Journal of Radioanalytical and Nuclear Chemistry
https://doi.org/10.1007/s10967-025-10413-7

Decontamination potential of radioactively contaminated wounds with purified clinoptilolite-tuff

Jan M. Welch[1] · Michaela Foster[1] · Johannes H. Sterba[1] · Dietmar Nagl[2] · Cornelius Tschegg[2]

Received: 6 May 2025 / Accepted: 16 September 2025

Abstract
Purified clinoptilolite-tuff (PCT) has successfully been tested for application in a PCT-doped wound dressing for use in radiolytically contaminated environments. Initial quantitative studies of the capacity of PCT for $SrCl_2$ utilizing ^{85}Sr radiotracered material and CsCl utilizing ^{134}Cs radiotracered material in both aqueous (AQ) and physiological (artificial wound fluid exudate; AWFE) media show that Cs^+ capacities for PCT differ slightly (AQ: 1.60 ± 0.05 mmol/g vs. AWFE: 307 1.37 ± 0.07 mmol/g) while Sr^{2+} capacities are not significantly different (AQ: 0.43 ± 0.01 mmol/g vs. AWFE: 0.41 ± 0.03 mmol/g). Additionally, preliminary qualitative information relating to the selectivity of PCT for Sr^{2+} and Cs^+ vs. Ca^{2+} has been obtained from these studies. Finally, experiments show the enhanced uptake of radio-Cs and radio-Sr by PCT-doped wound dressings compared to state-of-the-art alternatives.

Keywords Zeolite · Clinoptilolite · Strontium · Cesium · Ion exchange

Introduction

Zeolites are well known for their large and specific ion-exchange capacities [1–4]. In contrast to synthetic ion exchangers commonly used in water decontamination/deionisation and other applications, natural minerals' ion exchange properties are defined by their characteristic mineralogical solid-state structures. The structure of clinoptilolite ($(Na,K,Ca)_{2\text{-}3}Al_3(Al,Si)_2Si_{13}O_{36}{\cdot}12(H_2O)$), a natural zeolite-tuff, shows particularly good selectivity and high capacity for cesium and strontium [5, 6].

Such a material has been made safe and effective for health applications [9–12] by a proprietary purification process [7, 8]. The same material was tested clinically for benefits in wound repair and regeneration showing a high safety profile when topically administered [13].

The reported benefits in human applications combined with sorption capacities for Sr and Cs of purified clinoptilolite-tuff (PCT) suggest the potential use of a PCT-doped wound dressing in a radiolytically contaminated environment. Under such conditions, the sorption characteristics (capacity, selectivity over other physiological ions and exchange kinetics/rates) for ^{90}Sr and ^{137}Cs (the principal radiolytic environmental contaminants resulting from fission-related radionuclide releases) from wound-like media are essential information. To this end, initial quantitative studies of the capacity of specially prepared clinoptilolite for $SrCl_2$ utilizing ^{85}Sr radiotracered material and CsCl utilizing ^{134}Cs radiotacered material in both aqueous (AQ) and physiological (artificial wound fluid exudate; AWFE) media are reported. Additionally, preliminary qualitative information relating to the selectivity of the material studied for Sr^{2+} and Cs^+ vs. Ca^{2+} on the basis of radiotracer studies is also presented.

Materials and methods

Experimental design

The goal of the presented experiments is to establish the applicability of a specially prepared zeolitic material (PCT; purified clinoptilolite-tuff), pure or as a component of a

✉ Johannes H. Sterba
johannes.sterba@tuwien.ac.at

[1] Center for Labelling and Isotope Production, TRIGA Center Atominstitut, TU Wien, Stadionallee 2, 1020 Vienna, Austria

[2] GLOCK Health, Science and Research GmbH, Hausfeldstrasse 17, 2232 Deutsch-Wagram, Austria

Published online: 30 September 2025

wound dressing, to radiolytic decontamination of a physiological environment.

Purified clinoptilolite-tuff (PCT) is produced from a high-grade raw material, sourced from an open pit mine in the eastern Slovak Republic [7, 8]. The patented production process includes a thoroughly quality-controlled and validated ion-exchange purification process, micronization and terminal heating of the material. The resulting powder, which has been evaluated by independent institutions to be safe for a variety of medical applications, can further be doped into Ca-alginate fibers. The wound dressing used in the experiments is a mixture of PCT-doped Ca-alginate and cellulose fibers. The same dressing however without PCT integrated into the Ca-alginate fibers was used as negative control, together with a standard-of-care cotton dressing (Stepcel, Lohmann and Rauscher).

Since the principal longer-lived ($t_{1/2}$ ~ 30 a) radioactive contaminants resulting from a fission-related release are ^{90}Sr and ^{137}Cs, information concerning the fundamental sorption properties of this material toward Sr^{2+} and Cs^{+} is required. The first parameter needed to determine (and understand) these properties is the capacity of the material for both ions. To calculate these capacities and begin to understand the selectivity of the material for these ions, studies using ^{85}Sr and ^{134}Cs labelled material were initiated. The shorter-lived ^{85}Sr ($t_{1/2}$ ~ 65 d rather than 28.91 a for ^{90}Sr) and ^{134}Cs ($t_{1/2}$ = 2.07 a rather than 30.01 a for ^{137}Cs) are applied in these studies for ease of preparation (direct irradiation of target materials with thermal neutrons), handling (shorter half-lives) and measurement (strong characteristic gamma lines) as well as to spare disposal costs. All experiments were performed with radioactive labelled material.

^{85}Sr and ^{134}Cs labelled $SrCO_3$ and $CsNO_3$ are easily prepared by direct neutron irradiation of appropriate amounts of target material. In the case of $SrCO_3$, the full theoretical amount of Sr desired is irradiated (due to the relatively small cross section and scarcity of ^{84}Sr in natural Sr compounds). This material must subsequently be converted to the chloride, as it is the most common anion in a physiological environment, by dissolution in concentrated hydrochloric acid and drying. The resulting solids can then be taken up in a precisely controlled amount of the desired medium, aqueous (triply distilled water) or Artificial Wound Fluid Exudate (AWFE, Biochemazone CAS NO. 7732–18-6), to form test solutions. In the case of $CsNO_3$, only small (20 mg) portions are needed to produce ample activity on neutron irradiation. These small targets are easily converted to CsCl by repeated dissolution in HCl and subsequent evaporation to dryness. Small portions of a radionuclide stock solution generated by dissolving the resulting material may be combined with solid non-radioactive CsCl and additional water or AWFE to introduce the desired amount of activity into solutions with known concentrations of CsCl.

The choice of test concentrations was extrapolated from previous experiments showing the capacities of similar zeolitic materials [5]. The specific activities applied were generally similar for lower concentration test solutions, but in the case of the higher concentration solutions, for which only small differences in activity would have to be determined, larger activities were applied in order to achieve the necessary experimental precision.

Experiment scale was decreased (relative to our previous studies, [5]) to allow for treatment of 10 mg of PCT with 200 µL of test solution. This small scale allows for ready automated measurement of all experimental fractions and thus a more rapid and complete understanding of the exchange processes under study. In addition, for experimental simplicity, samples were allowed to stand overnight at 40 °C (imitation of physiological temperature) without mixing/agitation. Previous experiments have shown that under the conditions of this study, equilibrium for Sr and Cs solutions is reached on standing overnight.

Radionuclide preparation

To generate ^{85}Sr and ^{134}Cs labelled $SrCl_2$ and CsCl, two sets of targets were prepared. The first set consisted of eight samples of $SrCO_3$ (Merck, Optipur; samples described in SI) packed in polyethylene (PE, Carl Roth) irradiation tubes. These samples were encapsulated in a PE dry irradiation capsule, irradiated for 2 h in the dry irradiation channel (TBR) of the TRIGA Mk II research reactor at the Center for Labelling and Isotope Production (CLIP) at a thermal neutron flux of $1.8 \cdot 10^{12}$ neutrons$\cdot cm^{-2} \cdot s^{-1}$ and subsequently left to cool (radiolytically) for at least 16 h (overnight). The second set of targets included two further samples of $SrCO_3$ and two samples of $CsNO_3$ (Alfa Aesar, 99.999%; samples described in SI) packed in PE irradiation tubes. These samples were also encapsulated in a separate PE dry irradiation capsule, irradiated for 7 h in the dry irradiation channel and subsequently left to cool for at least 16 h (overnight).

Prior to unpacking for use, i.e. the conversion to chlorides and dissolution in appropriate medium, the irradiated targets were weighed and the activity generated assessed by measurement on an automatic gamma counter (HIDEX AMG; ^{85}Sr containing samples) or a dose calibrator (ISOMED 2010 Dose rate calibrator; ^{134}Cs containing samples).

Conversion to chloride salts

$SrCl_2$

Each irradiated $SrCO_3$ target was transferred to a 20 mL screw cap glass vial, weighed and measured on the gamma counter. The residue remaining in the irradiation vessel was also weighed and measured on gamma counter. Since

significant material/activity remained in the irradiation tubes, each irradiation vessel was rinsed two to three times with HCl (35% aqueous; 100 µL) until no remaining activity was detectable. Rapid gas evolution/fizzing was observed on addition and after reaction had ceased (1–2 min), the clear colorless liquid was transferred from to the 20 mL screw cap glass vial containing the previously transferred solids (further gas evolution and fizzing was observed). HCl was then added dropwise until vigorous gas evolution ceased and the vial was then warmed to 40–50 °C to completely dissolve solids resulting in clear colorless solutions (1–3 mL). These solutions were evaporated to constant mass (after cooling to RT) on a hot plate at 150 °C under flow of dry compressed air. The resulting colorless solid deposit of $SrCl_2$ in the 20 mL screw cap glass vial and the rinsed irradiation vessels (tubes) were then measured on the gamma counter showing a slight loss of activity.

CsCl

Each irradiated $CsNO_3$ target was transferred to a 20 mL screw cap glass vial, weighed and measured on the dose rate calibrator. No effort was made to rinse irradiation vessels. HCl (35% aqueous solution; ~ 20 drops) was added to each vial and the resulting clear colorless solution evaporated at 150 °C under a flow of dry compressed air to constant mass (after cooling to RT). This process was repeated three times for each sample to completely remove/destroy any residual nitrate.

Test solutions

$SrCl_2$, aqueous

^{85}Sr labelled $SrCl_2$ (as prepared above) was rinsed from the 20 mL screw cap glass vials (3x) with triply distilled water (1–3 mL) and transferred to a weighed glass volumetric flask (10.00 mL). The flask was filled to the 10 mL mark, shaken to completely dissolve any solids resulting in clear colorless solutions with precisely known (see SI) $SrCl_2$ concentrations, ^{85}Sr activities and masses. Aliquots (100 µL) of each solution were withdrawn and counted (1 h) to determine $SrCl_2$:^{85}Sr (detector response factor, R_f, in mmol·s/cts; Table SI9) for each of the five test solutions prepared.

CsCl, aqueous

Firstly a radionuclide solution was prepared by dissolving CsCl (13.4 mg, 80 µmol) in triply distilled water (15.0 mL, 14.9595 g, 5.4 mM CsCl, ~ 31 kBq/mL, 31.3 kBq/g). This solution was then combined with solid CsCl and triply distilled water in a glass volumetric flask (10.00 mL). The flask was shaken to completely dissolve any solids resulting in clear colorless solutions with well-defined CsCl concentrations, ^{134}Cs activities and masses (see SI). Aliquots (100 µL) of each solution were withdrawn and counted (1 h) to determine CsCl: ^{134}Cs (detector response factor, R_f in mmol·s/cts; Table SI11) for each of the six test solutions prepared.

$SrCl_2$, artificial wound fluid exudate (AWFE)

^{85}Sr labelled $SrCl_2$ (as prepared above) was rinsed from the 20 mL screw cap glass vials (3x) with AWFE (1–3 mL) and transferred to a weighed glass volumetric flask (10.00 mL). The flask was filled to the 10 mL mark, shaken to completely dissolve any solids and allowed to settle overnight. The resulting clear nearly colorless (slightly yellow) solutions with precisely known (see SI) $SrCl_2$ concentrations and ^{85}Sr activities. Aliquots (100 µL) of each solution were withdrawn and counted (1 h) to determine $SrCl_2$:^{85}Sr (detector response factor, R_f, in mmol·s/cts; Table SI13) for each of the five test solutions prepared.

CsCl, AWFE

Firstly, a radionuclide solution was prepared by dissolving CsCl (20.6 mg, 120 µmol) in AWFE (15.0 mL, 15.9681 g, 8.2 mM CsCl, ~ 53 kBq/mL, 50.0 kBq/g). This solution was then combined with solid CsCl and AWFE in a glass volumetric flask (10.00 mL). The flask was shaken to completely dissolve any solids resulting in clear nearly colorless (slightly yellow) solutions with well-defined compositions and activities. Aliquots (100 µL) of each solution were withdrawn and counted (1 h) to determine CsCl: ^{134}Cs (detector response factor, R_f, in mmol·s/cts; Table SI15) for each of the six test solutions prepared.

Application of test solutions to PCT samples

PCT (~ 10 mg) and test solution (200 µL) were weighed into Eppendorf tubes (1 mL polypropylene). The resulting heterogeneous mixture was vortexed (20 s, to ensure efficient mixing). Each tube was then weighed and placed in a drying oven (Memmert B30 universal oven/incubator) that had been previously thermally equilibrated to 40 °C. The samples were allowed to stand overnight (18–19 h) at 40 °C. Afterwards the Eppendorf tubes were removed from drying oven and cooled to RT. After weighing (to enable a correction for evaporative loss), the tubes were centrifuged and 100 µL aliquots of the supernatant were weighed into clean Eppendorf tubes.

Measurements

Each 100 µL test solution aliquot, 100 µL supernatant aliquot and the remaining PCT/supernatant was counted

for 1 h on an automated Gamma Counter (HIDEX AMG Gamma-Counter). In addition, six empty gamma counter auto sampler thimbles were counted for 1 h each as a background measurement. The sum of all counts over all detector channels was taken for each measurement and the average background (of the six measurements made) subtracted. The resulting value was then dived by the measurement time of 3600 s yielding a count rate value for each sample. These values were then subsequently decay-corrected to the time of measurement of the corresponding test solution aliquot.

Applications of test solutions to wound dressings

Samples of gauze material (~2.5 × 2.5 cm, ~200 mg) were cut from 10 × 10 cm pads. Three different materials were used: Stepcel (Lohmann and Rauscher), a standard-of-care cellulose fiber; S150, a prototype cellulose and calcium alginate fiber; and a newly developed compound dressing, composed of cellulose and calcium alginate fiber doped with ~4.3 wt % PCT. Treatment solutions were prepared by mixing triply distilled water (~10 mL) with radionuclide solution (~0.1 mL, see below) and subsequently adding gauze material to be tested. In the case of Stepcel only 1 square was treated, whereas in the case of S150 and PCT-doped alginate dressing 2 squares were treated to give a sample mass closer to ~200 mg. In addition, a control vessel containing no gauze was also prepared and all samples were sealed and warmed in a drying oven stabilized at 40 °C. After a given time period (15–16 h), an aliquot (~0.1 mL) was withdrawn from each sample and measured to quantify the radionuclide adsorption.

Results and discussion

Ion exchange capacity

From the measurement data acquired as described above the amount of analyte (Sr^{2+} or Cs^{+}) adsorbed per gram of PCT (gravimetric analyte concentration, c_{PCT} mmol/g) can be easily and most precisely calculated using Eq. 1 below:

$$C_{PCT} = \frac{c_{0sol} m_{0sol}}{m_{PCT}} - \frac{I_{aliquot} R_f \left(m_{0sol} - m_{evap}\right)}{m_{aliquot} m_{PCT}} \quad (1)$$

In Eq. 1, c_{0sol} represents the concentration of the test solution applied (mmol/g; Tables SI8, SI10, SI12 and SI14), m_{0sol} the mass of test solution applied (g; Table SI16), m_{PCT} the mass of PCT treated (g; Table SI16), $I_{aliquot}$ the count rate measured (cts/s; Table SI17) for the 100 µL aliquot of the supernatant after treatment, R_f the test solution response factor (mmol·s/cts; Tables SI9, SI11, SI13 and SI15), m_{evap} the mass of test solution overnight (g; Table SI16) and $m_{aliquot}$ the mass of 100 µL supernatant aliquot (g; Table SI16). The results of the calculations for studies in aqueous and AWFE media for both Sr^{2+} and Cs^{+} are displayed in Tables 1 and 2 and in Figs. 1 and 2.

Table 1 Equilibrium sorption of Sr^{2+} ($c_{PCT}(Sr^{2+})$) by PCT at 40 °C for different $[Sr^{2+}]_0$ values from aqueous and artificial wound fluid exudate media. Uncertainty in solution concentrations (first and third column) are reflected by the number of significant digits. Uncertainties of sorption values are typically dominated by counting statistics

Aqueous (AQ)		Wound exudate (AWFE)	
$[Sr^{2+}]_0$ mol/L	$c_{PCT}(Sr^{2+})$ mmol/g	$[Sr^{2+}]_0$ mol/L	$c_{PCT}(Sr^{2+})$ mmol/g
0.0169	0.258 ± 0.006	0.0135	0.131 ± 0.004
0.0265	0.291 ± 0.005	0.0269	0.200 ± 0.003
0.0507	0.357 ± 0.003	0.0505	0.248 ± 0.002
0.1000	0.381 ± 0.002	0.1000	0.291 ± 0.001
0.2040	0.409 ± 0.001	0.2060	0.372 ± 0.001

Analyte sorption was calculated exclusively from solution count rates rather than by any attempted direct analysis of the resulting solid PCT. This is so to suppress as fully as possible the effects of measurement efficiency due to differences in self-absorption for solid/heterogeneous samples versus liquid/homogenous samples.

Data was fit to a hyperbola (solution to quadratic equation resulting from mass action law describing ion exchange) $y = \frac{ax}{b+x}$. Since a is the theoretical maximum capacity of PCT and b is related to analyte selectivity over Ca^{2+}, sorption behavior (capacity and selectivity) of Sr^{2+} and Cs^{+} from aqueous and AWFE will be discussed.

The Sr^{2+} capacities for PCT measured under aqueous and physiological (AWFE) conditions are not significantly different (AQ: 0.43 ± 0.01 mmol/g vs. AWFE: 0.41 ± 0.03 mmol/g). Additionally, the capacity measured is in good agreement with previous studies [3, 5]. The Cs^{+}

Table 2 Equilibrium sorption of Cs^{+} ($c_{PCT}(Cs^{+})$) by PCT at 40 °C for different $[Cs^{+}]_0$ values from aqueous and artificial wound fluid exudate media. Uncertainty in solution concentrations (first and third column) are reflected by the number of significant digits. Uncertainties of sorption values are typically dominated by counting statistics

Aqueous (AQ)		Wound exudate (AWFE)	
$[Cs^{+}]_0$ mol/L	$c_{PCT}(Cs^{+})$ mmol/g	$[Cs^{+}]_0$ mol/L	$c_{PCT}(Cs^{+})$ mmol/g
0.0252	0.445 ± 0.015	0.0255	0.420 ± 0.009
0.0501	0.820 ± 0.015	0.0499	0.771 ± 0.008
0.0999	1.085 ± 0.009	0.0998	1.046 ± 0.006
0.2000	1.214 ± 0.006	0.2010	1.172 ± 0.005
0.4000	1.453 ± 0.003	0.4000	1.281 ± 0.003
0.8000	1.467 ± 0.001	0.8010	1.215 ± 0.001

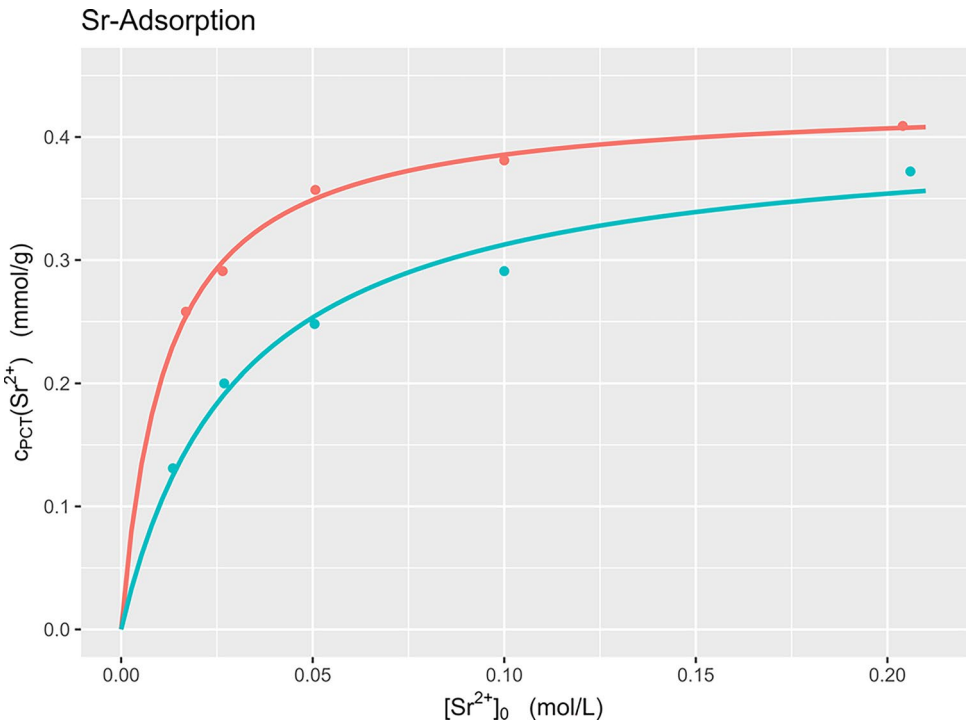

Fig. 1 Plot of $[Sr^{2+}]_0$ versus $c_{PCT}(Sr^{2+})$ for sorption by PCT at 40 °C. The curves depict the results of unweighted least-squares fits to $c_{PCT}(Sr^{2+}) = \frac{a[Sr^{2+}]_0}{b+[Sr^{2+}]_0}$ to data acquired in aqueous (red) and AWFE (turquoise) media for which $a_{aq}(Sr^{2+}) = 0.43 \pm 0.01$ mmol/g, $b_{aq}(Sr^{2+}) = 0.031 \pm 0.005$ mol/L, $a_{AWFE}(Sr^{2+}) = 0.41 \pm 0.03$ mmol/g and $b_{AWFE}(Sr^{2+}) = 0.012 \pm 0.001$ mol/L

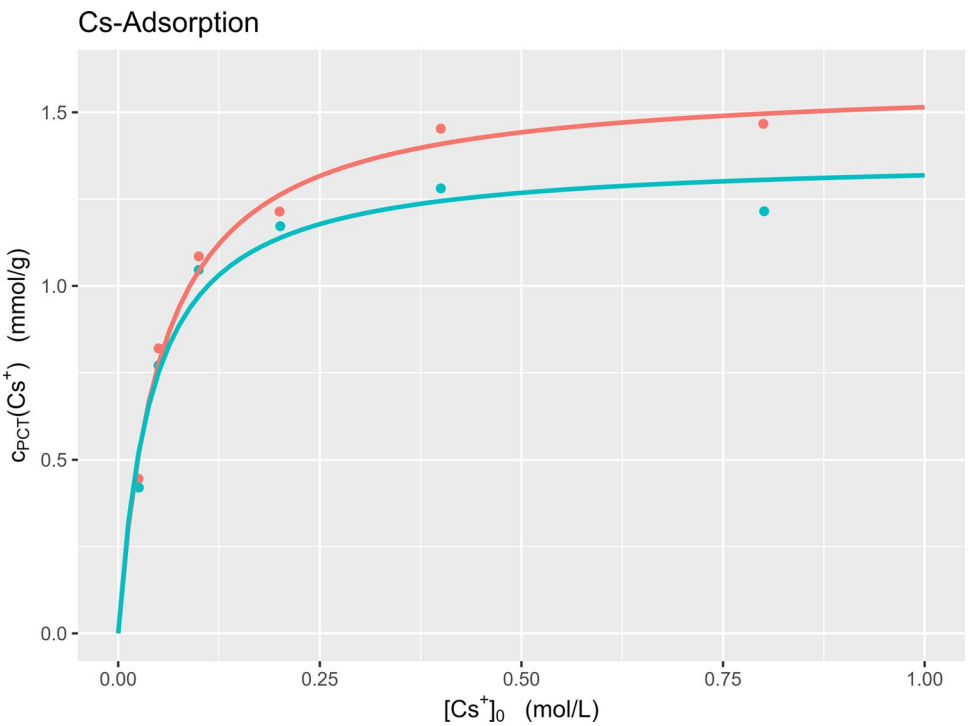

Fig. 2 Plot of $[Cs^{+}]_0$ versus $c_{PCT}(Cs^{+})$ for sorption by PCT at 40 °C. The curves depict the results of unweighted least-squares fits to $c_{PCT}(Cs^{+}) = \frac{a[Cs^{+}]_0}{b+[Cs^{+}]_0}$ to data acquired in aqueous (red) and AWFE (turquoise) media for which $a_{aq}(Cs^{+}) = 1.60 \pm 0.05$ mmol/g, $b_{aq}(Cs^{+}) = 0.053 \pm 0.007$ mol/L, $a_{AWFE}(Cs^{+}) = 1.37 \pm 0.07$ mmol/g and $b_{AWFE}(Cs^{+}) = 0.041 \pm 0.008$ mol/L

Table 3 Equilibrium sorption of radionuclides by wound dressing materials

	PCT-doped alginate dressing		Control alginate dressing		Control cellulose-based dressing	
Isotope	Applied (Bq)	Remaining (Bq)	Applied (Bq)	Remaining (Bq)	Applied (Bq)	Remaining (Bq)
^{89}Sr	77	44	77	26	77	74
^{134}Cs	3900	1300	3900	3400	3900	2800
^{137}Cs	6000	2300	6000	5600	6000	4700

capacities for PCT measured under aqueous and physiological (AWFE) conditions are slightly different (AQ: 1.60 ± 0.05 mmol/g vs. AWFE: 1.37 ± 0.07 mmol/g), with the measured capacity slightly reduced under physiological conditions. Uncertainties in capacity values are dominated by the appropriateness of the model and are thus larger than individual measurement uncertainties (see Tables 1 and 2). Nevertheless, the capacities measured are still in relatively good agreement with previous determinations. Finally, not entirely unexpectedly, the molar capacity of PCT for Cs^+ is nearly four times that for Sr^{2+}. This seems to indicate that Sr^{2+} and Cs^+ are exchanged at different (negatively charged) sites within the zeolite framework and a more limited number of sites appropriate for the divalent Sr^{2+} are available in clinoptilolite.

The selectivity of PCT for Sr^{2+} over Ca^{2+} is effected significantly by the conditions of study (aqueous or AWFE) with physiological ions competing significantly with Sr for Ca replacement in PCT (AQ: 0.031 ± 0.005 mol/L vs. AWFE: 0.012 ± 0.001 mol/L). On the other hand, the selectivity of PCT for Cs^+ over Ca^{2+} is not significantly effected by the medium (aqueous or physiological) under study and it therefore seems that physiological ions have little effect on selectivity of Cs^+ over Ca^{2+} in PCT.

Wound dressings

Initial qualitative ion-exchange studies with ^{134}Cs tracered solutions were carried out on the PCT-doped alginate wound dressing and two control samples (alginate wound dressing without PCT and a cellulose-based wound dressing). Aliquots were withdrawn after 10 min, 60 min, standing overnight and standing for two days. No weighing or quantification other than radiometric measurement of the aliquots was undertaken. Qualitatively, the results show that (1) Cs is most strongly absorbed by the PCT-doped alginate wound dressing (~ 50% Cs applied is no longer in solution) and (2) this process has certainly reached equilibrium after standing overnight (and is probably complete after 3–4 h). The majority of sorption typically occurs within the first 30 min [9, 10].

Subsequently, quantitative experiments with 75 µM CsCl solutions tracered with 4 kBq of ^{134}Cs were carried out including testing of a blank (no gauze material), control cellulose-based dressing, control alginate dressing and PCT-doped alginate wound dressing. The resulting mixtures were maintained at 40 °C overnight after which time they were checked for evaporative loss (by weighing) and precisely weighed aliquots were taken of each sample. These aliquots were measured radiometrically (gamma spectroscopy) and the amount of Cs absorbed by each sample was calculated. Additionally, quantitative experiments with ^{137}Cs (6 kBq) solutions of unknown Cs concentration were also carried out and the ^{137}Cs activity absorbed by each sample was calculated. For both solutions containing lower specific activity ^{134}Cs and the higher specific activity ^{137}Cs, Cs exchange behavior of all samples tested is similar with some exchange (~ 25% radiotracer removed from solution) by cellulosic control material alone, minimal exchange for the control alginate dressing (< 10% radiotracer removed from solution) and significant exchange (~ 65% radiotracer removed from solution) by the PCT-doped alginate dressing. Under the laboratory conditions described, PCT-doping of alginate dressings is favorable for the adsorption of low concentrations (representative of fission product concentrations) of Cs^+ ions. While we expect the favorable aspects of PCT-doping to be applicable under field conditions, further studies under these conditions will be demonstrate this.

Quantitative experiments with 3.5 mM $SrCl_2$ solutions tracered with $^{85/89}$Sr (~ 100 Bq each) were also conducted as described above and evaluated radiometrically (liquid scintillation counting). The results of these experiments are largely inconclusive due to the relatively large $SrCl_2$ concentrations applied to the test materials (the specific activity of ^{85}Sr produced by thermal neutron irradiation of natural Sr is fundamentally (neutron capture cross section) quite small). Nonetheless, qualitative exchange with alginate and PCT containing materials could be observed (See Table 3).

Conclusions

Radio-Cs^+ as well as -Sr^{2+} are proven to be bound by PCT (purified clinoptilolite-tuff) under different conditions:

- The Cs^+ capacities for PCT measured under aqueous and physiological (AWFE) conditions differ slightly (AQ:

1.60 ± 0.05 mmol/g vs. AWFE: 1.37 ± 0.07 mmol/g), but the preference of PCT for Cs^+ over Ca^{2+} seems to be qualitatively unaffected by medium.

- The Sr^{2+} capacities for PCT measured under aqueous and physiological (AWFE) conditions are not significantly different (AQ: 0.43 ± 0.01 mmol/g vs. AWFE: 0.41 ± 0.03 mmol/g), but the preference of PCT for Sr^{2+} over Ca^{2+} does seem to be affected by medium.
- Tests were conducted on wound dressings at Sr^{2+} and Cs^+ concentrations that mimic those found in fission-related radionuclide releases. Uptake of Cs^+ and Sr^{2+} by the PCT-doped alginate dressing significantly outperforms the cellulose standard-of-care control dressing, which demonstrates minimal sorption efficacy.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10967-025-10413-7.

Funding Open access funding provided by TU Wien (TUW).

Data availability All data is available in this publication and its supplementary information.

Declarations

Conflict of interest The authors declare no conflict of interests.

References

1. Ames LL Jr (1964) Some zeolite equilibriums with alkaline earth metal cations. Am Mineral 49:1099–1110
2. Ames LL Jr (1964) Some zeolite equilibriums with alkali metal cations. Am Mineral 49:127–145
3. Howery DG (1963) A study of ion exchange properties of the zeolite, clinoptilolite. University of North Carolina, Chapel Hill
4. Dyer A (2007). In: Cejka J, van Bekkum H, Corma A, Schüth F (eds) Introduction to zeolite science and practice, 3rd edn. Elsevier, Amsterdam. https://doi.org/10.1016/S0167-2991(07)80804-4
5. Sterba JH, Sperrer H, Wallenko F, Welch JM (2018) Adsorption characteristics of a clinoptilolite-rich zeolite compound for Sr and Cs. J Radioanal Nucl Chem 318:267–270. https://doi.org/10.1007/s10967-018-6096-6
6. Lihareva N, Dimowa L, Petrov O, Tzvetanova Y (2018) Evaluation of Bulgarian clinoptilolite as ion-exchanger for Cs+ removal from water solutions. J Radioanal Nucl Chem 316:37–47. https://doi.org/10.1007/s10967-018-5715-6
7. Tschegg C, Rice AHN, Grasemann B, Matiasek E, Kobulej P, Dzivák M, Berger T (2019) Petrogenesis of a large-scale Miocene zeolite tuff in the eastern Slovak Republic: the Nižný Hrabovec open-pit clinoptilolite mine. Econ Geol 114:1177–1194. https://doi.org/10.5382/econgeo.4679
8. Tschegg C, Hou Z, Rice AHN, Fendrych J, Matiasek E, Berger T, Grasemann B (2020) Fault zone structures and strain localization in clinoptilolite-tuff (Nižný Hrabovec, Slovak Republic). J Struct Geol. https://doi.org/10.1016/j.jsg.2020.104090
9. Haemmerle MM, Fendrych J, Matiasek E, Tschegg C (2021) Adsorption and release characteristics of purified and non-purified Clinoptilolite tuffs towards health-relevant heavy metals. Crystals. https://doi.org/10.3390/cryst11111343
10. Ranftler C, Nagl D, Sparer A, Röhrich A, Freissmuth M, El-Kasaby A, Nasrollahi Shirazi S, Koban F, Tschegg C, Nizet S (2021) Binding and neutralization of *C. difficile* toxins A and B by purified clinoptilolite-tuff. PLoS ONE. https://doi.org/10.1371/journal.pone.0252211
11. Samekova K, Firbas C, Irrgeher J, Opper C, Prohaska T, Retzmann A, Tschegg C, Meisslitzer C, Tchaikovsky A, Gouya G, Freissmuth M, Wolzt M (2021) Concomitant oral intake of purified clinoptilolite tuff (G-PUR) reduces enteral lead uptake in healthy humans. Sci Rep. https://doi.org/10.1038/s41598-021-94245-x
12. Anderle K, Wolzt M, Moser G, Keip B, Peter J, Meisslitzer C, Gouya G, Freissmuth M, Tschegg C (2022) Safety and efficacy of purified clinoptilolite-tuff treatment in patients with irritable bowel syndrome with diarrhea: randomized controlled trial. World J Gastroenterol 28:6573–6588. https://doi.org/10.3748/wjg.v28.i46.6573
13. Deinsberger J, Marquart E, Nizet S, Meisslitzer C, Tschegg C, Uspenska K, Gouya G, Niederdöckl J, Freissmuth M, Wolzt M, Weber B (2022) Topically administered purified clinoptilolite-tuff for the treatment of cutaneous wounds: a prospective, randomised phase I clinical trial. Wound Repair Regen 30:198–209. https://doi.org/10.1111/wrr.12991