Nuclear techniques for the in-situ detection of mineral scale in geothermal systems

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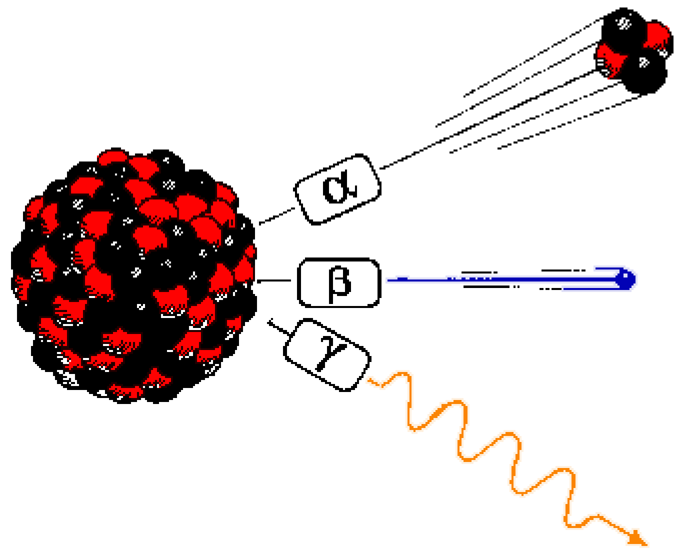
Radioactivity

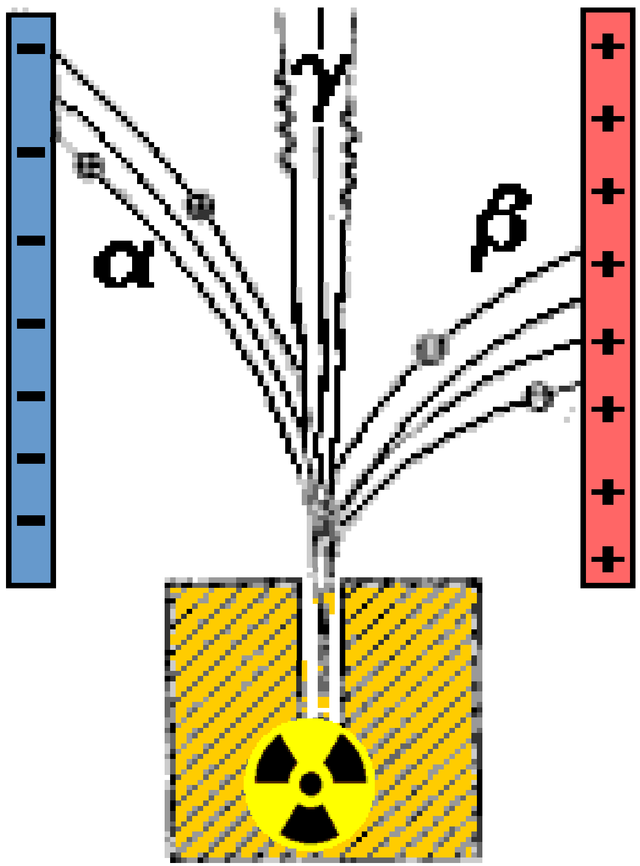
- The emission of partic-les or electromagnetic quanta from the atomic nucleus is called radio-activity.
- The emitted radiation is high-energetic and interact with matter.
- This is the basis for detection and practical use of radionuclides.



Irradiating radioactive nuclide

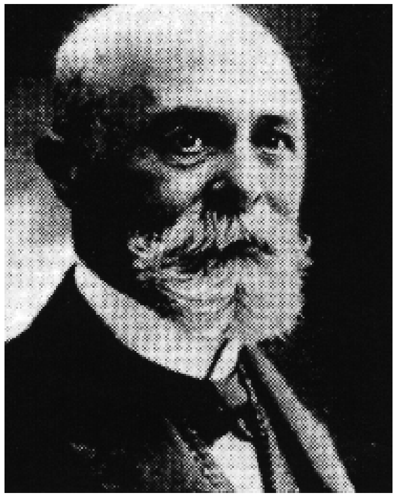
Different Radioactivity

- E. Rutherford discovered in 1899 that the radioactive emissions were of 3 different kinds:
  - α-radiation which was deflected towards the negative pole in an electric field,
  - β-radia-tion was deflected towards the positive pole
  - and γ- radiation was unaffected



Decay rate - activity

- Activity is defined as the number of nuclear desintegrations per second
- Activity is given in the unit of Becquerel



1 Bq = 1 desintegration per second (dps)

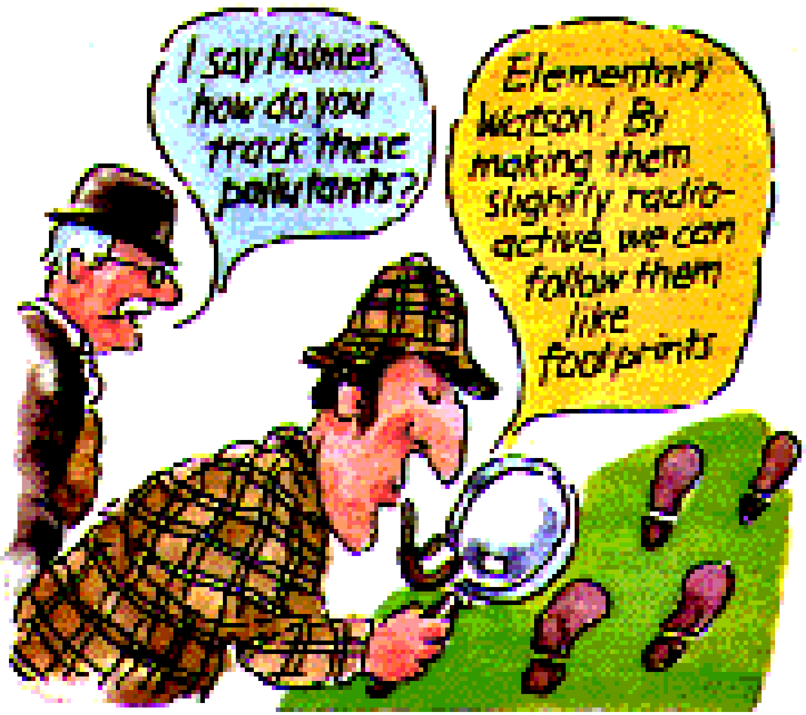
Henri Becquerel

Radioactivity & scale detection

- Various nuclear techniques for the *in-situ* detection of mineral scale in actual production systems have been reported during the last years:
  - Laboratory determinations of real-time scale deposition were recently reported using a radiotracer technique. The critical information provided by that technique was the induction time of scaling and the profile of the scale deposition along the deposition medium. (Stamatakis et al., 2005).
  - A gamma-ray attenuation method, based on continuous triple-energy gamma-ray attenuation measurements, has been presented for the detection of scale deposition in real-time in oilfield production tubulars (Poyet et al., 2002).
  - A handled device was developed to detect the presence of scale in surface piping by measuring the nuclear attenuation across the pipe diameter and two field cases were presented in which a dual-energy-venturi multiphase flow meter was used to detect and characterize scale according to the attenuation of the nuclear spectrum (Theuveny et al., 2001).
  - Dual-energy attenuation measurements for surface pipe scale detections. The method enables a simple monitoring device to detect and characterize scale in its earliest stages of formation (Kevin, 1999).

Why radioactivity?

- Effective scale management requires on-line monitoring of scaling tendencies as well as detection and identification of scale deposits.



- The advantages of using radioactivity for scale detection include the following:

✓ ***In situ monitoring*** – through tubing and walls when γ emitters or/and sources are used

✓ ***Non destructive***

✓ ***Sensitivity*** – easily detectable in extremely low concentrations (see next slide)

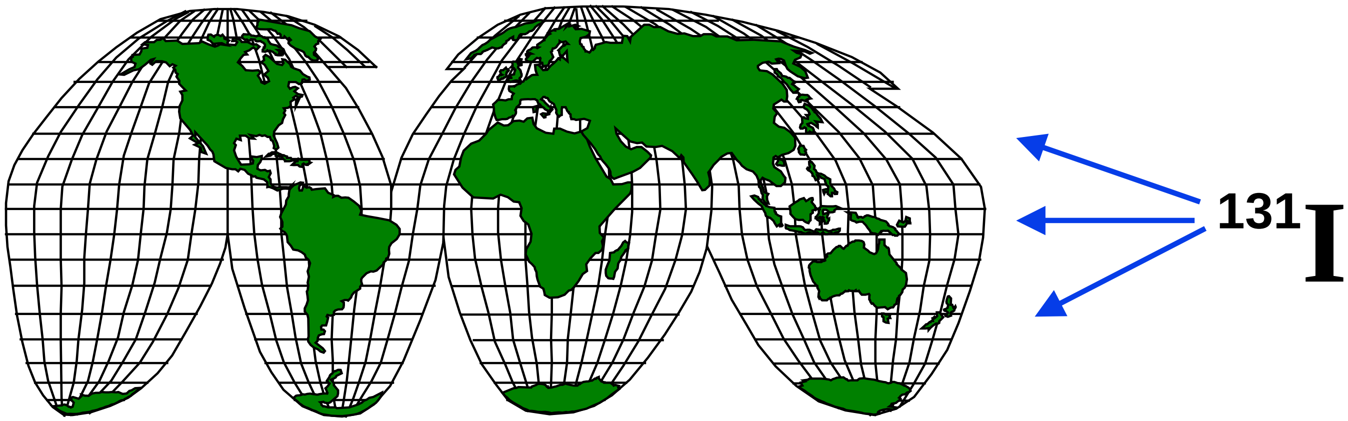
Sensibility of radioactivity

- Instruments used to detect radioactivity are very sensible

  Example:

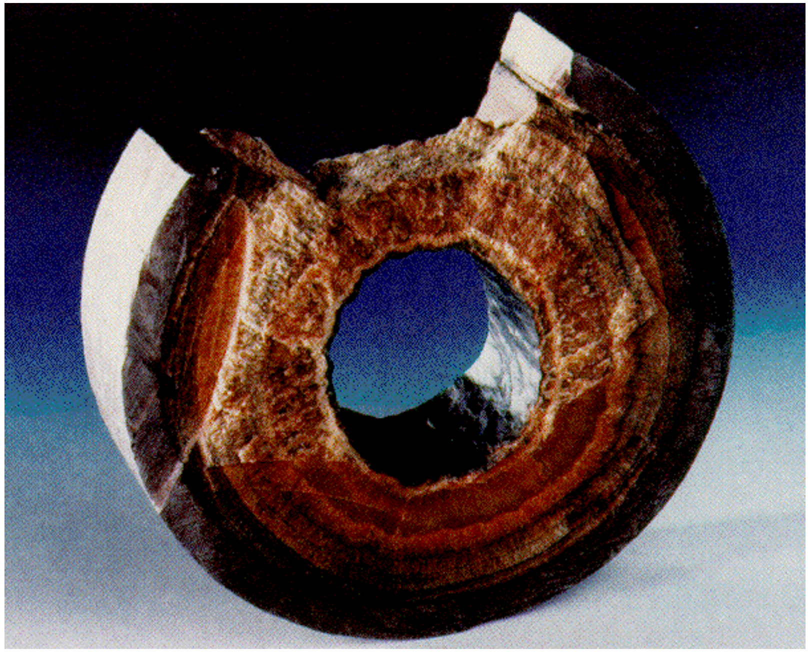
  ✓If 1 g of ^{131}I was spread over the entire surface of the earth, the resulting activity would be 10 Bq/m^2

  ✓This activity is measurable!



Scaling in geothermal installations

- The production, utilization and/or reinfection of brine found in geothermal reservoirs are often hampered by serious and very unique scale problems.
- Some of these scale problems are so severe that entire field operations are endangered.
- Three principal families of scale minerals occur in this field, carbonates, sulfates and silicates. Carbonate scale is precipitated at higher temperatures than sulfate and silicate scale.



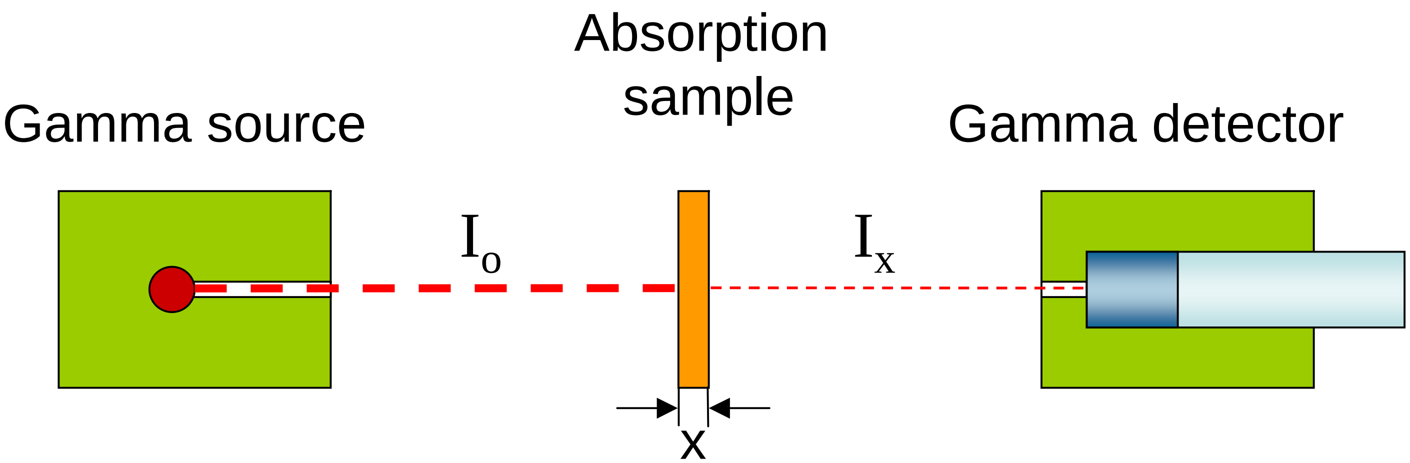
Nuclear based methods

Two nuclear-based techniques have been examined here for studying scaling phenomena:

❶ Gamma ***transmission*** based on use of external gamma sources

❷ Gamma ***emission*** based on radioactive tracers added to the flowing and reacting system

Principles of gamma transmission



Transmission of a mono-energetic beam of collimated photons through a simple absorption sample can be described by Lambert-Beer's equation

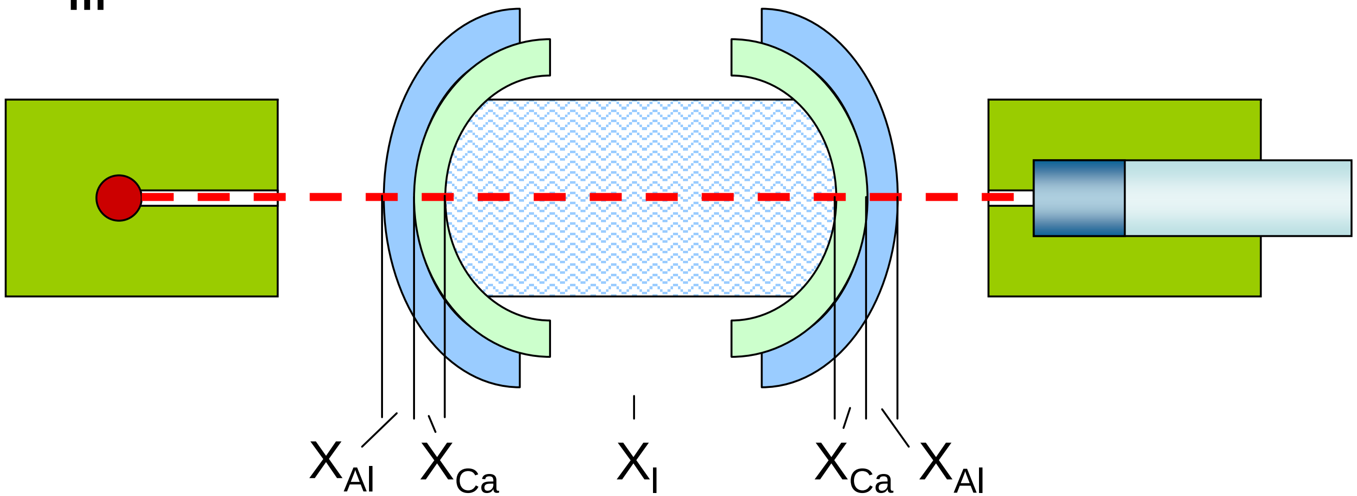
$$I_x = I_o \cdot e^{-\mu x}$$

→ μ is the linear mass absorption coefficient with dimension L^{-1} (cm^{-1}), x the sample thickness

Mass absorption coefficient

A quantity more commonly found tabulated is the <u>mass absorption coefficient</u> μ/ρ with dimension cm²/g. In a composite sample the attenuation is additive according to

$$I_{x_m} = I_o \cdot e^{\left(-\frac{2\mu_{Al} x_{m,Al}}{\rho_{Al}} - \frac{2\mu_{Ca} x_{m,Ca}}{\rho_{Ca}} - \frac{\mu_{\ell} x_{m,\ell}}{\rho_{\ell}}\right)}$$

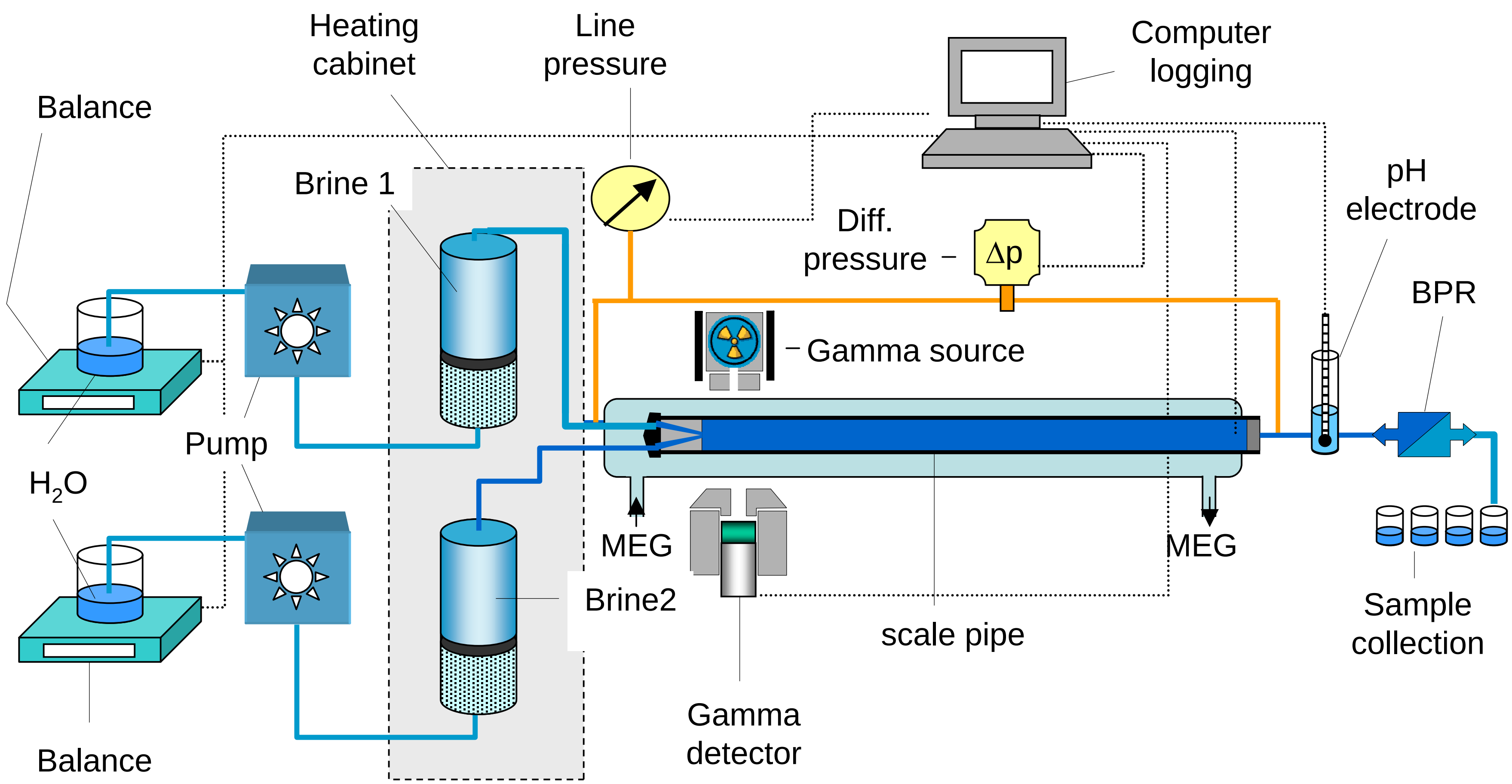


The gamma source

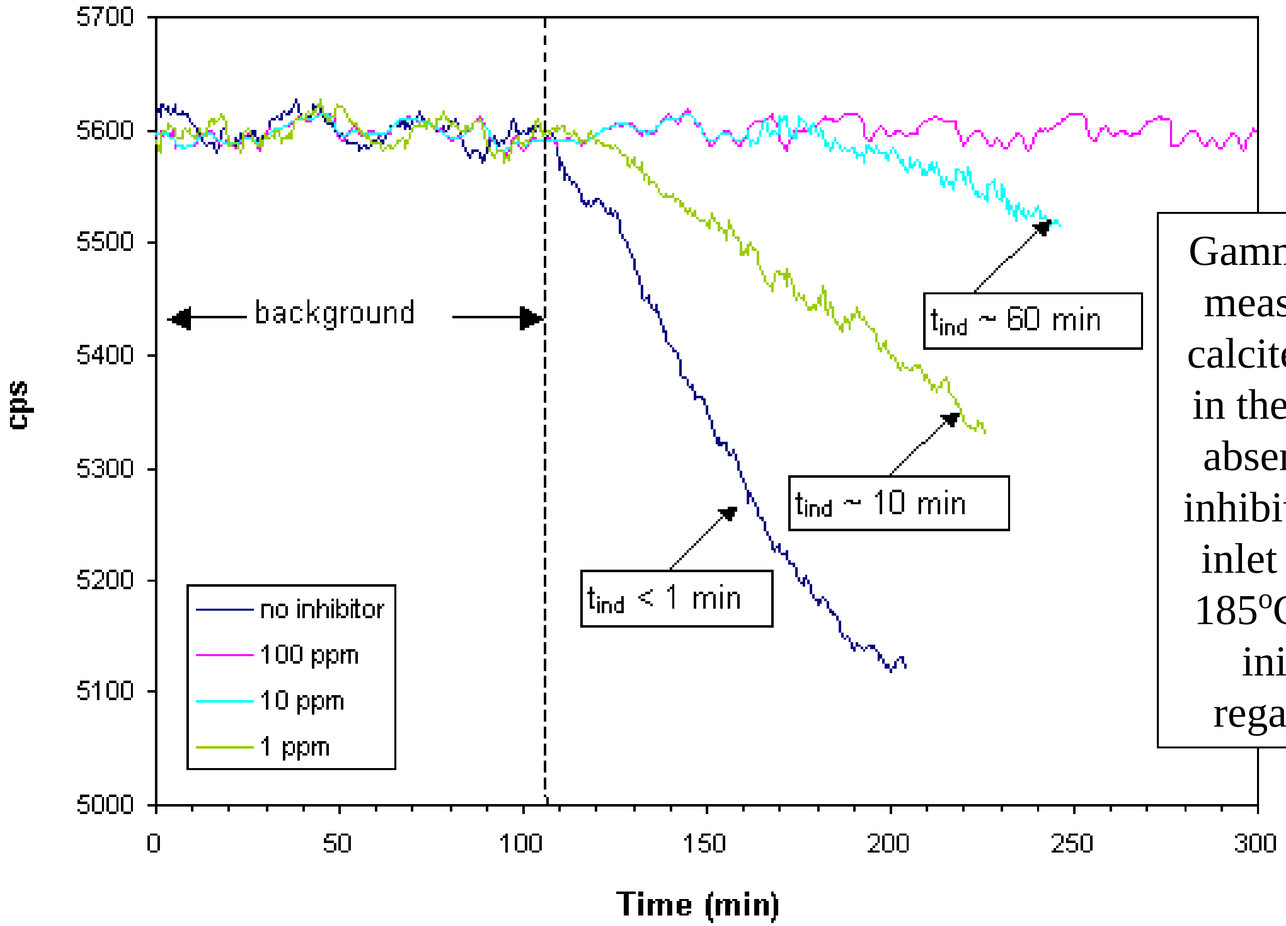
The gamma source used in the present experiment is ^{133}Ba due to suitable energies (see table below) and half-life (10.5 y). Main gamma-ray energies and intensities for ^{133}Ba are:

E_γ (keV)	I_{abs}(%)
80.998 ± 0.008	34.0 ± 0.3
276.397 ± 0.012	7.16 ± 0.07
302.851 ± 0.015	18.3 ± 0.1
356.005 ± 0.017	62.0 ± 0.8
383.851 ± 0.020	8.9 ± 0.1

Experimental setup: γ-transmission

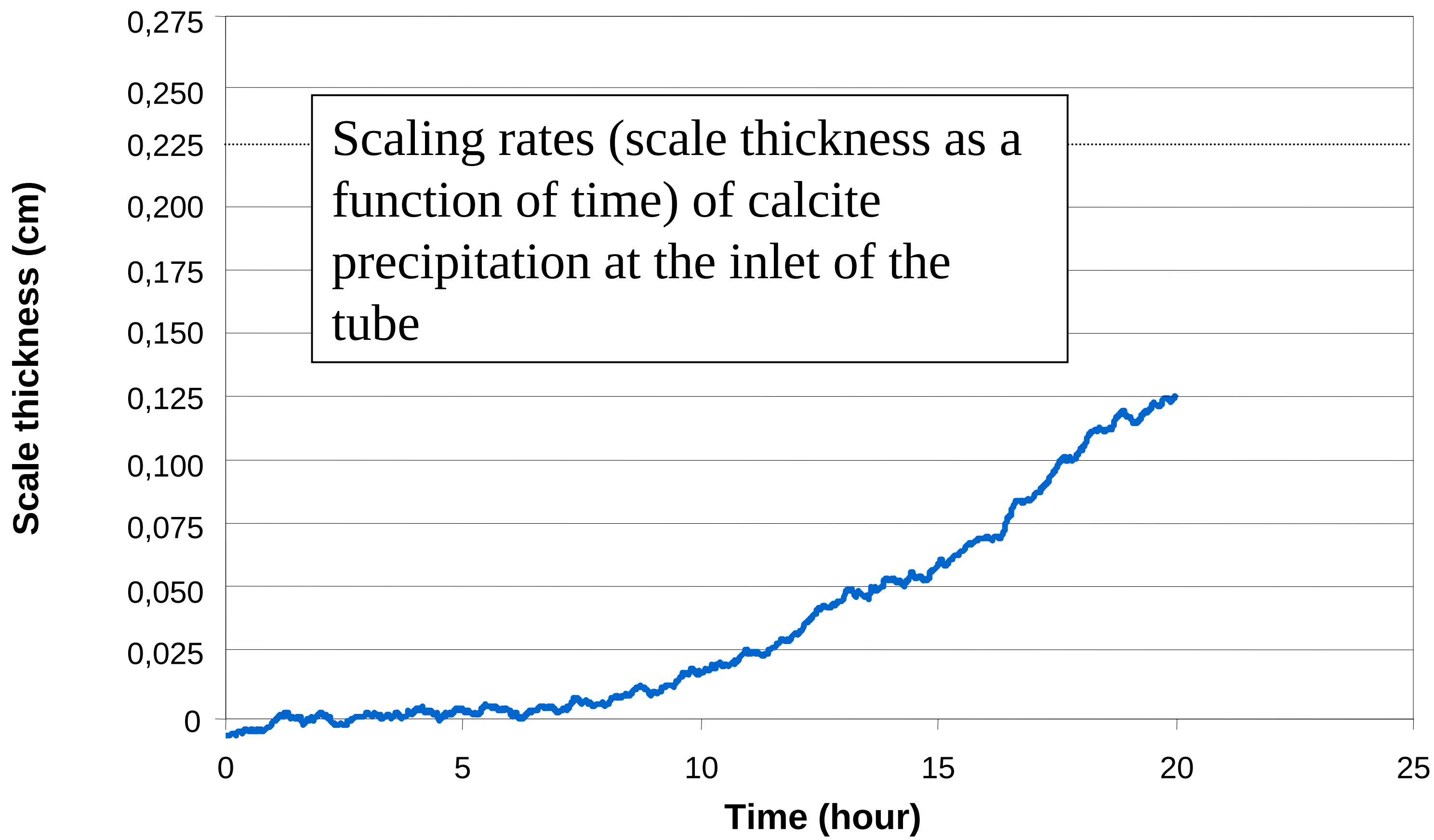


Gamma attenuation measurements

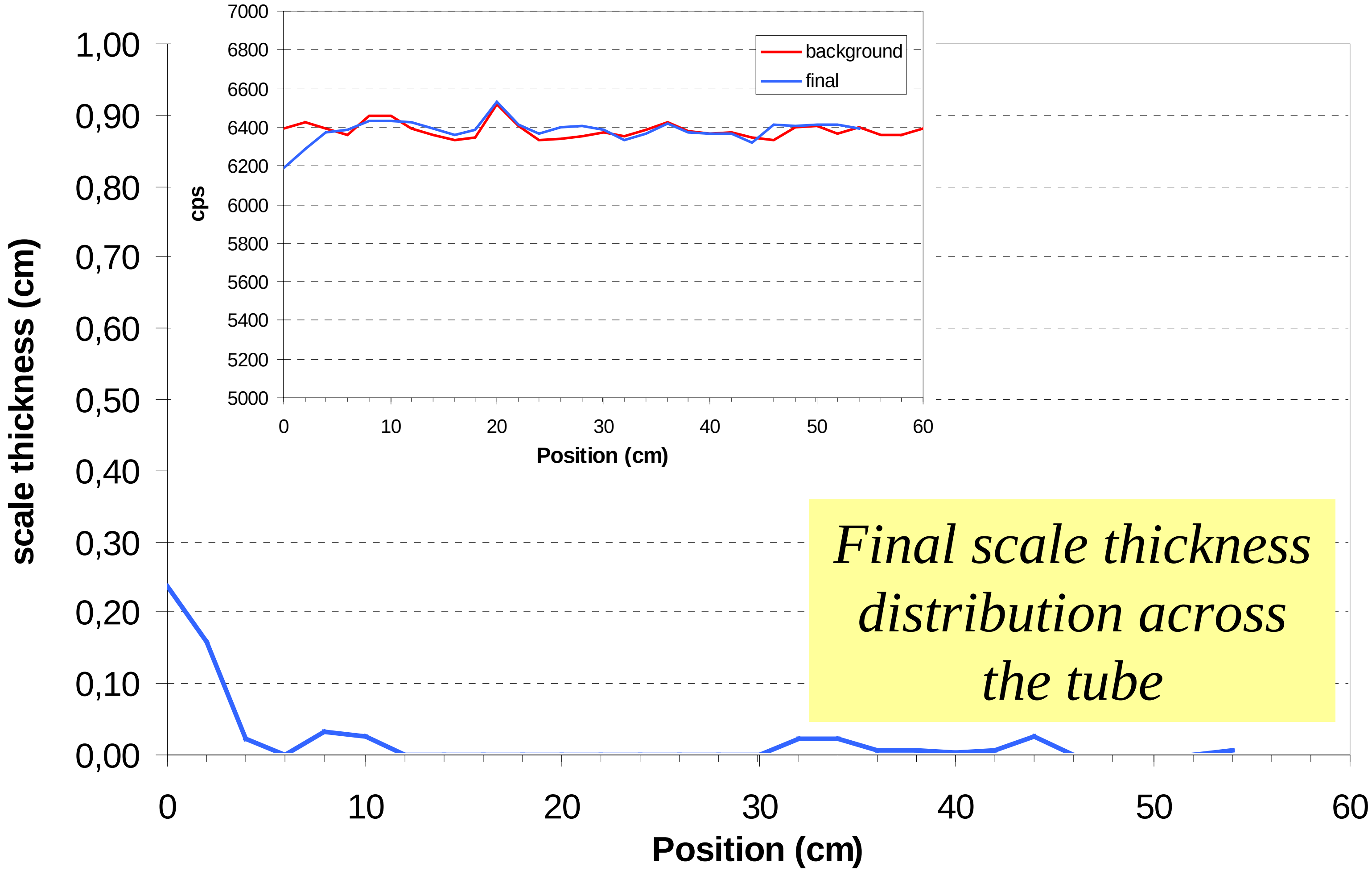


Gamma attenuation measurements for calcite precipitation in the presence and absence of a scale inhibitor 10cm from inlet of the tube at 185°C, 10 bars and initial SR=20 regarding calcite

Calcite growth rate



Calcite distribution across the tube



Summary for the γ-transmission

- The ^{133}Ba-source (30 mCi or 100 MBq) gives a typical counting rate of about 4500 cps (counts per second) in tube filled with water (ID = 10 mm) with a detector collimator opening of 4.5x4.5 mm.
- The brine-filled tube reduces the normalized incident intensity from 1.000 to 0.891when corrected for the Al-metal walls.
- The increased mass thickness (g/cm^2) due to scale obviously leads to an increased attenuation and to a reduction in contrast towards mass changes during the experiment.
- **Transmission experiments may be used to study calcite scaling in open tubes with the dimensions used here.**

Principles of the γ-emission method

- $CaCO_3$ scaling may be studied by radio-labeling of any of the chemical components involved.
- However, for on-line, continuous and non-intrusive detection, *gamma-ray emitters* are required.
- Neither O nor C have suitable gamma-ray emitting isotopes.
- Ca has only one suitable gamma-radioactive isotope, namely **^{47}Ca**, with a half-life of 4.54 days.

How to produce ^{47}Ca

^{47}Ca is produced in thermal neutron irradiation of Ca. The following nuclear reaction takes place:

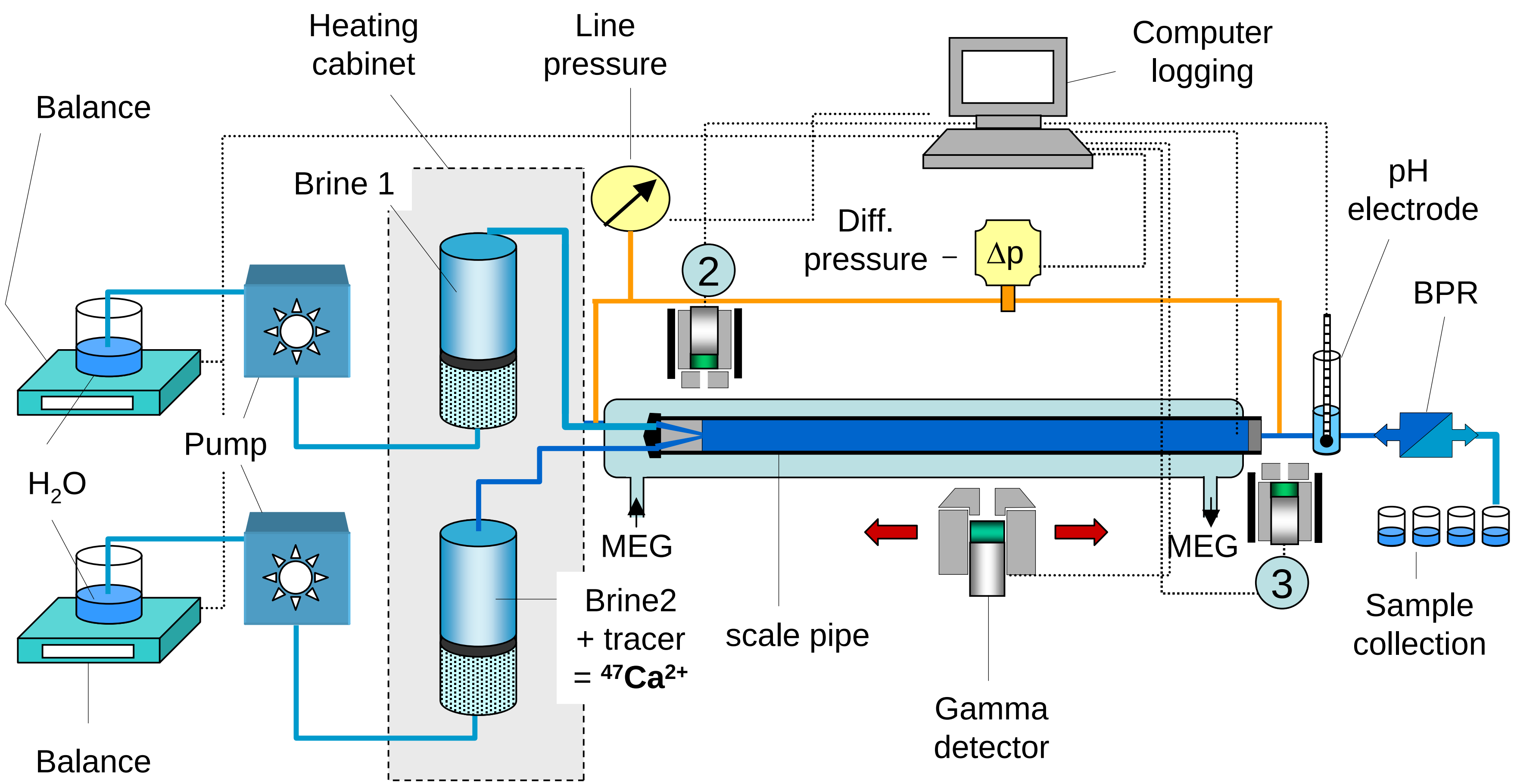
$$^{46}\mathbf{Ca}(\mathbf{n}_{\mathbf{th}},\gamma)^{47}\mathbf{Ca}\ (\gamma\textbf{-emitter})$$

Activation equation:

$$D = \sigma \cdot \varphi \cdot N \cdot (1 - e^{-\lambda t_i}) \cdot e^{-\lambda t_d}$$

σ =	reaction cross section in cm^{-2}
φ =	neutron flux ($n \cdot cm^{-2} \cdot s^{-1}$)
N =	number of target atoms
λ=	decay constant (= $\ln 2/T_{1/2}$)
t_i =	irradiation time
t_d =	decay time

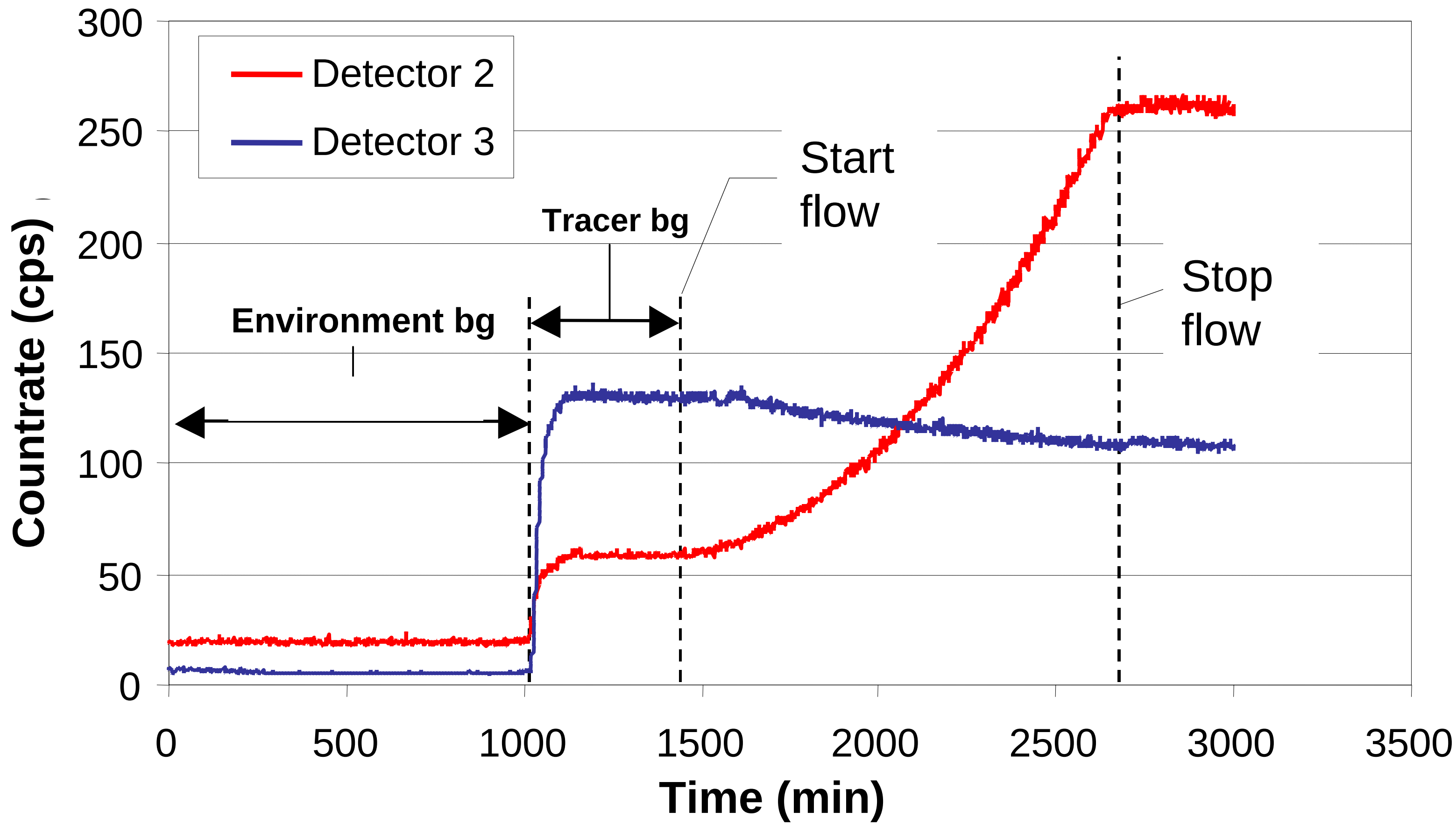
Experimental setup: γ-emission



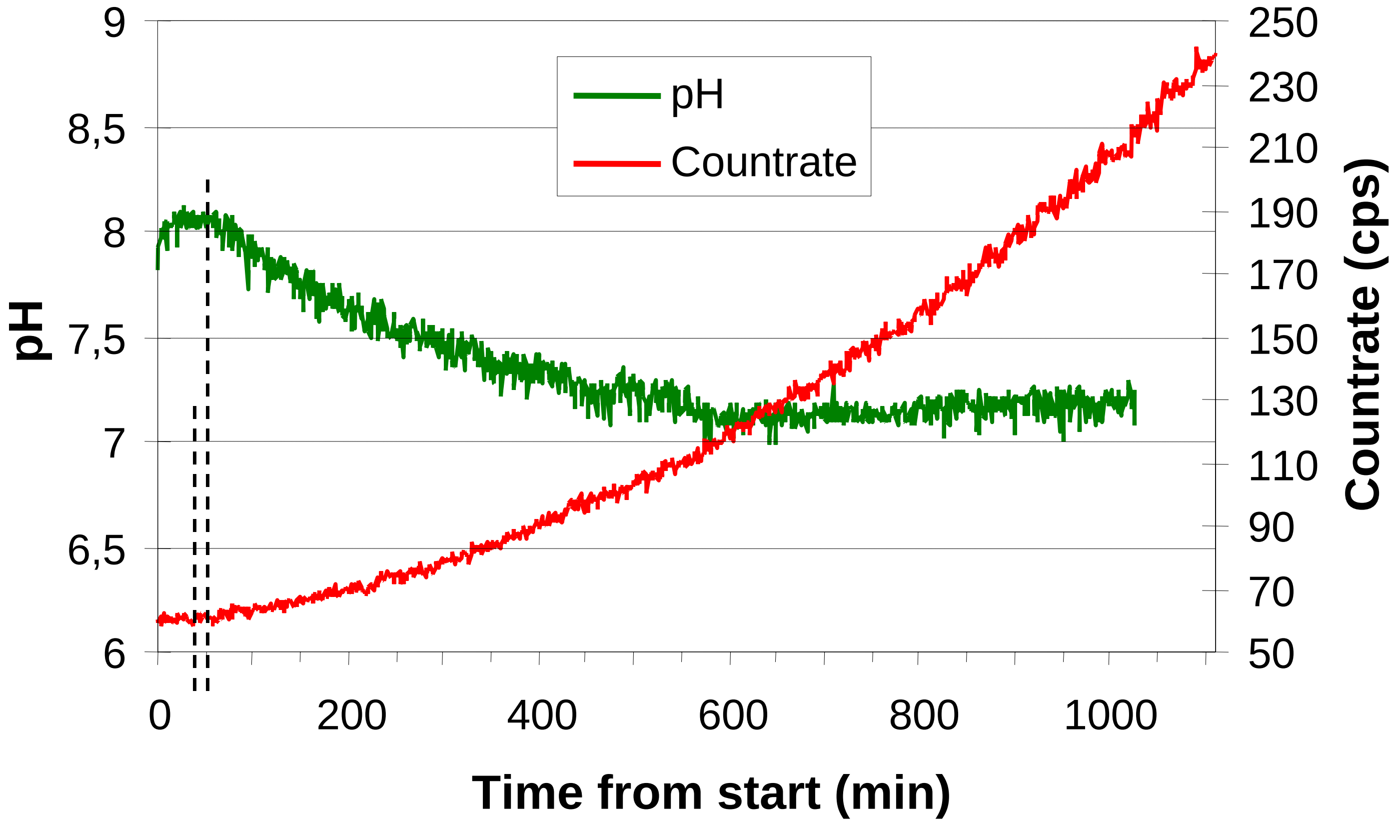
Brine preparation (run 1)

Brine 1	*(mMolal)*
NaCl	586
$NaHCO_3$	14
Brine 2	*(mMolal)*
NaCl	600
$^{47}CaCl_2$	0.21
$CaCl_2 \cdot 2H_2O$	6.79
T (°C)	80
P (bar)	4
q_t (cm/min)	3
Final SR	8

Run 1: Detector countrates

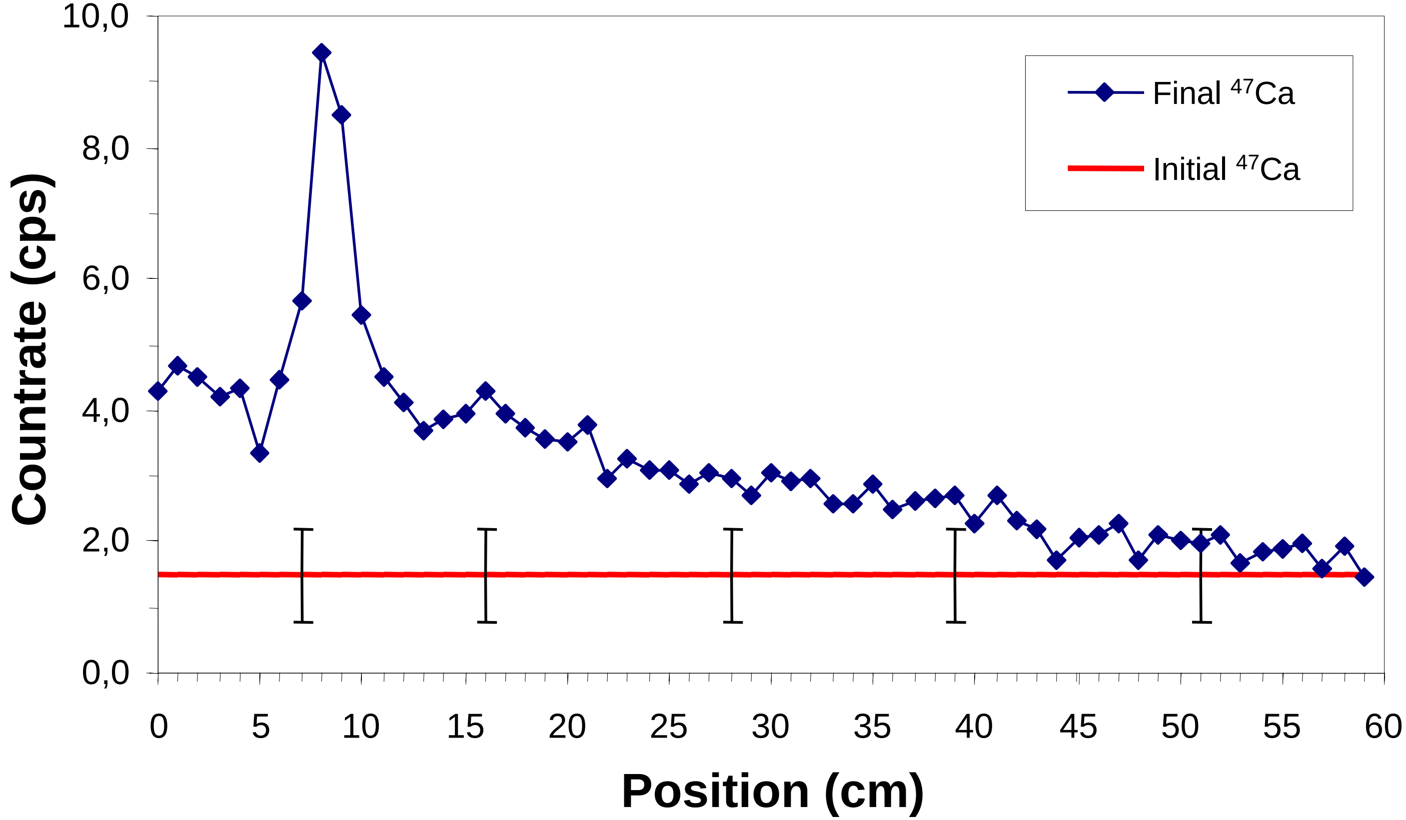


Run 1: Countrate detector 2 vs pH



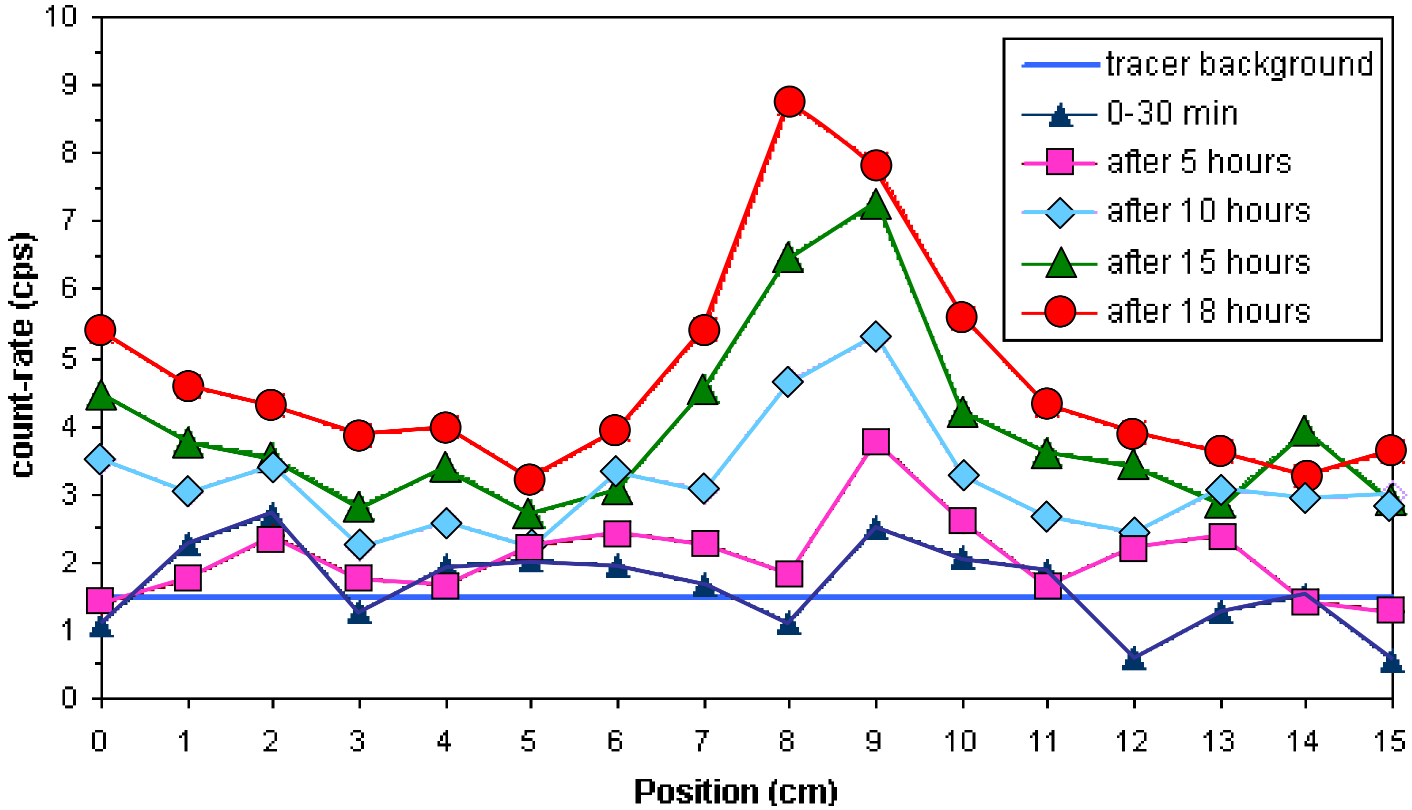
^{47}Ca countrate at the inlet and pH at the outlet versus time

Run 1: Core scan with detector 3



^{47}Ca final distribution profile along the tube

Run 1: Scan of core fraction



^{47}Ca distribution profile at different time steps for the first 15 cm of the tube

Summary for the γ-emission method

- Radiotracer technology is a very sensitive and non-ambiguous method to study formation of mineral scaling in porous media.
- For $CaCO_3$ scaling, application of the radiotracer ^{47}Ca has proven useful.
- Detection limit for the tracer technique is < 1 μg $CaCO_3$ per 1 cm tube section, corresponding to a scale thickness < 0.05 μm of $CaCO_3$ by using 4 % enriched ^{46}Ca for production of ^{47}Ca.

Final Conclusions

- ✓ Both methods are capable to visualize the distribution of the scale deposits, a result that is not readily obtained by methods commonly used in conventional dynamic scaling experiments.
- ✓ The techniques are sensitive to scaling, resulting generally in shorter induction times compared to Δp-monitoring.
- ✓ The methodologies can be easily used for the laboratory investigation of the scaling processes occurring in geological systems, including oilfield, geothermal and hydrology applications and for all kind of mineral scales.
- ✓ Their results are meant to be applicable at the field scale; the quantification of the earlier occurrence of scale precipitation that those techniques attain can be directly implemented in large scale simulators.

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