Biomolecules in hydrothermal systems: Calculation of the standard molal thermodynamic properties of nucleic-acid bases, nucleosides, and nucleotides at elevated temperatures and pressures

Douglas E. LaRowe [*], Harold C. Helgeson

Department of Earth and Planetary Science, University of California, Berkeley, CA 94720, USA

Abstract

Calculation of the thermodynamic properties of biomolecules at high temperatures and pressures is fundamental to understanding the biogeochemistry of hydrothermal systems. Ample evidence indicates that hyperthermophilic microbes interact chemically with their mineralogical environment in these systems. Nevertheless, little is known about the thermodynamic properties of the biomolecules involved in such processes. Recent advances in theoretical biogeochemistry make it possible to calculate these properties using the limited experimental data available in the literature, together with correlation and group additivity algorithms, reference model compounds, and the revised HKF equations of state. This approach permits calculation of the standard molal thermodynamic properties of the 120 common protonated and deprotonated nucleotides and their constituent nucleic-acid bases and nucleosides as a function of temperature and pressure. The requisite equations of state parameters can be calculated from experimental standard molal heat capacities, volumes, and compressibilities reported in the literature for nucleic-acid bases and nucleosides. Because no calorimetric or densimetric data are available for the nucleotides, experimental heats of reaction taken from the literature were used together with correlation and group additivity algorithms to generate provisional values of the corresponding equations of state parameters for the nucleotides. The thermodynamic properties and revised HKF equations of state parameters generated in the present study can be used to carry out comprehensive mass transfer and Gibbs energy calculations to describe and quantify the chemical interaction of minerals and microbes in hydrothermal systems.
© 2006 Elsevier Inc. All rights reserved.

1. Introduction

Much has been learned over the last 30 years about the mineralogy and aqueous geochemistry of the hydrothermal systems in which organisms are known to thrive. Similarly, the taxonomy, metabolic requirements, growth rates, energetics, proteomics, and genomics of hyperthermophilic microbes have received considerable attention (e.g., ZoBell, 1970; Brock, 1978; Fischer et al., 1983; Stetter et al., 1983; Deming and Baross, 1986; Stetter et al., 1986, 1990; Woese et al., 1990; Adams and Kelly, 1992; Adams, 1993). In contrast, little is understood about the chemical and thermodynamic factors responsible for stabilizing the biomolecules that support life at high temperatures and pressures (Shock, 1992; Amend and Shock, 2001; Daniel and Cowan, 2000). Because nucleic-acid bases, nucleosides, and nucleotides are requisite for life, quantifying their chemical and thermodynamic interaction in hydrothermal systems is essential to understanding the biogeochemistry of these systems. Nevertheless, the thermodynamic variables that regulate metabolic processes in these organisms have not been characterized. The relative stabilities of both nucleotides and minerals in hydrothermal systems are controlled by the chemical potentials of O_2, CO_2, H_2S, and other components that are shared among biomolecules and the aqueous and mineralogical environment in which hyperthermophilic microbes thrive. Consequently, the relative stabilities of thermophilic microbes, biomolecules, and the mineralogy and fluid chemistry of the hydrothermal system are intrinsically interdependent. Assessing this

[*] Corresponding author.
  E-mail address: larowe@berkeley.edu (D.E. LaRowe).

interdependence quantitatively requires not only the thermodynamic properties of minerals and inorganic aqueous species, but also those of the biomolecules in the system. The purpose of the present communication is to address this challenge by developing a comprehensive and internally consistent set of standard molal thermodynamic properties and equations of state parameters for the constituent biomolecules in nucleic acids at high and low temperatures and pressures. Calculation of the thermodynamic properties of nucleotides and their component molecules in hydrothermal systems provides a frame of reference that can be used to quantify the effect of temperature, pressure, and bulk composition on the ATP cycle, as well as eventually DNA and RNA polymerization in hyperthermophiles. Characterization of the relative stabilities of nucleic acids in these systems should have a beneficial impact on high-temperature biotechnology and genetic engineering.

Since the pioneering calorimetric studies of crystalline guanine and adenine over 70 years ago by Stiehler and Huffman (1935a,b), considerable attention has been devoted to measuring the thermodynamic properties of nucleotides, nucleosides, nucleic-acid bases, sugars, phosphate compounds, and reactions among them at or near 25 °C and 1 bar.[1] Selected data reported in a number of these papers have also been summarized in compilations (Mavrovouniotis, 1990, 1991; Alberty, 1998; Alberty, 2004b). More recently Ould-Moulaye et al. (2001, 2002) generated a comprehensive set of thermodynamic properties of nucleic-acid bases, nucleosides, and nucleotides at 25 °C and 1 bar, but the extent to which they are consistent with what is known experimentally about these properties at higher temperatures and pressures is not clear.

Although some heat capacity measurements are available at temperatures up to 90 °C (Szeminska et al., 1979), most experimental thermodynamic data reported in the literature for nucleotides and their constituent molecules at temperatures greater than 25 °C are restricted to temperatures ⩽55 °C (Patel and Kishore, 1995; Lee and

Chalikian, 2001). No experimental data other than heats of ionization (Oscarson et al., 1995) are available for nucleotides at the temperatures and pressures prevailing in many submarine hydrothermal systems. Nevertheless, experimental low-temperature data reported in the literature for reactions and reference model compounds can be combined with the revised HKF equations of state using correlation and group additivity algorithms to characterize the thermodynamic properties of nucleic-acid bases, nucleosides, and nucleotides at elevated temperatures and pressures. To ensure internal consistency and compatibility with the most recent experimental data reported in the literature, this approach requires reassessment of the values of ΔG_f°, ΔH_f°, and S° at 25 °C and 1 bar adopted by Ould-Moulaye et al. (2001, 2002). The group additivity strategies adopted below for this purpose make extensive use of experimental data reported in the literature for crystalline reference model compounds and the solubilities and heats of solution of nucleic acid bases and nucleosides. Many of the standard molal thermodynamic properties and revised HKF equations of state parameters for the biomolecules considered in the present communication were generated using group additivity algorithms, correlations, and reference model compounds and reactions. The resulting provisional estimates of the thermodynamic properties of these molecules should afford a better understanding of the biogeochemistry of hydrothermal systems in the interim until more experimental calorimetric data become available in the literature. The terms and symbols appearing in the present communication are explained in Table 1 and the thermodynamic relations used in the calculations are summarized below.

2. Thermodynamic relations

Standard molal Gibbs energies and enthalpies are expressed in the present communication as apparent standard molal Gibbs energies and enthalpies of formation (ΔG° and ΔH°, respectively), which are defined by (Benson, 1968; Helgeson, 1969)

$$\Delta G^\circ \equiv \Delta G_f^\circ + (G_{P,T}^\circ - G_{P_r,T_r}^\circ) \tag{1}$$

and

$$\Delta H^\circ \equiv \Delta H_f^\circ + (H_{P,T}^\circ - H_{P_r,T_r}^\circ), \tag{2}$$

where ΔG_f° and ΔH_f° refer to the standard molal Gibbs energy and enthalpy of formation from the elements in their stable form at the reference pressure (P_r) and temperature (T_r) of 1 bar and 298.15 K, and ($G_{P,T}^\circ - G_{P_r,T_r}^\circ$) and ($H_{P,T}^\circ - H_{P_r,T_r}^\circ$) stand for the differences in the standard molal Gibbs energy and enthalpy of any aqueous species at the pressure (P) and temperature (T) of interest, and those at P_r and T_r. The differences in Gibbs energies and enthalpies between the pressure and temperature of interest (P, T) and the reference pressure (1 bar) and temperature (298.15 K) (P_r, T_r) can be expressed by writing

[1] Krebs and Kornberg (1957), Wilhoit and Shiao (1964),Phillips et al. (1965), Phillips (1966), Alberty (1969), Brown (1969), Cox and Pilcher (1970), Herskovits and Bowen (1974), Nabavian et al. (1977), Sabbah et al. (1977), Høiland and Holvik (1978), Kilday (1978a,b,c,d), Wilson et al. (1979), Bardi et al. (1980), Ramirez and Marecek (1980), Sabbah (1980), Stern and Oliver (1980), Teplitsky et al. (1980), Ahmed et al. (1981), Glukhova et al. (1981), Kilday (1981), Jasra and Ahluwalia (1982), Teplitsky et al. (1982), Kanbour et al. (1983),Kirklin and Domalski (1983), DeVoe and Wasik (1984), Høiland et al. (1984), Stern and Hubler (1984), Zielenkiewicz et al. (1984), Apelblat (1986),Dawson et al. (1986), Gajewski et al. (1986), Colbert et al. (1987), Buckin (1988), Tewari et al. (1988), Buckin et al. (1989), Goldberg and Tewari (1989), Kishore et al. (1989), Kishore and Ahluwalia (1990a,b), Paljk et al. (1990), Goldberg and Tewari (1991), Tewari et al. (1991), Zolkiewski and Zielenkiewicz (1991), Alberty and Goldberg (1992), Larson et al. (1993), Zielenkiewicz et al. (1993), Goldberg and Tewari (1994),Zielenkiewicz et al. (1994b,a), Oscarson et al. (1995), Patel and Kishore (1995), Zielenkiewicz (1995), Zielenkiewicz et al. (1998), Zielenkiewicz (2000), Zielenkiewicz et al. (2000), Boerio-Goates et al. (2001), Lee and Chalikian (2001), Huber et al. (2002), Boyer et al. (2003), Alberty (2004a).

Table 1
Glossary of symbols and terms

Symbol or term	Explanation
A	adenosine
a	standard molal heat capacity power function coefficient in Eq. (6)
a'_i	activity of the ith reactant in the biological standard state
a_i	activity of the ith species
a_1, a_2, a_3, a_4	species specific revised-HKF equations of state regression parameters
(aq)	designation of the aqueous state
Arg	arginine
ATP	adenosine triphosphate
b	standard molal heat capacity power function coefficient in Eq. (6)
base	designation of a nucleic-acid base
C	cytidine
c	standard molal heat capacity power function coefficient in Eq. (6)
c_1, c_2	species-specific revised-HKF equations of state regression parameters
(cr)	designation of the crystalline state
C_p°	standard molal isobaric heat capacity
$C_{p_r}^\circ$	standard molal isobaric heat capacity at the subscripted reference pressure of 1 bar
$\Delta C_{p,s}^\circ$	standard molal isobaric heat capacity of solvation
$\Delta C_{p,n}^\circ$	non-solvation standard molal isobaric heat capacity
E_i°	standard molal expansibility of the ith species
d	designation that the nucleotide or nucleoside of interest consists of deoxyribose rather than ribose
(g)	designation of the gas state
G	guanosine
ΔG°	apparent standard molal Gibbs energy of formation at the pressure and temperature of interest which is defined in Eq. (1)
ΔG_f°	standard molal Gibbs energy of formation from the elements in their stable form at 298.15 K and 1 bar
ΔG_{hyd}°	standard molal Gibbs energy of hydration
$G_{P,T}^\circ$	standard molal Gibbs energy at the pressure and temperature of interest
G_{P_r,T_r}°	standard molal Gibbs energy at the reference pressure and temperature
ΔG_r°	standard molal Gibbs energy of reaction
ΔG_{sol}°	standard molal Gibbs energy of solution
ΔG_{sub}°	standard molal Gibbs energy of sublimation
ΔH°	apparent standard molal enthalpy of formation at the pressure and temperature of interest which is defined in Eq. (2)
ΔH_f°	standard molal enthalpy of formation from the elements in their stable form at 298.15 K and 1 bar
ΔH_{hyd}°	standard molal enthalpy of hydration
$\Delta H_{m,P_r}^\circ$	standard molal enthalpy of melting at the reference pressure of 1 bar
$H_n NMP_i^{(n-2)}$	generic nucleotide monophosphate consisting of the ith base, n more moles of H per mole of nucleotide monophosphate than the nucleotide monophosphate reference species, NMP_i^{2-} (see below), and $(n-2)$ charge
$H_n NDP_i^{(n-3)}$	generic nucleotide diphosphate consisting of the ith base, n more moles of H per mole of nucleotide diphosphate than the nucleotide diphosphate reference species, NDP_i^{-3} (see below), and $(n-3)$ charge

Table 1 (*continued*)

Symbol or term	Explanation
$H_n NTP_i^{(n-4)}$	generic nucleotide triphosphate consisting of the ith base, n more moles of H per mole of nucleotide triphosphate than the nucleotide triphosphate reference species, NTP_i^{-4} (see below), and $(n-4)$ charge
$H_{P,T}^\circ$	standard molal enthalpy at the pressure and temperature of interest
H_{P_r,T_r}°	standard molal enthalpy at the reference pressure and temperature
ΔH_r°	standard molal enthalpy of reaction
ΔH_{sol}°	standard molal enthalpy of solution
ΔH_{sub}°	standard molal enthalpy of sublimation
i	generic designation of a species
ioniz	abbreviation for ionization
K	equilibrium constant
(l)	designation of the liquid state
Lys	abbreviation for lysine
M_i	molarity of the ith species
m_i	molality of the ith species
n	general subscript denoting number of moles
N	designation of a Born function discussed in Tanger and Helgeson (1988)
NDP_i^{-3}	nucleotide diphosphate reference species consisting of the ith base with a charge of -3
NMP_i^{-2}	nucleotide monophosphate reference species consisting of the ith base with a charge of -2
NTP_i^{-4}	nucleotide triphosphate reference species consisting of the ith base with a charge of -4
nucleic-acid base	any of the heterocyclic nitrogenous purine or pyrimidine compounds that comprise part of a nucleotide or nucleoside
nucleoside	general term for a species consisting of a nucleic-acid base and a sugar (ribose or deoxyribose)
nucleotide	general term for a species consisting of a nucleic-acid base, sugar (ribose or deoxyribose), and one or more phosphate groups
P	pressure in bars
P_r	reference pressure of 1 bar
prot	abbreviation for protonated
R	gas constant, 1.9872 cal mol^{-1}K^{-1}
Q	designation of a Born function discussed in Tanger and Helgeson (1988)
S°	standard molal entropy at the pressure and temperature of interest
ΔS_{hyd}°	standard molal entropy of hydration
ΔS_f°	standard molal entropy of formation from the elements in their stable form at 298.15 K and 1 bar
ΔS_n°	non-solvation standard molal entropy
S_{P_r,T_r}°	standard molal entropy at the reference pressure and temperature
ΔS_s°	standard molal entropy of solvation
ΔS_{sol}°	standard molal entropy of solution
ΔS_{sub}°	standard molal entropy of sublimation
sugar	designation of either ribose or deoxyribose
T	temperature in °C or K
T	thymidine
T_r	reference temperature of 298.15 K
U	uridine
V°	standard molal volume at the pressure and temperature of interest
ΔV_n°	non-solvation standard molal volume
$\Delta V_{P_r,T_r}^\circ$	standard molal volume at the reference pressure and temperature
ΔV_s°	standard molal volume of solvation

Table 1 (*continued*)

Symbol or term	Explanation
X	designation of a Born function discussed in Tanger and Helgeson (1988)
$Y_{P,T}$	designation of a Born function discussed in Tanger and Helgeson (1988) at the subscripted pressure and temperature of interest
Y_{P_r,T_r}	designation of a Born function discussed in Tanger and Helgeson (1988) at the subscripted reference pressure and temperature
Z_i	charge of the ith species
$\alpha^{\circ}_{H_2O}$	coefficient of isobaric thermal expansion of H_2O
ϵ	dielectric constant of water
$\epsilon_{P,T}$	dielectric constant of water at the subscripted pressure and temperature of interest
ϵ_{P_r,T_r}	dielectric constant of water at the reference pressure and temperature
Θ	solvent parameter equal to 228 K for water
κ°_S	standard molal adiabatic compressibility
κ°_T	standard molal isothermal compressibility
$\Delta\kappa^{\circ}_{T,s}$	standard molal isothermal compressibility of solvation
$\Delta\kappa^{\circ}_{T,n}$	non-solvation contribution to standard molal isothermal compressibility
Ξ°	generic designation of any conventional standard molal property or equation of state parameter for aqueous species
$\Xi^{abs}_{H^+}$	any given absolute standard molal property of the hydrogen ion
Ξ_i	generic description of any given conventional standard molal property or equation of state parameter for the ith species
Ξ^{abs}_i	generic description of any given absolute standard molal property or equation of state parameter for the ith aqueous species
$\Delta\Xi^{\circ}_n$	generic designation of the non-solvation contribution to any conventional standard molal property or equation of state parameter for an aqueous species
$\Delta\Xi^{\circ}_s$	generic designation of the solvation contribution to any conventional standard molal property or equation of state parameter for an aqueous species
ξ	equation of state parameter defined by Eq. (21)
ρ	density
σ	equation of state parameter defined by Eq. (20)
Ψ	solvent parameter equal to 2600 bar for water
ω_i	Born solvation parameter for the ith aqueous species
$\omega_{i_{P,T}}$	Born solvation parameter for the ith aqueous species at the subscripted pressure and temperature of interest
$\omega_{i_{P_r,T_r}}$	Born solvation parameter for the ith aqueous species at the subscripted reference pressure and temperature
zwitterion	a molecule having separate positively and negatively charged atoms or groups

$$G^{\circ}_{P,T} - G^{\circ}_{P_r,T_r} = -S^{\circ}_{P_r,T_r}(T - T_r) + \int_{T_r}^{T} C^{\circ}_{P_r}\,dT$$
$$- T\int_{T_r}^{T} C^{\circ}_{P_r}\,d\ln T + \int_{P_r}^{P} V^{\circ}\,dP, \qquad (3)$$

and

$$H^{\circ}_{P,T} - H^{\circ}_{P_r,T_r} = \int_{T_r}^{T} C^{\circ}_{P_r}\,dT + \int_{P_r}^{P} V^{\circ}\,dP$$
$$- \left(T\int_{P_r}^{P}\left(\frac{\partial V^{\circ}}{\partial T}\right)_P\,dP\right)_T, \qquad (4)$$

which are consistent with

$$S^{\circ} = S^{\circ}_{P_r,T_r} + \int_{T_r}^{T} C^{\circ}_{P_r}\,d\ln T - \left(\int_{P_r}^{P}\left(\frac{\partial V^{\circ}}{\partial T}\right)_P\,dP\right)_T, \qquad (5)$$

where $C^{\circ}_{p_r}$ stands for the isobaric molal heat capacity of the species at the reference pressure, $(\frac{\partial V^{\circ}}{\partial T})_P$ represents its standard molal expansibility, and $S^{\circ}_{P_r,T_r}$ refers to the standard molal entropy of the species at the reference pressure and temperature.

2.1. Crystalline compounds

Consideration of a wide range of experimental data indicates that in the absence of lambda phase transitions the standard molal heat capacities at 1 bar of crystalline organic compounds including amino acids (Helgeson et al., 1998) can be represented as a function of temperature by the Maier–Kelley power function (Maier and Kelley, 1932), which can be written as

$$C^{\circ}_{P_r} = a + bT + cT^{-2}, \qquad (6)$$

where a, b, and c stand for temperature-independent coefficients of the species of interest.

Combining Eq. (6) with Eqs. (3)–(5) and integrating the heat capacity terms leads to

$$G^{\circ}_{P,T} - G^{\circ}_{P_r,T_r} = -S^{\circ}_{P_r,T_r}(T - T_r) + a\left(T - T_r - T\ln\left(\frac{T}{T_r}\right)\right)$$
$$- \left(\frac{(c - bT_r^2 T)(T - T_r)^2}{2T_r^2 T}\right) + \int_{P_r}^{P} V^{\circ}\,dP, \qquad (7)$$

$$H^{\circ}_{P,T} - H^{\circ}_{P_r,T_r} = a(T - T_r) + \frac{b}{2}(T^2 - T_r^2) - c\left(\frac{1}{T} - \frac{1}{T_r}\right)$$
$$+ \int_{P_r}^{P} V^{\circ}\,dP - \left(T\int_{P_r}^{P}\left(\frac{\partial V^{\circ}}{\partial T}\right)_P\,dP\right)_T, \qquad (8)$$

and

$$S^{\circ} = S^{\circ}_{P_r,T_r} + a\ln\left(\frac{T}{T_r}\right) + b(T - T_r) - \frac{c}{2}\left(\frac{1}{T^2} - \frac{1}{T_r^2}\right)$$
$$- \left(\int_{P_r}^{P}\left(\frac{\partial V^{\circ}}{\partial T}\right)_P\,dP\right)_T. \qquad (9)$$

As in the case of minerals (Helgeson et al., 1978) and organic crystals (Helgeson et al., 1998; Richard and Helgeson, 1998), the standard molal volumes of crystalline bases and nucleosides are insensitive to the changes in temperature and pressure considered in the present study, which range from 0 °C and 1 bar to 150 °C and 500 (less arbitrary) bar. Therefore, as a first approximation we can write

$$V^\circ = V^\circ_{P_r,T_r}, \tag{10}$$

which can be used to evaluate the volume integrals in Eqs. (7)–(9) for crystalline compounds.

2.2. Aqueous species

The conventional standard molal properties of aqueous species[2] are expressed in the revised-HKF equations of state (Helgeson and Kirkham, 1974a,b, 1976; Helgeson et al., 1981; Shock and Helgeson, 1988; Tanger and Helgeson, 1988; Shock et al., 1989; Shock and Helgeson, 1990; Johnson et al., 1992; Shock et al., 1992; Sverjensky et al., 1997) as the sum of structural (non-solvation) and solvation contributions, which can be expressed as

$$\Xi^\circ = \Delta\Xi^\circ_n + \Delta\Xi^\circ_s \tag{12}$$

where Ξ° stands for any conventional standard molal property of an aqueous species, and $\Delta\Xi^\circ_n$ and $\Delta\Xi^\circ_s$ refer to the conventional non-solvation and solvation contributions to that property, respectively.

2.2.1. Charged aqueous species

The solvation contributions to the standard molal heat capacity, volume, isothermal compressibility, and entropy of a charged aqueous species can be expressed in terms of Born transfer theory as (Shock et al., 1992)

$$\Delta C^\circ_{P,s} = \omega T X + 2TY\left(\frac{\partial\omega}{\partial T}\right)_P - T\left(\frac{1}{\epsilon}-1\right)\left(\frac{\partial^2\omega}{\partial T^2}\right)_P, \tag{13}$$

$$\Delta V^\circ_s = -\omega Q + \left(\frac{1}{\epsilon}-1\right)\left(\frac{\partial\omega}{\partial P}\right)_T, \tag{14}$$

$$\Delta\kappa^\circ_{T,s} = \omega N + 2Q\left(\frac{\partial\omega}{\partial P}\right)_T - \left(\frac{1}{\epsilon}-1\right)\left(\frac{\partial^2\omega}{\partial P^2}\right)_T, \tag{15}$$

and

$$\Delta S^\circ_s = \omega Y + \left(\frac{1}{\epsilon}-1\right)\left(\frac{\partial\omega}{\partial T}\right)_P, \tag{16}$$

where $\Delta C^\circ_{P,s}$, ΔV°_s, $\Delta\kappa^\circ_{T,s}$, and ΔS°_s refer to the standard molal heat capacity, volume, isothermal compressibility, and entropy of solvation, ϵ stands for the dielectric constant of H_2O, ω designates the conventional Born coefficient, and X, Y, N, and Q denote the Born functions defined

---

and tabulated in Helgeson and Kirkham (1974a) and further discussed in Tanger and Helgeson (1988).

The non-solvation contributions to the heat capacity $(\Delta C^\circ_{P,n})$, volume (ΔV°_n), and isothermal compressibility $(\Delta\kappa^\circ_{T,n})$ of an aqueous species are given by

$$\Delta C^\circ_{P,n} = c_1 + \frac{c_2}{(T-\Theta)^2} - \left(\frac{2T}{(T-\Theta)^3}\right)$$
$$\times \left(a_3(P-P_r) + a_4\ln\left(\frac{\Psi+P}{\Psi+P_r}\right)\right), \tag{17}$$

$$\Delta V^\circ_n = \sigma + \frac{\xi}{T-\Theta}$$
$$= a_1 + \frac{a_2}{\Psi+P} + \left(a_3 + \frac{a_4}{\Psi+P}\right)\left(\frac{1}{T-\Theta}\right), \tag{18}$$

and

$$-\Delta\kappa^\circ_{T,n} = \left(\frac{\partial\sigma}{\partial P}\right)_T + \left(\frac{\partial\xi}{\partial P}\right)_T\left(\frac{1}{T-\Theta}\right), \tag{19}$$

where

$$\sigma = a_1 + \frac{a_2}{\Psi+P}, \tag{20}$$

$$\xi = a_3 + \frac{a_4}{\Psi+P}, \tag{21}$$

$$\left(\frac{\partial\sigma}{\partial P}\right)_T = \frac{-a_2}{(\Psi+P)^2}, \tag{22}$$

and

$$\left(\frac{\partial\xi}{\partial P}\right)_T = \frac{-a_4}{(\Psi+P)^2}, \tag{23}$$

where c_1, c_2, a_1, a_2, a_3, a_4, σ, and ξ represent species-dependent non-solvation parameters and Ψ and Θ denote solvent parameters equal to 2600 bar and 228 K, respectively. The revised-HKF equations for the standard molal heat capacity, volume, isothermal compressibility, and entropy, and the standard molal enthalpy and Gibbs energy of formation of charged species are given by

$$C^\circ_P = \Delta C^\circ_{P,n} + \Delta C^\circ_{P,s} = c_1 + \frac{c_2}{(T-\Theta)^2} - \left(\frac{2T}{(T-\Theta)^3}\right)$$
$$\times \left(a_3(P-P_r) + a_4\ln\left(\frac{\Psi+P}{\Psi+P_r}\right)\right)$$
$$+ \omega T X + 2TY\left(\frac{\partial\omega}{\partial T}\right)_P - T\left(\frac{1}{\epsilon}-1\right)\left(\frac{\partial^2\omega}{\partial T^2}\right)_P, \tag{24}$$

$$V^\circ = \Delta V^\circ_n + \Delta V^\circ_s = \sigma + \frac{\xi}{T-\Theta}$$
$$= a_1 + \frac{a_2}{\Psi+P} + \left(a_3 + \frac{a_4}{\Psi+P}\right)\left(\frac{1}{T-\Theta}\right) - \omega Q$$
$$+ \left(\frac{1}{\epsilon}-1\right)\left(\frac{\partial\omega}{\partial P}\right)_T, \tag{25}$$

---

[2] The standard state adopted in the present study for aqueous species other than H_2O corresponds to unit activity of the species in a hypothetical one molal solution referenced to infinite dilution at any pressure and temperature. The standard molal thermodynamic properties of charged aqueous species used below are consistent with the hydrogen ion convention, which can be expressed as

$$\Xi_i = \Xi^{abs}_i - Z_i\Xi^{abs}_{H^+}, \tag{11}$$

where Ξ_i and Ξ^{abs}_i, respectively, stand for any given conventional and absolute standard molal property or equation of state parameter of the ith aqueous species, $\Xi^{abs}_{H^+}$ denotes the corresponding absolute standard molal property of the hydrogen ion, and Z_i represents the charge of the subscripted species. Hence, $\Xi_{H^+} = 0$ at all temperatures and pressures.

$$\kappa_T^\circ = \Delta\kappa_{T,n}^\circ + \Delta\kappa_{T,s}^\circ = -\left(\frac{\partial\sigma}{\partial P}\right)_T - \left(\frac{\partial\xi}{\partial P}\right)_T\left(\frac{1}{T-\Theta}\right)$$
$$+ \omega N + 2Q\left(\frac{\partial\omega}{\partial P}\right)_T - \left(\frac{1}{\epsilon}-1\right)\left(\frac{\partial^2\omega}{\partial P^2}\right)_T, \tag{26}$$

$$S^\circ = S_{P_r,T_r} + c_1\ln\left(\frac{T}{T_r}\right)$$
$$- \frac{c_2}{\Theta}\left[\left(\frac{1}{T-\Theta}\right)-\left(\frac{1}{T_r-\Theta}\right)+\frac{1}{\Theta}\ln\left(\frac{T_r(T-\Theta)}{T(T_r-\Theta)}\right)\right]$$
$$+ \left(\frac{1}{T-\Theta}\right)^2\left(a_3(P-P_r)+a_4\ln\left(\frac{\Psi+P}{\Psi+P_r}\right)\right)$$
$$+ \omega Y - \left(\frac{1}{\epsilon}-1\right)\left(\frac{\partial\omega}{\partial T}\right)_P - \omega_{P_r,T_r}Y_{P_r,T_r}, \tag{27}$$

$$\Delta H^\circ = \Delta H_f^\circ + c_1(T-T_r) - c_2\left(\left(\frac{1}{T-\Theta}\right)-\left(\frac{1}{T_r-\Theta}\right)\right)$$
$$+ a_1(P-P_r) + a_2\ln\left(\frac{\Psi+P}{\Psi+P_r}\right) + \left(\frac{2T-\Theta}{(T-\Theta)^2}\right)$$
$$\times\left(a_3(P-P_r)+a_4\ln\left(\frac{\Psi+P}{\Psi+P_r}\right)\right) + \omega\left(\frac{1}{\epsilon}-1\right)$$
$$+ \omega TY - T\left(\frac{1}{\epsilon}-1\right)\left(\frac{\partial\omega}{\partial T}\right)_P - \omega_{P_r,T_r}\left(\frac{1}{\epsilon_{P_r,T_r}}-1\right)$$
$$- \omega_{P_r,T_r}T_rY_{P_r,T_r}, \tag{28}$$

and

$$\Delta G^\circ = \Delta G_f^\circ - S_{P_r,T_r}(T-T_r) - c_1\left(T\ln\left(\frac{T}{T_r}\right)-T+T_r\right)$$
$$+ a_1(P-P_r) + a_2\ln\left(\frac{\Psi+P}{\Psi+P_r}\right)$$
$$- c_2\left(\left(\left(\frac{1}{T-\Theta}\right)-\left(\frac{1}{T_r-\Theta}\right)\right)\left(\frac{\Theta-T}{\Theta}\right)\right.$$
$$\left.- \frac{T}{\Theta^2}\ln\left(\frac{T_r(T-\Theta)}{T(T_r-\Theta)}\right)\right) + \left(\frac{1}{T-\Theta}\right)$$
$$\times\left(a_3(P-P_r)+a_4\ln\left(\frac{\Psi+P}{\Psi+P_r}\right)\right) + \omega\left(\frac{1}{\epsilon}-1\right)$$
$$- \omega_{P_r,T_r}\left(\frac{1}{\epsilon_{P_r,T_r}}-1\right) + \omega_{P_r,T_r}Y_{P_r,T_r}(T-T_r), \tag{29}$$

respectively.

2.2.2. Neutral aqueous species

As in the case of other neutral aqueous species (Shock et al., 1989; Shock and Helgeson, 1990), the effective Born coefficient (ω) of the various neutral bases, nucleosides, and nucleotides are taken to be independent of temperature and pressure.[3] Therefore, the solvation contributions to the standard molal properties of these species can be expressed as

---

[3] The effective Born coefficients for neutral aqueous species account for dipole–dipole interactions arising from the presence of the neutral aqueous molecules in a structured solution (Helgeson et al., 1981; Shock et al., 1992; Amend and Helgeson, 1997a).

$$\Delta C_{P,s}^\circ = \omega TX, \tag{30}$$
$$\Delta V_s^\circ = -\omega Q, \tag{31}$$
$$\Delta\kappa_{T,s}^\circ = \omega N, \tag{32}$$

and

$$\Delta S_s^\circ = \omega Y. \tag{33}$$

It follows that Eqs. (24)–(29) can be expressed for neutral nucleic-acid bases, nucleosides, and nucleotides as

$$C_P^\circ = \Delta C_{P,n}^\circ + \Delta C_{P,s}^\circ = c_1 + \frac{c_2}{(T-\Theta)^2} - \left(\frac{2T}{(T-\Theta)^3}\right)$$
$$\times\left(a_3(P-P_r)+a_4\ln\left(\frac{\Psi+P}{\Psi+P_r}\right)\right) + \omega TX, \tag{34}$$

$$V^\circ = \Delta V_n^\circ + \Delta V_s^\circ$$
$$= a_1 + \frac{a_2}{\Psi+P} + \left(a_3+\frac{a_4}{\Psi+P}\right)\left(\frac{1}{T-\Theta}\right) - \omega Q, \tag{35}$$

$$\kappa_T^\circ = \Delta\kappa_{T,n}^\circ + \Delta\kappa_{T,s}^\circ = -\left(\frac{\partial\sigma}{\partial P}\right)_T - \left(\frac{\partial\xi}{\partial P}\right)_T\left(\frac{1}{T-\Theta}\right) + \omega N, \tag{36}$$

$$S^\circ = S_{P_r,T_r} + c_1\ln\left(\frac{T}{T_r}\right) - \frac{c_2}{\Theta}\left[\left(\frac{1}{T-\Theta}\right)-\left(\frac{1}{T_r-\Theta}\right)\right.$$
$$\left.+ \frac{1}{\Theta}\ln\left(\frac{T_r(T-\Theta)}{T(T_r-\Theta)}\right)\right] + \left(\frac{1}{T-\Theta}\right)^2$$
$$\times\left(a_3(P-P_r)+a_4\ln\left(\frac{\Psi+P}{\Psi+P_r}\right)\right) + \omega(Y_{P,T}-Y_{P_r,T_r}), \tag{37}$$

$$\Delta H^\circ = \Delta H_f^\circ + c_1(T-T_r) - c_2\left(\left(\frac{1}{T-\Theta}\right)-\left(\frac{1}{T_r-\Theta}\right)\right)$$
$$+ a_1(P-P_r) + a_2\ln\left(\frac{\Psi+P}{\Psi+P_r}\right) + \left(\frac{2T-\Theta}{(T-\Theta)^2}\right)$$
$$\times\left(a_3(P-P_r)+a_4\ln\left(\frac{\Psi+P}{\Psi+P_r}\right)\right) + \omega\left(\frac{1}{\epsilon}-1\right)$$
$$+ \omega\left(TY_{P,T}-T_rY_{P_r,T_r} - \left(\frac{1}{\epsilon_{P_r,T_r}}-1\right) + \left(\frac{1}{\epsilon_{P,T}}-1\right)\right), \tag{38}$$

and

$$\Delta G^\circ = \Delta G_f^\circ - S_{P_r,T_r}(T-T_r) - c_1\left(T\ln\left(\frac{T}{T_r}\right)-T+T_r\right)$$
$$+ a_1(P-P_r) + a_2X\ln\left(\frac{\Psi+P}{\Psi+P_r}\right)$$
$$- c_2\left(\left(\left(\frac{1}{T-\Theta}\right)-\left(\frac{1}{T_r-\Theta}\right)\right)\left(\frac{\Theta-T}{\Theta}\right)\right.$$
$$\left.- \frac{T}{\Theta^2}\ln\left(\frac{T_r(T-\Theta)}{T(T_r-\Theta)}\right)\right) + \left(\frac{1}{T-\Theta}\right)$$
$$\times\left(a_3(P-P_r)+a_4\ln\left(\frac{\Psi+P}{\Psi+P_r}\right)\right)$$
$$+ \omega\left(Y_{P_r,T_r}(T-T_r) + \left(\frac{1}{\epsilon_{P,T}}-1\right) - \left(\frac{1}{\epsilon_{P_r,T_r}}-1\right)\right). \tag{39}$$

The parameters required to compute the standard molal thermodynamic properties of aqueous nucleic-acid bases, nucleosides, and nucleotides as a function of temperature and pressure from the revised HKF equations of state summarized above can be generated from the experimental data, group additivity algorithms, model compounds, and correlations summarized below.

3. Nucleic-acid bases

Nucleic-acid bases can be divided into two classes of partially aromatic heterocyclic nitrogen-bearing compounds consisting of either a single ring (pyrimidines) or two rings (purines). Of the many naturally occurring and synthetic purine and pyrimidine compounds, those consid-

ADENINE   CYTOSINE   GUANINE   THYMINE   URACIL
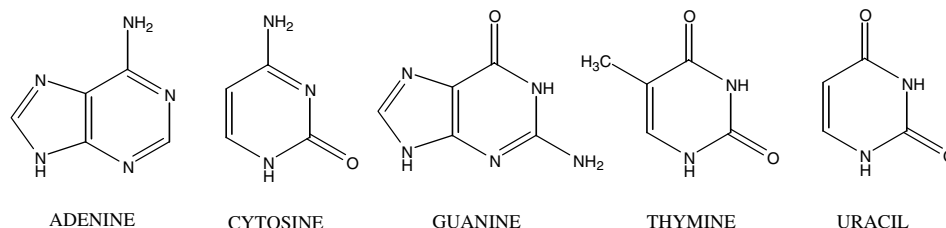
Fig. 1. Idealized structures and chemical formulas for selected nucleic-acid bases.

Table 2
Summary of values of the standard molal thermodynamic properties at 25 °C and 1 bar and revised HKF equation of state parameters for selected aqueous nucleic-acid bases, nucleosides, sugars and ribose-5-phosphate^{2-}

Compound	Formula	$\Delta G_f^{\circ\,[a]}$	$\Delta H_f^{\circ\,[a]}$	$S^{\circ\,[b]}$	$C_P^{\circ\,[b]}$	$V^{\circ\,[c]}$	$a_1^{[d]} \times 10$	$a_2^{[a]} \times 10^{-2}$	$a_3^{[e]}$	$a_4^{[f]} \times 10^{-4}$	$c_1^{[b]}$	$c_2^{[f]} \times 10^{-4}$	$\omega^{[a]} \times 10^{-5}$
Purines													
Adenine	$C_5H_5N_5$	74,770	31,235	53.41	56.24$^{[g]}$	89.59	21.5046	8.5010	−2.6632	−5.3561	87.88	−15.87	0.065$^{[h]}$
Guanine	$C_5H_5N_5O$	16,702	−34,803	51.19	60.06$^{[i]}$	97.9	23.298	7.4602	−5.4837	−3.4136	90.14	−15.87	0.23$^{[h]}$
Pyrimidines													
Cytosine	$C_4H_5N_3O$	−8411	−46,915	47.64	41.81	73.35	17.3106	5.8612	6.6034	−5.2201	70.51	−13.36	0.17$^{[h]}$
Thymine	$C_5H_6N_2O_2$	−61,315	−104,969	48.96	56.93	88.04	21.2655	7.2705	−1.0309	−5.0944	83.20	−12.39	0.12$^{[h]}$
Uracil	$C_4H_4N_2O_2$	−59,734	−94,587	45.88	36.19	71.55	17.5038	5.9312	−1.6074	−4.3091	56.57	−9.40	0.14$^{[h]}$
Sugars													
Ribose	$C_5H_{10}O_5$	−179,739	−247,132	59.53	66.46	95.71	22.6455	7.2930	−5.3875	−3.4054	134.7	−32.82	0.17$^{[j]}$
Deoxyribose	$C_5H_{10}O_4$	−144,433	−205,037	57.82	56.16	94.65	22.5370	7.2652	−5.3715	−3.4040	124.4	−32.82	0.17
Nucleosides													
Adenosine	$C_{10}H_{13}N_5O_4$	−46,499	−148,490	87.19	120.3	170.7	39.5452	12.901	8.9651	−8.8169	163.2	−20.10	0.23$^{[k]}$
Cytidine	$C_9H_{13}N_3O_5$	−130,179	−226,640	83.09	96.38	153.3	36.3116	7.9960	7.5934	−6.5938	132.6	−16.30	0.34$^{[k]}$
Guanosine	$C_{10}H_{13}N_5O_5$	−105,568	−214,528	88.33	124.9	174.2	42.2627	8.3757	−2.4562	−5.8937	169.3	−20.10	0.39$^{[k]}$
Thymidine	$C_{10}H_{14}N_2O_6$	−183,083	−284,694	84.42	110.5	167.4	38.1602	10.959	12.395	−7.1879	143.4	−14.90	0.29$^{[k]}$
Uridine	$C_9H_{12}N_2O_6$	−181,502	−274,312	81.34	95.14	151.8	36.1528	7.0910	5.1259	−5.6836	131.8	−16.65	0.31$^{[k]}$
Deoxynucleosides													
Deoxyadenosine	$C_{10}H_{13}N_5O_3$	−11,193	−106,386	85.48	111.2	170.0	38.0314	16.957	15.1636	−10.834	154.2	−20.10	0.23$^{[k]}$
Deoxycytidine	$C_9H_{13}N_3O_4$	−96,652	−184,534	87.35	87.28	154.0	35.8171	9.7174	7.4022	−6.5327	123.5	−16.30	0.34$^{[k]}$
Deoxyguanosine	$C_{10}H_{13}N_5O_4$	−71,539	−176,273	77.99	115.8	173.2	39.4526	15.498	14.2847	−10.569	160.3	−20.10	0.39$^{[k]}$
Deoxythymidine	$C_{10}H_{14}N_2O_5$	−14,9556	−242,588	88.68	101.4	167.5	38.8728	11.451	−7.7797	−3.6098	134.4	−14.90	0.29$^{[k]}$
Deoxyuridine	$C_8H_{12}N_2O_5$	−14,7975	−232,206	85.59	86.04	151.2	35.5945	9.6188	3.5015	−6.2803	122.8	−16.65	0.31$^{[k]}$
Other													
Ribose-5-phosphate$^{2-\,[l]}$	$C_5H_9O_8P^{2-}$	−378,243	−487,926$^{[m]}$	16.49$^{[m]}$	7.5	83.78	2.0659	57.7664	−17.55	0.3909	102.86	−32.92	2.96

Unless otherwise indicated, the properties and parameters given in this table were generated in the present study (see text).
[a] cal mol^{-1}.
[b] cal K^{-1} mol^{-1}.
[c] cm^3 mol^{-1}.
[d] cal mol^{-1} bar^{-1}.
[e] cal K mol^{-1} bar^{-1}.
[f] cal K mol^{-1}.
[g] Average of literature values summarized in Table A.2 in Appendix A.
[h] Calculated using Eq. (47).
[i] Calculated using Eq. (58).
[j] Amend and Plyasunov (2001).
[k] Calculated using Eq. (71).
[l] Discussed in Appendix B.
[m] Goldberg and Tewari (1989).

ered below consist of the normal nucleotide constituents of DNA and RNA corresponding to two purines (adenine and guanine) and three pyrimidines (cytosine, thymine, and uracil). The idealized structures and formulas of these nucleic-acid bases are shown in Fig. 1.

3.1. Standard molal Gibbs energies, enthalpies, and third law entropies at 25 °C and 1 bar

Values of $\Delta G^{\circ}_{f(aq)}$, $\Delta H^{\circ}_{f(aq)}$, and $S^{\circ}_{(aq)}$ at 25 °C and 1 bar for the five aqueous nucleic-acid bases considered in the

Table 3
Summary of C°_P power function coefficients and values of the standard molal thermodynamic properties at 25 °C and 1 bar for selected crystalline compounds

Compound	Formula	$\Delta G^{\circ\,a,b}_f$	$\Delta H^{\circ\,a}_f$	$S^{\circ c}$	$C^{\circ\,c}_P$	$V^{\circ d}$	a^c	$b^e \times 10^3$	$c^f \times 10^{-5}$
Purines									
Adenine	$C_5H_5N_5$	71,860	23,160[g]	36.09[h]	34.19	91.1[g]	0.375[i]	113.4[i]	0
Guanine	$C_5H_5N_5O$	11,402	−43,953[j]	38.29[h]	37.7	100.3[k]	2.49[i]	118.1[i]	0
Pyrimidines									
Cytosine	$C_4H_5N_3O$	−10,021	−52,890[l]	33.00	31.97	74.73[m]	15.28	65.97	−2.65
Thymine	$C_5H_6N_2O_2$	−63,392	−110,612[n]	37.05	34.95	86.68[o]	16.20	75.37	−3.31
Uracil	$C_4H_4N_2O_2$	−61,734	−101,400[l]	29.74	30.31	70.5[o]	4.175	92.67	−1.32
Monosaccharides									
Ribose	$C_5H_{10}O_5$	−177,660	−250,294[p]	41.99[q]	44.70[q]	94.42[r]	−7.398	168.8	1.577
Deoxyribose	$C_5H_{10}O_4$	−142,153	−207,770[p]	41.01[s]	32.52	84.36[r]	128.8	−215.4	−28.49
Nucleosides									
Adenosine	$C_{10}H_{13}N_5O_4$	−48,850[q]	−156,200[q]	69.22[q]	69.38	173.53[q]	−3.330	239.6	1.111
Cytidine	$C_9H_{13}N_3O_5$	−130,731	−232,250	66.12	67.15	157.16	11.58	192.2	−1.539
Guanosine	$C_{10}H_{13}N_5O_5$	−109,308	−223,313	71.41	72.87	182.73	−1.215	244.3	1.111
Thymidine	$C_{10}H_{14}N_2O_6$	−184,102	−289,972	70.14	70.13	169.11	12.50	201.6	−2.199
Uridine	$C_9H_{12}N_2O_6$	−182,444	−280,760	62.87	65.50	152.93	0.4697	218.9	−0.209
Deoxynucleosides									
Deoxyadenosine	$C_{10}H_{13}N_5O_3$	−13,343	−113,676	78.24	57.21	163.47	132.9	−144.6	−28.96
Deoxycytidine	$C_9H_{13}N_3O_4$	−95,224	−189,726	65.14	55.00	147.10	147.8	−192.0	−31.61
Deoxyguanosine	$C_{10}H_{13}N_5O_4$	−73,801	−180,789	70.43	60.71	172.67	135.0	−139.9	−28.96
Deoxythymidine	$C_{10}H_{14}N_2O_5$	−148,595	−247,448	69.16	57.96	159.05	148.7	−182.6	−32.27
Deoxyuridine	$C_9H_{12}N_2O_5$	−146,937	−238,236	61.89	53.35	142.87	136.7	−165.3	−30.28
Acids									
Phosphoric acid	H_3PO_4	−268,715	−306,974[t]	26.41[u]	25.36	52.97[v]	3.447	73.50	0
Citric acid	$C_6H_8O_7$	−296,096	−369,000[w]	60.25[x]	53.89	124.59[y]	11.25	143.0	0

[a] cal mol^{-1}.

[b] Calculated using Eq. (42) together with values of ΔH°_f and S° given above with values of S° of the elements taken from Cox et al. (1989) unless otherwise noted.

[c] cal K^{-1} mol^{-1}.

[d] cm^3 mol^{-1}.

[e] cal K^{-2} mol^{-1}.

[f] cal K mol^{-1}.

[g] Kirklin and Domalski (1983).

[h] Domalski and Hearing (1996).

[i] Calculated by regressing experimental C°_P data from Stiehler and Huffman (1935b) with Eq. (6).

[j] Cox and Pilcher (1970).

[k] Calculated from $V^{\circ}_{adenine}$ using group volumes taken from Immirzi and Perini (1977).

[l] Wilson et al. (1979).

[m] Calculated from V°_{uracil} using group volumes taken from Immirzi and Perini (1977).

[n] Nabavian et al. (1977).

[o] Calculated from density data given by Colbert et al. (1987).

[p] Colbert et al. (1987).

[q] Boerio-Goates et al. (2001).

[r] Calculated from density data from Boyer et al. (2003).

[s] Calculated using Eq. (63).

[t] Chase (1998).

[u] Egan and Wakefield (1957).

[v] Calculated from density from Egan and Wakefield (1957).

[w] Wilhoit and Shiao (1964).

[x] de Kruif et al. (1982).

[y] Calculated from density data from Apelblat (1986). See Table A.7 in Appendix A for additional literature values.

present study are shown in Table 2. The values of $\Delta G^{\circ}_{f(aq)}$ and $\Delta H^{\circ}_{f(aq)}$ given in this table were calculated from the standard molal Gibbs energies and enthalpies of formation of the crystalline nucleic-acid bases ($\Delta G^{\circ}_{f(cr)}$ and $\Delta H^{\circ}_{f(cr)}$, respectively) and the corresponding standard molal properties of solution (ΔG°_{sol} and ΔH°_{sol}) using

$$\Delta G^{\circ}_{f(aq)} = \Delta G^{\circ}_{f(cr)} + \Delta G^{\circ}_{sol} \tag{40}$$

and

$$\Delta H^{\circ}_{f(aq)} = \Delta H^{\circ}_{f(cr)} + \Delta H^{\circ}_{sol}. \tag{41}$$

The values of $S^{\circ}_{(aq)}$ given for the nucleic-acid bases listed in Table 2 were calculated by combining values of S°_i taken from Cox et al. (1989) with

$$S^{\circ}_{(aq)} = \frac{\Delta H^{\circ}_{f(aq)} - \Delta G^{\circ}_{f(aq)}}{T} - \sum_i n_i S^{\circ}_i, \tag{42}$$

where n_i denotes the number of moles of the ith element in a given nucleic-acid base and S°_i represents the standard molal third law entropy of the ith element in its stable state at 25 °C and 1 bar. The values of $\Delta G^{\circ}_{f(cr)}$ and $\Delta H^{\circ}_{f(cr)}$, and ΔG°_{sol}, and ΔH°_{sol} used to evaluate Eqs. (40) and (41) are listed in Tables 3 and 4, respectively. Because experimental values of $\Delta G^{\circ}_{f(cr)}$ are not available in the literature to compute values of $\Delta G^{\circ}_{f(aq)}$ for the aqueous pyrimidines listed in Table 3, values of $\Delta G^{\circ}_{f(cr)}$ for these species were estimated using the strategy described below.

Values of $\Delta G^{\circ}_{f(cr)}$ for the pyrimidines can be calculated by rearranging and combining Eq. (42) with experimental values of $\Delta H^{\circ}_{f(cr)}$ and those of S°_{cr} computed with the aid of the group additivity algorithms depicted in Table 5 using the $S^{\circ}_{(cr)}$ group contributions listed in Table 6. The values of the group contributions shown in Table 6 that are not available in the literature were estimated in the present study from the group additivity algorithms summarized in Table 7 using the properties of the reference model compounds listed in Table 8.

For example, the value of $\Delta G^{\circ}_{f(aq)}$ for aqueous uracil given in Table 2 was calculated from

$$\Delta G^{\circ}_{f(aq)\,\text{uracil}} = \Delta G^{\circ}_{f(cr)\,\text{uracil}} + \Delta G^{\circ}_{sol\,\text{uracil}}, \tag{43}$$

using the value of $\Delta G^{\circ}_{sol\,\text{uracil}}$ given in Table 4 and the value of $\Delta G^{\circ}_{f(cr)\,\text{uracil}}$ computed from

$$\Delta G^{\circ}_{f(cr)\,\text{uracil}} = \Delta H^{\circ}_{f(cr)\,\text{uracil}} - T\Delta S^{\circ}_{f(cr)\,\text{uracil}}, \tag{44}$$

which is given in Table 3. A value of $\Delta H^{\circ}_{f(cr)\,\text{uracil}}$ is also shown in Table 3 together with that of and $\Delta S^{\circ}_{f(cr)\,\text{uracil}}$, which was calculated from

Table 4
Summary of values of ΔG°_{sol}, ΔH°_{sol}, and ΔS°_{sol} at 25 °C and 1 bar for nucleic-acid bases, nucleosides, monosaccharides, and citric acid

Compound	Formula	ΔG°_{sol} [a]	ΔH°_{sol} [a]	S°_{sol} [b,c]
Purines				
Adenine	$C_5H_5N_5$	2908[d]	8075[d]	17.33
Guanine	$C_5H_5N_5O$	5300[d]	9150[d]	12.91
Pyrimidines				
Cytosine	$C_4H_5N_3O$	1610[d]	5975[d]	14.64
Thymine	$C_5H_6N_2O_2$	2077[d]	5643[d]	11.96
Uracil	$C_4H_4N_2O_2$	2000[e]	6813[d]	16.14
Nucleosides				
Adenosine	$C_{10}H_{13}N_5O_4$	2351[d]	7710[f]	17.97
Guanosine	$C_{10}H_{13}N_5O_5$	3740[g]	8785[i]	16.92
Cytidine	$C_9H_{13}N_3O_5$	552[h]	5610[i]	16.96
Thymidine	$C_{10}H_{14}N_2O_6$	1019[h]	5278[i]	14.28
Uridine	$C_9H_{12}N_2O_6$	942[h]	6448[i]	18.47
Deoxynucleosides				
Deoxyadenosine	$C_{10}H_{13}N_5O_3$	2150[d]	7292[i]	18.65
Deoxyguanosine	$C_{10}H_{13}N_5O_4$	2262[j]	4517[k]	7.56
Deoxycytidine	$C_9H_{13}N_3O_4$	−1428[j]	5192[k]	22.2
Deoxythymidine	$C_{10}H_{14}N_2O_5$	−961[j]	4860[k]	19.52
Deoxyuridine	$C_9H_{12}N_2O_5$	−1038[j]	6030[k]	23.71
Monosaccharides				
Ribose	$C_5H_{10}O_5$	−2079[l]	3151[d]	17.54
Deoxyribose	$C_5H_{10}O_4$	−2280[m]	2733[d]	16.81
Other				
Citric acid	$C_6H_8O_7$	−1084[n]	4473[d]	18.64

[a] cal mol^{-1}.
[b] cal K^{-1} mol^{-1}.
[c] Calculated from $\Delta S^{\circ}_{sol} = (\Delta H^{\circ}_{sol} - \Delta G^{\circ}_{sol})/T_r$.
[d] Average of literature values at 25 °C and 1 bar listed in Table A.8.
[e] Dawson et al. (1986).
[f] Stern and Oliver (1980).
[g] Herskovits and Bowen (1974).
[h] Calculated using Eq. (64).
[i] Calculated using Eqs. (65).
[j] Calculated using Eq. (68).
[k] Calculated using Eq. (70).
[l] Goldberg and Tewari (1991).
[m] Calculated from the group additivity relation represented by $\Delta G^{\circ}_{sol,Deoxyadenosine} + \Delta G^{\circ}_{sol,ribose} - \Delta G^{\circ}_{sol,adenosine} = \Delta G^{\circ}_{sol,deoxyribose}$.
[n] Calculated from the values of ΔG°_{cr} and ΔG°_{aq} for citric acid given in Tables 3 and B.0 in Appendix B, respectively. See Table A.8 in Appendix A for additional literature values.

Table 5
Summary of structural group algorithms used to calculate values of S° at 25 °C and 1 bar and the C°_P power function coefficients of selected crystalline pyrimidines
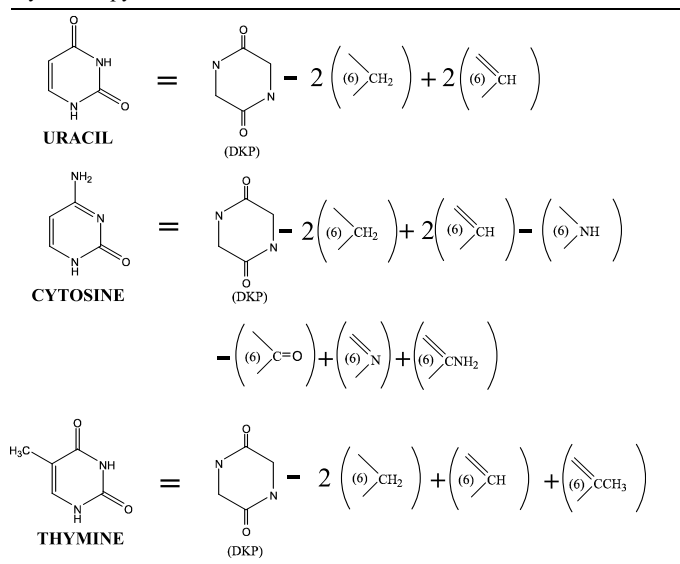
DKP stands for diketopiperazine.

Table 6

Summary of Maier–Kelley heat capacity power function coefficients and values of S° at 25 °C and 1 bar of the crystalline groups used in additivity algorithms to calculate the corresponding coefficients and properties of selected pyrimidines (see text)

Group	$S^{\circ a}$	a^{a}	$b^{b} \times 10^{3}$	$c^{c} \times 10^{-5}$
(6) CH$_2$	7.72[d]	−1.74[d]	22.4[d]	0.66[d]
(6) CH	5.19[d]	−0.37[d]	17.1[d]	0[d]
(6) NH	−3.51[e]	−4.5[e]	34.3[e]	−1.15[e]
(6) N	4.85[e]	1.909[e]	2.738[e]	0[e]
(6) C=O	13.19[e]	6.959[e]	−5.065[6]	0.489[e]
(6) C—NH$_2$	8.09[e]	1.435[e]	24.75[e]	0[e]
(6) C—CH$_3$	12.5[d]	11.66[d]	−0.20[d]	−1.99[d]

[a] cal K^{-1} mol^{-1}.
[b] cal K^{-2} mol^{-1}.
[c] cal K mol^{-1}.
[d] Taken from Richard and Helgeson (1998).
[e] Calculated with the algorithms depicted in Table 7 (see text).

Table 7

Summary of structural group algorithms used to calculate C_P° power function coefficients and S° at 25 °C and 1 bar of selected crystalline groups

$$\Delta S^{\circ}_{f(cr)\,\text{uracil}} = S^{\circ}_{(cr)\,\text{uracil}} - 4S^{\circ}_{\text{C, graphite}} - 2S^{\circ}_{\text{H}_2,g} - S^{\circ}_{\text{N}_2,g} - S^{\circ}_{\text{O}_2,g}, \tag{45}$$

using values of $S^{\circ}_{\text{C, graphite}}$, $S^{\circ}_{\text{H}_2,g}$, $S^{\circ}_{\text{N}_2,g}$, and $S^{\circ}_{\text{O}_2,g}$ taken from Cox et al. (1989). Finally, the value of $S^{\circ}_{(cr)\text{uracil}}$ was estimated using the first group additivity algorithm listed in Table 5. For entropy, this expression can be written as

$$S^{\circ}_{(cr)\,\text{uracil}} = S^{\circ}_{(cr)\,\text{DKP}} - 2S^{\circ}_{(cr)\,((6)>\text{CH}_2)} - 2S^{\circ}_{(cr)\,((6)\geqslant\text{CH})}. \tag{46}$$

The values of $S^{\circ}_{(cr)\,\text{DKP}}$ (DKP stands for diketopiperazine), $S^{\circ}_{(cr)\,((6)>\text{CH}_2)}$, and $S^{\circ}_{(cr)\,((6)\geqslant\text{CH})}$ used in the calculations are given in Tables 8 and 6.

The validity of the calculations described in the preceding paragraphs can be tested by inference from comparison of computed standard molal thermodynamic properties of nucleic-acid bases with their experimentally determined counterparts reported in the literature. For example, the structural group additivity algorithms used to calculate values of S°_{cr} for cytosine, thymine, and uracil (shown in Table 5) can also be used to compute values of $C^{\circ}_{P_r(cr)}$ for the same compounds, which can be compared to corresponding experimental values of $C^{\circ}_{P_r(cr)}$ reported in the literature. It can be seen in Table 9 that the computed values of $C^{\circ}_{P_r(cr)}$ for cytosine, thymine, and uracil are all within 1.5 cal mol^{-1} K^{-1} of the experimental standard molal heat capacities reported in the literature. In addition, the values of $\Delta G^{\circ}_{f(cr)}$, $\Delta H^{\circ}_{f(cr)}$, S°_{cr}, $\Delta G^{\circ}_{f(aq)}$, $\Delta H^{\circ}_{f(aq)}$, and $S^{\circ}_{(aq)}$ listed in Tables 2 and 3 compare favorably with those adopted by Ould-Moulaye et al. (2001, 2002). Such close agreement between literature values of standard molal thermodynamic properties estimated in the present study strongly supports the use of similar group additivity algorithms to calculate equations of state parameters and other thermodynamic properties of nucleic-acid bases for which few or no experimental data are available.

3.2. Equations of state parameters

Calculation of the thermodynamic properties of aqueous species as a function of temperature and pressure using the revised HKF equations of state requires values of species-dependent solvation and non-solvation parameters (see Section 2.2). These values can be generated by regressing with the revised HKF equations of state experimental standard molal isobaric heat capacities (C°_P), volumes (V°), and isothermal compressibilities (κ°_T) for a given species as a function of temperature. It can be demonstrated that accurate values of the solvation parameter (ω) can be retrieved from calorimetric data only if values of C°_P above ~100 °C are available in the literature for the aqueous species of interest (Helgeson and Kirkham, 1976; Helgeson et al., 1981; Tanger and Helgeson, 1988; Shock et al., 1989, 1992). In the absence of high-temperature calorimetric and densimetric data, experimental values of low-temperature C°_P, V°, and κ°_T reported in the literature can be combined with the revised-HKF equations of state using independently generated values of ω derived in the manner described below.

Table 8
Summary of C_P° power function coefficients and values of S° at 25 °C and 1 bar of reference compounds used in group additivity algorithms to estimate the corresponding coefficients and properties of selected groups

Compound	Formula	$S^{\circ a}$	$C_P^{\circ a,b}$	a^a	$b^c \times 10^3$	$c^d \times 10^{-5}$
Piperidine$_{(cr)}$	$C_5H_{11}N$	35.11[e]	32.84	−13.2[f]	146.3[f]	2.151[f]
Piperidine$_{(lq)}$	$C_5H_{11}N$	50.18[g]	42.96	2.42[f]	98.88[f]	9.831[f]
Diketopiperazine$_{(cr)}$	$C_4H_6N_2O_2$	34.8[h]	32.22	1.435[i]	103.3[i]	0[i]
Triazine$_{(cr)}$	$C_3H_3N_3$	30.107[j]	22.36	4.617[k]	59.51[k]	0[k]
1,3-Phenylenediamine$_{(cr)}$	$C_6H_8N_2$	36.93[j]	36.54	1.3905[l]	117.9[l]	0[l]
Cyclohexane$_{(cr)}$	C_6H_{12}	46.34[m]	34.02	−10.41[l]	134.2[l]	3.93[l]
Cyclohexanol$_{(cr\ 1)}$	$C_6H_{12}O$	47.32[n]	46.21	−146.6[o]	518.4[o]	34.00[o]
Cyclohexanol$_{(lq)}$	$C_6H_{12}O$	48.73[p]	51.05	−21.29[o]	241.1[o]	0[o]

[a] cal K^{-1} mol^{-1}.
[b] Calculated using Eq. (6) together with above values of a, b, and c.
[c] cal mol^{-1}.
[d] cal K mol^{-1}.
[e] Calculated from $S_{cr,298}^\circ = S_{lq,298}^\circ - \int_{T_{melt}}^{298} \frac{C_{P,(lq)}}{T} - \frac{\Delta H_{melt}}{T_{melt}} + \int_{T_{melt}}^{298} \frac{C_{P,(cr)}}{T}$ using values of $S_{lq,298}^\circ$, ΔH_{melt}, T_{melt}, and values of C_P° taken from Messerly et al. (1988).
[f] Calculated by regressing values of C_P° taken from Messerly et al. (1988) with Eq. (6).
[g] Messerly et al. (1988).
[h] Lebedev et al. (1981).
[i] Calculated by regressing values of C_P° taken from Lebedev et al. (1981).
[j] Domalski and Hearing (1996).
[k] Calculated using values of C_P° taken from Van Bommel et al. (1988) with Eq. (6).
[l] Calculated using values of C_P° taken from Rabinovich et al. (1984).
[m] Richard and Helgeson (1998).
[n] Calculated from $S_{cr,298}^\circ = S_{lq,298}^\circ - \int_{T_{melt}}^{298} \frac{C_{P,(lq)}}{T} - \frac{\Delta H_{melt}}{T_{melt}} + \int_{T_{melt}}^{298} \frac{C_{P,(cr)}}{T}$ using values of $S_{lq,298}^\circ$, ΔH_{melt}, T_{melt}, and values of C_P° taken from Adachi et al. (1968).
[o] Calculated by regressing values of C_P° taken from Adachi et al. (1968) with Eq. (6).
[p] Adachi et al. (1968).

Table 9
Summary of experimental and calculated values of C_P° for selected crystalline pyrimidines

Pyrimidine	Formula	$C_P^{\circ a}$	
		Experimental	Calculated[b]
Cytosine	$C_4H_5N_3O$	31.69[c]	31.97
Thymine	$C_5H_6N_2O_2$	35.90[c]	34.95
Uracil	$C_4H_4N_2O_2$	28.9[d]	30.31

[a] cal K^{-1} mol^{-1}.
[b] Calculated using the group additivity algorithms depicted in Table 5.
[c] Domalski and Hearing (1996).
[d] Kilday (1978d).

3.2.1. The solvation parameter, ω

High-temperature experimental values of C_P° for the aqueous nucleic-acid bases are not available in the literature. Nevertheless, estimates of ω can be computed from the correlation developed by (Plyasunov and Shock, 2001), who observed a relationship between values of ω in cal mol^{-1} and the standard molal Gibbs energy of hydration (ΔG_{hyd}°) in kcal mol^{-1}. This correlation for neutral aqueous species can be expressed as

$$\omega = \left(0.624 + \frac{18.51}{\Delta G_{hyd}^\circ - 21.7}\right)10^5. \qquad (47)$$

Although the requisite values of ΔG_{hyd}° for the nucleic-acid bases are not available in the literature, they can be calculated from

Table 10
Summary of standard molal thermodynamic properties of hydration at 25 °C and 1 bar for the nucleic-acid bases and sugars considered in the present study

Compound	Formula	ΔG_{hyd}° [a]	ΔH_{hyd}° [a]	ΔS_{hyd}° [b]
Purines				
Adenine	$C_5H_5N_5$	−11,506[c]	−22,400[d]	−36.54[e]
Guanine	$C_5H_5N_5O$	−24,948[c]	−35,350[f]	−34.89[e]
Pyrimidines				
Cytosine	$C_4H_5N_3O$	−19,314[c]	−30,810[g]	−38.56[e]
Thymine	$C_5H_6N_2O_2$	−15,303[c]	−23,920[h]	−28.90[e]
Uracil	$C_4H_4N_2O_2$	−16,761[c]	−21,800[i]	−16.90[e]
Monosaccharides				
Ribose	$C_5H_{10}O_5$	−19,243[c]	−34,609[f]	−51.54[e]
Deoxyribose	$C_5H_{10}O_4$	−19,444[c]	−35,027[f]	−52.27[e]

[a] cal mol^{-1}.
[b] cal K^{-1} mol^{-1}.
[c] Calculated using values of ΔG_{sol}° and ΔG_{sub}° taken from Tables 4 and 11, respectively.
[d] Zielenkiewicz et al. (1984).
[e] Calculated from $\Delta S_{hyd}^\circ = \left(\Delta H_{hyd}^\circ - \Delta G_{hyd}^\circ\right)/T_r$.
[f] Calculated from ΔH_{sol}° and ΔH_{sub}° taken from Tables 4 and 11, respectively.
[g] Zielenkiewicz et al. (1998).
[h] Zielenkiewicz (1995).
[i] Teplitsky et al. (1980).

$$\Delta G_{hyd}^\circ = \Delta G_{f(aq)}^\circ - \Delta G_{f(g)}^\circ = \Delta G_{sol}^\circ - \Delta G_{sub}^\circ, \qquad (48)$$

where $\Delta G_{f(aq)}^\circ$ and $\Delta G_{f(g)}^\circ$ stand for the standard molal Gibbs energies of formation of the aqueous and gas nucleic-acid bases at 298.15 K and 1 bar, and ΔG_{sol}° and ΔG_{sub}°

refer to the standard molal Gibbs energies of solution and sublimation for nucleic-acid bases. The values of $\Delta G_{f(g)}^\circ$, $\Delta G_{f(aq)}^\circ$, ΔG_{sol}°, ΔG_{hyd}°, and ΔG_{sub}° consistent with Eq. (48) for the nucleic-acid bases are given in Table A.1 in Appendix A and Tables 2, 4, 10, and 11, respectively. Values of $\Delta H_{f(g)}^\circ$, ΔH_{hyd}°, and ΔH_{sub}°, and $S_{(g)}^\circ$, ΔS_{hyd}°, and ΔS_{sub}° for the nucleic-acid bases are also shown in Table A.1 in Appendix A and Tables 10 and 11. Values of ω for the nucleic-acid bases computed from Eqs. (47) and (48) are listed in Table 2.

3.2.2. The non-solvation heat capacity parameters, c_1 and c_2

In the absence of experimental high-temperature calorimetric data, reliable values of c_1 and c_2 for nucleic-acid bases can be obtained by regressing low-temperature experimental values of C_P° using Eq. (34) and the values of ω generated in Section 3.2.1. For $P = P_r$, Eq. (34) can be simplified and rearranged into two particularly useful expressions,

$$\Delta C_{P,n}^\circ = C_P^\circ - \omega TX, \tag{49}$$

and

$$\Delta C_{P,n}^\circ = c_1 + \frac{c_2}{(T - \Theta)^2}. \tag{50}$$

The filled circular symbols in Fig. 2 represent values of $\Delta C_{P,n}^\circ$ for cytosine, thymine, and uracil calculated from Eq. (49) using experimental values of C_P° reported by Patel and Kishore (1995). Eq. (50) is consistent with the straight lines in Fig. 2. It follows that the intercepts and slopes of these straight lines correspond to values of c_1 and c_2, respectively, for cytosine, thymine, and uracil. It can be seen in Fig. 2 that the straight lines representing the revised HKF equations of state are closely consistent with the experimentally derived values of $\Delta C_{P,n}^\circ$ as a function of $1/(T - \Theta)^2$.

Experimental values of C_P° at temperatures other than 25 °C for adenine and guanine are not available in the literature. Nevertheless, values of c_1 and c_2 for these species can be estimated by taking account of the systematic similarities of the c_2 values for other nucleic-acid bases and their respective nucleosides. In a first approximation values of c_2 for adenine and guanine can be calculated from

$$c_{2\ nucleic\text{-}acid\ base_i} = c_{2\ nucleoside_i} - \delta c_2, \tag{51}$$

where δc_2 corresponds to the average difference in the c_2 values of the nucleosides, cytidine, thymidine, and uridine and their respective nucleic-acid bases, cytosine, thymine, and uracil in accord with

$$\delta c_2 = \frac{\sum_{i=1}^{3}\left(c_{2nucleoside_i} - c_{2\ nucleic\text{-}acid\ base_i}\right)}{3}, \tag{52}$$

where the terms $c_{2\ nucleic\text{-}acid\ base_i}$ and $c_{2\ nucleoside_i}$ designate the c_2 parameters for the nucleic-acid base and nucleoside of interest. Values of c_1 for adenine and guanine can be calculated from their respective values of c_2 and C_P° at 25 °C and 1 bar using Eqs. (49) and (50). The values of c_1 and c_2 calculated in this manner for adenine, cytosine, guanine, thymine, and uracil are listed in Table 2 and the corresponding experimental values of C_P° are given in Table

Table 11
Summary of standard molal thermodynamic properties of sublimation at 25 °C and 1 bar for the nucleic-acid bases adopted in the present study

Compound	Formula	ΔG_{sub}° [a]	ΔH_{sub}° [a]	ΔS_{sub}° [b]
Purines				
Adenine	$C_5H_5N_5$	14,414[c,d]	31,980[e]	58.92[f]
Guanine	$C_5H_5N_5O$	30,248[c,g]	44,500[g]	47.80[f]
Pyrimidines				
Cytosine	$C_4H_5N_3O$	20,924[c,i]	38,693[h]	59.60[f]
Thymine	$C_5H_6N_2O_2$	17,380[c,i]	32,051[h]	49.21[f]
Uracil	$C_4H_4N_2O_2$	18,761[c,j]	29,601[h]	36.36[f]

See Table A.6 in Appendix A for additional values.

[a] cal mol^{-1}.

[b] cal K^{-1} mol^{-1}.

[c] Extrapolated using vapor pressure data for temperatures ranging up to 340 K. ΔH_{sub}° was taken in a first approximation to be constant over this temperature range.

[d] Zielenkiewicz (2000).

[e] Average of values taken from Zielenkiewicz (2000) and Domalski and Hearing (1996).

[f] Calculated from $\Delta S_{sub}^\circ = (\Delta H_{sub}^\circ - \Delta G_{sub}^\circ)/T_{sub}$.

[g] Yanson et al. (1974).

[h] Calculated using ΔH_{fcr}° and ΔH_{fg}°.

[i] Ferro et al. (1980).
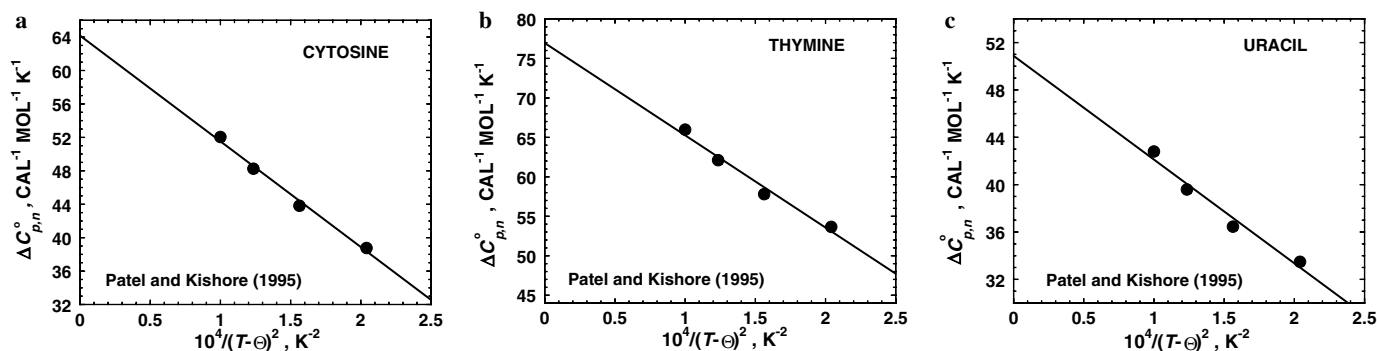
[j] Bardi et al. (1980).

Fig. 2. $\Delta C_{P,n}^\circ$ for aqueous cytosine, thymine, and uracil as a function of $10^4/(T - \Theta)^2$ at 1 bar. The symbols denote values of $\Delta C_{P,n}^\circ$ computed from Eq. (49) using values of ω and C_P° taken from Tables 2 and A.2 in Appendix A, respectively. The regression lines represent fits of Eq. (50) to the data.
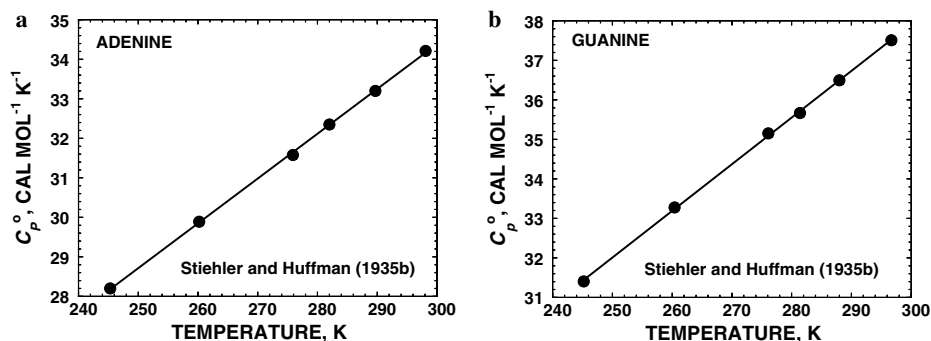
Fig. 3. Standard molal heat capacities (C_P°) of crystalline adenine and guanine as a function of temperature at 1 bar. The symbols denote values of C_P° taken from Stiehler and Huffman (1935b). The regression lines represent fits of Eq. (6) to the data.
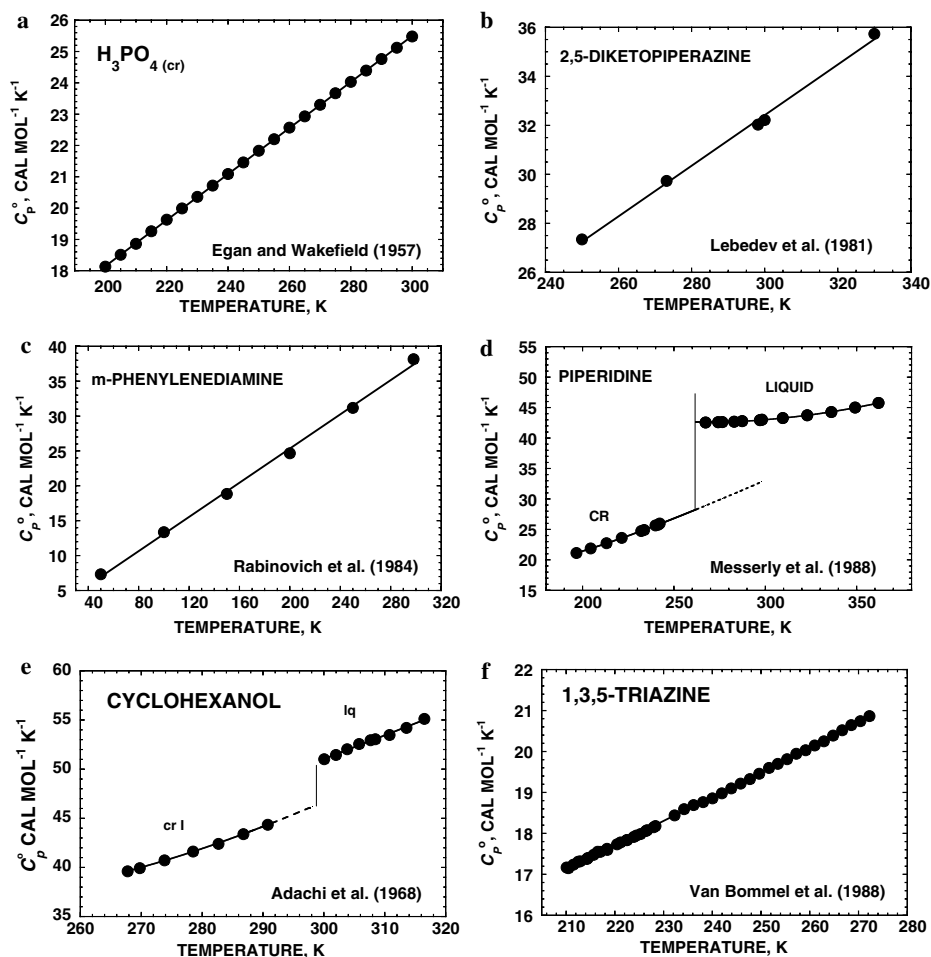

Fig. 4. Standard molal heat capacities (C_P°) of crystalline cyclohexanol, 2,5-diketopiperazine, m-phenylenediamine, piperazine, triazine, and H_3PO_4 as a function of temperature at 1 bar. The symbols denote values of C_P° taken from the literature. The regression lines represent fits of Eq. (6) to the data. The dashed lines in the piperidine and cyclohexanol plots correspond to a metastable extension and extrapolation, respectively, of C_P° for the crystalline phase.

A.2 in Appendix A. The c_2 values for the nucleosides computed in the manner described in Section 4.2.2 are also listed in Table 2.

3.2.3. The crystalline heat capacity parameters, a, b, and c

Values of the heat capacity power function coefficients (a, b, and c) in Eq. (6) for crystalline adenine and guanine, together with those of the groups derived from the corre-

sponding coefficients for reference model compounds are given in Tables 3, 6, and 8, respectively. The a, b, and c values for the groups depicted in Table 6 were calculated from the same group additivity algorithms used to calculate S_{cr}° for cytosine, thymine, and uracil (see above and Table 5). The filled circles in Figs. 3 and 4 represent experimental values of standard molal isobaric crystalline heat capacities ($C_{P(cr)}^\circ$) reported in the literature for adenine, guanine, and

the reference model compounds as a function of temperature at 1 bar. The straight lines shown in these figures for the crystalline compounds are consistent with the values of a, b, and c given in Tables 3 and 8 for these species, which were generated by regressing the experimental values of $C_{P(cr)}^{\circ}$ with Eq. (6).

3.2.4. The non-solvation volume and compressibility parameters, a_1, a_2, a_3, and a_4

In the absence of experimental high-temperature volumetric and compressibility data, values of the a_1, a_2, a_3, and a_4 parameters for the aqueous nucleic-acid bases can be generated by regressing experimental low-temperature aqueous standard molal volumes (V°) and isothermal compressibilities ($\Delta\kappa_T^{\circ}$) using the equations discussed in Section 2.2.2 and independently specified values of ω. The filled circles in Fig. 5 represent values of ΔV_n° for adenine, cytosine, thymine, and uracil calculated from corresponding values of V° reported by Lee and Chalikian (2001) using Eqs. (31) and (35), together with values of ω taken from Table 2. It follows that the intercepts and slopes of the straight lines in Fig. 5 correspond to values of the σ and ξ parameters in Eq. (18). Analogously, the symbols in Fig. 6 stand for values of $-\Delta\kappa_{T,n}^{\circ}$ for adenine, cytosine, thymine, and uracil calculated from corresponding values of the standard molal isothermal compressibilities (κ_T°) for these species, together with appropriate statements of Eqs. (32) and (36). The values of κ_T° were converted from adiabatic compressibilities (κ_S°) reported by Lee and Chalikian (2001) by taking account of (Desnoyers and Philip, 1972)

$$\kappa_{T,i}^{\circ} = \kappa_{S,i}^{\circ} + \frac{TV_{H_2O}^{\circ}\alpha_{H_2O}^{\circ}(2E_i^{\circ} - V_{H_2O}^{\circ}\alpha_{H_2O}^{\circ}C_{P,i}^{\circ}/C_{P,H_2O}^{\circ})}{C_{P,H_2O}^{\circ}}, \quad (53)$$

where i designates the solute of interest, E_i° refers to the standard molal expansibility of the solute, and $V_{H_2O}^{\circ}$, C_{P,H_2O}°, and $\alpha_{H_2O}^{\circ}$ stand for the standard molal volume, heat capacity, and coefficient of isobaric thermal expansion of water, respectively. The latter property is defined as

$$\alpha_{H_2O}^{\circ} = \frac{1}{V_{H_2O}^{\circ}}\left(\frac{\partial V_{H_2O}^{\circ}}{\partial T}\right)_P. \quad (54)$$

The standard molal properties of H_2O were calculated using the SUPCRT92 software package (Johnson et al., 1992). The values of E_i° for adenine, cytosine, thymine, and uracil used to evaluate Eq. (53) are given in Table A.3 in Appendix A. Note that it follows from Eq. (36) that the intercepts and slopes of the straight lines in Fig. 6 correspond, respectively, to values of the $\left(\frac{\partial\sigma}{\partial P}\right)_T$ and $\left(\frac{\partial\xi}{\partial P}\right)_T$ terms in Eq. (19). Values of a_2 and a_4 can thus be calculated directly from these partial derivatives using Eqs. (22) and (23). The a_2 and a_4 values can then be combined with values of σ and ξ using Eqs. (20) and (21) to compute values of a_1 and a_3. The values of a_1, a_2, a_3, and a_4 generated in this manner for adenine, cytosine, thymine, and uracil are given in Table 2. It can be seen in Figs. 5 and 6 that the straight lines representing the revised HKF equations of state are closely consistent with the experimentally derived values of ΔV_n° and $\Delta\kappa_{T,n}^{\circ}$. The experimental values of V° and κ_T° used to locate the symbols in these figures are listed in Tables A.4 and A.5 in Appendix A.
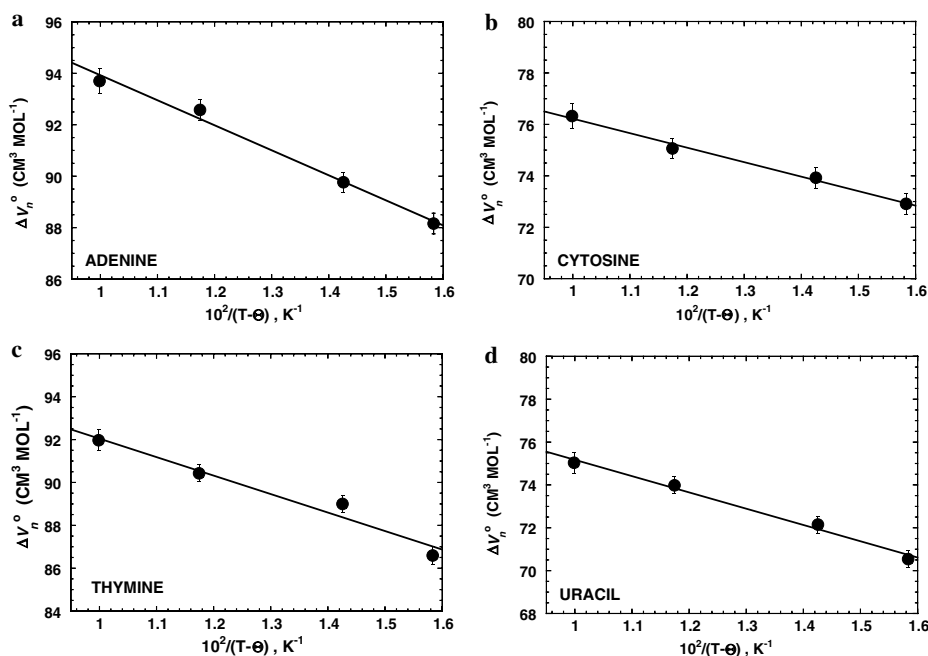

Fig. 5. ΔV_n° for aqueous adenine, cytosine, thymine, and uracil as a function of $1/(T-\Theta)$ at 1 bar. The symbols denote values of ΔV_n° computed from Eqs. (31) and (35) using values of ω and V° taken from Tables 2 and A.4 in Appendix A, respectively. The regression lines represent fits of Eq. (18) to the data. The vertical lines denote uncertainties in the experimental values of V° reported by Lee and Chalikian (2001).
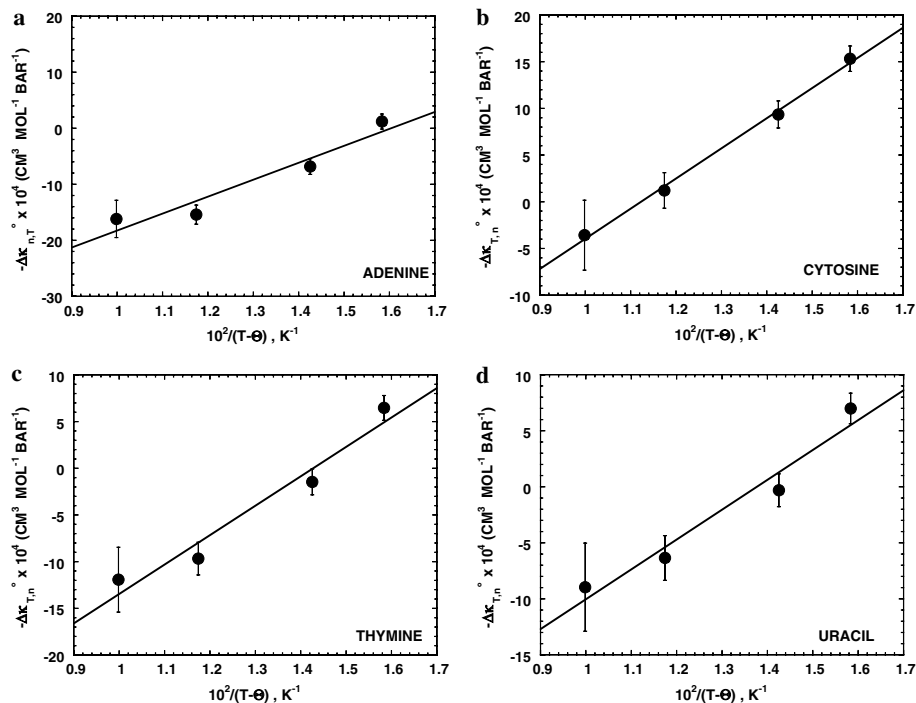
Fig. 6. $\Delta\kappa_{T,n}^{\circ}$ for adenine, cytosine, thymine, and uracil as a function of $1/(T - \Theta)$ at 1 bar. The symbols denote values of $\Delta\kappa_{T,n}^{\circ}$ computed from Eqs. (32) and (36) using values of ω and κ_T° taken from Tables 2 and A.5 in Appendix A, respectively. The regression lines represent fits of Eq. (19) to the data. The vertical lines designate uncertainties in the values of κ_T° computed from experimental values of κ_S° reported by Lee and Chalikian (2001) (see text).

Although values of V° and κ_T° are not available in the literature for guanine, estimates of the a_1, a_2, a_3, and a_4 parameters for this species can be generated from correlations among values of ΔV_n°, σ, a_1, a_2, and a_4 for the other nucleic-acid bases and nucleosides. The form of the correlation equations are similar to those developed by Shock and Helgeson (1988), but the slopes and intercepts are derived from the corresponding parameters for nucleic-acid bases and nucleosides listed in Table 2. The symbols in Figs. 7a and b represent values of a_1 and σ, respectively, taken from this table as a function of the experimentally derived values of ΔV_n° for adenine, cytosine, thymine, uracil, adenosine, cytidine, guanosine, thymidine, uridine, deoxyadenosine, deoxycytidine, deoxyguanosine, and deoxyuridine (see below for the nucleosides). The symbols

in Fig. 7c denote values taken from Table 2 for a_4 plotted as a function of a_2 for the same species. The straight lines generated from the trends in the parameters shown in Fig. 7 are consistent with

$$a_1 = 2.68 + 11.19\left(\frac{\Delta V_n^{\circ}}{41.8393}\right), \tag{55}$$

$$\sigma = 8.41 + 1.026\Delta V_n^{\circ}, \tag{56}$$

and

$$a_4 = 1.195 - 0.5749a_2. \tag{57}$$

The value of ΔV_n° at 25 °C and 1 bar used to calculate those of a_1 and σ for aqueous guanine from Eqs. (55) and (56), respectively, were calculated from the values of ω and V° given in Table 2 for this species using Eqs. (31) and (35).
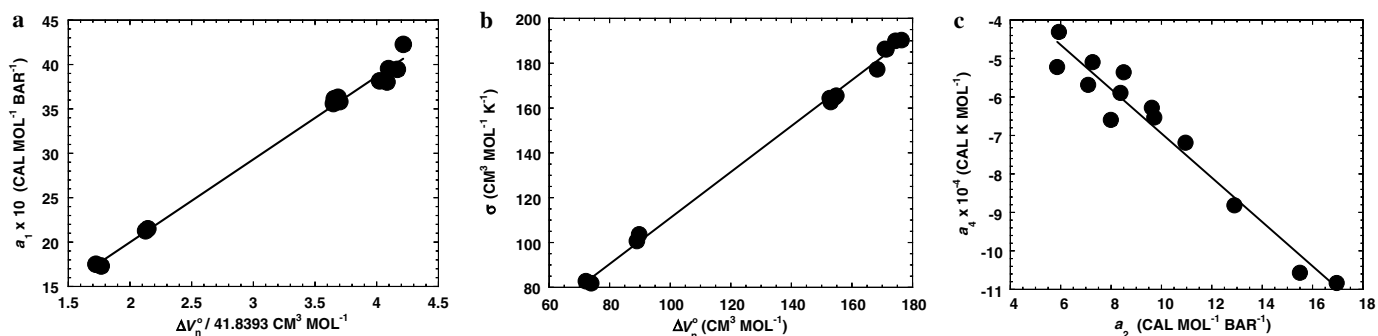

Fig. 7. Correlations of a_1 and σ with ΔV_n°, and a_2 with a_4 for nucleic-acid bases and nucleosides derived in the present study from experimental data available in the literature. The symbols denote values of ΔV_n° computed from Eqs. (31) and (35) using values of ω and V° taken from Table 2 and A.4 in Appendix A, respectively. The values of a_1, a_2, and a_4 were taken from Table 2, but those for σ were calculated from Eqs. (18) and (20).

Although no value of $V°$ at 25 °C and 1 bar for guanine is available in the literature, it was estimated in the present study using the standard molal volumes at 25 °C and 1 bar of the other nucleic-acid bases and their corresponding nucleosides as reference model compounds to evaluate the mean additivity approximation represented by

$$V°_{guanine} = V°_{guanosine} - \frac{\sum_i (V°_{nucleoside_i} - V°_{base_i})}{n}, \tag{58}$$

where $V°_{guanosine}$, $V°_{nucleoside_i}$, and $V°_{base_i}$ denote the standard molal volumes of guanosine, the ith nucleoside, and the corresponding ith base, respectively. These volumes are listed in Table 2.

The value of $V°$ for guanine at 25 °C and 1 bar computed from Eq. (58) using values of $V°$ given in Table 2 for the species on the right hand side of the equation was used, together with Eqs. (56) and (55), to generate values of σ and a_1 for guanine. These parameters were then in turn combined with Eqs. (18), (20), (21), and (57) to calculate values of a_2, a_3, and a_4 for guanine. The resulting values are shown in Table 2, along with the values of a_1 and $V°$ for guanine computed from Eqs. (55) and (58).

4. Nucleosides

The term nucleoside refers to a compound consisting of one nucleic-acid base bonded to either one ribose or deoxyribose sugar as shown in Fig. 8. For specific references to nucleosides comprised of deoxyribose, the prefix deoxy- is added to the nucleoside name. The common names of the nucleosides considered in the present study are formed by dropping the last several letters of the common name for their corresponding nucleic-acid bases, and replacing them with the suffix -idine in the case of pyrimidines, or -osine in the case of purines.

4.1. Standard molal Gibbs energies, enthalpies, and third law entropies at 25 °C and 1 bar

The values of $\Delta G°_{f(aq)}$ and $\Delta H°_{f(aq)}$ at 25 °C and 1 bar for the aqueous nucleosides can be calculated from corresponding values of $\Delta G°_{f(cr)}$, $\Delta H°_{f(cr)}$, $\Delta G°_{sol}$, and $\Delta H°_{sol}$ using Eqs. (40) and (41). The values of $S°_{(aq)}$ can then be computed from Eq. (42) using values of $S°_i$ taken from Cox et al. (1989). However, with the exception of adenosine, the values of $\Delta G°_{f(cr)}$ and $\Delta H°_{f(cr)}$ required to evaluate Eqs. (40) and (41) are not available in the literature. Similarly, values of $\Delta G°_{sol}$ and $\Delta H°_{sol}$ have not been reported in the literature for one of the 10 nucleosides considered in the present study. Nevertheless,
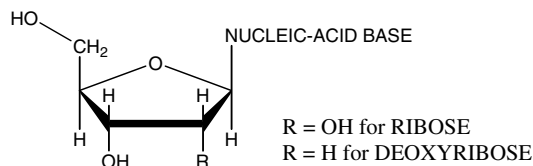
these properties can be estimated from the algorithms summarized below. Values of $\Delta G°_{f(aq)}$, $\Delta H°_{f(aq)}$, and $S°_{(aq)}$ at 25 °C and 1 bar for the 10 aqueous nucleosides considered in the present study are listed in Table 2 and those for their crystalline counterparts are shown in Table 3.

### 4.1.1. Crystalline values of $\Delta G°_f$, $\Delta H°_f$, and $S°$

Values of $\Delta G°_{f(cr)}$ and $\Delta H°_{f(cr)}$ for the ith crystalline nucleoside can be estimated in a first approximation from values of $\Delta G°_{f(cr)}$ and $\Delta H°_{f(cr)}$ for the ith crystalline nucleic-acid base, ribose, and water using

$$\Delta\Xi°_{nucleoside_{i(cr)}} = \Delta\Xi°_{ribose_{(cr)}} + \Delta\Xi°_{base_{i(cr)}} - \Delta\Xi°_{H_2O_{(l)}} + \Delta\Xi°_r \tag{59}$$

where $\Delta\Xi°$ stands for any standard molal thermodynamic property or equations of state parameter for the subscripted species and $\Delta\Xi°_r$ represents the corresponding properties of reaction for

$$base_{i(cr)} + sugar_{(cr)} \rightleftharpoons nucleoside_{i(cr)} + H_2O_{(l)}. \tag{60}$$
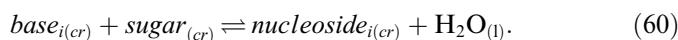
In the absence of experimental values reported in the literature of $\Delta G°_{f(cr)}$ and $\Delta H°_{f(cr)}$ for all of the crystalline nucleosides other than adenosine, the value of $\Delta\Xi°_r$ in Eq. (59) was taken in a first approximation to be equivalent to that for

$$adenine_{(cr)} + ribose_{(cr)} \rightleftharpoons adenosine_{(cr)} + H_2O_{(l)}, \tag{61}$$
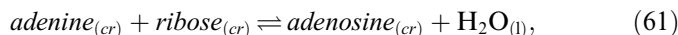
which is consistent with expressing $\Delta\Xi°_r$ in Eq. (59) as

$$\Delta\Xi°_r = \Xi°_{adenosine(cr)} + \Xi°_{H_2O(l)} - \Xi°_{adenine(cr)} - \Xi°_{ribose(cr)}. \tag{62}$$

The thermodynamic properties of $H_2O_{(l)}$ were taken from SUPCRT92 (Johnson et al., 1992).

Values of $\Delta G°_{f(cr)}$ and $\Delta H°_{f(cr)}$ for crystalline *adenosine*, *ribose*, *adenine*, and the other nucleic-acid bases which are required to evaluate Eqs. (59) and (62) for nucleosides are given in Table 3, together with the values of $\Delta G°_{f(cr)}$ and $\Delta H°_{f(cr)}$ for the latter species computed from Eq. (59). Except in the case of adenosine, the values of $S°_{(cr)}$ given in Table 3 for the nucleosides were generated from the corresponding values of $\Delta G°_{f(cr)}$ and $\Delta H°_{f(cr)}$ using Eq. (42). All of these values compare favorably with those calculated by Ould-Moulaye et al. (2001).

The values of $\Delta G°_{f(cr)}$, $\Delta H°_{f(cr)}$, and $S°_{(cr)}$ for the crystalline deoxynucleosides in Table 3 were computed using the same equations and algorithms used to calculate the corresponding properties of the crystalline nucleosides except that the standard molal thermodynamic properties for deoxyribose were used in place of those for ribose. Although values of $\Delta G°_{f(cr)}$ and $S°_{(cr)}$ for crystalline deoxyribose are not available in the literature the experimental value of $\Delta H°_{f(cr)}$ determined by Colbert et al. (1987) can be combined with an estimated value of $S°_{(cr)}$ to calculate a provisional value of $\Delta G°_{f(cr)}$ by rearranging Eq. (42). The group additivity algorithm used to estimate a value of $S°_{(cr)}$ for deoxyribose ($S°_{deoxyribose(cr)}$) is depicted in Fig. 9, which is consistent with

Fig. 8. Idealized generic structure of nucleosides and deoxynucleosides.

$$S°_{deoxyribose(cr)} = S°_{ribose(cr)} + S°_{cyclohexane(cr)} - S°_{cyclohexanol(cr)}, \tag{63}$$
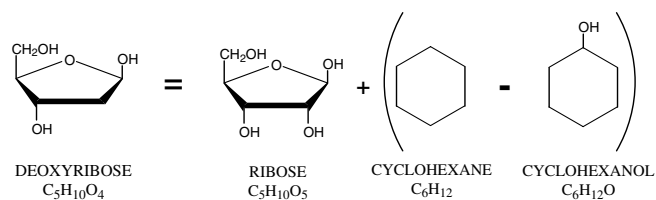
Fig. 9. Idealized structural representation of the group additivity algorithm used to calculate $S°$ and the C_P power function coefficients for crystalline deoxyribose.

where $S°_{ribose(cr)}$, $S°_{cyclohexane(cr)}$, and $S°_{cyclohexanol(cr)}$ refer to values of $S°$ for crystalline ribose, cyclohexane, and cyclohexanol, respectively. Eq. (63) was used together with the value of $S°$ given for $ribose_{(cr)}$ in Table 3 and those for crystalline cyclohexane and cyclohexanol in Table 8 to calculate the value of $S°_{(cr)}$ for deoxyribose shown in Table 3. The value of $\Delta G°_{f(cr)}$ given in Table 3 for this sugar was computed by rearranging Eq. (42) and combining the resulting expression with the value of $S°_{(cr)}$ and the experimental value of $\Delta H°_{f(cr)}$ shown for deoxyribose in Table 3. The values of $\Delta G°_{f(cr)}$ and $\Delta H°_{f(cr)}$ given for both the crystalline nucleosides and deoxynucleosides in Table 3 can be combined with corresponding values of $\Delta G°_{sol}$ and $\Delta H°_{sol}$ to calculate values of their aqueous counterparts in the manner described below.

4.1.2. $\Delta G°_{sol}$ and $\Delta H°_{sol}$

Experimental values of $\Delta G°_{sol}$ for adenosine, guanosine, and deoxyadenosine, and $\Delta H°_{sol}$ for adenosine taken from the literature are listed in Table 4. Experimental values of $\Delta G°_{sol}$ and $\Delta H°_{sol}$ for the other nucleosides considered in the present study can be estimated using the experimental values of these properties for adenosine, guanosine, and deoxyadenosine, together with those for nucleic-acid bases and ribose given in Table 4. These values of $\Delta H°_{sol}$ can be combined with the additivity algorithms discussed below to estimate corresponding values of $\Delta G°_{sol}$ and $\Delta H°_{sol}$ for nucleosides for which no experimental data are available in the literature. For example, values of $\Delta G°_{sol}$ and $\Delta H°_{sol}$ for the ith such nucleoside ($\Delta G°_{sol,nucleoside_i}$ and $\Delta H°_{sol,nucleoside_i}$, respectively) can be calculated from the corresponding values for the ith nucleic-acid base ($\Delta G°_{sol,base_i}$ and $\Delta H°_{sol,base_i}$) and ribose ($\Delta G°_{sol,ribose}$ and $\Delta H°_{sol,ribose}$) using

$$\Delta G°_{sol,nucleoside_i} = \Delta G°_{sol,base_i} + \Delta G°_{sol,ribose} + \delta G°_{sol} \quad (64)$$

and

$$\Delta H°_{sol,nucleoside_i} = \Delta H°_{sol,base_i} + \Delta H°_{sol,ribose} + \delta H°_{sol}, \quad (65)$$

where $\delta G°_{sol}$ and $\delta H°_{sol}$ represent the difference in the standard molal Gibbs energies and enthalpies of solution between a given nucleoside and the corresponding properties of its constituents. Owing to the paucity of experimental data available in the literature, the values of $\delta G°_{sol}$ and $\delta H°_{sol}$ in Eqs. (64) and (65) were estimated from

$$2\delta G°_{sol} = (\Delta G°_{sol,adenosine} - \Delta G°_{sol,adenine} - \Delta G°_{sol,ribose})$$
$$+ (\Delta G°_{sol,guanosine} - \Delta G°_{sol,guanine} - \Delta G°_{sol,ribose}) \quad (66)$$

and

$$\delta H°_{sol} = \Delta H°_{sol,adenosine} - \Delta H°_{sol,adenine} - \Delta H°_{sol,ribose}, \quad (67)$$

respectively. Values of $\Delta G°_{sol}$ and $\Delta H°_{sol}$ for nucleosides for which no experimental data are reported in the literature were computed using Eqs. (64)–(67), together with values of $\Delta G°_{sol,adenosine}$, $\Delta G°_{sol,guanosine}$, $\Delta G°_{sol,adenine}$, $\Delta G°_{sol,guanine}$, and $\Delta G°_{sol,ribose}$ and $\Delta H°_{sol,adenosine}$, $\Delta H°_{sol,adenine}$, and $\Delta H°_{sol,ribose}$ taken from Table 4. These values are also given in Table 4.

With the exception of deoxyadenosine for which experimental data are available in the literature, values of $\Delta G°_{sol}$ for the ith deoxynucleoside ($\Delta G°_{sol,deoxynucleoside_i}$) were estimated from

$$\Delta G°_{sol,deoxynucleoside_i} = \Delta G°_{sol,nucleoside_i} + \delta G°_{sol,d}, \quad (68)$$

where $\delta G°_{sol,d}$ stands for the analog of $\delta G°_{sol}$ for the difference in the standard molal Gibbs energies of the solution between a given deoxynucleoside and its constituent deoxy sugar and base. The value of $\delta G°_{sol,d}$ required to evaluate Eq. (68) was estimated by computing the difference in the solubilities of deoxyadenosine and adenosine in accord with

$$\delta G°_{sol,d} = \Delta G°_{sol,deoxyadenosine} - \Delta G°_{sol,adenosine}. \quad (69)$$

The values of $\Delta G°_{sol,deoxyadenosine}$ and $\Delta G°_{sol,adenosine}$ used in the calculations are listed in Table 4.

Although no values of $\Delta H°_{sol}$ for any of the deoxynucleosides considered in the present study are available in the literature, provisional values of $\Delta H°_{sol}$ for the ith deoxynucleoside ($\Delta H°_{sol,deoxynucleoside_i}$) can be estimated from the values of $\Delta H°_{sol,deoxyribose}$ and

$$\Delta H°_{sol,deoxynucleoside_i} = \Delta H°_{sol,base_i} + \Delta H°_{sol,deoxyribose} + \delta H°_{sol}. \quad (70)$$

The requisite value of $\Delta H°_{sol,deoxyribose}$ is shown in Table 4. Values of $\Delta G°_{sol}$ and $\Delta H°_{sol}$ for the nucleosides and deoxynucleosides calculated from the these equations are also given in Table 4.

As noted above, the values of $\Delta G°_{f(aq)}$ and $\Delta H°_{f(aq)}$ for the aqueous nucleosides and deoxynucleosides shown in Table 2 were calculated from the values of $\Delta G°_{sol}$ and $\Delta H°_{sol}$ for these species in Table 4 using Eqs. (40) and (41). The values of $S°_{(aq)}$ given in Table 2 for the aqueous nucleosides and deoxynucleosides were calculated from Eq. (42) using values of $\Delta G°_{f(aq)}$ and $\Delta H°_{f(aq)}$ taken from Table 2 and $S°$ of the elements from Cox et al. (1989).

4.2. Equations of state parameters

The revised HKF equations of state parameters represented by ω, c_1, c_2, a_1, a_2, a_3, and a_4 for the aqueous nucleosides and deoxynucleosides are listed in Table 2. These values were calculated in the manner described below.

4.2.1. The solvation parameter, ω

In the absence of high-temperature calorimetric data or values of $\Delta G°_{hyd}$, which are required to evaluate Eq. (47), provisional values of ω for a given nucleoside ($\omega_{nucleoside}$)

can be estimated from the group additivity algorithm represented by

$$\omega_{nucleoside} = \omega_{base} + \omega_{sugar}, \tag{71}$$

where ω_{base} and ω_{sugar} refer to values of ω for the nucleic-acid base in the nucleoside and the sugar of interest, ribose or deoxyribose. Because no experimental data are available in the literature from which to calculate a value of ω for deoxyribose ($\omega_{deoxyribose}$), it was taken in a first approximation in the present study to be equal to ω_{ribose} because both of these sugars have nearly identical chemical formulas and structures. Values of $\omega_{nucleoside}$ computed from Eq. (71) are listed in Table 2, together with those of the bases and sugars used in this calculation.

4.2.2. The non-solvation heat capacity parameters, c_1 and c_2

Reliable values of c_1 and c_2 for nucleosides can be obtained by regressing experimental values of C_P° using the procedure described in Section 3.2.2. The symbols shown in Fig. 10 correspond to values of $\Delta C_{P,n}^\circ$ for adenosine, cytidine, thymidine, uridine, 2-deoxycytidine, and ribose calculated from experimental values of C_P° reported by Patel and Kishore (1995) and Banipal et al. (1997) using Eq. (49) and values of ω taken from Table 2. The straight lines in Fig. 10 are consistent with Eq. (50). It follows that the intercepts and slopes of these lines correspond to values of c_1 and c_2, respectively, for adenosine, cytidine, thymidine, uridine, 2-deoxycytidine, and ribose. It can be deduced from Fig. 10 that the straight lines representing the revised-HKF equations of state are closely consistent with the experimentally derived values of $\Delta C_{P,n}^\circ$ as a function of $1/(T - \Theta)^2$. The values of c_1 and c_2 corresponding to the intercepts and slopes of these lines for adenosine, cytidine, thymidine, uridine, 2-deoxycytidine, and ribose are listed in Table 2.

Although no C_P° measurements are reported in the literature for guanosine, provisional values of the c_1 and c_2

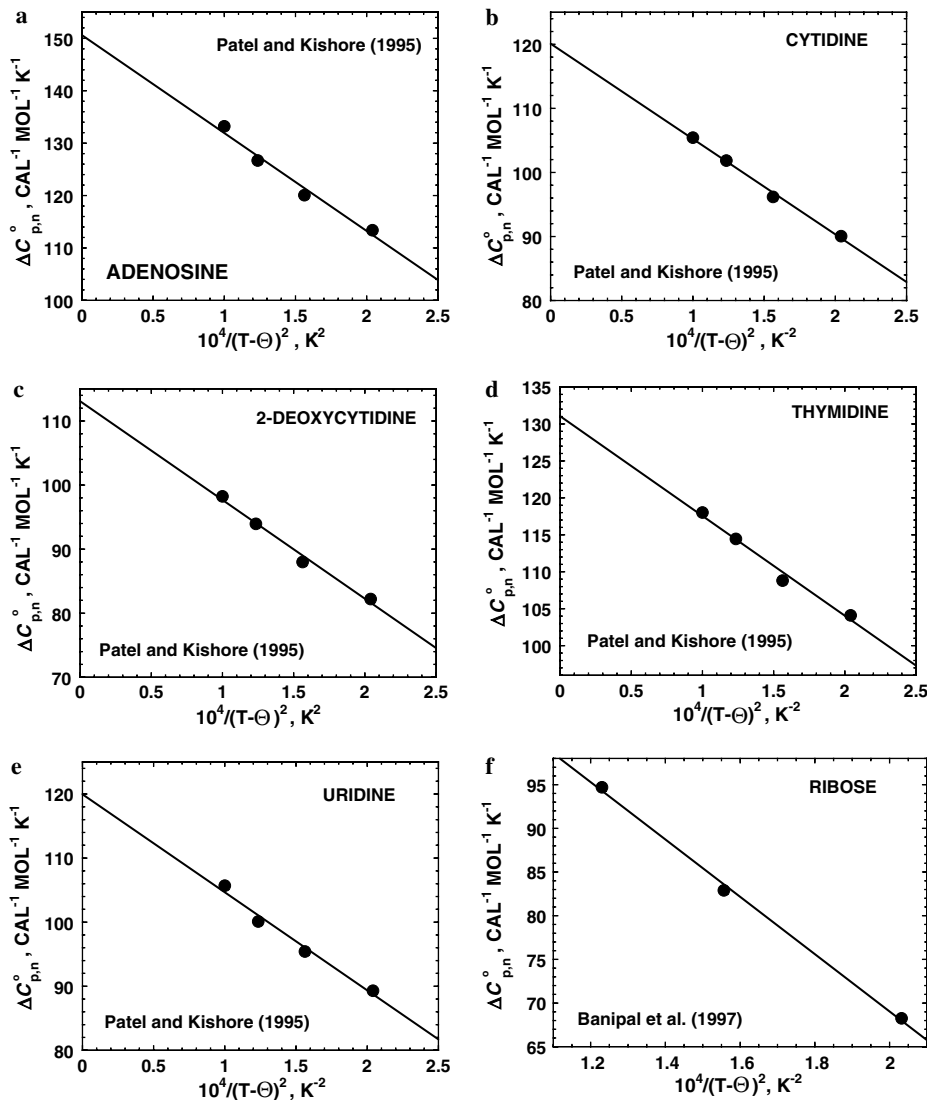Fig. 10. $\Delta C_{P,n}^\circ$ for aqueous adenosine, cytidine, 2-deoxycytidine, thymidine, and uridine as a function of $10^4/(T - \Theta)^2$ at 1 bar. The symbols denote values of $\Delta C_{P,n}^\circ$ computed from Eqs. (49) and (50) using values of ω and C_P° taken from Tables 2 and A.2 in Appendix A, respectively. The regression lines represent fits of Eq. (50) to the data.

parameters for this nucleoside can be estimated by taking advantage of the chemical and structural similarities of guanosine and adenosine. Hence, in a first approximation, $c_{2\,guanosine}$ can be taken to be equal to $c_{2\,adenosine}$, which can then be combined with Eqs. (49) and (50), together with an estimated value of C_P° for guanosine ($C_{P,guanosine}^\circ$) at 25 °C and 1 bar to compute a corresponding value of c_1 using the value of ω for guanosine given in Table 2. In the absence of relevant calorimetric data, the requisite value of $C_{P,guanosine}^\circ$ used in these calculations was estimated using the first approximation represented by

$$C_{P,guanosine}^\circ = C_{P,guanosine(cr)}^\circ + \Delta C_{P,sol,adenosine}^\circ, \tag{72}$$

where $\Delta C_{P,soladenosine}^\circ$ stands for the standard molal heat capacity of solution at 25 °C and 1 bar of crystalline adenosine which is given by

$$\Delta C_{P,sol\,adenosine}^\circ = C_{P\,adenosine}^\circ - C_{P\,adenosine(cr)}^\circ. \tag{73}$$

Combining the values given in Tables 2 and 3 for $C_{P\,adenosine}^\circ$, $C_{P\,adenosine(cr)}^\circ$, and $C_{P\,guanosine(cr)}^\circ$ with Eqs. (72) and (73) leads to the estimate of $C_{P\,guanosine}^\circ$ shown in Table 2. The calculated values of c_1 and c_2 for this aqueous nucleoside are also shown in Table 2.

Although 2-deoxycytidine is the only deoxynucleoside for which experimental low-temperature values of C_P° are available in the literature, comparison of the values of c_2 for cytidine and deoxycytidine can be used to estimate the c_1 and c_2 parameters for the other deoxynucleosides. For example, it can be seen that the slopes of the straight lines in Fig. 11, which correspond to values of c_2 for these species, are nearly identical. Generalizing this observation in a first approximation leads to $c_{2\,nucleoside_i} \approx c_{2\,deoxynucleoside_i}$ which can then be used to generate the values of c_2 shown for the deoxynucleosides listed in Table 2. These values were combined with Eqs. (49) and (50), together with the values of C_P° and ω for the deoxynucleosides given in Table 2 to calculate the values of c_1 for the these species in this table. The values of C_P° for the deoxynucleosides shown in Table 2 were estimated from the approximation represented by
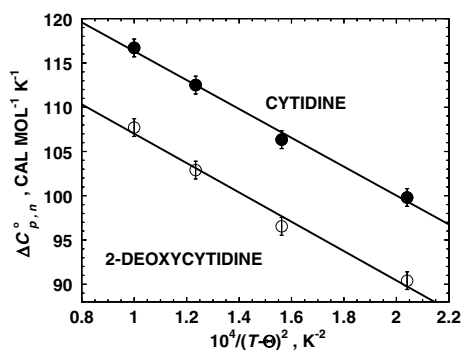

Fig. 11. Comparative plot of $\Delta C_{P,n}^\circ$ for aqueous cytidine and 2-deoxycytidine as a function of $10^4/(T - \Theta)^2$ at 1 bar. The symbols denote values of $\Delta C_{P,n}^\circ$ computed from Eqs. (49) and (50) using values of ω and C_P° taken from Tables 2 and A.2 in Appendix A, respectively. The experimental values of C_P° were reported by Patel and Kishore (1995). The regression lines represent fits of Eq. (50) to the data.

$$C_{P,deoxynucleoside_i}^\circ = C_{P,nucleoside_i}^\circ + \delta C_P^\circ, \tag{74}$$

where δC_P° represents the difference in the experimental values of C_P° shown in the table for 2-deoxycytidine and cytidine at 25 °C and 1 bar, which is given by

$$\delta C_P^\circ = C_{P,2\text{-deoxycytidine}}^\circ - C_{P,cytidine}^\circ. \tag{75}$$

Although no experimental values of C_P° for deoxyribose are available in the literature, provisional values for its c_1 and c_2 parameters can be estimated from those of ribose. It can be seen in Table 2 that the independently derived values of c_2 for aqueous 2-deoxycytidine and cytidine are identical. Because the chemical formulas of aqueous ribose and deoxyribose differ by the same chemical group as deoxycytidine and cytidine, in a first approximation we can take $c_{2,deoxyribose}$ to be equal to $c_{2,\,ribose}$. A value of c_1 for deoxyribose can then be calculated from the values shown in Table 2 of c_2 and ω for deoxyribose using Eqs. (49) and (50), together with an estimated value of C_P° for this species at 25 °C and 1 bar computed from

$$C_{P,deoxyribose}^\circ = C_{P,deoxyribose(cr)}^\circ - \Delta C_{P,sol,d}^\circ, \tag{76}$$

where $\Delta C_{P,sol,d}^\circ$ corresponds to the standard molal heat capacity of solution of deoxyribose. In a first approximation, $\Delta C_{P,sol,d}^\circ$ in Eq. (76) can be taken to be equal to $\Delta C_{P,sol}^\circ$ for

$$ribose_{cr} \rightleftharpoons ribose_{aq}, \tag{77}$$

which can be calculated using the values of C_P° shown for aqueous and crystalline ribose in Tables 2 and 3, respectively.

The values of c_1 and c_2 for deoxyribose computed in the manner described above are listed in Table 2.

4.2.3. The crystalline heat capacity parameters, a, b, and c

Values of the heat capacity power function coefficients (a, b, and c in Eq. (6)) for crystalline nucleosides, deoxynucleosides, ribose, and deoxyribose are shown in Table 3. The values of a, b, and c given in this table for adenosine and ribose were obtained by regressing with Eq. (6) experimental values reported in the literature for the standard molal isobaric heat capacities of the crystalline species ($C_{P(cr)}^\circ$) represented by the symbols shown in Fig. 12. The regression lines shown in this figure are consistent with the values of a, b, and c given in Table 3 for these species.

Despite the dearth of experimental values of $C_{P(cr)}^\circ$ for the other nucleosides considered in the present communication, provisional values of a, b, and c for the ith nucleoside can be calculated from

$$\Xi_{nucleoside_i} = \Xi_{sugar} + \Xi_{base_i} - (\Xi_{H_2O} - \Delta\Xi_r) \tag{78}$$

where Ξ refers to any of the a, b, and c parameters for the subscripted species, *sugar* denotes ribose for nucleosides and deoxyribose for deoxynucleosides, and the $(\Xi_{H_2O} - \Delta\Xi_r)$ term can be evaluated in a first approximation by rearranging Eq. (62) to give

$$(\Xi_{H_2O} - \Delta\Xi_r) = \Xi_{adenine} + \Xi_{ribose} - \Xi_{adenosine}. \tag{79}$$
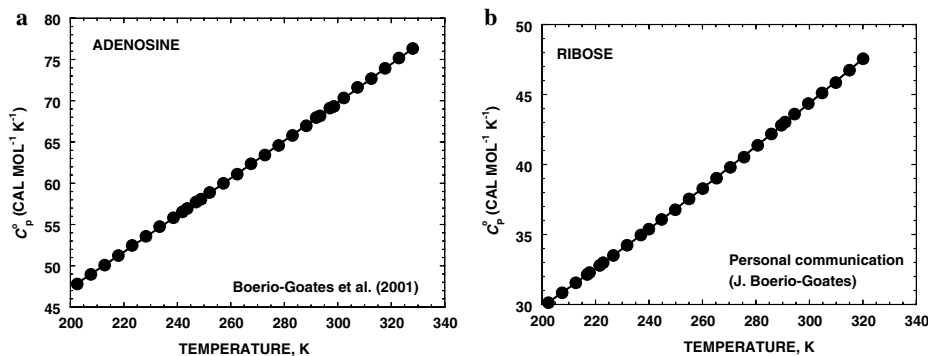
Fig. 12. C_P° for crystalline adenosine and ribose as a function of temperature at 1 bar. The symbols denote values of C_P° reported by Boerio-Goates et al. (2001) and by personal communication from J. Boerio-Goates. The regression lines represent fits of Eq. (6) to the data.

The values of *a*, *b*, and *c* given in Table 3 for the deoxynucleosides were calculated using the same procedure as that adopted above to compute values of these parameters for the nucleosides, except in the case of the deoxynucleosides, values of *a*, *b*, and *c* for deoxyribose were used to represent the Ξ_{sugar} term on the right side of Eq. (78). The values of the *a*, *b*, and *c* parameters given in Table 3 for deoxyribose

were estimated in a first approximation using the group additivity algorithm depicted in Fig. 9, which is consistent with

$$\Xi_{deoxyribose} = \Xi_{ribose} + \Xi_{cyclohexane} - \Xi_{cyclohexanol}. \qquad (80)$$

The values of *a*, *b*, and *c* for ribose and the reference model compounds, cyclohexane and cyclohexanol, are given in

Fig. 13. ΔV_n° for aqueous adenosine, cytidine, deoxyadenosine, deoxycytidine, deoxyguanosine, deoxyuridine, guanosine, thymidine, and uridine as a function of $1/(T - \Theta)$ at 1 bar. The symbols denote values of ΔV_n° computed from Eqs. (31) and (35) using values of ω and V° taken from Tables 2 and A.4 in Appendix A, respectively. The regression lines represent fits of Eq. (18) to the data. The vertical lines designate uncertainties in the experimental values of V° reported by Lee and Chalikian (2001).

Tables 3 and 8, respectively. The values of a, b, and c shown in Table 8 for cyclohexanol were obtained by regressing experimental values reported in the literature for the standard molal isobaric heat capacities of the crystalline species ($C_{P(cr)}^\circ$). These values are represented by the symbols shown for crystalline cyclohexanol (crystal I phase) in Fig. 4. The regression line shown in this figure for crystalline cyclohexanol is consistent with the values of a, b, and c.

4.2.4. The non-solvation volume and compressibility parameters, a_1, a_2, a_3, and a_4

In the absence of experimental high-temperature volumetric and compressibility data, values of the a_1, a_2, a_3, and a_4 parameters for the aqueous nucleosides can be computed from Eqs. (20) and (21) for $P = 1$ bar by first regressing experimentally derived low-temperature values of ΔV_n° and $-\Delta \kappa_{T,n}^\circ$ for these species with Eqs. (18) and (19), respec-

tively, as a function of $(1/(T - \theta))$ at 1 bar. The symbols shown in Fig. 13 represent values of ΔV_n° for adenosine, cytidine, guanosine, thymidine, uridine, deoxyadenosine, deoxycytidine, deoxyguanosine, and deoxyuridine calculated from corresponding values of V° reported by Lee and Chalikian (2001) using Eqs. (31) and (35), together with independent values of ω taken from Table 2. Note that the intercepts and slopes of the straight regression lines in Fig. 13 correspond respectively to values of the σ and ξ parameters in Eq. (18). Analogously, the symbols shown in Fig. 14 represent values of $-\Delta \kappa_{T,n}^\circ$ for adenosine, cytidine, guanosine, thymidine, uridine, deoxyadenosine, deoxycytidine, deoxyguanosine, and deoxyuridine calculated from corresponding values of κ_T° reported by Lee and Chalikian (2001) using Eqs. (32) and (36), together with values of ω taken from Table 2. It follows from Eq. (19) that the intercepts and slopes of the straight regression lines in Fig. 14, respectively, correspond to values of $\left(\frac{\partial \sigma}{\partial P}\right)_T$ and
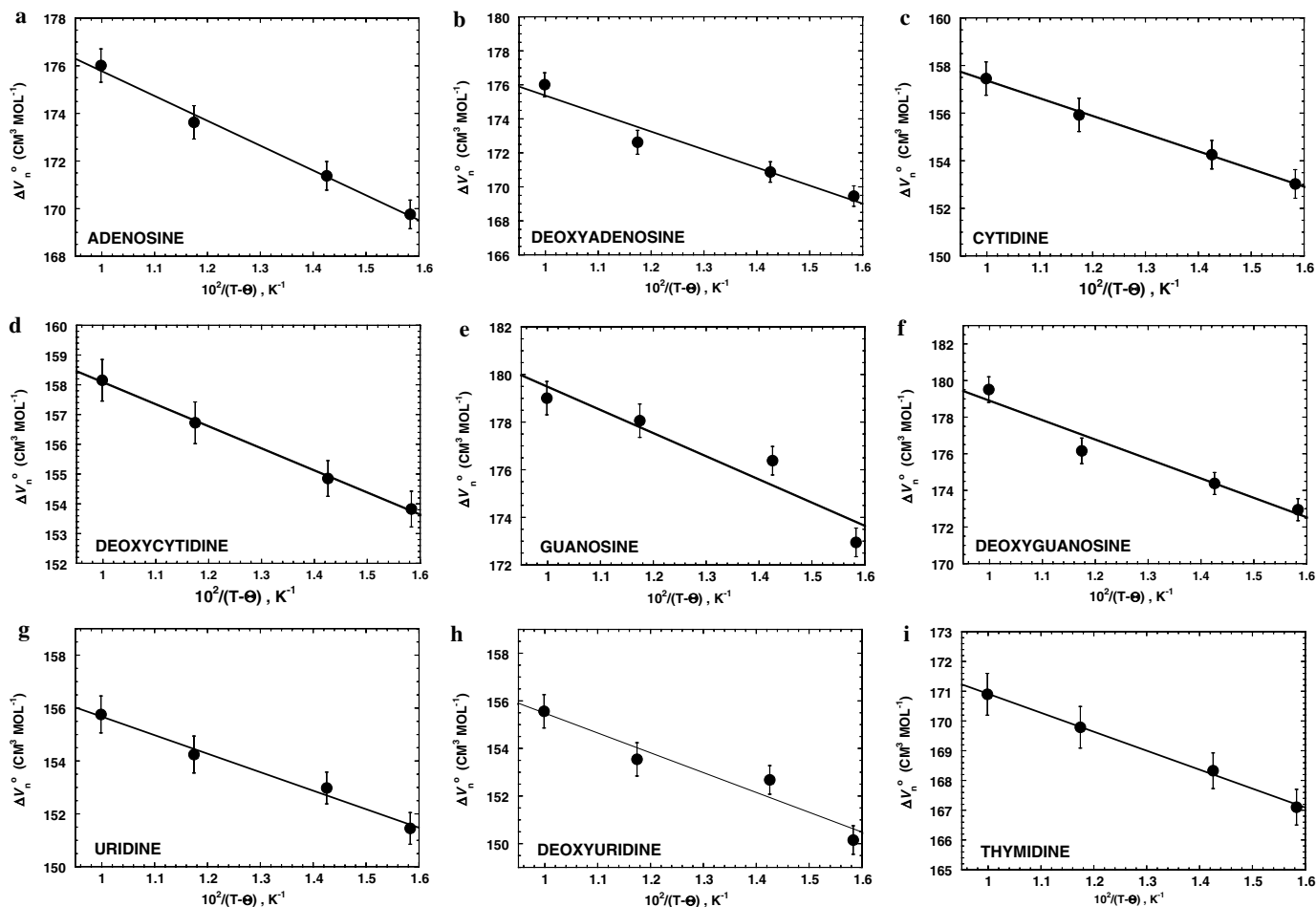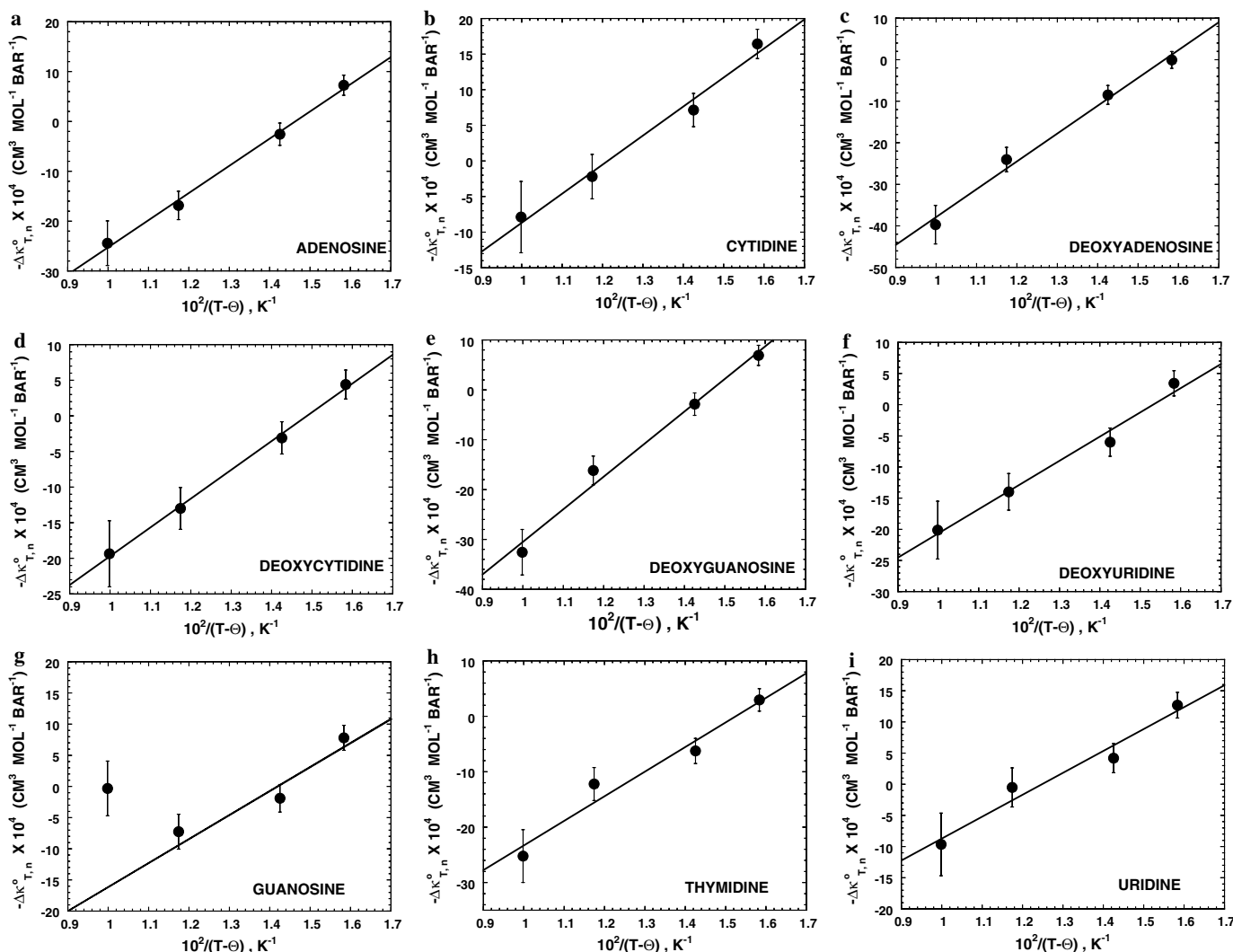

Fig. 14. $\Delta \kappa_{T,n}^\circ$ for aqueous adenosine, cytidine, deoxyadenosine, deoxycytidine, deoxyguanosine, deoxyuridine, guanosine, thymidine, and uridine as a function of $1/(T - \Theta)$ at 1 bar. The symbols denote values of $\Delta \kappa_{T,n}^\circ$ computed from Eqs. (32) and (36) using values of ω and κ_T° taken from Tables 2 and A.5 in Appendix A, respectively. The regression lines represent fits of Eq. (19) to the data. The vertical lines designate uncertainties in the experimental values of κ_T°.

$\left(\frac{\partial \xi}{\partial P}\right)_T$ for the nucleosides and deoxynucleosides. Values of a_2 and a_4 can be calculated directly from these partial derivatives using Eqs. (22) and (23). The values of a_2 and a_4 for these species can then be combined with values of σ and ξ in Eqs. (20) and (21) to calculate corresponding values of a_1 and a_3. With the exception of those for deoxythymidine, values of a_1, a_2, a_3, and a_4 for the aqueous nucleosides and deoxynucleosides computed in this manner are given in Table 2.

Although values of V° and κ_T° as a function of temperature are not available in the literature from which to calculate values of ΔV_n° and $\Delta\kappa_{T,n}^\circ$ as a function of $(1/(T-\theta))$ for deoxythymidine, provisional values of the a_1, a_2, a_3, and a_4 parameters for this species can be estimated from Eqs. (18), (20), (21), and (56), (57). The estimates of these parameters for deoxythymidine in Table 2 were calculated in this manner using the experimental value of V° at 25 °C and 1 bar for deoxythymidine reported by Buckin et al. (1989), which was combined with the value of ω for this species given in Table 2 and Eqs. (31) and (35) to calculate the value of ΔV_n° required to evaluate Eqs. (55)–(57) for deoxythymidine.

It can be deduced from Figs. 13 and 14 that the straight lines representing the revised HKF equations of state are closely consistent with the bulk of the experimentally derived values of ΔV_n° and $\Delta\kappa_{T,n}^\circ$. The experimental values of V° and κ_T° used to generate the latter values are listed in Tables A.4 and A.5 in Appendix A.

4.2.5. Standard molal crystalline volumes, $V_{(cr)}^\circ$

In the absence of experimental data, values of the standard molal volumes of the ith crystalline nucleoside $(V_{nucleoside(cr)_i}^\circ)$ can be calculated from

$$V_{nucleoside(cr)_i}^\circ = V_{base(cr)_i}^\circ + V_{sugar(cr)}^\circ - V_{H_2O(l)}^\circ + \Delta V_r^\circ, \quad (81)$$

which is consistent with Reaction (60). The standard molal volume of this reaction can be taken to be equal in a first approximation to that computed from and

$$\Delta V_r^\circ = V_{adenosine(cr)}^\circ + V_{H_2O(l)}^\circ - V_{adenine(cr)}^\circ - V_{ribose(cr)}^\circ, \quad (82)$$

which corresponds to a specific statement of Eq. (61). Experimental values of $V_{(cr)}^\circ$ for the ith crystalline base $(V_{base(cr)_i}^\circ)$ and crystalline adenosine, adenine, ribose, and deoxyribose are given in Table 3. As in Eq. (60), the subscript *sugar* in Eq. (81) refers to ribose in the case of nucleosides and deoxyribose in the case of deoxynucleosides. The values of $V_{(cr)}^\circ$ at 25 °C and 1 bar for the crystalline nucleosides and deoxynucleosides computed in this manner are listed in Table 3. The value of $V_{H_2O(l)}^\circ$ (18.07 cm³ mol⁻¹) was taken from SUPCRT92 (Johnson et al., 1992).

5. Nucleotides

The term nucleotide refers to any nucleoside bonded by its sugar to one or more phosphate groups as shown in Fig. 15.
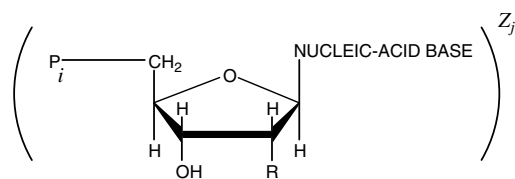
where P_i designates the number of phosphates in the nucleotide; i.e.,

i = 1: NUCLEOTIDE MONOPHOSPHATE
i = 2: NUCLEOTIDE DIPHOSPHATE R = OH: RIBOSE
i = 3: NUCLEOTIDE TRIPHOSPHATE R = H: DEOXYRIBOSE
Z_j = overall charge: 0,- 1,- 2,- 3, or - 4

Fig. 15. Idealized generic structure of nucleotides and deoxynucleotides.

The 120 nucleotides considered in the present communication are commonly referred to by the generic acronyms NMP, NDP, and NTP which stand for nucleotide monophosphate, nucleoside diphosphate, and nucleoside triphosphate, respectively. Specific nucleotides are referred to by the same designations except that the 'N' is replaced with the first letter of the nucleoside of interest. Charged nucleotides can be represented by $H_n NMP^{(n-2)}$, $H_n NDP^{(n-3)}$, and $H_n NTP^{(n-4)}$ where H stands for hydrogen and n denotes the number of hydrogen atoms protonating the phosphate oxygens in the generic ionized species, NMP^{2-}, NDP^{3-}, and NTP^{4-}, respectively. Each of the abbreviations for these species stands for all of the nucleotides in that group. For example, NMP refers to AMP, CMP, GMP, TMP, and UMP. A lower case 'd' precedes the same abbreviations for deoxynucleotides (e.g. dNMP). It should be noted that the abbreviated names for some of the protonated nucleotides used in the following text conceal the commonly accepted notion that these nucleotides exist as zwitterions in solution (Oscarson et al., 1995). The specific nucleotides thought to be zwitterions are denoted as such by a superscripted '+' before the acronym and a superscripted '−' after it in Tables 12–17. The abbreviations used below refer to the overall charge of the specified nucleotide or family of nucleotides, unless stated otherwise.

5.1. Standard molal Gibbs energies, enthalpies, and third law entropies at 25 °C and 1 bar

Values of $\Delta G_{f(aq)}^\circ$, $\Delta H_{f(aq)}^\circ$, and $S_{(aq)}^\circ$ at 25 °C and 1 bar for the variously protonated aqueous mono-, di- and triphosphate nucleotides and deoxynucleotides containing the nucleic-acid bases adenine, cytosine, guanine, thymine, and uracil are listed in Tables 12–17. Because experimental calorimetric measurements are not available in the literature for these nucleotides, the standard molal Gibbs energies and enthalpies of formation of the nucleotides shown in Tables 12–17, with the exception of the overall neutral nucleoside triphosphates (see below), were calculated from the standard molal Gibbs energies and enthalpies of the reactions listed in Tables 18 and 19, which are discussed below. Values of the standard molal third law entropies of

Table 12

Summary of equations of state parameters and the standard molal thermodynamic properties at 25 °C and 1 bar for aqueous nucleotide monophosphates (NMPs)

NMP	Formula	ΔG_f° [a]	ΔH_f° [a]	S° [b]	C_P° [b]	V° [c]	a_1 [d] $\times 10$	a_2 [a] $\times 10^{-2}$	a_3 [e]	a_4 [f] $\times 10^{-4}$	c_1 [b]	c_2 [e] $\times 10^{-4}$	ω [a] $\times 10^{-5}$
AMP^{2-}	$C_{10}H_{12}N_5O_7P^{2-}$	−247,417	−389,148	52.89	61.68	161.03	2.3198	108.81	−18.734	−1.7194	130.2	−19.82	3.1
$HAMP^-$	$C_{10}H_{13}N_5O_7P^-$	−255,617	−388,308	83.21	114.39	187.55	2.4065	126.25	−19.139	−2.4403	188.0	−22.30	3.1
$^+H_2AMP^-$	$C_{10}H_{14}N_5O_7P$	−260,817	−392,608	86.23	120.01	187.02	2.3993	124.81	−19.105	−2.3806	181.6	−19.10	2.5
CMP^{2-}	$C_9H_{12}N_3O_8P^{2-}$	−331,097	−467,460	48.24	37.71	142.39	2.2606	96.923	−18.459	−1.2278	101.1	−16.40	3.3
$HCMP^-$	$C_9H_{13}N_3O_8P^{1-}$	−340,147	−466,110	83.09	90.60	168.91	2.3474	114.36	−18.863	−1.9487	158.8	−18.76	3.3
$^+H_2CMP^-$	$C_9H_{14}N_3O_8P$	−345,337	−470,410	86.11	96.06	168.37	2.3411	113.10	−18.834	−1.8965	154.1	−16.01	2.8
GMP^{2-}	$C_{10}H_{12}N_5O_8P^{2-}$	−306,486	−455,676	52.39	65.81	159.80	2.3194	108.74	−18.733	−1.7163	140.8	−21.21	3.5
$HGMP^-$	$C_{10}H_{13}N_5O_8P^{1-}$	−315,586	−454,226	87.77	118.45	186.32	2.4062	126.18	−19.137	−2.4372	198.5	−23.70	3.5
$^+H_2GMP^-$	$C_{10}H_{14}N_5O_8P$	−320,786	−458,526	90.79	123.82	185.79	2.3990	124.73	−19.104	−2.3774	192.3	−20.70	2.9
TMP^{2-}	$C_{10}H_{13}N_2O_9P^{2-}$	−384,001	−525,514	49.58	51.85	155.97	2.3042	105.68	−18.662	−1.5896	111.0	−14.76	3.2
$HTMP^-$	$C_{10}H_{14}N_2O_9P^{1-}$	−393,021	−524,279	83.97	104.80	182.49	2.3909	123.11	−19.066	−2.3105	168.7	−17.10	3.2
$^+H_2TMP^-$	$C_{10}H_{15}N_2O_9P$	−398,221	−528,579	86.99	110.62	181.97	2.3838	121.67	−19.033	−2.2510	162.3	−13.76	2.6
UMP^{2-}	$C_9H_{11}N_2O_9P^{2-}$	−382,420	−515,132	46.49	36.19	141.33	2.2572	96.226	−18.442	−1.1990	101.1	−17.15	3.3
$HUMP^-$	$C_9H_{12}N_2O_9P^{1-}$	−391,470	−514,012	80.6	89.05	167.85	2.3439	113.66	−18.847	−1.9199	158.8	−19.52	3.3
$^+H_2UMP^-$	$C_9H_{13}N_2O_9P$	−396,670	−518,312	83.62	94.70	167.31	2.3367	112.22	−18.813	−1.8601	152.5	−16.32	2.7

These values were generated as described in Section 5.

  [a] cal mol^{-1}.
  [b] cal K^{-1} mol^{-1}.
  [c] cm^3 mol^{-1}.
  [d] cal mol^{-1} bar^{-1}.
  [e] cal K mol^{-1} bar^{-1}.
  [f] cal K mol^{-1}.

Table 13

Summary of equations of state parameters and the standard molal thermodynamic properties at 25 °C and 1 bar for aqueous deoxynucleotide monophosphates (dNMPs)

dNMP	Formula	ΔG_f° [a]	ΔH_f° [a]	S° [b]	C_P° [b]	V° [c]	a_1 [d] $\times 10$	a_2 [a] $\times 10^{-2}$	a_3 [e]	$a^{4f} \times 10^{-4}$	c_1 [b]	c_2 [e] $\times 10^{-4}$	ω [a] $\times 10^{-5}$
$dAMP^{2-}$	$C_{10}H_{12}N_5O_6P^{2-}$	−212,111	−347,206	50.63	53.02	160.05	2.3166	108.17	−18.720	−1.6929	121.5	−19.80	3.1
$dHAMP^-$	$C_{10}H_{13}N_5O_6P$	−221,205	−346,166	84.61	105.70	186.57	2.4033	125.61	−19.124	−2.4138	179.3	−22.32	3.1
$d^+H_2AMP^-$	$C_{10}H_{14}N_5O_6P$	−226,401	−350,466	87.62	111.28	186.05	2.3962	124.17	−19.091	−2.3543	172.9	−19.12	2.5
$dCMP^{2-}$	$C_9H_{12}N_3O_7P^{2-}$	−297,270	−425,354	52.5	28.13	144.34	2.2679	98.389	−18.493	−1.2884	94.34	−17.34	3.4
$dHCMP^-$	$C_9H_{13}N_3O_7P^{1-}$	−306,660	−424,314	86.48	86.48	170.80	2.3547	115.83	−18.987	−2.0093	152.0	−19.74	3.4
$d^+H_2CMP^-$	$C_9H_{14}N_3O_7P$	−311,860	−428,614	89.5	86.59	170.32	2.3475	114.38	−18.864	−1.9495	145.7	−16.54	2.8
$dGMP^{2-}$	$C_{10}H_{12}N_5O_7P^{2-}$	−272,457	−417,092	43.15	56.41	158.23	2.3143	107.71	−18.709	−1.6736	131.4	−21.21	3.5
$dHGMP^-$	$C_{10}H_{13}N_5O_7P^{1-}$	−281,547	−416,052	77.13	109.06	184.75	2.401	125.15	−19.113	−2.3945	189.1	−23.70	3.5
$d^+H_2GMP^-$	$C_{10}H_{14}N_5O_7P$	−286,747	−420,352	80.14	114.46	184.22	2.3938	123.70	−19.080	−2.3347	182.9	−20.67	2.9
$dTMP^{2-}$	$C_{10}H_{13}N_2O_8P^{2-}$	−350,474	−483,408	53.83	43.05	156.72	2.3066	106.17	−18.673	−1.6100	102.2	−14.76	3.2
$dHTMP^-$	$C_{10}H_{14}N_2O_8P^{1-}$	−359,564	−482,368	87.81	96.00	183.24	2.3934	123.61	−19.078	−2.3309	159.9	−17.10	3.2
$d^+H_2TMP^-$	$C_{10}H_{15}N_2O_8P$	−364,764	−486,668	90.83	101.82	183.72	2.3862	122.17	−19.044	−2.2714	153.5	−13.76	2.6
$dUMP^{2-}$	$C_9H_{11}N_2O_8P^{2-}$	−348,893	−473,026	50.75	27.36	140.78	2.2549	95.772	−18.432	−1.1180	92.27	−17.15	3.3
$dHUMP^-$	$C_9H_{12}N_2O_8P^{1-}$	−357,983	−471,986	84.73	84.73	167.16	2.3417	113.21	−18.836	−1.9011	145.0	−19.55	3.3
$d^+H_2UMP^-$	$C_9H_{13}N_2O_8P$	−363,183	−476,286	87.74	85.83	166.62	2.3345	111.76	−18.803	−1.8413	143.7	−16.35	2.7

These values were generated as described in Section 5.

  [a] cal mol^{-1}.
  [b] cal K^{-1} mol^{-1}.
  [c] cm^3 mol^{-1}.
  [d] cal mol^{-1} bar^{-1}.
  [e] cal K mol^{-1} bar^{-1}.
  [f] cal K mol^{-1}.

these species were calculated from the values of $\Delta G_{f(aq)}^{\circ}$ and $\Delta H_{f(aq)}^{\circ}$ using Eq. (42), together with values of S_i° for the elements taken from Cox et al. (1989).

Values of $\Delta G_{f(aq)}^{\circ}$ and $\Delta H_{f(aq)}^{\circ}$ for the ith ionized reference species, NMP_i^{2-}, NDP_i^{3-}, and NTP_i^{4-} were calculated from experimental values of the standard molal Gibbs energies and enthalpies of the phosphorylation reactions for *nucleoside$_i$*, NMP_i^{2-}, and NDP_i^{3-} given in Table 18, i.e.,

$$nucleoside_i + HPO_4^{2-} \rightleftharpoons NMP_i^{2-} + H_2O, \qquad (83)$$

Table 14
Summary of equations of state parameters and the standard molal thermodynamic properties at 25 °C and 1 bar for aqueous nucleotide diphosphates (NDPs)

NDP	Formula	$\Delta G_f^{\circ\,a}$	$\Delta H_f^{\circ\,a}$	$S^{\circ\,b}$	$C_P^{\circ\,b}$	$V^{\circ\,c}$	$a_1^d \times 10$	$a_2^a \times 10^{-2}$	a_3^e	$a_4^f \times 10^{-4}$	c_1^b	$c_2^e \times 10^{-4}$	$\omega^a \times 10^{-5}$
ADP^{3-}	C$_{10}$H$_{12}$N$_5$O$_{10}$P$_2$$^{3-}$	−452,649	−624,106	52.17	41.54	191.72	2.4286	130.680	−19.242	−2.6233	128.7	−24.87	4.0
HADP^{2-}	C$_{10}$H$_{13}$N$_5$O$_{10}$P$_2$$^{2-}$	−462,549	−623,266	88.2	107.59	202.95	2.4633	137.657	−19.403	−2.9117	186.2	−21.65	3.8
$^+$H$_2$ADP^{2-}	C$_{10}$H$_{14}$N$_5$O$_{10}$P$_2$$^{1-}$	−468,249	−627,666	92.56	136.40	202.41	2.4533	135.665	−19.357	−2.8294	193.1	−14.87	2.9
$^+$H$_3$ADP^1	C$_{10}$H$_{15}$N$_5$O$_{10}$P$_2$	−470,749	−625,106	109.53	169.36	207.55	2.4543	135.848	−19.361	−2.8370	204.0	−11.89	1.2
CDP^{3-}	C$_9$H$_{12}$N$_3$O$_{11}$P$_2$$^{3-}$	−53,6329	−702,338	47.8	18.49	173.36	2.3692	118.752	−18.965	−2.1302	99.37	−21.42	4.1
HCDP^{2-}	C$_9$H$_{13}$N$_3$O$_{11}$P$_2$$^{2-}$	−54,6119	−700,998	85.13	83.59	184.30	2.4041	125.762	−19.128	−2.4200	157.1	−18.25	4.0
$^+$H$_2$CDP^{2-}	C$_9$H$_{14}$N$_3$O$_{11}$P$_2$$^{1-}$	−551,819	−705,398	89.49	112.41	183.77	2.3942	123.770	−19.081	−2.3376	164.0	−11.48	3.1
$^+$H$_3$CDP^{1-}	C$_9$H$_{15}$N$_3$O$_{11}$P$_2$	−554,319	−702,838	106.64	145.32	188.96	2.3951	123.960	−19.086	−2.3255	175.0	−8.545	1.4
GDP^{3-}	C$_{10}$H$_{12}$N$_5$O$_{11}$P$_2$$^{3-}$	−511,718	−690,384	52.51	45.87	190.49	2.4273	130.437	−19.236	−2.6133	137.7	−25.78	4.3
HGDP^{2-}	C$_{10}$H$_{13}$N$_3$O$_{11}$P$_2$$^{2-}$	−521,518	−688,904	90.34	111.91	201.71	2.4619	137.394	−19.397	−2.9009	195.0	−22.49	4.1
$^+$H$_2$GDP^{2-}	C$_{10}$H$_{14}$N$_5$O$_{11}$P$_2$$^{1-}$	−527,218	−693,304	94.7	140.73	201.18	2.4520	135.402	−19.351	−2.8185	201.8	−15.70	3.2
$^+$H$_3$GDP^{1-}	C$_{10}$H$_{15}$N$_5$O$_{11}$P$_2$	−529,718	−690,744	111.68	173.68	206.33	2.4525	135.500	−19.353	−2.8226	212.0	−12.60	1.4
TDP^{3-}	C$_{10}$H$_{13}$N$_2$O$_{12}$P$_2$$^{3-}$	−589,233	−760,392	49.13	31.84	186.68	2.4128	127.511	−19.168	−2.4923	109.2	−19.67	4.1
HTDP^{2-}	C$_{10}$H$_{14}$N$_2$O$_{12}$P$_2$$^{2-}$	−599,033	−759,182	86.06	97.83	197.90	2.4477	134.521	−19.331	−2.7821	167.0	−16.54	3.9
$^+$H$_2$TDP^{2-}	C$_{10}$H$_{15}$N$_2$O$_{12}$P$_2$$^{1-}$	−604,733	−763,582	90.42	126.65	197.37	2.4377	132.528	−19.284	−2.6997	173.9	−9.780	3.0
$^+$H$_3$TDP^{1-}	C$_{10}$H$_{16}$N$_2$O$_{12}$P$_2$	−607,233	−761,022	107.39	159.63	202.50	2.4382	132.620	−19.287	−2.7035	184.0	−6.602	1.2
UDP^{3-}	C$_9$H$_{11}$N$_2$O$_{12}$P$_2$$^{3-}$	−587,652	−750,010	46.04	16.08	172.03	2.3658	118.055	−18.949	−2.1014	99.37	−22.16	4.2
HUDP^{2-}	C$_9$H$_{12}$N$_2$O$_{12}$P$_2$$^{2-}$	−597,432	−748,930	82.47	82.09	183.24	2.4006	125.065	−19.111	−2.3912	157.1	−18.99	4.0
$^+$H$_2$UDP^{2-}	C$_9$H$_{13}$N$_2$O$_{12}$P$_2$$^{1-}$	−603,132	−753,330	86.83	110.91	182.71	2.3907	123.073	−19.065	−2.3088	164.0	−12.22	3.1
$^+$H$_3$UDP^{1-}	C$_9$H$_{14}$N$_2$O$_{12}$P$_2$	−605,632	−750,770	103.8	143.87	187.85	2.3912	123.171	−19.067	−2.3129	174.2	−9.078	1.3

These values were generated as described in Section 5.

[a] cal mol^{-1}.
[b] cal K^{-1} mol^{-1}.
[c] cm^3 mol^{-1}.
[d] cal mol^{-1} bar^{-1}.
[e] cal K mol^{-1} bar^{-1}.
[f] cal K mol^{-1}.

Table 15
Summary of equations of state parameters and the standard molal thermodynamic properties at 25 °C and 1 bar for aqueous deoxynucleotide diphosphates (dNDPs)

dNDP	Formula	$\Delta G_f^{\circ\,a}$	$\Delta H_f^{\circ\,a}$	$S^{\circ\,b}$	$C_p^{\circ\,b}$	$V^{\circ\,c}$	$a_1^d \times 10$	$a_2^a \times 10^{-2}$	a_3^e	$a_4^f \times 10^{-4}$	c_1^b	$c_2^e \times 10^{-4}$	$\omega^a \times 10^{-5}$
dADP^{3-}	C$_{10}$H$_{12}$N$_5$O$_9$P$_2$$^{3-}$	−417,343	−582,164	49.91	32.91	190.75	2.4254	130.043	−19.227	−2.597	120.0	−24.87	4.0
dHADP^{2-}	C$_{10}$H$_{13}$N$_5$O$_9$P$_2$$^{2-}$	−427,243	−581,324	85.94	98.91	201.98	2.4601	137.019	−19.389	−2.8854	177.5	−21.65	3.8
$^+$dH$_2$ADP^{2-}	C$_{10}$H$_{14}$N$_5$O$_9$P$_2$$^{1-}$	−432,943	−585,742	90.3	127.72	201.44	2.4502	135.027	−19.342	−2.803	184.4	−14.87	2.9
$^+$dH$_3$ADP^{1-}	C$_{10}$H$_{15}$N$_5$O$_9$P$_2$	−435,443	−583,164	107.27	160.66	206.58	2.4511	135.210	−19.347	−2.8106	195.2	−11.89	1.2
dCDP^{3-}	C$_9$H$_{12}$N$_3$O$_{10}$P$_2$$^{3-}$	−502,802	−660,232	52.05	10.69	175.45	2.3761	120.127	−18.997	−2.187	91.57	−21.42	4.1
dHCDP^{2-}	C$_9$H$_{13}$N$_3$O$_{10}$P$_2$$^{2-}$	−512,592	−658,892	89.39	74.99	186.25	2.4105	127.044	−19.157	−2.473	148.5	−18.25	4.0
$^+$dH$_2$CDP^{2-}	C$_9$H$_{14}$N$_3$O$_{10}$P$_2$$^{1-}$	−518,292	−663,292	93.75	103.81	185.72	2.4006	125.052	−19.111	−2.3906	155.4	−11.48	3.1
$^+$dH$_3$CDP^{1-}	C$_9$H$_{15}$N$_3$O$_{10}$P$_2$	−520,792	−660,732	110.72	135.91	190.73	2.4010	125.150	−19.113	−2.3947	165.6	−8.545	1.4
dGDP^{3-}	C$_{10}$H$_{12}$N$_5$O$_{10}$P$_2$$^{3-}$	−477,689	−651,800	43.27	36.48	188.92	2.4222	129.405	−19.212	−2.5706	128.3	−25.78	4.3
dHGDP^{2-}	C$_{10}$H$_{13}$N$_5$O$_{10}$P$_2$$^{2-}$	−487,489	−650,320	81.11	102.51	200.14	2.4568	136.362	−19.373	−2.8582	185.6	−22.49	4.1
$^+$dH$_2$GDP^{2-}	C$_{10}$H$_{14}$N$_5$O$_{10}$P$_2$$^-$	−493,189	−654,720	85.47	131.33	199.61	2.4469	134.369	−19.327	−2.7758	192.4	−15.70	3.2
$^+$dH$_3$GDP^1	C$_{10}$H$_{15}$N$_5$O$_{10}$P$_2$	−495,689	−652,160	102.44	164.28	204.76	2.4474	134.467	−19.329	−2.7799	202.6	−12.60	1.4
dTDP^{3-}	C$_{10}$H$_{13}$N$_2$O$_{11}$P$_2$$^{3-}$	−555,706	−718,286	53.39	22.98	187.42	2.4152	127.998	−19.179	−2.5124	100.4	−19.67	4.1
dHTDP^{2-}	C$_{10}$H$_{14}$N$_2$O$_{11}$P$_2$$^{2-}$	−565,506	−717,076	90.31	88.99	198.65	2.4501	135.014	−19.342	−2.8025	158.1	−16.54	3.9
$^+$dH$_2$TDP^{2-}	C$_{10}$H$_{15}$N$_2$O$_{11}$P$_2$$^{1-}$	−571,206	−721,476	94.67	117.81	198.12	2.4402	133.021	−19.296	−2.7201	165.0	−9.780	3.0
$^+$dH$_3$TDP^{1-}	C$_{10}$H$_{16}$N$_2$O$_{11}$P$_2$	−573,706	−718,916	111.65	150.79	203.25	2.4406	133.113	−19.298	−2.7239	175.1	−6.602	1.2
dUDP^{-3}	C$_9$H$_{11}$N$_2$O$_{11}$P$_2$$^{3-}$	−554,125	−707,904	50.3	7.25	171.34	2.3635	117.602	−18.938	−2.0827	90.54	−22.16	4.2
dHUDP^{2-}	C$_9$H$_{12}$N$_2$O$_{11}$P$_2$$^{2-}$	−563,905	−706,824	86.73	73.26	182.55	2.3984	124.611	−19.101	−2.3724	148.3	−18.99	4.0
$^+$dH$_2$UDP^{2-}	C$_9$H$_{13}$N$_2$O$_{11}$P$_2$$^{1-}$	−569,605	−711,224	91.09	102.08	182.02	2.3885	122.619	−19.055	−2.2901	155.2	−12.22	3.1
$^+$dH$_3$UDP^{1-}	C$_9$H$_{14}$N$_2$O$_{11}$P$_2$	−572,105	−708,664	108.06	135.04	187.16	2.3889	122.717	−19.057	−2.2941	165.3	−9.078	1.3

These values were generated as described in Section 5.

[a] cal mol^{-1}.
[b] cal K^{-1} mol^{-1}.
[c] cm^3 mol^{-1}.
[d] cal mol^{-1} bar^{-1}.
[e] cal K mol^{-1} bar^{-1}.
[f] cal K mol^{-1}.

Table 16
Summary of equations of state parameters and the standard molal thermodynamic properties at 25 °C and 1 bar for aqueous nucleotide triphosphates (NTPs)

NTP	Formula	$\Delta G_f^{\circ \, a}$	$\Delta H_f^{\circ \, a}$	$S^{\circ \, b}$	$C_P^{\circ \, b}$	$V^{\circ c}$	$a_1^{\, d} \times 10$	$a_2^{\, a} \times 10^{-2}$	$a_3^{\, e}$	$a_4^{\, f} \times 10^{-4}$	$c_1^{\, b}$	$c_2^{\, e} \times 10^{-4}$	$\omega^a \times 10^{-5}$
ATP^{4-}	C$_{10}$H$_{12}$N$_5$O$_{13}$P$_3{}^{4-}$	−657,038	−859,264	47.96	21.34	196.77	2.4540	135.79	−19.360	−2.8345	128.4	−30.27	5.0
HATP^{3-}	C$_{10}$H$_{13}$N$_5$O$_{13}$P$_3{}^{3-}$	−667,538	−857,864	87.87	92.83	212.26	2.5037	145.79	−19.592	−3.2479	199.2	−30.37	4.9
$^+$H$_2$ATP^{3-}	C$_{10}$H$_{14}$N$_5$O$_{13}$P$_3{}^{2-}$	−673,738	−861,764	95.59	133.39	211.73	2.5002	145.08	−19.576	−3.2186	239.3	−31.04	4.7
$^+$H$_3$ATP^{2-}	C$_{10}$H$_{15}$N$_5$O$_{13}$P$_3{}^{1-}$	−676,438	−860,264	109.67	194.02	222.95	2.5350	152.09	−19.738	−3.5083	296.4	−30.22	4.5
$^+$H$_4$ATP$^-$	C$_{10}$H$_{16}$N$_5$O$_{13}$P$_3$	−678,500	−858,553	122.33	250.04	228.09	2.5509	155.28	−19.812	−3.6404	351.9	−30.40	4.4
CTP^{4-}	C$_9$H$_{12}$N$_3$O$_{14}$P$_3{}^{4-}$	−740,718	−937,496	43.58	−2.79	178.13	2.3948	123.89	−19.084	−2.3427	99.59	−27.07	5.2
HCTP^{3-}	C$_9$H$_{13}$N$_3$O$_{14}$P$_3{}^{3-}$	−751,148	−935,746	84.44	67.84	193.62	2.4446	133.90	−19.316	−2.7564	171.0	−27.91	5.1
$^+$H$_2$CTP^{3-}	C$_9$H$_{14}$N$_3$O$_{14}$P$_3{}^{2-}$	−757,348	−939,646	92.15	108.54	193.09	2.4410	133.18	−19.300	−2.7268	211.1	−28.49	4.9
$^+$H$_3$CTP^{2-}	C$_9$H$_{15}$N$_3$O$_{14}$P$_3{}^{1-}$	−760,048	−938,146	106.24	169.34	204.31	2.4759	140.20	−19.462	−3.0169	268.1	−27.53	4.7
$^+$H$_4$CTP$^-$	C$_9$H$_{16}$N$_3$O$_{14}$P$_3$	−762,090	−936,314	119.23	225.00	209.45	2.4918	143.39	−19.536	−3.1489	323.3	−27.75	4.6
GTP^{4-}	C$_{10}$H$_{12}$N$_5$O$_{14}$P$_3{}^{4-}$	−716,107	−925,542	48.3	25.36	195.54	2.4522	135.43	−19.352	−2.8198	136.1	−30.73	5.3
HGTP^{3-}	C$_{10}$H$_{13}$N$_5$O$_{14}$P$_3{}^{3-}$	−726,537	−923,792	89.15	95.50	211.03	2.5028	145.62	−19.588	−3.2409	209.2	−32.18	5.3
$^+$H$_2$GTP^{3-}	C$_{10}$H$_{14}$N$_5$O$_{14}$P$_3{}^{2-}$	−732,737	−927,692	96.86	135.94	210.5	2.4993	144.91	−19.572	−3.2115	249.3	−32.92	5.1
$^+$H$_3$GTP^{2-}	C$_{10}$H$_{15}$N$_5$O$_{14}$P$_3{}^{1-}$	−735,437	−926,192	110.95	196.82	221.72	2.5346	152.01	−19.736	−3.5051	307.2	−32.33	4.9
$^+$H$_4$GTP$^-$	C$_{10}$H$_{16}$N$_5$O$_{14}$P$_3$	−737,480	−924,362	123.94	252.16	226.86	2.5505	155.20	−19.810	−3.6372	361.0	−32.04	4.8
TTP^{4-}	C$_{10}$H$_{13}$N$_2$O$_{15}$P$_3{}^{4-}$	−793,622	−995,550	44.92	11.48	191.72	2.4384	132.65	−19.287	−2.7048	109.4	−25.31	5.1
HTTP^{3-}	C$_{10}$H$_{14}$N$_2$O$_{15}$P$_3{}^{3-}$	−803,972	−993,530	86.4	81.89	207.21	2.4890	142.84	−19.524	−3.1259	182.4	−26.6	5.1
$^+$H$_2$TTP^{3-}	C$_{10}$H$_{15}$N$_2$O$_{15}$P$_3{}^{2-}$	−810,172	−997,430	94.12	122.61	206.68	2.4854	142.12	−19.507	−3.0962	222.5	−27.18	4.9
$^+$H$_3$TTP^{2-}	C$_{10}$H$_{16}$N$_2$O$_{15}$P$_3{}^{1-}$	−812,872	−995,930	108.21	183.15	218.18	2.5221	149.50	−19.678	−3.4012	281.1	−26.69	4.8
$^+$H$_4$TTP$^-$	C$_{10}$H$_{17}$N$_2$O$_{15}$P$_3$	−815,000	−994,118	121.42	237.83	223.04	2.5372	152.52	−19.748	−3.5260	334.4	−26.45	4.7
UTP^{4-}	C$_9$H$_{11}$N$_2$O$_{15}$P$_3{}^{4-}$	−792,041	−985,168	41.83	−4.51	177.08	2.3909	123.11	−19.066	−2.3104	98.40	−27.33	5.2
HUTP^{3-}	C$_9$H$_{12}$N$_2$O$_{15}$P$_3{}^{3-}$	−802,441	−983,278	83.05	65.83	192.57	2.4416	133.30	−19.302	−2.7314	171.4	−28.66	5.2
$^+$H$_2$UTP^{3-}	C$_9$H$_{13}$N$_2$O$_{15}$P$_3{}^{2-}$	−808,641	−987,178	90.77	106.77	192.03	2.4385	132.67	−19.288	−2.7056	212.3	−29.52	5.0
$^+$H$_3$UTP^{2-}	C$_9$H$_{14}$N$_2$O$_{15}$P$_3{}^{1-}$	−811,341	−985,678	104.85	167.22	203.25	2.4742	139.86	−19.455	−3.0030	270.9	−29.07	4.9
$^+$H$_4$UTP$^-$	C$_9$H$_{15}$N$_2$O$_{15}$P$_3$	−813,380	−983,806	117.97	222.65	208.39	2.4901	143.06	−19.529	−3.1351	324.6	−28.65	4.8

These values were generated as described in Section 5.

   ^a cal mol^{-1}.
   ^b cal K^{-1} mol^{-1}.
   ^c cm^3 mol^{-1}.
   ^d cal mol^{-1} bar^{-1}.
   ^e cal K mol^{-1} bar^{-1}.
   ^f cal K mol^{-1}.

$$\mathrm{NMP}_i^{2-} + \mathrm{HPO_4}^{2-} + \mathrm{H}^+ \rightleftharpoons \mathrm{NDP}_i^{3-} + \mathrm{H_2O}, \tag{84}$$

and

$$\mathrm{NDP}_i^{3-} + \mathrm{HPO_4}^{2-} + \mathrm{H}^+ \rightleftharpoons \mathrm{NTP}_i^{4-} + \mathrm{H_2O} \tag{85}$$

for which we can write

$$\Xi^{\circ}_{\mathrm{NMP}^{2-}} = \Xi^{\circ}_{nucleoside_i} + \Xi^{\circ}_{\mathrm{HPO_4}^{2-}} - \Xi^{\circ}_{\mathrm{H_2O}} + \Delta\Xi^{\circ}_{r(83)}, \tag{86}$$

$$\Xi^{\circ}_{\mathrm{NDP}^{3-}} = \Xi^{\circ}_{\mathrm{NMP}^{2-}} + \Xi^{\circ}_{\mathrm{HPO_4}^{2-}} - \Xi^{\circ}_{\mathrm{H_2O}} + \Delta\Xi^{\circ}_{r(84)}, \tag{87}$$

and

$$\Xi^{\circ}_{\mathrm{NTP}^{4-}_i} = \Xi^{\circ}_{\mathrm{NDP}^{3-}_i} + \Xi^{\circ}_{\mathrm{HPO_4}^{2-}} - \Xi^{\circ}_{\mathrm{H_2O}} + \Delta\Xi^{\circ}_{r(85)}, \tag{88}$$

respectively, where Ξ°_i stands for either $\Delta G^{\circ}_{f(aq)}$ or $\Delta H^{\circ}_{f(aq)}$ of the subscripted species in the reactions and $\Delta\Xi^{\circ}_{r(83)}$, $\Delta\Xi^{\circ}_{r(84)}$, and $\Delta\Xi^{\circ}_{r(85)}$ denote the corresponding properties of the reactions, which are given in Table 18. Although experimental values of the latter reaction properties are not available in the literature for the phosphorylation of all of the nucleotides, provisional values of $\Delta\Xi^{\circ}_{r(83)}$, $\Delta\Xi^{\circ}_{r(84)}$, and $\Delta\Xi^{\circ}_{r(85)}$, can be estimated by taking the average of the values for the nucleotides for which experimental data are available to be equal in a first approximation to those of the nucleotides for which no experimental data are available.

These estimates, taken together with corresponding values of $\Xi^{\circ}_{\mathrm{HPO_4^{2-}}}$ are listed in Tables 18 and A.10 in Appendix A. The values of $\Xi^{\circ}_{nucleoside_i}$ used in the calculations were taken from Table 2. Values of additional reaction properties are also given in Table A.10 in Appendix A.

Standard molal Gibbs energies and enthalpies of formation for the i th protonated nucleotide mono-, di- and triphosphate (H$_n$ NMP$_i^{(n-2)}$, H$_n$NDP$_i^{(n-3)}$, and H$_n$NTP$_i^{(n-4)}$) can be calculated from experimental values of ΔG_r°, ΔH_r°, and ΔS_r° for the generic protonation reactions represented by

$$\mathrm{H}_{(n-1)}\mathrm{NMP}_i^{(n-3)} + \mathrm{H}^+ \rightleftharpoons \mathrm{H}_n\mathrm{NMP}_i^{(n-2)}, \tag{89}$$

$$\mathrm{H}_{(n-1)}\mathrm{NDP}_i^{(n-4)} + \mathrm{H}^+ \rightleftharpoons \mathrm{H}_n\mathrm{NDP}_i^{(n-3)}, \tag{90}$$

and

$$\mathrm{H}_{(n-1)}\mathrm{NTP}_i^{(n-5)} + \mathrm{H}^+ \rightleftharpoons \mathrm{H}_n\mathrm{NTP}_i^{(n-4)} \tag{91}$$

for $n = 1$ and 2 in Reaction (89) and $n = 1, 2,$ and/or 3 for Reactions (90) and (91). Reactions (89)–(91) represent the successive protonation of the generic NMP$_i^{2-}$, NDP$_i^{3-}$, and NTP$_i^{4-}$ species. The generalized equations used to calculate values of $\Delta G^{\circ}_{f(aq)}$, $\Delta H^{\circ}_{f(aq)}$, and $S^{\circ}_{(aq)}$ for these protonated nucleotides can be written as

Table 17
Summary of equations of state parameters and the standard molal thermodynamic properties at 25 °C and 1 bar for aqueous deoxynucleotide triphosphates (dNTPs)

dNTP	Formula	ΔG_f°[a]	ΔH_f°[a]	S°[b]	C_P°[b]	V°[c]	a_1[d] $\times 10$	a_2[a] $\times 10^{-2}$	a_3[e]	a_4[f] $\times 10^{-4}$	c_1[b]	c_2[e] $\times 10^{-4}$	ω[a] $\times 10^{-5}$
dATP^{4-}	$C_{10}H_{12}N_5O_{12}P_3{}^{4-}$	−621,732	−817,322	45.7	12.60	195.80	2.4508	135.150	−19.345	−2.8081	119.7	−30.27	5.0
dHATP^{3-}	$C_{10}H_{13}N_5O_{12}P_3{}^{3-}$	−632,233	−815,922	85.61	84.15	211.29	2.5014	145.335	−19.581	−3.2292	190.5	−30.37	4.9
d$^+$H$_2$ATP^{3-}	$C_{10}H_{14}N_5O_{12}P_3{}^{2-}$	−638,432	−819,822	93.33	124.71	210.76	2.4988	144.803	−19.569	−3.2071	230.6	−31.04	4.7
d$^+$H$_3$ATP^{2-}	$C_{10}H_{15}N_5O_{12}P_3{}^{1-}$	−641,132	−818,322	107.42	185.29	221.98	2.5346	151.996	−19.736	−3.5045	287.7	−30.22	4.5
d$^+$H$_4$ATP$^-$	$C_{10}H_{16}N_5O_{12}P_3$	−643,200	−816,614	120.08	241.34	227.12	2.5505	155.198	−19.810	−3.6369	343.2	−30.40	4.4
dCTP^{4-}	$C_9H_{12}N_3O_{13}P_3{}^{4-}$	−707,191	−895,390	47.84	−12.00	180.08	2.4012	125.175	−19.114	−2.3957	90.63	−27.07	5.2
dHCTP^{3-}	$C_9H_{13}N_3O_{13}P_3{}^{3-}$	−717,621	−893,640	88.69	58.82	195.57	2.4518	135.360	−19.350	−2.8168	162.0	−27.91	5.1
d$^+$H$_2$CTP^{3-}	$C_9H_{14}N_3O_{13}P_3{}^{2-}$	−723,821	−897,540	96.41	99.57	195.04	2.4492	134.834	−19.338	−2.7950	202.1	−28.49	4.9
d$^+$H$_3$CTP^{2-}	$C_9H_{15}N_3O_{13}P_3{}^{1-}$	−726,521	−896,040	110.49	160.34	206.26	2.4850	142.028	−19.505	−3.0924	259.1	−27.53	4.7
d$^+$H$_4$CTP$^-$	$C_9H_{16}N_3O_{13}P_3$	−728,570	−894,253	123.36	216.00	211.40	2.5009	145.223	−19.579	−3.2245	314.3	−27.75	4.6
dGTP^{4-}	$C_{10}H_{12}N_5O_{13}P_3{}^{4-}$	−682,078	−886,958	39.06	16.20	193.97	2.4475	134.492	−19.330	−2.7809	127.9	−30.73	5.3
dHGTP^{3-}	$C_{10}H_{13}N_5O_{13}P_3{}^{3-}$	−692,508	−885,208	79.91	87.27	209.46	2.4982	144.678	−19.566	−3.2020	201.0	−32.18	5.3
d$^+$H$_2$GTP^{3-}	$C_{10}H_{14}N_5O_{13}P_3{}^{2-}$	−698,708	−889,108	87.63	127.74	208.93	2.4955	144.145	−19.554	−3.1800	241.1	−32.92	5.0
d$^+$H$_3$GTP^{2-}	$C_{10}H_{15}N_5O_{13}P_3{}^{1-}$	−701,408	−887,608	101.71	188.66	220.15	2.5313	151.345	−19.721	−3.4776	299.0	−32.33	4.9
d$^+$H$_4$GTP$^-$	$C_{10}H_{16}N_5O_{13}P_3$	−703,450	−885,778	114.7	243.96	225.29	2.5472	154.540	−19.795	−3.6097	352.8	−32.04	4.8
dTTP^{4-}	$C_{10}H_{13}N_2O_{14}P_3{}^{4-}$	−760,095	−953,444	49.17	2.64	192.47	2.4408	133.144	−19.299	−2.7252	100.5	−25.31	5.1
dHTTP^{3-}	$C_{10}H_{14}N_2O_{14}P_3{}^{3-}$	−770,445	−951,424	90.66	72.98	207.96	2.4915	143.330	−19.535	−3.1463	173.5	−26.6	5.1
d$^+$H$_2$TTP^{3-}	$C_{10}H_{15}N_2O_{14}P_3{}^{2-}$	−776,645	−955,324	98.38	113.73	207.43	2.4888	142.797	−19.523	−3.1242	213.6	−27.18	4.9
d$^+$H$_3$TTP^{2-}	$C_{10}H_{16}N_2O_{14}P_3{}^{1-}$	−779,345	−953,824	112.46	174.23	218.65	2.5246	149.991	−19.689	−3.4216	272.2	−26.69	4.8
d$^+$H$_4$TTP$^-$	$C_{10}H_{17}N_2O_{14}P_3$	−781,370	−954,020	118.6	228.93	223.79	2.5405	153.186	−19.764	−3.5537	325.5	−26.45	4.7
dUTP^{4-}	$C_9H_{11}N_2O_{14}P_3{}^{4-}$	−758,514	−943,062	46.09	−12.88	176.39	2.3886	122.656	−19.055	−2.2916	89.57	−27.33	5.2
dHUTP^{3-}	$C_9H_{12}N_2O_{14}P_3{}^{3-}$	−768,914	−941,172	87.31	57.01	191.87	2.4393	132.841	−19.292	−2.7127	162.6	−28.66	5.2
d$^+$H$_2$UTP^{3-}	$C_9H_{13}N_2O_{14}P_3{}^{2-}$	−775,114	−945,072	95.02	97.96	191.34	2.4367	132.309	−19.279	−2.6907	203.5	−29.52	5.0
d$^+$H$_3$UTP^{2-}	$C_9H_{14}N_2O_{14}P_3{}^{1-}$	−777,814	−943,572	109.11	158.49	202.56	2.4720	139.411	−19.444	−2.9842	262.1	−29.07	4.9
d$^+$H$_4$UTP$^-$	$C_9H_{15}N_2O_{14}P_3$	−779,850	−940,671	125.67	213.85	207.70	2.4888	142.790	−19.522	−3.1239	315.8	−28.65	4.8

These values were generated as described in Section 5.

[a] cal mol^{-1}.
[b] cal K^{-1} mol^{-1}.
[c] cm^3 mol^{-1}.
[d] cal mol^{-1} bar^{-1}.
[e] cal K mol^{-1} bar^{-1}.
[f] cal K mol^{-1}.

$$\Xi^{\circ}_{\mathrm{H}_n\mathrm{NMP}_i^{(n-2)}} = \Xi^{\circ}_{\mathrm{H}_{(n-1)}\mathrm{NMP}_i^{(n-3)}} + \Delta\Xi^{\circ}_{r(89)}, \qquad (92)$$

$$\Xi^{\circ}_{\mathrm{H}_n\mathrm{NDP}_i^{(n-3)}} = \Xi^{\circ}_{\mathrm{H}_{(n-1)}\mathrm{NDP}_i^{(n-4)}} + \Delta\Xi^{\circ}_{r(90)}, \qquad (93)$$

and

$$\Xi^{\circ}_{\mathrm{H}_n\mathrm{NTP}_i^{(n-4)}} = \Xi^{\circ}_{\mathrm{H}_{(n-1)}\mathrm{NTP}_i^{(n-5)}} + \Delta\Xi^{\circ}_{r(91)}, \qquad (94)$$

where Ξ_i° stands for values of $\Delta G_{f(aq)}^{\circ}$, $\Delta H_{f(aq)}^{\circ}$, or $S_{(aq)}^{\circ}$ for the subscripted species, and $\Delta\Xi_r^{\circ}$ represents the corresponding standard molal reaction properties. The values of $\Delta\Xi_r^{\circ}$ used to evaluate Eqs. (92)–(94) are listed in Table 19. The values of $\Delta\Xi_r^{\circ}$ for Reactions (92)–(94) for the cases of $n = 2$, $n = 2$ and 3, and $n = 2$ and 3, respectively, for all of the nucleotides except the adenosine nucleotides were taken in a first approximation to be equal to experimental values of $\Delta\Xi_r^{\circ}$ for the analogous adenosine reactions. For example, the values of ΔG_r°, ΔH_r°, and ΔS_r° for

$$\mathrm{HCMP}^- + \mathrm{H}^+ \rightleftharpoons {}^+\mathrm{H}_2\mathrm{CMP}^- \qquad (95)$$

were taken to be equal to those of

$$\mathrm{HAMP}^- + \mathrm{H}^+ \rightleftharpoons {}^+\mathrm{H}_2\mathrm{AMP}^-. \qquad (96)$$
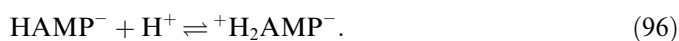
Additional experimental values of $\Delta\Xi_r^{\circ}$ reported in the literature for Reactions (89)–(91) are listed in Table A.11 in Appendix A.

Although there are no calorimetric data available in the literature for the protonation reaction forming the ith overall neutral nucleotide triphosphate zwitterion, $^+\mathrm{H}_4\mathrm{NTP}_i^-$, values of $\Delta G_{f(aq)}^{\circ}$ for these species can be calculated in a first approximation using a correlation between charge and values of $\Delta G_{f(aq)}^{\circ}$ for the nucleotides in a given charge series. For example, the symbols shown in Fig. 16 represent values of $\Delta G_{f(aq)}^{\circ}$ for ATP^{4-}, HATP^{3-}, H$_2$ATP^{2-}, and H$_3$ATP$^-$ taken from Table 16, which are plotted against the square of the overall charge of each species. It can be demonstrated that similar plots for the other $\mathrm{H}_n\mathrm{NTP}_i^{(n-4)}$ charge series exhibit the same dependence on charge (slope) with different intercepts. Hence, the equations of all of these straight lines in all of these plots can be expressed as

$$\Delta G^{\circ}_{f,\mathrm{H}_n\mathrm{NTP}_i^{(n-4)}} = \Delta G^{\circ}_{f,\mathrm{H}_4\mathrm{NTP}_i^{\circ}} + mZ^2 \qquad (97)$$

where $\Delta G^{\circ}_{f,\mathrm{H}_n\mathrm{NTP}_i^{(n-4)}}$ denotes the Gibbs energy of formation of $\mathrm{H}_n\mathrm{NTP}_i^{(n-4)}$ for $n = 0$, 1, 2, and 3 and Z refers to the overall charge of the nucleotide. Values of m are given in Table 20. Eq. (97) was used to calculate values of $\Delta G_{f(aq)}^{\circ}$ for all of the H$_4$NTP$_i$ species, which are shown in Table 16.

Provisional values of $S_{(aq)}^{\circ}$ for the H$_4$NTP$_i^{\circ}$ species can be estimated from a correlation between experimentally derived values of $S_{(aq)}^{\circ}$ for the ith NTP species $(S_{\mathrm{H}_n\mathrm{NTP}_i^{(n-4)}}^{\circ}$

Table 18

Standard molal Gibbs energies, enthalpies and entropies of reaction at 25 °C and 1 bar for selected phosphorylation reactions

Reaction	$\Delta G_r^{\circ\,a}$	$\Delta H_r^{\circ\,a}$	$\Delta S_r^{\circ\,b,c}$
Adenosine + $HPO_4^{2-} \leftrightarrow AMP^{2-} + H_2O$	2704[d]	−160[d]	−9.60
Guanosine + $HPO_4^{2-} \leftrightarrow GMP^{2-} + H_2O$	2704[e]	−650[f]	−11.25
Nucleoside$_i$ + $HPO_4^{2-} \leftrightarrow NMP_i^{2-} + H_2O$	2704[e]	−322[g]	−10.15
$AMP^{2-} + HPO_4^{2-} + H^+ \leftrightarrow ADP^{3-} + H_2O$	−1610[h]	5540[i]	23.98
$GMP^{2-} + HPO_4^{2-} + H^+ \leftrightarrow GDP^{3-} + H_2O$	−1610[j]	5790[k]	24.82
$NMP_i^{2-} + HPO_4^{2-} + H^+ \leftrightarrow NDP_i^{3-} + H_2O$	−1610[j]	5620[l]	24.25
$ADP^{3-} + HPO_4^{2-} + H^+ \leftrightarrow ATP^{4-} + H_2O$	−767[m]	5340[n]	20.48
$GDP^{3-} + HPO_4^{2-} + H^+ \leftrightarrow GTP^{4-} + H_2O$	−767[o]	5330[f]	20.45
$NDP^{i3-} + HPO_4^{2-} + H^+ \leftrightarrow NTP^{i4-} + H_2O$	−767[o]	5340[p]	20.48

See Table A.10 in Appendix A for additional literature values.
[a] cal mol^{-1}.
[b] cal K^{-1}mol^{-1}.
[c] Calculated from $\Delta S_r^{\circ} = (\Delta H_r^{\circ} - \Delta G_r^{\circ})/T_r$.
[d] Average of values taken from Table A.10 in Appendix A.
[e] Taken in a first approximation to be the same as ΔG_r° for the first AMP^{2-} reaction above.
[f] Tewari et al. (1988).
[g] Average of ΔH_r° for the AMP^{2-} and GMP^{2-} reactions.
[h] Goldberg and Tewari (1994).
[i] Average of values taken from Table A.11 in Appendix A.
[j] Taken in a first approximation to be the same as ΔG_r° for the ADP^{3-} reaction.
[k] Calculated from ΔH_r° for the sixth and seventh reactions given in Table taken from Table A.10 in Appendix A.
[l] Average of ΔH_r° for the ADP^{3-} and GDP^{3-} reactions.
[m] Average of values of ΔG_r° taken from Table A.10 in Appendix A.
[n] Average of values of ΔH_r° taken from Table A.10 in Appendix A.
[o] Taken in a first approximation to be the same as ΔG_r° for the ATP^{4-} reaction.
[p] Taken in a first approximation to be the same as ΔH_r° for the ATP^{4-} reaction.

and corresponding experimental values of $S_{(aq)}^{\circ}$ for like-charged diphosphates, $S_{H_nP_2O_7^{(n-4)}}^{\circ}$. For example, it can be seen in Fig. 17 that the values of $S_{(aq)}^{\circ}$ for $H_nATP^{(n-4)}$ increase as a linear function of the corresponding values of $S_{(aq)}^{\circ}$ for like-charged diphosphate species (Table 21). The equation of the straight line representing this correlation for all of the like-nucleotides is given by

$$S_{H_nNTP_i^{(n-4)}}^{\circ} = b_i + m_i(S_{H_nP_2O_7^{(n-4)}}^{\circ}), \tag{98}$$

where b_i and m_i denote the intercept and slope for for the ith kind of nucleotide (e.g., $H_nATP^{(n-4)}$, $H_nGTP^{(n-4)}$, etc.). Values of b_i and m_i are given in Table 20.

The values of $S_{(aq)}^{\circ}$ shown in Table 16 for the $^+H_4NTP_i^-$ species were calculated from the appropriate expressions of Eq. (98) using values of $S_{H_nNTP_i^{(n-4)}}^{\circ}$ taken from Table A.9 in Appendix A. The values of $\Delta H_{f(aq)}^{\circ}$ shown in table for the $^+H_4NTP_i^-$ species were calculated from the values of $\Delta G_{f(aq)}^{\circ}$ and $S_{(aq)}^{\circ}$ using a rearranged version of Eq. (42), together with values of S_i° taken from Cox et al. (1989).

5.2. Equations of state parameters

Experimental values of C_P°, V°, and κ_T° have not been reported in the literature for nucleotides. Nevertheless, provisional values of their revised HKF equations of state

Table 19

Standard molal Gibbs energies, enthalpies, and entropies of reaction at 25 °C and 1 bar for the nucleotide protonation reactions considered in the current study

Reaction	$\Delta G_r^{\circ\,a}$	$\Delta H_r^{\circ\,a}$	$\Delta S_r^{\circ\,b}$
$AMP^{2-} + H^+ \leftrightarrow HAMP^-$	−8200[c]	840[d]	32.0[d]
$GMP^{2-} + H^+ \leftrightarrow HGMP^-$	−9100[e]	1450[e]	35.3[e]
$CMP^{2-} + H^+ \leftrightarrow HCMP^-$	−9040[e]	1350[e]	34.8[e]
$UMP^{2-} + H^+ \leftrightarrow HUMP^-$	−9050[e]	1120[e]	34.0[e]
$TMP^{2-} + H^+ \leftrightarrow HTMP^-$	−9020[f]	1235[g]	34.4[g]
$dAMP^{2-} + H^+ \leftrightarrow dHAMP^-$	−9090[e]	1040[e]	33.8[e]
$HAMP^- + H^+ \leftrightarrow {}^+H_2AMP^-$	−5200[c]	−4300[d]	3.1[d]
$ADP^{3-} + H^+ \leftrightarrow HADP^{2-}$	−9900[c]	840[d]	35.9[d]
$GDP^{3-} + H^+ \leftrightarrow HGDP^{2-}$	−9800[e]	1480[e]	37.7[e]
$CDP^{3-} + H^+ \leftrightarrow HCDP^{2-}$	−9790[e]	1340[e]	37.4[e]
$UDP^{3-} + H^+ \leftrightarrow HUDP^{2-}$	−9780[e]	1080[e]	36.4[e]
$TDP^{3-} + H^+ \leftrightarrow HTDP^{2-}$	−9800[f]	1210[g]	36.9[g]
$HADP^{2-} + H^+ \leftrightarrow {}^+H_2ADP^{2-}$	−5700[c]	−4400[d]	4.4[d]
$^+H_2ADP^{2-} + H^+ \leftrightarrow {}^+H_3ADP^-$	−2500[c]	2560[d]	17[d]
$ATP^{4-} + H^+ \leftrightarrow HATP^{3-}$	−10,500[c]	1400[d]	40[d]
$GTP^{4-} + H^+ \leftrightarrow HGTP^{3-}$	−10,430[e]	1750[e]	40.8[e]
$CTP^{4-} + H^+ \leftrightarrow HCTP^{3-}$	−10,430[e]	1750[e]	40.8[e]
$UTP^{4-} + H^+ \leftrightarrow HUTP^{3-}$	−10,350[e]	2020[e]	41.4[e]
$TTP^{4-} + H^+ \leftrightarrow HTTP^{3-}$	−10,400[f]	1890[g]	41.4[g]
$HATP^{3-} + H^+ \leftrightarrow {}^+H_2ATP^{3-}$	−6200[c]	−3900[d]	7.6[d]
$^+H_2ATP^{3-} + H^+ \leftrightarrow {}^+H_3ATP^{2-}$	−2700[c]	1500[d]	14[d]

The standard molal Gibbs energies, enthalpies, and entropies of reaction at 25 °C and 1 bar for the deoxyribonucleotide protonation reactions were taken in a first approximation to be equal to the corresponding properties of the analogous ribonucleotide reactions given above. Supporting this hypothesis is the observation that the values of the aforementioned reaction properties for the $dAMP^{2-} + H^+ \rightleftharpoons dHAMP^-$ reaction are within several percent of the reaction properties among the ribonucleotide monophosphates. See Table A.11 in Appendix A for additional literature values.
[a] cal mol^{-1}.
[b] cal K^{-1} mol^{-1}.
[c] Calculated from $\Delta G_r^{\circ} = \Delta H_r^{\circ} - T\Delta S_r^{\circ}$.
[d] Oscarson et al. (1995).
[e] Phillips et al. (1965).
[f] Calculated from $\Delta G_r^{\circ} = \Delta H_r^{\circ} - T\Delta S_r^{\circ}$.
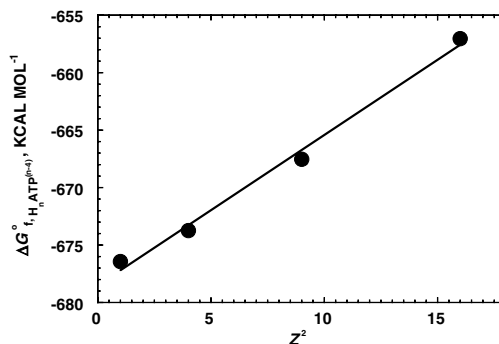[g] Estimated in a first approximation by averaging the values of ΔS_r° for the other pyrimidines.

Fig. 16. $\Delta G_{fH_nATP^{(n-4)}}^{\circ}$ as a function of the square of the charge (Z^2) for $n = 0,1,2,$ and 3. The values of $\Delta G_{fH_nATP^{(n-4)}}^{\circ}$ were taken from Table 16.

parameters can be estimated by taking account of experimental enthalpies of reaction involving reference model compounds, and group additivity and correlation algorithms.

Table 20
Values of m and b_i and m_i for Eqs. (97) and (98), respectively

Nucleotide series	m	b_i	m_i
$H_nATP_i^{(n-4)}$	1.3019	75.032	0.9275
$H_nCTP_i^{(n-4)}$	1.3019	71.176	0.94233
$H_nGTP_i^{(n-4)}$	1.3019	75.891	0.94217
$H_nTTP_i^{(n-4)}$	1.3019	72.861	0.95214
$H_nUTP_i^{(n-4)}$	1.3019	69.625	0.94794
$dH_nATP_i^{(n-4)}$	1.3085	72.774	0.92764
$dH_nCTP_i^{(n-4)}$	1.3039	75.310	0.94217
$dH_nGTP_i^{(n-4)}$	1.3039	66.651	0.94217
$dH_nTTP_i^{(n-4)}$	1.2986	70.493	0.94327
$dH_nUTP_i^{(n-4)}$	1.3019	77.114	0.95215
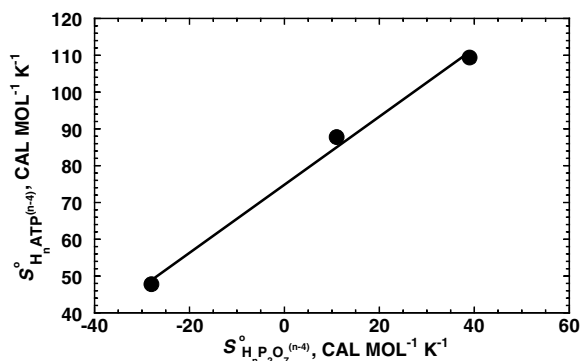
Fig. 17. $S^\circ_{H_nP_2O_7^{(n-4)}}$ plotted against $S^\circ_{H_nATP^{(n-4)}}$ for equally protonated phosphate groups. Although the overall charge on the $H_nATP^{(n-4)}$ species may not be the same as that for the corresponding $H_nP_2O_7^{(n-4)}$ species (some nucleotides are zwitterionic), the charge contributed by the phosphate groups on the nucleotides are equal to those of the corresponding diphosphate species.

5.2.1. The ω, c_1, and c_2 parameters

In the absence of experimental calorimetric data, provisional values of c_1, c_2, and ω for the nucleotides can be obtained by progressively regressing estimated values of C_P° for these species with a combined expression of Eqs. (49) and (50) using trial values of ω (see below). The reactions and corresponding equations used to calculate values of C_P° as a function of temperature for the aqueous nucleotides considered in the present study, other than the overall neutral nucleotide triphosphates, correspond to those denoted as (1A–11A) in Table 22. The values of $\Delta C_{P,r}^\circ$ in these equations were taken in a first approximation to be equal to the corresponding isobaric standard molal heat

capacities of reaction for the corresponding reference model reactions designated as (1B–11B) in Table 22. The reactions from which (1B–11B) were derived are shown in the lower section of the first column in Table 22. The equations and strategies employed to generate the revised HKF equations of state parameters used to calculate values of C_P° as a function of temperature for (*ribose-5-phosphate*)$^{2-}$ and the citrate species are discussed in Appendix B. The equations used to calculate values of C_P° as a function of temperature for the other reactant and product species in the reference model reactions are discussed below.

Values of C_P° for $HAMP^-$, $^+H_2AMP^-$, ADP^{3-}, ATP^{4-}, $HATP^{3-}$, $^+H_2ATP^{3-}$, and $^+H_3ATP^{2-}$ were calculated in the present study by taking finite difference derivatives of experimentally derived values of the standard molal enthalpy of formation of each of these species as a function of temperature in accord with

$$C_p^\circ \equiv \left(\frac{\partial H^\circ}{\partial T}\right)_P \approx \left(\frac{\delta H^\circ}{\delta T}\right)_P, \quad (99)$$

where δ stands for the finite difference derivative. The values of δH° required for these calculations were computed as a function of temperature using the equations listed in the second column of Table 23 next to the reactions from which the equations were derived.

The validity of using the equations and reference model reactions listed in Table 22 to estimate values of C_P° for nucleotides as a function of temperature can be inferred from comparisons of other experimental standard molal thermodynamic properties of reaction involving nucleotides for which calorimetric data are available in the literature. For example, it can be deduced from Table 19 that the respective experimentally derived values of ΔG_r° and ΔH_r° for the protonation of GMP^{2-}, CMP^{2-}, UMP^{2-}, TMP^{2-}, and $dAMP^{2-}$ to $HGMP^-$, $HCMP^-$, $HUMP^-$, $HTMP^-$, and $dHAMP^-$ are within 80 and 410 cal mol^{-1} of each other, respectively, which is of the order of the uncertainties in the experimental values. This observation supports by inference the hypothesis adopted in the present study that the values of $\Delta C_{P,r}^\circ$ for Reactions (2) and (3) in Table 22 are essentially equivalent to those of protonation reactions for nucleotide monophosphate species containing different bases. Note also that the experimentally derived values of ΔH_r° for the nucleotide phosphorylation reactions given in Table 18 differ from one another by 250 cal mol^{-1} or less for the monophosphates and by only 10 cal mol^{-1}

Table 21
Summary of values of ΔH_r° in cal mol^{-1} for selected phosphorylation reactions as a function of temperature at 1 bar

Reaction	Temperatures (K)					
	298.15	304.15	304.55	304.65	309.95	310.15
Ribose-5-phosphate^{2-} + H_2O ↔ ribose + HPO_4^{2-}	−1202[a]			−1331[a]		−1377[a]
AMP^{2-} + H_2O ↔ adenosine + HPO_4^{2-}	215[b]		67[b]			143[b]
ATP^{4-} + H_2O ↔ ADP^{3-} + HPO_4^{2-} + H^+	−4892[c]	−5251[c]			−5557[c]	

[a] Tewari et al. (1988).
[b] Gajewski et al. (1986).
[c] Larson et al. (1993).

Table 22

Summary of the reactions (left column) and corresponding equations (right column) used to calculate values of C_P° for selected nucleotides

Reactions for which the equations used to calculate C_P° were derived		Equations used to calculate values of C_P° for the subscripted nucleotides
$Nucleoside_i + HPO_4^{2-} \rightleftharpoons NMP_i^{2-} + H_2O$	(1A)	$C_{P,NMP_i^{2-}}^\circ = C_{P,nucleoside_i}^\circ + C_{P,HPO_4^{2-}}^\circ - C_{P,H_2O}^\circ + \Delta C_{P,r1A}^\circ$
$NMP_i^{2-} + H^+ \rightleftharpoons HNMP_i^-$	(2A)	$C_{P,HNMP_i^-}^\circ = C_{P,NMP_i^{2-}}^\circ + \Delta C_{P,r2A}^\circ$
$HNMP_i^- + H^+ \rightleftharpoons {}^+H_2NMP_i^-$	(3A)	$C_{P,{}^+H_2NMP_i^-}^\circ = C_{P,HNMP_i^-}^\circ + \Delta C_{P,r3A}^\circ$
$NMP_i^{2-} + HPO_4^{2-} + H^+ \rightleftharpoons NDP_i^{3-} + H_2O$	(4A)	$C_{P,NDP_i^{3-}}^\circ = C_{P,NMP_i^{2-}}^\circ + C_{P,HPO_4^{2-}}^\circ - C_{P,H_2O}^\circ + \Delta C_{P,r4A}^\circ$
$NDP_i^{3-} + H^+ \rightleftharpoons HNDP_i^{2-}$	(5A)	$C_{P,HNDP_i^{2-}}^\circ = C_{P,NDP_i^{3-}}^\circ + \Delta C_{P,r5A}^\circ$
$HNDP_i^{2-} + H^+ \rightleftharpoons {}^+H_2NDP_i^{2-}$	(6A)	$C_{P,{}^+H_2NDP_i^{2-}}^\circ = C_{P,HNDP_i^{2-}}^\circ + \Delta C_{P,r6A}^\circ$
${}^+H_2NDP_i^{2-} + H^+ \rightleftharpoons {}^+H_3NDP_i^-$	(7A)	$C_{P,{}^+H_3NDP_i^-}^\circ = C_{P,{}^+H_2NDP_i^{2-}}^\circ + \Delta C_{P,r7A}^\circ$
$NDP_i^{3-} + HPO_4^{2-} + H^+ \rightleftharpoons NTP_i^{4-} + H_2O$	(8A)	$C_{P,NTP_i^{4-}}^\circ = C_{P,NDP_i^{3-}}^\circ + C_{P,HPO_4^{2-}}^\circ - C_{P,H_2O}^\circ + \Delta C_{P,r8A}^\circ$
$NTP_i^{4-} + H^+ \rightleftharpoons HNTP_i^{3-}$	(9A)	$C_{P,HNTP_i^{3-}}^\circ = C_{P,NTP_i^{4-}}^\circ + \Delta C_{P,r9A}^\circ$
$HNTP_i^{3-} + H^+ \rightleftharpoons {}^+H_2NTP_i^{3-}$	(10A)	$C_{P,{}^+H_2NTP_i^{3-}}^\circ = C_{P,HNTP_i^{3-}}^\circ + \Delta C_{P,r10A}^\circ$
${}^+H_2NTP_i^{3-} + H^+ \rightleftharpoons {}^+H_3NTP_i^{2-}$	(11A)	$C_{P,{}^+H_3NTP_i^{2-}}^\circ = C_{P,{}^+H_2NTP_i^{3-}}^\circ + \Delta C_{P,r11A}^\circ$
Reference model reactions from which $\Delta C_{P,r}^\circ$ was calculated		**Equations used to calculate $\Delta C_{P,r}^\circ$**
$Ribose + HPO_4^{2-} \rightleftharpoons R5P^{2-} + H_2O$	(1B)	$\Delta C_{P,r1B}^\circ = C_{P,R5P^{2-}}^\circ + C_{P,H_2O}^\circ - C_{P,ribose}^\circ - C_{P,HPO_4^{2-}}^\circ$
$AMP^{2-} + H^+ \rightleftharpoons HAMP^-$	(2B)	$\Delta C_{P,r2B}^\circ = C_{P,HAMP^-}^\circ - C_{P,AMP^{2-}}^\circ$
$HAMP^- + H^+ \rightleftharpoons {}^+H_2AMP^-$	(3B)	$\Delta C_{P,r3B}^\circ = C_{P,{}^+H_2AMP^-}^\circ - C_{P,HAMP^-}^\circ$
$ADP^{3-} + HPO_4^{2-} + H^+ \rightleftharpoons ATP^{4-} + H_2O$	(4B)	$\Delta C_{P,r4B}^\circ = C_{P,ATP^{4-}}^\circ + C_{P,H_2O}^\circ - C_{P,ADP^{3-}}^\circ - C_{P,HPO_4^{2-}}^\circ$
$Citrate^{3-} + H^+ \rightleftharpoons Hcitrate^{2-}$	(5B)	$\Delta C_{P,r5B}^\circ = C_{P,Hcitrate^{2-}}^\circ - C_{P,citrate^{3-}}^\circ$
$Hcitrate^{2-} + H^+ \rightleftharpoons H_2citrate^-$	(6B)	$\Delta C_{P,r6B}^\circ = C_{P,H_2citrate^-}^\circ - C_{P,Hcitrate^{2-}}^\circ$
$H_2citrate^- + H^+ \rightleftharpoons H_3citrate$	(7B)	$\Delta C_{P,r7B}^\circ = C_{P,H_3citrate}^\circ - C_{P,H_2citrate^-}^\circ$
$ADP^{3-} + HPO_4^{2-} + H^+ \rightleftharpoons ATP^{4-} + H_2O$	(8B)	$\Delta C_{P,r8B}^\circ = C_{P,ATP^{4-}}^\circ + C_{P,H_2O}^\circ - C_{P,ADP^{3-}}^\circ - C_{P,HPO_4^{2-}}^\circ$
$ATP^{4-} + H^+ \rightleftharpoons HATP^{3-}$	(9B)	$\Delta C_{P,r9B}^\circ = C_{P,HATP^{3-}}^\circ - C_{P,ATP^{4-}}^\circ$
$HATP^{3-} + H^+ \rightleftharpoons {}^+H_2ATP^{3-}$	(10B)	$\Delta C_{P,r10B}^\circ = C_{P,{}^+H_2ATP^{3-}}^\circ - C_{P,HATP^{3-}}^\circ$
${}^+H_2ATP^{3-} + H^+ \rightleftharpoons {}^+H_3ATP^{2-}$	(11B)	$\Delta C_{P,r11B}^\circ = C_{P,{}^+H_3ATP^{2-}}^\circ - C_{P,{}^+H_2ATP^{3-}}^\circ$

The values of $\Delta C_{P,r}^\circ$ for Reactions (1B)–(11B) were used in a first approximation to evaluate the equations used to calculate values of C_P° for the subscripted nucleotides. That is, values of $\Delta C_{P,r1B}^\circ$ are taken to be equal to those of $\Delta C_{P,r1A}^\circ$ and $\Delta C_{P,r2B}^\circ = \Delta C_{P,r2A}^\circ$ and so on. The reference model reactions are discussed further in the text.

The values of C_P° as a function of temperature required to evaluate the equations in column 2 were calculated with the aid of the SUPCRT92 software package Johnson et al. (1992) using the revised HKF equations of state parameters for the subscripted species given in Tables 2, 12, 14, and 16, and B.1 in Appendix B. The strategies used to generate values of the equations of state parameters for $R5P^{2-}$ and the citrate species are discussed in Appendix B. $R5P^{2-}$ stands for $(ribose\text{-}5\text{-}phosphate)^{2-}$.

Table 23

Summary of the reactions (left column) and corresponding equations (right column) used to calculate the values of ΔH° as a function of temperature required to evaluate Eq. (99) for selected reference model nucleotide species

Reactions for which experimental values of ΔH_r° are available in the literature		Equations used to calculated ΔH° of the subscripted nucleotide
$AMP^{2-} + H^+ \rightleftharpoons HAMP^-$	(1)	$\Delta H_{HAMP^-}^\circ = \Delta H_{AMP^{2-}}^\circ + \Delta H_{r1}^\circ$
$HAMP^- + H^+ \rightleftharpoons {}^+H_2AMP^-$	(2)	$\Delta H_{{}^+H_2AMP^-}^\circ = \Delta H_{HAMP^-}^\circ + \Delta H_{r2}^\circ$
$ADP^{3-} + HPO_4^{2-} + H^+ \rightleftharpoons ATP^{4-} + H_2O$	(3)	$\Delta H_{ADP^{3-}}^\circ = \Delta H_{AMP^{2-}}^\circ + \Delta H_{HPO_4^{2-}}^\circ - \Delta H_{H_2O}^\circ + \Delta H_{r3}^\circ,$
$ADP^{3-} + HPO_4^{2-} + H^+ \rightleftharpoons ATP^{4-} + H_2O$	(4)	$\Delta H_{ATP^{4-}}^\circ = \Delta H_{ADP^{3-}}^\circ + \Delta H_{HPO_4^{2-}}^\circ - \Delta H_{H_2O}^\circ + \Delta H_{r4}^\circ$
$ATP^{4-} + H^+ \rightleftharpoons HATP^{3-}$	(5)	$\Delta H_{HATP^{3-}}^\circ = \Delta H_{ATP^{4-}}^\circ + \Delta H_{r5}^\circ$
$HATP^{3-} + H^+ \rightleftharpoons H_2ATP^{2-}$	(6)	$\Delta H_{{}^+H_2ATP^{3-}}^\circ = \Delta H_{HATP^{3-}}^\circ + \Delta H_{r6}^\circ$
${}^+H_2ATP^{3-} + H^+ \rightleftharpoons {}^+H_3ATP^{2-}$	(7)	$\Delta H_{{}^+H_3ATP^{2-}}^\circ = \Delta H_{{}^+H_2ATP^{3-}}^\circ + \Delta H_{r7}^\circ$

The values of ΔH° as a function of temperature required to evaluate the equations in column 2 were calculated with the aid of the SUPCRT92 software package Johnson et al. (1992) using the revised HKF equations of state parameters for the subscripted species given in Tables 12, 14, and 16, and A.9 in Appendix A. The values of ΔH_{r3}° as a function of temperature were taken from Larson et al. (1993) and those for all of the other equations from Oscarson et al. (1995).

for the diphosphates. Hence, in a first approximation the standard molal thermodynamic properties of phosphorylation reactions between nucleotides containing different bases but the same number of phosphate groups can be taken to be equivalent within experimental uncertainty.

The validity of using values of $\Delta C_{P,r}^\circ$ for reference model Reactions (5B)–(7B) in Table 22 as respective proxies for those of analogous nucleotide diphosphate anion protonation reactions can be assessed by comparing calculated standard molal thermodynamic properties of species in the protonated ADP series with the few experimental data available in the literature for these species. This can be done by first adopting a constant heat capacity approximation representing the difference of ΔH_r° at 125 °C and that at 25 °C given by (Oscarson et al., 1995) for

$$ADP^{3-} + H^+ \rightleftharpoons HADP^{2-}, \tag{100}$$

$$HADP^{2-} + H^+ \rightleftharpoons H_2ADP^-, \tag{101}$$

and

$$H_2ADP^- + H^+ \rightleftharpoons H_3ADP. \qquad (102)$$

This approach results in values of $\Delta C_{P,r}^\circ$ for Reactions (100)–(102) of 62.10, 23.07, and 36.89 cal mol^{-1} K^{-1}, respectively. The corresponding values of $\Delta C_{P,r}^\circ$ computed for Reactions (5B)–(7B) in Table 22 and inserted into the corresponding equations in Table 22 at temperatures ranging from 25 to 125 °C are 66.05–62.76, 28.82–25.29, and 32.96–41.84 cal mol^{-1} K^{-1}. Hence, both approaches lead to similar values of $\Delta C_{P,r}^\circ$ for protonation of the $H_nADP^{(n-3)}$ series of dinucleotides.

The validity of using values of $\Delta C_{P,r}^\circ$ for Reaction (9B) in Table 22 to estimate values of C_P° for the other trivalent nucleotide triphosphate anions can be assessed by comparing experimental standard molal properties of reaction for analogous nucleotide reactions. For example, it can be deduced from Table 19 that the respective values of ΔG_r° and ΔH_r° for the protonation of GTP^{4-}, CTP^{4-}, UTP^{4-}, and TTP^{4-} to form HGTP^{3-}, HCTP^{3-}, HUTP^{3-}, and HTTP^{3-}, respectively, differ from one another by only 80 and 270 cal mol^{-1} or less. This observation supports the hypothesis that the values of $\Delta C_{P,r}^\circ$ for Reaction (9) in Table 22 can be taken in a first approximation to be equivalent, within experimental uncertainty, to those of protonation reactions for nucleotide triphosphates species containing different bases.

Values of c_1 and c_2 for the all of the nucleotides other than the overall neutral zwitterionic nucleotide triphosphate species considered in the present communication

were generated by first calculating values of $\Delta C_{P,n}^\circ$ from Eq. (49) as a function of $1/(T - \Theta)^2$ for these species using corresponding values of C_P° determined in the manner described above for various temperatures, together with trial values of ω. In the case of ADP^{3-}, an initial estimate of ω was calculated from $\omega = 4.8107 - 0.01516 (S^\circ)$, which represents a correlation algorithm for trivalent anions taken from Shock and Helgeson (1988). Following the procedure discussed above in Sections 3.2.2 and 4.2.2, these values of $\Delta C_{P,n}^\circ$ were then plotted as trial values against $1/(T - \Theta)^2$. Successive perturbation of the trial values of ω used to generate those of $\Delta C_{P,n}^\circ$ resulted in the straight lines shown in Figs. 18 and 19, which are consistent with the revised HKF equations of state (Tanger and Helgeson, 1988; Shock et al., 1992; Amend and Helgeson, 1997b, 2000). The intercepts and slopes of the straight regression lines representing the values $\Delta C_{P,n}^\circ$ for the nucleotides as a function of $1/(T - \Theta)^2$ in Figs. 18 and 19 correspond, respectively, to values of c_1 and c_2 for these species. For example, the symbols shown in Fig. 18 correspond to calculated values of $\Delta C_{P,n}^\circ$ for ADP^{3-} and ATP^{4-} and HAMP$^-$, H$_2$AMP, HATP^{3-}, H$_2$ATP^{2-}, and H$_3$ATP$^-$ as a function of $1/(T - \Theta)^2$. The intercepts and slopes, respectively, of the straight lines in these figures correspond to values of c_1 and c_2 in the equations of state for ADP^{3-} and ATP^{4-} and HAMP$^-$, H$_2$AMP, HATP^{3-}, H$_2$ATP^{2-}, and H$_3$ATP$^-$. It can be seen in Figs. 18 and 19 that the straight lines representing the revised HKF equations of state closely represent the values of $\Delta C_{P,n}^\circ$ corresponding to the symbols. The values of c_1 and c_2 corresponding to the
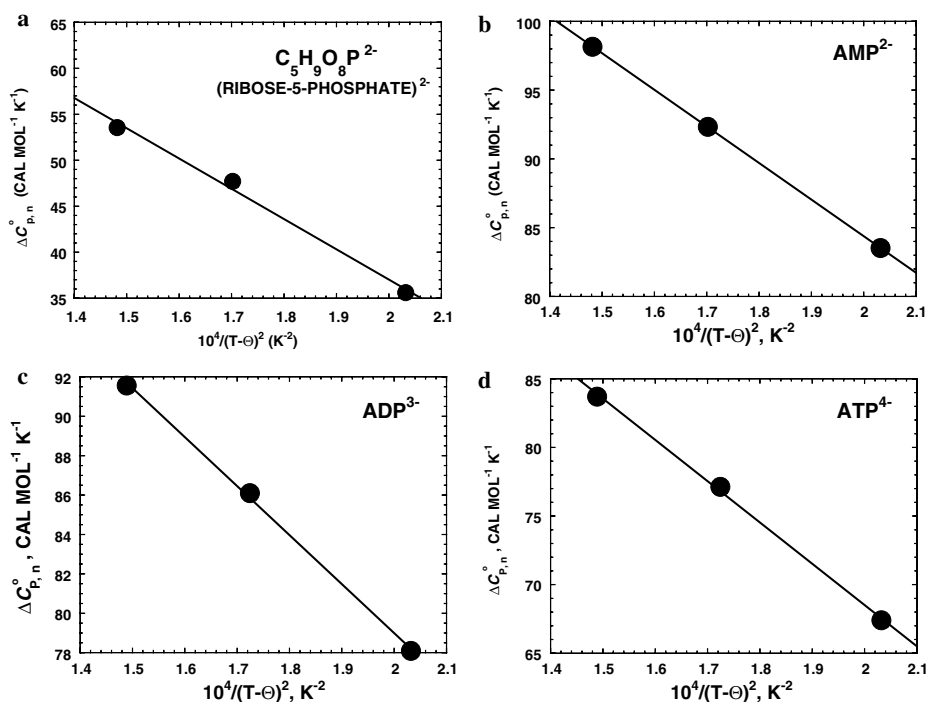

Fig. 18. $\Delta C_{P,n}^\circ$ for aqueous ribose-5-phosphate^{2-}, AMP^{2-}, ADP^{3-}, and ATP^{4-} as a function of $10^4/(T - \Theta)^2$ at 1 bar. The symbols denote values of $\Delta C_{P,n}^\circ$ computed from Eqs. (17) and (24) using values of ω and C_P° taken from Tables 2, 12, 14, and 16 (see text). The regression lines represent fits of Eq. (17) to the data.
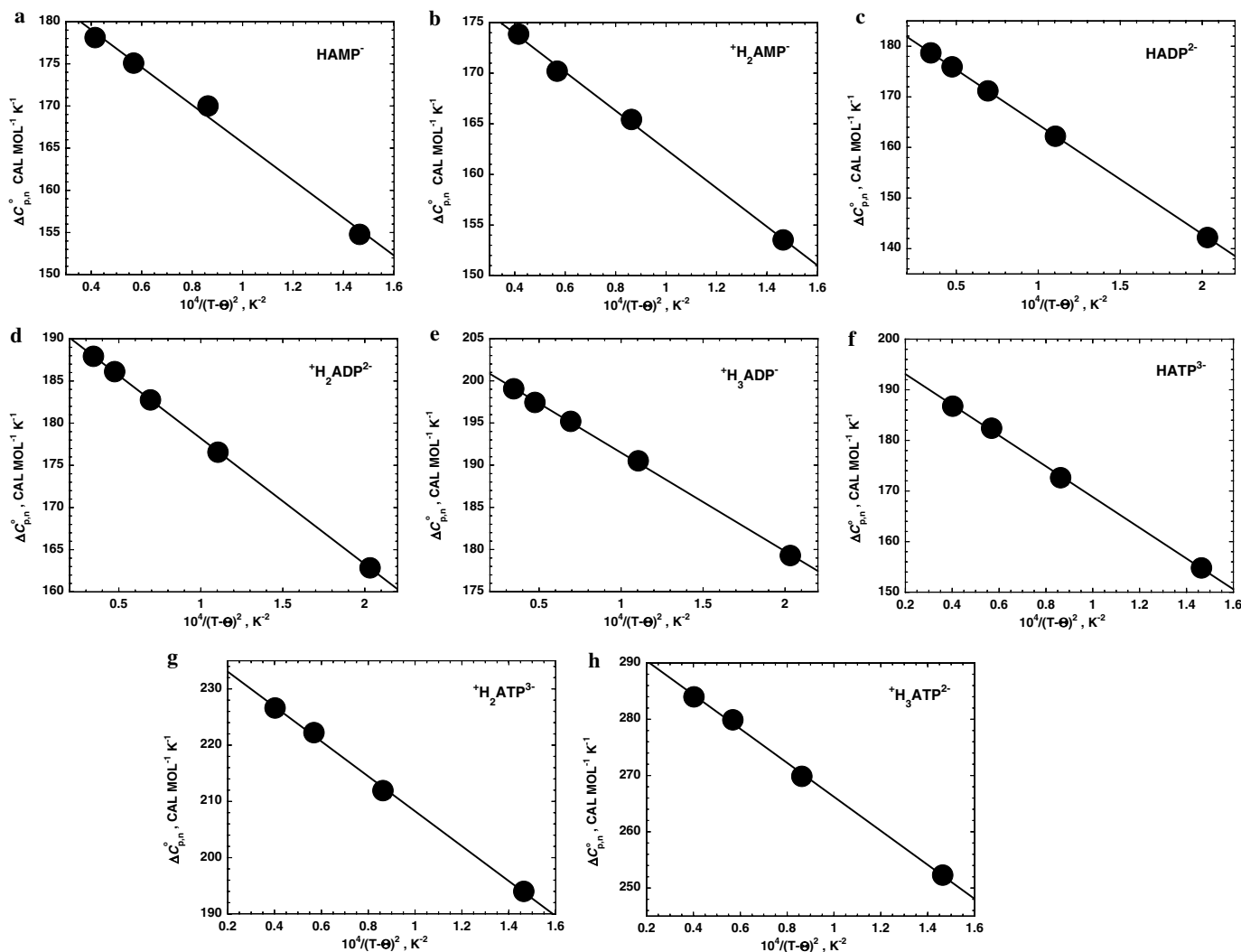
Fig. 19. $\Delta C_{P,n}^{\circ}$ for aqueous HAMP$^-$, $^+$H$_2$AMP$^-$, HADP^{2-}, $^+$H$_2$ADP^{2-}, $^+$H$_3$ADP$^-$, HATP^{3-}, $^+$H$_2$ATP^{3-}, and $^+$H$_3$ATP^{2-} as a function of $1/(T - \Theta)^2$ at 1 bar. The symbols represent values of $\Delta C_{P,n}^{\circ}$ computed from Eqs. (17) and (24) using values of ω and C_P° taken from Tables 12, 14, and 16 (see text). The regression lines represent fits of Eq. (17) to the data.

intercepts and slopes of the regression lines depicted in Figs. 18 and 19 are listed in Tables 2 and 12–17, together with the values of ω used to generate the straight lines.

Despite the dearth of experimental calorimetric data reported in the literature for the overall neutral zwitterionic nucleotide triphosphates, values of the c_1, c_2, and ω equation of state parameters for these species ($^+$H$_4$ NTP$_i^-$) can be estimated by comparing corresponding values of the c_1, c_2, and ω parameters for the other nucleotide triphosphates listed in Table 16. For example, it can be deduced from this table that the values of ω for a given series of protonated NTP species (e.g., ATP^{4-}, HATP^{3-}, H$_2$ATP^{2-}, and H$_3$ATP$^-$) decrease by $0.1 - 0.2 \times 10^5$ cal mol^{-1} per proton added to the NTP$_i^{4-}$ nucleotide. Hence, it appears that values of ω for the $^+$H$_4$NTP$_i^-$ species can be taken in a first approximation to be 0.1×10^5 cal mol^{-1} less than the corresponding values of the respective $^+$H$_3$NTP$_i^{2-}$ species. Note also in Table 16 that the values of c_2 for a given proton-

ation series of nucleotide species are nearly the same. Hence, the values of c_2 for the overall neutral zwitterionic nucleotide triphosphates were taken to be equal in a first approximation to the average of the c_2 values for the other triphosphate species in the series containing the same nucleoside. Values of c_1 were then calculated from Eq. (24) for $P = 1$ bar and constant ω using the values of ω, c_2, and the estimated values of C_P° for the overall neutral zwitterionic nucleotide triphosphate at 25 °C. The latter estimates were calculated from the group additivity algorithm represented by

$$C_{P,\mathrm{H_4NTP}_i^{\circ}}^{\circ} = C_{P,\mathrm{H_3NTP}_i^-}^{\circ} + (c_{1,\mathrm{H_4NTP}_i} - c_{1,\mathrm{H_3NTP}_i^-}). \qquad (103)$$

Values of the c_1, c_2, and ω parameters for all of the deoxynucleotides considered in the present communication were calculated using a strategy analogous to that adopted above to calculate values of these parameters for the corresponding nucleotides. However, in the case of the deoxynu-

cleotides, the standard molal thermodynamic properties of these species were used in place of the corresponding properties for ribonucleosides and ribonucleotides in the equations employed in the calculations. For example, values of C_P° for the ith deoxynucleoside ($C_{P,deoxynucleoside_i}^\circ$) were used to evaluate the first equation listed in Table 22, instead of values of $C_{P,nucleoside_i}^\circ$.

The standard molal reaction properties for ribonucleotides and the corresponding deoxyribonucleotides were taken in a first approximation to be equal in these calculations. The validity of this hypothesis is supported by the scant thermodynamic data available in the literature. For example, experimentally derived values of ΔG_r° and ΔH_r° for the protonation of AMP^{2-} and those for the deoxy-analog reaction involving dAMP^{2-} shown in Table 19 differ, respectively, by $\sim$900 and 200 cal mol^{-1}, which are less than the corresponding experimental uncertainty.

5.2.2. Non-solvation volume and the compressibility parameters, a_1, a_2, a_3, and a_4

Although no experimental values of V° or κ_T° have been reported in the literature for aqueous nucleotides, values of the a_1, a_2, a_3, and a_4 parameters for the nucleotides considered in the present study can be calculated from correlation algorithms for charged organic species given by Shock (1995) using estimated values of V° at 25 °C and 1 bar and the values of ω given for the nucleotides in Tables 12–17 (see above). The correlation algorithms used for this purpose are similar to those employed in Section 3.2.4 to calculate values of the a_1, a_2, a_3, and a_4 parameters for guanine.

Values of the a_1 parameters for the nucleotides can be calculated from the correlation algorithm presented by (Shock, 1995)

$$a_1 = 0.013684\left(\frac{\Delta V_n^\circ}{41.8393}\right) + 0.1765. \tag{104}$$

The requisite values of ΔV_n° at 25 °C were calculated from Eqs. (14) and (25) using estimated values of V° (see below) and values of ω taken from Tables 12–17. Values of the a_2 parameters were then calculated from these values of a_1 using Eq. (20) and values of σ, which were calculated from the correlation algorithm given by Shock (1995)

$$\sigma = 1.0714(\Delta V_n^\circ) + 3.0. \tag{105}$$

The a_2 parameters were in turn used to calculate values of a_4 from (Shock, 1995)

$$a_4 = 27790 - 4.134(a_2). \tag{106}$$

Finally, values of a_3 were computed from the values of a_4 using the first identity in Eq. (18), together with Eq. (21).

Owing to the dearth in the literature of experimental values of the standard molal volumes of nucleotides, the values of V° at 25 °C and 1 bar used in the calculations described above were computed by first estimating values of the standard molal volumes of the crystalline (V_{cr}°) nucleotides, together with the standard molal volumes of

solution (ΔV_{sol}°) for the hypothetical non-zwitterionic[4] H$_2$NMP reference species using the relation,

$$V^\circ = V_{cr}^\circ + \Delta V_{sol}^\circ. \tag{107}$$

This approach makes it possible to use the few experimental values of V_{cr}°, ΔV_{sol}°, and V° for nucleic-acid bases, nucleosides, ribose, and phosphate species that are available in the literature to estimate values of V° for the nucleotides in the manner described below.

The values of V_{cr}° required to evaluate Eq. (107) can be calculated for the ith fully protonated crystalline NMP species ($V_{H_2NMP_{i(cr)}}^\circ$) from values of V_{cr}° for the ith nucleoside ($V_{nucleoside_{i(cr)}}^\circ$) and V° for phosphoric acid ($V_{H_3PO_{4(cr)}}^\circ$) and H$_2$O ($V_{H_2O_{(l)}}^\circ$) using

$$V_{H_2NMP_{i(cr)}}^\circ = V_{nucleoside_{i(cr)}}^\circ + V_{H_3PO_{4(cr)}}^\circ - V_{H_2O_{(l)}}^\circ + \Delta V_r^\circ, \tag{108}$$

where ΔV_r° corresponds to the standard molal volume of reaction for

$$nucleoside_{i(cr)} + H_3PO_{4(cr)} \rightleftharpoons H_2NMP_{i(cr)} + H_2O_{(l)}. \tag{109}$$
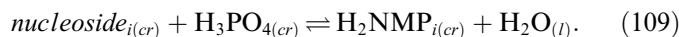
Because values of ΔV_r° are not available in the literature for the set of reactions represented by this reaction, values of ΔV_r° in Eq. (108) were taken in a first approximation to be equal to ΔV_r° of the dehydration reaction represented by

$$base_{i(cr)} + ribose_{(cr)} \rightleftharpoons nucleoside_{i(cr)} + H_2O_{(l)} \tag{110}$$
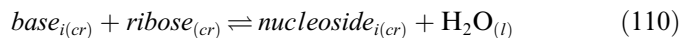
for which we can write

$$\Delta V_r^\circ = V_{nucleoside_{i(cr)}}^\circ + V_{H_2O_{(l)}}^\circ - V_{base_{i(cr)}}^\circ - V_{ribose_{(cr)}}^\circ. \tag{111}$$

The values of V° for $ribose$ ($V_{ribose_{(cr)}}^\circ$) and the ith $base$ ($V_{base_{i(cr)}}^\circ$) and $nucleoside$ ($V_{nucleoside_{i(cr)}}^\circ$) required to calculate ΔV_r° from Eq. (111) were taken from Table 3. $V_{H_2O}^\circ$ was computed using SUPCRT92. The calculated values of ΔV_r° were used together with Eq. (108) to calculate estimates of $V_{H_2NMP_{i(cr)}}^\circ$ for the various nucleotides.

The values of ΔV_{sol}° required to evaluate Eq. (107) for 25 °C and 1 bar can be calculated from the standard molal volumes of solution for the ith base ($\Delta V_{sol\,base_i}^\circ$), the ith nucleoside, ($\Delta V_{sol\,nucleoside_i}^\circ$), H$_3PO_4$ ($\Delta V_{sol\,H_3PO_4}^\circ$), and $ribose$ ($\Delta V_{sol\,ribose}^\circ$) using

$$\Delta V_{sol\,H_2NMP_i}^\circ = \Delta V_{sol\,H_3PO_4}^\circ + \Delta V_{sol\,nucleoside_i}^\circ - \delta V_{sol}^\circ \tag{112}$$

together with values of δV_{sol}° which were taken to be equal in a first approximation to those represented by

$$\delta V_{sol}^\circ = \Delta V_{sol\,base_i}^\circ + \Delta V_{sol\,ribose}^\circ - \Delta V_{sol\,nucleoside_i}^\circ. \tag{113}$$

The values of ΔV_{sol}° for the $nucleosides$, $nucleic$-$acid$ $bases$, $ribose$, and phosphoric acid used to evaluate Eqs. (112) and (113) were calculated from the corresponding values of V° and V_{cr}° given in Tables 2 and 3. The values of $\Delta V_{sol\,H_2NMP_i}^\circ$ generated in this manner were then combined with Eq. (107) and the values of $V_{H_2NMP_{i(cr)}}^\circ$ computed in

---

[4] Because some nucleotides are thought to be zwitterions (Oscarson et al., 1995) the overall charge of a nucleotide is only partially attributable to the phosphate group(s) in the species.

Table 24
Summary of the reactions (left column) and corresponding equations (right column) used to calculate values of V° for the subscripted nucleotides

Reactions from which the equations used to calculate V° were derived		Equations used to calculate values of V° for the subscripted nucleotides
$^+H_2NMP_i^- + H_3PO_4 \rightleftharpoons {}^+H_3NDP_i^- + H_2O$	(1)	$V^\circ_{^+H_3NDP_i^-} = V^\circ_{^+H_2NMP_i^-} + V^\circ_{H_3PO_4^\circ} - V^\circ_{H_2O} + \Delta V^\circ_{r1}$
$^+H_3NDP_i^- + H_3PO_4 \rightleftharpoons {}^+H_4NTP_i^- + H_2O$	(2)	$V^\circ_{^+H_4NTP_i^-} = V^\circ_{^+H_3NDP_i^-} + V^\circ_{H_3PO_4^\circ} - V^\circ_{H_2O} + \Delta V^\circ_{r2}$
$HNMP_i^- + H^+ \rightleftharpoons {}^+H_2NMP_i^-$	(3)	$V^\circ_{HNMP_i^-} = V^\circ_{^+H_2NMP_i^-} - \Delta V^\circ_{r3}$
$HNDP_i^{2-} + H^+ \rightleftharpoons {}^+H_2NDP_i^{2-}$	(4)	$V^\circ_{HNDP_i^{2-}} = V^\circ_{^+H_2NDP_i^{2-}} - \Delta V^\circ_{r4}$
$HNTP_i^{3-} + H^+ \rightleftharpoons {}^+H_2NTP_i^{3-}$	(5)	$V^\circ_{HNTP_i^{3-}} = V^\circ_{^+H_2NTP_i^{3-}} - \Delta V^\circ_{r5}$
$HNMP_i^- \rightleftharpoons NMP_i^{2-} + H^+$	(6)	$V^\circ_{NMP_i^{2-}} = V^\circ_{HNMP_i^-} + \Delta V^\circ_{r6}$
$^+H_3NDP_i^- \rightleftharpoons {}^+H_2NDP_i^{2-} + H^+$	(7)	$V^\circ_{^+H_2NDP_i^{2-}} = V^\circ_{^+H_3NDP_i^-} + \Delta V^\circ_{r7}$
$^+H_4NTP_i^- \rightleftharpoons {}^+H_3NTP_i^- + H^+$	(8)	$V^\circ_{^+H_3NTP_i^-} = V^\circ_{^+H_4NTP_i^-} + \Delta V^\circ_{r8}$
$HNDP_i^{2-} \rightleftharpoons NDP_i^{3-} + H^+$	(9)	$V^\circ_{NDP_i^{3-}} = V^\circ_{HNDP_i^{2-}} + \Delta V^\circ_{r9}$
$^+H_3NTP_i^{2-} \rightleftharpoons {}^+H_2NTP_i^{3-} + H^+$	(10)	$V^\circ_{^+H_2NTP_i^{3-}} = V^\circ_{^+H_3NTP_i^{2-}} + \Delta V^\circ_{r10}$
$HNTP_i^{3-} \rightleftharpoons NTP_i^{4-} + H^+$	(11)	$V^\circ_{NTP_i^{4-}} = V^\circ_{HNTP_i^{3-}} - V^\circ_{H^+} + \Delta V^\circ_{r11}$
Reactions from which the equations used to calculate ΔV°_r were derived		**Equations used to calculate ΔV°_r**
$H_2PO_4^- + H_3PO_4^\circ \rightleftharpoons H_3P_2O_7^- + H_2O$	(A)	$\Delta V^\circ_{rA} = V^\circ_{H_3P_2O_7^-} + V^\circ_{H_2O} - V^\circ_{H_2PO_4^-} - V^\circ_{H_3PO_4^\circ}$
Average of $Arg^+ \rightleftharpoons Arg + H^+$ and	(B)	$\Delta V^\circ_{rB} = (V^\circ_{Arg} - V^\circ_{Arg^+} + V^\circ_{Lys} - V^\circ_{Lys^+})/2$
$Lys^+ \rightleftharpoons Lys + H^+$		
$H_2PO_4^- \rightleftharpoons HPO_4^{2-} + H^+$	(C)	$\Delta V^\circ_{rC} = V^\circ_{HPO_4^{2-}} - V^\circ_{H_2PO_4^-}$
$H_3P_2O_7^- \rightleftharpoons H_2P_2O_7^{2-} + H^+$	(D)	$\Delta V^\circ_{rd} = V^\circ_{H_2P_2O_7^{2-}} - V^\circ_{H_3P_2O_7^-}$
$H_2P_2O_7^{2-} \rightleftharpoons HP_2O_7^{3-} + H^+$	(E)	$\Delta V^\circ_{rE} = V^\circ_{HP_2O_7^{3-}} - V^\circ_{H_2P_2O_7^{2-}}$
$HP_2O_7^{3-} \rightleftharpoons P_2O_7^{4-} + H^+$	(F)	$\Delta V^\circ_{rF} = V^\circ_{P_2O_7^{4-}} - V^\circ_{HP_2O_7^{3-}}$

The values of ΔV°_r calculated using Reactions (A)–(F) were used in a first approximation to evaluate Eqs. (1)–(11). The value of ΔV°_{rA} is taken to be equal to that for Reactions (1) and (2), ΔV°_{rB} for Reactions (3)–(5), ΔV°_{rC} for Reaction (6), ΔV°_{rD} for Reactions (7) and (8), ΔV°_{rE} for Reactions (9) and (10), and ΔV°_{rF} for Reaction (11). The reference model reactions are discussed further in the text.
The values of V° required to evaluate the equations in column 2 were taken from Tables 12, 14 and 16, A.9 in Appendix A, and in the case of Arg, Lys, Arg$^+$, and Lys$^+$, from Dick J.M., LaRowe D. E., and Helgeson, H. C., Temperature, pressure, and electrochemical constraints on protein speciation: Group additivity calculation of the standard molal thermodynamic properties of ionized unfolded proteins, Biogeosciences, submitted.

the manner described above to calculate values of V° for the various hypothetical non-zwitterionic reference aqueous nucleotides represented by H_2NMP_i.

Let us now consider the zwitterionic aqueous nucleotides represented by $^+H_2NMP_i^-$ (Oscarson et al., 1995) in the context of the hypothetical reference model species, H_2NMP_i. The volume change associated with the simultaneous ionization of the phosphate group and protonation of a nitrogen atom in $H_2NMP_i^\circ$ in accord with

$$H_2NMP_i \rightleftharpoons {}^+H_2NMP^- \tag{114}$$

can be estimated in a first approximation from

$$\Delta V^\circ_r = V^\circ_{^+H_2NMP_i^-} - V^\circ_{H_2NMP_i} = \Delta V^\circ_{prot} + \Delta V^\circ_{ioniz}, \tag{115}$$

where ΔV°_{prot} stands for the volume change associated with protonation of the nitrogen atom and ΔV°_{ioniz} refers to the volume change accompanying ionization of the phosphate group. The volume change due to the protonation of the nitrogen atom in the nucleic-acid base (ΔV°_{prot}) in this equation can be estimated from the average volume change associated with protonation of the nitrogen atom in the positively charged amino acids, lysine ($\Delta V^\circ_{prot,Lys}$) and arginine ($\Delta V^\circ_{prot,Arg}$) using

$$\Delta V^\circ_{prot} = (\Delta V^\circ_{prot,Lys} + \Delta V^\circ_{prot,Arg})/2. \tag{116}$$

The volume change due to the ionization of the phosphate group (ΔV°_{ioniz}) in Eq. (115) can be estimated in a first approximation from that resulting from the ionization of phosphoric acid represented by

$$H_3PO_4 \rightleftharpoons H_2PO_4^- + H^+ \tag{117}$$

using

$$\Delta V^\circ_{ioniz} = V^\circ_{H_2PO_4^-} - V^\circ_{H_3PO_4}, \tag{118}$$

together with the standard molal volumes of the subscripted species taken from Table A.9 in Appendix A. After combining and rearranging the second identity in Eqs. (115) and (118) and (116), the standard molal volume of the ith zwitterionic nucleotide monophosphate ($V^\circ_{^+H_2NMP_i^-}$) can be expressed as

$$V^\circ_{^+H_2NMP_i^-} = V^\circ_{H_2NMP_i} + (\Delta V^\circ_{prot,Lys} + \Delta V^\circ_{prot,Arg})/2 + V^\circ_{H_2PO_4^-} - V^\circ_{H_3PO_4}, \tag{119}$$

which was used to calculate the value of V° for these species given in Table 12.

Values of V° for the other nucleotide mono-, di-, and triphosphate species considered in the present study were calculated using Eqs. (1)–(11), corresponding to the adjacent reactions, listed in Table 24. Provisional values of ΔV°_r required to evaluate these algorithms were estimated in a first approximation using reference model Reactions (A)–(F) in Table 24, which correspond to the adjacent reactions. The values of V° for the reactants and products depicted in the reference model reaction listed in Table 24 are taken from Table A.9 in Appendix A and the source cited in the preceding footnote.

The standard molal volumes of the deoxynucleotide analogs of the nucleotides shown in Tables 13, 15, and 17 were generated in the same manner as that described above for the nucleotides, except that the crystalline volumes and

volumes of solution of deoxyribose and the deoxynucleosides were used instead of the crystalline volumes and volumes of solution of ribose and the nucleosides. The standard molal volumes listed in Tables 12–17 for the nucleotides and deoxynucleotides were used in conjunction with the corresponding values of ω given in these tables to estimate the values of a_1, a_2, a_3, and a_4 shown in the tables for the nucleotides and deoxynucleotides using Eqs. (14), (20), (25), and (104), (105), (106).

6. Uncertainties

Because so few pertinent experimental data are available in the literature, it is difficult to assess the uncertainties associated with values of the standard molal thermodynamic properties and the revised HKF equations of state parameters adopted in the present study for aqueous nucleic-acid bases, nucleosides, and nucleotides. However, the uncertainties associated with $\Delta G^\circ_{f(aq)}$, $\Delta H^\circ_{f(aq)}$, $S^\circ_{(aq)}$, $C^\circ_{P(aq)}$ and $V^\circ_{(aq)}$ at 25 °C and 1 bar and the ω, a_1, a_2, a_3, a_4, c_1, and c_2 parameters of the species considered above can be estimated by propagating the uncertainties associated with the experimental data used to generate values for these properties and parameters.

6.1. Nucleic-acid bases and nucleosides

6.1.1. ΔG°_f, ΔH°_f, S°, C°_P and V° at 25 °C and 1 bar

The uncertainties associated with the values of $\Delta G^\circ_{f(aq)}$, $\Delta H^\circ_{f(aq)}$, and $S^\circ_{(aq)}$ adopted in the present study for aqueous adenine, guanine, and adenosine at 25 °C and 1 bar can be assessed by combining the uncertainties associated with the experimentally determined values of $\Delta G^\circ_{f(aq)}$, $\Delta H^\circ_{f(aq)}$, and $S^\circ_{(aq)}$ in the crystalline state with those associated with ΔG°_{sol}, ΔH°_{sol}, and ΔS°_{sol} for these compounds. Uncertainties characterized in this manner for $\Delta G^\circ_{f(aq)}$ and $\Delta H^\circ_{f(aq)}$ for adenine, guanine, and adenosine are approximately ± 500 cal mol^{-1}, and ± 3 cal mol^{-1} K^{-1} for $S^\circ_{(aq)}$. In the absence of similar experimentally determined calorimetric data for the other nucleic-acid bases and nucleosides, the uncertainties associated with the values of $\Delta G^\circ_{f(aq)}$, $\Delta H^\circ_{f(aq)}$, and $S^\circ_{(aq)}$ for adenine, guanine, and adenosine can be considered to represent minimum values of the uncertainties associated with the values of $\Delta G^\circ_{f(aq)}$, $\Delta H^\circ_{f(aq)}$, and $S^\circ_{(aq)}$ for the other nucleic-acid bases and nucleosides.

The uncertainties associated with the values of $C^\circ_{P(aq)}$ and $V^\circ_{(aq)}$ at 25 °C and 1 bar for most of the nucleic-acid bases and nucleosides can be assessed by comparing the values of these properties reported in the literature (see Appendix A Tables A.2 and A.4) . The resulting uncertainties associated with values of $C^\circ_{P(aq)}$ and $V^\circ_{(aq)}$ at 25 °C and 1 bar for nucleic-acid bases and nucleosides are $\leqslant \pm 3$ cal mol^{-1} K^{-1} and $\leqslant 1$ cm^3 mol^{-1}, respectively.

6.1.2. Revised HKF equations of state parameters

Maximum uncertainties associated with the revised HKF equations of state non-solvation parameters can be assessed by taking into account the scatter of the experimental data reported in the literature for values of $C^\circ_{P(aq)}$ and $V^\circ_{(aq)}$ and $\kappa^\circ_{(aq)}$ as a function of $(T - \Theta)^{-2}$ and $(T - \Theta)^{-1}$, respectively.

Because the values of c_1 and c_2 for cytosine, thymine, uracil, adenosine, cytidine, thymidine, uridine, and 2-deoxycytidine correspond to the intercepts and slopes, respectively, of the straight lines in Figs. 2 (nucleic-acid bases) and 10 (nucleosides), the uncertainties associated with these parameters can be assessed by fitting alternate lines to the values of $\Delta C^\circ_{P,n}$ in these figures, and determining the corresponding slopes and intercepts. The intercepts and slopes of other reasonable lines that could be fitted to the values of $\Delta C^\circ_{P,n}$ in Figs. 2 and 10 only differ from the ones adopted in the present study by $\leqslant 5\%$ and 10%, respectively. The uncertainties in values of c_1 and c_2 for adenine, guanine, guanosine, and the deoxynucleotides other than deoxycytidine are inherently larger than those for the nucleic-acid bases and nucleosides for which experimental values of $C^\circ_{P(aq)}$ as a function of temperature are available in the literature.

Analogous to c_1 and c_2, the relative uncertainties associated with the values of a_2 and a_4 for adenine, cytosine, thymine, uracil, adenosine, cytidine, guanosine, thymidine, uridine, deoxyadenosine, deoxycytidine, deoxyguanosine, and deoxyuridine correspond to the intercepts and slopes, respectively, of the straight lines fitted to values of $\Delta \kappa^\circ_{T,n}$ as shown in Figs. 6 (nucleic-acid bases) and 14 (nucleosides). The uncertainties for the values of these parameters can be assessed by determining the maximum and minimum slopes and intercepts of the lines reasonably fitted to values of $\Delta \kappa^\circ_{T,n}$ in these figures. The maximum and minimum intercepts and slopes of the lines that could be fitted to the values of $\Delta \kappa^\circ_{T,n}$ in Figs. 6 and 14 only differ from the ones adopted in the current study by $\leqslant 15\%$ and 30%, respectively. How this effects $\Delta G^\circ_{f(aq)}$ as a function of temperature and pressure is discussed below.

The uncertainties associated with values of a_1 and a_3 for adenine, cytosine, thymine, uracil, adenosine, cytidine, guanosine, thymidine, uridine, deoxyadenosine, deoxycytidine, deoxyguanosine, and deoxyuridine can be assessed by the possible variations in the intercepts and slopes, respectively, fitted to the straight lines in Figs. 5 (nucleic-acid bases) and 13 (nucleosides). The intercepts and slopes in these lines correspond to values of the σ and ξ parameters, respectively, which are in turn related to values of the a_1 and a_2 and a_3 and a_4, respectively, through Eqs. (20) and (21). The uncertainties associated with the σ and ξ parameters, and thus the a_1 and a_3 parameters, can be assessed by determining the maximum and minimum slopes and intercepts of reasonable lines fitted to values of ΔV°_n in these figures. The intercepts and slopes of these lines in Figs. 5 and 13 only differ from the ones adopted in the current study by $\leqslant 10\%$ and 15%, respectively.

Values of the uncertainties associated with values of a_1, a_2, a_3, and a_4 for guanine and deoxythymidine are inherently larger than those for the nucleic-acid bases and nucleosides for which experimental values of $\kappa^{\circ}_{T(aq)}$ (or those that can be calculated from experimentally available values of κ°_S) and $V^{\circ}_{(aq)}$ as a function of temperature are available in the literature. But because values of a_1, a_2, a_3, and a_4 for guanine and deoxythymidine were generated using correlations of these parameters for nucleic-acid bases and nucleosides for which experimental values of $\kappa^{\circ}_{T(aq)}$ and $V^{\circ}_{(aq)}$ as a function of temperature are available in the literature, the uncertainties for these species is not expected to significantly exceed those of the other nucleic-acid basis and nucleosides considered in the present study.

Uncertainties associated with the correlation algorithm from which values of the revised HKF non-solvation ω parameter for the nucleic-acid bases were calculated were not reported in the study from which they were taken (Plyasunov and Shock, 2001). Because the ω parameters for the nucleosides were estimated from an additivity algorithm using values of ω for the nucleic-acid bases, the uncertainties in the non-solvation ω parameters for the nucleosides are also difficult to assess.

The uncertainties associated with the values of $\Delta G^{\circ}_{f(aq)}$, $\Delta H^{\circ}_{f(aq)}$, $S^{\circ}_{(aq)}$, $C^{\circ}_{P(aq)}$, and $V^{\circ}_{(aq)}$ for nucleic-acid bases and nucleosides at elevated temperatures and pressures can be calculated by taking into account the maximum additive uncertainties of the equations of state parameters that have been assessed above. For example, using the maximum error in the equation of state parameters for cytosine as a function of temperature and as a function of temperature and pressure, the uncertainties associated with values of the Gibbs energy for this species under different conditions can be assessed. The maximum uncertainty in the HKF parameters for cytosine combine to yield an uncertainty of ± 50 cal mol^{-1} to the value of ΔG° for cytosine at 150 °C and 5 bar. At 150 °C and 800 bar, the uncertainties increases to nearly ± 400 cal mol^{-1}. Combining the uncertainty in $\Delta G^{\circ}_{f(aq)}$ for cytosine at 25 °C and 1 bar with these values results in a total maximum uncertainty on the order of ± 1 kcal mol^{-1} at elevated temperatures and pressures.

6.2. Nucleotides

Because so few experimental thermodynamic data are available in the literature for the nucleotides considered in the present study, the relative uncertainties associated with values of $\Delta G^{\circ}_{f(aq)}$, $\Delta H^{\circ}_{f(aq)}$, $S^{\circ}_{(aq)}$, $C^{\circ}_{P(aq)}$, and $V^{\circ}_{(aq)}$ and the revised HKF equations of state parameters adopted in the present study cannot be easily determined. Nonetheless, uncertainties associated with the corresponding thermodynamic properties and parameters of the constituent nucleosides that comprise the nucleotides can be used to estimate the relative uncertainties associated with

these nucleotides. For example, if the relative uncertainties associated with the standard molal thermodynamic properties at 25 °C and 1 bar and the HKF equations of state parameters for the nucleosides considered above can be taken to be of the same magnitude for those of the nucleotides, then the maximum uncertainty of ΔG° for HADP^{2-} at 150 °C and 5 bar is 1200 cal mol^{-1} and at 150 °C and 800 bar it is around 700 cal;mol^{-1}. See Shock and Helgeson (1988) and Shock et al. (1989) for a detailed discussion of how uncertainties in values of the revised HKF parameters are propagated as a function of temperature and pressure.

7. Concluding remarks

The equations of state parameters and standard molal thermodynamic properties of aqueous nucleic-acid bases, nucleosides, and nucleotides computed above make it possible to quantify the thermodynamic properties of a wide variety of reactions among these and other aqueous species at both ambient and elevated temperatures and pressures. Calculations of this kind can be used to guide experimental studies of the relative stabilities of aqueous biomolecules by identifying possible metastable equilibrium states and providing a basis for calculating the chemical affinities (A) of a wide variety of biogeochemical reactions. Values of A are calculated using (Kondepudi and Prigogine, 1998)

$$A = RT \ln \left(\frac{K}{Q} \right), \tag{120}$$

where R stands for the gas constant, T represents the absolute temperature in Kelvin, K refers the equilibrium constant, and Q denotes the reaction quotient given by
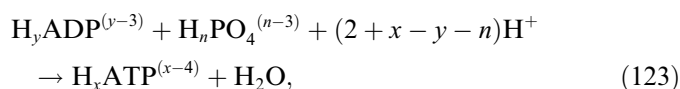
$$Q = \prod_i a_i^{v_i}. \tag{121}$$

Where a_i and v_i denote the activity and stoichiometric reaction coefficient, respectively, for the ith species in the reaction.

The thermodynamics of fundamental biochemical processes such as the energetics of the ATP-ADP cycle, the polymerization of nucleotides into nucleic acids (i.e., RNA and DNA), and the de novo synthesis of nucleotides can be generalized for extremophiles and mesophiles alike. For instance, the generic (unbalanced) reaction summarizing the synthesis of ATP from ADP and phosphate, P$_i$, which is usually represented in the biochemical literature by

$$ADP + P_i \rightarrow ATP, \tag{122}$$

can be rendered more explicit by writing

$$H_y ADP^{(y-3)} + H_n PO_4^{(n-3)} + (2 + x - y - n)H^+$$
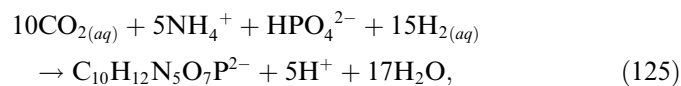$$\rightarrow H_x ATP^{(x-4)} + H_2O, \tag{123}$$

where the acronyms ATP, ADP, and P_i in Reaction (122) stand for the sum of the variously charged and complexed aqueous adenosine triphosphates, adenosine diphosphates, and monophosphate species, respectively, and y, n, and x in Reaction (123) refer to the number of moles of H bonded per mole of the respective reference species.[5] Speciation calculations can now be carried out to determine which ADP and ATP species predominate at a given pH, temperature, and pressure so that the energetics of Reaction (123) can be calculated for a range of different environments. Similarly, the thermodynamic properties and parameters reported in the present communication contribute to quantifying the energetics of the polymerization of nucleotides into nucleic acids at high and low temperatures and pressures. This can be done by first writing a polymerization reaction such as

$$\sum_i n\text{NMP}_i \rightarrow \text{RNA} + (n-1)\text{H}_2\text{O}, \qquad (124)$$
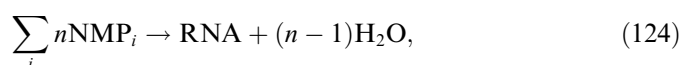
which represents the sequence of dehydration reactions that characterizes the synthesis of RNA from nucleotide monophosphates. Although the thermodynamic properties of strands of RNA have not been reported in the literature, an additivity algorithm using the reaction properties reported above could be used in a first approximation to calculate those of short strands of RNA. Similarly, the deoxy-equivalent of RNA could be taken into account as well by replacing NMP_i with dNMP_i and RNA with DNA.

The thermodynamic properties generated in the present study can also be used to characterize quantitatively part of the energetic cost of living in a hydrothermal environment by examining the thermodynamic potential of synthesizing nucleotides de novo (see Amend and Shock, 1998). For example, the chemical affinity of the synthesis reaction for AMP^{2-} ($\text{C}_{10}\text{H}_{12}\text{N}_5\text{O}_7\text{P}^{2-}$) at a given pressure and temperature can be quantified by calculating $\ln K$ for

$$10\text{CO}_{2(aq)} + 5\text{NH}_4^+ + \text{HPO}_4^{2-} + 15\text{H}_{2(aq)}$$
$$\rightarrow \text{C}_{10}\text{H}_{12}\text{N}_5\text{O}_7\text{P}^{2-} + 5\text{H}^+ + 17\text{H}_2\text{O}, \qquad (125)$$

and combining it in Eq. (120) with values of Q computed from the activities of $\text{CO}_{2(aq)}$, NH_4^+, HPO_4^{2-}, $\text{H}_{2(aq)}$, $\text{C}_{10}\text{H}_{12}\text{N}_5\text{O}_7\text{P}^{2-}$, and H^+ in the hydrothermal fluid. Furthermore, quantifying reactions like Reaction 125 can help to constrain under what conditions the nucleic-acid bases, nucleosides, and nucleotides could form abiotically.

Assessing the accuracy of the estimation strategies employed to compute the standard molal thermodynamic properties and revised HKF equations of state parameters for the species considered in the present study requires more calorimetric, densimetric, and sound

velocity data. Of particular interest in this regard is the experimental determination of the standard molal heat capacities and volumes of nucleotides at temperatures in excess of 25 °C and preferably beyond 100 °C. In the interim, the standard molal thermodynamic properties and revised HKF equations of state parameters generated in the present study from the group additivty algorithms and reference model compounds summarized above provide a provisional comprehensive and internally consistent frame of reference for thermodynamic investigation of biogeochemical systems at elevated temperatures and pressures. The equations of state parameters and standard molal thermodynamic properties at 25 °C and 1 bar generated in the present study are being incorporated into a biogeochemical analog of the SUPCRT92 software package called OBIGT (OrganoBioGeoTherm). This software package will be available at no cost from affinity.berkeley.edu at the Laboratory of Theoretical Geochemistry and Biogeochemistry (otherwise known as Prediction Central) at the University of California, Berkeley.

Associate editor: Jan P. Amend

Appendix A. Standard molal thermodynamic data retrieved from the literature

See Tables A.1–A.10, and A.11.

---

[5] The reference basis species for ADP and ATP adopted here are ADP^{3-} and ATP^{4-}, which correspond to $\text{C}_{10}\text{H}_{12}\text{N}_5\text{O}_{10}\text{P}_2^{3-}$ and $\text{C}_{10}\text{H}_{12}\text{N}_5\text{O}_{13}\text{P}_3^{4-}$, respectively.

Table A.1
Summary of standard molal thermodynamic properties at 25 °C and 1 bar of gaseous compounds adopted in the present study

Compound	Formula	ΔG_f° [a]	ΔH_f° [a]	S° [b]
Purines				
Adenine	$C_5H_5N_5$	86,274[c]	55,140[d]	95.01[e]
Guanine	$C_5H_5N_5O$	41,650[c]	547[d]	86.06[e]
Pyrimidines				
Cytosine	$C_4H_5N_3O$	32,326[c]	−14,197[f]	
		92.60[e]		
Thymine	$C_5H_6N_2O_2$	−46,012[c]	−78,561[g]	
		86.26[e]		
Uracil	$C_4H_4N_2O_2$	−42,973[c]	−72,433[g]	66.10[e]
Monosaccharides				
Ribose	$C_5H_{10}O_5$	−160,496[c]	−212,534[d]	111.1[e]
Deoxyribose	$C_5H_{10}O_4$	−124,989[c]	−170,010[d]	110.1[e]

[a] cal mol^{-1}.
[b] cal K^{-1} mol^{-1}.
[c] Calculated from $\Delta G_{fg}^{\circ} = \Delta G_{fcr}^{\circ} + \Delta G_{sub}$. The values of ΔG_{fcr}° and ΔG_{sub} are taken from Tables 3 and 11.
[d] Calculated from $\Delta H_{fg}^{\circ} = \Delta H_{fcr}^{\circ} + \Delta H_{sub}$. The values of ΔH_{fcr}° and ΔH_{sub} are taken from Tables 3 and 11.
[e] Calculated using Eq. (42).
[f] Sabbah (1980).
[g] Nabavian et al. (1977).

Table A.2
Values of standard molal heat capacities (C_P°) [a] for aqueous nucleic-acid bases, nucleosides, and sugars reported in the literature for temperatures at and above 25 °C at 1 bar

Compound	Temperature (K)					
	298.15	308	318	328	333	363
Adenine	54.64[b], 57.8[c]					
Cytosine	42.1[d], 41.1[d],	47.3[d]	51.9[d]	55.9[d]		
	42.1[d], 49.71[d]					
Thymine	52.6[e], 57.4[d],	61.7[d]	66.2[d],	70.3[d]	69.3[e]	82.0[e]
	57.6[d], 57.1[d],		59.8[e]			
	61.2[d]					
Uracil	36.6[d], 32.7[e]	39.7[d]	43.0[d],	46.4[d]	49.2[e]	63.1[e]
			39.9[e]			
Adenosine	121[d]	128[d]	135[d]	142[d]		
Cytidine	96.6[d], 93[d], 95.4[d]	103[d]	109[d]	113[d]		
Thymidine	111[d], 112[d]	116[d]	122[d]	126[d]		
Uridine	95.4[d], 96.1[d], 95.1[d]	102[d]	10[d]	113[d]		
2′-Deoxycytidine	87.2[d]	93.2[d]	99.4[d]	104[d]		
Ribose	65.97[f], 70.3[g,h],	81.3[k]	93.0[k]			
	68.1[i], 65.0[j],					
	67.7[k]					
2′-Deoxyribose	75.6[g,h]					

[a] cal K^{-1} mol^{-1}.
[b] Zielenkiewicz et al. (1994b).
[c] Kishore and Ahluwalia (1990a).
[d] Patel and Kishore (1995).
[e] Szeminska et al. (1979).
[f] Goldberg and Tewari (1989).
[g] 303 K.
[h] Jasra and Ahluwalia (1982).
[i] Morel et al. (1986).
[j] Galema et al. (1993).
[k] Banipal et al. (1997).

Table A.3
Values of standard molal expansibilities (E°) [a] for aqueous nucleic-acid bases, nucleosides, and sugars reported in the literature for a range of temperatures (K) at 1 bar

Compound	Temperature (K)			
	291	298.15	313	328
Adenine	0.27[b]	0.23[b]	0.13[b]	0.06[b]
Cytosine	0.11[b]	0.10[b]	0.08[b]	0.06[b]
Thymine	0.24[b]	0.20[b]	0.11[b]	0.03[b]
Uracil	0.21[b]	0.18[b]	0.1[b]	0.02[b]
Adenosine	0.19[b]	0.26[c], 0.18[b]	0.16[b]	0.13[b]
Guanosine	0.36[b]	0.28[b]	0.1[b]	−0.08[b]
Cytidine	0.15[b]	0.14[b]	0.1[b]	0.07[b]
Thymidine	0.14[b]	0.13[b]	0.01[b]	0.07[b]
Uridine	0.15[b]	0.13[b]	0.01[b]	0.06[b]
2′-Deoxyadenosine	0.11[b]	0.25[c], 0.13[b]	0.18[b]	0.22[b]
2′-Deoxyguanosine	0.11[b]	0.13[b]	0.17[b]	0.21[b]
2′-Deoxycytidine	0.15[b]	0.14[b]	0.1[b]	0.07[b]
2′-Deoxyuridine	0.2[b]	0.17[b]	0.11[b]	0.06[b]
Ribose		0.12[c]		
2′-Deoxyribose		0.09[c]		

[a] cm^3 mol^{-1} K^{-1}.
[b] Lee and Chalikian (2001).
[c] Buckin et al. (1989).

Table A.4
Values of standard molal volumes (V°) [a] for aqueous nucleic-acid bases, nucleosides, and sugars reported in the literature for a range of temperatures (K) at 1 bar

Compound	Temperature (K)				
	291	298.15	308	313	328
Adenine	88.0[b]	89.3[c], 90.4[d], 89.6[b]		92.4[b]	93.5[b]
Cytosine	72.5[b]	73.3[c], 73.6[d], 73.15[e] 73.5[b]		74.6[b]	75.8[b]
Thymine	86.3[b]	88.2[e], 88.8[d], 88.49[e], 88.7[b]		90.1[b]	91.6[b]
Uracil	70.2[b]	71.7[c], 72.3[d], 71.94[e], 71.8[b]		73.6[b]	74.6[b]
Adenosine	169.2[b]	171.4[d], 171.38[e], 170.8[f], 170.8[b]		173[b]	175.3[b]
Guanosine	172.0[b]	178.2[f], 175.4[b]		177[b]	177.8[b]
Cytidine	152.2[b]	154.2[d], 153.59[e], 153.5[g], 153.4[b], 153.7[f]		155[b]	156.7[b]
Thymidine	166.4[b]	168.0[f], 167.9[e], 167.55[g], 167.6[h]		169[b]	170[b]
Uridine	150.7[b]	152.3[d], 152.1[e], 151.45[g], 152.2[b], 151.7[f]		153.4[b]	154.8[b]
2′-Deoxyadenosine	168.9[b]	169.8[f], 170.3[b]		172[b]	175.3[b]
2′-Deoxyguanosine	172.0[b]	173.7[f], 173.4[b]		175.1[b]	178.3[b]
2′-Deoxycytidine	153.0[b]	153.4[f], 154.0[b]		155.8[b]	157.1[b]
2′-Deoxyuridine	149.4[b]	152.2[f], 151.9[b]		152.7[b]	154.6[b]
2′-Deoxythymidine		167.6[f]			
Ribose		95.1[f], 95.3[h], 95.2[i,j], 95.56[k], 95.26[l]		96.11[l], 96.5[j] 97.4[j]	97.08[l],
2′-Deoxyribose		94.7[f], 93.5[k]			

[a] cm^3 mol^{-1}.
[b] Lee and Chalikian (2001).
[c] Buckin (1988).
[d] Kishore et al. (1989).
[e] Patel and Kishore (1995).
[f] Buckin et al. (1989).
[g] Høiland et al. (1984).
[h] Franks et al. (1972).
[i] Høiland and Holvik (1978).
[j] Paljk et al. (1990).
[k] Jasra and Ahluwalia (1982).
[l] Banipal et al. (1997).

Table A.5
Values of standard molal compressibilities $(\kappa^\circ)^a \times 10^4$ for aqueous nucleic-acid bases, nucleosides, and sugars reported in the literature for a range of temperatures (K) at 1 bar

Compound	Temperature (K)			
	291	298.15	313	328
Adenine	−1.8[b]	−4.6[c], 6.2[b]	14.7[b]	15.4[b]
Cytosine	−16.8[b]	−11.8[c], −10.9[b]	−3.0[b]	1.5[b]
Thymine	−7.53[b]	−1.4[c],0.34[b]	8.4[b]	10[b]
Uracil	−8.24[b]	−3.1[c],−1.0[b]	4.9[b]	7.3[b]
Adenosine	−9.31[b]	3.1[d],0.41[b]	14[b]	21.7[b]
Guanosine	−11[b]	−1.26[d], −1.76[b]	3.2[b]	−4.4[b]
Cytidine	−19[b]	−13.5[c], −12.3[d], −10.3[b]	−1.4[b]	3.8[b]
Thymidine	−5.5[b]	0.2[e], 0.353[b]	9.2[b]	22[b]
Uridine	−2[b]	−12.7[e], −9.5[d], −7.10[b]	−2.7[b]	5.9[b]
2′-Deoxyadenosine	−10.4[b]	9.9[d], 6.32[b]	21.6[b]	36.9[b]
2′-Deoxyguanosine	−7.4[b]	−1.6[d], −0.794[b]	12[b]	28[b]
2′-Deoxycytidine	−6.2[b]	−1.5[d], −0.097[b]	9.4[b]	15.3[b]
2′-Deoxyuridine		3.26[d], 3.10[b]	11[b]	16.4[b]
2′-Deoxythymidine		2.4[d]		
Ribose		−8.03[d], −8.93[f]		
2′-Deoxyribose		−1.8[d]		

[a] cm^3 mol^{-1} bar^{-1}.
[b] Lee and Chalikian (2001).
[c] Buckin (1988).
[d] Buckin et al. (1989).
[e] Høiland et al. (1984).
[f] Franks et al. (1972).

Table A.6
Summary of standard molal thermodynamic properties of sublimation at 25 °C and 1 bar reported in the literature for gaseous nucleic-acid bases

Compound	Formula	ΔG°_{sub} [a]	ΔH°_{sub} [a]
Purines			
Adenine	$C_5H_5N_5$	14,414[b,c]	30,400[d], 33,560[c]
Guanine	$C_5H_5N_5O$	30,248[b,e]	44,500[e]
Pyrimidines			
Cytosine	$C_4H_5N_3O$	20,924[b,f]	36,260[g], 42,065[h], 39,914[f], 37,046[i]
Thymine	$C_5H_6N_2O_2$	17,280[b,f]	29,730[j], 32,050[k], 32,983[f], 31,381[i]
Uracil	$C_4H_4N_2O_2$	18,761[b,m]	28,800[j], 30,234[k], 31,310[m]

[a] cal mol^{-1}.
[b] Calculated from vapor pressure data.
[c] Zielenkiewicz (2000).
[d] Zielenkiewicz et al. (1984).
[e] Yanson et al. (1974).
[f] Ferro et al. (1980).
[g] Zielenkiewicz et al. (1998).
[h] Sabbah (1980).
[i] Burkinshaw and Mortimer (1984).
[j] Zielenkiewicz (1995).
[k] Nabavian et al. (1977).
[l] Teplitsky et al. (1980).
[m] Bardi et al. (1980).

Table A.7
Summary of values of ΔG°_f, ΔH°_f, S°, C°_P, and V° at 25 °C and 1 bar reported in the literature for selected crystalline nucleic-acid bases, sugars, and nucleosides

Compound	Formula	ΔG°_f [a]	ΔH°_f [a]	S° [b]	C°_P [b]	V° [c]
Purines						
Adenine	$C_5H_5N_5$	71860[d]	23160[e]	36.09[f]	35.21[f], 34.21[f]	91.1[e]
Guanine	$C_5H_5N_5O$	11402[d]	−43953[g]	38.29[f]	37.51[f], 38.41[h]	
Pyrimidines						
Cytosine	$C_4H_5N_3O$		−52890[i]		31.69[f]	
Thymine	$C_5H_6N_2O_2$		−110612[j]		35.90[f]	86.68[k]
Uracil	$C_4H_4N_2O_2$		−101400[i] −102667[j]		28.9[l]	70.5[k]
Monosaccharides						
Ribose	$C_5H_{10}O_5$	−177660[d]	−250294[m]	41.99[n]	44.70[n]	94.42[o]
Deoxyribose	$C_5H_{10}O_4$		−207770[m]			84.36[o]
Nucleoside						
Adenosine	$C_{10}H_{13}N_5O_4$	−48850[p]	−156200[p]	71.36[p]	69.36[p]	173.53[p]

[a] cal mol^{-1}.
[b] cal K^{-1} mol^{-1}.
[c] cm^3 mol^{-1}.
[d] Calculated from ΔH°_f and S° using values of S° of the elements taken from Wagman et al. (1982).
[e] Kirklin and Domalski (1983).
[f] Domalski and Hearing (1996).
[g] Kilday (1981).
[h] Cox and Pilcher (1970).
[i] Wilson et al. (1979).
[j] Nabavian et al. (1977).
[k] Calculated from density from Nabavian et al. (1977) and molecular weight.
[l] Kilday (1978d).
[m] Colbert et al. (1987).
[n] Personal communication from J. Boerio-Goates.
[o] Calculated from density data in Boyer et al. (2003) and molecular weight.
[p] Boerio-Goates et al. (2001).

Table A.8
Summary of values of ΔG°_{sol} and ΔH°_{sol} at 25 °C (unless otherwise noted) and 1 bar reported in the literature for selected crystalline compounds

Compound	Formula	ΔG°_{sol} [a]	ΔH°_{sol} [a]
Purines			
Adenine	$C_5H_5N_5$	3000[b], 1300[b,c], 5170[d,e] 2810[g], 2920[h], 2900[i]	8000[d], 7070[f,e], 8150[g]
Guanine	$C_5H_5N_5O$	4600[d], 6000[g]	6500[j], 11,800[g]
Pyrimidines			
Cytosine	$C_4H_5N_3O$	1610[k], 1600[b], 3750[f,e], 1620[i]	5450[l], 7676[f,e], 6500[k]
Thymine	$C_5H_6N_2O_2$	2120[m], 2000[b], 2110[i]	5520[n], 5810[n], 5430[n], 5813[m]
Uracil	$C_4H_4N_2O_2$	4430[f,e], 2000[b]	6390[o], 7000[n], 7050[p], 6700[f,e]
Nucleosides			
Guanosine	$C_{10}H_{13}N_5O_5$	3740[h], 3000[b,q], 1700[b,c]	
Adenosine	$C_{10}H_{13}N_5O_4$	2340[h], 2350[i] 2364[r]	7710[s]
Deoxyadenosine	$C_{10}H_{13}N_5O_3$	2140[h], 2160[i]	
Monosaccharides			
Ribose	$C_5H_{10}O_5$	−2079[t]	3184[u], 3117[v]
Deoxyribose	$C_5H_{10}O_4$		2900[u], 2565[v],2961[v,w]

Table A.8 (*continued*)

Compound	Formula	ΔG_{sol}° [a]	ΔH_{sol}° [a]
Other			
Citric acid	$C_6H_8O_7$		4353[x], 4592[y]

[a] cal mol^{-1}.
[b] Dawson et al. (1986).
[c] At 100 °C.
[d] Kilday (1978a).
[e] At 37 °C.
[f] Scruggs et al. (1972).
[g] DeVoe and Wasik (1984).
[h] Herskovits and Bowen (1974).
[i] Robinson and Grant (1966).
[j] Kilday (1981).
[k] Kilday (1978c).
[l] Zielenkiewicz et al. (1998).
[m] Kilday (1978b).
[n] Ahmed et al. (1981).
[o] Zolkiewski and Zielenkiewicz (1991).
[p] Kilday (1978d).
[q] At 18 °C.
[r] Boerio-Goates et al. (2001).
[s] Stern and Oliver (1980).
[t] Goldberg and Tewari (1991).
[u] Stern and Hubler (1984).
[v] Jasra and Ahluwalia (1982).
[w] At 35 °C.
[x] Apelblat (1986).
[y] Bald and Barczynska (1993).

Table A.11

Standard molal thermodynamic properties of reaction at 25 °C and 1 bar reported in the literature for selected nucleotide protonation reactions

Reaction	ΔG_r° [a]	ΔH_r° [a]	ΔS_r° [b]
$AMP^{2-} + H^+ \leftrightarrow HAMP^-$	−9100[c],	850[c],	33.4[c],
	−9180[d],	1290[f],	35.1[f],
	−8700[e]	840[g]	32[g]
$GMP^{2-} + H^+ \leftrightarrow HGMP^-$	−9100[c]	1450[c]	35.3[c]
$CMP^{2-} + H^+ \leftrightarrow HCMP^-$	−9040[c]	1350[c]	34.8[c]
$UMP^{2-} + H^+ \leftrightarrow HUMP^-$	−9050[c]	1120[c]	34[c]
$dAMP^{2-} + H^+ \leftrightarrow dHAMP^-$	−9090[c]	1040[c]	33.8[c]
$HAMP^- + H^+ \leftrightarrow {}^+H_2AMP^-$	−5450[d],	−4300[f],	3.8[f],
	−5200[e]	−4300[g]	3.1[g]
$ADP^{3-} + H^+ \leftrightarrow HADP^{2-}$	−9800[c],	1370[c],	37.4[c],
	−9790[d],	1300[f],	37.5[f],
	9900[e]	840[g]	35.7[g]
$GDP^{3-} + H^+ \leftrightarrow HGDP^{2-}$	−9800[c]	1480[c]	37.7[c]
$CDP^{3-} + H^+ \leftrightarrow HCDP^{2-}$	−9790[c]	1340[c]	37.4[c]
$UDP^{3-} + H^+ \leftrightarrow HUDP^{2-}$	−9780[c]	1080[c]	36.4[c]
$HADP^{2-} + H^+ \leftrightarrow {}^+H_2ADP^{2-}$	−5950[d],	−4210[f],	6.0[f],
	−5700[e]	−4400[g]	4.4[g]
${}^+H_2ADP^{2-} + H^+ \leftrightarrow {}^+H_3ADP^-$	−2500[e]	2560[g]	17[g]
$ATP^{4-} + H^+ \leftrightarrow HATP^{3-}$	−10480[c],	1680[c],	40.7[c],
	−10370[d],	1500[f],	39.9[f],
	−10500[e]	1400[g]	40[g]

Table A.9

Summary of the standard molal thermodynamic properties at 25 °C and 1 bar and equations of state parameters for aqueous mono- and diphosphates

Species	ΔG_f° [a]	ΔH_f° [a]	S° [b]	C_p° [b]	V° [c]	$a_1^{d} \times 10$	$a_2^{a} \times 10^{-2}$	a_3^{e}	$a_4^{f} \times_{10-4}$	c_1^{b}	$c_2^{e} \times 10^{-4}$	$\omega^{a} \times 10^{-5}$
$H_3PO_4^{\circ}$	−273,100	−307,920	38	23.58	48.17	8.2727	12.4182	0.8691	−3.2924	17.9708	1.7727	−0.22
$H_2PO_4^-$	−270,140	−309,820	21.6	−6.87	30.9	6.4875	8.0594	2.5823	−3.1122	14.0435	−4.4605	1.3003
HPO_4^{2-}	−260,310	−308,815	−8	−57.96	4.38	3.6315	1.0857	5.3233	−2.8239	2.7357	−14.9103	3.3363
PO_4^{3-}	−243,500	−305,300	−53	−114.32	−32.32	−0.5258	−9.0576	9.2927	−2.4045	−15.1599	−28.4155	5.6114
$H_4P_2O_7^{\circ}$	−485,700	−542,200	64.1	58.8	56.6	9.2975	14.9199	−0.113	−3.3957	34.8301	8.943	−0.6292
$H_3P_2O_7^-$	−483,600	−544,100	51	37.4	51.7	9.1292	14.5122	0.0398	−3.3788	35.9785	4.5838	0.8568
$H_2P_2O_7^{2-}$	−480,400	−544,600	39	17.6	47.1	9.0963	14.4299	0.076	−3.3754	40.6359	0.5505	2.6218
$HP_2O_7^{3-}$	−471,400	−543,700	11	−28.7	36.5	8.3302	12.5558	0.8208	−3.298	32.1587	−8.8807	4.647
$P_2O_7^{4-}$	−458,700	−542,800	−28	−139.1	21.7	7.0687	9.4773	2.0273	−3.1707	−11.7223	−31.3692	6.9069

The monophosphate properties and parameters are those given in SUPCRT92 (Johnson et al., 1992). All diphosphate properties and parameters were taken from Shock et al. (1997).

[a] cal mol^{-1}.
[b] cal K^{-1} mol^{-1}.
[c] cm^3 mol^{-1}.
[d] cal mol^{-1} bar^{-1}.
[e] cal K mol^{-1} bar^{-1}.

Table A.10

Standard molal thermodynamic properties of reaction at 25 °C and 1 bar reported in the literature for selected phosphorylation reactions

Reaction	ΔG_r° [a]	ΔH_r° [a]	ΔS_r° [b]
Ribose-5-phosphate^{2-} + H_2O ↔ HPO_4^{2-} + ribose		−1202[c]	
AMP^{2-} + H_2O ↔ adenosine + HPO_4^{2-}	−2300[d], −3107[e]	100[d], 215[e]	
ADP^{3-} + H_2O ↔ AMP^{2-} + HPO_4^{2-} + H^+	1610[d]	−5810[c], −5260[d]	
$2ADP^{3-}$ ↔ ATP^{4-} + AMP^{2-}		−360[f]	
ATP^{4-} + H_2O ↔ ADP^{3-} + HPO_4^{2-} + H^+	810[g], 724[d]	−4900[f,d], −5310,[c] −5810[d]	−4.1[f]
GMP^{2-} + H_2O ↔ guanosine + HPO_4^{2-}		650[c]	
GDP^{3-} + $2H_2O$ ↔ guanosine + $2HPO_4^{2-}$ + H^+		−5140[c]	
GTP^{4-} + H_2O ↔ GDP^{3-} + HPO_4^{2-} + H^+		−5330[c]	
GTP^{4-} + $3H_2O$ ↔ guanosine + $3HPO_4^{2-}$ + $2H^+$		−11,000[c]	

[a] cal mol^{-1}.
[b] cal K^{-1} mol^{-1}.
[c] Tewari et al. (1988).
[d] Goldberg and Tewari (1994).
[e] Alberty and Goldberg (1992).
[f] Goldberg and Tewari (1991).

Table A.11 (*continued*)

Reaction	$\Delta G_r^{\circ a}$	$\Delta H_r^{\circ a}$	$\Delta S_r^{\circ b}$
$GTP^{4-} + H^+ \leftrightarrow HGTP^{3-}$	-10430^c	1750^c	40.8^c
$CTP^{4-} + H^+ \leftrightarrow +HCTP^{3-}$	-10430^c	1750^c	40.8^c
$UTP^{4-} + H^+ \leftrightarrow +HUTP^{3-}$	-10350^c	2020^c	41.4^c
$HATP^{3-} + H^+ \leftrightarrow {}^+H_2ATP^{3-}$	-6380^d,	-3560^f,	9.6^f,
	-6200^e	-3900^g	7.6^g
${}^+H_2ATP^{3-} + H^+ \leftrightarrow {}^+H_3ATP^{2-}$	-2700^e	1500^g	14^g

[a] cal mol^{-1}.
[b] cal K^{-1} mol^{-1}.
[c] Phillips et al. (1965).
[d] Calculated from ΔH_r° and ΔS_r° reported in Oscarson et al. (1995).
[e] Calculated from ΔH_r° and ΔS_r° reported in Goldberg and Tewari (1991).
[f] Goldberg and Tewari (1991).
[g] Oscarson et al. (1995).

Appendix B. Calculation of the revised HKF equations of state parameters and standard molal thermodynamic properties of miscellaneous species

B.1. Ribose-5-phosphate^{2-}

Values of c_1 and c_2 for $R5P^{2-}$ were generated in the present study from experimentally derived values of C_P° for this species as a function of temperature using Eqs. (13) and (24), together with a value of ω estimated from (Shock and Helgeson, 1988)

$$\omega = 3.2134 - 0.015161(S^\circ).\qquad(B.1)$$

As in the case of other aqueous species considered above in Section 3.2.2 and elsewhere, the values of c_1 and c_2 for

$R5P^{2-}$ correspond to the intercept and slope of the straight line depicted in Fig 18b. The symbols shown in this figure represent values of $\Delta C_{P,n}^\circ$ for $R5P^{2-}$ calculated from values of C_P° using Eq. (24). Due to the dearth of experimental heat capacity measurements for $R5P^{2-}$, the values of C_P° required to evaluate Eq. (24) were calculated as finite difference derivatives of experimental values of ΔH° for $R5P^{2-}$ at different temperatures at 1 bar using Eq. (99). The values of ΔH° for $R5P^{2-}$ at the different temperatures were computed using corresponding values of ΔH° for HPO_4^{2-}, *Ribose*, and H_2O to evaluate

$$\Delta H_{R5P^{2-}}^\circ = \Delta H_{HPO_4^{2-}}^\circ + \Delta H_{ribose}^\circ - \Delta H_{H_2O}^\circ + \Delta H_r^\circ.\qquad(B.2)$$
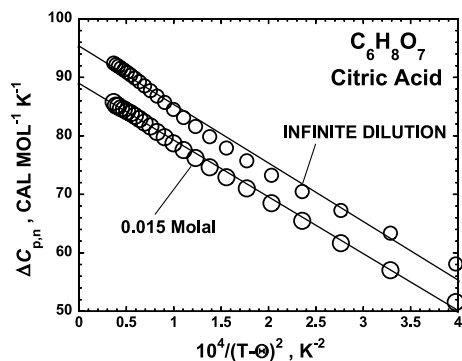

Fig. B.2. $\Delta C_{P,n}$ for citric acid$_{(aq)}$ as a function of $10^4/(T-\Theta)^2$ at 1 bar calculated in the manner described in the figure caption for Fig. B.1 using values of C_P reported by Patterson and Woolley (2001) at 0.015 molal and infinite dilution, respectively (see text). The symbols denote the calculated values of $\Delta C_{P,n}$ and the straight lines represent fits of Eq. (17) to the data.
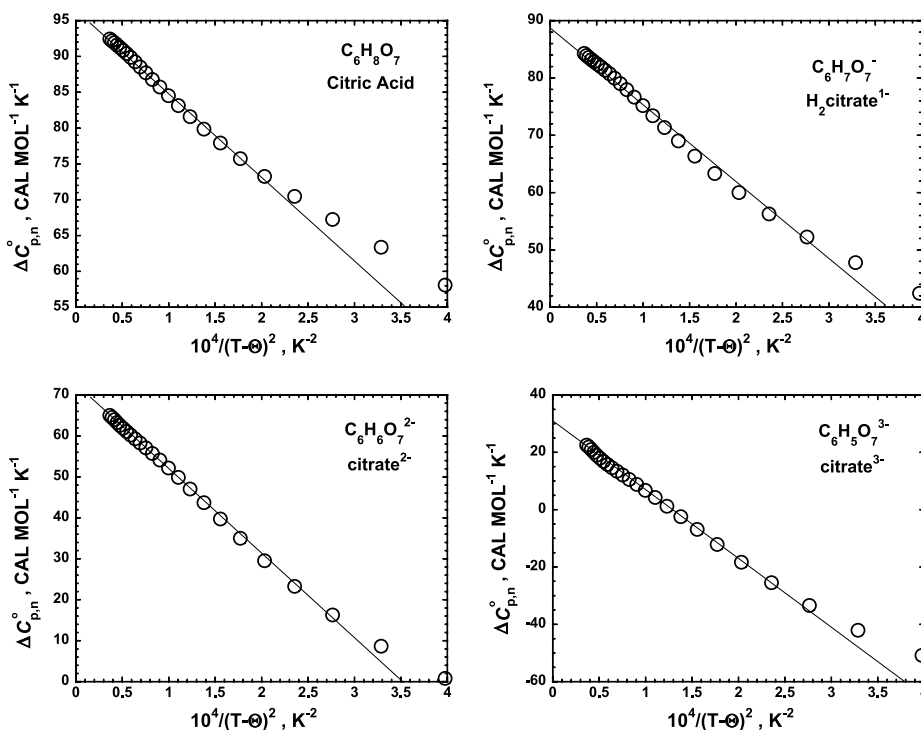

Fig. B.1. $\Delta C_{P,n}^\circ$ for citric acid$_{(aq)}$, H$_2$citrate$^-$, Hcitrate^{2-}, and citrate^{3-} as a function of $10^4/(T-\Theta)^2$ at 1 bar. The symbols denote values of $\Delta C_{P,n}^\circ$ computed from Eqs. (17) and (24) using values of ω and C_P° taken from Table B.1 and Patterson and Woolley (2001), respectively. The regression lines represent fits of Eq. (17) to the data.

Table B.1

Summary of the standard molal thermodynamic properties at 25 °C and 1 bar and equations of state parameters for aqueous citric acid and deprotonated citrate species

Compound	Formula	$\Delta G_f^{\circ\,a}$	$\Delta H_f^{\circ\,a}$	$S^{\circ\,b}$	$C_P^{\circ\,b}$	$V^{\circ c,d}$	$c_1^{\,b}$	$c_2^{\,e} \times\,^{10-4}$	$\omega^a \times 10^{-5}$
Citric acid$_{(q)}$	$C_6H_8O_7$	-297180^f	-364527^g	78.89^h	112.98	73.47	96.43	-11.57	-0.06
Citrate^{1-}	$C_6H_7O_7^-$	-292912^i	-363530^i	67.92^i	102.48	47.04	89.40	-14.12	1.50
Citrate^{2-}	$C_6H_6O_7^{2-}$	-286417^i	-362947^i	48.09^i	91.08	7.71	73.14	-21.06	2.48
Citrate^{3-}	$C_6H_5O_7^{3-}$	$-277690^{f,i}$	-363750^i	16.13^i	74.08	-43.16	31.50	-24.41	2.75

[a] cal mol^{-1}.
[b] cal K^{-1} mol^{-1}.
[c] cm^3 mol^{-1}.
[d] Patterson and Woolley (2001).
[e] cal K^{-2} mol^{-1}.
[f] Evans et al. (1962).
[g] Calculated from ΔH_{fcr}° and ΔH_{sol}° taken from Table 3 and an average of values from Apelblat (1986) and Bald and Barczynska (1993).
[h] Calculated from S_{cr}° taken from Table 3 and ΔS_{sol}° which was calculated using ΔG_{sol}° and ΔH_{sol}°.
[i] Calculated using $\Delta \Xi_{citricacidaq}^{\circ}$ and values of $\Delta \Xi_r^{\circ}$ for the ionization of each species taken from Goldberg and Tewari (2002).

The values of ΔH_r° in Eq. (B.2) were taken from Table 21, but those for the other species shown in this equation were calculated for the different temperatures with the aid of the SUPCRT 92 software package and, in the case of *ribose*, the equations of state parameters listed in Table 2. The calculated values of c_1, c_2, and ω of $R5P^{2-}$ are listed in Table 2.

B.2. Citric acid and citrates

Values of the c_1, c_2, and ω parameters for *citric acid* and the first three ionized citrate species, $H_2citrate^-$, $Hcitrate^{2-}$, and $citrate^{3-}$, were calculated by regressing experimental high-temperature values of C_P° for these species with the revised HKF equations of state. Following the procedure discussed in Section 3.2.2, values of $\Delta C_{P,n}^{\circ}$ for citric acid, $H_2citrate^-$, $Hcitrate^{2-}$, and $citrate^{3-}$ were calculated using values of C_P° taken from Patterson and Woolley (2001), together with Eqs. 13, 17, and 24. These values are represented by the symbols shown in the graphs in Fig. B.1. Eq. (24) is consistent with the straight lines depicted in the graphs shown in Fig. B.1. It follows that the intercepts and slopes of the straight lines in these figures correspond, respectively, to values of c_1 and c_2 for citric acid, $H_2citrate^-$, $Hcitrate^{2-}$, and $citrate^{3-}$. It can be seen in Figs. B.1a–d that the straight lines representing the revised-HKF equations of state are closely consistent with the experimentally derived values of $\Delta C_{P,n}^{\circ}$ as a function of $1/(T - \Theta)^2$. The values of ω required to evaluate Eqs. 13, 17, and 24 were assessed by using successive trial values of ω in Eqs. (13) and (24) until the values of $\Delta C_{P,n}^{\circ}$ for temperatures $\geqslant 25$ °C in Figs. B.1a–d plotted on straight lines as a function of of $10^4/(T - \Theta)^2$ at 1 bar, which is consistent with the revised HKF equations of state and corresponding plots for many other aqueous species (e.g., see Shock (1993, 1995);Schulte and Rogers (2004)).

The higher temperature values of $\Delta C_{P,n}^{\circ}$ in Fig. B.1 were weighted more heavily than the lower temperature values in the calculations required to generate the regression lines in these plots. This was done because the extrapolation pro-

cedure that Patterson and Woolley (2001) used to calculate values of C_P° at infinite dilution from calorimetric data obtained at higher concentrations disproportionately affects lower temperature values of C_P° more than those at higher temperatures. For example, it can be seen in Fig. B.2 that the values of $\Delta C_{P,n}^{\circ}$ computed from the C_P° data measured for 0.015 molal solutions of citric acid are nearly a linear function of $10^4/(T - \Theta)^2$ at the low-temperature end of the plot, whereas those calculated from the values of C_P° at infinite dilution exhibit a larger deviation from linearity. The c_1, c_2, and ω parameters for citric acid, $citrate^-$, $citrate^{2-}$, $citrate^{3-}$ calculated in the present study are shown in Table B.1, together with the standard molal thermodynamic properties of these species at 25 °C and 1 bar.

References

Adachi, K., Suga, H., Seki, S., 1968. Phase changes in crystalline and glassy-crystalline cyclohexanol. *Bull. Chem. Soc. Jpn* **41** (5), 1073–1087.

Adams, M.W.W., 1993. Enzymes and proteins from organisms that grow near and above 100 °C. *Annu. Rev. Microbiol.* **47**, 627–658.

Adams, M.W.W., Kelly, R.M. (Eds.) 1992. *Biocatalysis at Extreme Temperatures: Enzyme Sytems Near and Above 100 °C*. ACS Symposium Series, American Chemical Society.

Ahmed, J.K., Derwish, G.A.W., Kanbour, F.I., 1981. Enthalpies of solution of thymine and uracil in water and dimethylsulfoxide. *J. Sol. Chem.* **10** (5), 343–350.

Alberty, R.A., 1969. Standard Gibbs free energy, enthalpy, and entropy changes as a function of pH and pMg for several reactions involving adenosine phosphates. *J. Biol. Chem.* **244** (12), 3290.

Alberty, R.A., 1998. Change in the binding of hydrogen ions and magnesium ions in the hydrolysis of ATP. *Biophys. Chem.* **70** (2), 109–119.

Alberty, R.A., 2004a. Thermodynamic properties of nucleotide reductase reactions. *Biochemistry* **43** (30), 9840–9845.

Alberty, R.A., 2004b. Use of standard Gibbs free energies and standard enthalpies of adenosine(aq) and adenine(aq) in the thermodynamics of enzyme-catalyzed reactions. *J. Chem. Thermodyn.* **36** (7), 593–601.

Alberty, R.A., Goldberg, R.N., 1992. Standard thermodynamic formation properties for the adenosine 5′-triphosphate series. *Biochemistry* **31** (43), 10610–10615.

Amend, J.P., Helgeson, H.C., 1997a. Calculation of the standard molal thermodynamic properties of aqueous biomolecules at elevated tem-

peratures and pressures. 1. L-α-amino acids. *J. Chem. Soc. Faraday Trans.* **93** (10), 1927–1941.

Amend, J.P., Helgeson, H.C., 1997b. Group additivity equations of state for calculating the standard molal thermodynamic properties of aqueous organic species at elevated temperatures and pressures. *Geochim. Cosmochim. Acta* **61** (1), 11–46.

Amend, J.P., Helgeson, H.C., 2000. Calculation of the standard molal thermodynamic properties of aqueous biomolecules at elevated temperatures and pressures II. Unfolded proteins. *Biophys. Chem.* **84** (2), 105–136.

Amend, J.P., Plyasunov, A.V., 2001. Carbohydrates in thermophile metabolism: calculation of the standard molal thermodynamic properties of aqueous pentoses and hexoses at elevated temperatures and pressures. *Geochim. Cosmochim. Acta* **65** (21), 3901–3917.

Amend, J.P., Shock, E.L., 1998. Energetics of amino acid synthesis in hydrothermal ecosystems. *Science* **281** (5383), 1659–1662.

Amend, J.P., Shock, E.L., 2001. Energetics of overall metabolic reactions of thermophilic and hyperthermophilic Archaea and Bacteria. *FEMS Microbiol. Rev.* **25** (2), 175–243.

Apelblat, A., 1986. Enthalpy of solution of oxalic, succinic, adipic, maleic, malic, tartaric, and citric acids, oxalic-acid dihydrate, and citric-acid monohydrate in water at 298.15 K. *J. Chem. Thermodyn.* **18** (4), 351–357.

Bald, A., Barczynska, J., 1993. Enthalpies of solution of citric-acid in water at 298.15 K—The effect of association processes on thermochemical properties of electrolyte solutions. *Thermochim. Acta* **222** (1), 33–43.

Banipal, P.K., Banipal, T.S., Lark, B.S., Ahluwalia, J.C., 1997. Partial molar heat capacities and volumes of some mono-, di- and trisaccharides in water at 298.15, 308.15 and 318.15 K. *J. Chem. Soc. Faraday Trans.* **93** (1), 81–87.

Bardi, G., Bencivenni, L., Ferro, D., Martini, B., Nunziantecesaro, S., Teghil, R., 1980. Thermodynamic study of the vaporization of uracil. *Thermochim. Acta* **40** (2), 275–282.

Benson, S.W., 1968. *Thermochemical Kinetics: Methods for the Estimation of Thermochemical Data and Rate Parameters*, second ed. John Wiley, New York.

Boerio-Goates, J., Francis, M.R., Goldberg, R.N., da Silva, M.A.V., da Silva, M.D.M., Tewari, Y.B., 2001. Thermochemistry of adenosine. *J. Chem. Thermodyn.* **33** (8), 929–947.

Boyer, J.S., Francis, M.R., Boerio-Goates, J., 2003. Heat-capacity measurements and thermodynamic functions of crystalline adenine: Revised thermodynamic properties of aqueous adenine. *J. Chem. Thermodyn.* **35** (12), 1917–1928.

Brock, T.D., 1978. *Thermophilic Microorganisms and Life at High Temperatures*. Springer, New York.

Brown, H.D. (Ed.), 1969. *Biochemical Microcalorimetry*. Academic Press, New York.

Buckin, V.A., 1988. Hydration of nucleic bases in dilute aqueous solutions—Apparent molar adiabatic and isothermal compressibilities, apparent molar volumes, and their temperature slopes at 25 °C. *Biophys. Chem.* **29** (3), 283–292.

Buckin, V.A., Kankiya, B.I., Kazaryan, R.L., 1989. Hydration of nucleosides in dilute aqueous solutions: ultrasonic velocity and density measurements. *Biophys. Chem.* **34** (3), 211–223.

Burkinshaw, P.M., Mortimer, C.T., 1984. Enthalpies of sublimation of transition-metal complexes. *J. Chem. Soc. Dalton Trans.* **13** (1), 75–77.

Chase Jr., M.W., 1998. NIST-JANAF Thermochemical Tables, fourth ed. *J. Phys. Chem. Ref. Data, Mono. 9*, **27**, 1–1951.

Colbert, J.C., Domalski, E.S., Coxon, B., 1987. Enthalpies of combustion of D-ribose and 2-deoxy-D-ribose. *J. Chem. Thermodyn.* **19** (4), 433–441.

Cox, J.D., Pilcher, G., 1970. *Thermochemistry of Organic and Organometallic Compounds*. Academic Press, London.

Cox, J.D., Wagman, D.D., Medvedev, V.A., 1989. *CODATA Key Values for Thermodynamics*. Hemisphere, New York.

Daniel, R.M., Cowan, D.A., 2000. Biomolecular stability and life at high temperatures. *Cell. Mol. Life Sci.* **57** (2), 250–264.

Dawson, R.M.C., Elliott, D.C., Elliott, W.H., Jones, K.M., 1986. *Data for Biochemical Research*, third ed. Clarendon Press, Oxford.

de Kruif, C.G., Van Miltenburg, J.C., Sprenkels, A.J.J., Stevens, G., DeGraaf, W., DeWit, H.G.M., 1982. Thermodynamic properties of citric acid and the system citric-acid water. *Thermochim. Acta* **58** (3), 341–354.

Deming, J.W., Baross, J.A., 1986. Solid medium for culturing black smoker bacteria at temperatures to 120 °C. *Appl. Environ. Microbiol.* **51** (2), 238–243.

Desnoyers, J.E., Philip, P.R., 1972. Isothermal compressibilities of aqueous solutions of tetraalkylammonium bromides. *Can. J. Chem.* **50**, 1094–1096.

DeVoe, H., Wasik, S.P., 1984. Aqueous solubilities and enthalpies of solution of adenine and guanine. *J. Sol. Chem.* **13** (1), 51–60.

Domalski, E.S., Hearing, E.D., 1996. Heat capacities and entropies of organic compounds in the condensed phase. *J. Phys. Chem. Ref. Data* **25** (1), 1–525.

Egan, E.P., Wakefield, Z.T., 1957. Low temperature heat capacity and entropy of crystalline orthophosphoric acid. *J. Phys. Chem.* **61** (11), 1500–1504.

Evans, D.M., Hoare, F.E., Melia, T.P., 1962. Heat capacity, enthalpy and entropy of citric acid monohydrate. *Trans. Faraday Soc.* **58**, 1511–1514.

Ferro, D., Bencivenni, L., Teghil, R., Mastromarino, R., 1980. Vapor pressures and sublimation enthalpies of thymine and cytosine. *Thermochim. Acta* **42** (1), 75–83.

Fischer, F., Zillig, W., Stetter, K.O., Schreiber, G., 1983. Chemolithoautotrophic metabolism of anaerobic extremely thermophilic Archaebacteria. *Nature* **301** (5900), 511–513.

Franks, F., Ravenhill, J.R., Reid, D.S., 1972. Thermodynamic studies of dilute aqueous solution of cyclic ethers and simple carbohydrates. *J. Sol. Chem.* **1**, 3–16.

Gajewski, E., Steckler, D.K., Goldberg, R.N., 1986. Thermodynamics of the hydrolysis of adenosine 5′-triphosphate to adenosine 5′-diphosphate. *J. Biol. Chem.* **261** (27), 2733–2737.

Galema, S.A., Engberts, J.B.F.N., Høiland, H., Forland, G.M., 1993. Informative thermodynamic properties of the effect of stereochemistry on carbohydrate hydration. *J. Phys. Chem.* **97** (26), 6885–6889.

Glukhova, O.T., Kiselev, V.D., Teplitsky, A.B., Ustyugov, A.N., Yanson, I.K., 1981. Hydration of nucleic-acid bases—Cytosine and its methyl-derivatives. *Biofizika* **26** (2), 351–352.

Goldberg, R.N., Tewari, Y.B., 1989. Thermodynamic and transport properties of carbohydrates and their monophosphates—The pentoses and hexoses. *J. Phys. Chem. Ref. Data* **18** (2), 809–880.

Goldberg, R.N., Tewari, Y.B., 1991. Thermodynamics of the disproportionation of adenosine 5′-diphosphate to adenosine 5′-triphosphate and adenosine 5′-monophosphate. 1. Equilibrium Model. *Biophys. Chem.* **40** (3), 241–261.

Goldberg, R.N., Tewari, Y.B., 1994. Thermodynamics of enzyme-catalyzed reactions. 2. Transferases. *J. Phys. Chem. Ref. Data* **23** (4), 547–617.

Goldberg, R.N., Tewari, Y.B., 2002. Thermochemistry of the biochemical reaction: {pyrophosphate(aq)+H$_2$O(l) = 2 phosphate(aq)}. *J. Chem. Thermodyn.* **34** (6), 821–839.

Helgeson, H.C., 1969. Thermodynamics of hydrothermal systems at elevated temperatures and pressures. *Am. J. Sci.* **267**, 729–804.

Helgeson, H.C., Kirkham, D.H., 1974a. Theoretical prediction of thermodynamic behavior of aqueous electrolytes at high pressures and temperatures: 1. Summary of thermodynamic-electrostatic properties of the solvent. *Am. J. Sci.* **274** (10), 1089–1198.

Helgeson, H.C., Kirkham, D.H., 1974b. Theoretical prediction of thermodynamic behavior of aqueous electrolytes at high pressures and temperatures: 2. Debye-Hückel parameters for activity coefficients and relative parital molal properties. *Am. J. Sci.* **274** (10), 1199–1261.

Helgeson, H.C., Kirkham, D.H., 1976. Theoretical prediction of thermodynamic behavior of aqueous electrolytes at high pressures and temperatures: 3. Equation of state for aqueous species at infinite dilution. *Am. J. Sci.* **276** (2), 97–240.

Helgeson, H.C., Delany, J.M., Nesbitt, H.W., Bird, D.K., 1978. Summary and critique of the thermodynamic properties of rock-forming minerals. *Am. J. Sci.* **278**, 1–229.

Helgeson, H.C., Kirkham, D.H., Flowers, G.C., 1981. Theoretical prediction of thermodynamic behavior of aqueous electrolytes at high pressures and temperatures: 4. Calculation of activity coefficients, osmotic coefficients, and apparent molal and standard and relative partial molal properties to 600 °C and 5 kb. *Am. J. Sci.* **281** (10), 1249–1516.

Helgeson, H.C., Owens, C.E., Knox, A.M., Richard, L., 1998. Calculation of the standard molal thermodynamic properties of crystalline, liquid, and gas organic molecules at high temperatures and pressures. *Geochim. Cosmochim. Acta* **62** (6), 985–1081.

Herskovits, T.T., Bowen, J.J., 1974. Solution studies of nucleic-acid bases and related model compounds—solubility in aqueous urea and amide solutions. *Biochemistry* **13** (27), 5474–5483.

Høiland, H., Holvik, H., 1978. Partial molal volumes and compressibilities of carbohydrates in water. *J. Sol. Chem.* **7** (8), 587–596.

Høiland, H., Skauge, A., Stokkeland, I., 1984. Changes in partial molar volumes and isentropic partial molar compressibilities of stacking of some nucleobases and nucleoside in water at 298.15 K. *J. Phys. Chem.* **88** (25), 6350–6353.

Huber, H., Diller, S., Horn, C., Rachel, R., 2002. *Thermovibrio ruber* gen. nov., sp nov., an extremely thermophilic, chemolithoautotrophic, nitrate-reducing bacterium that forms a deep branch within the phylum. *Aquificae. Int. J. Syst. Evol. Microbiol.* **52**, 1859–1865.

Immirzi, A., Perini, B., 1977. Prediction of density in organic crystals. *Acta Crystallogr. A* **33**, 216–218.

Jasra, R.V., Ahluwalia, J.C., 1982. Enthalpies of solution, partial molal heat capacities and apparent molal volumes of sugars and polyols in water. *J. Sol. Chem.* **11** (5), 325–338.

Johnson, J.W., Oelkers, E.H., Helgeson, H.C., 1992. SUPCRT92—A software package for calculating the standard molal thermodynamic properties of minerals, gases, aqueous species, and reactions from 1 bar to 5000 bar and 0 °C to 1000 °C. *Comput. Geosci.* **18** (7), 899–947.

Kanbour, F.I., Ahmed, J.K., Derwish, G.A.W., 1983. Enthalpies of solution of purine and adenine in water and in dimethylsulfoxide. *J. Sol. Chem.* **12** (11), 763–770.

Kilday, M.V., 1978a. Enthalpies of solution of nucleic-acid bases. 1. Adenine in water. *J. Res. Nat. Bur. Stand.* **83** (4), 347–370.

Kilday, M.V., 1978b. Enthalpies of solution of nucleic-acid bases. 2. Thymine in water. *J. Res. Nat. Bur. Stand.* **83** (6), 529–537.

Kilday, M.V., 1978c. Enthalpies of solution of nucleic-acid bases. 3. Cytosine in water. *J. Res. Nat. Bur. Stand.* **83** (6), 539–546.

Kilday, M.V., 1978d. Enthalpies of solution of nucleic-acid bases. 4. Uracil in water. *J. Res. Nat. Bur. Stand.* **83** (6), 547–554.

Kilday, M.V., 1981. Enthalpies of solution of nucleic-acid bases. 6. Guanine in aqueous HCl and NaOH, and guanine hydrochlorides in aqueous HCl. *J. Res. Nat. Bur. Stand.* **86** (4), 367–382.

Kirklin, D.R., Domalski, E.S., 1983. Enthalpy of combustion of adenine. *J. Chem. Thermodyn.* **15** (10), 941–947.

Kishore, N., Ahluwalia, J.C., 1990a. Partial molar heat capacities and volumes of some nucleic-acid bases, nucleoside and nucleotides in aqueous urea solutions at 298.15 K. *J. Chem. Soc. Faraday Trans.* **86** (6), 905–910.

Kishore, N., Ahluwalia, J.C., 1990b. Partial molar heat capacities and volumes of transfer of nucleic-acid bases, nucleosides and nucleotides from water to aqueous solutions of sodium and calcium chloride at 25 °C. *J. Sol. Chem.* **19** (1), 51–64.

Kishore, N., Bhat, R., Ahluwalia, J.C., 1989. Thermodynamics of some nucleic-acid bases and nucleosides in water, and their transfer to aqueous glucose and sucrose solutions at 298.15 K. *Biophys. Chem.* **33** (3), 227–236.

Kondepudi, D., Prigogine, I., 1998. *Modern Thermodynamics: From Heat Engines to Dissipative Structures*. John Wiley & Sons, New York.

Krebs, H.F., Kornberg, H.L., 1957. *Energy Transformations in Living Matter: A Survey*. Springer, Berlin.

Larson, J.W., Tewari, Y.B., Goldberg, R.N., 1993. Thermochemistry of the reactions between adenosine, adenosine 5′-monophosphate, inosine and inosine 5′-monophosphate—The conversion of L-histidine to (urocanic acid + ammonia). *J. Chem. Thermodyn.* **25** (1), 73–90.

Lebedev, B.V., Kulagina, T.G., Kiparisova, E.G., 1981. Thermodynamics of 2,5-diketopiperazine in the 0–330 K region. *Zh. Obshch. Khim.* **51** (1), 199–203.

Lee, A., Chalikian, T.V., 2001. Volumetric characterization of the hydration properties of heterocyclic bases and nucleosides. *Biophys. Chem.* **92** (3), 209–227.

Maier, C.G., Kelley, K.K., 1932. An equation for the representation of high-temperature heat content data. *J. Am. Chem. Soc.* **54**, 3243–3246.

Mavrovouniotis, M.L., 1990. Group contributions for estimating standard Gibbs energies of formation of biochemical compounds in aqueous solutions. *Biotech. Bioeng.* **36** (10), 1070–1082.

Mavrovouniotis, M.L., 1991. Estimation of standard Gibbs energy changes of biotransformations. *J. Biol. Chem.* **266** (22), 14440–14445.

Messerly, J.F., Todd, S.S., Finke, H.L., Good, W.D., Gammon, B.E., 1988. Condensed-phase heat capacity studies and derived thermodynamic properties for six cyclic nitrogen compounds. *J. Chem. Thermodyn.* **20** (2), 209–224.

Morel, J.P., Lhermet, C., Moreldesrosiers, N., 1986. Interactions between cations and sugars. 2. Enthalpies, heat capacities, and volumes of aqueous solutions of Ca^{2+}-D-ribose and Ca^{2+}-D-arabinose at 25 °C. *Can. J. Chem. -Rev. Can. Chim.* **64** (5), 996–1001.

Nabavian, P.M., Sabbah, R., Chastel, R., Laffitte, M., 1977 (*Thermodynamique de composés azotés. II. Etude thermochimique des acides aminobenzoïques, de la pyrimidine, de l'uracile et de la thymine*). *J. Chim. Phys.* **74**, 115–126.

Oscarson, J.L., Wang, P.M., Gillespie, S.E., Izatt, R.M., Watt, G.D., Larsen, C.D., Renuncio, J.A.R., 1995. Thermodynamics of protonation of AMP, ADP, and ATP from 50 °C to 125 °C. *J. Sol. Chem.* **24** (2), 171–200.

Ould-Moulaye, C.B., Dussap, C.G., Gros, J.B., 2001. A consistent set of formation properties of nucleic acid compounds—purines and pyrimidines in the solid state and in aqueous solution. *Thermochim. Acta* **375** (1–2), 93–107.

Ould-Moulaye, C.B., Dussap, C.G., Gros, J.B., 2002. A consistent set of formation properties of nucleic acid compounds—Nucleosides, nucleotides and nucleotide-phosphates in aqueous solution. *Thermochim. Acta* **387** (1), 1–15.

Paljk, S., Klofutar, C., Kac, M., 1990. Partial molar volumes and expansibilities of some D-pentoses and D-hexoses in aqueous solution. *J. Chem. Eng. Data* **35** (1), 41–43.

Patel, S.G., Kishore, N., 1995. Thermodynamics of nucleic-acid bases and nucleosides in water from 25 °C to 55 °C. *J. Sol. Chem.* **24** (1), 25–38.

Patterson, B.A., Woolley, E.M., 2001. Thermodynamics of proton dissociations from aqueous citric acid: apparent molar volumes and apparent molar heat capacities of citric acid and its sodium salts at the pressure 0.35 MPa and at temperatures from 278.15 K to 393.15 K. *J. Chem. Thermodyn.* **33** (12), 1735–1764.

Phillips, S.J., 1966. Adenosine and adenine nucleotides. Ionization metal complex formation and conformation in solution. *Chem. Rev.* **66** (5), 501–527.

Phillips, S.J., Eisenberg, P., George, P., Rutman, R.J., 1965. Thermodynamic data for the secondary phosphate ionizations of adenosine, guanosine, inosine, cytidine, and uridine nucleotides and triphosphates. *J. Biol. Chem.* **240**, 4393–4397.

Plyasunov, A.V., Shock, E.L., 2001. Correlation strategy for determining the parameters of the revised Helgeson-Kirkham-Flowers model for aqueous nonelectrolytes. *Geochim. Cosmochim. Acta* **65** (21), 3879–3900.

Rabinovich, I.B., Karyakin, N.V., Dzharimova, E.S., Siling, S.A., Ponomarev, I.I., Vinogradova, S.V., 1984. Thermodynamics of condensation of pthalonitrile with *m*-phenlyenediamine. *Bull. Acad. Sci. USSR, Div. Chem. Sci.*, 716–723.

Ramirez, F., Marecek, J.F., 1980. Phosphorylations by adenosine 5′-triphosphate. *Pure Appl. Chem.* **52** (9), 2213–2227.

Richard, L., Helgeson, H.C., 1998. Calculation of the thermodynamic properties at elevated temperatures and pressures of saturated and aromatic high molecular weight solid and liquid hydrocarbons in kerogen, bitumen, petroleum, and other organic matter of biogeochemical interest. *Geochim. Cosmochim. Acta* **62** (23–24), 3591–3636.

Robinson, D.R., Grant, M.E., 1966. Effects of aqueous salt solutions on activity coefficients of purine and pyrimidine base and their relation to denaturation of deoxyribonucleic acid by salts. *J. Biol. Chem.* **241** (17), 4030–4042.

Sabbah, R., 1980. Thermodynamics of nitrogen compounds. 5. Thermochemical study of cytosine. *Thermochim. Acta* **35** (1), 73–77.

Sabbah, R., Nabavian, M., Laffitte, M., 1977. Enthalpy of formation of cytosine in solid state. *Compt. Rend. Acad. Sci. C* **284** (23), 953–954.

Schulte, M.D., Rogers, K.L., 2004. Thiols in hydrothermal solution: standard partial molal properties and their role in the organic geochemistry of hydrothermal environments. *Geochim. Cosmochim. Acta* **68** (5), 1087–1097.

Scruggs, R.L., Ross, P.D., Achter, E.K., 1972. Thermodynamic effects of exposing nucleic-acid bases to water—solubility measurements in water and organic solvents. *Biopolymers* **11** (9), 1961–1972.

Shock, E.L., 1992. Stability of peptides in high temperature aqueous solutions. *Geochim. Cosmochim. Acta* **56** (9), 3481–3491.

Shock, E.L., 1993. Hydrothermal dehydration of aqueous organic compounds. *Geochim. Cosmochim. Acta* **57** (14), 3341–3349.

Shock, E.L., 1995. Organic acids in hydrothermal solutions—standard molal thermodynamic properties of carboxylic acids and estimates of dissociation constants at high temperatures and pressures. *Am. J. Sci.* **295** (5), 496–580.

Shock, E.L., Helgeson, H.C., 1988. Calculation of the thermodynamic and transport properties of aqueous species at high pressures and temperatures—correlation algorithms for ionic species and equation of state predictions to 5 kb and 1000 °C. *Geochim. Cosmochim. Acta* **52** (8), 2009–2036.

Shock, E.L., Helgeson, H.C., 1990. Calculation of the thermodynamic and transport properties of aqueous species at high pressures and temperatures—standard partial molal properties of organic species. *Geochim. Cosmochim. Acta* **54** (4), 915–945.

Shock, E.L., Helgeson, H.C., Sverjensky, D., 1989. Calculation of the thermodynamic and transport properties of aqueous species at high pressures and temperatures—standard partial molal properties of inorganic neutral species. *Geochim. Cosmochim. Acta* **53** (9), 2157–2183.

Shock, E.L., Oelkers, E., Johnson, J., Sverjensky, D., Helgeson, H.C., 1992. Calculation of the thermodynamic properties of aqueous species at high pressures and temperatures—effective electrostatic radii, dissociation constants and standard partial molal properties to 1000 °C and 5 kbar. *J. Chem. Soc. Faraday Trans.* **88** (6), 803–826.

Shock, E.L., Sassani, D., Willis, M., Sverjensky, D., 1997. Inorganic species in geologic fluids: correlations among standard molal thermodynamic properties of aqueous ions and hydroxide complexes. *Geochim. Cosmochim. Acta* **61** (5), 907–950.

Stern, J.H., Hubler, P.M., 1984. Hydrogen bonding in aqueous solutions of D-ribose and 2-deoxy-D-ribose. *J. Phys. Chem.* **88** (9), 1680–1681.

Stern, J.H., Oliver, D.R., 1980. Thermodynamics of nucleoside–solvent interactions—inosine and adenosine in water and in 1-*m*-ethanol between 25 °C and 35 °C. *J. Chem. Eng. Data* **25** (3), 221–223.

Stetter, K.O., Fiala, G., Huber, G., Huber, R., Segerer, A., 1990. Hyperthermophilic microorganisms. *FEMS Microbiol. Rev.* **75** (2–3), 117–124.

Stetter, K.O., Konig, H., Stackebrandt, E., 1983. *Pyrodictium*, gen. nov., a new genus of submarine disc-shaped sulfur-reducing archaebacteria growing optimally at 105 °C. *Syst. Appl. Microbiol.* **4** (4), 535–551.

Stetter, K.O., Segerer, A., Zillig, W., Huber, G., Fiala, G., Huber, R., Konig, H., 1986. Extremely thermophilic sulfur-metabolizing archaebacteria. *Syst. Appl. Microbiol.* **7** (2–3), 393–397.

Stiehler, R.D., Huffman, H.M., 1935a. Thermal data. IV. The heats of combustion of adenine, hypoxanthine, guanine, xanthine, uric acid, allantoin and alloxan. *J. Am. Chem. Soc.* **57**, 1734–1740.

Stiehler, R.D., Huffman, H.M., 1935b. Thermal data. V. The heat capacities, entropies, and free energies of adenine, hypoxanthine, guanine, xanthine, uric acid, allantoin and alloxan. *J. Am. Chem. Soc.* **57**, 1741–1743.

Sverjensky, D., Shock, E.L., Helgeson, H.C., 1997. Prediction of the thermodynamic properties of aqueous metal complexes to 1000 °C and 5 kb. *Geochim. Cosmochim. Acta* **61** (7), 1359–1412.

Szeminska, J., Zielenliewicz, W., Wierzchowski, K.L., 1979. Thermochemistry of aqueous solutions of alkylated nucleic-acid bases. 1. Apparent molar heat capacities of uracil, thymine and their derivatives. *Biophys. Chem.* **10** (3–4), 409–414.

Tanger, J.C., Helgeson, H.C., 1988. Calculation of the thermodynamic and transport properties of aqueous species at high pressures and temperatures—revised equations of state for the standard partial molal properties of ions and electrolytes. *Am. J. Sci.* **288** (1), 19–98.

Teplitsky, A.B., Glukhova, O.T., Sukhodub, L.F., Yanson, I.K., Zielenkiewicz, A., Zielenkiewicz, W., Kosinski, J., Wierzchowski, K.L., 1982. Thermochemistry of aqueous solutions of alkylated nucleic-acid bases. 4. Enthalpies of hydration of 5-alkyluracils. *Biophys. Chem.* **15** (2), 139–147.

Teplitsky, A.B., Yanson, I.K., Glukhova, O.T., Zielenkiewicz, A., Zielenkiewicz, W., Wierzchowski, K.L., 1980. Thermochemistry of aqueous solutions of alkylated nucleic-acid bases. 3. Enthalpies of hydration of uracil, thymine, and their derivatives. *Biophys. Chem.* **11** (1), 17–21.

Tewari, Y.B., Goldberg, R.N., Advani, J.V., 1991. Thermodynamics of the disproportionation of adenosine 5′-phosphate to adenosine 5′-triphosphate and adenosine 5′-monophosphate. 2. Experimental data. *Biophys. Chem.* **40** (3), 263–276.

Tewari, Y.B., Steckler, D.K., Goldberg, R.N., Gitomer, W.L., 1988. Thermodynamics of hydrolysis of sugar phosphates. *J. Biol. Chem.* **26** (8), 3670–3675.

Van Bommel, M.J., Van Miltenburg, J.C., Schuijff, A., 1988. Heat-capacity measurements and thermodynamic function of 1,3,5-triazine and 1,3,5-trioxane. *J. Chem. Thermodyn.* **20** (4), 397–403.

Wagman, D.D., Evans, W.H., Parker, V.B., Schumm, R.H., Halow, I., Bailey, S.M., Churney, K.L., Nuttall, R.L., 1982. The NBS tables of chemical thermodynamic properties—selected values for inorganic and C-1 and C-2 organic substances in SI units. *J. Phys. Chem. Ref. Data* **11** (Suppl. 2), 1–392.

Wilhoit, R.C., Shiao, D., 1964. Thermochemistry of biologically important compounds. Heats of combustion of solid organic acids. *J. Chem. Eng. Data* **9**, 595–599.

Wilson, S.R., Watson, I.D., Malcolm, G.N., 1979. Enthalpies of formation of solid cytosine, L-histidine, and uracil. *J. Chem. Thermodyn.* **11** (9), 911–912.

Woese, C.R., Kandler, O., Wheelis, M.L., 1990. Towards a natural system of organisms—proposal for the domains Archaea, Bacteria, and Eucarya. *Proc. Natl. Acad. Sci. USA* **87** (12), 4576–4579.

Yanson, I.K., Verkin, B.I., Shklyare, O.I., Teplitsk, A.B., 1974. Sublimation heats of nitrogen bases of nucleic-acids. *Studia Biophys.* **46** (1), 29–44.

Zielenkiewicz, A., Wszelaka-Rylik, M., Poznanski, J., Zielenkiewicz, W., 1998. Thermochemistry of aqueous solutions of alkylated nucleic acid bases. X. Enthalpies of hydration of cytosine and some methylated, hydroxy and methoxy derivatives of cytosine. *J. Sol. Chem.* **27** (3), 235–243.

Zielenkiewicz, A., Zielenkiewicz, W., Sukhodub, L.F., Glukhova, O.T., Teplitsky, A.B., Wierzchowski, K.L., 1984. Thermochemistry of aqueous solutions of alkylated nucleic-acid bases. 5. Enthalpies of hydration of N-methylated adenines. *J. Sol. Chem.* **13** (11), 757–765.

Zielenkiewicz, W., 1995. Thermochemistry of aqueous solutions of nucleic-acid bases and their alkylated derivatives. *J. Therm. Anal.* **45** (4), 615–629.

Zielenkiewicz, W., 2000. Enthalpies of sublimation and vapor pressures of adenine, 1-methyladenine, 2-methyladenine, 3-methyladenine, and 8-methyladenine. *J. Chem. Eng. Data* **45** (4), 626–629.

Zielenkiewicz, W., Poznanski, J., Zielenkiewicz, A., 2000. Partial molar volumes of aqueous solutions of some halo and amino derivatives of uracil. *J. Sol. Chem.* **29** (8), 757–769.

Zielenkiewicz, W., Zielenkiewicz, A., Wierzchowski, K.L., 1993. Thermochemistry of aqueous solutions of alkylated nucleic-acid bases. 8. Enthalpies of hydration of 6-alkyluracils. *J. Sol. Chem.* **22** (11), 975–981.

Zielenkiewicz, W., Zielenkiewicz, A., Wierzchowski, K.L., 1994a. Thermochemistry of alkylated uracils in aqueous solutions—enthalpies of hydration of 3-alkyluracils. *Pure Appl. Chem.* **66** (3), 503–507.

Zielenkiewicz, W., Zielenkiewicz, A., Wierzchowski, K.L., 1994b. Thermochemistry of aqueous solutions of alkylated nucleic-acid bases. 9. Enthalpies of hydration of 9-methyl-8-alkyladenines and 6,9-dimethyl-8-alkyladenines. *J. Sol. Chem.* **23** (10), 1125–1131.

ZoBell, C.E., 1970. Pressure effects on morphology and life of bacteria. In: Zimmerman, A.M. (Ed.), *High Pressure Effects on Cellular Processes*. Academic Press, New York, pp. 85–130.

Zolkiewski, M., Zielenkiewicz, W., 1991. Enthalpies of solvation of alkylated uracils in water, non-aqueous, and mixed solvents. *J. Sol. Chem.* **20** (5), 517–530.