341. *A Polarographic Investigation of the Tautomerism of 2-Hydroxy- and 2 : 6-Dihydroxy-anthraquinol.*

By R. Gill and H. I. Stonehill.

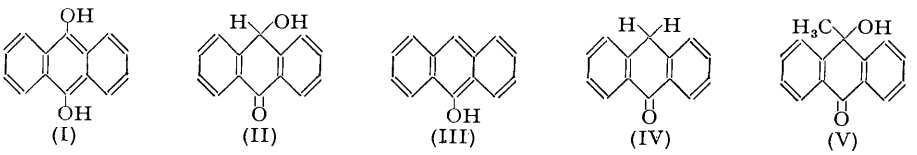
Over a certain pH range for each, 2-hydroxy- and 2 : 6-dihydroxy-anthraquinol give polarographic oxidation waves which decrease in height with time. This is shown to be due to reversible tautomerisation to the corresponding oxanthrols, which are polarographically reducible at highly negative potentials. The tautomeric equilibrium point varies with pH, maximum equilibrium conversion into the oxanthrol occurring at pH 8·85—9·59 for the 2-hydroxy-compound. From this it is deduced that the particular state of ionisation of the quinol responsible for the tautomerisation is that in which only one of the three hydroxy-groups is ionised. The tautomeric oxanthrol is stabilised relative to the anthraquinol by ionic *para*-resonance, which is possible only if an ionised 2-hydroxy-group is present. In 1 : 2-dihydroxyanthraquinol, the 1-hydroxy-group prevents tautomerisation by causing hydrogen bonding in the quinol and steric hindrance in the oxanthrol.

The velocity of the tautomerisation is in accordance with the assumption of first-order kinetics for the forward and the reverse reaction.

During the investigation reported in the preceding paper, in which all experimental details are given, it was observed that 2-hydroxy- and 2 : 6-dihydroxy-anthraquinone, alone amongst the compounds studied, gave in the leuco-form, over a certain pH range for each, anodic diffusion currents (wave-heights) which decreased with time to non-zero equilibrium values, although the position and shape of the polarographic wave (*i.e.*, values

of half-wave potential E_m and semiquinone formation constant K) remained unchanged. In the oxidised (quinone) form, the compounds gave corresponding cathodic waves with height independent of time. At the same time as the normal anodic wave for the anthraquinols diminished, a new cathodic wave appeared at much more negative potentials, which increased in height at approximately the same rate as the decrease of the normal wave, reaching a maximum equilibrium value after about 40 minutes at room temperature.

The tautomerism of anthraquinol (I) $\rightleftharpoons$ oxanthranol (II), and the similar behaviour of anthranol (III) $\rightleftharpoons$ anthrone (IV), are well known. We now show that the abnormal



polarography of 2-hydroxyanthraquinol, and presumably also of 2 : 6-dihydroxyanthraquinol, is due to tautomerisation similar to (I) $\rightleftharpoons$ (II) occurring in a particular state of ionisation, the tautomer analogous to (II) undergoing reduction at highly negative potentials to the analogue of (IV).

Results.—Figs. 1 and 2 show typical polarograms for the two anthraquinones in various states of reduction, and refer to solutions which were equilibrated before being polarographed,

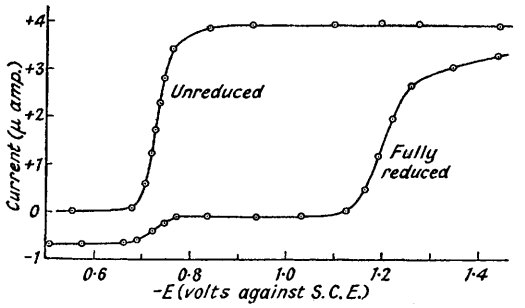


FIG. 1. *Polarograms for* $9{\cdot}47 \times 10^{-4}$M-*2-hydroxyanthraquinone :* pH 9·59, 25°.

by waiting for 1 hour after adding any dithionite (hydrosulphite) required. Table 1 shows that the unreduced 2-hydroxyanthraquinone does not undergo conversion at any pH investigated, whereas the anthraquinol is converted to an extent which at equilibrium varies with pH. That the conversion reaches an equilibrium follows from the fact that the normal anodic wave, due to unconverted anthraquinol, never disappears entirely, as shown in Table 1 and also in cols. 1—3 of Table 2.

On reduction of 2-hydroxyanthraquinone with dithionite at pH $<$ *ca.* 11, the colour

TABLE 1. *Equilibrium diffusion current constants for 2-hydroxyanthra-quinone and -quinol in aqueous buffers at* 25°.

Buffer	N-NaOH	0·1N-NaOH	Phosphate	Phosphate	Borate	Borate
Ionic strength	1·0	0·1	0·1	0·1	0·1	0·1
pH	13·79	12·87	12·00	11·27	9·59	8·85
Diffusion current constant } Quinone	3·00	3·08	3·03	3·12	3·09	3·04
Diffusion current constant } Quinol ...	3·01	2·96	2·66	1·31	0·61	0·58

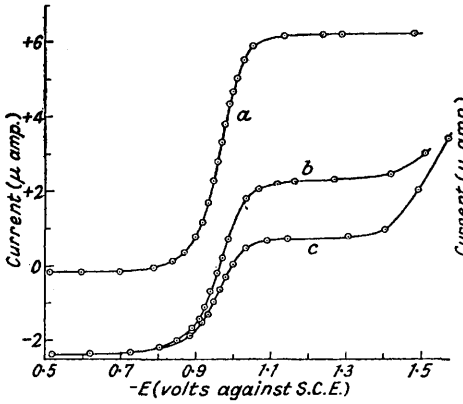
TABLE 2. *Equilibrium concentrations of various species in* $1{\cdot}415 \times 10^{-3}$M-*2-hydroxyanthraquinone in different states of reduction.*

In aqueous phosphate buffer, pH 11·27, ionic strength 0·1, at 25°. $E_m = -0{\cdot}7910$ v (S.C.E.), $\sqrt{K} = 0{\cdot}86$, $m = 0{\cdot}924$ mg./sec., $t = 4{\cdot}68$ sec.

State of solution	Wave height (μamp.): cathodic	anodic	$-E$ (S.C.E.) at zero current	$r + s + t$	y	r	s	y/r	y/s
Unreduced	5·41	0·00	—	5·41	0·00	—	—	—	—
Partly reduced	1·27	1·84	0·7952	3·11	2·30	1·27	0·927	1·81	2·48
Further reduced	0·33	2·04	0·8245	2·37	3·04	1·81	0·423	1·68	7·19

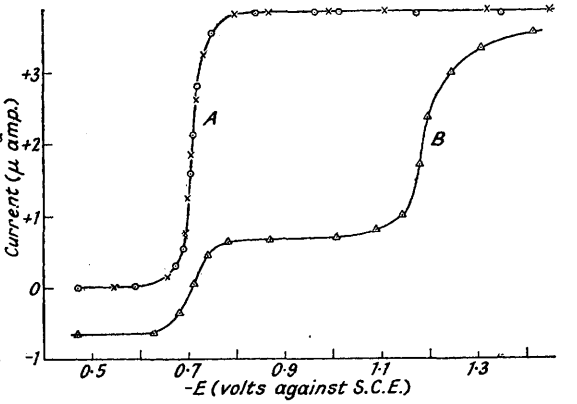
changes from red through orange to yellow, and remains yellow as the anthraquinol wave-height decreases. Upon reoxidation of the equilibrated anthraquinol solution by bubbling air through it, the red colour returns slowly (1—2 hours), in contrast with the almost instantaneous reoxidation observed at pH 13, or with the other compounds with normal polarographic behaviour studied in the preceding paper. That the reoxidation gives a

FIG. 2. *Polarograms for* $1{\cdot}8 \times 10^{-3}$M-2 : 6-*dihydroxyanthraquinone :* pH 12·87, 25°.



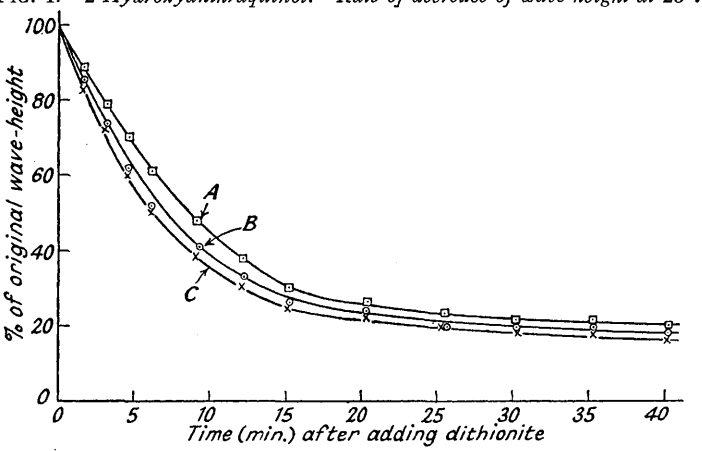
a, *Unreduced :* $E_m = -0{\cdot}964$ v.
b, *Half reduced :* $E_m = -963$ v.
c, *Further reduced :* $E_m = -959$ v.

FIG. 3. *Polarograms for* $1{\cdot}286 \times 10^{-3}$M-2-*hydroxyanthraquinone :* pH 9·34, 15°.



—⊙— *Before reduction.*
—△— *After partial reduction.*
—×— *After reoxidation.*

FIG. 4. 2-*Hydroxyanthraquinol. Rate of decrease of wave height at* 25°.



A, $2{\cdot}38 \times 10^{-4}$M, pH 8·85. *B*, $1{\cdot}48 \times 10^{-3}$M, pH 8·85. *C*, $9{\cdot}46 \times 10^{-4}$M, pH 9·59.

quantitative yield of 2-hydroxyanthraquinone is shown by the following. A $1{\cdot}286 \times 10^{-3}$M-solution of the quinone at pH 9·34 and 15° gave a cathodic wave at about −0·7 v against the saturated calomel electrode (S.C.E.), of height 3·85 μamp. (Fig. 3, *A*). This solution was part-reduced with dithionite, and after time had been allowed for equilibration gave a diminished wave at the same potential, of height 1·36 μamp. (Fig. 3, *B*). The solution was reoxidised with an air stream, and after 12 hours' standing and then removal of excess of air with nitrogen, it gave a polarogram almost identical with the original one, with wave-height 3·88 μamp.

Fig. 4 gives some typical results illustrating the effects of change of concentration and of pH upon the rate of decrease of wave-height for 2-hydroxyanthraquinol with time after reduction of the anthraquinone. It is clear from these and other similar results that the rate of change is practically independent of initial concentration and pH. Results

such as those of Fig. 4 were obtained by starting with unreduced quinone in the polarographic cell, and, with nitrogen bubbling through the solution to promote rapid mixing, adding the calculated equivalent amount of standard dithionite from a microburette as rapidly as possible. Nitrogen-bubbling was continued for 1 minute after the addition, and then periodically the current was measured at a potential of −0·45 v (S.C.E.), corresponding to the bottom plateau of the anthraquinol anodic wave; time was measured with a stop-watch from the point when half the dithionite had been added.

Table 3 gives the variation with time of the relative height of the anodic wave

TABLE 3. *Effect of temperature on time-dependence of wave-height for* 10^{-3}M-*hydroxyanthraquinone, fully reduced, in aqueous buffer,* pH 9·40, *ionic strength* 0·1.

t (min. after adding $Na_2S_2O_4$)		0	1·5	3	4·5	6	9	12
Relative wave height	15°	100	89·0	79·6	70·4	63·3	51·5	45·5
	25°	100	82·2	65·8	57·5	47·6	34·3	29·8
	35°	100	70·5	54·4	39·9	30·1	21·6	17·3
t (min. after adding $Na_2S_4O_2$)		15	20	25	30	35	40	∞ (extrap.)
Relative wave height	15°	39·6	33·6	27·7	24·8	22·8	21·2	20·0
	25°	24·3	21·9	21·0	19·7	18·9	18·6	18·6
	35°	15·3	13·8	13·2	12·9	12·9	12·9	12·9

of 2-hydroxyanthraquinol at three different temperatures, pH and ionic strength being kept constant. Clearly, the rate of change and also the final equilibrium extent of the change increase with rise of temperature.

DISCUSSION

Identification of Conversion Product.—The complete regeneration of 2-hydroxyanthraquinone on reoxidation strongly suggests that the conversion product of the quinol is the corresponding oxanthranol, by analogy with the systems (I) $\rightleftharpoons$ (II) and (III) $\rightleftharpoons$ (IV). This view is supported by the fact that the product from 2-hydroxyanthraquinol gives a reduction wave with E_m about −1·2 v (S.C.E.) (Figs. 1 and 3), whereas Stone and Furman (*J. Amer. Chem. Soc.*, 1948, **70**, 3062) find that 10-hydroxy-10-methylanthrone (V), *i.e.*, 10-methyloxanthranol, gives in 40% dioxan at 25° at apparent pH 7—10 a two-electron reduction wave with similar diffusion current constant and E_m about −1·3 v (S.C.E.) in phosphate or borate buffers, which value they state is not likely to be greatly different in aqueous solutions. The conversion product of 2 : 6-dihydroxyanthraquinol gives a similar wave (Fig. 2) with E_m about −1·55 v (S.C.E.). The shift in E_m here due to the second substituent hydroxy-group (−0·35 v) is similar in direction to but greater than the corresponding effect (−0·14 v) in the anthraquinones (preceding paper).

For all three substituted oxanthranols, the height of the reduction wave corresponds to a two-electron process, the product of which is probably the corresponding anthrone. Supporting evidence is given by the appearance of a wave at about −1·35 v (S.C.E.), merging with the top of the 2-hydroxyoxanthranol wave, in Fig. 1. This wave would be expected for 2-hydroxyanthrone by comparison with the wave given by unsubstituted anthrone at about −1·0 v (S.C.E.) in alkaline buffers in 40% dioxan (Stone and Furman, *loc. cit.*), and at about −1·27 v in 50% ethanol (Day and Kirkland, *ibid.*, 1950, **72**, 2766), if we assume that the effect of the 2-hydroxy-group on the E_m of anthrone is similar to that of the 6-hydroxy-group on the E_m of 2-hydroxyoxanthranol.

Identification of Tautomerising Species.—Since the equilibrium fractional conversion into tautomer is independent of initial concentration of 2-hydroxyanthraquinol and of pH (Fig. 4), the tautomerisation may be represented by X $\rightleftharpoons$ Y, where X represents the anthraquinol in an un-ionised or incompletely ionised state (since on complete ionisation at pH $\approx$13 it no longer tautomerises), and Y represents the tautomer, 2-hydroxyoxanthranol, in a corresponding state of ionisation. Lower-case italic letters being used to denote concentrations of species represented by the corresponding capital letters, the tautomerisation equilibrium constant is

$$K' = y/x = (y/r)(r/x)$$

where r is the total concentration of the anthraquinol (R) in all four states of ionisation

A, B, C, D, corresponding to ionisation of 0, 1, 2, and 3 hydroxy-groups, respectively. It is shown in Appendix I that, at any fixed pH, the ratios a/r, b/r, c/r, and d/r are independent of r. Since X is one or other of A, B, and C, r/x is also independent of r, and thus K' is proportional to y/r, for a given pH.

The value of y cannot be obtained from the height of the oxanthranol reduction wave, since this is ill-defined (Fig. 1). It is given, however, by the equilibrium decrease in height of the original wave at about −0·7 v (S.C.E.). In the same arbitrary units, the value of r is obtainable from the height of this same wave as follows. The wave height is equal to $r + s + t$, where s and t denote the concentrations of anthra-semiquinone and anthraquinone species in the solution. Geake (*Trans. Faraday Soc.*, 1938, **34**, 1395) has shown that

$$t/s = 1\sqrt{PK};\ r/s = \sqrt{P/K},\ \text{where } P = e^{2F(E^{\circ\prime} - E)/RT}$$

and K is the semiquinone formation constant; $E^{\circ\prime}$, the virtual standard redox potential for a given pH, may be replaced by E_m, and E, the potential of an inert electrode, may be replaced by the potential of the dropping mercury electrode at the point on the wave where the current is zero, since then the composition of the solution at the mercury-drop interface is identical with that of the bulk of the solution.

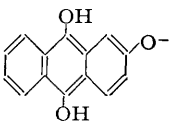
Applying these equations to the results in columns 2—4 of Table 2, with the value of K obtained from the preceding paper, we obtain the figures in the last six columns of the table. The variability of y/s indicates that the semiquinone is not the tautomerising species, and since the quinone does not tautomerise, the quinol must be the form which does tautomerise. This is confirmed by the approximate constancy of y/r. A similar constancy is found at other pH values, but the value of this ratio varies with pH as shown in Table 4, having a maximum at a pH between 8·85 and 9·59. In Appendix II it is shown that a/r increases to an asymptotic maximum as pH increases, d/r behaves similarly as pH decreases, c/r is maximal at pH ~11·32, and b/r maximal at pH ~9·38. Hence X may be identified with B (VI).

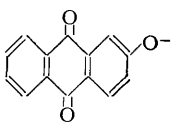
TABLE 4. *Equilibrium* y/r *values at* 25° : *variation with* pH.

pH	13·79	12·87	12·00	11·27	9·59	9·40	8·85	6·0 *
y/r	0·00	0·03	0·13	1·7	4·1	4·4	4·2	0·00

* 50% Ethanol required to dissolve quinone.

Explanation of the Tautomerism.—Unreduced 2-hydroxyanthraquinone, in the ionised state corresponding to that of the tautomerising form B of the quinol, is stabilised by ionic *para*-resonance of the type (VII) ⟷ (VIII), which is estimated to shift the redox potential by −120 mv (preceding paper), equivalent to increase in stabilisation of the quinone relatively to the quinol by about 5·5 kcal. per g.-mol. Upon reduction to the


(VI)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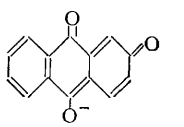
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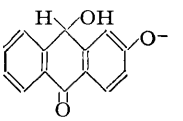
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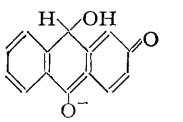
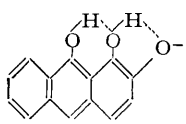

(X)


(XI)

quinol, this resonance possibility is lost, but may be regained by tautomerisation to (IX) ⟷ (X). Since at least one hydroxy-group in 2-anthraquinol must be ionised to permit *para*-resonance, while at least two hydroxy-groups must be un-ionised to permit tautomerism, only the species B can fulfil these conditions, confirming the conclusion already reached. A similar explanation applies to 2 : 6-dihydroxyanthraquinol. The anomalous absence of tautomerism in 1 : 2-dihydroxyanthraquinol, in spite of the presence of a 2-hydroxy-

group, is probably the result of stabilisation of the quinol by hydrogen bonding involving the 1-hydroxy-group, as in (XI), and also a steric hindrance effect of this group in the oxanthranol.

Branch and Calvin ("The Theory of Organic Chemistry," Prentice-Hall Inc., 1941, p. 291) have shown that ΔH for the change anthranol $\longrightarrow$ anthrone is very small. If we make the reasonable assumption that, for the related change anthraquinol $\longrightarrow$ oxanthranol, ΔH and thus the resonance energy stabilising oxanthranol relatively to anthraquinol are very small, we may calculate approximately the tautomerisation equilibrium constant K'' for the latter change, as follows. Combining the values of y/r for 2-hydroxyanthraquinol at pH 8·85 and 9·59 (Table 4) with the corresponding values of b/r calculated from the information given in Appendix I, the mean value obtained for the tautomerisation equilibrium constant $K' = y/b$ for the species B is about 8·2. The resonance energy stabilising the oxanthranol in this case is about 5·5 kcal., and thus the difference in resonance energy for the two systems is also about 5·5 kcal. Hence

$$5500 = \boldsymbol{R}T \ln K'/K'' = 596 \ln 8{\cdot}2/K''$$

whence $K'' = 0{\cdot}001$ approx. This is in keeping with the observation that in alcoholic hydrochloric acid anthraquinol is only 3% converted into oxanthranol at equilibrium

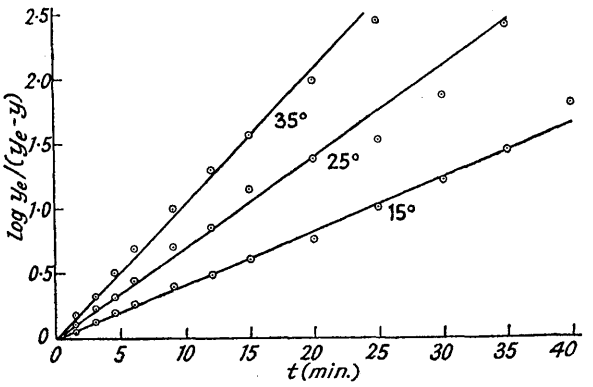


FIG. 5. 10^{-3}M-2-*Hydroxyanthraquinol*: pH 9·40; $I = 0{\cdot}1$.

Verification of first-order kinetics of tautomerisation.

(Karrer, "Organic Chemistry," Elsevier, 1947, p. 578). A similar result may be expected for all the anthraquinols studied in the preceding paper, other than the 2-hydroxy- and the 2 : 6-dihydroxy-derivative. This would explain why these other compounds gave no polarographic indication of tautomerisation.

Kinetics of the Tautomerisation of 2-Hydroxyanthraquinol.—Assuming that the reaction is B $\underset{k'}{\overset{k}{\rightleftharpoons}}$ Y, as suggested by the rate of the forward reaction being independent of r or pH, we have $\mathrm{d}y/\mathrm{d}t = kb - k'y$. For the data of Table 3, which refer to fully reduced 2-hydroxyanthraquinone at a fixed pH, $b = k''r$ (k'' is a constant), and since s and t are virtually zero, the height of the main wave is equal to $r = r_0 - y$, where r_0 is the initial value of r, before appreciable tautomerisation has occurred. Thus

$$\mathrm{d}y/\mathrm{d}t = kk''r - k'y = kk''(r_0 - y) - k'y = kk''r_0 - y(kk'' + k')$$

At the completion of tautomeric equilibration, when $y = y_e$ and $\mathrm{d}y/\mathrm{d}t = 0$,

$$0 = kk''r_0 - y_e(kk'' + k')$$

and thus by subtraction

$$\mathrm{d}y/\mathrm{d}t = (y_e - y)(kk'' + k')$$

which upon integration and insertion of the condition $y = 0$ at $t = 0$ gives

$$\log y_e/(y_e - y) = t(kk'' + k')/2{\cdot}303$$

The data of Table 3 lead to plots of $\log y_e/(y_e - y)$ against t which, at least for the earlier t values, where sensitivity to error in the extrapolated y_e value is small, are linear and pass

through the origin (Fig. 5), confirming the last equation and the assumption of first-order kinetics for both directions of the tautomerisation reaction.

From the same data for $t \ll 9$ minutes, where y is small and the reverse reaction velocity is negligible, values of kk'' for three temperatures were obtained from the slopes of plots of log r against t, which are linear. The slope of the linear plot of log kk'' against $1/T$ gave the apparent activation energy of the reaction $R \longrightarrow Y + H^+$ as 8·67 kcal./mol. This is the sum of the activation energy of the tautomerisation $B \longrightarrow Y$ and the unknown heat of the ionisation $R \longrightarrow B + H^+$.

Appendix I.

$$A = B + H^+;\ bh/a = K_1^r;\ b = K_1^r a/h$$
$$B = C + H^+;\ ch/b = K_2^r;\ c = K_2^r b/h = K_1^r K_2^r a/h^2$$
$$C = D + H^+;\ dh/c = K_3^r;\ d = K_3^r c/h = K_1^r K_2^r K_3^r a/h^3$$

For 2-hydroxyanthraquinol, $pK_1^r = 8{\cdot}70$, $pK_2^r = 10{\cdot}05$, $pK_3^r = 12{\cdot}60$ (preceding paper). Also

$$r = a + b + c + d = a(1 + K_1^r/h + K_1^r K_2^r/h^2 + K_1^r K_2^r K_3^r/h^3)$$
$$= a(h^3 + K_1^r h^2 + K_1^r K_2^r h + K_1^r K_2^r K_3^r)/h^3 = af/h^3$$

where $f =$ the factor in parentheses. Thus $a/r = h^3/f$, $b/r = K_1^r h^2/f$, $c/r = K_1^r K_2^r h/f$, and $d/r = K_1^r K_2^r K_3^r/f$. These four fractions are functions of h (pH) but are independent of r.

Appendix II.

From Appendix I, $a = h^3 r/f$, and hence at constant r,

$$\partial a/\partial h = [3rh^2 f - h^3 r\,(3h^2 + 2K_1^r h + K_1^r K_2^r)]/f^2 = h^2 r\,(2K_1^r K_2^r h + 3K_1^r K_2^r K_3^r + K_1^r h^2)/f^2$$

This is always positive, hence a increases as h increases, until, when $h > K_1^r > K_2^r > K_3^r$, $\partial a/\partial h \to 0$ and $a \to r$, as is obvious from first principles.

Similarly, $b = K_1^r r h^2/f$, and thus at constant r,

$$\partial b/\partial h = K_1^r r h\,(K_1^r K_2^r h + 2K_1^r K_2^r K_3^r - h^3)/f^2$$

This equals zero when $h^3 = K_1^r K_2^r (h + 2K_3^r) \approx K_1^r K_2^r h$ if we assume that $h \gg K_3^r$. Thus b is maximal when $h = (K_1^r K_2^r)^{\frac{1}{2}}$, or $pH = \frac{1}{2}(pK_1^r + pK_2^r) = \frac{1}{2}(8{\cdot}70 + 10{\cdot}05) = 9{\cdot}38$.

The assumption that $h \gg K_3^r$ is thus justified, since $pK_3^r = 12{\cdot}60$. That b is maximal and not minimal is shown by the negative value of $\partial^2 b/\partial h^2$ when $h = (K_1^r K_2^r)^{\frac{1}{2}}$.

Since $c = K_1^r K_2^r h r/f$, we have at constant r, $\partial c/\partial h = K_1^r K_2^r r(K_1^r K_2^r K_3^r - K_1^r h^2 - 2h^3)/f^2$, which equals zero when $0 = 1 - h^2/K_2^r K_3^r - 2h^3/K_1^r K_2^r K_3^r \approx 1 - h^2/K_2^r K_3^r$ if we assume that $K_1^r \gg h$. This gives $h = (K_2^r K_3^r)^{\frac{1}{2}}$, or $pH = \frac{1}{2}(pK_2^r + pK_3^r) = \frac{1}{2}(10{\cdot}05 + 12{\cdot}60) = 11{\cdot}32$. Since $pK_1^r = 8{\cdot}70$, the assumption $K_1^r \gg h$ is justified. The value $h = 11{\cdot}32$ makes $\partial^2 c/\partial h^2$ negative, and thus corresponds to a maximum for c.

Since $d = K_1^r K_2^r K_3^r r/f$, we have at constant r, $\partial d/\partial h = -K_1^r K_2^r K_3^r r(3h^2 + 2K_1^r h + K_1^r K_2^r)/f^2$, which is always negative. Thus d decreases as h increases, tending to zero when $h \gg K_1^r > K_2^r > K_3^r$, as is obvious from first principles.

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