Electronic Supplementary Materials (ESM)

Kinetic studies of Cs^{+} and Sr^{2+} ion exchange using clinoptilolite in static columns and an agitated tubular reactor (ATR)

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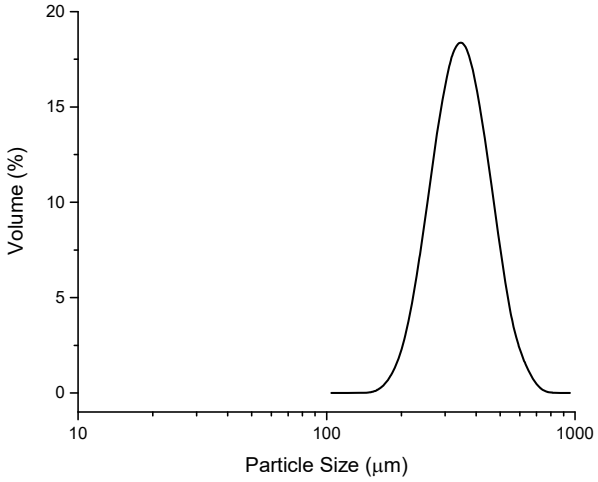

Figure S1: Particle size distribution of clinoptilolite after sieving.

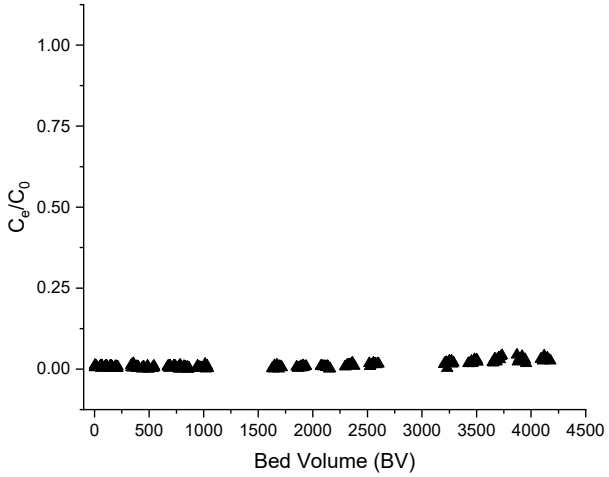

Figure S2: The breakthrough of cesium at 5 ppm initial concentration.

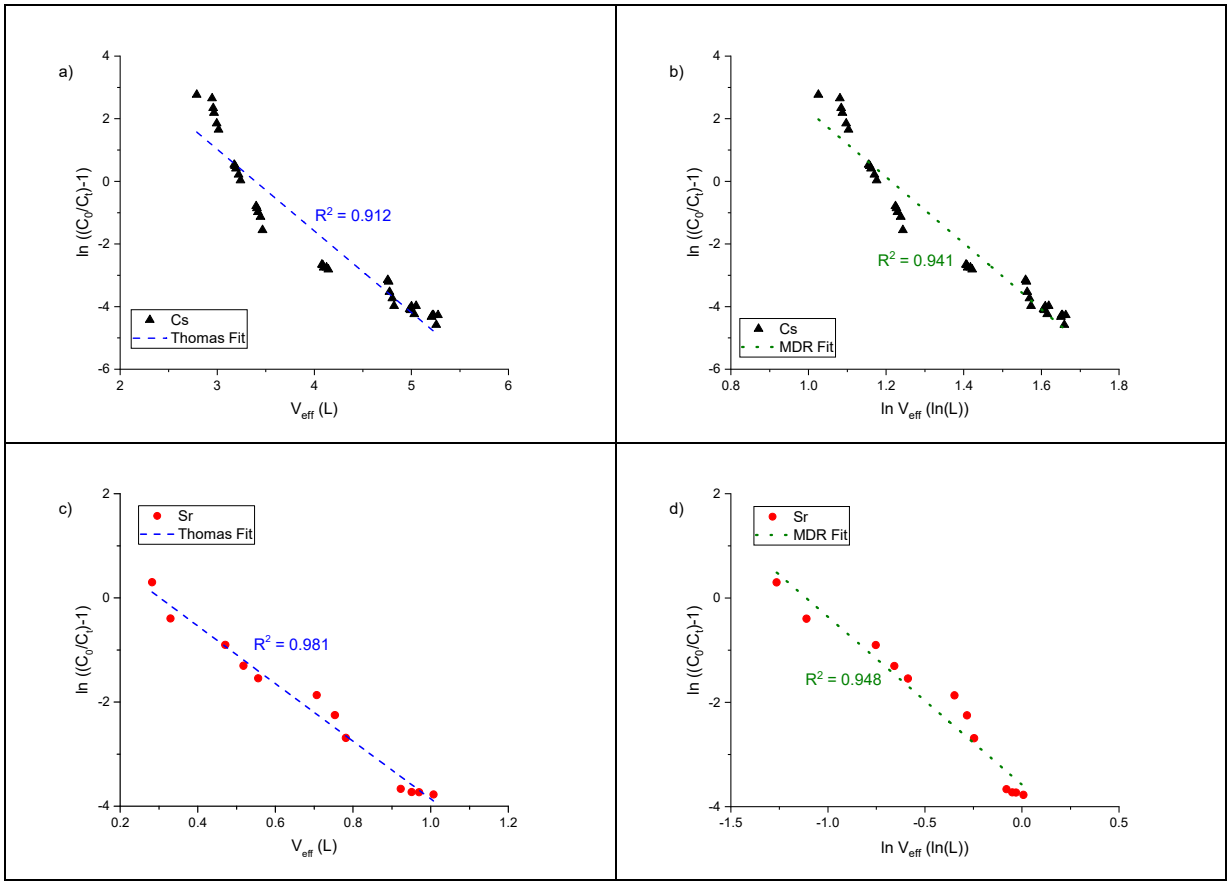

Figure S3: The linearised column breakthrough fits for cesium and strontium solutions at 200 ppm. Shown is a) Thomas model for cesium; b) MDR model for cesium; c) Thomas model for strontium and d) MDR model for strontium. The dashed lines represent linear fits.

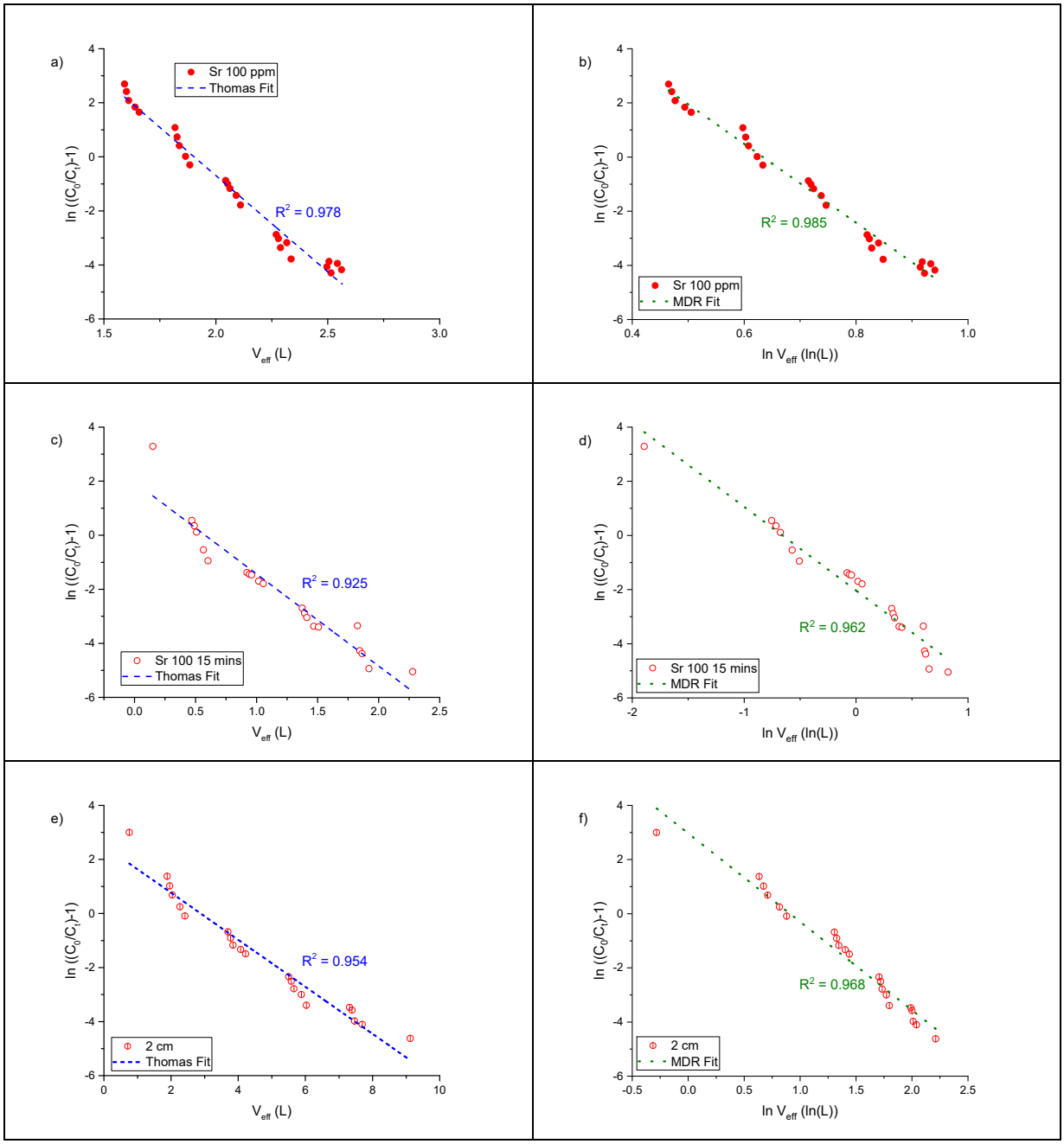

Figure S4: The linearised column breakthrough fitting for strontium at 100 ppm. Shown is a) Thomas model for 30 mins residence time; b) MDR model for 30 mins residence time; c) Thomas model for 15 mins residence time; d) MDR model for 15 mins residence time; e) Thomas model for 15 mins residence time at 2 cm column diameter and f) MDR model for 15 mins residence time at 2 cm column diameter. The dashed lines represent linear fits.

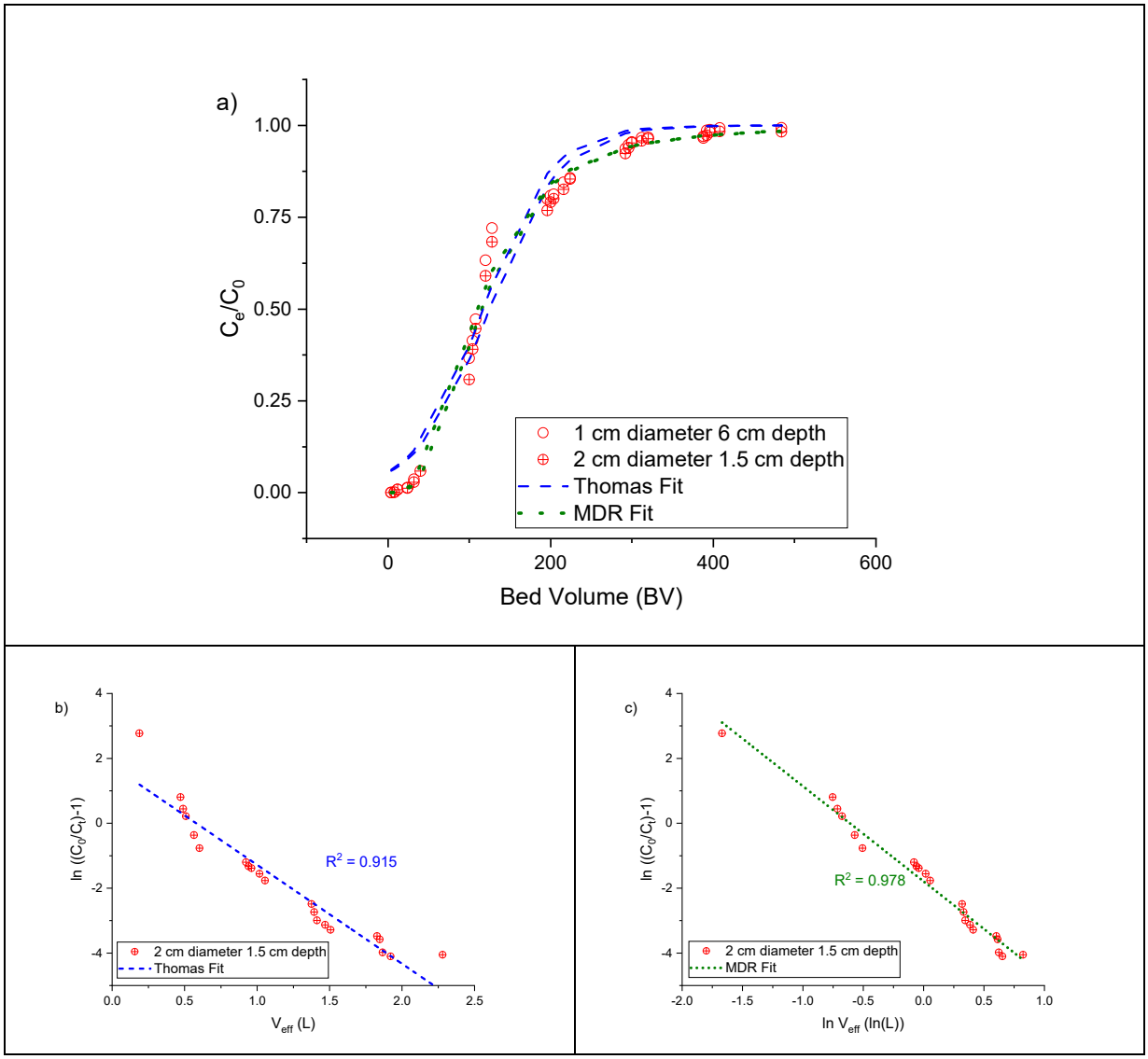

Figure S5: a) Experimental breakthrough data and Thomas and MDR fits, for strontium at 100 ppm concentration for two systems with identical residence times (15 mins) and the same adsorbent volume, with increasing column diameter; b) The linearised fitting of Thomas model for the 1.5 cm adsorbent height and 2 cm diameter column; c) The linearised fitting of MDR model for the 1.5 cm adsorbent height and 2 cm diameter column. The dashed lines in b) and c) represent linear fits.

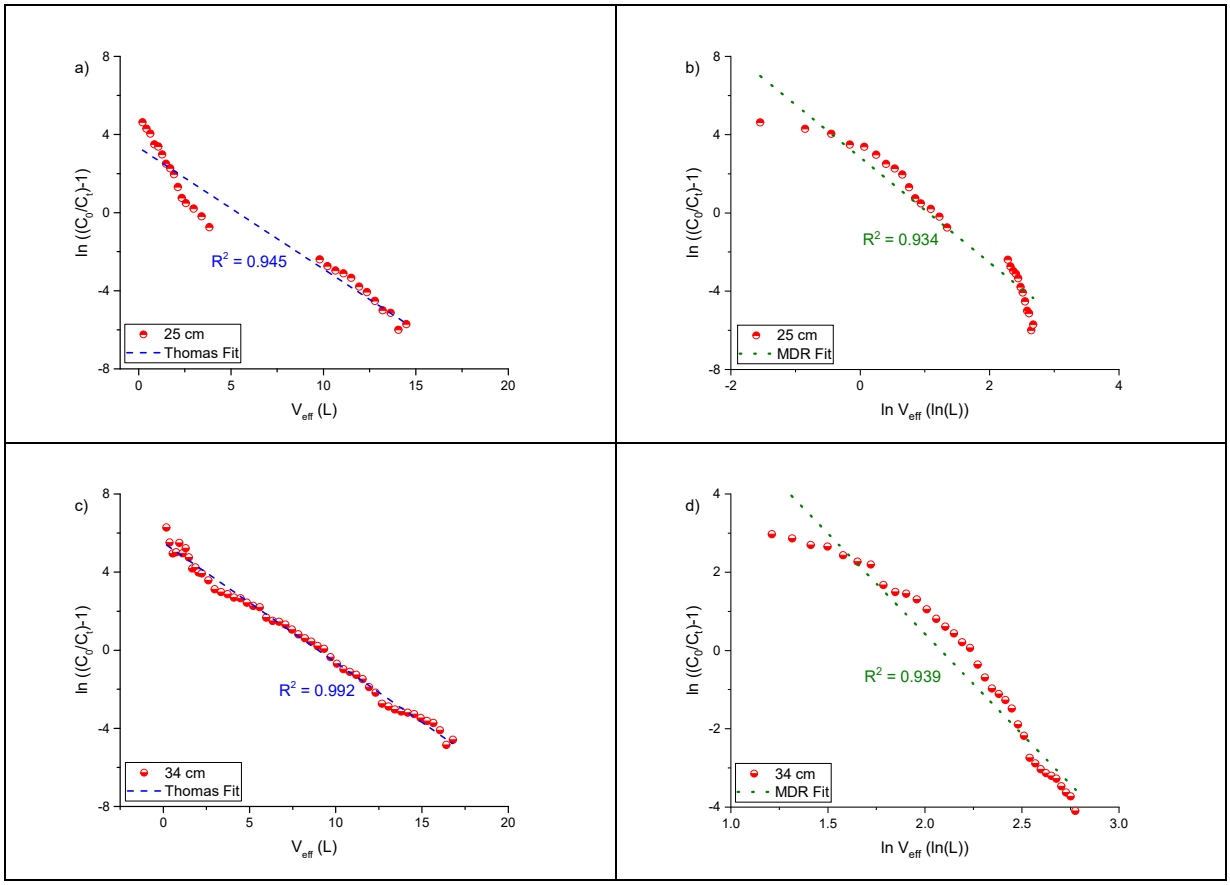

Figure S6: The linearised breakthrough fitting data from the agitated tubular reactor (ATR). Shown is a) Thomas model with 25 cm of adsorbent bed length; b) MDR model with 25 cm of adsorbent bed length; c) Thomas model with 34 cm of adsorbent bed length; and d) MDR model in 34 cm of adsorbent bed length. The dashed lines represent linear fits.

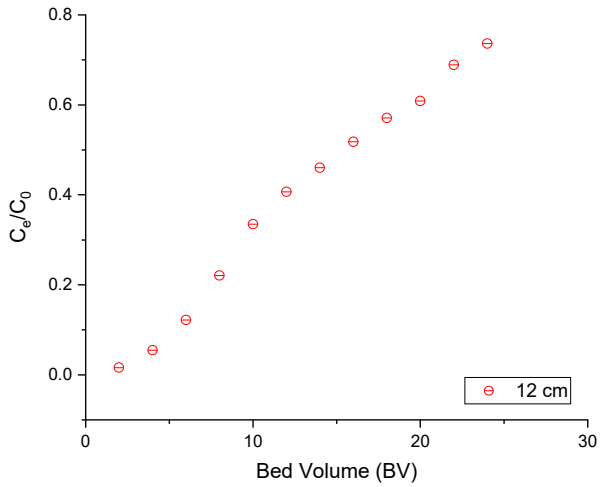

Figure S7: Preliminary breakthrough data from the agitated tubular reactor (ATR) with a 12 cm column length (for a 100 ppm strontium liquid concentration). Note, trial was aborted after C_e/Co reached ~0.75, due to poor performance.

Dataset: 1: Static column breakthrough data – showing outlet concentration (Ce, in mg/L) for increasing volume of processed liquid (in bed volumes).

Table 1 S1 a): Strontium 200 ppm, 30 minutes.

Bed Volume	Ce	Ce	Ce	Average Ce (mg/L)	StdDev (%)
2	0.7215	0.604	0.6365	0.654	9.28
12	5.42275	5.129	5.21025	5.254	2.89
20	13.2443	11.604	12.0577	12.302	6.89
50	45.25415	43.635	44.08285	44.324	1.89
60	86.40775	84.375	84.93725	85.24	1.23
70	121.4708	118.357	119.2183	119.682	1.34
100	149.5812	137.004	140.4828	142.356	4.56
110	161.8148	154.001	156.1623	157.326	2.56
118	170.6828	160.519	163.3303	164.844	3.18
150	180.4646	167.878	171.3594	173.234	3.75
160	182.6443	179.695	180.5108	180.95	0.84
166	190.2846	185.03	186.4834	187.266	1.45
196	195.5093	194.668	194.9007	195.026	0.22
202	195.7374	194.983	195.1917	195.304	0.20
206	195.6783	195.0546	195.2271	195.32	0.16
214	195.8676	195.266	195.4324	195.522	0.16

Table 1 S1 b): Cesium 200 ppm, 30 minutes.

bed volume	Ce1	Ce2	Ce3	Average Ce (mg/L)	StdDev (%)
2	0.868	0.754	0.691	0.771	11.64
4	0.833	0.761	0.722	0.772	7.29
6	0.837	0.765	0.726	0.776	7.26
12	0.819	0.775	0.752	0.782	4.35
16	0.888	0.844	0.821	0.851	4.00
50	1.068	0.924	0.846	0.946	11.91
52	1.024	0.952	0.913	0.963	5.85
54	1.079	0.965	0.902	0.982	9.14
60	1.085	0.985	0.93	1	7.86
64	1.166	1.036	0.966	1.056	9.61
98	1.516	1.142	0.939	1.199	24.41
100	1.279	1.193	1.146	1.206	5.59
102	1.764	1.232	0.943	1.313	31.72
108	1.7	1.542	1.456	1.566	7.90
112	2.125	1.521	1.193	1.613	29.31
194	1.796	1.738	1.707	1.747	2.59
196	2.151	1.721	1.486	1.786	18.88
198	1.955	1.811	1.733	1.833	6.14
204	2.35	1.92	1.685	1.985	16.99
208	2.378	1.962	1.735	2.025	16.10
242	2.43	2.158	2.009	2.199	9.71
244	2.548	2.204	2.016	2.256	11.96
246	2.764	2.232	1.943	2.313	18.00
252	2.766	2.35	2.123	2.413	13.51
256	2.896	2.422	2.164	2.494	14.89
290	2.743	2.485	2.344	2.524	8.02
292	2.967	2.537	2.302	2.602	12.96

294	**3.152**	**2.65**	**2.376**	**2.726**	**14.44**
300	**2.877**	**2.805**	**2.766**	**2.816**	**2.00**
304	**3.409**	**2.921**	**2.655**	**2.995**	**12.77**
338	**3.519**	**2.959**	**2.654**	**3.044**	**14.41**
340	**3.534**	**3.204**	**3.024**	**3.254**	**7.95**
342	**3.63**	**3.256**	**3.053**	**3.313**	**8.83**
348	**3.738**	**3.566**	**3.472**	**3.592**	**3.76**
352	**3.833**	**3.761**	**3.722**	**3.772**	**1.49**
386	**4.127**	**3.797**	**3.617**	**3.847**	**6.72**
388	**3.96**	**3.902**	**3.871**	**3.911**	**1.16**
390	**4.421**	**3.833**	**3.512**	**3.922**	**11.75**
396	**4.198**	**3.91**	**3.754**	**3.954**	**5.70**
400	**4.419**	**3.917**	**3.643**	**3.993**	**9.86**
530	**4.326**	**3.982**	**3.794**	**4.034**	**6.69**
532	**4.272**	**4.1**	**4.006**	**4.126**	**3.27**
534	**4.32**	**4.162**	**4.076**	**4.186**	**2.96**
540	**4.82**	**4.202**	**3.866**	**4.296**	**11.26**
544	**4.454**	**4.34**	**4.277**	**4.357**	**2.06**
578	**4.462**	**4.418**	**4.395**	**4.425**	**0.77**
580	**5.598**	**5.31**	**5.154**	**5.354**	**4.21**
582	**8.133**	**7.573**	**7.268**	**7.658**	**5.73**
588	**9.123**	**8.993**	**8.923**	**9.013**	**1.13**
592	**12.146**	**11.802**	**11.614**	**11.854**	**2.28**
626	**13.544**	**13.128**	**12.901**	**13.191**	**2.47**
628	**17.947**	**17.501**	**17.259**	**17.569**	**1.99**
630	**20.819**	**20.037**	**19.612**	**20.156**	**3.04**
636	**27.668**	**27.04**	**26.697**	**27.135**	**1.81**
640	**33.041**	**31.943**	**31.346**	**32.11**	**2.68**
674	**74.612**	**73.901**	**73.514**	**74.009**	**0.75**
676	**76.805**	**75.803**	**75.257**	**75.955**	**1.03**
678	**80.15**	**79.57**	**79.254**	**79.658**	**0.57**
684	**89.747**	**89.285**	**89.033**	**89.355**	**0.41**
688	**99.153**	**98.183**	**97.654**	**98.33**	**0.77**
722	**138.206**	**137.76**	**137.518**	**137.828**	**0.25**
724	**141.227**	**140.211**	**139.657**	**140.365**	**0.57**
726	**145.867**	**145.276**	**144.955**	**145.366**	**0.32**
732	**152.014**	**151.203**	**150.761**	**151.326**	**0.42**
736	**166.205**	**165.086**	**164.477**	**165.256**	**0.53**
866	**187.586**	**186.822**	**186.406**	**186.938**	**0.32**
868	**187.443**	**187.056**	**186.846**	**187.115**	**0.16**
870	**188.305**	**187.963**	**187.777**	**188.015**	**0.14**
876	**188.258**	**187.969**	**187.812**	**188.013**	**0.12**
880	**189.143**	**188.604**	**188.311**	**188.686**	**0.22**
1010	**192.433**	**191.65**	**191.224**	**191.769**	**0.32**
1012	**192.473**	**192.169**	**192.003**	**192.215**	**0.12**
1014	**195.259**	**194.158**	**193.558**	**194.325**	**0.44**
1020	**196.304**	**195.185**	**194.576**	**195.355**	**0.45**
1024	**196.684**	**196.261**	**196.03**	**196.325**	**0.17**
1058	**197.627**	**196.515**	**195.91**	**196.684**	**0.44**
1060	**197.479**	**196.667**	**196.224**	**196.79**	**0.32**
1062	**196.791**	**196.289**	**196.015**	**196.365**	**0.20**
1068	**197.724**	**197.052**	**196.686**	**197.154**	**0.27**

1072	196.833	196.235	195.91	196.326	0.24
1106	198.237	197.26	196.727	197.408	0.39
1108	197.805	197.158	196.805	197.256	0.26
1110	197.782	197.161	196.822	197.255	0.25
1116	198.857	197.829	197.269	197.985	0.41
1120	197.87	197.144	196.748	197.254	0.29

Table 1 S1 c): Strontium 100 ppm, 30 minutes.

bed volume	Ce 1	Ce 2	Ce 3	Average Ce (mg/L)	StdDev (%)
2	0.093	0.082	0.077	0.084	9.74
4	0.079	0.074	0.072	0.075	4.81
6	0.067	0.065	0.063	0.065	3.08
12	0.092	0.08	0.074	0.082	11.18
16	0.081	0.073	0.068	0.074	8.86
50	0.102	0.094	0.089	0.095	6.90
52	0.131	0.124	0.12	0.125	4.45
54	0.127	0.114	0.107	0.116	8.75
60	0.151	0.145	0.142	0.146	3.14
64	0.139	0.138	0.137	0.138	0.72
98	0.222	0.209	0.202	0.211	4.81
100	0.273	0.261	0.255	0.263	3.48
102	0.367	0.361	0.358	0.362	1.27
108	0.375	0.362	0.355	0.364	2.79
112	0.397	0.389	0.384	0.390	1.68
146	0.564	0.562	0.56	0.562	0.36
148	0.654	0.632	0.619	0.635	2.79
150	0.664	0.65	0.642	0.652	1.71
156	0.77	0.752	0.743	0.755	1.82
160	0.783	0.752	0.736	0.757	3.16
194	0.912	0.892	0.881	0.895	1.76
196	1.013	0.987	0.973	0.991	2.05
198	1.134	1.123	1.118	1.125	0.73
204	1.257	1.216	1.193	1.222	2.65
208	1.325	1.304	1.292	1.307	1.28
242	2.328	2.303	2.29	2.307	0.84
338	6.374	6.32	6.29	6.328	0.67
340	8.24	8.209	8.193	8.214	0.29
342	11.152	11.105	11.079	11.112	0.33
348	13.748	13.689	13.657	13.698	0.34
352	16.094	16.067	16.052	16.071	0.13
386	25.42	25.355	25.32	25.365	0.20
388	32.376	32.363	32.356	32.365	0.03
390	40.137	39.793	39.605	39.845	0.68
396	50.075	49.543	49.254	49.624	0.84
400	57.935	57.419	57.137	57.497	0.70
434	70.974	70.63	70.442	70.682	0.38
436	73.398	73.312	73.265	73.325	0.09
438	76.913	76.267	75.915	76.365	0.66
444	80.933	80.603	80.423	80.653	0.32
448	86.028	85.554	85.296	85.626	0.43
482	95.017	94.587	94.352	94.652	0.36

484	95.791	95.289	95.015	95.365	0.41
486	96.995	96.593	96.374	96.654	0.33
492	96.121	95.963	95.877	95.987	0.13
496	98.263	97.689	97.376	97.776	0.46
530	98.397	98.311	98.264	98.324	0.07
532	98.299	97.897	97.678	97.958	0.32
534	98.885	98.613	98.464	98.654	0.22
540	98.154	98.096	98.065	98.105	0.05
544	98.731	98.443	98.287	98.487	0.23

Table 1 S1 d): Strontium 100 ppm, 15 minutes.

bed volume	Ce 1	Ce 2	Ce 3	Average Ce (mg/L)	StdDev (%)
4	0.025	0.065	0.059	0.049667	43.43
8	0.125	0.11	0.165	0.133333	21.32
12	0.765	0.857	0.904	0.842	8.40
24	1.573	1.445	1.113	1.377	17.24
32	3.673	3.57	3.583	3.608667	1.55
100	35.652	37.25	36.985	36.629	2.34
104	40.987	40.225	42.952	41.388	3.40
108	48.365	47.02	46.25	47.21167	2.27
120	63.35	63.887	62.557	63.26467	1.06
128	73.19	72.61	70.202	72.00067	2.20
196	79.02	80.685	80.112	79.939	1.06
200	80.365	80.658	81.665	80.896	0.84
204	80.958	81.257	81.511	81.242	0.34
216	84.993	84	84.569	84.52067	0.59
224	85.231	86.295	85.532	85.686	0.64
292	93.799	93.966	93.325	93.69667	0.35
296	94.665	94.224	95.265	94.718	0.55
300	95.234	95.856	95.254	95.448	0.37
312	96.165	96.588	97.258	96.67033	0.57
320	96.356	95.689	98.235	96.76	1.36
388	95.936	97.862	96.025	96.60767	1.13
392	97.265	99.258	99.355	98.626	1.20
396	98.552	98.5	99.25	98.76733	0.42
408	99.185	99.087	99.587	99.28633	0.27
484	99.215	99.218	99.652	99.36167	0.25

Table 1 S1 e): Strontium 100 ppm, 15 minutes, 2 cm diameter column.

bed volume	Ce 1	Ce 2	Ce 3	Average Ce (mg/L)	StdDev (%)
4	0.025	0.088	0.078	0.063667	53.18
8	0.105	0.099	0.125	0.109667	12.41
12	0.51	0.57	0.562	0.547333	5.95
24	0.958	0.845	0.775	0.859333	10.75
32	1.253	1.325	1.558	1.378667	11.56
40	4.256	4.856	5.125	4.745667	9.37
100	18.686	20.565	21.256	20.169	6.59
104	25.325	26.36	27.856	26.51367	4.80
108	33.256	35.586	31.853	33.565	5.62

120	**45.365**	**44.856**	**41.256**	**43.82567**	**5.11**
128	**51.025**	**53.365**	**52.325**	**52.23833**	**2.24**
196	**61.025**	**69.875**	**68.255**	**66.385**	**7.10**
200	**71.232**	**70.325**	**72.362**	**71.30633**	**1.43**
204	**75.365**	**76.325**	**77.258**	**76.316**	**1.24**
216	**79.398**	**79.325**	**78.698**	**79.14033**	**0.49**
224	**81.225**	**82.685**	**81.035**	**81.64833**	**1.11**
292	**91.324**	**90.558**	**91.683**	**91.18833**	**0.63**
296	**93.32**	**93.852**	**90.258**	**92.47667**	**2.10**
300	**94.695**	**94.005**	**93.846**	**94.182**	**0.48**
312	**94.996**	**95.115**	**95.665**	**95.25867**	**0.37**
320	**96.356**	**95.689**	**98.235**	**96.76**	**1.36**
388	**97.115**	**97.862**	**96.025**	**97.00067**	**0.95**
392	**97.265**	**98.213**	**96.365**	**97.281**	**0.95**
396	**97.889**	**98.5**	**98.115**	**98.168**	**0.31**
408	**98.255**	**98.225**	**98.658**	**98.37933**	**0.25**
484	**98.221**	**99.218**	**99.652**	**99.03033**	**0.74**

Dataset: 2: Agitated tubular reactor (ATR) data – showing outlet concentration (Ce, in mg/L) for increasing volume of processed liquid (in bed volumes).

Table S2 a): ATR 25 cm, 15 minutes residence time.

bed volume	Ce 1	Ce 2	Ce 3	Average Ce (mg/L)	StdDev (%)
6	0.601	1.531	0.795	0.976	50.29
12	1.291	1.661	1.095	1.349	21.31
17	1.591	2.071	1.507	1.723	17.66
23	2.601	3.241	3.025	2.956	11.02
29	3.031	3.671	3.165	3.289	10.26
35	4.961	4.431	5.125	4.839	7.50
40	7.031	7.981	7.585	7.532	6.34
46	9.401	8.985	9.835	9.407	4.52
52	13.701	12.231	11.105	12.346	10.54
58	22.831	19.661	21.125	21.206	7.48
64	33.261	32.245	31.102	32.203	3.35
69	37.254	37.856	39.352	38.154	2.83
81	45.286	44.658	44.998	44.981	0.70
93	56.325	54.368	53.658	54.784	2.52
104	66.325	67.856	69.365	67.849	2.24
266	91.258	91.325	92.325	91.636	0.65
278	93.325	94.256	94.284	93.955	0.58
289	94.256	95.356	95.651	95.088	0.77
301	96.321	95.256	95.658	95.745	0.56
312	96.354	96.686	96.685	96.575	0.20
324	97.254	98.114	98.001	97.790	0.48
335	98.256	98.332	98.365	98.318	0.06
347	98.254	99.254	99.256	98.921	0.58
358	98.989	99.359	99.654	99.334	0.34
370	99.365	99.211	99.658	99.411	0.23
382	99.385	99.889	99.986	99.753	0.32
393	99.986	99.658	99.365	99.670	0.31

Table S2 b): ATR 34 cm, 15 minutes residence time.

bed volume	Ce 1	Ce 2	Ce 3	Average Ce (mg/L)	StdDev (%)
4	0.251	0.151	0.16	0.187	29.53
7	0.553	0.431	0.221	0.402	41.81
11	0.654	0.682	0.772	0.703	8.77
15	0.654	0.883	0.441	0.659	33.53
19	0.251	0.431	0.551	0.411	36.74
22	0.855	0.652	0.581	0.696	20.43
26	0.774	0.251	0.581	0.535	49.40
30	0.855	0.722	0.992	0.856	15.77
33	1.257	1.565	1.694	1.505	14.92
37	1.357	1.585	1.363	1.435	9.05
41	1.76	1.856	1.885	1.834	3.57
45	1.971	1.957	1.885	1.938	2.38
52	2.544	2.689	2.997	2.743	8.43
60	4.133	4.214	4.361	4.236	2.73
67	4.977	4.706	4.922	4.868	2.94

74	**5.148**	**5.268**	**5.784**	**5.400**	**6.26**
82	**6.355**	**6.272**	**6.366**	**6.331**	**0.81**
89	**6.284**	**6.683**	**6.767**	**6.578**	**3.92**
97	**7.29**	**7.797**	**9.123**	**8.070**	**11.73**
104	**9.301**	**9.151**	**9.574**	**9.342**	**2.30**
112	**10.166**	**10.285**	**9.574**	**10.008**	**3.81**
119	**15.344**	**15.734**	**16.261**	**15.780**	**2.92**
127	**17.345**	**19.316**	**18.266**	**18.309**	**5.39**
134	**18.35**	**19.316**	**19.378**	**19.015**	**3.03**
141	**21.337**	**22.377**	**20.301**	**21.338**	**4.86**
149	**25.499**	**25.769**	**26.396**	**25.888**	**1.78**
156	**30.416**	**30.786**	**31.298**	**30.833**	**1.44**
164	**35.394**	**35.342**	**35.088**	**35.275**	**0.46**
171	**38.531**	**39.717**	**39.539**	**39.262**	**1.63**
179	**43.488**	**45.807**	**44.962**	**44.752**	**2.62**
186	**49.3**	**45.476**	**50.376**	**48.384**	**5.32**
194	**56.63**	**58.451**	**61.473**	**58.851**	**4.16**
201	**65.941**	**66.479**	**67.428**	**66.616**	**1.13**
208	**71.642**	**72.58**	**73.433**	**72.552**	**1.23**
216	**75.774**	**72.57**	**77.413**	**75.252**	**3.27**
223	**78.077**	**78.149**	**77.744**	**77.990**	**0.28**
231	**81.667**	**80.276**	**82.566**	**81.503**	**1.42**
238	**85.719**	**86.618**	**88.24**	**86.859**	**1.47**
246	**90.143**	**89.197**	**90.205**	**89.848**	**0.63**
253	**93.763**	**93.973**	**94.115**	**93.950**	**0.19**
261	**94.768**	**94.575**	**94.786**	**94.710**	**0.12**
268	**95.23**	**95.58**	**95.44**	**95.417**	**0.18**
275	**95.69**	**95.69**	**96.11**	**95.830**	**0.25**
283	**95.66**	**96.33**	**96.32**	**96.103**	**0.40**
290	**96.2**	**96.3**	**96.58**	**96.360**	**0.20**
298	**96.25**	**97.36**	**97.33**	**96.980**	**0.65**
305	**97.36**	**97.22**	**97.66**	**97.413**	**0.23**
313	**97.36**	**97.36**	**98.25**	**97.657**	**0.53**
320	**97.86**	**98.39**	**98.86**	**98.370**	**0.51**
327	**99.19**	**98.86**	**99.61**	**99.220**	**0.38**
335	**98.75**	**98.85**	**99.38**	**98.993**	**0.34**