

Care should be taken in handling these materials for during work on the hexenyl compounds the hands of the investigator became poisoned. No remedies appeared to help the itching and burning. The affected parts dried up within three weeks leaving a yellow scar which soon disappeared.

Heptenyl Derivatives

Diheptenylpyrogallol, $(C_7H_{13})_2C_6H(OH)_3$.—This synthesis followed the procedure given for dihexenylpyrogallol (II). From 0.4 mole of pyrogallol and 0.8 mole of 1-bromo-2-heptene there was obtained 100 g. of crude reaction product (soluble in benzene and not extracted by alkali) which gave rise to 10 cc. of distillate in a closed system at 200° (0.001 mm. or less). This 10-cc. portion was fractionated in the Hickman still: (a) 1 cc., n^{20}_D 1.4596; (b) 2.8 cc., refractionated into five cuts respectively of n^{20}_D 1.4882, 1.5090, 1.5170, 1.5190 and 1.5201; (c) 5.5 cc., n^{20}_D 1.5201 and redistilled without change. Analysis of fraction (c) confirmed its identity as diheptenylpyrogallol.

Heptenylpyrogallol.—The alkaline solution from the preparation of diheptenylpyrogallol was acidified and extracted with benzene. Distillation in a closed system (150° , 0.001 mm.) removed the admixed pyrogallol. Further heating to 200° gave rise to a water-insoluble distillate. It was washed with water and redistilled. The heptenylpyrogallol solidified on standing. It weighed 8 g. and melted at 52 – 53° .

The benzoyl ester of this compound, made by the Schotten-Baumann reaction with benzoyl chloride, was an oil.

Heptenylpyrogallol Ethyl Triether, $C_7H_{13}C_6H_2(OC_2H_5)_3$.—Heptenylpyrogallol (2.4 g.) was ethylated by stirring for one and a half hours with 5.9 g. of ethyl sulfate and 50 cc. of 20% sodium hydroxide. After standing overnight, the oil which separated was distilled twice in the Hickman still; yield, 1.8 cc. The two final fractions collected gave n^{20}_D values of 1.5082 and 1.5122. The former predominated and was analyzed. Since heptenylpyrogallol gave rise to this ethyl triether, it excludes the possibility that the former was a heptenyl monoether.

Summary

Pyrogallol alkenyl ethers rearrange into alkenylpyrogallols at temperatures of about 200° .

Various allyl, hexenyl and heptenyl derivatives of pyrogallol are included in this study. Most of the compounds are oils and their low vapor pressure necessitates the use of a molecular still for distillation.

Bactericidal data for several of these compounds are included.

EVANSTON, ILLINOIS

RECEIVED MARCH 18, 1935

[CONTRIBUTION FROM THE WILLIAM G. KERCKHOFF LABORATORIES OF THE BIOLOGICAL SCIENCES, CALIFORNIA INSTITUTE OF TECHNOLOGY]

Thermal Data. IV. The Heats of Combustion of Adenine, Hypoxanthine, Guanine, Xanthine, Uric Acid, Allantoin and Alloxan

BY ROBERT D. STIEHLER¹ AND HUGH M. HUFFMAN

In continuation of our plan,² of obtaining thermal data on compounds of physiological interest, we present in this paper the combustion data on seven organic compounds containing nitrogen.

Calorimetric Method and Apparatus

The method and apparatus used were essentially those described in a previous communication.³ Several minor changes have been made which tend to increase the precision of the measurements. We have adopted the constant range method which requires that the initial and final temperatures of all combustions be the same within narrow limits. For convenience in attaining the initial temperature the calorimeter was equipped with an auxiliary heating coil. We have also used exclusively the platinum wire technique³ in which the mass of the filter paper

has been arbitrarily standardized and kept constant within very narrow limits. The accuracy of the mass determinations of the combustible materials was increased by making all weighings on a micro balance sensitive to 0.001 mg. Finally by using a platinum crucible of about 3 g. mass we have decreased the number of combustions in which carbon resulted. The combustions were all made with an oxygen pressure of 30 atm. and with 1 ml. of water in the bomb.

Calibration

Owing to changes in our calorimeter new determinations of its energy equivalent were necessary. These measurements were made at varying intervals throughout the experimental period in order to check the constancy of the system. To determine the energy equivalent we have burned Bureau of Standards benzoic acid standard sample No. 39d. The isothermal heat of com-

(1) National Research Fellow.

(2) Huffman and Borsook, *THIS JOURNAL*, **54**, 4297 (1932).

(3) Huffman and Ellis, *ibid.*, **57**, 41 (1935).

bustion of this material at 25° under the standard conditions as proposed by Washburn,⁴ has been recently determined by Jessup and Green⁵ as 26,419 International joules per gram true mass. This value when converted to calories by multiplying by the factor 1.0004/4.185 becomes 6315.3 cal._{15°}. The mean of eight determinations, calculated in the usual manner, gave as the energy equivalent of our calorimeter at 25°, with 2775.5 g. of water but minus the contents of the bomb, the value 3157.3 cal._{15°} with a mean deviation of 0.2 calorie and an extreme deviation of 0.4 calorie.

As a further check on the accuracy of our calorimetry, we have burned salicylic acid from three different sources, namely, Kahlbaum, Schuchardt (both for calorimetric analyses) and Merck reagent. These compounds were further purified by us by recrystallizing from water and carefully drying over phosphoric anhydride *in vacuo*. The results of five combustions at 25° on each of these samples gave the following mean values for $-\Delta U_B$ in cal._{15°} per gram, Kahlbaum 5233.5 \pm 0.4, Merck 5233.3 \pm 0.4 and Schuchardt 5234.7 with a final mean of 5233.9 \pm 1.5. The limits chosen are in each case the extreme deviation from the mean. Verkade⁶ has proposed a value for salicylic acid of 5237.7 cal._{15°} per gram true mass and at 19.5°. Corrected to 25° and in terms of the new value for benzoic acid this becomes 5234.5 cal._{15°} in excellent agreement with our value of 5233.9 cal._{15°}.

Units.—The unit of energy used throughout this paper is the defined conventional calorie which has been derived from the International joule by multiplying by the factor 1.0004/4.185. The unit of mass is the gram true mass which is derived from the mass in air against brass weights by use of a suitable correction factor. In cases where the density of the material in question was not available in the literature, we have made rough estimates from the mass and volume of the pelleted substance.

Corrections.—In addition to the energy liberated by the substance burned, three other sources of energy are present. These are (1) the electrical energy of firing, (2) the energy from the combustion of the filter paper fuse and (3) the energy from the formation of nitric acid. The effects of absolute errors in (1) and (2) were made negligibly small by having the conditions of volt-

age, resistance and time and of the mass of the filter paper (determined by weighing for each combustion) the same within narrow limits for all of the combustions including those of calibration. The electrical energy was always 1.4 \pm 0.2 calorie and the energy from the filter paper was kept between the limits 14.8–16.8 calories with one or two exceptions.

Since all of our results were calculated for the reaction in which the end-products were H₂O(l_{iq.}), CO₂(g_{as}) and N₂(g_{as}), a correction was necessary for the small amounts of nitric acid produced. The quantity of nitric acid formed in a combustion was determined by titration with dilute sodium hydroxide using brom cresol green as the indicator. The amount of nitric acid formed from any particular compound was fairly constant but was not the same for different compounds. Furthermore, the concentration of the nitric acid was different for each compound due to different amounts of water formed in the combustion. However, since the heat of dilution of nitric acid is small in the range of concentrations with which we are concerned, one to two molal, we have used the value 14,800 calories which we have calculated from the data in the "International Critical Tables"⁷ as the energy evolved in the formation of one mole of aqueous nitric acid from nitrogen, oxygen and water at 25° and at constant volume. In addition to nitric acid small amounts of nitrous acid are formed. Tests for this substance, by a sensitive colorimetric method,⁸ on combustions selected at random have always shown it to be negligible.

Occasional combustions showed small deposits of carbon in the crucible. The mass of this carbon was determined and a correction applied on the basis of a loss of heat evolution of 8 calories per milligram of carbon formed. The amount of carbon deposited rarely exceeds 0.1 mg.

The mean temperature of all our combustions has been 25°. Hence, to correct the experimental data to the isothermal process at this temperature, we have used the equations and data of Washburn⁴ in conjunction with our own heat capacity data⁹ on the substance burned. The energy evolved in the isothermal bomb process per mole is represented throughout this paper by the symbol $-\Delta U_B$.

(7) "International Critical Tables," McGraw-Hill Book Co., New York, Vol. V.

(8) Treadwell-Hall, "Analytical Chemistry," John Wiley & Sons, Inc., New York, p. 306.

(9) Stiehler and Huffman, THIS JOURNAL, 57, 1741 (1935).

(4) Washburn, *Bur. Standards J. Research*, 10, 552 (1933).

(5) Jessup and Green, *ibid.*, 13, 491 (1934).

(6) Verkade, *J. chim. phys.*, 29, 297 (1932).

The values of the bomb process were corrected to the process $C_aH_bO_cN_d(s)_{,1 \text{ atm.}} + (a + (b - 2c)/4 - O_{2(g), 1 \text{ atm.}} = aCO_{2(g), 1 \text{ atm.}} + b/2H_2O(l)_{, 1 \text{ atm.}} + d/2N_{2(g), 1 \text{ atm.}}$ where the reactants and products are each at a pressure of 1 atm. by means of a correction factor calculated from the equations of Washburn.⁴ This factor was calculated on the assumption that nitrogen behaves essentially the same as oxygen in gas mixtures. The energy evolved in this process is represented by the symbol $-\Delta U_R$. From this quantity $-\Delta H_R$ the energy evolved in the isobaric process at 1 atm. was obtained by addition of the proper work term. Finally $-\Delta H^\circ_{298.1}$, the heat of formation from the elements, was calculated from $-\Delta H_R$ by use of $-68,313 \text{ cal.}$ ¹⁰ and $-94,240 \text{ cal.}$ ¹¹ respectively, for the heats of formation of H_2O and CO_2 .

Purity and Dryness of the Materials Used

In the determination of accurate values for the heats of combustion of organic compounds a knowledge of their purity is essential. In general, the usual analytical methods, such as nitrogen determinations, titrations, etc., are of no particular value except to show that the substance is roughly what it is supposed to be. In addition to the possibility of contamination with organic or inorganic impurities, there is always the problem of the removal of the last traces of water.

To assure ourselves of the purity of the compounds, we have used two general methods. The first consists in burning samples from different commercial sources or prepared by different methods; the second of burning samples from successive crystallizations from a suitable solvent. At times we have resorted to a combination of the two methods. We feel that when the combustions are the same on the different samples the purity is well established.

The problem of drying the materials is a serious one. We have used three methods: (1) prolonged desiccation of the material *in vacuo* over phosphoric anhydride, (2) desiccation over drierite *in vacuo* at a temperature of 65–70°, and (3) treatment of the sample in air at a temperature of 100 to 110°, hereafter referred to as drying at 100°. When possible the material has been dried by each of these methods to see if a change in the combustion value was produced. This was not always possible since some of the compounds showed a tendency to decompose at elevated temperatures.

In the tables we have indicated in a brief manner the source, purification and drying of each sample which we have burned.

We have noted that the marked discrepancies in the combustion values obtained by different workers are often far outside of the experimental accuracy claimed for their measurements. This may, of course, be due to a number of factors, such as for example poor calorimetry, impure

samples or improper drying. Another possible source of these discrepancies has occurred to us, that is, the proper definition of the physical state of the compound. It is not enough to know that the composition of the substance corresponds to the assigned formula. Consistent results on different samples of the same compound may not be expected if polymorphous forms are used. Furthermore, in the case of amorphous materials the energy conditions are affected by the history as well as the PVT relations.

For these reasons we have, in addition to the name, formula and molecular weight, further defined these compounds by photomicrographs (Fig. 1) of their crystalline condition.

Preparation, Purification and Heats of Combustions of the Compounds

Adenine.—Yeast nucleic acid was hydrolyzed¹² by heating with sulfuric acid on a water-bath. The hydrolysate was neutralized to Congo red with concentrated ammonium hydroxide while still hot and then filtered. To the filtrate an excess of hot saturated picric acid solution was added and the adenine picrate filtered off. The picrate was twice recrystallized from 25% (by volume) acetic acid solution. The adenine picrate was then decomposed with hot 10% (by weight) sulfuric acid solution. The picric acid was extracted from the hot solution by toluene in a continuous extractor. Concentrated ammonium hydroxide was added to the solution after extraction and the adenine crystallized out. The precipitate of adenine was filtered from the mother liquor and dissolved in hot water, norite was added, the solution filtered and the adenine allowed to crystallize. The adenine thus obtained was twice more crystallized from redistilled water, preparation (a). A portion of the above preparation was crystallized from redistilled water, preparation (b). These two preparations appeared very different under the microscope (see Fig. 1). The 2x material was evidently adenine-3H₂O [adenine (a)] and the 3x material the anhydrous pyramids [adenine (b)] described by Levene and Bass.¹³ Several attempts which were made to obtain adenine-3H₂O by crystallizing small batches of the 2x material always resulted in the production of the pyramids. For this reason we were able to obtain combustion data on only one preparation of adenine (a).

In view of the fact that the appearance of adenine (a) and (b) is so different, the question arises as to whether this difference is due to polymorphism or merely to a difference in crystal habit. We have attempted to answer this question by means of combustion data obtained on these two different types of adenine. From our combustion data on adenine (a) it is apparent that it undergoes no transition, involving energy, in the temperature range 20 to 100°.

With adenine (b) we have not been able to obtain the same clear-cut results. When this material was dried in phosphoric anhydride vacuum at room temperature a combustion value much lower than that for adenine (a) was obtained. When dried *in vacuo* at 70° a higher value was obtained, which was, however, still lower than that for

(10) Rossini, *Bur. Standards J. Research*, **6**, 34 (1931).

(11) Parks and Huffman, "Free Energies of Some Organic Compounds," The Chemical Catalog Co., New York, p. 45.

(12) Jones, "Nucleic Acids," Longman, Green & Co., New York, 1920, p. 107.

(13) Levene and Bass "Nucleic Acids," The Chemical Catalog Co., New York, p. 117.

adenine (a). These samples were observed to decrease in mass with more drastic heating treatment. The problem then became one of deciding whether the apparent difference in combustion value was due to polymorphism or to tenaciously held water. To decide this question a group of samples of adenine (b) were first dried to constant weight in the vacuum oven. Portions of these samples were then transferred to the 100° oven and again dried to constant weight. These two groups of samples were then burned. Those which were dried at 100° agreed with those for adenine (a) and were higher than those dried at 70° by an amount which could be accounted for on the basis that the additional loss in mass was water.

From the above results we are inclined to believe that these two materials are not polymorphs, at any rate, when anhydrous. Since adenine (a) crystallizes from water with three molecules of water, it may be that on losing this water the ghosts retain the shape of the hydrated crystal but are actually made up of submicroscopic crystals of the form of adenine (b). Duplicate Dumas nitrogen determinations on the 2x material gave a mean value 51.98%, calcd. 51.85%. The ash content was found to be negligible.

Hypoxanthine.—A solution of adenine was treated with nitrous acid as described by Levene and Bass.¹³ The hot solution thus obtained was neutralized to Congo red (acid to litmus). The hypoxanthine which crystallized out on cooling was filtered off and redissolved in hot water. This solution was treated with norite, filtered and the hypoxanthine crystallized out in the cold. The crystals thus obtained were subjected to two additional recrystallizations from redistilled water, preparation (a).

A portion of this sample was subjected to an additional recrystallization from redistilled water (preparation (b)). Dumas nitrogen determinations on the 2xH₂O material gave 41.30%, calcd. 41.20%. The ash content was found to be negligible.

Guanine.—The precipitate obtained in the hydrolysis of the nucleic acid, described under the adenine preparation, was dissolved in the minimum amount of hot 5% hydrochloric acid, treated with norite, filtered and precipitated hot with concd. ammonium hydroxide (alkaline to Congo red, acid to litmus). The precipitate was again treated by the above procedure, the guanine precipitate thus obtained was put through the same process for the third time except this time the hydrochloride was allowed to crystallize out in the cold. The hydrochloride was recrystallized once from 2% hot hydrochloric acid, twice more from hot 1.5% hydrochloric acid. The guanine hydrochloride thus obtained was dissolved in ten times its weight of hot redistilled water with just enough concd. hydrochloric acid to effect solution. This solution was filtered, and neutralized (Congo red) while hot with concd. ammonium hydroxide. The precipitate of guanine was filtered and washed free of chloride with hot redistilled water (preparation (a)). A portion of this preparation was dissolved in a dilute solution of ammonium hydroxide and precipitated by boiling off the ammonia (preparation (b)).

Duplicate Dumas nitrogen determinations on the 3xHCl material gave a value for nitrogen of 46.34%, calcd. 46.35%. Ash determinations showed this material to have of the order of 0.01 to 0.02% ash.

We have also burned a synthetic guanine obtained from Hoffmann-LaRoche. This material was further purified by us by dissolving in hot dilute ammonia and boiling off the ammonia. Two combustions on this material carefully dried at 100° gave a mean value of 3973.1 ± 0.4 calories. This substance did not appear to be crystalline under the microscope and the high value may be due to its being amorphous. Furthermore, the analyses (kindly supplied by Hoffmann-LaRoche) on the original material showed the nitrogen content to be only 99.2% of the theoretical. Due to the small quantity of the substance available, we were unable to attempt further purification. In view of the above we are inclined to believe that the value we have given is the better of the two and we are presenting it as a preliminary value until we can do further work to definitely decide this point.

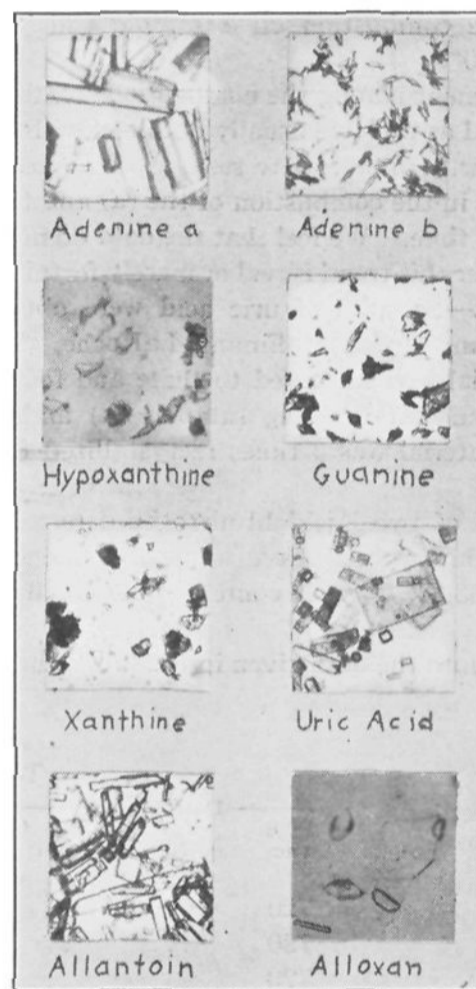


Fig. 1.

Xanthine.—This material was obtained from two sources. The first was prepared by the action of nitrous acid¹³ on the guanine obtained from nucleic acid. The xanthine thus obtained was purified by dissolving in hot dilute (3–5%) ammonium hydroxide and treating with norite. This solution was filtered and the xanthine precipitated by boiling off the ammonia. This procedure was repeated twice with norite and finally two times without norite (preparation (a)). A portion of this material was subjected to an additional precipitation from ammonium hydroxide (preparation (b)).

In addition to the above preparation a synthetic product, made by the reduction of uric acid, obtained from Hoffmann-LaRoche, was subjected to an additional precipitation from ammonium hydroxide (preparation (c)).

All three of these preparations were slightly yellow in color. One Dumas nitrogen determination on the Hoffmann-LaRoche material gave, nitrogen found 36.83%, theoretical 36.84%. Determinations showed these materials to have less than 0.01% ash.

In addition to the values given in the table other combustions were done on all three of these preparations which had been dried to constant weight, both in the vacuum oven at 70° and in phosphoric anhydride vacuum at room temperature. The results of these combustions were in beautiful agreement, yielding a mean value of 3397.6 ± 0.6 cal. However, two of the samples used in the work, which were dried to constant weight in the vacuum oven and then treated at 100° lost additional mass which just accounted for the increased combustion value on the assumption that water was lost. To be sure that all of the water was removed by desiccation at 100°, we have included one combustion on a sample which had been heated to 140°.

The agreement among the combustions on this material is not as good as we have usually obtained with other compounds. Furthermore, there seems to be a trend toward lower values in the combustion of the (a) and (c) samples, with heating time. We feel that the data do not definitely prove whether this trend is real or merely fortuitous.

Uric Acid.—Samples of uric acid were obtained from Pfanstiehl and from Hoffmann-LaRoche. The Pfanstiehl material was subjected to three and four recrystallizations from water giving samples (a) and (b). The H. L. R. material was 3 times recrystallized from water, sample (c).

The mean of two Kjeldahl nitrogen determinations on the Pfanstiehl material gave a mean value of 33.31%, theoretical 33.34%. Ash content was found to be less than 0.01%.

In addition to the data given in the table, three combus-

tions on sample (a) dried *in vacuo* gave a result about 1.3 calories lower. This material tends to gain weight rapidly when exposed to the air.

Allantoin.—Samples of allantoin were obtained from Hoffmann-LaRoche and from Eastman. They were further purified by recrystallization from redistilled water once and three times, respectively, samples (a) and (b).

The mean of two Kjeldahl nitrogen determinations on the Eastman product gave a mean value of 35.26%, theoretical 35.44%. Ash content was found to be negligible. This material was optically inactive.

In addition to the results given in the table, combustions were done on samples which had been dried at 100°. These combustions showed a tendency to increase with drying time and the pellets showed signs of charring. These results have not been considered in obtaining the final value for the heat of combustion of allantoin.

Alloxan.—Materials obtained from Eastman and from Hoffmann-LaRoche were burned without further purification, samples (a) and (c), and after recrystallizing once from redistilled water, samples (b) and (d).

Three Kjeldahl nitrogen determinations on the sample from Hoffmann-LaRoche gave for the nitrogen content 17.42%, theoretical 17.50%. Ash content was found to be negligible. This material showed a tendency to decompose at 100° so no combustions were done on material dried at that temperature.

The experimental results of the combustions on these seven compounds are given in Table I.

In addition to the experimental values given in Table I we have also calculated the quantities $-\Delta U_B$, $-\Delta U_R$, $-\Delta H_R$, and $-\Delta H_f^\circ$ which we have previously defined. We have also calculated the temperature coefficient of ΔU_R . These

TABLE I
THE EXPERIMENTAL DATA

Sample	Desiccation			True mass	Total heat evolved, cal.	Cal. from HNO ₃	Total corr. in cal.	$-U_B/m$, cal. g. ⁻¹	Deviation
	P ₂ O ₅ vac.	Vac. 70° hours	Oven, 100°						
Adenine (a)	720	...	...	1.27680	6348.9	45.6	-62.9	4923.3	0.2
Adenine (a)	720	...	...	1.27420	6333.3	41.6	-59.4	4923.8	0.7
Adenine (a)	720	...	...	1.27530	6338.4	41.9	-58.7	4924.1	1.0
Adenine (a)	720	...	38	1.27520	6337.3	43.4	-60.8	4922.0	-1.1
Adenine (a)	720	15	...	1.27490	6334.9	40.5	-57.5	4923.8	0.7
Adenine (a)	720	...	16	1.27550	6338.9	41.3	-58.3	4924.0	.9
Adenine (a)	720	20	...	1.27560	6338.5	41.6	-59.0	4922.7	-.4
Adenine (b)	120	...	50	1.25740	6248.4	42.0	-59.7	4921.9	-1.2
Adenine (b)	120	...	44	1.27595	6337.8	42.9	-57.7	4921.9	-1.2
Adenine (b)	168	288	162	1.27525	6339.2	42.3	-60.9	4923.2	0.1
Mean								4923.1	$\pm .8$
Hypoxanthine (a)	940	...	...	1.46885	6340.7	39.8	-56.6	4274.1	-.6
Hypoxanthine (a)	940	...	...	1.46925	6336.9	39.2	-56.9	4274.2	-.5
Hypoxanthine (a)	940	...	...	1.46895	6333.7	36.6	-54.0	4274.9	.2
Hypoxanthine (a)	..	...	68	1.47135	6346.2	38.3	-55.6	4275.3	.6
Hypoxanthine (a)	..	...	93	1.46945	6338.9	39.4	-56.7	4275.2	.5
Hypoxanthine (b)	144	...	...	1.46985	6336.8	36.4	-53.5	4274.8	.1
Hypoxanthine (b)	96	20	...	1.47035	6340.1	38.2	-55.2	4274.5	-.2
Hypoxanthine (b)	200	...	24	1.46895	6334.2	38.1	-54.2	4274.7	.0
Mean								4274.7	$\pm .4$

TABLE I (Concluded)

Sample	Desiccation			True mass	Total heat evolved, cal.	Cal. from HNO ₃	Total, corr. in cal.	-U _B /m, cal. g. ⁻¹	Deviation
	P ₂ O ₅ vac.	Vac., 70°, hours	Oven, 100°						
Guanine (a)	720	...	45	1.58350	6335.8	45.3	-62.7	3961.5	-.1
Guanine (a)	..	...	96	1.58155	6322.9	41.2	-58.6	3960.9	-.7
Guanine (b)	..	192	...	1.58590	6340.8	41.2	-58.4	3961.4	-.2
Guanine (b)	..	192	...	1.58500	6334.5	38.7	-56.1	3961.1	-.5
Guanine (b)	..	120	...	1.58320	6332.5	39.2	-59.2	3962.5	.9
Guanine (b)	..	216	...	1.57870	6314.7	42.6	-59.8	3962.1	.5
Mean								3961.6	
Xanthine (a)	720	192	130	1.83910	6319.2	37.6	-55.2	3406.1	.7
Xanthine (a)	..	...	168	1.84050	6320.7	36.8	-54.0	3404.9	-.5
Xanthine (a)	..	...	430	1.84175	6322.8	37.6	-54.6	3403.4	-2.0
Xanthine (b)	..	...	112 ^a	1.84010	6323.7	38.1	-55.5	3406.4	1.0
Xanthine (b)	720	...	38	1.84660	6346.5	40.4	-57.6	3405.6	0.2
Xanthine (c)	2400	192	65	1.83800	6316.8	37.5	-54.6	3407.0	1.6
Xanthine (c)	..	...	170	1.83970	6320.1	38.0	-55.3	3405.4	0.0
Xanthine (c)	..	...	240	1.83685	6307.3	36.7	-53.8	3404.5	-.9
Mean								3405.4	≠ .9
Uric acid (a)	264	...	90	2.29715	6352.6	32.8	-50.0	2743.7	.5
Uric acid (a)	720	20	...	2.29470	6345.4	32.1	-49.6	2743.6	.4
Uric acid (a)	720	20	...	2.28860	6326.6	31.4	-48.6	2743.2	.0
Uric acid (b)	960	...	30	2.30600	6374.6	34.6	-50.5	2742.4	-.8
Uric acid (c)	48	96	120	2.28930	6331.6	34.4	-51.4	2743.3	.1
Uric acid (c)	48	96	144	2.29010	6333.6	34.3	-51.5	2743.2	.0
Mean								2743.2	≠ .3
Allantoin (a)	480	...	...	2.42150	6346.0	29.7	-46.9	2601.3	-.6
Allantoin (a)	..	88	...	2.41930	6342.9	31.1	-47.3	2602.2	.3
Allantoin (a)	..	88	...	2.42045	6345.5	29.5	-46.8	2602.3	.4
Allantoin (b)	..	41	...	2.41565	6334.5	31.8	-48.8	2602.1	.2
Allantoin (b)	..	96	...	2.41950	6340.7	30.8	-46.9	2601.3	-.6
Allantoin (b)	..	120	...	2.42230	6349.5	29.4	-46.6	2602.0	.1
Mean								2601.9	≠ .4
Alloxan (a)	120	...	...	3.6440	6311.5	17.4	-34.4	1722.6	-.2
Alloxan (a)	240	...	...	3.6556	6331.5	18.2	-35.7	1722.2	-.6
Alloxan (a)	240	...	...	3.6596	6341.1	16.5	-35.8	1723.0	.2
Alloxan (b)	144	...	...	3.6594	6338.1	17.9	-34.1	1722.7	-.1
Alloxan (b)	144	...	...	3.6595	6339.8	18.3	-34.9	1722.9	.1
Alloxan (b)	144	18	...	3.6579	6336.2	18.2	-34.5	1722.8	.0
Alloxan (c)	48	...	...	3.6532	6325.0	18.4	-35.6	(1721.6) ^b	(1.2)
Alloxan (c)	72	24	...	3.6566	6332.7	19.2	-33.2	1722.8	0.0
Alloxan (d)	72	24	...	3.6554	6334.3	18.9	-35.3	1723.2	.4
Mean								1722.8	≠ .2

^a Heated at 140°. ^b Not used in obtaining mean.

TABLE II
SUMMARY OF DERIVED DATA^a

Substance	Formula	Mol. wt.	Density	-ΔU _B , kcal. mole ⁻¹	-ΔU _R , kcal. mole ⁻¹	-ΔH _R , kcal. mole ⁻¹	-ΔH _f ^o , kcal. mole ⁻¹	ΔU _R /dT, cal. mole ⁻¹
Adenine	C ₅ H ₅ N ₅	135.079	1.4	665.01 ± 0.16	664.48 ± 0.21	663.74 ± 0.21	-21.76	26
Hypoxanthine	C ₅ H ₄ ON ₄	136.063	1.5	581.63 ± .09	581.09 ± .14	580.20 ± .14	27.63	22
Guanine	C ₅ H ₅ ON ₅	151.079	1.4	598.52	597.93	596.89	45.09	25
Xanthine	C ₅ H ₄ O ₂ N ₄	152.063	1.6	517.84 ± .30	517.20 ± .36	516.02 ± .36	91.81	18
Uric acid	C ₅ H ₄ O ₃ N ₄	168.063	1.89	461.03 ± .14	460.32 ± .20	458.84 ± .20	148.98	17
Allantoin	C ₄ H ₆ O ₃ N ₄	158.079	1.5	411.31 ± .10	410.73 ± .16	409.55 ± .16	172.35	28
Alloxan	C ₄ H ₄ O ₆ N ₂	160.047	1.6	275.73 ± .10	275.06 ± .16	273.58 ± .16	240.01	14

^a All thermal values are for 25°. See text for explanation of symbols.

values along with certain other auxiliary data appear in Table II.

Discussion of the Results

In choosing the limits of accuracy assigned to our measurements, we have not used the formulas derived from the probability equation, but in each case have used the extreme deviation from the mean. We feel that in most cases the purity of the compound has been well enough established so that absolute errors due to this cause have been eliminated. Where we have used the Washburn equations⁴ to calculate $-\Delta U_R$, we have arbitrarily increased the limits to include a possible error of 10% in the calculation of this correction.

In the calculation of $-\Delta H_f^\circ$, the heat of formation from the elements, we have not felt justified in assigning any absolute limits of error since this would involve the accuracy with which the heats of formation of carbon dioxide and water are known and in general for intercomparison these uncertainties will cancel, so that the uncertainties are merely those of the heats of combustion of the compounds involved.

All of these compounds with the exception of adenine have been burned by earlier workers. Berthelot¹⁴ has burned hypoxanthine and xanthine, Stohmann and Langbein¹⁵ have burned guanine and uric acid, Matignon¹⁶ has burned uric acid, allantoin and alloxan, and Emory and Benedict¹⁷ have burned uric acid and allantoin. In view of the low precision of the measurements of most of these authors, as well as the lack of experimental details in regard to the calorimetric procedure, methods of purification of the compounds and energy units used, it is possible to

(14) (a) Berthelot, *Ann. chim. phys.*, [7] **20**, 189 (1900); (b) Berthelot and Andre, *ibid.*, [7] **17**, 433 (1899).

(15) Stohmann and Langbein, *J. prakt. Chem.*, [2] **44**, 336 (1891).

(16) Matignon, *Ann. chim. phys.*, [6] **28**, p. 105, 299, 349 (1893).

(17) Emory and Benedict, *Am. J. Physiol.*, **28**, 301 (1911).

correct them so that they are only roughly comparable to our values. We have done this and the corrected values with the deviations from our values are shown in Table III. In all cases, except that of guanine, the deviation is less than 1%. We are not prepared to say why the difference is so great in this case. The differences, we believe, show the need for redetermination of practically all of the older values in the literature.

TABLE III
COMPARISON OF PRESENT DATA WITH VALUES FROM THE LITERATURE

Substance	Refer- ence	Older data		New value, kcal. mole ⁻¹	Differ- ence, %
		Value, kcal. mole ⁻¹			
Adenine	..	.....		663.74 ± 0.21	..
Hypoxan- thine	14a	581.2 ± 1.1		580.20 ± 0.14	0.17
Guanine	15	585.2 ± 1.8		596.89	-1.96
Xanthine	14b	511.4 ± 1.5		516.02 ± .36	-0.90
Uric acid	15	459.2 ± 1.2		458.84 ± .20	.08
Uric acid	16	460.1 ± 1.2		458.84 ± .20	.28
Uric acid	17	458.2 ± 1.2		458.84 ± .20	-.14
Allantoin	17	406.8 ± 1.2		409.55 ± .16	-.67
Allantoin	16	412.5 ± 0.7		409.55 ± .16	.72
Alloxan	16	275.4 ± 0.8		273.58 ± .16	.66

Acknowledgment.—We wish to express our thanks to Dr. Emory L. Ellis, of this Laboratory, for his preparation of the photomicrographs and assistance in several purification processes.

Summary

1. The combustion data at constant pressure and 25° on seven purine and pyrimidine derivatives have been presented.
2. From the experimental results in conjunction with other data the heats of formation of these substances have been calculated.
3. The results of this investigation have been compared with the older work and discrepancies from 0.1 to 2.0% were found.

PASADENA, CALIFORNIA

RECEIVED APRIL 2, 1935