Modeling the Leaching of $^{222}\mathbf{Rn}$ Daughters into the SNO+ Detector

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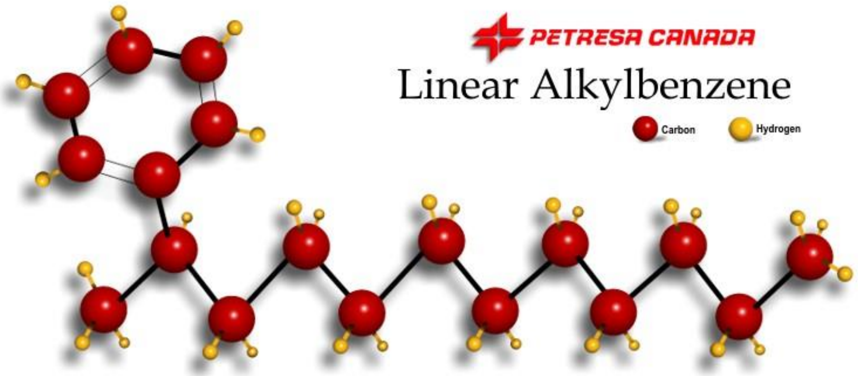
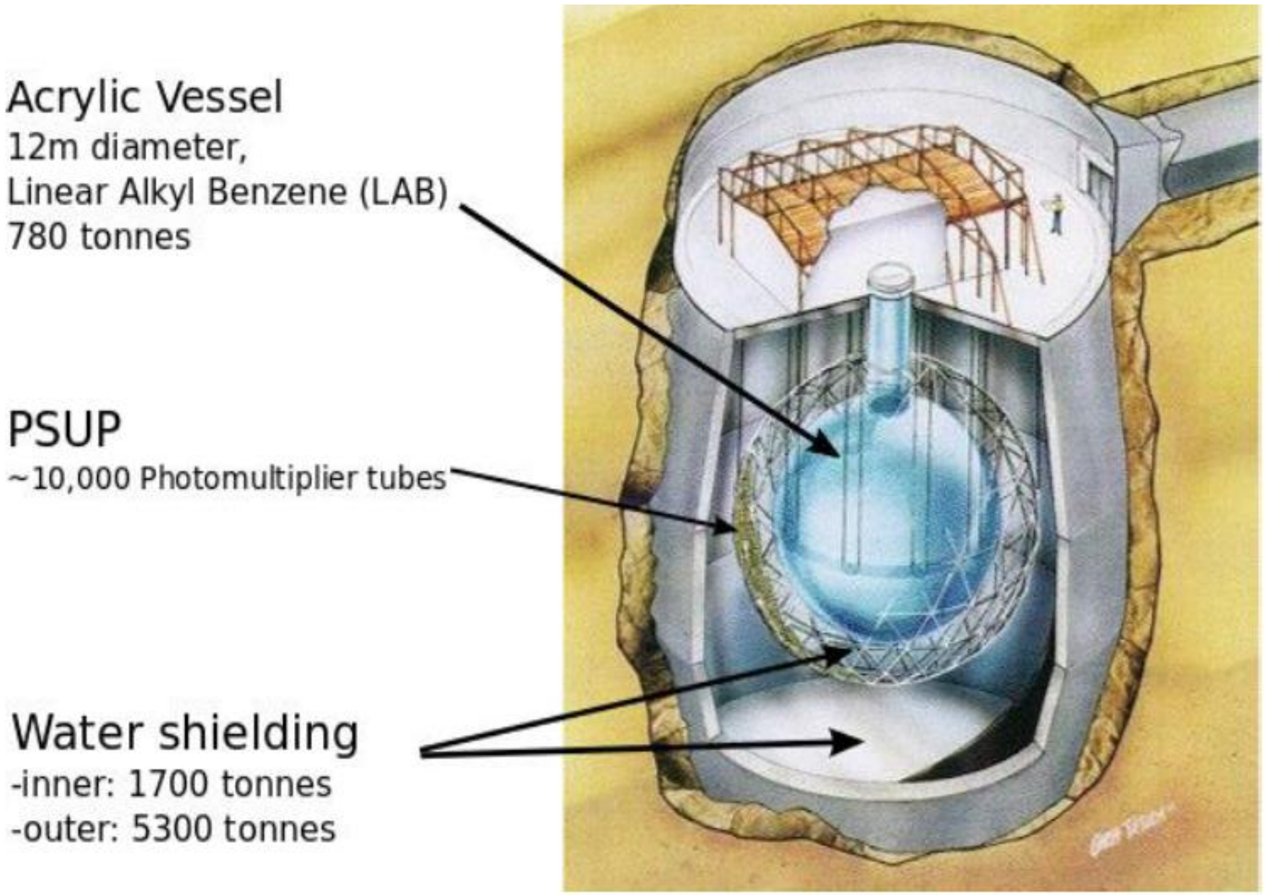
SNO+ Physics

- SNOLAB, Creighton Mine (2070m $\approx 6000\ m.w.e$)
- Linear Alkyl Benzene (LAB)



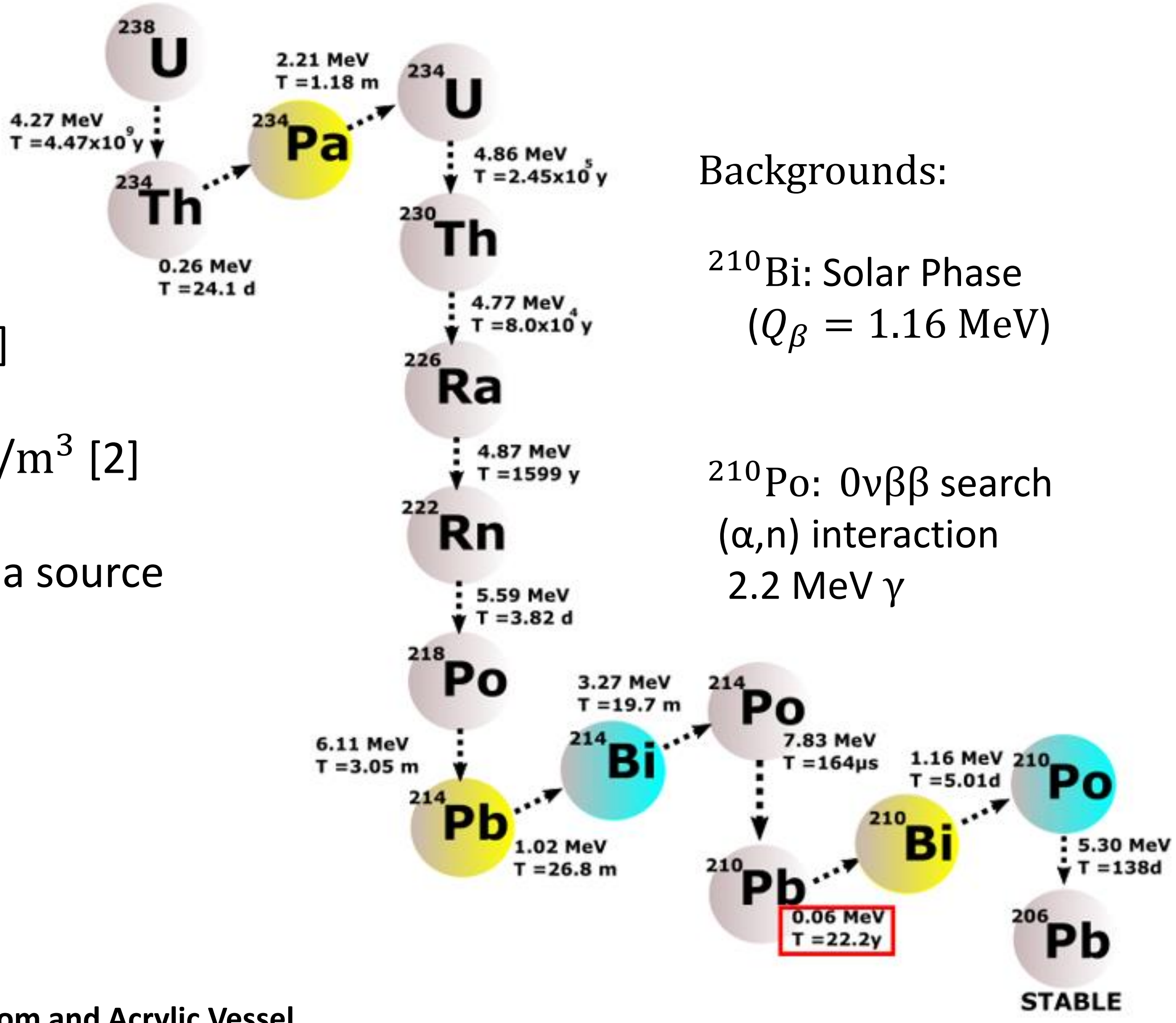
Physics Goals:

- Neutrino-less double beta decay (^{130}Te-loaded scintillator)
- Low energy solar neutrinos
- Geo and reactor anti neutrinos
- Supernova neutrinos
- Nucleon decay (water phase)



Backgrounds from the implanted radon daughters

- Stringent background limits
- Scintillator target goal: $^{238}\mathrm{U} \sim 10^{-17}$ g/g [1]
- Level of $^{222}\mathrm{Rn}$ in the lab air $\sim 131 \pm 6.7\ \mathrm{Bq/m^3}$ [2]
- Implanted radon daughters in the acrylic are a source of background for SNO+



Backgrounds:

$^{210}\mathrm{Bi}$: Solar Phase
($Q_\beta = 1.16$ MeV)

$^{210}\mathrm{Po}$: $0\nu\beta\beta$ search
(α,n) interaction
2.2 MeV γ

[1] **M. Pallavicini, Nucl. Phys. B (Proc. Suppl.) 217,101–106 (2011)**

[2] **Ian. T. Lawson, Radon Levels in the SNO+ Radon Reduction Room and Acrylic Vessel, SNO+ internal report, 2012**

Leaching model of $^{222}\mathrm{Rn}$ daughters

❖ **Question**: How quickly will the surface contaminants leach into the liquid?

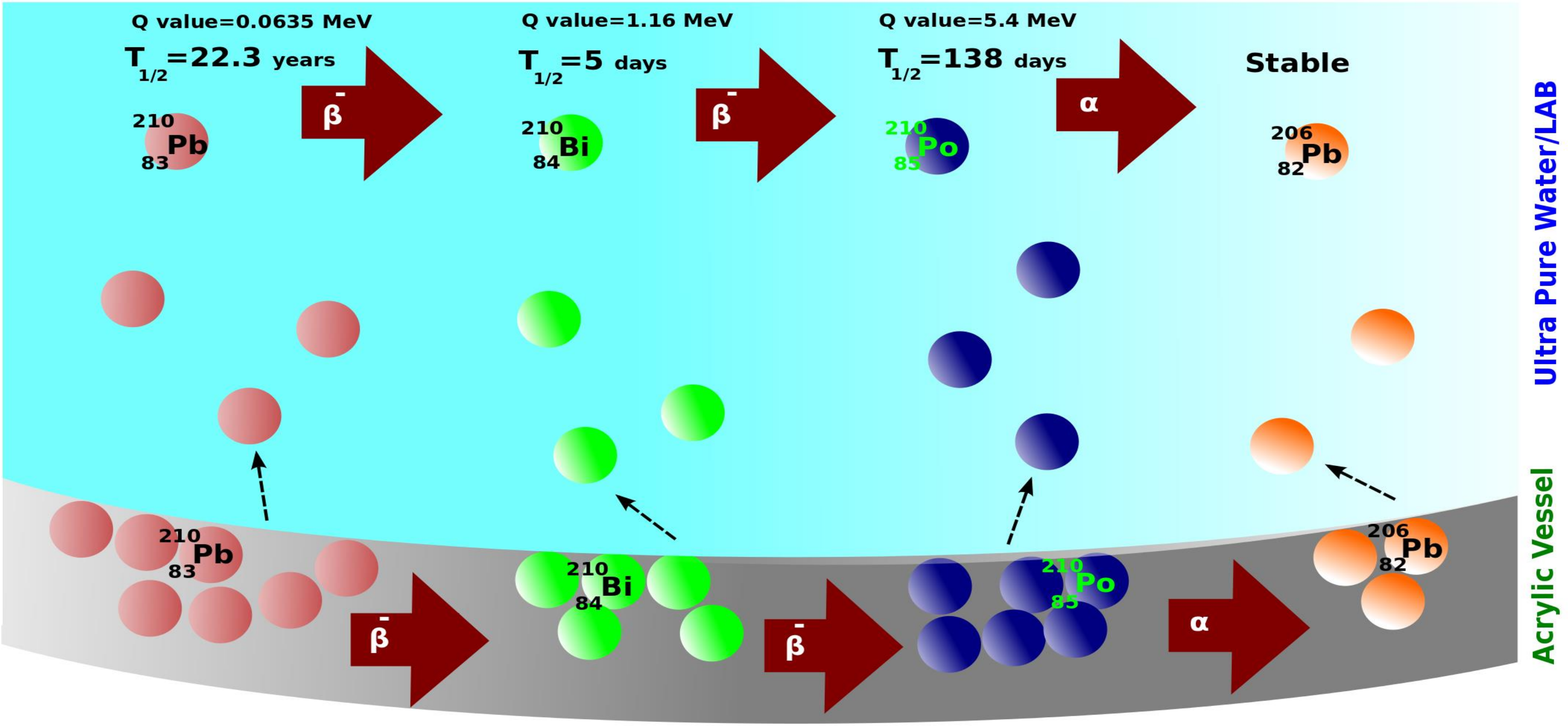
- Molecular leaching:

  first order process.

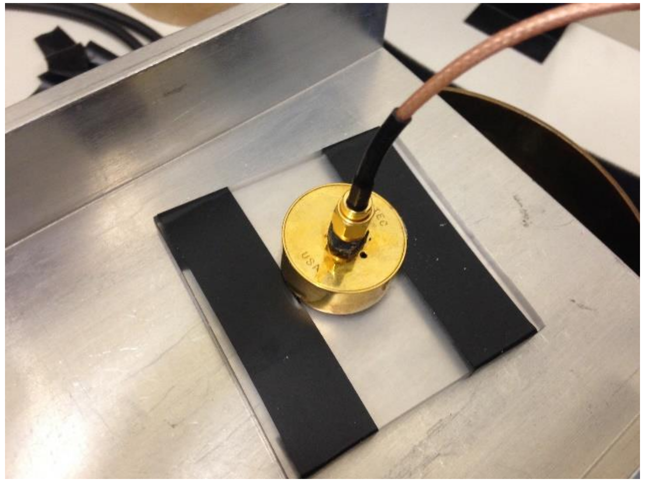
$$\frac{dN(t)}{dt} = -k(T)\,N(t)$$

- Temperature dependency:

$$k(T) = A\,e^{\frac{-E_a}{R\,T}}$$



Leaching rate measurements



- Bench-top measurements (spiked acrylic samples):
  - Activity of $^{210}\mathrm{Pb}$: high efficiency gamma counter $(E = 46.5 \text{ KeV})$
  - Activity of $^{210}\mathrm{Po}$: Silicon alpha counter $(E_{\alpha} = 5.3 \text{ MeV})$

- *In-situ* measurements of the activity.

(All the measurements has been performed by Dr. Oleg Chkvoret.)

❖ Measurements were performed for different temperatures and into different media (UPW, LAB, Te+LAB, EDTA+UPW, etc.).

Nuclide	Temperature[$^{\circ}C$]	L.R.[1/day]	ΔL.R.[1/day]	τ[day]	$\Delta\tau$[day]	Note
^{210}Pb	**25**	2.2×10^{-3}	2.2×10^{-4}	455	45	Bottom of AV
^{210}Pb		2.0×10^{-3}	6×10^{-4}	500	150	
^{210}Po		2.1×10^{-3}	6.5×10^{-4}	476	143	
^{210}Pb	**12**	4.8×10^{-4}	1.15×10^{-4}	2083	500	EDTA Wash
^{210}Po		3.8×10^{-4}	5.78×10^{-5}	2632	400	
^{210}Pb	**95**	1.5	0.35	0.66	0.15	Spiked Acrylic
^{210}Po		2	0.5	0.5	0.1	

A tool has been developed to determine the amount of desorbed contaminants.

Medium / Nuclide	ACRYLIC	LIQUID
^{210}Pb	$\frac{dN_{\mathrm{Pb}}}{dt} = -k_{\mathrm{Pb}} N_{\mathrm{Pb}} - \lambda_{\mathrm{Pb}} N_{\mathrm{Pb}}$	$\frac{dN'_{\mathrm{Pb}}}{dt} = k_{\mathrm{Pb}} N_{\mathrm{Pb}} - \lambda_{\mathrm{Pb}} N'_{\mathrm{Pb}}$
^{210}Bi	$\frac{dN_{\mathrm{Bi}}}{dt} = -k_{\mathrm{Bi}} N_{\mathrm{Bi}} - \lambda_{\mathrm{Bi}} N_{\mathrm{Bi}} + \lambda_{\mathrm{Pb}} N_{\mathrm{Pb}}$	$\frac{dN'_{\mathrm{Bi}}}{dt} = k_{\mathrm{Po}} N_{\mathrm{Po}} - \lambda_{\mathrm{Bi}} N'_{\mathrm{Bi}} + \lambda_{\mathrm{Pb}} N'_{\mathrm{Pb}}$
^{210}Po	$\frac{dN_{\mathrm{Po}}}{dt} = -k_{\mathrm{Po}} N_{\mathrm{Po}} - \lambda_{\mathrm{Po}} N_{\mathrm{Po}} + \lambda_{\mathrm{Bi}} N_{\mathrm{Bi}}$	$\frac{dN'_{\mathrm{Po}}}{dt} = k_{\mathrm{Po}} N_{\mathrm{Po}} - \lambda_{\mathrm{Po}} N'_{\mathrm{Po}} + \lambda_{\mathrm{Bi}} N'_{\mathrm{Bi}}$

- Fitting the model to the data points.
- Interpolate the leaching rate according to the temperature and the nature of contaminant.
- Determine the amount of desorbed contaminant through the equations.
- Output: discrete data set of activity + generate a plot

Concentration of $^{222}\mathrm{Rn}$ daughters for a possible timeline

- Ethylenediaminetetraacetic acid (EDTA) suggested to accelerate the leaching process.
- Bismuth and polonium are in equilibrium with lead.
- Initial Activity $\sim$ 1.15 kBq

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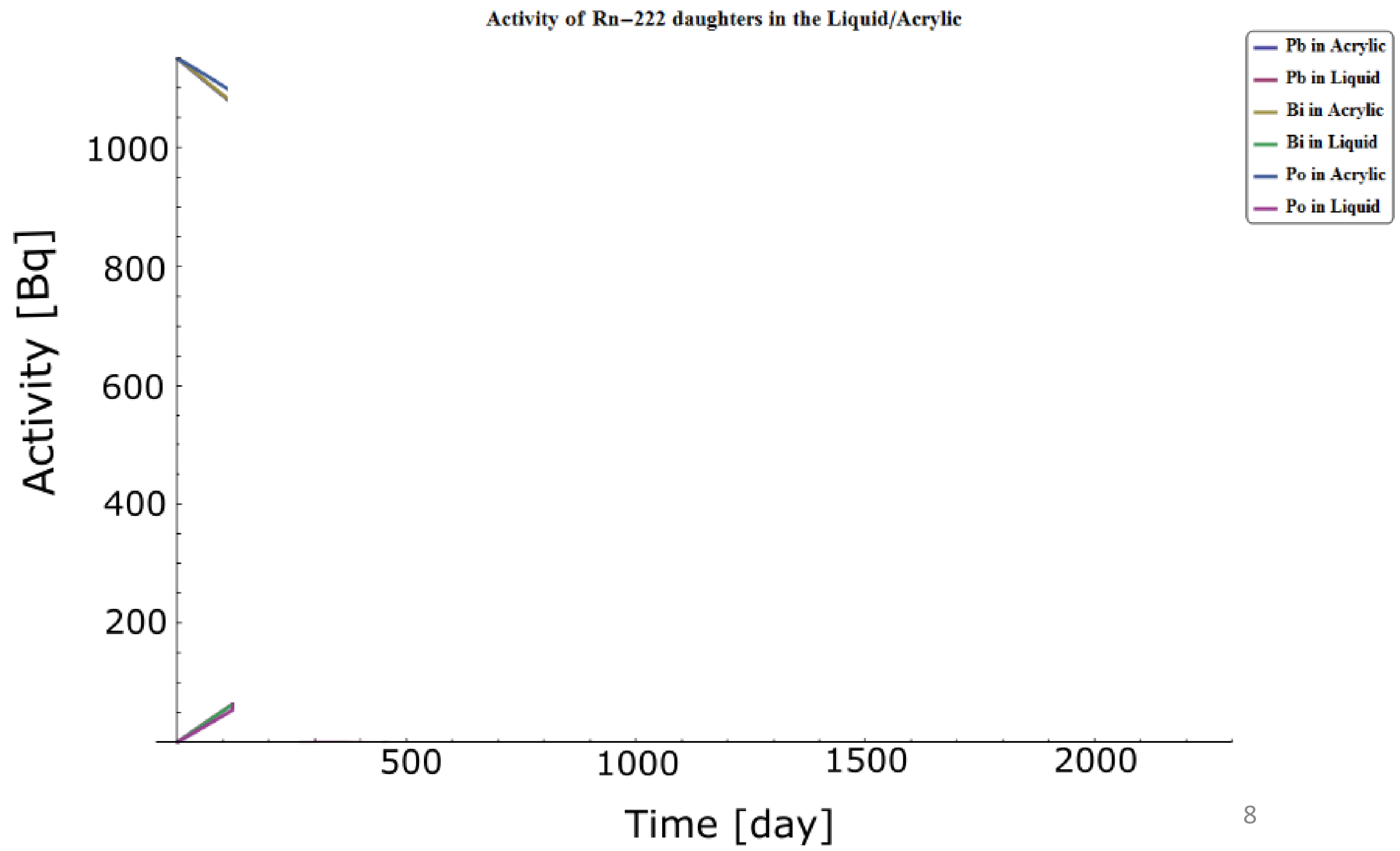
i. 4 months UPW (12 $^{\circ}C$)



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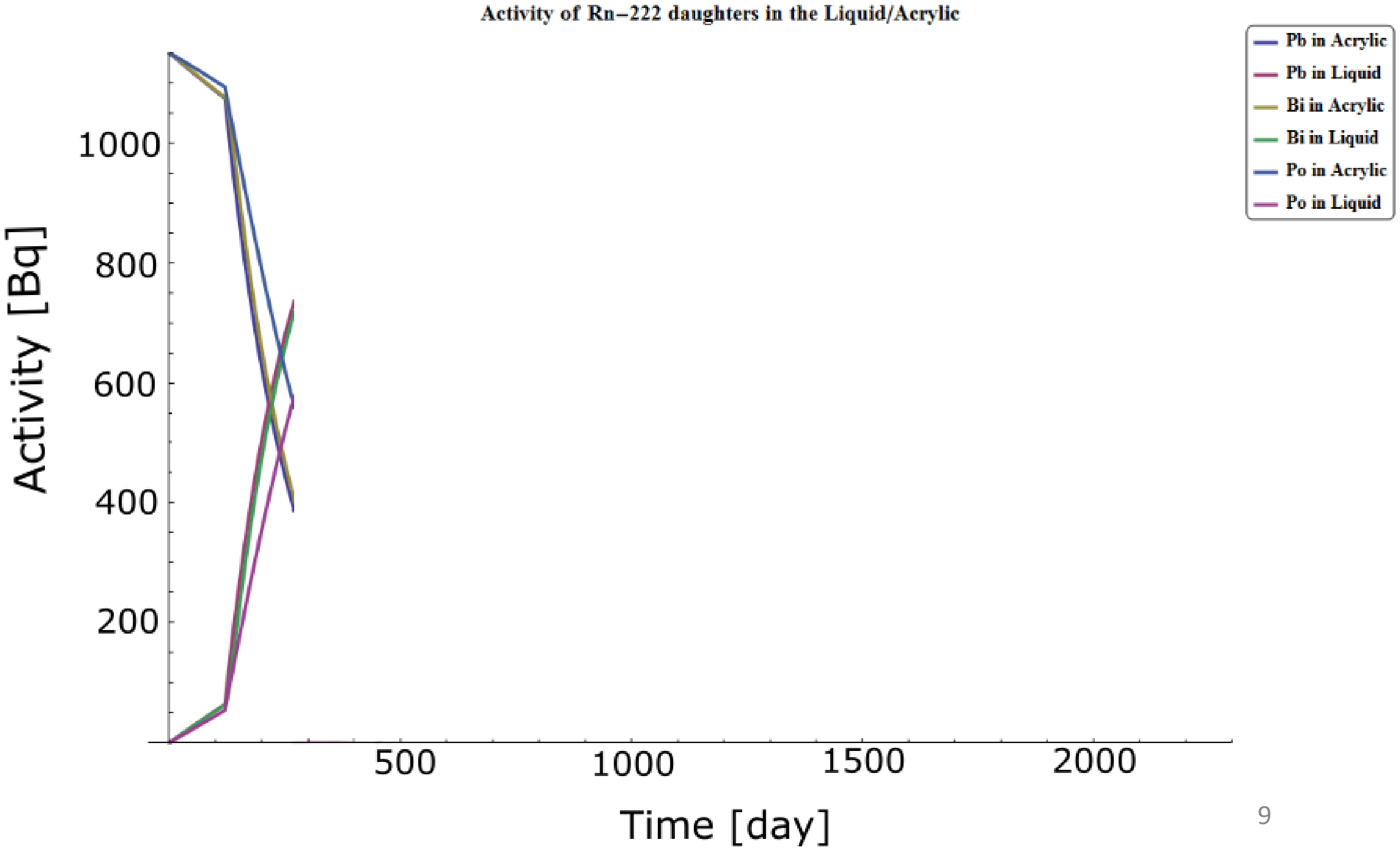
ii. 5 months of UPW + (0.027M) EDTA ($12\,^{\circ}C$)



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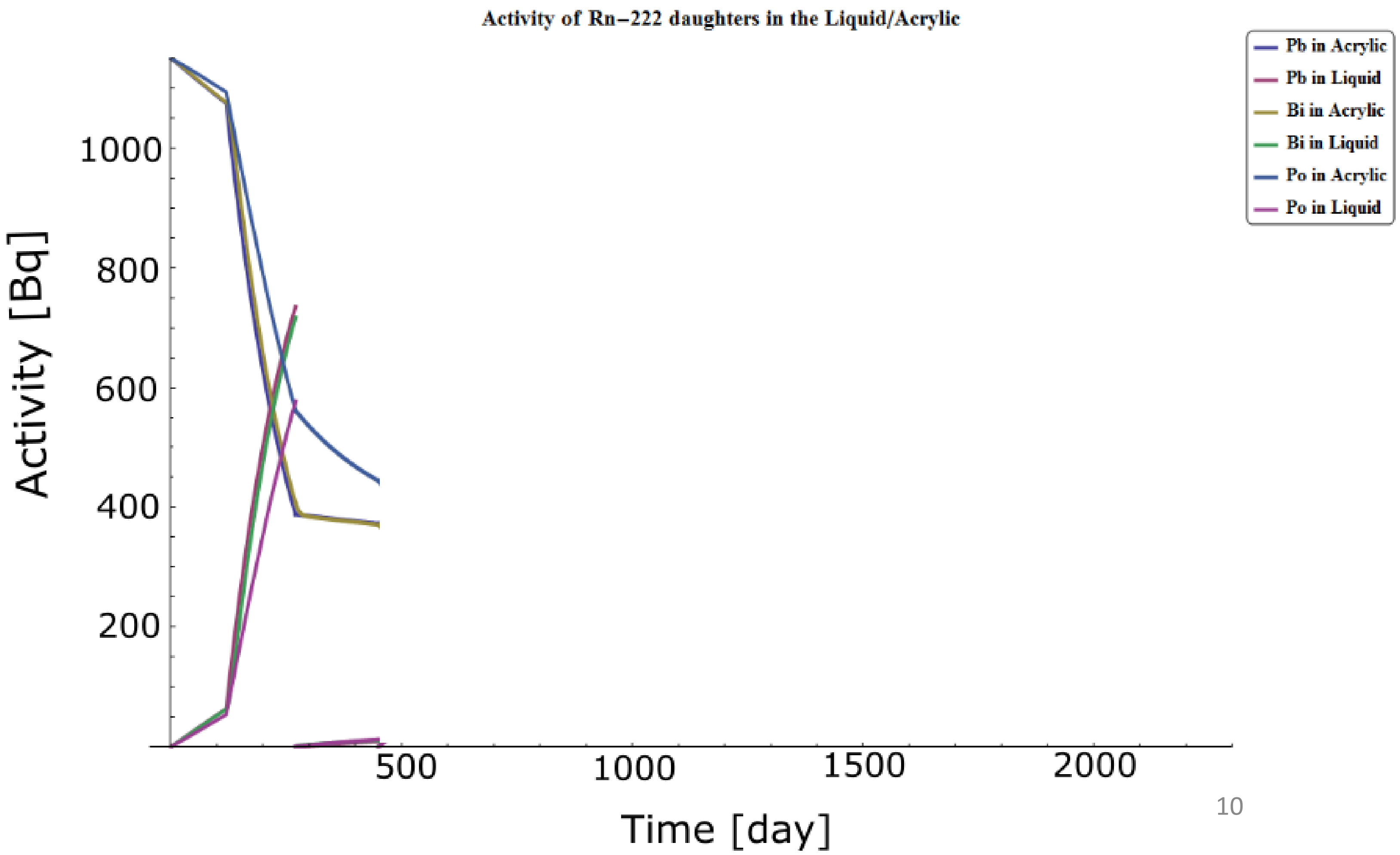
iii. Water will be removed
iv. 6 months of liquid scintillator



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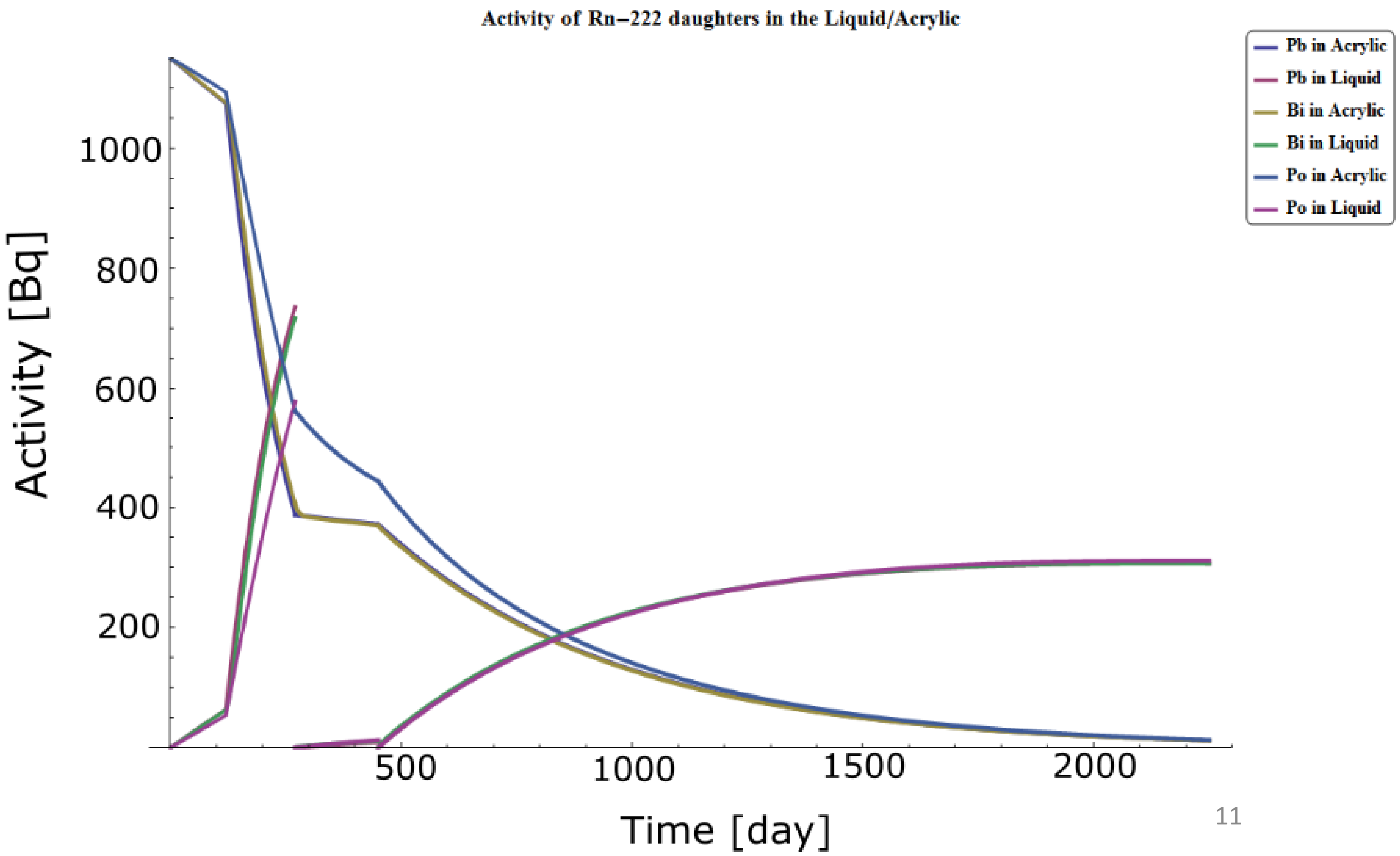

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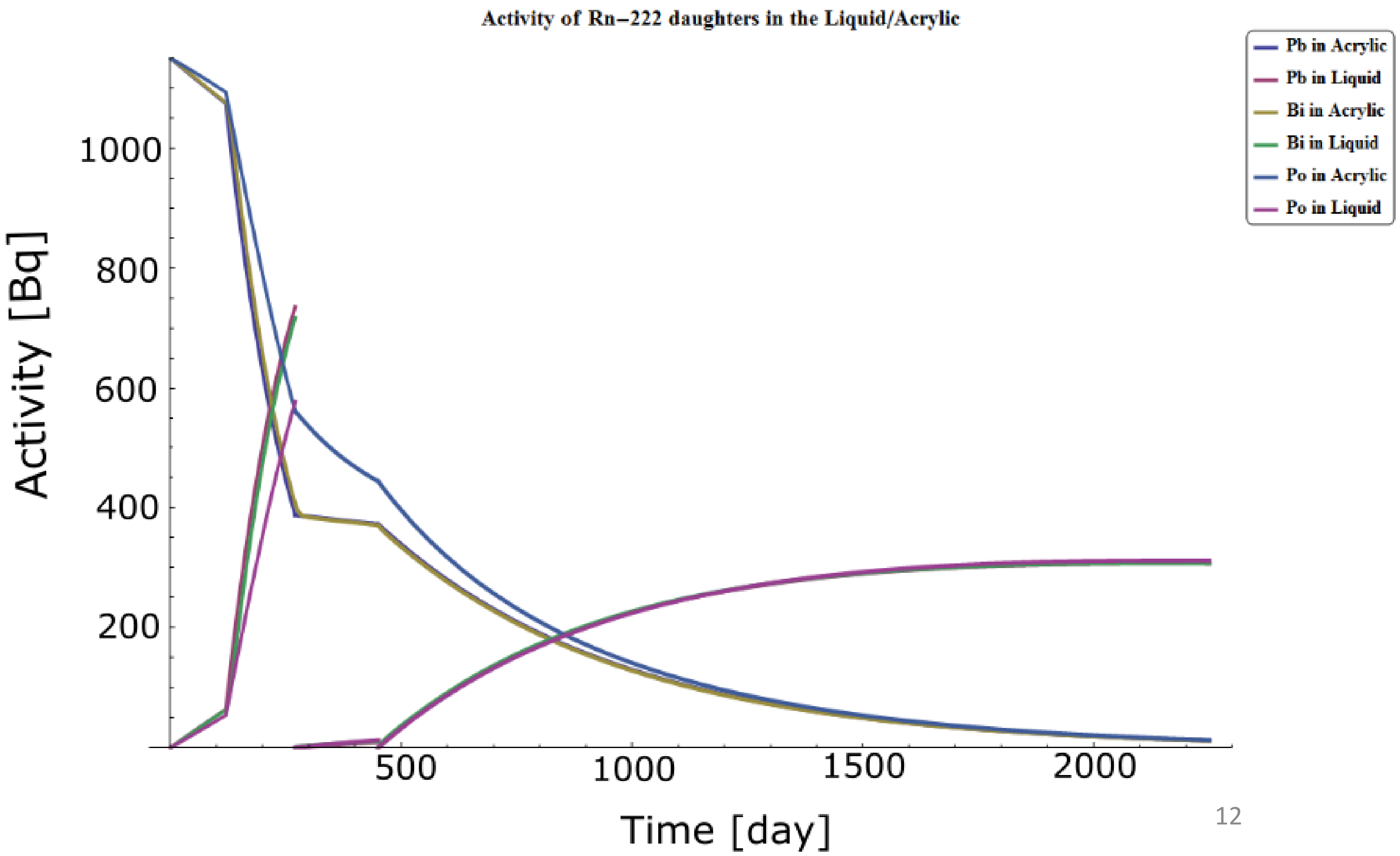
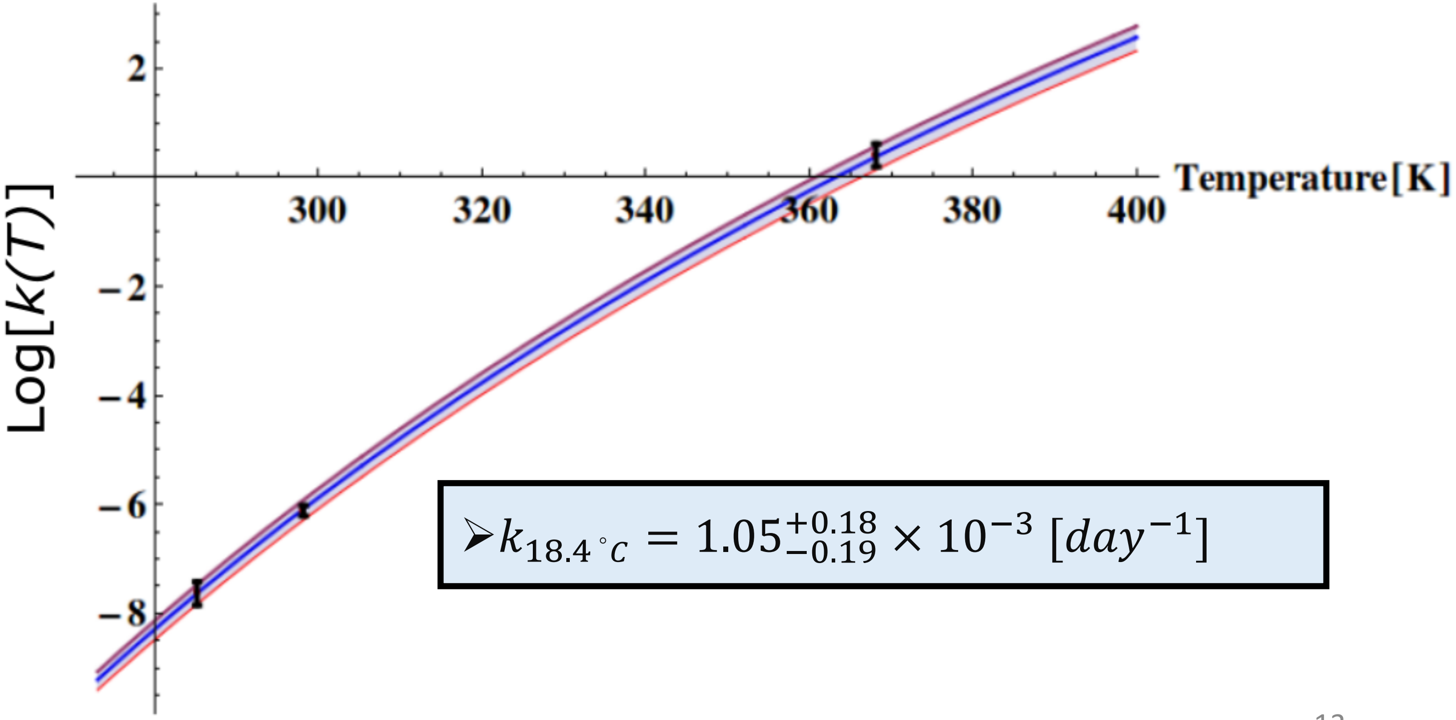


The activity of the radon daughters reduced by 90% in less than 3 years with the suggested timeline.

Interpolation of the leaching constant for the water-fill

- Jan 27th-28th : water assay performed (water-fill since Oct 11th)
- The water level was monitored.
- Temperature was recorded: $T_{avg} = 18.4\,^{\circ}C$
- Using high efficiency gamma counter, specific activity of lead = $0.26^{+0.04}_{-0.04}\ \mathrm{Bq/m^3}$

- The leaching constant for $18.4\,^{\circ}C$ was interpolated through the model.



➢$k_{18.4\,^{\circ}C} = 1.05^{+0.18}_{-0.19} \times 10^{-3}\ [day^{-1}]$

Determination of desorbed lead during the water-fill

- Initial activity of the acrylic $\sim 2.3 \pm 0.8\ \mathrm{Bq/m^2}$
- Leaching per unit area: $$\frac{dC_a(t)}{dt} = -k(T)C_a(t) - \lambda C_a(t)$$ $$\frac{dC_w(t)}{dt} = k(T)C_a(t) - \lambda C_w(t)$$

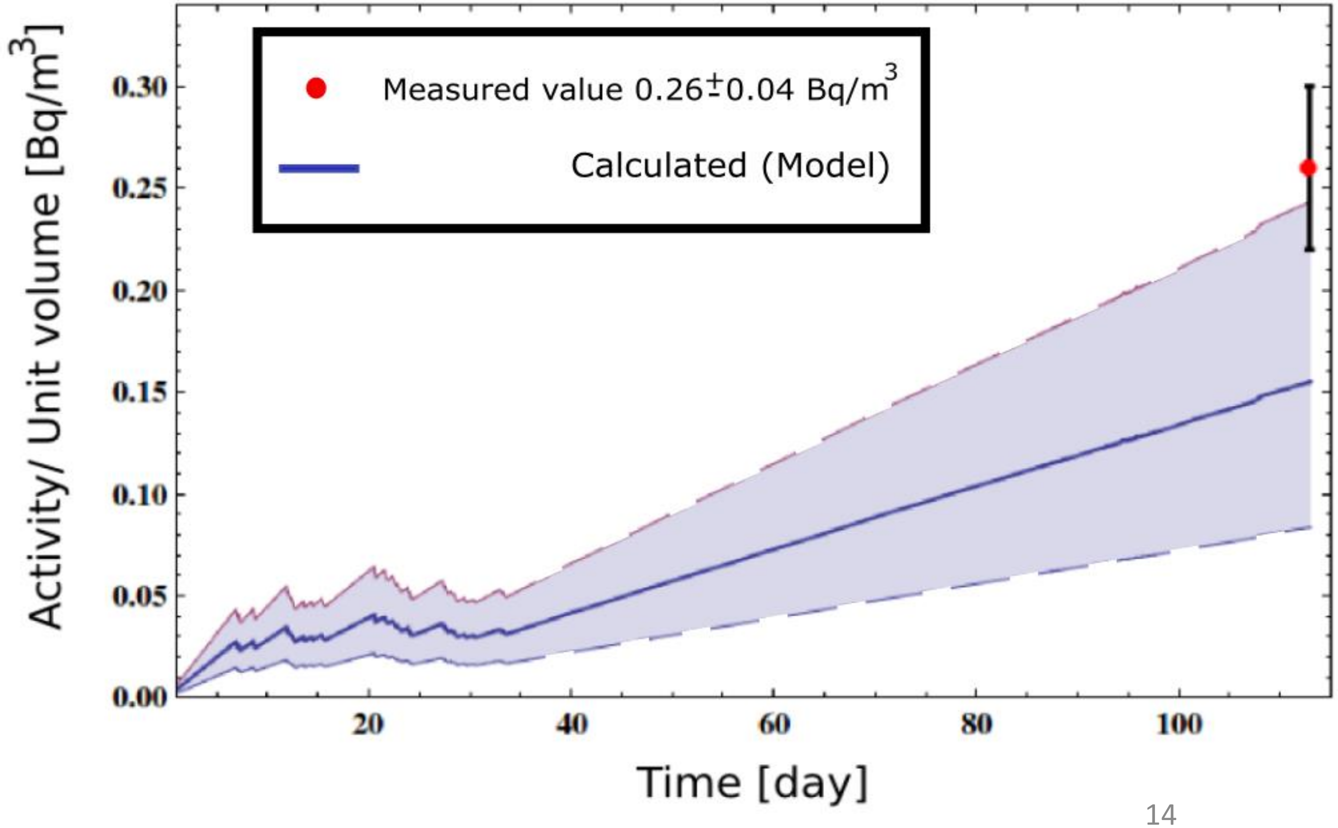
Calculated desorbed lead:

$$A = 0.155^{+0.088}_{-0.071}\ \mathrm{Bq/m^3}$$

- Total specific activity of desorbed lead through a summation over the water levels:

$$A(t) = \frac{\lambda}{V(t)} \sum_{1}^{t/\Delta\tau} C_w(t - i\Delta\tau)\ (h_{i+1} - h_i).\ 2\pi R$$

- Subtract the removed water (lead)



Other sources of $^{210}\mathrm{Pb}$ in water

- Lead concentration in a blank sample of UPW

➢ Water plant assay (August 2014) → $A = 0.047 \pm 0.010$ mBq/m^3 (negligible)

- Diffusion of the radon in the lab air into the water
- Radon level inside the acrylic vessel ~ $(0.6703 \pm 0.0026) \times (131 \pm 6.7)\mathrm{Bq/m}^3$
- Partition coefficient of $^{222}\mathrm{Rn}$ between UPW and air at $18.4\,^{\circ}C$ $\boldsymbol{\kappa = 0.266}$

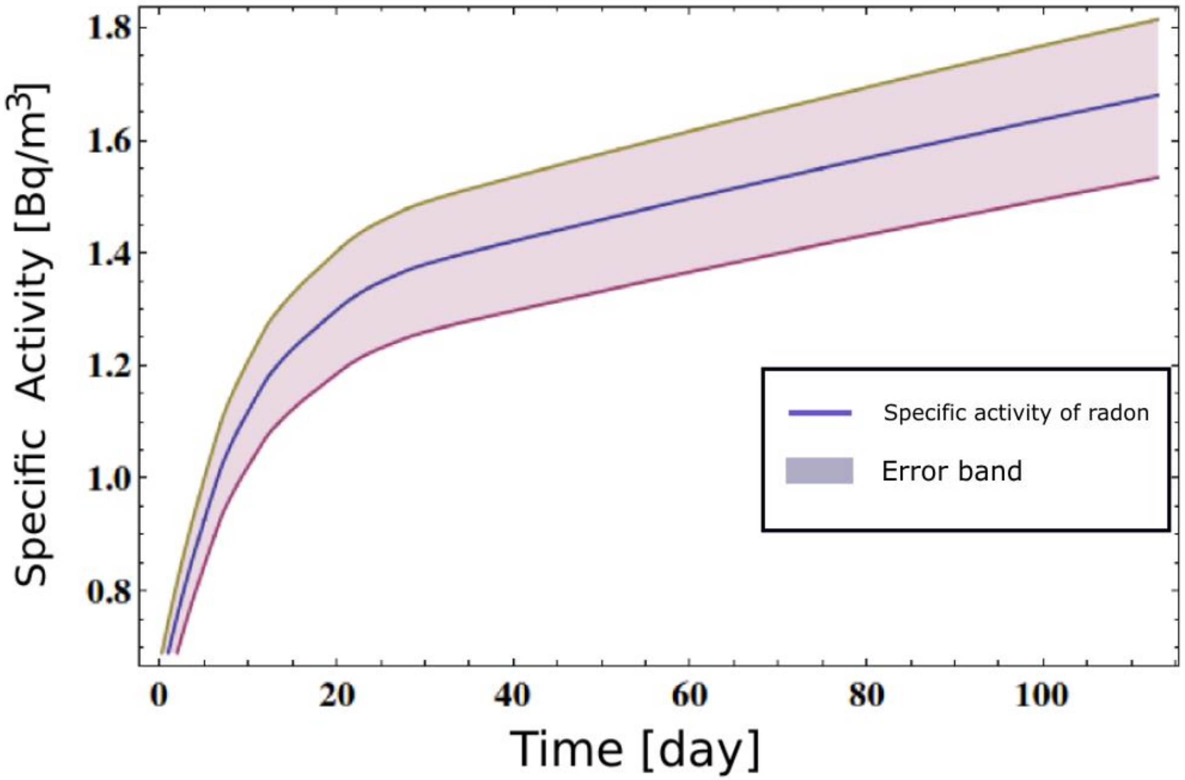
- Fick's Law: $\frac{\partial C(z,t)}{\partial t} = D\,\Delta C(z,t)$

$$C_w(z,t) = \kappa\, C_{air}\,\left(1 - \frac{4}{\pi}\sum_{n=0}^{\infty}\frac{1}{(2n+1)}\,e^{\left(-2(n+1)^2\pi^2\frac{Dt}{4h^2}\right)}\,\sin\frac{(2n+1)\pi\,z}{2h}\right)$$

$$A(z,t) = \int C_w(z,t)\,dV$$

Radon diffusion into water

- Total activity of the diffused radon into water: $$A_w(t) = \sum_{i=0}^{i=t/\Delta\tau} \int_0^{h_i} C_w(z,t)\, S(z)\, dz$$



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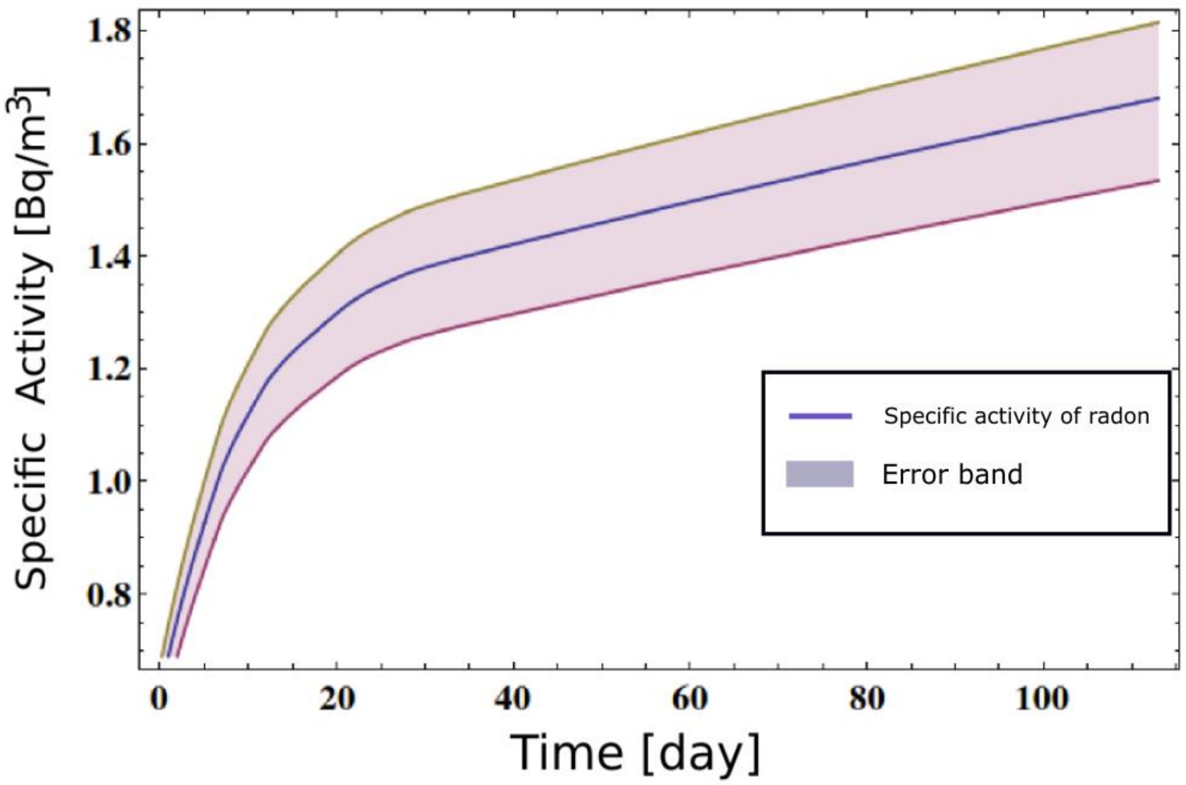
- Generated a discrete data set to determine the amount of produced lead.



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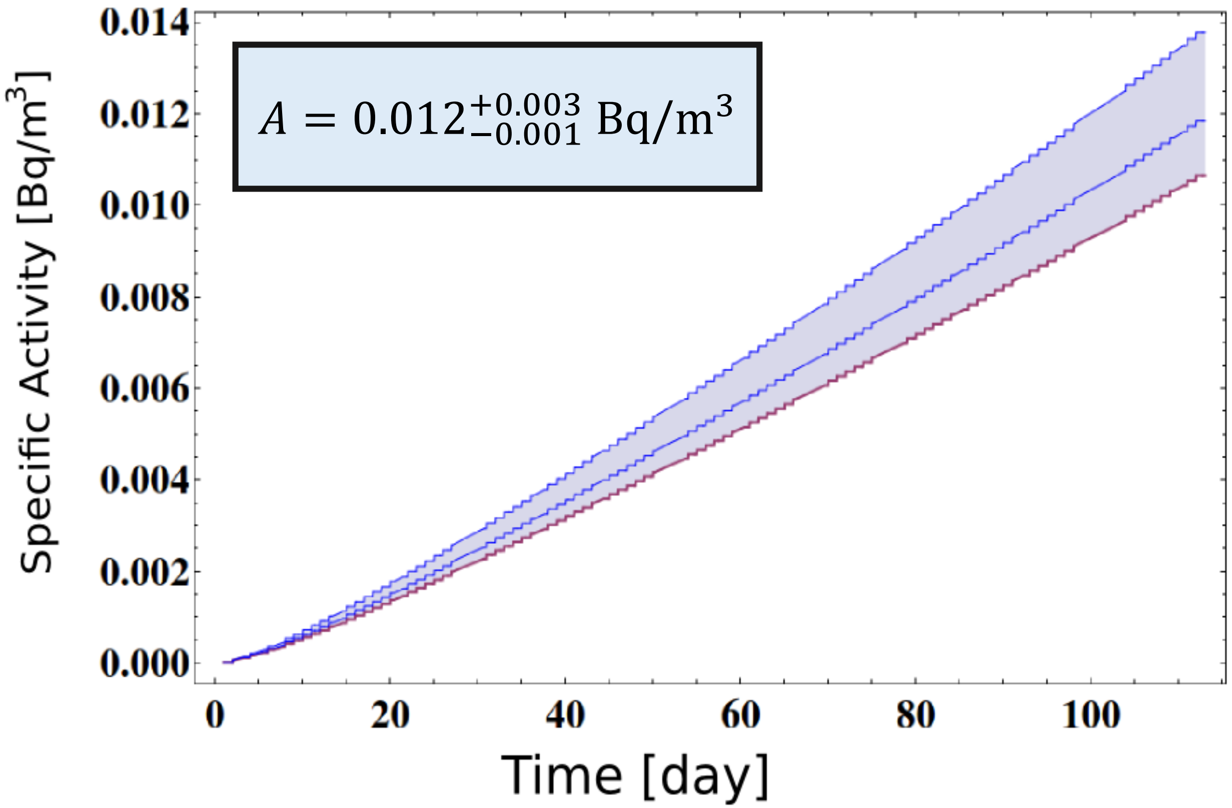


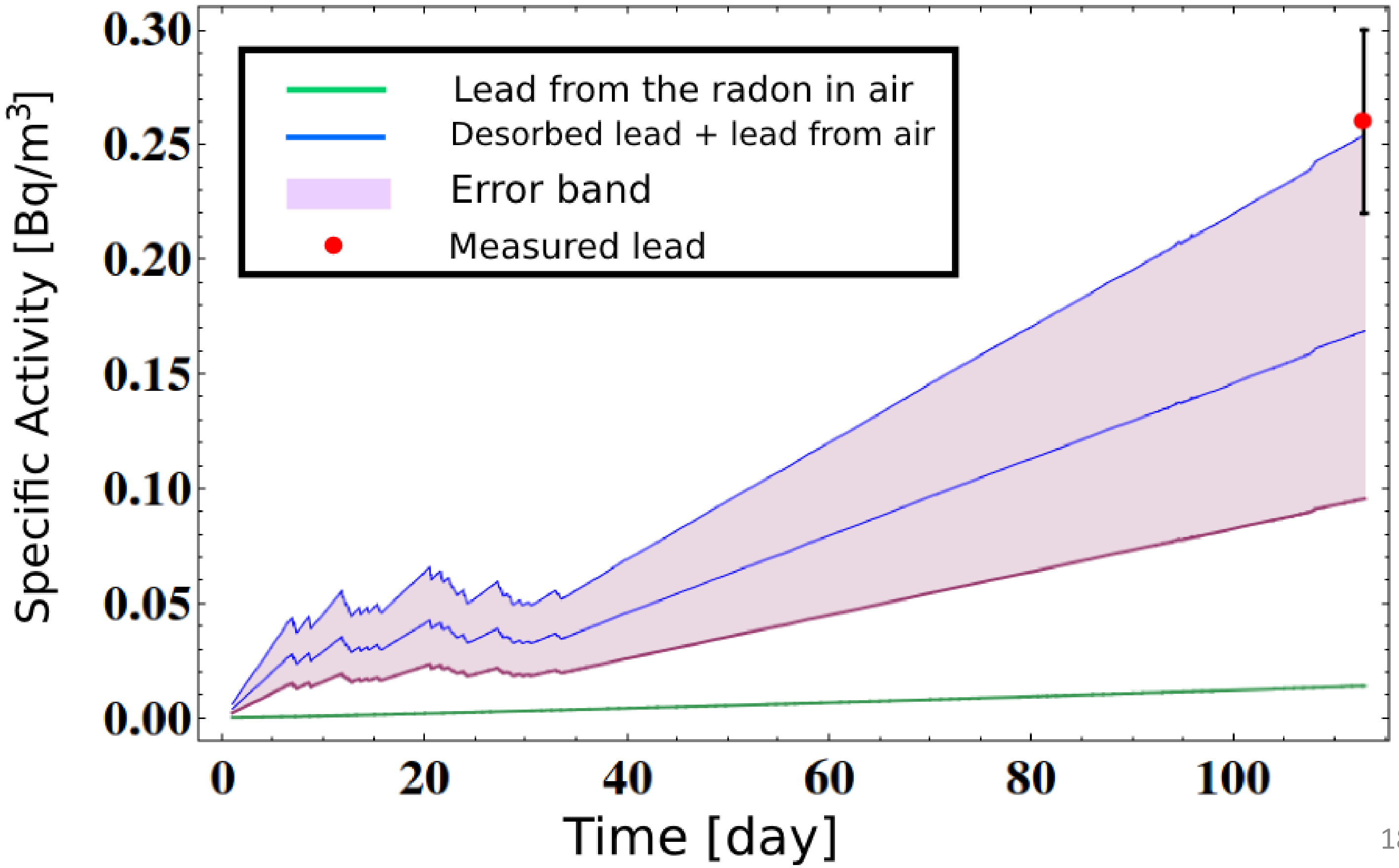
Lead concentration from the radon in air

Conclusion: The leaching model works!

- Specific Activity of produced lead from the diffused radon in UPW: $A = 0.012^{+0.003}_{-0.001}\ \mathrm{Bq/m^3}$
- Desorbed lead + lead from air: $A_{calculated} = 0.169^{+0.085}_{-0.073}\ \mathrm{Bq/m^3}$
- Measured lead from the water assay: $A_{measured} = 0.26^{+0.04}_{-0.04}\ \mathrm{Bq/m^3}$

- Calculated Activity is compatible With measured value to within 1 sigma.

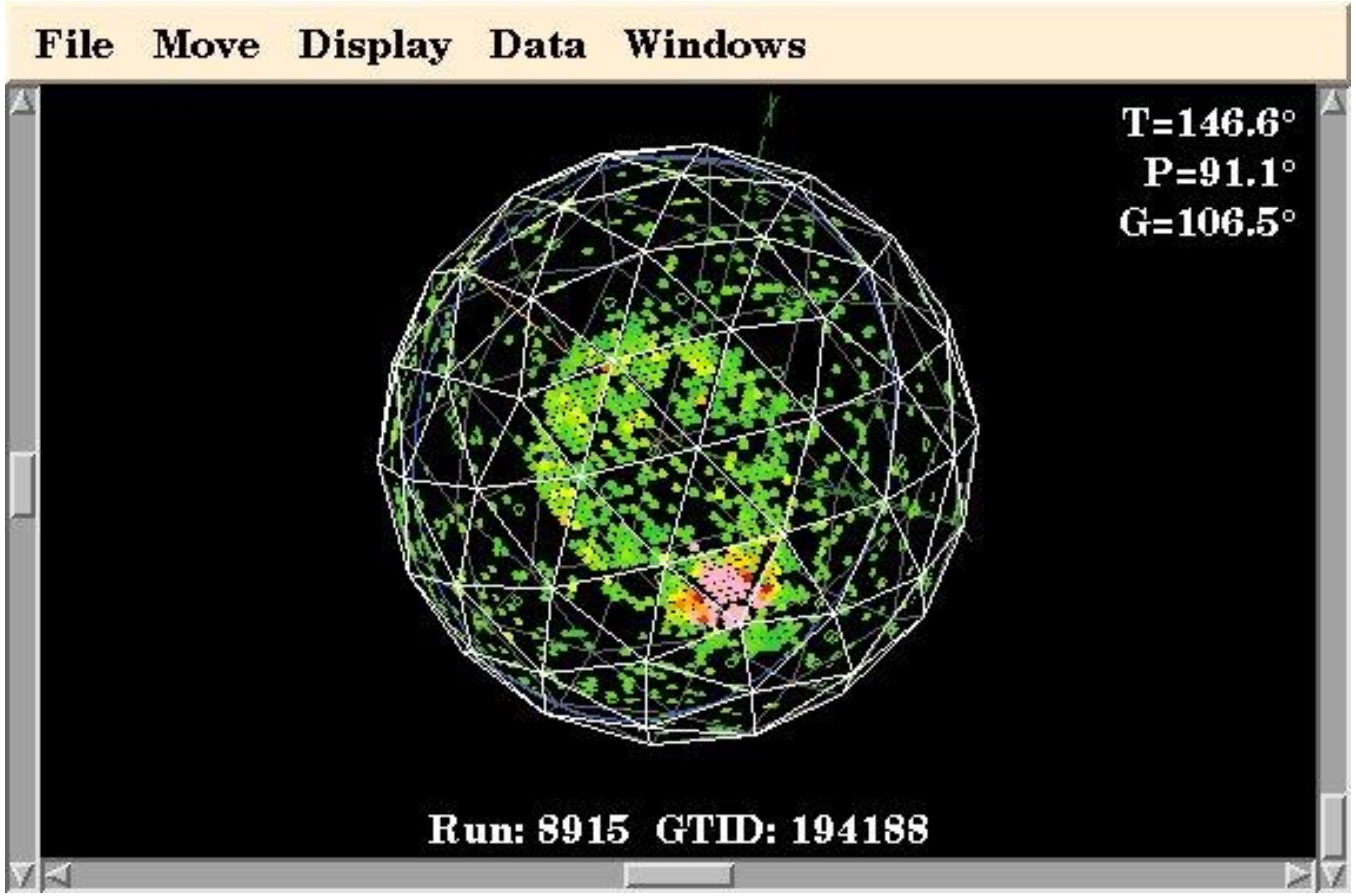
- Diffusion of $^{222}\mathrm{Rn}$ from air into water is complicated due to the temperature gradient from the bottom of AV.



Thanks for your attention…

Special thanks to the SNO+ collaboration…

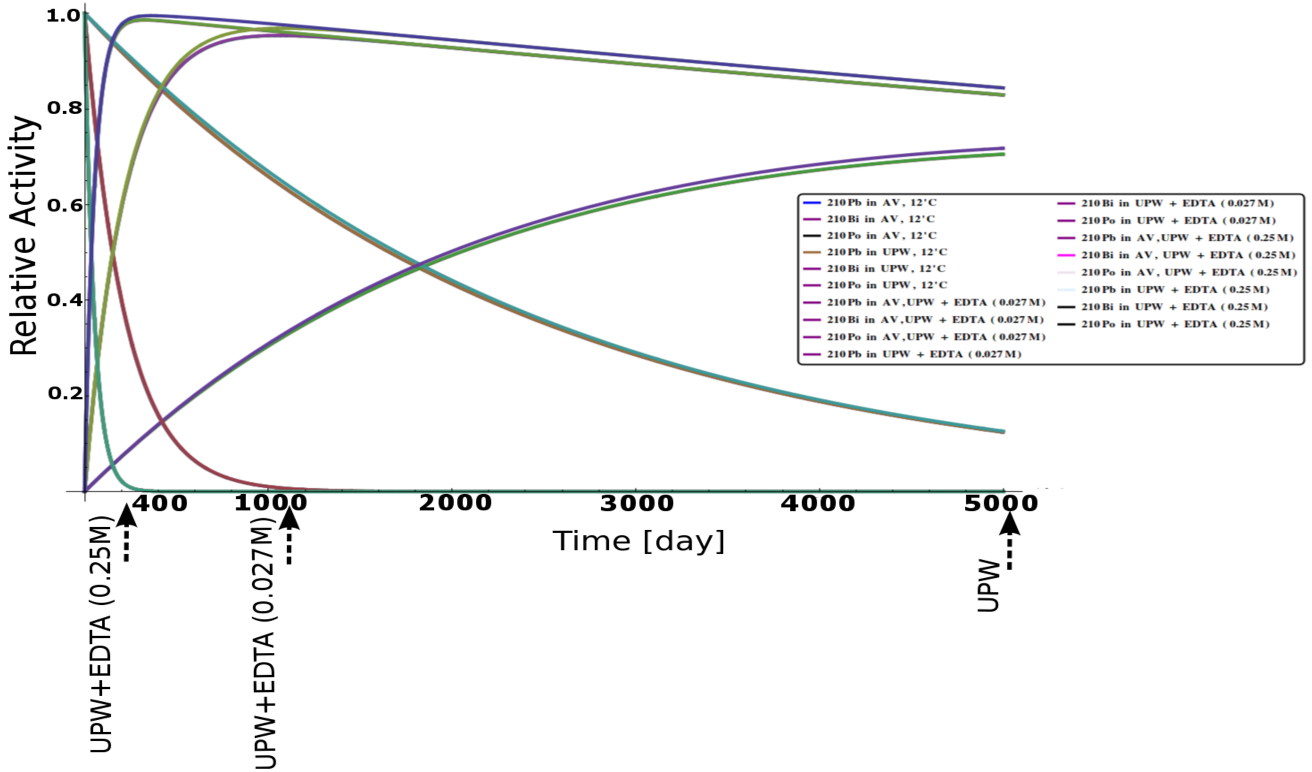
Questions?



Muon Cherenkov light observed during the dark run on December 2014…

Backup EDTA

- Ethylenediaminetetraacetic acid (EDTA) was suggested to accelerate the leaching rate.
- Has no effect on the leaching rate of $^{210}\mathrm{Bi}$ and $^{210}\mathrm{Po}$
- UPW+ EDTA (0.25M) accelerates the leaching process of $^{210}\mathrm{Pb}$ by factor of 30



Backup (Radon diffusion)

- Radon diffusion as a function of depth