BOILING POINT RISE OF BAYER PLANT LIQUORS

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This paper presents a method for calculating the boiling point rise of Bayer plant caustic-aluminate liquors within about ±0.1°C from the chemical analyses of the liquors. The effect of impurities present in significant amounts is included.

The boiling point rise of these liquors has been found to be identical to the boiling point rise of pure sodium hydroxide solutions at equal molality and liquor temperature. This is consistent with the Debye-Huckel definition of total ionic strength for uni-univalent ions, indicating that divalent anions (CO_3^{--}, SO_4^{--}) may only be singly ionized in the concentrated solutions. The existence of AlO_2^- rather than $Al(OH)_4^-$ also is supported.

Principal sources of error are thought to be the chemical analyses, identification of organic constituents, and literature data on the vapor pressures of NaOH solutions.

Combination of the vapor pressure data with an equation of state for water permits calculation of the heat of evaporation.

Introduction

Knowledge of the boiling point rise (BPR) of Bayer plant streams is required for the design of evaporators and heat recovery units for new plants and for monitoring the operating efficiency after commissioning. Presently, BPR values must be determined experimentally, and values for use in the design of new plants must be estimated from prior experience.

Further, a portion of the economic benefits of operating expensive processes for control of impurity levels in plant streams derive from the savings of plant energy requirements that may be obtained by preventing the BPR values from increasing during the operating life of the plant. The value of operating these processes must be taken on faith since several years may be required to obtain a significant change in the composition of the large inventory of plant liquor.

A method of estimating BPR values from liquor compositions was sought as a means of improving the estimates of BPR for new plants and for identifying the individual and combined effects of various impurities found in Reynolds' Bayer plant liquor streams. An approach based on the work of Professor H. P. Meissner at Massachusetts Institute of Technology was chosen. The results obtained have been better than expected.

Presentation of Results

Figure 1 shows the agreement over a range of temperatures and molalities between the boiling point rise of Bayer liquors and of sodium hydroxide solutions at equal molalities for a high-temperature Bayer plant using 240°C digestion. The curves show the variation of the BPR of sodium hydroxide solutions with temperature at NaOH molalities equal to the molalities of liquors 20 to 29 of Tables I and II. The data points were obtained by Carithers and Brown (1) for 0.35 and 0.64 alumina to free soda (expressed as Na_2CO_3) weight ratios, for a range of free soda concentrations from 100 to 200 grams/kilogram liquor obtained by dilution with water. The liquor molalities (Table 2) range between 2.87 and 7.56, hence the liquors must be considered concentrated solutions that would not be expected to obey the classical laws of dilute solutions. The fit of the curves to the data points is thought to be satisfactory for Bayer plant use.

Tables I and II also present chemical analyses of 19 other liquors and the boiling point rise at 1 atmosphere pressure from a study by Sanders (2). In Table II "m" is the sum of the individual molalities of the anions shown (cations were considered in calculation of the water), "m^1" is the molality of the sodium hydroxide solution having the same boiling point rise as the liquor (equal water activity) and the "calc. BPR" is the boiling point rise of a sodium hydroxide solution of the same molality as the liquor. The difference between the observed and calculated BPR values is satisfactorily small and the standard error for the 29 liquors is only 0.14°C.

Table I. Chemical Analyses of BPR-Study Liquors

Liquor Source	No.	A/C	C/S	C	S	A	TOS	K_2O	Cl^-	F^-	$SO_4^=$
							(Grams/Kg Liquor)				
Sinter Plant	1	.271	.934	158.14	169.35	42.81	0.0	5.64	0.64	0.43	18.01
	2	.271	.934	150.06	160.69	40.62	0.0	5.36	0.61	0.41	17.08
	3	.271	.934	142.41	152.50	38.55	0.0	5.08	0.58	0.39	16.22
(4) +Na_2SO_4	4	.282	.908	144.12	158.71	40.60	0.0	5.14	0.59	0.39	16.41
	5	.282	.908	142.04	156.40	40.01	0.0	5.07	0.58	0.38	26.37
	6	.282	.908	188.09	207.13	52.99	0.0	6.71	0.77	0.51	21.42
143°C Digestion	7	.372	.677	155.84	230.21	57.97	5.07	8.58	2.47	1.55	8.38
	8	.372	.677	149.85	221.36	55.74	4.88	8.25	2.38	1.49	8.06
	9	.372	.677	144.29	213.15	53.68	4.69	7.94	2.29	1.44	7.76
	10	.372	.677	138.63	204.79	51.57	4.51	7.63	2.20	1.38	7.45
(7) +NaCl	11	.372	.677	152.08	224.66	56.57	4.95	8.37	17.09	1.51	8.18
(7) +Na_2SO_4	12	.372	.677	153.57	226.85	57.12	5.00	8.46	2.43	1.53	17.88
Desalted	13	.377	.861	200.27	232.52	75.56	4.12	9.62	2.47	0.79	2.18
	14	.377	.861	170.23	197.64	64.23	3.50	8.18	2.10	0.67	1.85
	15	.377	.861	148.18	172.04	55.91	3.05	7.18	1.83	0.58	1.61
240°C Digestion	16	.395	.856	173.87	203.10	68.68	20.00	4.12	23.30	—	17.55
	17	.395	.856	166.32	194.28	65.66	19.13	3.94	22.29	—	16.94
	18	.395	.856	154.73	180.75	61.09	17.80	3.67	20.74	—	15.62
	19	.395	.856	147.12	171.85	58.08	16.92	3.49	19.72	—	14.85
	20	.35	.823	100	121.52	34.96	7.92	2.37	4.97	—	6.53
	21	.35	.823	125	151.90	43.70	9.90	2.96	6.22	—	8.16
	22	.35	.823	150	182.28	52.49	11.88	3.56	7.46	—	9.79
	23	.35	.823	175	212.66	61.18	13.87	4.15	8.70	—	11.42
	24	.35	.823	200	243.04	69.91	15.85	4.74	9.95	—	13.05
	25	.64	.823	100	121.52	63.96	7.92	2.37	4.97	—	6.53
	26	.64	.823	125	151.90	79.94	9.90	2.96	6.22	—	8.16
	27	.64	.823	150	182.28	95.93	11.88	3.56	7.46	—	9.79
	28	.64	.823	175	212.66	111.92	13.87	4.15	8.70	—	11.42
	29	.64	.823	200	243.04	127.91	15.85	4.74	9.95	—	13.05

Figure 1
BOILING POINT RISE OF 240°C PLANT LIQUOR

Y-axis: BOILING POINT RISE - °C (0 to 16)
X-axis: BOILING TEMPERATURE - °C (40 to 300)

Legend
Calculated Curves
——— 1963 - 0.35 A/C
– – – 1963 - 0.64 A/C

Data Points
o — 1963 - 0.35 A/C
x — 1963 - 0.64 A/C

Curve labels: 100C, 125C, 150C, 175C, 200C

Table II. Reduced Data from Boiling Point Rise Studies

Liquor No.	Liquor Composition – Molal Basis – Anions Only Shown								Obs. BPR (1 atm)	m¹ From Obs. BPR	Calc. BPR (from m)	ΔBPR Obs.–Calc.	Ratio m¹/m
	OH^-	AlO_2^-	Cl^-	F^-	$NaCO_3^-$	$NaSO_4^-$	Org.⁻	Total "m"					
1	2.674	1.045	0.023	0.028	0.132	0.234	0.0	4.135	4.55	4.18	4.45	0.10	1.011
2	2.506	0.980	0.021	0.027	0.123	0.219	0.0	3.875	4.22	3.95	4.12	0.10	1.019
3	2.351	0.919	0.020	0.025	0.115	0.205	0.0	3.636	3.88	3.70	3.80	0.08	1.018
4	2.364	0.977	0.020	0.025	0.205	0.210	0.0	3.767	4.03	3.96	3.96	0.07	1.009
5	2.365	0.978	0.020	0.025	0.169	0.342	0.0	3.900	4.18	3.93	4.14	0.04	1.008
6	3.312	1.370	0.029	0.035	0.237	0.294	0.0	5.276	6.01	5.20	6.10	−0.09	0.986
7	2.472	1.555	0.096	0.112	0.960	0.066	0.053	5.379	6.24	5.37	6.30	0.06	0.998
8	2.344	1.475	0.091	0.106	0.910	0.062	0.043	5.100	5.86	5.10	5.87	0.04	1.000
9	2.28	1.402	0.086	0.101	0.865	0.059	0.036	4.848	5.46	4.83	5.50	0.01	0.996
10	2.228	1.330	0.082	0.096	0.820	0.056	0.066	4.598	4.83	4.60	4.83	−0.02	1.000
11	2.113	1.555	0.675	0.112	0.960	0.102	0.066	5.959	5.96	5.82	5.96	−0.24	0.977
12	2.471	1.554	0.095	0.112	0.959	0.066	0.066	5.516	6.37	5.42	6.50	−0.23	0.983
13	3.124	2.012	0.095	0.057	0.413	0.031	0.053	5.782	6.96	5.81	6.90	0.06	1.005
14	2.521	1.623	0.076	0.045	0.334	0.025	0.043	4.665	5.23	4.67	5.23	0.0	1.001
15	2.115	1.361	0.064	0.038	0.280	0.021	0.036	3.915	4.261	3.97	4.16	0.08	1.014
16	2.821	1.961	0.955	0.402	0.458	0.266	0.148	6.433	8.50	6.80	8.61	−0.11	0.991
17	2.643	1.836	0.895	0.377	0.433	0.252	0.194	5.812	7.86	6.39	7.95	−0.09	0.993
18	2.390	1.660	0.809	0.341	0.387	0.226	0.244	5.423	6.87	5.76	6.95	−0.08	0.991
19	2.230	1.548	0.755	0.280	0.362	0.211	0.361	5.423	6.29	5.39	6.35	−0.06	0.994
20	1.424	0.811	0.166	0.148	0.241	0.0816	0.152	2.869	2.94	2.85	2.87	0.07	0.993
21	1.866	1.063	0.217	0.194	0.315	0.106	0.201	3.759	4.11	3.87	3.97	0.14	1.029
22	2.356	1.343	0.274	0.244	0.398	0.133	0.256	4.738	5.33	4.75	5.33	0.03	1.002
23	2.890	1.645	0.336	0.300	0.488	0.164	0.317	5.822	6.87	5.85	6.97	0.0	1.005
24	3.489	1.987	0.406	0.361	0.588	0.197	0.388	7.029	9.00	7.00	8.93	0.07	1.010
25	0.774	1.528	0.171	0.248	0.083	0.327	0.152	2.958	3.28	3.23	2.97	0.31	1.093
26	1.024	2.020	0.226	0.327	0.110	0.201	0.201	3.907	4.56	4.21	4.17	0.39	1.078
27	1.304	2.573	0.287	0.416	0.140	0.256	0.256	4.975	5.78	5.07	5.69	0.09	1.019
28	1.620	3.200	0.357	0.418	0.174	0.317	0.317	6.183	7.78	6.35	7.55	−0.23	1.027
29	1.981	3.909	0.437	0.632	0.212	0.388	0.388	7.559	9.67	7.52	9.78	−0.13	0.995
Mean												0.02	1.008
Std. Dev.												0.14	0.025

Table III shows the results of calculations made to determine the most useful method of expressing the composition of the liquors. The comparative results are expressed as the value of m¹ divided by the Debye-Huckel ionic strength of the solution calculated from the data of Table II by three different assumptions, viz:

1. (Column 3) Uni-univalent ions as shown in Table II.

2. (Column 5) Full dissociation to a mixture of univalent cations and uni- and di-valent anions; and

3. (Column 7) Uni-univalent ions with $Al(OH)_4^-$ instead of AlO_2^-.

It is apparent that the assumption of uni-univalent ions is more useful than the assumption of mixed valency for the concentrated solutions normally encountered in a Bayer plant. (This might not be true for very dilute liquors.) Use of the tetrahydroxy ion yields a ratio different from unity that also shows a statistically signficant variation with the solution concentration. It is believed that this comparison supports the existence of AlO_2^- in the concentrated liquors.

Derived Data and Assumptions

Computer Algorithm of Boiling Point Rise

Handbook data (3) for the vapor pressure of water over sodium hydroxide solutions over the ranges 0 to 10 molal and 60 to 300°C were converted to boiling point rise values and correlated with the aid of a stepwise multiple regression computer program. The resulting equation is:

$$BPR\ (^\circ C) = 0.00182 + 0.55379(M/10.)^7 + 0.0040625MT +$$
$$(1/T)(-286.66M + 29.919M^2 + 0.6228M^3) -$$
$$0.032647M(MT/1000.)^2 +$$
$$(T/1000.)^5(5.9705M - 0.57532M^2 + 0.10417M^3) \quad (1)$$

Std. error of estimate = 0.068°C

M = Molality – gm. mols/kg H_2O

T = K = °C + 273.150

The constant may be omitted.

Equation 1 is believed to represent the boiling point rise of sodium hydroxide solutions within the accuracy of the available data and therefore the boiling point rise of Bayer liquors with comparable accuracy.

Table III. Test of Correlation Methods

Liquor No.	Univalent Anions m^1	Univalent Anions m^1/m	Uni + divalent Anions I	Uni + divalent Anions m^1/I	Univalent Anions With Al(OH)$_4^-$ m_2	Univalent Anions With Al(OH)$_4^-$ m^1/m_2
1	4.18	1.011	4.867	0.859	4.297	0.973
2	3.95	1.019	4.559	0.866	4.017	0.983
3	3.70	1.018	4.278	0.865	3.760	0.984
4	3.80	1.009	4.525	0.840	3.903	0.974
5	3.93	1.008	4.922	0.799	4.042	0.972
6	5.20	0.986	6.343	0.820	5.555	0.936
7	5.37	0.998	7.700	0.697	5.721	0.936
8	5.10	1.000	7.297	0.699	5.407	0.943
9	4.83	0.995	6.935	0.697	5.125	0.942
10	4.60	1.000	6.585	0.699	4.846	0.949
11	5.82	0.977	8.282	0.703	6.339	0.855
12	5.42	0.983	8.113	0.668	5.866	0.924
13	5.81	1.005	6.788	0.856	6.245	0.930
14	4.67	1.001	5.475	0.853	4.961	0.941
15	3.97	1.014	4.593	0.864	4.121	0.963
16	6.80	0.991	8.525	0.798	7.391	0.920
17	6.39	0.993	8.014	0.797	6.900	0.926
18	5.76	0.991	7.226	0.797	6.190	0.931
19	5.39	0.994	6.740	0.800	5.751	0.937
20	2.85	0.993	3.621	0.787	2.960	0.963
21	3.87	1.029	4.744	0.816	3.915	0.989
22	4.75	1.002	5.982	0.794	4.990	0.952
23	5.85	1.005	7.354	0.796	6.206	0.943
24	7.10	1.010	8.879	0.800	7.595	0.935
25	3.23	1.093	3.726	0.867	3.130	1.032
26	4.21	1.078	4.927	0.855	4.219	0.998
27	5.07	1.019	6.276	0.808	5.494	0.923
28	6.35	1.027	7.804	0.814	7.005	0.906
29	7.52	0.995	9.544	0.788	8.825	0.852
Mean		1.008		0.797		0.945
S.D.		0.025		0.060		0.037

Heat of Vaporization of Bayer Liquors

The heat of vaporization of Bayer liquors may be calculated by rigorous thermodynamic relations (4) with the aid of an equation of state for water or the steam tables, using Equation 1 and water vapor pressures to calculate $\Delta p/\Delta T$ for use in the standard relation

$$\Delta H_v = (\Delta p/\Delta T)_{(T,M)} (V_v - \bar{V}) \qquad (2)$$

ΔH_v = heat of vaporization, in PV units.

V_v = vapor volume at the solution temperature and the water saturation pressure at (T–BPR).

$\bar{V}$ = partial molar volume of liquid H_2O in the solution at T.

It is assumed that $\bar{V}$ at T can be taken as the partial molar volume of H_2O at 20°C times the ratio of the volume of liquid water at t°C to that at 20°C. The relation

$$1/\bar{V} \ (20°C) = 1.042753 + 0.045431 \mathrm{Sin} \ ((M-7.4)/5.9) \qquad (3)$$

Std. error of $\bar{V}$ = 0.049% of $\bar{V}$

$\bar{V}$ in cm^3/gram H_2O

M = Molality

The argument of the Sin is in radians.

for sodium hydroxide solutions at 20°C, and thus also for Bayer liquors of equal molality, was devised from published data (5) on the density of sodium hydroxide solutions.

Calculated values of boiling point rise and heat of vaporization for a range of molalities and temperatures are tabulated in Table IV. Values are given to 3 and 4 significant digits, respectively, for convenience of those wishing to prepare graphs.

Definition of Organates

No rigorous definition of the sodium organate compounds present in the liquors has been found. The following assumptions, discussed in Appendix 2, were used in the present study and appear to be satisfactory.

A. For 140°C digestion plant
      100% sodium oxalate, molecular weight 134, two acid groups per molecule.

Table IV. BPR and Heat of Vaporization of Bayer Liquors and NaOH Solutions

Solution Temp., °C	50		100		150		200		250		300	
Molality	BPR	HV	BPR	HV	BPR	HV	BPR	HV	BPR	HV	BPR	HV
0	0	2382	0	2256	0	2115	0	1940	0	1713	0	1404
1	0.54	2375	0.86	2255	1.18	2119	1.50	1949	1.84	1730	2.21	1437
2	1.25	2373	1.87	2258	2.47	2125	3.09	1960	3.73	1748	4.44	1469
3	2.13	2376	3.00	2263	3.85	2133	4.73	1972	5.65	1768	6.66	1500
4	3.17	2384	4.24	2273	5.31	2145	6.40	1987	7.57	1787	8.85	1530
5	4.36	2398	5.59	2286	6.82	2159	8.09	2003	9.47	1807	11.01	1559
6	5.72	2418	7.04	2304	8.38	2176	9.79	2021	11.34	1828	13.11	1585
7	7.23	2444	8.58	2326	9.97	2196	11.47	2040	13.17	1848	15.15	1611
8	8.92	2478	10.22	2335	11.61	2218	13.15	2060	14.95	1868	17.12	1634
9	10.81	2520	11.99	2386	13.30	2245	14.84	2083	16.70	1889	19.06	1656
10	12.96	2574	13.94	2427	15.11	2277	16.57	2109	18.47	1911	21.00	1677

NOTES:
BPR: Boiling point rise, °C
HV: Heat of Vaporization, KJ/Kg vapor
Molality: gm mols/Kg H_2O

B. For 240°C digestion plant
    20 mol % sodium oxalate,
    45 mol % sodium acetate,
    35 mol % sodium formate,
    Mean molecular weight 87.5,
    1.2 acid groups per mean molecule.

The mols of organate in solution are calculated from the total organic soda (TOS in Table 1), which is obtained as the difference in total titratable soda between the liquor and a sample of the liquor that has been dried and burned on O_2 or air to destroy the organic materials.

Sources of Error

The major sources of error are believed to reside in the chemical analyses. Titration analyses by competent analysts on liquors and accurate dilutions of liquors made over a period of time (i.e. not simultaneous duplicates) have shown standard deviations about the mean values of 0.8% of the value for free soda (C), 0.6% for total titratable soda (S), 1.5% for alumina (A), and 4.4% for carbonate (S-C). Since these errors affect both the amount of the compound and the amount of water in opposite ways, the effects on the calculated molality values are greater. Thus it is recommended that mean values of a number of analyses taken over a period of time be used for boiling point rise computations.

The accuracy of the assumptions for organate ions can be assessed only from the fit of the molality-BPR correlation. For plants with substantially different digestion conditions than those cited or with very high organate levels it is recommended that the organate assumptions be tested against BPR data and revised if necessary.

The sodium hydroxide solution vapor pressure data and the correlation for BPR derived therefrom are believed to be sufficiently accurate to satisfy the needs of plants for BPR data. Calculation of the heat of vaporization requires obtaining the derivative dp/dt, or preferably $\Delta p/\Delta t$. This should introduce additional error but data for testing is limited. Thus the accuracy of the heat of vaporization values is unknown.

Appendix

Calculation of Molality from Chemical Assay

The objective is to obtain as accurate a value as possible of the total molality of the liquor. All compounds dissolved in the liquor should be considered, but in practice some of the trace impurities with the lowest concentrations may be neglected without introducing intolerable errors.

A sample calculation of the molality of liquor No. 16 is presented in Tables V and VI to illustrate the method. Table V presents the liquor analysis after converting all values to grams per kilogram liquor, and a division of the alkaline elements into sodium and potassium components (trace amounts of lithium in the

Table V. Liquor No. 16

Liquor Analysis – in grams/Kg liquor[1]

C (Free Soda as Na_2CO_3	173.87
S (Titratable Soda as Na_2CO_3)	203.10
A	68.68
Total Organic Soda (TOS) as Na_2CO_3	20.00
K_2O	4.12
Cl^-	23.30
F^-	0.0
$SO_4^=$	17.55

Total Alkali Calculation

S	203.10
TOS	20.00
Cl^- x 105.99/(2x35.45)	34.83
F^- x 105.99/(2x19.0)	0.0
$SO_4^=$ x 105.99/96.07	19.36
Sum = Total alkali as Na_2CO_3	277.29
Less K_2O x 105.99/94.20	4.636
Total Na_2O as Na_2CO_3	272.65

[1] Mean value of assays on original liquor and on three dilutions calculated back to original concentration.

Table VI. Liquor No. 16 – Molality Calculation

ion	Wgt. Calculation	gms ion per Kg Liq.	M.W. ion	Gram Mols Per Kg Liq.	Gram Mols Per Kg H_2O
OH^-	2x17x(C/105.99–A/101.96)	32.873	17.0	1.9337	2.804
AlO_2^-	Ax2x58.98/101.96	79.458	58.98	1.3472	1.953
Cl^-		23.30	35.45	0.6573	0.953
F^-		0.0	19.0	0.0	
$CO_3^=$	(S–C)x60.01/105.99	16.551	60.01	0.2758	0.400
$SO_4^=$		17.55	96.07	0.1827	0.265
ORG.	TOSx2x59.9/(1.2x105.96)	18.844	59.9	0.3146	0.456
Sum Anions		188.576		4.7113	6.831
Na^+	Tot. Na_2CO_3x2x22.99/105.99	118.280	22.99		
K^+	K_2Ox2x39.10/94.20	3.420	39.10		
Total Weight ions, gms.		310.276			
Wgt. H_2O 1000.–Wgt. ions		689.724			
Multiplier = 1000./wgt. H_2O					1.4499

Molality for B.P.R. Calculation = 6.831

liquors were neglected). Table VI presents the calculation of the weights and molar amounts of the anions and cations, the weight of water by difference and the molality. The calculations are simplified if the anions are taken as completely dissociated (i.e., free of Na or K) and the total weight of Na and K calculated separately, as shown in Table VI. Numerical coefficients of the conversion equations are given in terms of molecular weights and ions per molecule to assist interpretation by the reader.

Development of Organate Assumptions

Diluted samples of a high-temperature and of a low-temperature plant liquor were assayed for total organic soda (TOS) by ignition, oxidizable carbon by permanganate titration, and sodium oxalate and a molar balance was made as follows:

	High Temperature Liquor	Low Temperature Liquor
Mols COO^- from TOS	0.2266	0.0362
Mols COO^- in oxalate	0.0587	0.0345
Excess mols COO^-	0.1679	0.0017
Mols C by permanganate	0.1319	0.0836
Mols C in oxalate	0.0587	0.0345
Excess mols C	0.0732	0.0491
Ratio – Excess C/Excess COO^-	0.44	28.9

For the low-temperature liquor (143°C) the number of acid groups calculated from the oxalate assay is nearly equal to the total number of acid groups calculated from the total organic soda (TOS) assay. Thus the mols of carbon found by the permanganate titration in excess of those with the oxalate must represent carbon groups in a relatively minor amount of undecomposed, or partially decomposed, humic acids. Since the data indicated the presence of only minor molar amounts of other organates, it was thought that the best estimate of the organates would be obtained by assuming that the acid groups found by the TOS assay are all present as oxalates.

Results obtained for the high-temperature liquor are quite different. Acid groups with oxalate account for only 26% of the total acid groups calculated from the TOS assay. Also, the mols of carbon obtained by the permanganate assay are not sufficient even to account for the acid groups present, suggesting the presence of low molecular weight acids such as acetic acid that are not easily oxidized by permanganate. No data on the distribution of low molecular weight organates in high-temperature liquor was found. However, G. Lever (7) reported, for a low-temperature plant liquor, a molar distribution of 7% Succinic, 1% lactic, 17% oxalic, 45% acetic and 30% formic acids with a mean ionic weight of 65.4 and 1.24 acid groups per mean ion. For the higher temperature plant, a molar distribution of 20% oxalic, 45% acetic, 35% formic acids, mean ionic weight

59.9 with 1.20 acid groups per mean ion, was assumed to allow for greater degradation during digestion. The assumption is arbitrary and may not be satisfactory for all plants.

References

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