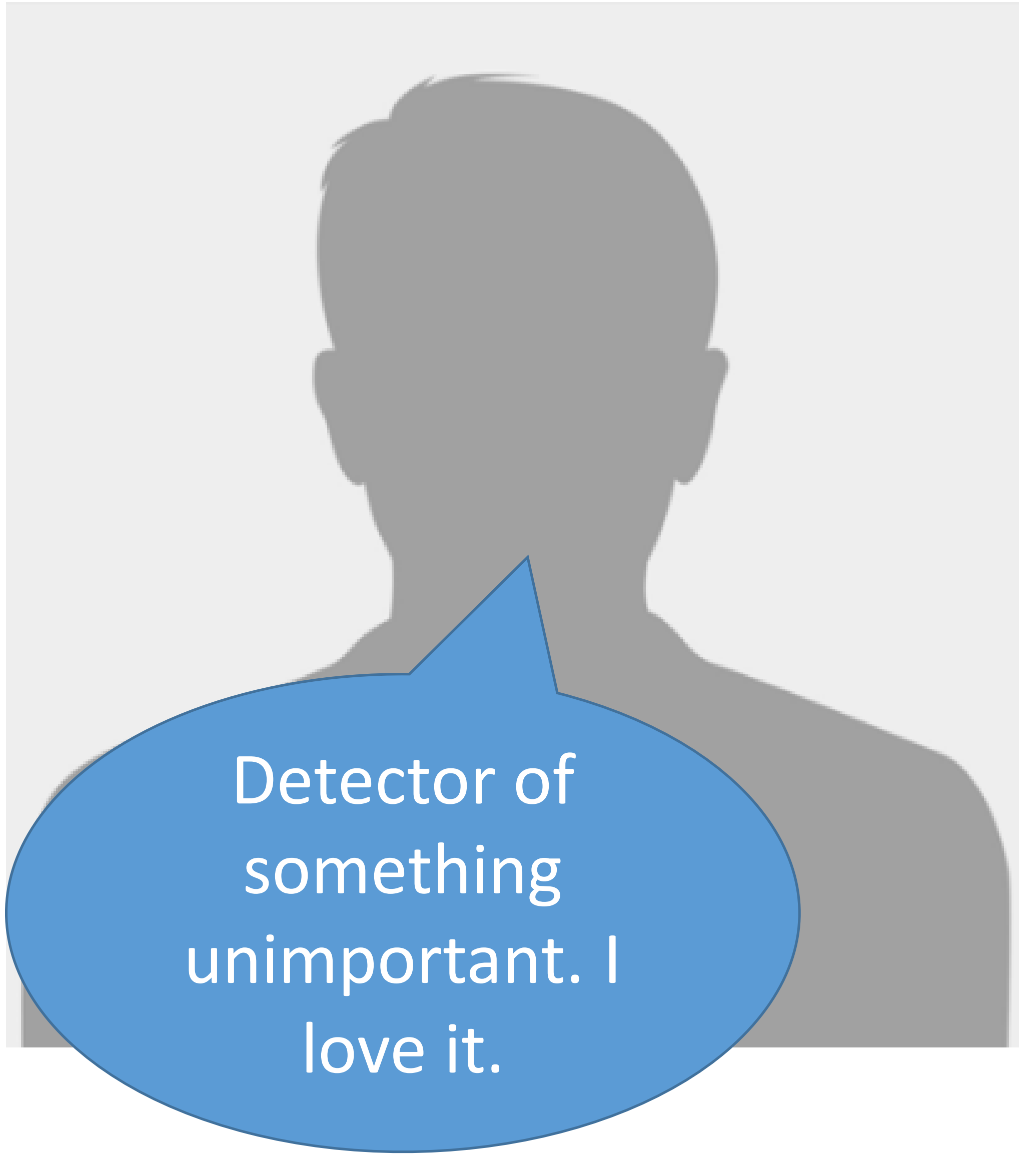
- TSL
  - LiF:Mg,Ti (MTS)
  - LiF:Mg,Cu,P (MCP)
  - CaF_2:Mn
  - $Li_2B_4O_7$
    - Hygroscopic, closest to tissue equivalence
  - Others…
- OSL
  - BeO
    - Linear 0.01- units Gy, dose underestimation for low photon energies (filtering is the solution), extremely low fading
  - Al_2O_3:C
    - 0.05-10 Sv, reproducibility (10 % signal loss after 25 cycles)

Personal dosimetry – advantages / disadvantages

- Advantages
  - Re-usable
  - Relatively cheap
  - Small
  - Simple measurement automatization
  - Large dynamic range
- Disadvantages
  - Hard to identify
  - One (or few) reading(s)
  - No possibility of contamination idetification
  - No possibility of ide
  - Fading (can be very small)
  - More filters → more detectors

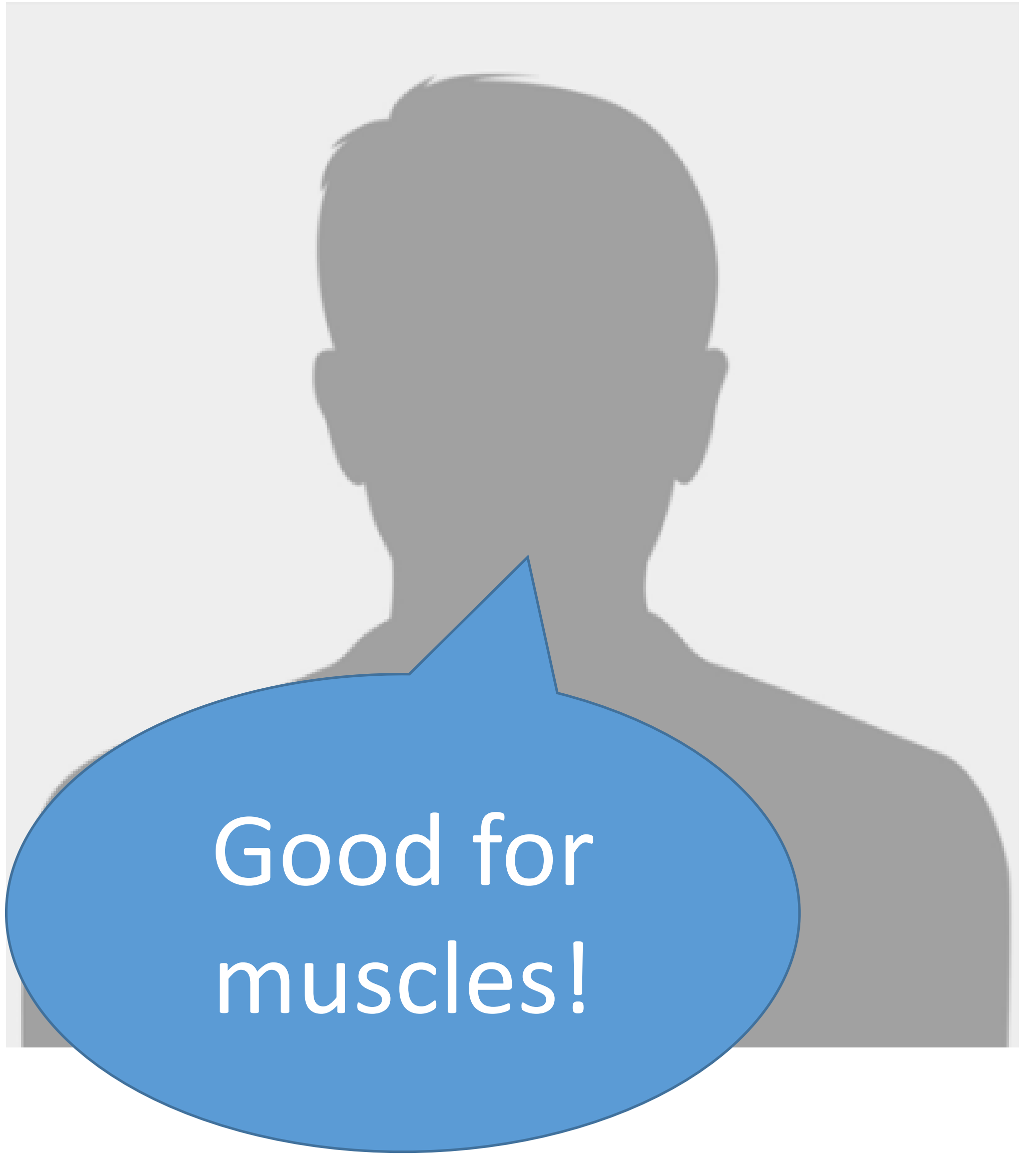
Personal neutron dosimetry – albedo dosimeter

- Some facts…
  - TSL materials sensitive to thermal neutrons are available: $Li_2B_4O_7$, LiF, $CaSO_4$:Dy,Li
    - $^{6}Li + n \rightarrow {}^{3}H + \alpha$
    - $^{10}B + n \rightarrow {}^{7}Li + \alpha$
    - ^{11}B and ^{7}Li are insensitive
    - → compensation principle could be applied
  - Compensation
    - 2 detectors – ^{6}Li enriched, ^{7}Li enriched (^{6}LiF / ^{7}LiF)
    - Same response caused by γ and β radiation
    - Different response caused by thermal neutrons
    - R (^{6}LiF) – R(^{7}LiF) = R(thermal neutrons)
  - Thermal neutrons are negligible contributors to effective dose



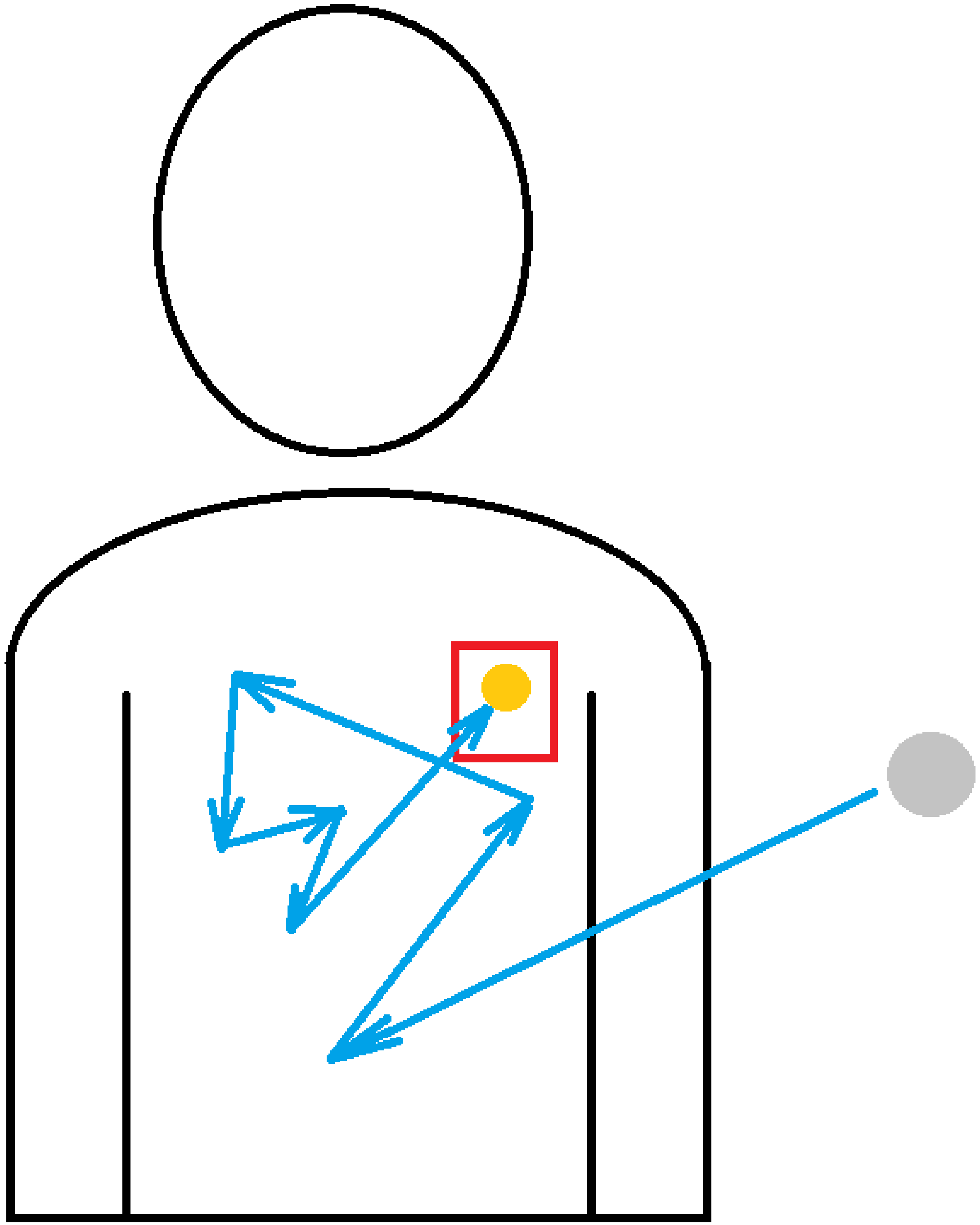
Personal neutron dosimetry – albedo dosimeter

- Some other facts…
  - Fast neutrons are important contributors to effective dose (if present)
  - Moderation
    - Fast neutrons → thermal neutrons
- Eureka!
  - Solution: Moderator in TSL dosimeter vicinity
  - How much moderator?
  - Several kg should be enough



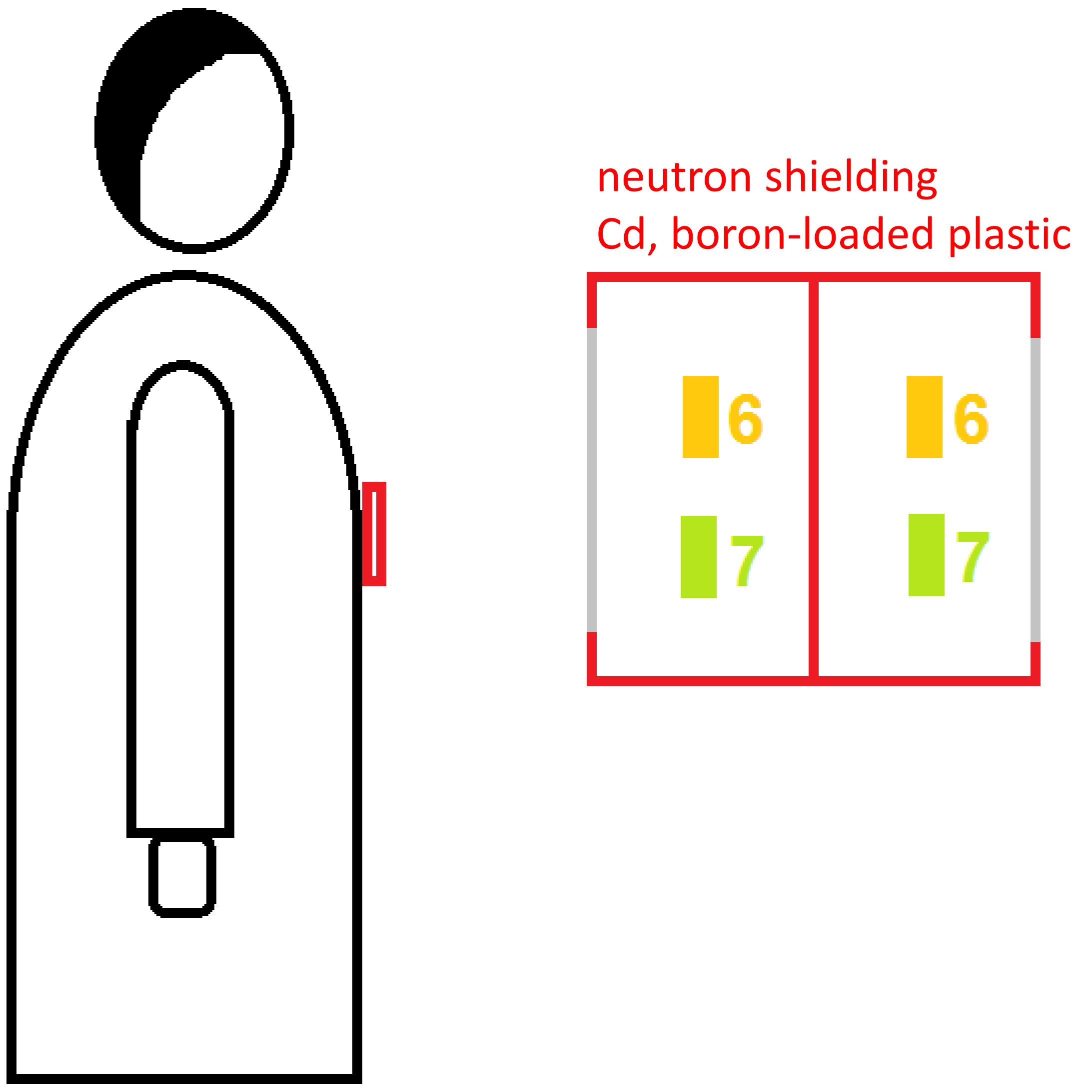
Actually…

Everyone carries several kg of moderator naturally...



Personal neutron dosimetry – albedo dosimeter

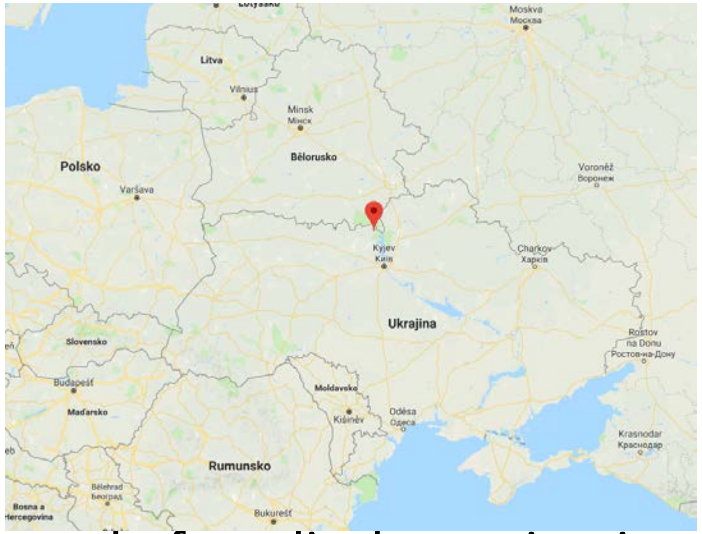
- R(thermal neutron) = R_{tn}
- Neutron $H_p(10) = C\, R_{tn}$
  - C – calibration constant, (strongly) dependent on neutron spectrum
- Possibilities
  - 1) neutron spectrum is constant in time and known
    - One pair of dosimeters is enough
  - 2) spectrum of neutron source is known, but moderation is variable
    - Multi-element albedo dosimeter must be used
    - C is unambiguously dependent on ratio of responses albedo/direct
  - 3) different sources
    - Combination with other neutron dosimeters is necessary



Enviromental monitoring

- Requirements similar to materials for personal dosimetry…
  - Dose range 0.1 mSv – tens of mSv
  - Tissue equivalence welcomed
  - Able to withstand environmental conditions (higher/lower temperature, humidity)
  - Longer exposure period (up to 1 year)
    - Very low fading required
- Complex calibration, evaluation and correction procedure
  - Several sets of control dosimeters
    - Fading – irradiation at site, but shielded
    - Response to zero dose – not at site, not irradiated
    - Calibration – irradiated by known dose, not at site

Emergency dosimetry



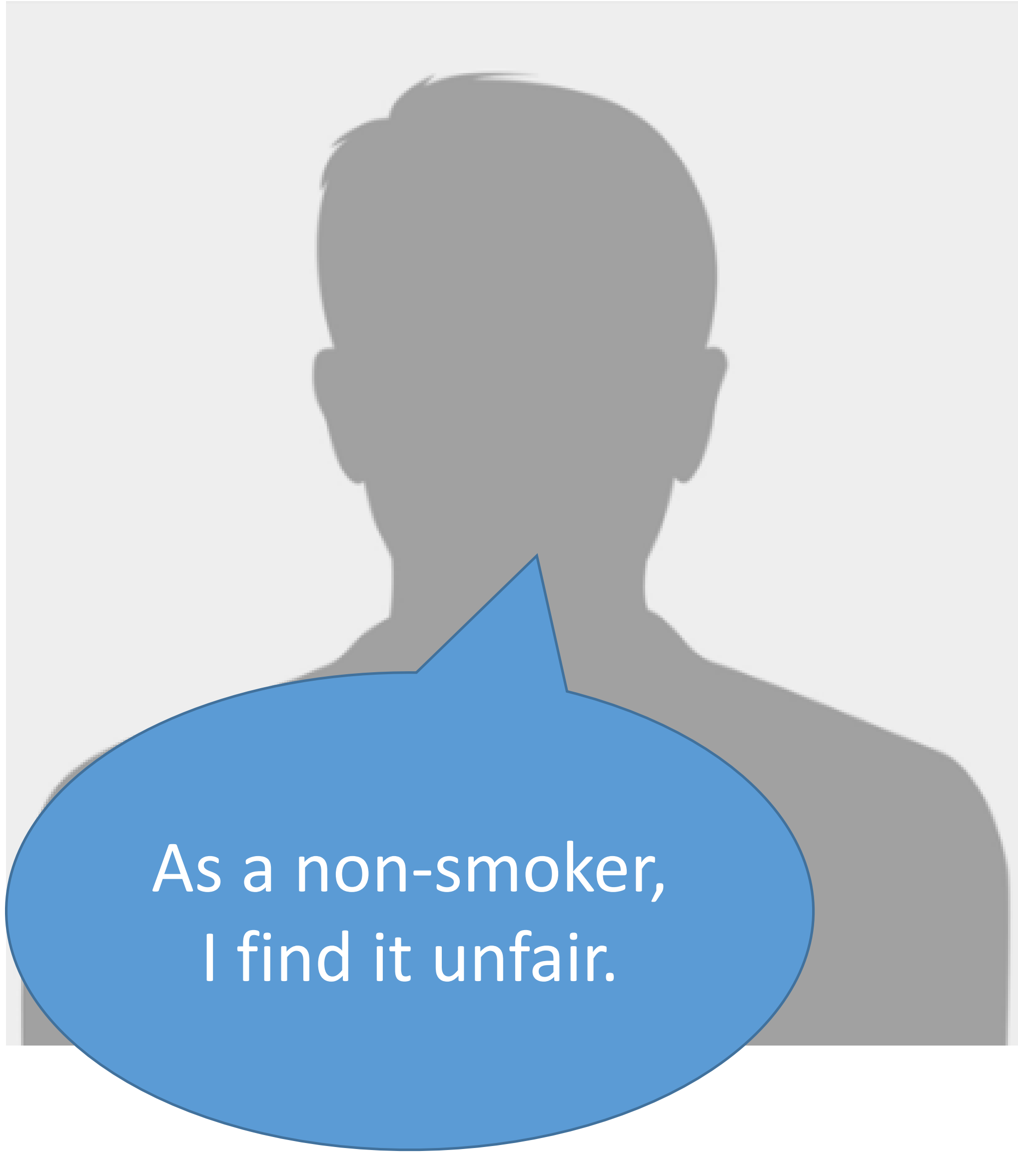
- Idea:
  - Accidents do happen
  - Higher dose → higher risk → higher need of medical examination
  - → we should know individual dose (2 Gy level considered a value dividing people as OK/needing intensive care)
  - General public members do not have dosimeters
- Application of naturally occurring TSL/OSL materials
- Application of artificial materials not produced as TSL/OSL materials, but having TSL/OSL properties
- People are surrounded by materials of various dosimetric properties
  - Investigate those properties
  - Choose the best materials
  - Optimize the methods of their evaluation

Emergency dosimetry - requirements

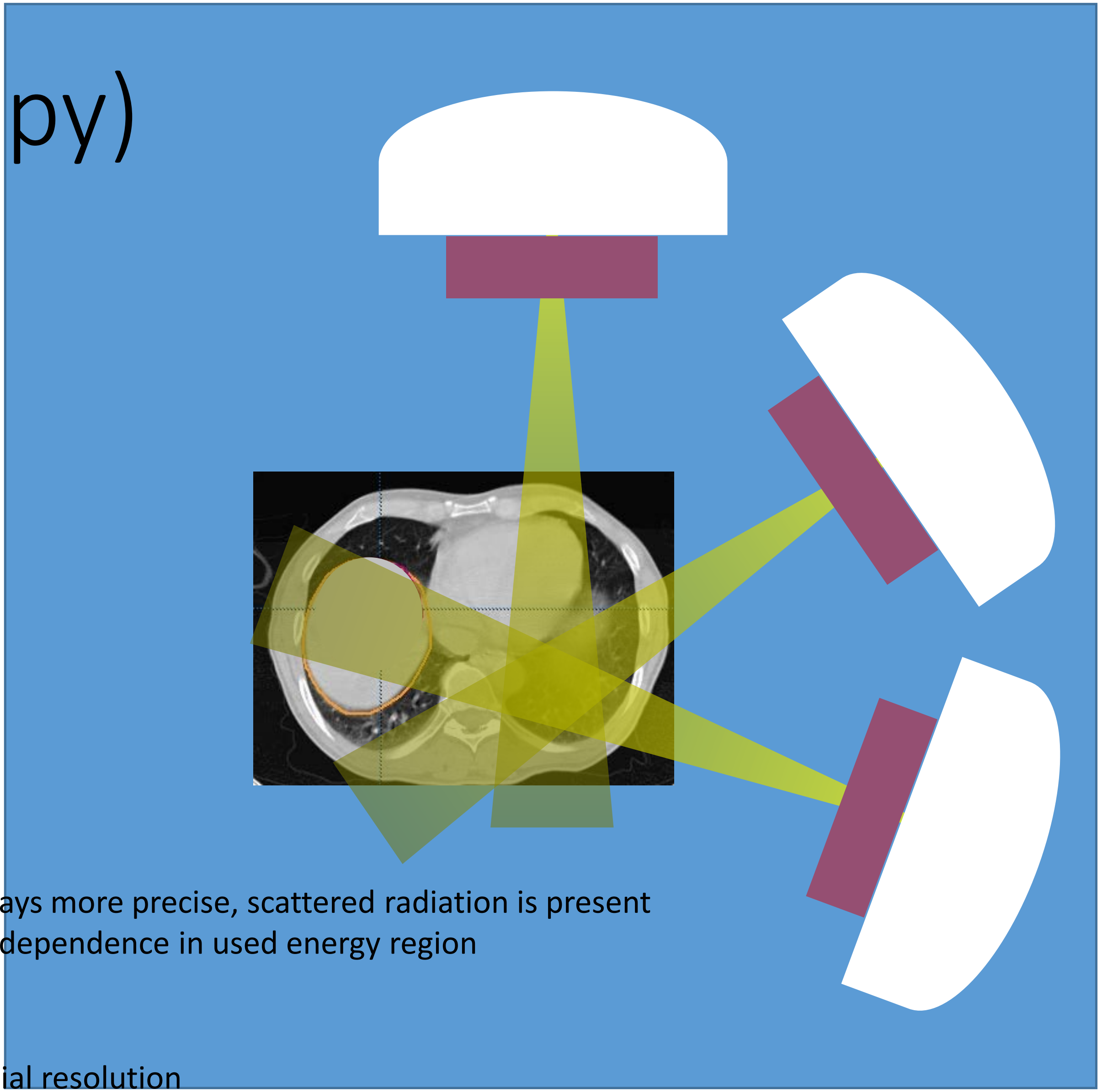
- Common materials
  - In every household
  - Optimal: anything carried all the time/most of the time by everyone
- Reproducible response
- Adequate dose range
- → difficult problem
- Examples
  - OSL - S. Sholom et al. Rad. Meas. 46 (2011) 1866
    - Linear response of all materials up to 3 Gy
    - Nails – MMD_{24} (minimum measurable dose) after 24 h – 0.2-10 Gy
      - Only “dirty” nails produces signal (sand?)
    - Teeth – MMD_{24} 0.15-8.0 Gy
      - People love their teeth, in vivo measurement technique must be developed
    - Buttons – MMD_{24} 0.09-0.3 Gy
      - Some sensitive, some not
    - Credit cards – MMD_{24} 0.05-2.0 Gy
      - Some sensitive, some not

Emergency dosimetry

- Examples
  - S. Sholom, S.W.S. McKeever, RPD 170 (2016) 398
    - TL/OSL of mobile phones (integrated circuits in them)
    - Response linear up to 2 Gy
    - MMD 0.13-0.26 Gy
    - Double exponential fading $T_{½,1}$ = 0.056 d $T_{½,2}$ = 1.27 d
      - If exposure time known, reconstruction possible
  - J.A. Ademola, C. Woda, E. Bortolin
    - TL response of tobacco dust
    - Probably contains some feldspar
    - Linear response 0.1-10 Gy



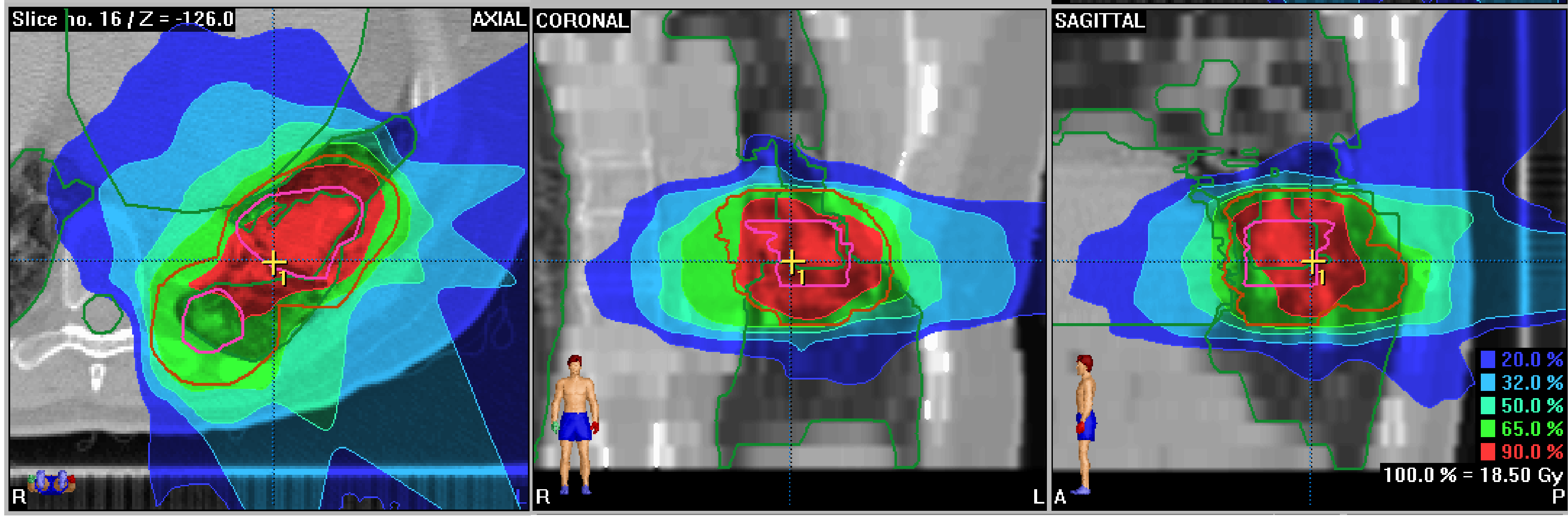
Radiotherapy (teletherapy)



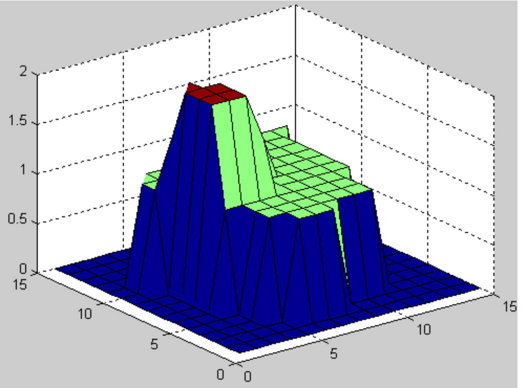
- Energies used
  - kV beams (x-ray tubes)
  - ^{60}Co (1.17 + 1.33 MeV)
  - MV beams (linacs)
- Particles used
  - Almost exclusively photons
  - Protons application is on the rise
  - Neutron capture therapy seems to be not promising
- Applied doses:
  - Inside target volume – tens of Gy
  - Outside target volume – lower doses
- Other requirements
  - Tissue equivalence needed?
    - Arguments for yes: dosimetric casing should be small, always more precise, scattered radiation is present
    - Arguments for no: energies are known, very small energy dependence in used energy region
  - Linearity of response
  - Small size
    - Application in field of high dose rate gradient (IMRT); spatial resolution
    - No influence on radiation field (in vivo measurement); small thickness
  - Precision: ± 3 % (D; ~~$H_p(10)$~~)

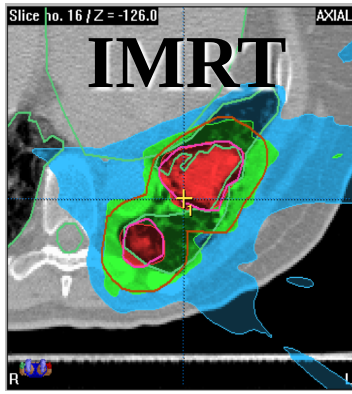
Radiotherapy

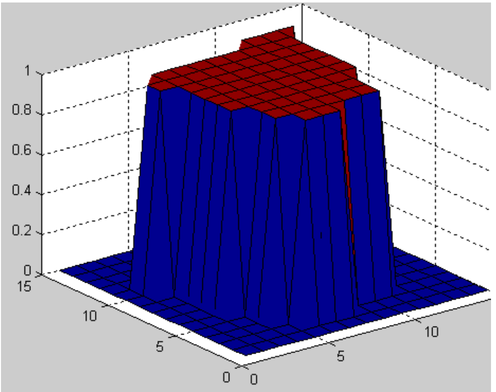
- Dose rates
  - Up tu Gy/min
- Contact with body
  - Temperature
  - Humidity
  - Body fluids
  - Sterilization
  - Non-toxic
- Measured quantities
  - Entrance absorbed dose
    - Machine output
    - Patient position
  - Exit absorbed dose
    - Delivered dose
  - Intracavitary absorbed dose
- Purpose
  - Irradiation plan verification
- Type of measurement
  - Phatom measurement
    - Simple
    - Antropomorfic
  - In vivo measurement

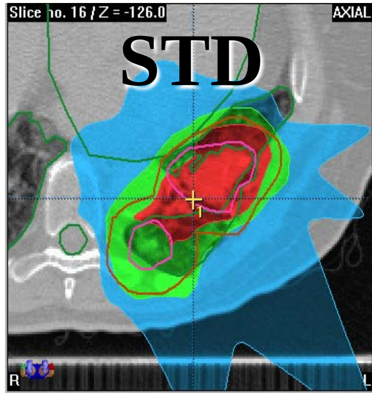


WP34 Calibration Water Phantom



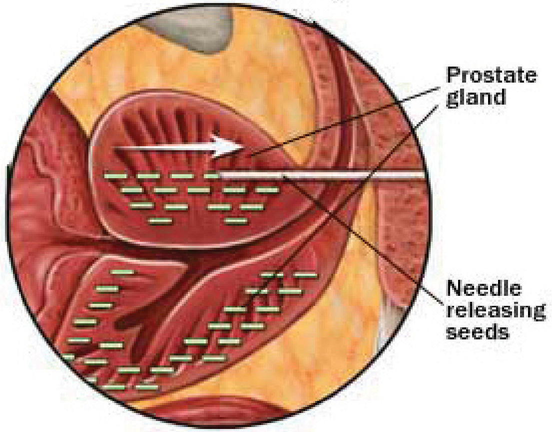






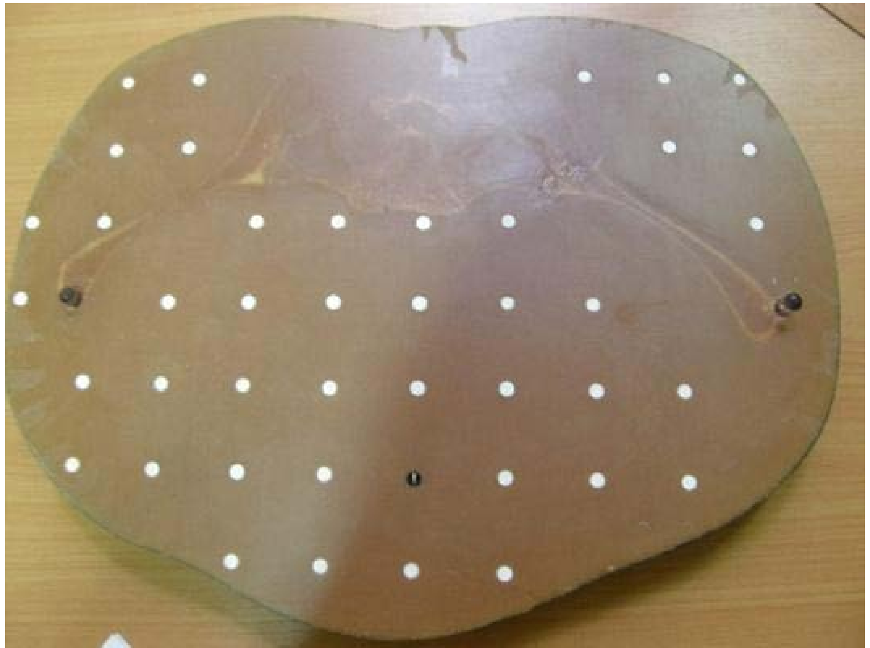
Radiotherapy – other modalities

- Brachytherapy
  - Used energies are small
  - Beta radiation is used
  - S. Kirov et al. Phys. Med. Biol. 40 (1995) 2015
    - ^{192}Ir dose distribution in water phantom; TLD-100 (LiF:Mg,Ti)
  - L.A. DeWerd et al. Rad. Meas. 71 (2014) 276
    - Determined precise energy dependence (1.04-1.13; 1.0 ≈ ^{60}Co)
    - ^{125}I, ^{103}Pd, ^{192}Ir used; measurement using TLD-100
- Nuclear medicine
  - Much more complicated
    - Short penetrating range of particles
    - Changing distribution of radionuclide in body through time
  - TL/OSL application has limited value



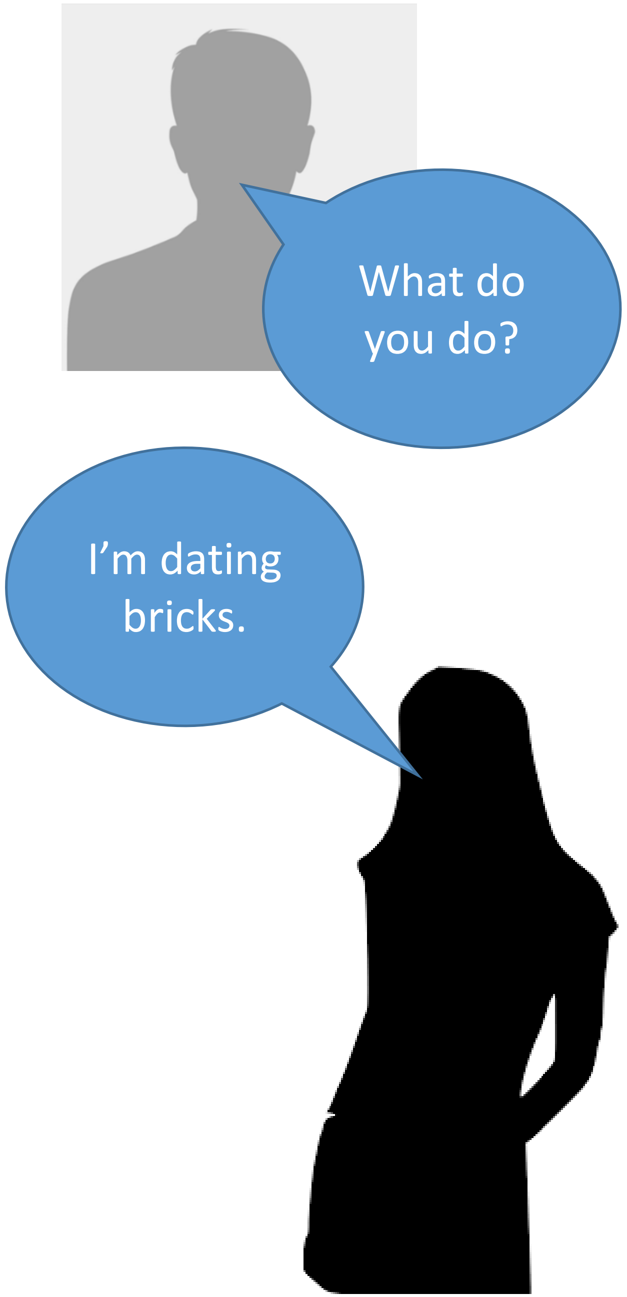
Radiodiagnostics

- Purpose
  - Determination of absorbed dose
  - → intercomparison of departments using same modalities
  - → Diagnostic reference levels determination
  - Justification, optimization (radiation protection)
- Energies
  - Up to 120 kV (skiagraphy, CT)
  - Around 200 keV (SPECT, Gamma camera)
  - 511 keV (PET)
- Doses
  - Abdominal CT, PET, SPECT – approximately 10 mSv (Dual energy CT even higher)
  - Skiagraphy of joints, extremities – 10 µSv
- Measurements
  - In vivo
  - Antropomorphic phantoms
- Tissue equivalence important
  - Radiation field unchanged (energy in kV range)



Thermoluminescence dating

- $t = \frac{D}{\dot{D}}$
  - t – object age
  - D – measured dose
  - $\dot{D}$- dose rate
- t = 0
  - Moment of annealing, i.e. trap emptying
  - = heating of the object
    - Firing of pottery, bricks, etc.
    - Fire burial
    - Fire



Thermoluminescence dating

- D is tricky
  - Supralinearity?
  - Sublinearity?
  - Fading?
    - Plateau test
- $\dot{D}$ is tricky
  - Was it constant through the ages?
  - How can we measure it?
    - α
    - β
    - γ
    - cosmic

$$t = \frac{D_\beta}{k\dot{D}_\alpha + \dot{D}_\beta + \dot{D}_\gamma + \dot{D}_{cosmic}}$$

Thermoluminescence dating

- Techniques to make it easier
  - Quartz inclusion
    - Quartz α activity is low
    - Take large inclusion
    - Remove layer irradiated by α from outside
  - Fine-grain
    - Use only small grains (< 10 μm)
    - Everything is irradiated homogeneously
  - Subtraction dating
    - Fine-grain – quartz
    - For objects removed from original environment (museum)
  - Zircon inclusion
    - High α activity

$$t = \frac{D_\beta}{k\dot{D}_\alpha + \dot{D}_\beta + \dot{D}_\gamma + \dot{D}_{cosmic}}$$

$$t = \frac{D_\beta}{k\dot{D}_\alpha + \dot{D}_\beta + \dot{D}_\gamma + \dot{D}_{cosmic}}$$

$$t = \frac{D_\beta}{k\dot{D}_\alpha + \dot{D}_\beta + \dot{D}_\gamma + \dot{D}_{cosmic}}$$

negligible

Thermoluminescence dating - faking

- TL dating is prone to be deceived by fakes
- Example from: https://www3.nd.edu/~nsl/Lectures/phys10262_2014/art-chap5-4.pdf
  - What dose is equivalent to 1200 yrs (clay horse – T'ang dynasty)?
  - 6.11 Gy
- What to do?
  - Combine methods – they should not contradict themselves
    - Problem: one method = one sample; many methods = many samples → object gone
  - Combine with non-invasive methods (e.g. archeomagnetism)