

Enthalpies of Solution of the Nucleic Acid Bases. 4. Uracil in Water

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An adiabatic solution calorimeter was used to measure enthalpies of solution in water of 7 uracil samples in a concentration range of 3 to 45 mmol·kg⁻¹ and over a temperature range of 298 K to 325 K. Analytical data for the samples are given.

Our best value for the enthalpy of solution is

$$\Delta H^\circ(\infty, 298.15 \text{ K}) = (29.3 \pm 1.2) \text{ kJ} \cdot \text{mol}^{-1}$$

and for the change in heat capacity for the reaction with temperature,

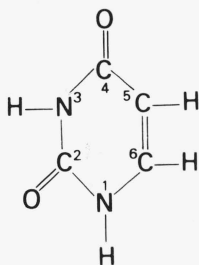
$$\Delta C_p^\circ = (57 \pm 13) \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}.$$

No change in the enthalpy of solution with concentration was found in this range. Values were calculated for the entropy of solution, $\Delta S^\circ = (68.1 \pm 4.2) \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$, and for the apparent molal heat capacity at infinite dilution, $C_{p2}^\circ = (178 \pm 15) \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$.

Keywords: Calorimetry; 2,4-dioxypyrimidine; nucleic acid bases; 2,4(1H, 3H)-pyrimidinedione; thermochemistry; uracil: density, enthalpy of solution, entropy of solution.

1. Introduction

Three earlier papers in this series have described our measurements of the enthalpies of solution in water of adenine, thymine, and cytosine [1, 2, 3].¹ Similar information is given in this paper for uracil, a pyrimidine base of the nucleic acids. The structural formula [4] is



The solubility in H₂O is 3.0 g·L⁻¹ [5]² at 298 K; uracil sublimates and decomposes before melting. Only one value for

the enthalpy of solution in H₂O has been reported previously [7], and that was a small part of a study of transfer coefficients where the purity of the samples was not a major consideration.

In this series, characterization of the samples is emphasized in order to assign realistic uncertainty limits to the measured values for the enthalpy of solution. Samples of uracil as received from three commercial sources are compared with samples which were further purified by sublimation and by recrystallization from H₂O and from ethyl alcohol. Enthalpies of solution of uracil in H₂O were measured in the temperature range, 298 to 325 K, and in the concentration range, 3 to 45 mmol·kg⁻¹.

2. The Uracil (Ura) Samples

Enthalpies of solution were measured on three uracil samples as received from commercial sources.³ The following information about these samples was obtained primarily from

¹ Figures in brackets indicate the literature references at the end of this paper.

² The National Bureau of Standards (U.S.) has recently recommended the use of the symbol "L" for the liter, the metric unit commonly used to measure volume [6].

³ The information presented in this paper is in no way intended as an endorsement nor a condemnation of any of the materials or services used. Commercial sources are named only for specific identification.

labels, catalogs, and brochures supplied by the manufacturer:

Ura 1 Calbiochem, Cat. No. 6630, Lot 802190, Grade A, 100 g, received about 1970—exact date unknown. Analysis: Nitrogen, 25.10%. Spectra at pH 7: 250/260 0.83, 280/260 0.16, λ max 260 μm , ϵ max 8130. Chromat. Homogeneous.

Ura_a2 Eastman Organic Chemicals, Cat. No. 2504, Lot 24A, 10 g received about 1970—exact date unknown. MP 335° dec. (This material had an off-white color when compared with Ura 1 and 3.)

Ura 3 E-M Laboratories, Cat. No. 8460, for biochemistry, Lot 4955541, 100 g received August 1974. Type Analysis: Assay 98% (ref. to dried substance). Optical properties, measured values at pH 7: λ max 260, E_{250}/E_{260} 0.83 \pm 0.02, E_{280}/E_{260} 0.20 \pm 0.02, E_{290}/E_{260} < 0.02. Thin layer chromatography: Layer: TLC plates PEI-Cellulose F, precoated, Solvent: 1M NaCl solution, R_f value: \sim 0.7.

Ura 4 Same as Ura 3 except 25 g received November 1974.

Portions of Ura 3 were further purified in this laboratory according to the following procedures:

Ura 3a and 3b were recrystallized from H₂O and 90% ethyl alcohol and dried according to the procedures described in detail for Thy 3a and 3b [2]. Approximately 1.5 g of Ura 3a and 14 g of Ura 3b were obtained as the final products.

Ura 3c was vacuum-sublimed according to the procedures described previously for Ade 1c and 5c [1]. The sublimation temperature was 425 to 428 K. After about 40 h the sublimation was stopped with some of the unsublimed material remaining at the bottom of the vessel. The vessel, still under vacuum, was transferred to a dry box where the sublimate was removed. It was very finely divided and adhered tightly to the condenser (unlike thymine and cytosine which were fluffy and easily removed). The uracil sublimate was chipped off the glass surface, with a stainless steel spatula, in flakes which were shiny on the side which had been next to the glass surface. However, the glass surface showed no evidence of having been attacked by the sublimate. Transfers of this material to the calorimetric sample holder were done in a dry box.

Ura 3d was the unsublimed residue from the sublimation where Ura 3c was the product. The residue was discolored with some light brown or beige material which was undoubtedly a decomposition product.

2.1 Characterization of the Samples

The purity of the uracil could not be determined from freezing-temperature measurements because it decomposes before melting. Therefore, a search for impurities was made, and some of the intensive properties of the samples were measured to define the materials on which enthalpies of solution were determined.

In this laboratory the samples were analyzed for H₂O and volatile matter, impurities by paper and thin layer chromatography (TLC), and approximate values for the density were measured. Other laboratories contributed measurements of the enthalpy of combustion, heat capacity of the crystalline

materials, and analyses of emission spectra, x-ray powder patterns, and elemental composition.

2.1.1. Density, Volatile Matter, and H₂O

The densities of Ura 1, 2, and 3 as received were measured by displacement of CCl₄ (analytical reagent for which the specified density at 298 K was in the range of 1.583 to 1.585 g·mL⁻¹). Details of the procedure were described previously [1]. The density of the CCl₄ under laboratory conditions was 1.5897 g·mL⁻¹ which is the mean of three measurements with an average deviation of \pm 0.0008 g·mL⁻¹. The measured densities for uracil are as follows: Ura 1, 1.607 and 1.595 g·mL⁻¹; Ura 2, 1.605 g·mL⁻¹; and Ura 3, 1.594 g·mL⁻¹. It was determined that the uracil was not soluble in the CCl₄ by filtering and weighing the dried samples after the density measurements; the loss in mass was 0.2 percent or less. When the filtrates were evaporated to dryness at room temperature, there was no visible residue. The mean of the four density measurements, (1.600 \pm 0.011) g·mL⁻¹, was used in calculating the buoyancy factor, 1.00060, for the uracil mass corrections in this work. This value for the density of uracil is in good agreement with those obtained from single crystals: 1.590 g·mL⁻¹ from x-ray data and 1.625 g·mL⁻¹ by floatation [8].

The following observations were made on the volatility and hygroscopicity of the uracil samples:

Three portions (1 to 4 g) of Ura 1 and of Ura 2 (contained in covered flat aluminum moisture dishes) were weighed, then heated at 340 K under vacuum (see [1] for details) for 4 h, cooled in a desiccator, and reweighed; the procedure was repeated with 2-h heating periods for a total of 10 to 14 h of heating at which time the materials had either reached constant mass or a constant rate of loss in mass. The samples of Ura 1 apparently reached constant mass after 6 h heating with a loss of \sim 0.4 mg·g⁻¹; for those of Ura 2, the loss was \sim 0.9 mg·g⁻¹. These samples were subsequently exposed to the atmosphere occasionally over a period of 2 years. A second series of observations was then made similar to those described above except that the vacuum drying was at 375 K and single 3-g portions were taken of Ura 1, 2, 3, and 4. After about 6 h of heating, Ura 1 again appeared to be at nearly constant mass with a loss of \sim 0.6 mg·g⁻¹; Ura 3 and 4 were also at nearly constant mass, with a loss of \sim 0.9 mg·g⁻¹. However, Ura 2 lost 1.6 mg·g⁻¹ during the first 4 h and continued loss at a rate of \sim 0.1 mg·g⁻¹·h⁻¹; if this rate of loss (assumed to be due to sublimation) is extrapolated to zero time, we obtain the loss due to volatile matter, \sim 1.2 mg·g⁻¹, which is only slightly larger than the mass loss at 340 K.

At this time, the dish containing Ura 1 was opened exposing the sample to the atmosphere (35% relative humid-

ity) while on a balance. After 7 h, a gain of $\sim 0.8 \text{ mg} \cdot \text{g}^{-1}$ ($\sim 0.1\%$) was observed but there was no change after an additional 18 h. (The gain in mass corresponding to the formation of the monohydrate would be 16%.) This agrees with the observation of Falk [9] that uracil does not form hydrates even at 93 percent relative humidity. Therefore, the samples for calorimetric measurements (except the product of sublimation, Ura 3c) were transferred to the sample holder in the laboratory atmosphere (the maximum exposure time was approximately 10 min).

A third series of vacuum drying observations was made at 375 K; these were at ~ 22 -h heating intervals for about 140 h. This series included the same samples of Ura 1 and 2 discussed above and the recrystallized samples of Ura 3a and 3b (in glass weighing bottles) which had been previously dried overnight at 340 K at atmospheric pressure. Ura 1 lost mass at the constant rate of about $50 \mu\text{g} \cdot \text{g}^{-1} \cdot \text{h}^{-1}$ and Ura 2 at $90 \mu\text{g} \cdot \text{g}^{-1} \cdot \text{h}^{-1}$. These rates would not have been detected in the shorter heating intervals. Ura 3a lost mass at the rate of about $15 \mu\text{g} \cdot \text{g}^{-1} \cdot \text{h}^{-1}$ for the first 70 h; thereafter the rate increased to about $50 \mu\text{g} \cdot \text{g}^{-1} \cdot \text{h}^{-1}$. Ura 3b showed a constant rate of loss in mass of $15 \mu\text{g} \cdot \text{g}^{-1} \cdot \text{h}^{-1}$ for 115 h of heating. These constant rates of mass loss are assumed to be sublimation rates under these conditions; however the abrupt increase observed in the sublimation rate for Ura 3a cannot be explained since the materials were heated simultaneously.

It is assumed that the best value for volatile matter in the commercial samples as received is obtained by extrapolating the results obtained in the second series of vacuum-drying to zero time. This gives the following values for volatile matter in mass percent: Ura 1, 0.04; Ura 2, 0.12; Ura 3 and 4, 0.05. The recrystallized samples, Ura 3a and 3b, which were vacuum dried for extended periods, and the sublimed sample, Ura 3c, are assumed to be free of volatile impurities.

Karl Fischer titrations for H_2O (as described [2]) indicated 0.05, 0.30, 0.10, and 0.13 mass percent for Ura 1, 2, 3, and 4, respectively. The uncertainty in these measurements

is estimated to be about ± 0.1 mass percent. The solubility of the uracil samples in the methanol solvent was about one-fourth that of the other pyrimidine bases, thymine and cytosine. These results support the assumption that H_2O was the volatile matter determined by vacuum-drying. Corrections to the calorimetric measurements for H_2O in the samples were based on the volatile matter determinations because the uncertainties were smaller than those in the titrations.

2.1.2. Other Analyses

The emission spectra⁴ of Ura 1, 2, 3, and 4 indicated (in addition to the possible background impurity limits listed previously [1]) the presence in Ura 2 of 0.02 mass percent of Fe and Si, and a trace of Mg and a trace of Ag in Ura 3 and 4. These small amounts of impurities are not regarded as a source of significant error in the enthalpy of solution measurements.

Duplicate elemental analyses⁵ of Ura 1, 2, 3, and 3a are given in table 1 where the estimated uncertainty in each determination is 0.2 mass percent. The C and N analyses for all of the samples are somewhat higher than those of the theoretical composition of anhydrous uracil. The oxygen is high on Ura 1 and 3a but a little low on Ura 2. These departures from the theoretical composition cannot be explained on the basis of any of the other analytical data such as H_2O or volatile matter. Ura 3 appears to be closer to the theoretical composition of anhydrous uracil than the recrystallized sample, Ura 3a which had been vacuum dried. This would indicate that all occluded H_2O may not have been removed during the vacuum drying. In general, there appears to be greater variation in the purity of these uracil samples than was found in the other bases previously described in

⁴ Analyses by J. A. Norris, Center for Analytical Chemistry, National Measurement Laboratory, National Bureau of Standards.

⁵ By Micro Analysis, Inc. Wilmington, DE.

Table 1. Elemental analyses of uracil samples.

Substance	Empirical Formula	Molecular Mass	C	H	O	N (Kjeldahl)	Sulfated Ash	E
Theoretical Composition:								
Ura	$\text{C}_4\text{H}_4\text{N}_2\text{O}_2$	112.0878	42.86	3.60	28.55	24.99	---	100.00
Ura· H_2O	$\text{C}_4\text{H}_6\text{N}_2\text{O}_3$	130.103	36.93	4.65	36.89	21.53	---	100.00
Analyses:								
Ura 1	-----	-----	43.68 43.83	3.38 3.56	29.47 29.18	25.32 25.48	0.00 0.01	101.85 102.06
Ura 2	-----	-----	43.03 43.20	3.60 3.59	28.07 28.29	25.18 25.30	0.02 0.04	99.90 100.42
Ura 3	-----	-----	43.10 43.09	3.59 3.56	28.72 28.44	25.52 25.36	0.01 0.01	100.94 100.46
Ura 3a	-----	-----	43.35 43.11	3.62 3.49	29.21 29.20	25.39 25.28	0.04 0.02	101.61 101.10

this series. However, there appears to be little if any hydration in the samples.

Paper and TLC analyses of the four commercial uracil samples as received (Ura 1, 2, 3, and 4) produced the R_f values (distance traveled by the major component/distance traveled by the solution front) given in table 2. Four carrier solutions were used with Whatman No. 1 and No. 40 chromatography papers and with glass TLC plates coated with MN300F Cellulose (with fluorescent indicator). Details of procedures including observations regarding background and sensitivities were discussed previously [1]. Our R_f

values are compared in table 2 with those given on page 152-3 of the National Academy of Sciences (NAS) publication [10]. The latter are somewhat lower than our values but still within variations to be expected under different experimental conditions. The estimated uncertainty in reading the chromatograms is $\pm 0.02 R_f$ unit. In the four carrier solutions, the four uracil samples have the same R_f values within the uncertainty; and no impurities were detected in any of the samples. Thus, all four samples are of equal purity (probably 95% or more) within the limits of chromatographic detection.

Table 2. R_f values for the uracil samples in NH_4OH (aq, $1 \text{ mol}\cdot\text{L}^{-1}$) solutions on fluorescent TLC plates and two papers with four carrier solutions, A, B, C, and D.

Uracil Sample No.	A ^a			B ^a			C ^a			D ^a		
	TLC	P-1	P-40	TLC	P-1	P-40	TLC	P-1	P-40	TLC	P-1	P-40
1	0.65	0.69	0.70	0.57	0.62	0.70	0.71	0.71	-	0.89	0.78	0.78
2	.65	.67	.71	.57	.62	.69	.72	.71	-	.90	.78	.77
3	.65	.69	.72	.57	.62	.69	.72	.71	-	.93	.77	.76
4	.64	.66	.72	.56	.62	.71	.72	.71	-	.91	.78	.75
NAS [10] ^b			0.63			0.59			0.70			0.70

^aThe compositions of the carrier (or tank) solutions was as follows:

Soln A: 5 parts of iso-butyric acid + 3 parts of NH_4OH (aq, $0.5 \text{ mol}\cdot\text{L}^{-1}$).

Soln B: 7 parts of iso-propyl alcohol + 1 part of conc. NH_4OH + 2 parts of H_2O .

Soln C: 7 parts of 95% ethyl alcohol + 3 parts of sodium acetate (aq, $1 \text{ mol}\cdot\text{L}^{-1}$).

Soln D: H_2O adjusted to pH 10 with NH_4OH (~ 1 drop of conc. NH_4OH in 300 mL H_2O).

^bThe reference lists HCl (aq, $1 \text{ mol}\cdot\text{L}^{-1}$) as the solvent; this may have been an error since we found uracil to be insoluble in HCl (aq, $1 \text{ mol}\cdot\text{L}^{-1}$).

2.1.3. Calorimetric Characterization

Measurements⁶ of the heat capacity of our samples of crystalline uracil at 298 K using a drop micro-calorimeter gave the following values for C_p° : Ura 1, (1.075 ± 0.008) $\text{J}\cdot\text{g}^{-1}\cdot\text{K}^{-1}$, and Ura 3, (1.075 ± 0.004) $\text{J}\cdot\text{g}^{-1}\cdot\text{K}^{-1}$ [11]. The value used in later calculations was (120.5 ± 1.8) $\text{J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$.

Two measurements⁷ of the enthalpy of combustion of Ura 1 were made in June 1974 using an adiabatic bomb calorimeter described previously [12]. The ratios of the CO_2 in the actual products of combustion to the theoretical CO_2 in the products of combustion of pure uracil were 0.999 and 0.997 for the two measurements; this is another indication of the purity of the sample. The following values for the enthalpy of combustion were obtained: ΔH_c° (298.15 K) = -1717.73 and $-1717.36 \text{ kJ}\cdot\text{mol}^{-1}$. These may be compared with the value of (-1716.14 ± 0.28) $\text{kJ}\cdot\text{mol}^{-1}$ [13] from 9 measurements on a commercial sample of unknown purity; the products of combustion were not analysed.

⁶ By Ernesto Friere, Department of Pharmacology, University of Virginia, Charlottesville, VA.

⁷ By Walter H. Johnson, Center for Thermodynamics and Molecular Science, National Measurement Laboratory.

3. Enthalpy of Solution

The platinum-lined adiabatic solution calorimeter previously described [14] was used for the 29 measurements (between January 1974 and October 1976) of the enthalpy of solution of 7 uracil samples in water reported here. The calorimeter vessel contained approximately 300 mL of distilled water. The platinum sample holder has interchangeable cylinders; the two used in this work were 0.7 and 3.0 mL in volume. Since the solution of uracil proceeded without difficulty, a moderate stirring rate, 550 revolutions per min, was used.

In each experiment, the system was calibrated electrically before and after the uracil reaction. During the endothermic solution reactions, precisely measured electrical energy was added in most experiments to prevent a decrease in the calorimeter temperature and loss of adiabatic conditions. The calorimeter temperature was measured with a quartz oscillator thermometer system [1, 14]. The calibrations of this system and those of the standard cell and standard resistors used in the electrical energy measurements were given previously [1]. The general procedures for making the measurements and the methods for calculations were de-

scribed in detail [14]. The 1975 Table of Atomic Weights [15] was used in calculating the following molecular masses used in this work: uracil, 112.0878 and H₂O, 18.0152. For energy conversions, 1 thermochemical calorie = 4.184 joules.

The data for the enthalpy of solution measurements of uracil in water are given in table 3. The Experiment Number is a serial number for experiments with this calorimeter and indicates the chronological order of the experiments. The Reaction Period is the elapsed time between initiating the reaction and the beginning of the rating period which follows the reaction. T_{reaction} is the mean of the initial and final temperatures of reaction. The estimated calorimetric uncertainty for an experiment, Cal. Unc., is based on the duration of the reaction, the magnitude of the temperature change

from the reaction, and the standard deviation of the slope of the rating period following the reaction (see [1] for details). The heat of the solution reaction, Q_{reaction} , is given by the following equation:

$$Q_{\text{reaction}} = \Delta T_{\text{reaction}} \left(\frac{\epsilon_i + \epsilon_f}{2} \right) - q_{\text{vap}}$$

where the electrical energy equivalents (in J·K⁻¹) of the initial and final systems are ϵ_i and ϵ_f , the temperature change due to the solution reaction is $\Delta T_{\text{reaction}}$, and the heat of vaporization of water into the air space in the sample holder upon opening is q_{vap} . $\Delta T_{\text{reaction}} = \Delta T - \text{Et} \left(\frac{\epsilon_i + \epsilon_f}{2} \right)^{-1}$ where ΔT (not given in table 3) is the net

Table 3. Data for measurements of the enthalpy of solution in H₂O of various samples of uracil.

Expt. No.	Size Code	Sample Mass x10 ⁵ g	H ₂ O Mass -30.0g g	Concentration x10 ⁵ mol/kg	Reaction Period min	T _{reaction} K	Cal. Unc. x10 ² J	Electrical Energy Equivalent - 1730 J/K		$\Delta T_{\text{reaction}}$ x10 ⁵ K	Et x10 ⁷ J	q_{vap} x10 ³ J	$-Q_{\text{reaction}}$ x10 ² J	$\Delta H_m(T)$		corr. to 298.15 K J/mol	$\Delta H_m(298.15 \text{ K})$ J/mol
								Initial	Final					J/g	J/mol		
Ura 1: Calbiochem Lot 802190																	
904	U	10323	2.459	3045	12	298.172	28	8.74	7.80	1555	-----	2	2701	261.65	29328	-1	29327
905	U	12481	2.469	3681	12	298.072	18	8.53	7.97	1906	-----	2	3311	265.28	29735	+4	29739
906	U	12960	2.469	3823	24	298.152	20	8.14	7.64	2017	-----	2	3503	270.29	30296	0	30296
908	U	12434	2.404	3668	17	309.120	11	7.34	6.66	1958	-----	4	3397	273.20	30622	-628	29993
1112	2	90090	2.444	26575	32	314.383	4	6.94	6.76	14201	86904	20	24646	273.57	30664	-930	29734
1113	1	91682	2.454	27044	27	314.398	5	6.53	6.39	14381	88190	20	24951	272.15	30504	-931	29573
																	Mean = 29777
Ura 2: Eastman Lot 24A																	
1114	1	90922	2.444	26820	87	314.407	13	5.78	5.89	13490	88972	20	^c 24029	264.28	29623	-932	28691
1115	2	89825	2.459	26496	52	314.432	4	6.26	6.50	13674	86972	20	23724	264.11	29604	-933	28671
1116	4	62361	2.454	18395	22	314.433	13	6.29	4.67	9535	88427	22	16526	265.00	29704	-933	28771
1118	2	41556	2.025	12275	27	315.147	6	6.14	6.44	6348	86583	24	10997	264.43	29662	-974	28688
																	Mean = 28705
Ura 3: E-M Lot 4955541																	
1103	2	53503	2.479	15781	96	298.171	11	4.44	3.87	8040	91043	9	13934	260.43	29191	-1	29190
1104	2	90043	2.464	26559	67	314.174	7	7.65	7.29	13953	85617	20	24223	269.02	30153	-918	29235
1105	2	90508	2.494	26694	52	324.798	11	10.83	10.07	14232	86660	32	24738	273.32	30636	-1527	29109
1106	2	90162	2.484	26593	37	319.759	9	8.16	8.14	14026	86406	26	24533	270.10	30275	-1238	29037
1107	2	89920	2.459	26524	82	309.607	11	5.27	5.89	13774	85466	15	23890	265.68	29780	-656	29124
1108	2	90549	2.469	26708	47	314.392	8	8.13	8.40	13869	86905	20	24088	266.02	29818	-931	28887
1109	2	141796	2.454	41826	62	324.867	5	11.28	9.92	22421	86838	28	38999	275.04	30828	-1531	29297
1110	2	29683	2.454	8756	47	324.872	14	8.66	8.47	4732	88206	8	8218	276.86	31032	-1531	29501
1111	3	145985	2.479	43058	72	324.775	4	10.26	9.66	23007	85579	28	40003	274.02	30714	-1526	29188
																	Mean = 29174
Ura 3a: Twice recrystallized from H₂O																	
1119	U	89332	2.474	26349	72	314.419	10	6.99	6.55	13859	88997	20	24051	269.23	30178	-932	29246
1120	U	85448	2.469	25204	87	314.535	8	6.97	6.86	13227	86850	20	22954	268.63	30110	-939	29171
1121	U	54648	2.424	16121	62	314.580	13	5.72	5.92	8436	87774	22	14621	267.55	29989	-941	29048
																	Mean = 29155
Ura 3b: Thrice recrystallized from 90% EtOH																	
1122	U	106560	2.444	31433	82	314.374	6	6.87	6.79	16513	86900	19	28661	268.96	30148	-930	29218
1123	U	86790	2.469	25599	82	314.441	11	7.10	6.93	13481	87512	20	23397	269.58	30217	-933	29284
1124	U	102016	2.489	30088	127	314.785	6	7.03	6.99	15963	87600	19	27709	271.61	30445	-953	29492
																	Mean = 29331
Ura 3c: Sublimed																	
1198	U	123611	2.379	36471	67	313.825	5	6.56	6.84	18811	88862	27	32643	264.08	29600	-898	28702
1199	U	99039	2.419	29217	57	313.334	5	6.01	6.26	15133	88206	29	26244	264.99	29702	-870	28832
1200	U	84321	2.429	24874	47	313.897	6	5.56	6.14	12923	91369	30	22402	265.68	29779	-902	28877
																	Mean = 28804
Ura 3d: Unsublimed residue from sublimation																	
1201	U	38109	2.454	11241	32	313.342	7	5.59	5.25	5971	86722	34	10328	271.01	30377	-870	29506

^aSize code: 1, the sample was retained on No. 35 standard sieve (SS); 2, the sample passed No. 35 but was retained on No. 100 SS; 3, the sample passed No. 100 but was retained on No. 200 SS; 4, the sample passed No. 200 SS; and U, the sample was unieved by this laboratory.

^bThe smallest sample cylinder, 0.7 ml, was used in Expts. 904-908, and 1110; the largest cylinder, 3.0 ml, was used in all other experiments. The samples from the products of sublimation, Ura 3c and 3d, were transferred in a dry box where the relative humidity (RH) was zero; all other samples were transferred in the laboratory atmosphere where RH = 0.35 ± .10.

^cA correction of 6.34 J was added to the heat of reaction because of a temporary malfunction of the control for the adiabatic shield near the end of the reaction period where an increase in temperature occurred and was then followed by a continuation of the same time-temperature slope.

temperature change resulting from the endothermic solution reaction and the electrical energy added, EIt . $q_{\text{vap}} = \Delta H_{\text{vap}} \left(V - \frac{s}{d} \right) (1 - RH)$ where ΔH_{vap} is the enthalpy of vaporization of water per unit volume at the mean temperature of reaction, V is the internal volume of the sample holder, s is the mass of sample, d is the density of the sample, and RH is the relative humidity of the atmosphere in which the sample was transferred to the sample holder (for the transfer in the dry box, $RH = 0$; in the laboratory atmosphere, $RH = 0.35 \pm 0.10$). The enthalpy of solution per gram at the temperature of reaction and at the concentration of the measurements is $\Delta H_m(T) = -Q_{\text{reaction}} (\text{Sample mass})^{-1}$.

The lengths of the reaction periods given in table 3 are dependent on the temperature of reaction, the amount of sample, and the sample itself. For example, in Expt. No. 1112, 1115, and 1104 with Ura 1, 2, and 3 at the same temperature and concentration, the reaction periods were 32, 52, and 67 min, respectively. In some preliminary experiments, incomplete reactions were believed to have been caused by large particles in the samples; sieving the sample greatly reduced the problem. However, small amounts of undissolved material were visible at the end of Expt. No. 1103 and 1107 which were both at lower temperatures than most of the other experiments. The measurements with Ura 2 using various particle sizes (see size code in table 3) indicate that the smaller particles dissolved more quickly, but there was no significant difference in the enthalpies of solution. Apparently sieving was not necessary in the samples which had been vacuum-dried (Ura 3a, 3b, 3c, and 3d). Under comparable conditions, the reaction periods for Ura 1 were generally shorter than for the other samples; and it will be shown later that the pH of the final solution and the enthalpy of solution were somewhat larger than those of the other samples; the reason for this is unknown.

The change in the enthalpy of solution of uracil with temperature, ΔC_p , was obtained from 14 experiments with Ura 3, 3a, and 3b (omitting Expt. 1110 because of the low concentration). These data are given in table 3 and plotted in figure 1 where the straight line is the result of a least squares fit to the data for T_{reaction} and $\Delta H_m(T)$ to a linear equation. The slope of this line is $(57.3 \pm 5.9) \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$ and the uncertainty is the standard error. Thus, in the temperature range, $298 \text{ K} < T < 325 \text{ K}$, $\Delta C_p = (57 \pm 13) \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$ with the uncertainty at the 95 percent confidence level. This value was used to calculate the correction to $T = 298.15 \text{ K}$ given in table 3 which was added to $\Delta H_m(T)$ to obtain the enthalpy of solution at the standard temperature and at the concentration of the measurement.

In figure 1 the radius of a circle is equal to the estimated calorimetric uncertainty (about 0.1%) for each experiment. It is evident that about one-half of the circles are not close to the line. Sample inhomogeneity is probably the cause of this

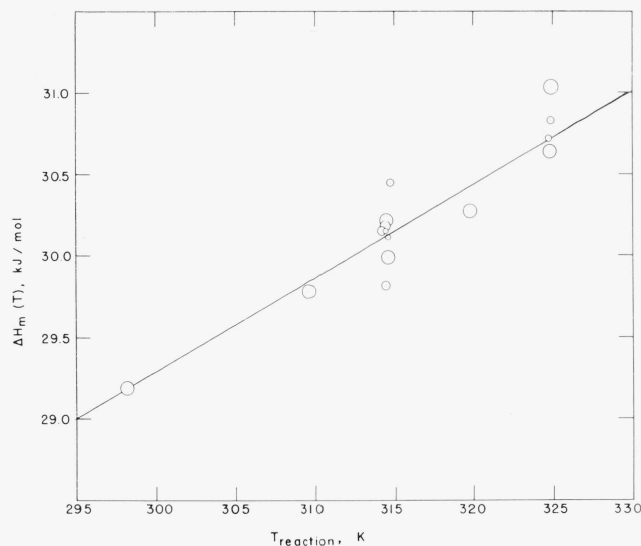


FIGURE 1. Plot showing the relationship of the enthalpy of solution of uracil in water and the temperature of reaction. The slope of the straight line is $\Delta C_p = (57 \pm 13) \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$.

additional uncertainty of 0.1 to 0.2 percent of the enthalpy of solution.

Figure 2 is a plot of all values for $\Delta H_m(298.15 \text{ K})$ in table 3 versus the concentration of uracil in the final solutions. The points for the various samples are distinguished by different symbols, and the radius of a circle (or a circle circumscribed by the other geometric figures) is equal to the estimated calorimetric uncertainty for the experiment. There appears to be no significant change in the enthalpy of solution in the concentration range of 10 to $45 \text{ mmol} \cdot \text{kg}^{-1}$ based on the data for Ura 3 (open circles); the one value near $9 \text{ mmol} \cdot \text{kg}^{-1}$ is a little larger than the others, but may still be within the uncertainty due to sample inhomogeneity.

The four values for Ura 1 (squares in fig. 2) between 3 and $4 \text{ mmol} \cdot \text{kg}^{-1}$ suggest the possibility of an increase in the enthalpy of solution at the lower concentration, however, the two values near $27 \text{ mmol} \cdot \text{kg}^{-1}$ are also higher than those for the other samples. Thus, these higher values for Ura 1 are probably characteristic of this sample. The larger calorimetric uncertainties at the low concentrations are to be expected.

The measurements with Ura 3 (open circles) agree within the homogeneity uncertainty with those of the recrystallized samples, Ura 3a (right half-shaded circles) and Ura 3b (left half-shaded circles). The three experiments with the sublimed sample, Ura 3c (lower half-shaded circles), are all at the lower limit of the range of measurements with Ura 3, 3a, and 3b; and the single measurements with the unsublimed residue, Ura 3d (upper half-shaded circle) is at the upper limit of that range. The four measurements of Ura 2 (diamonds) are lower than any of the others.

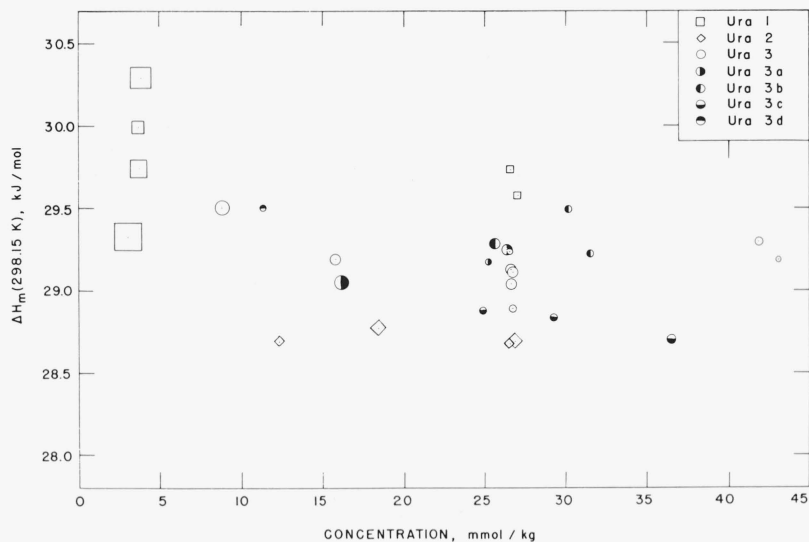


FIGURE 2. Plot showing that the enthalpy of solution of uracil in water is independent of concentration in this range, and that there are differences between various samples which cannot be resolved on the basis of analytical data.

See text for description of the samples represented by the various symbols.

The calorimetric measurements on Ura 1, 2, and 3 were made on the materials as received (except for sieving in some cases) and without drying or further purification. If the mean values for ΔH_m (298.15 K) are corrected for H_2O found in the determination of volatile matter (Ura 1, 0.25 mol%; Ura 2, 0.75 mol%; and Ura 3, 0.31 mol%) we obtain 29.85, 28.92, and 29.26 $\text{kJ}\cdot\text{mol}^{-1}$, respectively, for the mean enthalpies of solution. It was assumed that the other samples, which were vacuum dried for long periods, contained no water although the elemental analysis of Ura 3a introduces a question as to the validity of this assumption.

Measurements of enthalpies of solution have detected differences in the various uracil samples which were not evident from the analytical data; this was also true for adenine, thymine, and cytosine [1, 2, 3]. The mean values for ΔH_m (298.15 K) in $\text{kJ}\cdot\text{mol}^{-1}$, corrected for H_2O where it was measured, are (in descending order): Ura 1, $29.85 \pm 0.35 \text{ kJ}\cdot\text{mol}^{-1}$; Ura 3d, 29.51; Ura 3b, 29.33 ± 0.36 ; Ura 3, 29.26 ± 0.13 ; Ura 3a, 29.16 ± 0.25 ; Ura 2, 28.92 ± 0.07 ; and Ura 3c, 28.80 ± 0.23 . The experimental uncertainties are at the 95 percent confidence level. The single value for Ura 3d was eliminated from consideration because of the apparent decomposition evidenced by the discoloration of the sample. The low value for the sublimed sample, Ura 3c, was rejected because of the probability of a tautomer or of a lower order of crystallinity as was found for sublimed adenine [1]. Ura 3 was probably of high purity because the enthalpies of solution of the recrystallized sample, Ura 3a and 3b, agreed within the uncertainties with that of the parent material. There was no analytical evidence that the

purities of Ura 1 and Ura 2 were higher or lower than that of Ura 3. Therefore, the mean of the five values for Ura 1, 2, 3, 3a, and 3b was taken as our best value for the enthalpy of solution of uracil in water, and ΔH (298.15 K) = $(29.3 \pm 1.2) \text{ kJ}\cdot\text{mol}^{-1}$ in the concentration range 10 to 45 $\text{mmol}\cdot\text{kg}^{-1}$. The assigned uncertainty is twice the square root of the sum of the squares of the individual uncertainties. This uncertainty is large enough to include uncertainties in the measurements and in the purity of the samples.

The pH of solutions of Ura 1, 2, and 3 containing approximately 25 $\text{mmol}\cdot\text{kg}^{-1}$ was measured and found to be significantly higher in the solution of Ura 1 than in those of Ura 2 or 3; the measured pH was 5.2 for Ura 1, 4.2 for Ura 2, and 4.5 for Ura 3. Since the H^+ concentration of the final solutions was 4 to 5 orders of magnitude smaller than the ionization constant, 3×10^9 [4], and the correction to infinite dilution was negligibly small, our measured value for the enthalpy of solution was considered to be equal to that at infinite dilution.

4. Discussion and Summary

Larsen and Magid [7] reported $(26.78 \pm 0.84) \text{ kJ}\cdot\text{mol}^{-1}$ for the enthalpy of solution in H_2O at infinite dilution for a sample of uracil which was "carefully purified by standard techniques"; no analytical data were given. The results from six measurements were "extrapolated to infinite dilution by linear least squares analysis." The mean of four of these measurements in the concentration range of our work is $(21.98 \pm 0.13) \text{ kJ}\cdot\text{mol}^{-1}$ (the uncertainty is the standard

deviation of the mean) which is 25 percent lower than our value. However, the uncertainty of the extrapolated value falls within the lower limit of our assigned uncertainty.

From their solubility measurements, Scruggs et al. [5] calculated ΔH (37°C) = 6700 cal·mol⁻¹ for the enthalpy of solution of uracil in water. Using the ΔC_p value determined in this work, we obtain 6536 cal·mol⁻¹ or 27.34 kJ·mol⁻¹ at 298.15 K which is nearly 7 percent less than our value but within the uncertainty assigned.

We have shown that significant differences exist in the enthalpies of solution of uracil samples from different sources and these differences cannot be resolved on the basis of the analytical results. Until the purity of uracil samples can be defined more accurately than was done in this work, the value for the enthalpy of solution in water is taken as

$$\Delta H^\circ(\infty, 298.15 \text{ K}) = (29.3 \pm 1.2) \text{ kJ} \cdot \text{mol}^{-1}$$

and

$$\Delta C_p^\circ = (57 \pm 13) \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}, 298 \text{ K} < T < 325 \text{ K}.$$

No change in the enthalpy of solution with concentration was detected in this work.

Other useful thermodynamic data may be calculated with these values. The apparent molal heat capacity of uracil at infinite dilution, C_{p2}° , is (178 ± 15) J·mol⁻¹·K⁻¹ which is the sum of the ΔC_p° (above) and the C_p° for the crystalline uracil given in section 2.1.3. From the solubility measurements of Scruggs, et al. [5] we calculate the molal solubility at 298.15 K to be (0.0269 ± 0.0013) mol·kg⁻¹, and $\Delta G^\circ = -RT \ln m = 9.0 \pm 0.4 \text{ kJ} \cdot \text{mol}^{-1}$. Combining this with our value for the enthalpy of solution we obtain

$$\Delta S^\circ = \frac{\Delta H^\circ - \Delta G^\circ}{T} = (68.1 \pm 4.2) \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}.$$

The average of 4 measurements of the density of uracil was (1.60 ± 0.01) g·mL⁻¹.

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