P2.3-204

Coupling condensation with decay-chains: A refined model for the calculation of the radioxenon source term produced by underground nuclear explosions

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INTRODUCTION AND MAIN RESULTS

Radioxenon precursors are moderately volatile elements that condense within the magma of the nuclear cavity as it cools down. This could affect the amount of radioxenon available for subsequent migration into the atmosphere and its detection.

We present a model that couples condensation with radioactive decay in order to predict the radioxenon source term. For a given host rock composition and for each nuclide in the decay chains, thermodynamic calculations are used to determine the chemical forms (speciation), the associated vapor pressure, and the net condensation rate along the time-evolving pressure–temperature conditions.

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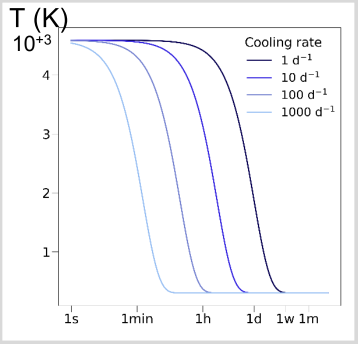
Input parameters

- ✓ Cavity pressure close to lithostatic pressure.
- ✓ Constant cavity volume (function of DOB, lithology and yield).
- ✓ Temperature decreases exponentially over time (the cooling rate is a free parameter).



Model

The temporal evolution of the quantity *N* of an isotope *i* in the vapor phase is given by:

$$\frac{dN_i^v}{dt} = -\lambda_i N_i^v + \lambda_{i-1} N_{i-1}^v - \left(\frac{dN_i^v}{dt}\right)_c$$

Loss by decay

Gain from decay of the parent element

Gain from evaporation and loss from Condensation

with:

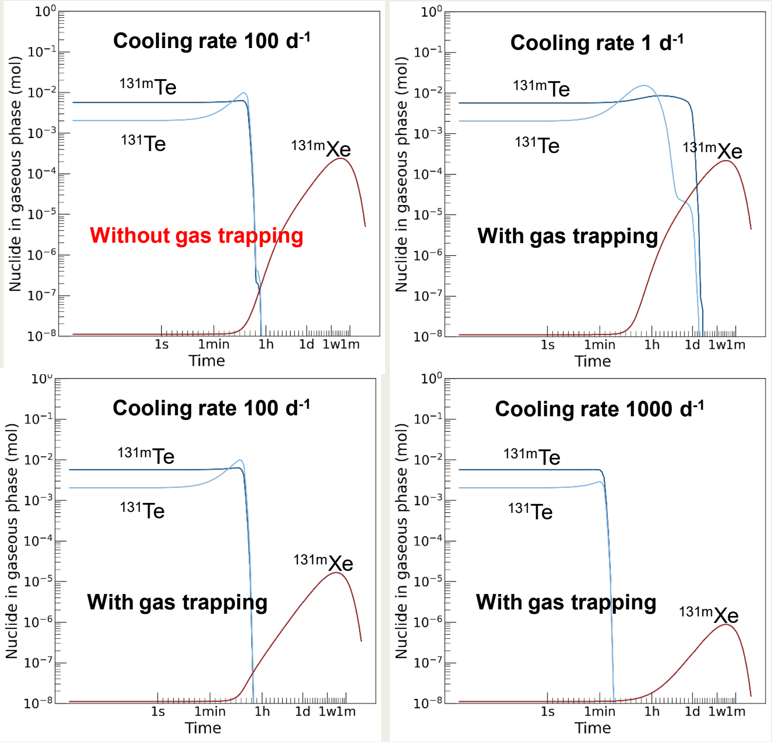
$$\left(\frac{dN_i^v}{dt}\right)_c = \alpha_i \left(\frac{AP_i}{\sqrt{2\pi M_i RT}} - \frac{AP_{isat}}{\sqrt{2\pi M_i RT}}\right)$$

Condensation flux (mol.s-1)　*Evaporation flux (mol.s-1)*

The vapor pressures (P_{isat}) are obtained using the computational thermodynamic software FactSage (Bale et al., 2016) according to the method described by Bourdon & Pili (2023).

Temporal evolution of radioxenon

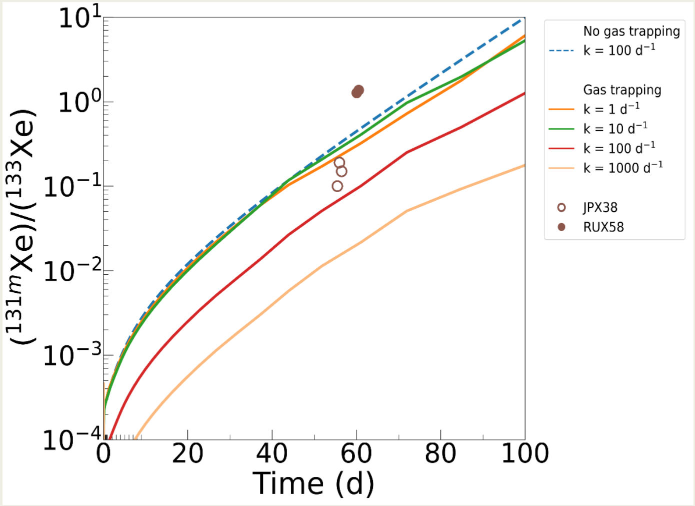
Evolution of the quantities of ^{131}Te, ^{131m}Te and ^{131m}Xe in the vapor phase for various cooling rates considering gas trapping (volatile elements decayed from non-volatile precursors remain trapped in the magma), compared to the case without gas trapping:



With gas trapping, the impact of condensation is significant: the faster the cooling, the less radioxenon there is, because condensation of tellurium occurs before its decay.

Application to real cases

Evolution of ^{131m}Xe/^{133}Xe activity ratio in gas phase over time , with gas trapping, for different cooling rates. The colored points show measurements of ^{131m}Xe/^{133}Xe from IMS stations in Japan and Russia following the 2013 DPRK event:



With radioxenon and its more refractory precursors being trapped in the magma, the model is consistent with the measurements obtained at the JPX38 station. This indicates that the seepage could have come from the cavity itself. In contrast, the signal recorded by the RUX58 station originated from elsewhere in the system, most likely the chimney.

Bale, C.W. et al. (2016), FactSage thermochemical software and databases. Calphad 55, 1-19
Bourdon, B., Pili, E. (2023). Thermodynamic determination of condensation behavior for the precursory elements of radioxenon following an underground nuclear explosion. JER 261, 107125.

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