Using Ubiquitous Insulator Materials as Retrospective Dosimeters

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Retrospective dosimetry

- Personnel dosimetry
- Film badges
- Thermoluminescent dosimeters (TLD)
- Optically stimulated luminescent dosimeters (OSLD)

Figure 1. Historical trends for personnel dosimetry including on the left, an early film badge design\(^1\), center DOELAP accredited TLD designs still in use\(^2\), and on the right is the current trend of an OSLD\(^3\).

\(^{1}\) [https://www.orau.org/ptp/collection/dosimeters/omifilmmod2film.htm](https://www.orau.org/ptp/collection/dosimeters/omifilmmod2film.htm)
\(^{2}\) [https://www.suro.cz/cz/rms/tld](https://www.suro.cz/cz/rms/tld)
\(^{3}\) [http://www.landauer.com](http://www.landauer.com)
TL/OSL
Band Gap Theory

• A pair of electrons in a bonding orbital are comprised of a bonding and antibonding set.
• Periodic structures allow wave-function overlap
• Pauli exclusion on periodic structures prevents identical orbital configurations from having identical quantum numbers (energy).
• The antibonding orbitals have higher energy than the lower energy bonding orbitals and become the conduction band
• Maintaining distinct quantum numbers is accomplished by arbitrarily small perturbations in energy which for Avogadro's number of perturbations becomes a spread known as the energy band
Results of defects in the band gap

- A defect with an affinity for electrons is an electron trap
  - Like a p-type material
- A defect with a more loosely bound electron is a hole trap (easily will lose an electron).
  - Like an n-type material
- Creation of holes and trapped electrons is proportional to an ionizing radiation dose when all were originally empty.
- Counting trapped electrons and holes (a hole also representing an unpaired electron) is one means of measuring dose (as done with TLD’s and OSLD’s).
Solid State Physics

Conduction band

Electron traps

Output signal

High energy photon

Hole traps

Valence band
Electron Paramagnetic Resonance (EPR)

- NIST recommended secondary standard for dose rate calibration
- Optimum method for population epidemiology
- Optimum for organic insulating materials
  - Sugar, plastics, fingernails, bone, shell etc.
- Non-destructive signal measurement

\[
\Delta E = +\frac{BHg}{2} \\
\Delta E = -\frac{BHg}{2}
\]

Electron spins

No Applied External Magnetic Field

Applied External Magnetic Field H

https://www.bruker.com/products/mr/epr/emxplus/overview.html
EPR background

• A free radical is simply an unpaired electron
• EPR is a nondestructive means to measure free radicals in a solid.
• The lowest energy state in a crystalline material is comprised of chemical bonds which are almost completely paired electron orbitals.
• Defects such as interstitials, vacancies along with grain boundaries and similar point defects all provide different energy levels in their vicinity.
Dose Depth Profiles

• Exponential attenuation along a linear transport path has to be coupled (multiplied and normalized) with inverse square decrease in intensity from a point or kernel source.

• Easily accomplished with modern radiation transport codes such as MCNP but not critical for a closed form equation able to give a reasonable approximation.

\[
A(r) = I_0 \cdot e^{-(H/\sin \theta) \cdot \mu(E)}
\]

\[
A(H, L, \theta, \phi) = M \cdot [\left(\frac{H}{\cos \theta}\right)^2 + \left(\frac{L}{\sin \phi}\right)^2]^{-1}
\]
Cheap commercial bricks in NC
Irradiation
Sample preparation
Individual core sample results using TL/OSL
$^{60}$Co and $^{137}$Cs in brick using TL/OSL
UF₆ assay (ORIGEN for neutrons)
Decay gammas calculated with ORIGEN and $^{234}\text{mPa}$ Bremsstrahlung calculated with mcnp

- $^{238}\text{U}$: $\alpha$ decay
  - $T_{1/2}=4.5\times10^9 \gamma$
  - $113 \text{ keV} \gamma @ 0.01\%$

- $^{234}\text{Th}$: $\beta$ decay
  - $T_{1/2}=24.1 \text{ d}$
  - $92 \text{ keV} \gamma @ 2\%$

- $^{234}\text{mPa}$: Internal transition
  - $T_{1/2}=69.5 \text{ s}$
  - Multiple $\text{IT} \gamma$
    - $1001 \text{ keV} @ 0.842\%$

- $^{234}\text{Pa}$: $\beta$ decay
Decay gamma spectra outside a canister

- HEU
- LEU

Using MCNP
Transmitted Bremsstrahlung

2.2 MeV beta source term

- $^{238}\text{U}$ α decay
  - $T_{1/2}=4.5\times 10^9 \, \gamma$
- $^{234}\text{Th}$ β decay
  - $T_{1/2}=24.1 \, \text{d}$
  - 113 keV γ @ 0.01%
- $^{234}\text{mPa}$ Internal transition
  - Multiple 1T γ
  - 1001 keV @ 0.842%
  - T$_{1/2}=69.5 \, \text{s}$
- $^{234}\text{Pa}$ β decay

Graph showing x-ray photon flux per starting particle versus photon energy (MeV).
Components of UF₆ have distinct dose deposition profiles
Conclusions

• Practical demonstration shows theory can be accomplished but calibration is needed.
  – Theoretical considerations indicate UF$_6$ sample characterization can be accomplished using dose depth profiles
  – Characterization can mean isotopics or in some cases simply energy groupings
  – Energy groupings can mean discrimination of industrial, medical, NORM and SNM
  – Retrospective characterization could extend to spent fuel, SNM or RDD materials