TABLE II

FREE ENERGIES OF REACTIONS OF GLYCOLYSIS, AND OF OXIDATIVE AND REDUCTIVE PENTOSE PHOSPHATE CYCLES

Reaction	$\Delta G'$ (*kcal*)	*Calculation basis*	*Ref. No.* (*a*)
(1) NADH + ½ O_2 + H^+ → NAD^+ + H_2O	−52.41	e' = 1.136 V (b)	13, 15, 16
(2) NADPH + ½ O_2 + H^+ → $NADP^+$ + H_2O	−52.59	e' = 1.140 V (b)	13, 15, 16
(3) α-D-Glc + ATP^{4-} → Glc-6-P^{2-} + ADP^{3-} + H^+	− 4.35	K' = 1.55·10^3 (c)	17
(4) Glc-6-P^{2-} + H_2O → α-D-Glc + P_i^{2-}	− 3.29	K' = 2.60·10^2	18
(5) ATP^{4-} + H_2O → ADP^{3-} + P_i^{2-} + H^+	− 7.64	Reactions 3, 4 (d)	
(6) Glc-6-P^{2-} → Fru-6-P^{2-}	+ 0.50	K' = 0.43	20
(7) α-L-Glycerol-P^{2-} + H_2O → glycerol + P_i^{2-} + H_2O	− 2.40	K' = 59.6 (e)	21
(8) α-L-Glycerol-P^{2-} + NAD^+ → NADH + dihydroxyacetone-P^{2-} + H^+	+ 5.80	K' = 5.5·10^{-5} (f)	15
(9) Dihydroxyacetone-P^{2-} → glyceraldehyde-3-P^{2-}	+ 1.82	K' = 4.5·10^{-2} (g)	22
(10) Fru-1,6-P_2^{4-} → dihydroxyacetone-P^{2-} + glyceraldehyde-3-P^{2-}	+ 5.25	K' = 1.4·10^{-4} (h)	23
(11) H_2O + Fru-1,6-P_2^{4-} → P_i^{2-} + Fru-6-P^{2-}	− 3.44	Reactions 1, 4, 6–10 (i)	
(12) Glyceraldehyde-3-P^{2-} + NAD^+ + P_i^{2-} → 1,3-P_2-glycerate^{4-} + NADH + H^+	+ 0.27	K' = 0.63 (j)	24
(13) 1,3-P_2-glycerate^{4-} + ADP^{3-} → 3-P-glycerate^{3-} + ATP^{4-}	− 4.77	K' = 3.18·10^3	25
(14) 3-P-glycerate^{3-} → 2-P-glycerate^{3-}	+ 1.40	K' = 0.095 (k)	26
(15) 2-P-glycerate^{3-} → P-enolpyruvate^{3-} + H_2O	− 0.82	K' = 4.0 (k)	27
(16) P-enolpyruvate^{3-} + H^+ + ADP^{3-} → ATP^{4-} + pyruvate$^-$	− 5.60	K' = 1.3·10^4 (l)	28
(17) Xyl-5-P^{2-} + Ery-4-P^{2-} → Fru-6-P^{2-} + glyceraldehyde-3-P^{2-}	− 1.47	K' = 11.9	29
(18) Xyl-5-P^{2-} + Rib-5-P^{2-} → Sed-7-P^{2-} + glyceraldehyde-3-P^{2-}	− 0.10	K' = 1.18	29
(19) Fru-6-P^{2-} + Ery-4-P^{2-} → Sed-7-P^{2-} + glyceraldehyde-3-P^{2-}	− 0.38	K' = 1.90 (m)	30
(20) Ribul-5-P^{2-} → Xyl-5-P^{2-}	− 0.24	K' = 1.5	31
(21) Rib-5-P^{2-} → Ribul-5-P^{2-}	+ 0.54	ΔH = −3.06 kcal ΔS = −12.1 e.u.	31
(22) Xyl-5-P^{2-} → Rib-5-P^{2-}	− 0.30	Reactions 20 + 21	
(23) H_2O + Sed-1,7-P_2^{4-} → P_i^{2-} + Sed-7-P^{2-}	− 3.44	Analogy with Reaction 11 (n)	
(24) H_2O + Ribul-1,5-P_2^{4-} → P_i^{2-} + Ribul-5-P^{2-}	− 2.40	Analogy with Reaction 7 (o)	
(25) Glc-6-P^{2-} + $NADP^+$ + H_2O → 6-P-gluconate^{3-} + NADPH + $2H^+$	− 8.44	(p)	
(26) 6-P-Gluconate^{3-} + $NADP^+$ → Ribul-5-P^{2-} + CO_2 + NADPH	+ 1.56	(p)	

Abbreviations: see Table I.

(a) Reference is to data from which K' or e' is obtained. In some cases, K' has been calculated from data and is not the constant given by original authors. Explanations are given in subsequent footnotes. Values are carried to two decimal places in this table to avoid increasing errors by calculation. In Reactions 1–24 the values are believed to be accurate ± 0.2 kcal, but those in Reactions 25 and 26 may be no better than ± 1.5 kcal.

(b) From the oxidation potential of O_2 → H_2O at pH 7, which is +0.816 V[16], and the reduction potential of NADH → NAD^+ at pH 7, which is +0.320 V[15], or of NADPH → $NADP^+$ at pH 7, which is +0.324 V[15].

(c) K' given at 30°. We assume it to be the same at 25°.

(d) A value of −7.69 kcal is obtained by using the data reviewed by ATKINSON *et al.*[19] for Reaction 4 (this table), and the conversion of glucose 1-phosphate to glucose 6-phosphate (−1.68 kcal), the conversion of galactose 1-phosphate to glucose 1-phosphate (+0.70 kcal), the galactokinase reaction forming galactose 1-phosphate (−1.91 kcal), and the conversion of α-D-glucose to α-D-galactose (−1.51 kcal), from the free energies of formation of glucose and galactose from

the elements[13]. The data of BENZINGER *et al.*[20] on glutamine synthetase and glutamine hydrolase lead to a value of $\Delta G' = -7.91$ for Reaction 5, when total ATP and ADP species (the convention used throughout this paper) in the presence of Mg^{2+}, rather than $ATP \cdot Mg^{2-}$ and $ADP \cdot Mg^{-}$, are considered. The value obtained from glucokinase and glucose-6-phosphatase reactions is the most direct and is chosen in this report.

(e) Measured at 38°. At pH 8.5, $K_{8.5} = 38.5$ (selected value); at pH 5.8, $K_{5.8} = 82.5$. Interpolation of the logarithms gave log $K' = 1.761$, $K' = 59.6$; this value was used for calculation of $\Delta G'$.

(f) The standard equilibrium constant was given as $5.5 \cdot 10^{-12}$, so $K' = 5.5 \cdot 10^{-5}$.

(g) At 25°, found 4.3 % glyceraldehyde-3-P^{2-} in equilibrium with dihydroxyacetone-P^{2-} (95.7 %).

(h) At 10 mM Mg^{2+}, $K' = 1.4 \cdot 10^{-4}$. Equilibrium constant is strongly dependent on Mg^{2+} concentration.

(i) From the ΔG of formation of α-D-glucose, 1 M, aq. (−219.22 kcal)[13], ΔG formation of Fru-6-P^{2-} is calculated *via* Reactions 4, 6, and 7 to be P −215.43 (see also Table III). From the ΔG of formation of glycerol, 1 M, aq. (−116.76 kcal)[13], ΔG formation of Fru-1,6-P_2^{4-} is calculated *via* Reactions 1, 7, 8, 9, and 10 to be 2P−211.99 kcal (Table III), the $\Delta G'$ of Reaction 11 is determined as the difference, the P represents the difference in the ΔG of formation of phosphate and water (see text).

(j) Choosing values measured at relatively low ionic strengths and averaging values at each pH, we got $K_{6.0} = 0.072$, $K_{6.95} = 0.68$, $K_{7.15} = 0.81$, $K_{8.2} = 8.3$. When corrected to pH = 7.0, log K's were −0.242, −0.142, −0.117, −0.280; av. log $K' = -0.195$, $K' = 0.63$.

(k) In order to avoid reliance on determinations of [2-*P*-glycerate]/[3-*P*-glycerate] by measurement of optical rotation, which have given widely varying results, we chose to use [*P*-enolpyruvate]/[3-*P*-glycerate] ratios and the accurately determined K' for 2-*P*-glycerate → *P*-enolpyruvate. From the data of WOLD AND BALLOU[27], K' at 10 mM Mg^{2+} is 4.0 for Reaction 15, and $\Delta G' = -0.82$. UTTER AND WERKMAN[26] found in an equilibrium mixture of 2-*P*-glycerate, 3-*P*-glycerate, and *P*-enolpyruvate at 24°, 29 % *P*-enolpyruvate at pH 7.4 and 16.4 % at pH 5.8. The same authors found about 10 % as much 2-*P*-glycerate as 3-*P*-glycerate, so we calculate $K_{7.4}$ for [3-*P*-glycerate]/[*P*-enolpyruvate] = 64 : 29 = 2.21 and $K_{5.8} = 75 : 16 = 4.6$. Interpolating the logarithms, log $K' = 0.424$ and $\Delta G' = +0.58$ kcal for 3-*P*-glycerate → *P*-enolpyruvate. It then follows that for Reaction 14, $\Delta G' = +0.58 - (-0.82) = +1.40$ kcal. This is larger than most published values, but is reasonable for transfer of phosphate from primary to secondary position, a transfer which in the case of glucose 6-phosphate → glucose 1-phosphate has a $\Delta G' = +1.68$ kcal (see Footnote d).

(l) The average values of K in forward and reverse directions at pH 7.4, 8.0, 8.4, and 9.0, when corrected to pH 7 in accordance with Reaction 16, gave values whose logarithms were 4.210, 4.336, 4.361, and 4.565, respectively. When these are plotted *vs.* pH, they fall on a straight line, which extrapolates to 4.11 at pH 7.0, giving $K' = 1.3 \cdot 10^4$ and $\Delta G' = -5.60$ kcal.

(m) Authors[30] state that $K' = 0.95$, but from their data we calculate $K' = 1.90$.

(n) In order to evaluate the free energy of formation of sedoheptulose 1,7-diphosphate we have had to make an assumption regarding the free energy for the esterification of the hydroxyl on C-1 of sedoheptulose 7-phosphate. We estimate this free energy to be the same as that which we calculated for the esterification of the C-1 of fructose 6-phosphate, namely, +3.44 kcal. This is also quite close to the value +3.29 kcal calculated from equilibrium data for the esterification of glucose to give glucose 6-phosphate. The energy of esterification of fructose to give fructose 6-phosphate can be calculated from the data in Tables II and III as +3.35 kcal. Apparently, destabilization of pyranose and furanose rings by the presence of attached phosphate groups increases the negative free energy of hydrolysis by approx. 1.0 kcal per phosphate group, since for α-glycerol phosphate hydrolysis, $\Delta G' = +2.40$ kcal.

(o) Since ribulose 1,5-diphosphate is assumed to be in the form of a straight chain (non-cyclized) sugar, hydrolysis of the C-1 phosphate group should be accompanied by about the same negative free energy change as in the case of glycerol phosphate.

(p) Complete data on Reactions 25 and 26 appear to be not available. From the data and calculations of STRECKER AND KORKES[32], the $\Delta G'$ for conversion of glucose, water, and NAD^+ to gluconate, 2 H^+, and NADH was calculated to be −7.93 kcal. Using this value and Reaction 1, $\Delta G'$ of formation of gluconate ion was calculated to be −270.01 kcal. The phosphate hydrolysis energy of 6-*P*-gluconate^{3-} is estimated to be −2.60 kcal, intermediate between −2.40 for α-glycerol phosphate[21] and −3.1 for 3-*P*-glycerate^{3-} (ref. 33). Thus $\Delta G'$ of formation of 6-*P*-gluconate^{3-} is calculated to be P−267.41 kcal. This value, *plus* Reaction 2 and $\Delta G'$ formation of Ribul-5-*P*, CO_2, and H_2O (Table III) permit calculation of the $\Delta G'$ values for Reactions 25 and 26. Reaction 26 has been found to be reversible[34], although seemingly not with a positive $\Delta G'$. However, high ionic strength in the reaction mixture makes precise calculation of the equilibrium constant from published data uncertain.