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APPENDICES

APPENDIX A

**PERMEATE FLUX: CONCENTRATION POLARIZATION
EXPERIMENT**

Table A-1 Permeate flux until the 1,000 ml of permeate water obtained of fluoride 0 mM at 0.1 MPa

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	2.00	687	2.426E-06
0.50	2.00	670	2.488E-06
1.00	2.00	657	2.537E-06
2.00	2.00	660	2.525E-06
3.00	2.00	661	2.521E-06
4.00	2.00	667	2.499E-06
5.00	2.00	663	2.514E-06
6.00	2.00	654	2.548E-06
10.00	2.00	657	2.537E-06
11.00	2.00	662	2.518E-06
21.00	2.00	660	2.525E-06
22.50	2.00	652	2.556E-06

Table A-2 Permeate flux until the 1,000 ml of permeate water obtained of fluoride 10 mM at 0.1 MPa

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	2.00	951	1.753E-06
0.50	2.04	960	1.736E-06
1.00	2.04	962	1.733E-06
2.00	2.04	1023	1.629E-06
3.00	2.04	1016	1.640E-06
6.00	2.04	1022	1.631E-06
8.00	2.04	1094	1.523E-06
9.00	2.04	999	1.668E-06
10.00	2.04	968	1.722E-06
16.00	2.04	1098	1.518E-06
18.00	2.04	1115	1.495E-06
24.00	2.04	1074	1.552E-06
27.00	2.04	955	1.745E-06
28.00	2.04	955	1.745E-06
31.00	2.04	959	1.738E-06

Table A-3 Permeate flux until the 1,000 ml of permeate water obtained of fluoride 25 mM at 0.1 MPa

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	2.00	1068	1.561E-06
1.00	2.04	1020	1.634E-06
2.00	2.00	1009	1.652E-06
3.00	2.00	1042	1.599E-06
4.00	2.00	1084	1.538E-06
5.00	2.00	1109	1.503E-06
6.00	2.00	993	1.678E-06
9.00	2.04	1068	1.561E-06
12.00	2.08	1020	1.634E-06
14.00	2.04	1185	1.406E-06
25.00	2.04	1047	1.592E-06
27.00	2.04	1016	1.640E-06
30.00	2.04	1076	1.549E-06
32.00	2.04	1084	1.538E-06

Table A-4 Permeate flux until the 1,000 ml of permeate water obtained of fluoride 50 mM at 0.1 MPa

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	1.96	901	1.850E-06
1.00	2.04	948	1.758E-06
3.00	2.08	967	1.724E-06
6.00	2.04	1013	1.645E-06
8.00	2.04	993	1.678E-06
9.00	2.04	893	1.866E-06
12.00	2.04	1001	1.665E-06
17.00	2.08	957	1.742E-06
22.00	2.04	1044	1.596E-06
24.00	2.04	1040	1.603E-06
25.00	2.04	1055	1.580E-06
27.00	2.04	1085	1.536E-06
28.00	2.04	1078	1.546E-06
29.00	2.08	1086	1.535E-06

Table A-5 Permeate flux until the 1,000 ml of permeate water obtained of fluoride 0 mM at 0.3 MPa

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	1.72	220	7.576E-06
0.50	1.72	213	7.825E-06
1.00	1.72	194	8.591E-06
1.50	1.72	195	8.547E-06
2.00	1.72	198	8.418E-06
2.50	1.72	208	8.013E-06
3.00	1.72	209	7.974E-06
3.50	1.72	212	7.862E-06
4.00	1.72	215	7.752E-06
4.50	1.72	218	7.645E-06
5.00	1.72	220	7.576E-06
5.50	1.72	220	7.576E-06
6.00	1.72	221	7.541E-06

Table A-6 Permeate flux until the 1,000 ml of permeate water obtained of fluoride 10 mM at 0.3 MPa

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	1.72	302	5.519E-06
0.50	1.80	290	5.747E-06
1.00	1.84	272	6.127E-06
1.50	1.84	278	5.995E-06
2.00	1.84	273	6.105E-06
2.50	1.84	275	6.061E-06
3.00	1.84	272	6.127E-06
4.00	1.84	280	5.952E-06
5.00	1.84	274	6.083E-06
5.50	1.84	275	6.061E-06
6.00	1.84	281	5.931E-06
6.50	1.88	275	6.061E-06
7.00	1.84	276	6.039E-06
8.00	1.84	278	5.995E-06

Table A-7 Permeate flux until the 1,000 ml of permeate water obtained of fluoride 25 mM at 0.3 MPa

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	1.72	210	7.937E-06
0.50	1.72	225	7.407E-06
1.00	1.84	229	7.278E-06
2.00	1.84	249	6.693E-06
3.00	1.84	250	6.667E-06
3.50	1.84	269	6.196E-06
4.00	1.84	270	6.173E-06
4.50	1.84	275	6.061E-06
5.00	1.84	276	6.039E-06
5.50	1.88	279	5.974E-06
6.00	1.88	282	5.910E-06
6.50	1.88	288	5.787E-06
7.50	1.88	289	5.767E-06

Table A-8 Permeate flux until the 1,000 ml of permeate water obtained of fluoride 50 mM at 0.3 MPa

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	1.80	248	6.720E-06
0.50	1.92	257	6.485E-06
1.00	1.88	262	6.361E-06
1.50	1.88	260	6.410E-06
2.00	1.88	260	6.410E-06
3.00	1.88	273	6.105E-06
4.00	1.88	276	6.039E-06
4.50	1.88	265	6.289E-06
5.00	1.88	272	6.127E-06
6.00	1.88	286	5.828E-06
7.00	1.88	277	6.017E-06
7.50	1.88	293	5.688E-06
8.00	1.88	295	5.650E-06

Table A-9 Permeate flux until the 1,000 ml of permeate water obtained of fluoride 0 mM at 0.5 MPa

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	0.48	123	1.355E-05
0.50	0.48	120	1.389E-05
1.00	0.48	122	1.366E-05
1.50	0.48	121	1.377E-05
2.00	0.48	120	1.389E-05
2.50	0.48	121	1.377E-05
3.00	0.48	120	1.389E-05
3.50	0.48	121	1.377E-05

Table A-10 Permeate flux until the 1,000 ml of permeate water obtained of fluoride 10 mM at 0.5 MPa

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	0.16	151	1.104E-05
0.50	0.16	147	1.134E-05
1.00	0.12	143	1.166E-05
1.50	0.12	143	1.166E-05
2.00	0.12	141	1.182E-05
2.50	0.16	143	1.166E-05
3.00	0.16	143	1.166E-05
3.50	0.12	143	1.166E-05
4.00	0.16	143	1.166E-05

Table A-11 Permeate flux until the 1,000 ml of permeate water obtained of fluoride 25 mM at 0.5 MPa

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	0.20	167	9.980E-06
0.50	0.16	175	9.524E-06
1.00	0.16	173	9.634E-06
1.50	0.16	179	9.311E-06
2.00	0.16	178	9.363E-06
2.50	0.16	179	9.311E-06
3.00	0.16	178	9.363E-06
3.50	0.12	175	9.524E-06
4.00	0.12	179	9.311E-06
5.00	0.12	179	9.311E-06

Table A-12 Permeate flux until the 1,000 ml of permeate water obtained of fluoride 50 mM at 0.5 MPa

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	0.24	213	7.825E-06
0.50	0.26	224	7.440E-06
1.00	0.12	231	7.215E-06
1.50	0.12	236	7.062E-06
2.00	0.12	243	6.859E-06
2.50	0.16	255	6.536E-06
3.00	0.12	256	6.510E-06
3.50	0.16	258	6.460E-06
4.00	0.16	263	6.337E-06
5.00	0.16	264	6.313E-06
6.00	0.16	263	6.337E-06
6.50	0.16	263	6.337E-06

Table A-13 Permeate flux until the 1,000 ml of permeate water obtained of fluoride 75 mM at 0.5 MPa

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	0.16	316	5.274E-06
0.50	0.16	321	5.192E-06
1.50	0.16	314	5.308E-06
2.00	0.16	329	5.066E-06
2.50	0.16	345	4.831E-06
4.00	0.16	368	4.529E-06
5.00	0.16	346	4.817E-06
6.00	0.16	380	4.386E-06
7.00	0.16	372	4.480E-06
8.00	0.12	383	4.352E-06
9.00	0.08	373	4.468E-06
10.00	0.16	376	4.433E-06

APPENDIX B

PERMEATE FLUX: SILICA FOULING EXPERIMENT

Table B-1 Permeate flux of Run 1 until the 1,000 ml of permeate water obtained

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	2.00	619	2.693E-06
0.50	2.04	573	2.909E-06
3.00	2.04	570	2.924E-06
4.00	2.04	608	2.741E-06
9.00	2.08	611	2.728E-06
11.00	2.08	620	2.688E-06
14.00	2.08	629	2.650E-06
14.50	2.08	636	2.621E-06
16.00	2.08	643	2.592E-06
17.50	2.08	654	2.548E-06

Table B-2 Permeate flux of Run 2 until the 1,000 ml of permeate water obtained

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	1.76	800	2.083E-06
0.50	1.84	782	2.131E-06
1.00	1.84	776	2.148E-06
1.50	1.84	765	2.179E-06
2.00	1.84	773	2.156E-06
3.00	1.84	781	2.134E-06
5.00	1.84	744	2.240E-06
10.00	1.84	753	2.213E-06
16.50	1.84	747	2.231E-06
18.00	1.84	760	2.193E-06
20.00	1.84	765	2.179E-06
21.50	1.84	761	2.190E-06

Table B-3 Permeate flux of Run 3 until the 1,000 ml of permeate water obtained

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	1.88	818	2.037E-06
1.00	1.88	772	2.159E-06
3.00	1.88	780	2.137E-06
5.00	1.88	805	2.070E-06
9.00	1.88	783	2.129E-06
12.00	1.88	754	2.210E-06
18.00	1.88	796	2.094E-06
20.00	1.88	897	1.858E-06
22.00	1.88	953	1.749E-06
23.00	1.88	944	1.766E-06

Table B-4 Permeate flux of Run 4 until the 1,000 ml of permeate water obtained

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	1.76	232	7.184E-06
0.50	1.76	232	7.184E-06
1.00	1.76	229	7.278E-06
1.50	1.76	228	7.310E-06
2.50	1.80	224	7.440E-06
3.00	1.76	227	7.342E-06
3.50	1.76	227	7.342E-06
4.00	1.76	227	7.342E-06
4.50	1.76	227	7.342E-06
5.00	1.76	227	7.342E-06
6.00	1.76	227	7.342E-06
6.50	1.76	227	7.342E-06

Table B-5 Permeate flux of Run 5 until the 1,000 ml of permeate water obtained

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	1.64	234	7.123E-06
0.50	1.72	223	7.474E-06
1.00	1.72	210	7.937E-06
1.50	1.68	200	8.333E-06
2.00	1.68	197	8.460E-06
2.50	1.68	202	8.251E-06
3.00	1.68	213	7.825E-06
3.50	1.68	210	7.937E-06
4.00	1.68	211	7.899E-06
4.50	1.68	211	7.899E-06
5.00	1.68	218	7.645E-06
5.50	1.68	224	7.440E-06
6.50	1.68	229	7.278E-06

Table B-6 Permeate flux of Run 6 until the 1,000 ml of permeate water obtained

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	1.72	207	8.052E-06
0.50	1.76	243	6.859E-06
1.00	1.72	236	7.062E-06
1.50	1.72	221	7.541E-06
2.00	1.72	220	7.576E-06
2.50	1.72	216	7.716E-06
3.00	1.68	227	7.342E-06
3.50	1.68	224	7.440E-06
4.00	1.68	218	7.645E-06
4.50	1.68	226	7.375E-06
5.00	1.68	219	7.610E-06
5.50	1.68	227	7.342E-06
6.00	1.68	232	7.184E-06

Table B-7 Permeate flux of Run 7 until the 1,000 ml of permeate water obtained

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	0.32	125	1.333E-05
0.50	0.32	123	1.355E-05
1.00	0.24	124	1.344E-05
1.50	0.24	123	1.355E-05
2.00	0.28	124	1.344E-05
2.50	0.24	124	1.344E-05
3.50	0.24	124	1.344E-05

Table B-8 Permeate flux of Run 8 until the 1,000 ml of permeate water obtained

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	0.28	145	1.149E-05
0.50	0.28	143	1.166E-05
1.00	0.28	139	1.199E-05
2.00	0.24	137	1.217E-05
2.50	0.24	135	1.235E-05
3.00	0.24	135	1.235E-05
3.50	0.24	136	1.225E-05
4.00	0.24	135	1.235E-05

Table B-9 Permeate flux of Run 9 until the 1,000 ml of permeate water obtained

Time	Flow	Time of V = 10 ml	Flux
(hr)	(l/min)	(sec)	(m³/m²/sec)
0.00	0.04	151	1.104E-05
0.50	0.32	142	1.174E-05
1.00	0.16	128	1.302E-05
2.00	0.16	122	1.366E-05
2.50	0.20	127	1.312E-05
3.00	0.20	127	1.312E-05
3.50	0.24	133	1.253E-05
4.00	0.24	137	1.217E-05

APPENDIX C

MASS TRANSFER COEFFICIENT

Mass transfer coefficient (k) can be calculated by using the Equation (2-5).

$$k = \frac{(J_v)_{solute}}{\ln \left\{ \frac{\Delta P}{\pi_B - \pi_P} \cdot \left[1 - \frac{(J_v)_{solute}}{(J_v)_{H_2O}} \right] \right\}} \quad (2-5)$$

where $(J_v)_{H_2O}$ = the permeate flux of pure water, ΔP = the transmembrane pressure, π_B = the osmotic pressure of the bulk solution, π_P = the osmotic pressure of the permeate solution

Example

Sample	TMP (MPa)	Concentrated water (C _B)		Permeate water (C _P)		$\Delta\pi$	Permeate flux $J_v \times 10^5$
		mM	π_B	mM	π_P	$\pi_B - \pi_P$	m ³ /m ² -s
C1	0.1	0.00	0.000	0.00	0.000	0.000	0.256
C2	0.1	9.71	0.045	3.01	0.014	0.031	0.174
C3	0.1	25.76	0.119	17.54	0.081	0.038	0.155
C4	0.1	52.47	0.241	43.98	0.202	0.039	0.153

Sample C2:
$$k = \frac{0.174 \times 10^{-5}}{\ln \left\{ \frac{0.100}{0.031} \cdot \left[1 - \frac{0.174 \times 10^{-5}}{0.256 \times 10^{-5}} \right] \right\}} = 5.32 \times 10^{-5} \text{ m/s}$$

Sample C3:
$$k = \frac{0.155 \times 10^{-5}}{\ln \left\{ \frac{0.100}{0.038} \cdot \left[1 - \frac{0.155 \times 10^{-5}}{0.256 \times 10^{-5}} \right] \right\}} = 4.13 \times 10^{-5} \text{ m/s}$$

Sample C4:
$$k = \frac{0.153 \times 10^{-5}}{\ln \left\{ \frac{0.100}{0.039} \cdot \left[1 - \frac{0.153 \times 10^{-5}}{0.256 \times 10^{-5}} \right] \right\}} = 4.91 \times 10^{-5} \text{ m/s}$$

Table C-1 Mass transfer coefficient of 0.1 MPa

Sample	TMP	<i>k</i>
	MPa	m/s
C2	0.1	5.32E-05
C3	0.1	4.13E-05
C4	0.1	4.91E-05
Average <i>k</i>		4.79E-05

Table C-2 Mass transfer coefficient of 0.3 MPa

Sample	TMP	k
	MPa	m/s
C6	0.3	3.51E-05
C7	0.3	3.47E-05
C8	0.3	5.40E-05
Average k		4.12E-05

Table C-3 Mass transfer coefficient of 0.5 MPa

Sample	TMP	k
	MPa	m/s
C10	0.5	2.85E-05
C11	0.5	3.19E-05
C12	0.5	3.25E-05
C13	0.5	3.69E-05
Average k		3.24E-05

APPENDIX D

CONCENTRATION POLARIZATION EXPERIMENT:

FLUORIDE CONCENTRATION ON MEMBRANE SURFACE (C_M)

According to the thin-film model, the fluoride concentration on a membrane surface can be estimated by the following equation:

$$(J_v)_{solute} = k \ln \left(\frac{C_M - C_P}{C_B - C_P} \right) \quad (2-4)$$

where k = mass transfer coefficient, $(J_v)_{solute}$ = the permeate flux of the solute solution, C_M = the fluoride concentration on the membrane surface, C_P = the fluoride concentration in the permeate solution, and C_B = the fluoride concentration in the bulk solution

Sample	k	Concentrated water (C_B)	Permeate water (C_P)	Permeate flux $J_v \times 10^5$
	m/s	mM	mM	$m^3/m^2 \cdot s$
C2	4.79×10^{-5}	9.71	3.01	0.174

Example of C_M calculation for sample C2:

$$0.174 \times 10^{-5} = 4.79 \times 10^{-5} \ln \left(\frac{C_M - 3.01}{9.71 - 3.01} \right)$$

$$C_M = 10.07 \text{ mM}$$

APPENDIX E

SILICA FOULING EXPERIMENT:

CONCENTRATION OF FLUORIDE ON SURFACE OF GEL LAYER (C_G) AND CONCENTRATION OF FLUORIDE ON MEMBRANE SURFACE (C_M)

The concentration of fluoride on the surface of the gel layer (C_G) was determined by Equation (2-4), when the C_M was considered as the C_G .

$$(J_v)_{solute} = k \ln \left(\frac{C_G - C_P}{C_B - C_P} \right) \quad (2-4)$$

The fluoride concentration on the membrane surface (C_M) can be estimated by Equation (2-7).

$$J_i = k_i (C_M - C_P) \quad (2-7)$$

where $J_i = J_v \times C_P$, k_i = the solute mass transfer coefficient through the membrane

Run no.	Permeate flux, J_v ($\text{m}^3/\text{m}^2\text{-s}$)	C_P (mg/L)	C_B (mg/L)	k (m/s)	k_i (m/s)
2	0.219×10^{-5}	0.66	17.11	4.79×10^{-5}	1.06×10^{-7}

Example of C_G calculation for Run no.2:

$$0.219 \times 10^{-5} = 4.79 \times 10^{-5} \ln \left(\frac{C_G - 0.66}{17.11 - 0.66} \right)$$

$$C_G = 17.88 \text{ mg/L}$$

Example of C_M calculation for Run no.2:

$$(0.219 \times 10^{-5}) \times 0.66 = 1.06 \times 10^{-7} (C_M - 0.66)$$

$$C_M = 14.38 \text{ mg/L}$$

APPENDIX F

FLUORIDE REJECTION

The percentages of fluoride rejection in membrane fouling can be determined by using equation as follows:

$$\%R = \left(1 - \frac{C_P}{C_B}\right) \times 100$$

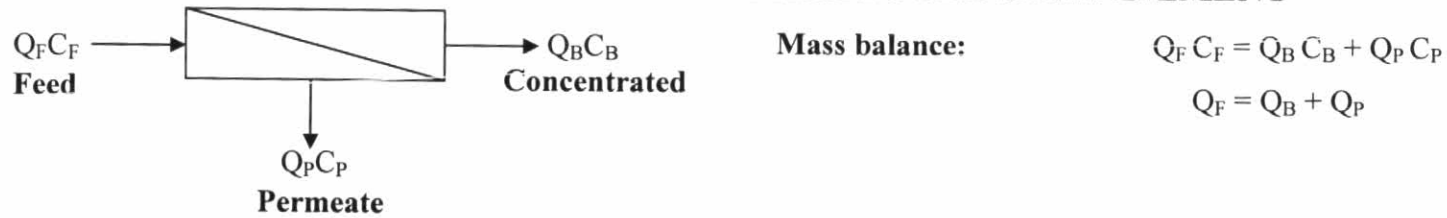
where %R = Percentages of fluoride rejection, C_P = Fluoride concentration in permeate solution, C_B = Fluoride concentration in bulk solution

Table F-1 Percentages of fluoride rejection

Run no.	TMP (MPa)	Silica concentration (mg/L)	C_P (mg/L)	C_B (mg/L)	%R
1	0.1	0	2.32	17.86	87.0
2	0.1	100	0.66	17.11	96.1
3	0.1	300	0.77	18.22	95.8
4	0.3	0	0.83	18.53	95.5
5	0.3	100	0.22	17.27	98.7
6	0.3	300	0.96	18.90	94.9
7	0.5	0	0.96	19.34	95.1
8	0.5	100	0.21	18.20	98.8
9	0.5	300	0.43	21.30	98.0

APPENDIX G

MASS BALANCE OF FLUORIDE FOR SILICA FOULING EXPERIMENT



Run no.	Q_F	Q_P	Q_B	C_F	C_P	C_B	$Q_B C_B$	$Q_P C_P$	$Q_B C_B + Q_P C_P$	$Q_F C_F$
	L/min	L/min	L/min	mg/L	mg/L	mg/L	mg/min	mg/min	mg/min	mg/min
1	2.081	9.144×10^{-4}	2.080	16.84	2.32	17.86	37.149	2.121×10^{-3}	37.151	35.041
2	1.841	7.884×10^{-4}	1.840	16.84	0.66	17.11	31.482	5.203×10^{-4}	31.483	31.003
3	1.881	6.372×10^{-4}	1.880	17.27	0.77	18.22	34.254	4.906×10^{-4}	34.254	32.484
4	1.763	2.642×10^{-4}	1.760	17.53	0.83	18.53	32.613	2.193×10^{-3}	32.615	30.895
5	1.683	2.627×10^{-4}	1.680	16.26	0.22	17.27	29.014	5.758×10^{-4}	29.014	27.364
6	1.683	2.585×10^{-4}	1.680	18.10	0.96	18.90	31.752	2.481×10^{-3}	31.754	30.454
7	0.245	4.848×10^{-3}	0.240	16.30	0.96	19.34	4.642	4.645×10^{-3}	4.646	3.996
8	0.244	4.456×10^{-3}	0.240	17.06	0.21	18.20	4.368	9.337×10^{-4}	4.369	4.179
9	0.244	4.381×10^{-3}	0.240	17.74	0.43	21.30	5.112	1.796×10^{-3}	5.114	4.334

Example:

Run no. 1

$$Q_F C_F = Q_B C_B + Q_P C_P$$

$$2.081 \times 16.84 = (2.080 \times 17.86) + (9.144 \times 10^{-4} \times 2.32)$$

$$35.041 = 37.151$$

BIOGRAPHY

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