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The Crystal Structure of the Monoclinic Form of Dilituric Acid Trihydrate

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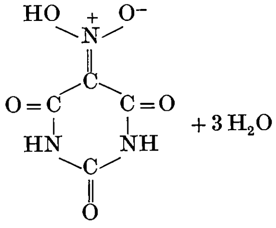
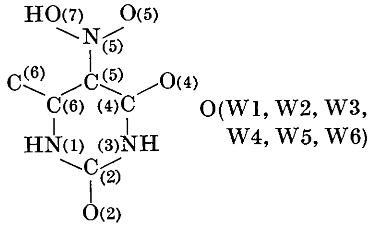
The structure of the monoclinic form of the trihydrate of dilituric acid (5-nitrobarbituric acid), $C_4H_3O_5N_3.3H_2O$, has been determined by a three-dimensional X-ray analysis using photographic data. There are two crystallographically independent dilituric acid molecules and six water molecules in the unit cell. Both the acid molecules are the aci triketo tautomeric form, in contrast to those in the anhydrous crystals which are the diketo monohydroxy tautomers (Bolton, 1963*a*). The dilituric acid molecules form hydrogen-bonded sheets which are approximately coplanar and parallel to (010). The water molecules are hydrogen-bonded in channels with an 'ice-like' hydrogen-bond chain parallel to the *b* axis. There are two unusually short oxygen–oxygen distances of 2·38 and 2·47 Å. There are 22 oxygen to oxygen and oxygen to nitrogen distances less than 2·9 Å, and only 18 protons, per asymmetric unit. Although the hydrogen atom positions have not been determined, it is believed that there are four bifurcated hydrogen bonds between the water molecules and dilituric acid molecules. There is no intramolecular hydrogen-bonding, as was observed in the diketo monohydroxy molecules of the anhydrous crystals (Bolton, 1963*a*).

Introduction

Dilituric (5-nitrobarbituric) acid trihydrate, (I), has been reported by Bolton (1963*a*) to exist in both a monoclinic and triclinic form of which the monoclinic form is stable in air at room temperature. The crystals of both hydrates show marked cleavage (monoclinic on (010), triclinic on (110)) and a preliminary investigation of their structures showed that, in both, the molecules lay in approximately planar sheets parallel to the cleavage plane and separated by 3·2 Å.



(I)



molecule A
molecule B

The present work was undertaken in order to investigate particularly the nature of hydrogen bonding with the water molecules and to compare the structure and tautomeric form of the dilituric acid molecule in the trihydrate crystals with that in the anhydrous crystals studied by Bolton (1963*a*).

Experimental

Colorless crystals of the monoclinic form of dilituric acid trihydrate were obtained by the slow evaporation of an aqueous solution at room temperature. The crystals were prisms elongated along *b* with well-developed (101) faces. The crystal data are as follows,

$$a=20\cdot911\pm0\cdot008\text{ Å},\ b=6\cdot452\pm0\cdot006\text{ Å},$$
$$c=14\cdot114\pm0\cdot005\text{ Å};\ \beta=110^\circ\,48'\pm10';$$
$$D_m=1\cdot690\text{ g.cm}^{-3},\ D_x=1\cdot695\text{ g.cm}^{-3};\ Z=8\ .$$

Space group, $P2_1/n$, from systematically absent spectra, $h0l$ for $h+l$ odd, $0k0$ for k odd. The cell parameters were measured with a General Electric XRD 5 diffractometer and single-crystal orienter, with Cu $K\alpha$ radiation. The intensity data were recorded from crystals of dimensions $0\cdot1\times0\cdot2\times0\cdot4$ mm on multifilm equi-inclination integrated Weissenberg photographs, with Cu $K\alpha$ radiation. The integrated intensities, which were measured by microphotometer, ranged from 1 to 5000 on an arbitrary scale. The recorded data consisted of five layers with a crystal mounted on *b* and nine layers with a crystal mounted on [101]. It was found that the intensities of the reflections fall off very rapidly with increasing *k*, a result which was attributed partly to considerable anisotropy in thermal vibrations and partly to the tendency for the crystal to deform along the [*b*] direction. Because of the difficulty in indexing the reflections in the higher layers, the structure analysis was based on the intensities of the reflections *hkl* up to a maximum value $k=4$. A total of 2500 independent reflections were

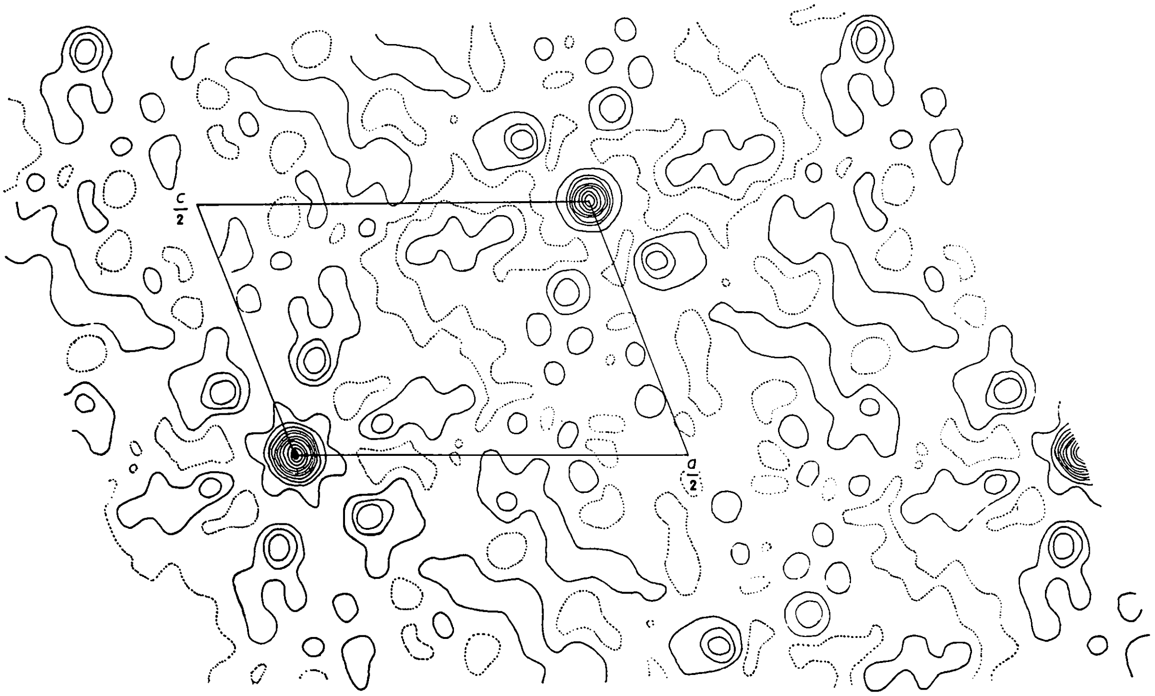


Fig. 1. Dilituric acid trihydrate. Patterson section $v=0$, showing the symmetrical distribution of intramolecular vector peaks around the origin.

measured, of which 688 were too weak to be estimated. These unobserved reflections were assigned intensities of half the minimum observable value. The data reduction was carried out by means of a series of FORTRAN programs for the IBM 7070 computer (Craven, 1963), which incorporated interlayer scaling by a least-squares method similar to that described by Rollett & Sparks (1960). The intensity data were not corrected for X-ray absorption.

The determination of the structure

Although the absent spectra were consistent with the space group $P2_1/n$, this did not necessarily eliminate the possibility of the space group being $P2/n$ or Pn. The very intense reflections 020 and 040 indicated that the structure consisted of almost coplanar sheets of atoms separated by $b/2$, and in such a structure the odd order of reflections 010 and 030 would be expected to be very weak, irrespective of whether the layers were related by twofold screw axes. However, it was observed that the structure was pseudo B centered (reflections hkl were, in general, weak when $h+l$ was odd), and this required the molecular sheets to lie close to the glide planes, rather than interleaving them. In this case, space groups Pn and $P2/n$ are improbable, since if the structure possessed either of these space groups, adjacent layers would be crystallographically independent and it was considered unlikely that there would be two *different* modes of molecular packing within a sheet of a given lattice periodicity. Although such possibilities were considered, only one trial structure could be derived which satisfied the requirements of molecular packing and hydrogen bonding and this corresponded to the space group $P2_1/n$. This model was later confirmed by the completed structure analysis.

The three-dimensional Patterson synthesis was calculated by a Fourier program of McMullan, Chu & Shiono (1963) for the IBM 7070 computer. In the section $v=0$, which is shown in Fig. 1, the set of six peaks surrounding the origin at a distance of 2·5 Å required the 5-nitrobarbituric acid molecules to be in one of two orientations related by a center of symmetry. Thus the crystallographically independent dilituric acid molecules within a given sheet must be related by a pseudo-center of symmetry. These results were in agreement with the trial model which had previously been derived. Assuming this trial model for a given sheet, it was necessary to study the Patterson

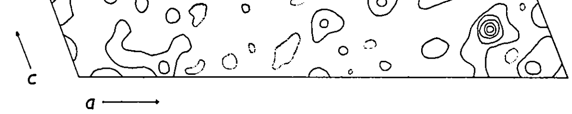


Fig. 2. Dilituric acid trihydrate. Patterson section $v=\frac{1}{2}$.

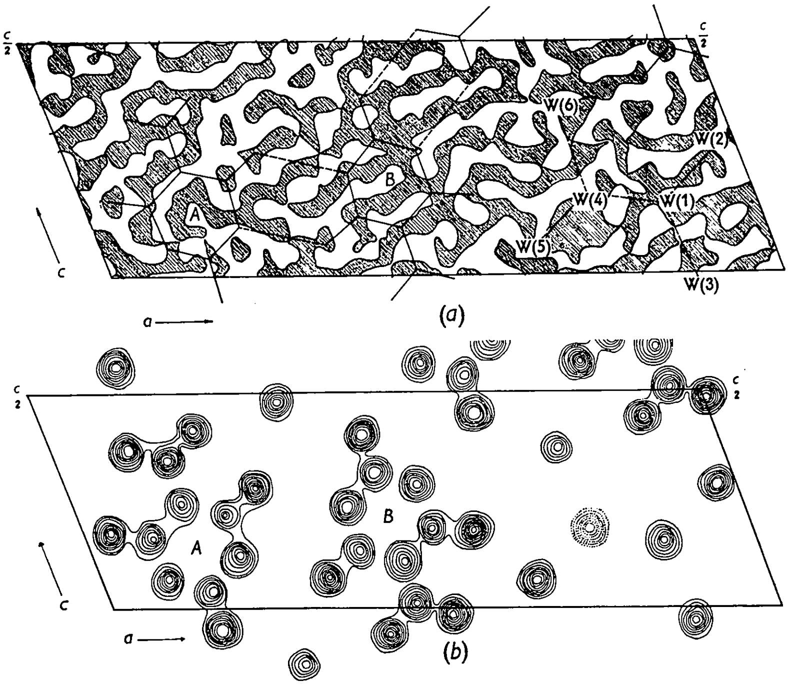


Fig.3. (*a*) Dilituric acid trihydrate. Difference Fourier synthesis at $y = \frac{1}{4}$; positive area unshaded, negative area shaded; maximum value $\pm 0{\cdot}30$ e.Å^{-3}. (*b*) Fourier synthesis at $y = 0{\cdot}250$, with W(4) (dotted lines) inserted from section $y = 0{\cdot}100$. Contour intervals 1 e.Å^{-3}, zero omitted.

Table 2. *Fractional atomic coordinates and thermal parameters*

(With estimated standard deviations in parentheses)

Molecule *A*

Atom	*x*	*y*	*z*	*B*11	*B*22	*B*33	*B*12	*B*23	*B*31
N(1)	0·5973 (0·0002)	0·2339 (0·0012)	0·5669 (0·0004)	2·19 (0·18)	4·82 (0·45)	2·57 (0·21)	−0·06 (0·44)	−0·07 (0·50)	1·27 (0·29)
C(2)	0·6542 (0·0003)	0·2304 (0·0013)	0·5420 (0·0004)	1·80 (0·20)	3·94 (0·53)	2·91 (0·27)	−0·84 (0·48)	−0·15 (0·61)	1·02 (0·35)
O(2)	0·6507 (0·0002)	0·2304 (0·0011)	0·4519 (0·0003)	2·20 (0·16)	8·02 (0·47)	1·74 (0·17)	−0·32 (0·43)	0·22 (0·47)	1·14 (0·24)
N(3)	0·7152 (0·0002)	0·2246 (0·0012)	0·6185 (0·0004)	2·70 (0·21)	5·70 (0·53)	3·58 (0·27)	−0·44 (0·50)	−0·10 (0·61)	1·66 (0·34)
C(4)	0·7237 (0·0003)	0·2189 (0·0011)	0·7201 (0·0004)	1·47 (0·17)	3·01 (0·46)	1·83 (0·21)	−0·02 (0·41)	0·17 (0·49)	0·84 (0·28)
O(4)	0·7843 (0·0002)	0·2160 (0·0009)	0·7825 (0·0003)	2·14 (0·17)	6·51 (0·43)	2·75 (0·20)	0·19 (0·41)	0·42 (0·49)	0·94 (0·28)
C(5)	0·6626 (0·0003)	0·2235 (0·0013)	0·7444 (0·0005)	2·24 (0·22)	4·02 (0·53)	3·23 (0·28)	0·45 (0·50)	−0·66 (0·61)	1·21 (0·37)
N(5)	0·6682 (0·0002)	0·2185 (0·0011)	0·8462 (0·0003)	1·77 (0·16)	3·78 (0·41)	1·64 (0·18)	−0·22 (0·38)	0·07 (0·43)	1·01 (0·25)
O(5)	0·7233 (0·0002)	0·2184 (0·0014)	0·9160 (0·0004)	1·98 (0·18)	11·49 (0·64)	2·22 (0·22)	0·09 (0·55)	0·08 (0·63)	0·71 (0·31)
O(7)	0·6130 (0·0002)	0·2224 (0·0010)	0·8667 (0·0003)	2·37 (0·16)	7·55 (0·47)	2·41 (0·19)	0·47 (0·43)	−0·09 (0·49)	1·42 (0·26)
C(6)	0·5969 (0·0002)	0·2326 (0·0013)	0·6641 (0·0004)	2·02 (0·18)	3·61 (0·52)	2·29 (0·22)	−0·63 (0·45)	−0·79 (0·53)	1·56 (0·28)
O(6)	0·5402 (0·0002)	0·2397 (0·0011)	0·6731 (0·0003)	2·32 (0·17)	8·74 (0·53)	3·19 (0·22)	−0·15 (0·47)	0·01 (0·57)	1·62 (0·28)

Table 2 (*cont.*)

Molecule *B*

Atom	*x*	*y*	*z*	B11	B22	B33	B12	B23	B31
N(1)	0·0248	0·2419	0·7874	2·50	7·60	2·72	−1·14	−0·17	1·22
	(0·0003)	(0·0013)	(0·0004)	(0·21)	(0·60)	(0·25)	(0·55)	(0·64)	(0·35)
C(2)	0·9683	0·2347	0·8135	1·83	4·06	2·06	0·74	−0·14	1·24
	(0·0002)	(0·0011)	(0·0004)	(0·18)	(0·50)	(0·21)	(0·44)	(0·52)	(0·28)
O(2)	0·9719	0·2362	0·9018	2·44	6·55	3·24	0·35	0·28	1·55
	(0·0002)	(0·0011)	(0·0003)	(0·17)	(0·46)	(0·21)	(0·43)	(0·51)	(0·28)
N(3)	0·9066	0·2260	0·7363	2·24	4·44	1·94	−0·29	−0·14	1·13
	(0·0002)	(0·0011)	(0·0004)	(0·14)	(0·44)	(0·19)	(0·42)	(0·47)	(0·27)
C(4)	0·8972	0·2313	0·6343	2·45	4·46	3·05	0·51	0·56	1·33
	(0·0003)	(0·0012)	(0·0005)	(0·22)	(0·58)	(0·27)	(0·53)	(0·64)	(0·36)
O(4)	0·8379	0·2138	0·5741	1·46	5·82	2·17	−0·44	−0·32	0·65
	(0·0002)	(0·0011)	(0·0003)	(0·14)	(0·38)	(0·17)	(0·33)	(0·41)	(0·23)
C(5)	0·9587	0·2369	0·6104	1·77	3·85	2·23	−0·72	0·50	1·02
	(0·0003)	(0·0013)	(0·0005)	(0·18)	(0·49)	(0·22)	(0·44)	(0·52)	(0·29)
N(5)	0·9532	0·2483	0·5101	1·53	4·52	2·04	−0·71	−0·38	0·91
	(0·0002)	(0·0012)	(0·0004)	(0·16)	(0·43)	(0·20)	(0·39)	(0·47)	(0·26)
O(5)	0·8981	0·2523	0·4395	2·39	9·84	2·13	0·02	−0·04	0·96
	(0·0002)	(0·0014)	(0·0004)	(0·18)	(0·55)	(0·20)	(0·50)	(0·55)	(0·28)
O(7)	0·0064	0·2461	0·4875	2·75	9·09	2·93	0·67	0·48	1·48
	(0·0002)	(0·0012)	(0·0004)	(0·19)	(0·55)	(0·22)	(0·51)	(0·58)	(0·30)
C(6)	0·0246	0·2413	0·6886	2·55	5·35	2·86	−0·22	−1·41	1·31
	(0·0002)	(0·0014)	(0·0004)	(0·23)	(0·58)	(0·26)	(0·54)	(0·62)	(0·36)
O(6)	0·0814	0·2455	0·6807	1·68	8·37	2·07	−0·36	−0·09	0·85
	(0·0002)	(0·0012)	(0·0003)	(0·16)	(0·48)	(0·18)	(0·43)	(0·50)	(0·26)
				Water molecules					
W(1)	0·3577	0·2204	0·6568	4·31	8·51	4·33	0·29	0·25	1·49
	(0·0003)	(0·0016)	(0·0005)	(0·30)	(0·61)	(0·33)	(0·67)	(0·75)	(0·48)
W(2)	0·4683	0·2464	0·7848	3·03	14·52	2·70	−0·60	−0·45	1·45
	(0·0003)	(0·0016)	(0·0004)	(0·22)	(0·83)	(0·25)	(0·71)	(0·78)	(0·36)
W(3)	0·3665	0·2726	0·4831	3·96	10·59	3·59	0·35	−0·38	1·59
	(0·0003)	(0·0015)	(0·0004)	(0·26)	(0·63)	(0·27)	(0·64)	(0·70)	(0·40)
W(4)	0·2527	0·4201	0·6827	3·92	7·88	3·20	0·29	0·86	1·36
	(0·0003)	(0·0013)	(0·0004)	(0·24)	(0·55)	(0·25)	(0·57)	(0·61)	(0·37)
W(5)	0·1465	0·2355	0·5649	3·61	7·64	4·54	−0·01	−0·09	1·93
	(0·0003)	(0·0013)	(0·0004)	(0·23)	(0·56)	(0·29)	(0·55)	(0·67)	(0·37)
W(6)	0·2533	0·3225	0·8688	3·03	9·48	3·21	−0·24	−0·50	1·25
	(0·0002)	(0·0013)	(0·0004)	(0·21)	(0·59)	(0·25)	(0·56)	(0·64)	(0·35)

section at $v=\frac{1}{2}$ in order to determine the relative translation of adjacent sheets, *i.e.* the positions of the crystallographic centers of symmetry and twofold screw axes with respect to the sheets. It should be noted that, as a result of the pseudo *B* centering of the lattice, unless atoms are displaced in some way from the glide planes at $y=\frac{1}{4}$, $\frac{3}{4}$, there is no practical distinction between choosing the origin at a center of symmetry or a twofold screw axis, and at this stage the atomic displacements were unknown. The Patterson section at $v=\frac{1}{2}$ is shown in Fig. 2. There are two large peaks corresponding to the superpositions of the vectors relating similar atoms in adjacent sheets, and it was necessary to select one of these arbitrarily as defining the relative translation of the sheets with respect to a center of symmetry at the crystallographic origin. This gave a set of x, y, z parameters which were refined by three-dimensional reiterative Fourier methods using at first only the reflections hkl with $h+l$ even, since these were relatively insensitive to errors in the y parameters. An R index of 0·26 was obtained for the reflections $h0l$ and $h1l$ with $\sin\theta<0·700$ assuming all atoms are at $y=\frac{1}{4}$ or $\frac{3}{4}$. The structure factors for reflections hkl with $h+l$ odd were then calculated for a variety of trial structures in which the dilituric acid molecules and water molecules were displaced by small shifts in various chemically plausible ways from the planes $y=\frac{1}{4}$ and $\frac{3}{4}$. The agreement obtained between observed and calculated structure factors was not generally good, but when one of the more likely trial structures was subjected to Fourier refinement based on all available hkl data, it improved significantly and converged at a value of $R=0{\cdot}23$. This solution to the phase problem, was, however, obviously false, since two water molecules (W(4) and W(6)) in adjacent layers lay within 2·0 Å of each other. Since the structure factors in the $h0l$ zone alone gave much better agreement of 0·13, the effect of interchanging the position of the screw axis and symmetry center in the [b] projection was examined. It was then found that further three-dimensional refinement by Fourier and differential synthesis improved the agreement for all hkl reflections to 0·18. The distance between W(4) and W(6) atoms in adjacent sheets was then 2·66 Å, corresponding to a normal hydrogen bond. The IBM 7070 programs of Shiono (1962) were used. With these coordinates a calculation of the best least-square plane through the individual dilituric acid molecules showed small, but significant, non-planarity which was difficult to explain on the grounds of stereochemistry, or the presence of close intermolecular contacts. It was now believed that the structure was essentially correct except possibly for certain small displacement of atoms from $y=\frac{1}{4}$. In order to determine whether there was any correlation between the y parameters, the anisotropic thermal parameters B_{22} and errors in the overall scaling factor, a full-matrix least-squares computation was carried out with the program of Busing & Levy (1959) for the IBM 704 computer. In order to minimize the computations, a relaxation technique was used. The 210 x, z and B_{11}, B_{12}, B_{33}, B_{13}, B_{23} parameters were assumed from the previous refinement, and not permitted to vary. Three cycles of least squares on the sixty-one y and B_{22} parameters and the overall scale factor were computed. This reduced the R index to 0·16 for all reflections, or 0·14 omitting the unobserved reflections, and led to small shifts in the y parameters. These shifts were such that, although the 5-nitrobarbituric acid molecules remained non-planar, the distortions from coplanarity were more reasonable and similar in both molecules. The largest shifts in the y parameters were for atoms O(4), 0·082 Å, and O(5), 0·085 Å, of molecule B. If an atom was displaced slightly from the plane $y=\frac{1}{4}$, but in the wrong sense, or if the structure was actually disordered with respect to such displacements, it would be expected that there would be considerable correlation between the y parameters and the B_{22} parameters. Such correlations cannot be taken into account in a refinement by differential synthesis, and it was believed that this might have caused the significant differences in the O(4) and O(5) y parameters from the differential synthesis and the least-squares refinement. However, the y, B_{22} correlation factors (Geller, 1961) were found on examination to be quite small, the largest being $\varrho(y\text{W}(1), B_{22}\text{W}(1))=0{\cdot}07$ and $\varrho(y\text{W}(2), B_{22}\text{W}(2))=0{\cdot}05$. The structure refinement was then completed by two more cycles of differential synthesis in which all the parameters were permitted to vary. The final R index was 0·150 for all reflections or 0·129 omitting the unobserved reflections. A final difference Fourier synthesis was calculated both for the b-axis projection and the three-dimensional sections close to $y=\frac{1}{4}$. The latter is shown in Fig. 3(a). The corresponding Fourier synthesis is shown in Fig. 3(b). There were no large areas of residual electron density, and it proved impossible to locate the hydrogen atoms with any degree of certainty.

The final calculated and observed structure factors are given in Table 1*. The atomic parameters with their estimated standard deviations are listed in Table 2. The bond angles and bond lengths are shown in Table 3. The mean e.s.d. in bond lengths within a sheet is 0·01 Å and in bond angles is 0·3°. The hydrogen bond lengths are shown in Table 4, and other intermolecular approaches less than 4·0 Å are listed in Tables 5 and 6. The least-square planes through the

Table 3. *Bond lengths and valence angles*

Molecule *A*

Distances		Angles	
N(1)–C(2)	1·354 Å	N(1)–C(2)–O(2)	121·8°
C(2)–O(2)	1·247	O(2)–C(2)–N(3)	120·8
		N(1)–C(2)–N(3)	117·4
C(2)–N(3)	1·349	C(2)–N(3)–C(4)	124·7
N(3)–C(4)	1·381	N(3)–C(4)–C(5)	116·7
		N(3)–C(4)–O(4)	116·9
C(4)–O(4)	1·261	O(4)–C(4)–C(5)	126·4
C(4)–C(5)	1·437	C(5)–N(5)–O(5)	122·7
		C(4)–C(5)–N(5)	119·1
C(5)–N(5)	1·400	O(5)–N(5)–O(7)	118·8
N(5)–O(5)	1·221	N(5)–C(5)–C(6)	121·3
		O(7)–N(5)–C(5)	118·4
N(5)–O(7)	1·287	C(4)–C(5)–C(6)	119·6
C(5)–C(6)	1·438	O(6)–C(6)–N(1)	116·6
		C(5)–C(6)–O(6)	127·0
C(6)–O(6)	1·239	C(5)–C(6)–N(1)	116·4
C(6)–N(1)	1·374	C(6)–N(1)–C(2)	125·2

Molecule *B*

N(1)–C(2)	1·357 Å	N(1)–C(2)–O(2)	122·2°
C(2)–O(2)	1·222	O(2)–C(2)–N(3)	120·9
		N(1)–C(2)–N(3)	116·9
C(2)–N(3)	1·363	C(2)–N(3)–C(4)	125·2
N(3)–C(4)	1·382	N(3)–C(4)–C(5)	115·8
		N(3)–C(4)–O(4)	116·9
C(4)–O(4)	1·234	O(4)–C(4)–C(5)	127·0
C(4)–C(5)	1·442	C(5)–N(5)–O(5)	123·0
		C(4)–C(5)–N(5)	119·1
C(5)–N(5)	1·381	O(5)–N(5)–O(7)	117·0
N(5)–O(5)	1·227	N(5)–C(5)–C(6)	119·9
		O(7)–N(5)–C(5)	120·0
N(5)–O(7)	1·261	C(4)–C(5)–C(6)	121·0
C(5)–C(6)	1·428	O(6)–C(6)–N(1)	115·5
		C(5)–C(6)–O(6)	128·8
C(6)–O(6)	1·234	C(5)–C(6)–N(1)	115·7
C(6)–N(1)	1·392	C(6)–N(1)–C(2)	125·3

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* Table 1, which is not reproduced here, has been deposited as Document number 7677 with the ADI Auxiliary Publications Project, Photoduplication Service, Library of Congress, Washington 25, D.C., U.S.A. A copy may be secured by citing the Document number and remitting $6·25 for photoprints or $2·50 for 35 mm microfilm. Advance payment is required. Make check or money order payable to Chief, Photoduplication Service, Library of Congress.

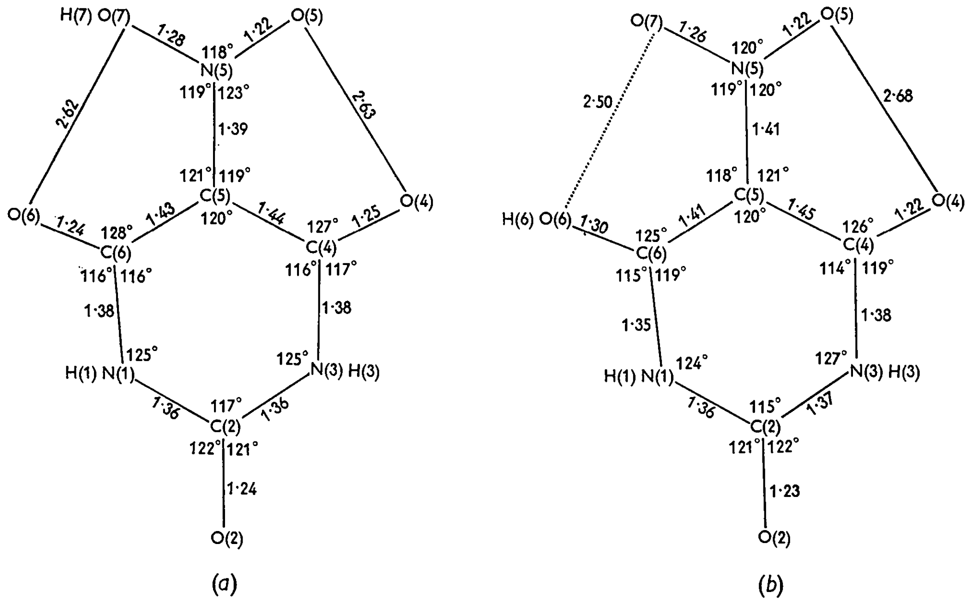


Fig. 4. (*a*) Mean bond lengths and angles in the two crystallographically independent aci-triketo molecules of dilituric acid. (*b*) Bond lengths and angles in the monohydroxy diketo molecule of dilituric acid (Bolton, 1963*a*).

Molecule *A*

Molecule *B*

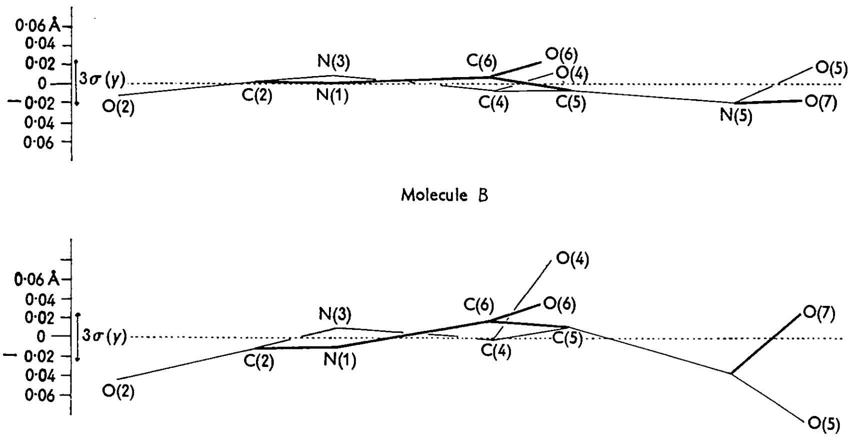


Fig. 5. Deviations from planarity in dilituric acid molecules viewed along (010) perpendicular to [*c*]. The vertical scale is 17 times the horizontal scale.

5-nitrobarbituric acid molecules together with the distances of atoms from these planes are given in Table 7. These structural data were obtained with programs written by Chu (1963) for the IBM 1620 computer.

Discussion

The structure of the dilituric acid molecules

Within the estimated errors of the analysis, the bond lengths and angles of the two crystallographically independent molecules are the same. The averaged values are shown in Fig. 4(*a*). The largest disagreement in bond lengths between the two molecules is 0·027 Å in C(4)–O(4), and although this corresponds to a quite different intermolecular environment for the carbonyl groups, it is not significant in terms of the calculated standard deviations. Both molecules are somewhat distorted from planarity, as shown in Fig. 5. The pyrimidine rings are not significantly different and both show a tendency to boat-shape. The displacement of the substituent O(4) and the nitro oxygen atoms are significantly different in the two molecules.

The C–O distances correspond to normal carbonyl groups. The difference in the N–O distances of 1·287, 1·261 for N(5)–O(7) compared with 1·221, 1·227 Å for

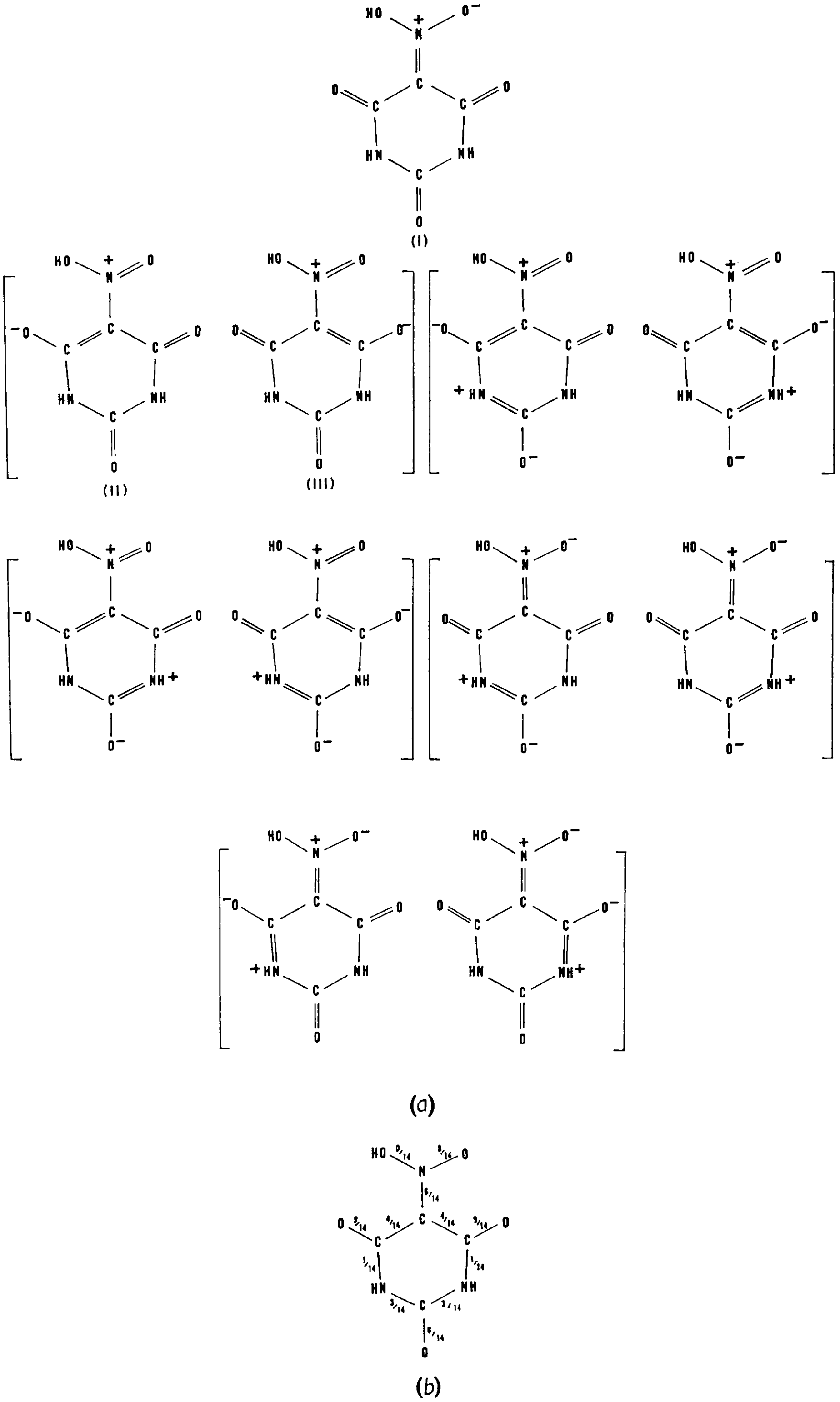


Fig. 6. Valence bond diagrams for the aci-triketo dilituric acid molecule.

N(5)–O(5), shows that the molecules are the aci triketo tautomeric form shown in (I). This is in contrast to the structure of the anhydrous dilituric acid (Bolton, 1963*a*) where the molecules are the diketo monohydroxy tautomers (Fig. 4(*b*)). Consequently the strong C–OH · · · O=N intramolecular hydrogen bond bound in the anhydrous crystals does not occur in the trihydrate.

The bond length distribution can be accounted for qualitatively in terms of the valence bond diagrams shown in Fig. 6(*a*), if the forms (I), (II), (III), which have a single charge separation are given double weight relative to those with double charge separation. The bond orders, shown in Fig. 6(*b*), predict that the C(2)–N(1) and C(2)–N(3) bonds should be shorter than C(6)–N(1) and C(4)–N(3), and this is observed experimentally in the mean values of 1·356 and 1·382 Å respectively. The mean C–C bond length is 1·436 Å in good agreement with the predicted value of 1·433 Å for a bond of double bond-order 4/14 (Pauling, 1960).

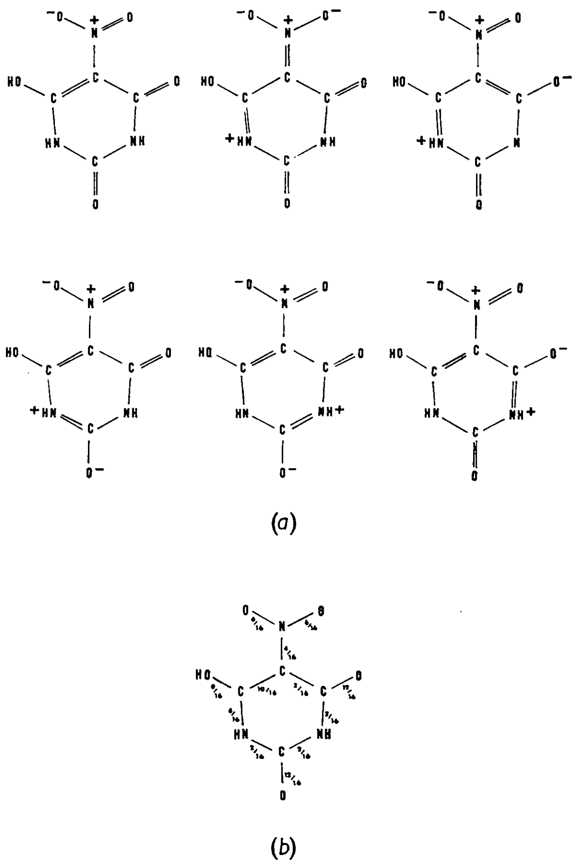


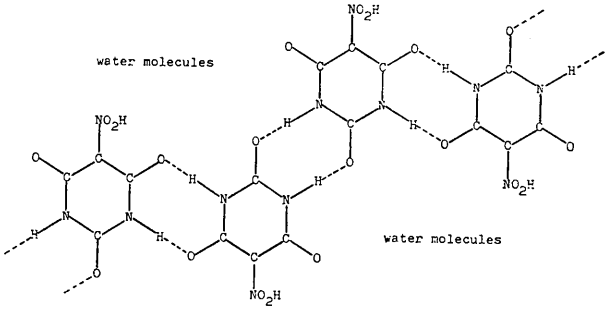
Fig. 7. Valence bond diagrams for the monohydroxy diketo molecule of dilituric acid.

The pyrimidine ring in the triketo form has *mm* symmetry, as also observed in both the dihydrate and anhydrous forms of barbituric acid (Jeffrey, Ghose & Warwicker, 1961; Bolton, 1963*b*). The ring symmetry is reduced to *m* in the diketo monohydroxy tautomer of the anhydrous crystals, and this can be accounted for by the valence bond diagrams and bond orders shown in Figs. 7(*a*) and (*b*), which are analogous to those in Figs. 6(*a*) and (*b*).

The molecular packing and hydrogen bonding

The crystal structure consists of almost coplanar layers of hydrogen-bonded dilituric acid and water molecules, characteristic of the compact, high density, crystals found in the simple barbiturates and related pyrimidine derivatives. The mean separation between the layers is 3·22 Å, as compared with 3·12 Å in barbituric acid dihydrate (Jeffrey, Ghose & Warwicker, 1961) and 3·10 Å in violuric acid monohydrate (Craven & Mascarenhas, 1964). Figs. 8(*a*) and (*b*) show a single layer and two superimposed layers respectively.

In each layer the nitropyrimidine rings are hydrogen-bonded in continuous zigzag chains through N(1)H · · · O(2) and N(3)H · · · O(4) as shown in formula IV.



(IV)

Table 4. *Hydrogen bonding distances*

O · · · O Hydrogen bonding distances

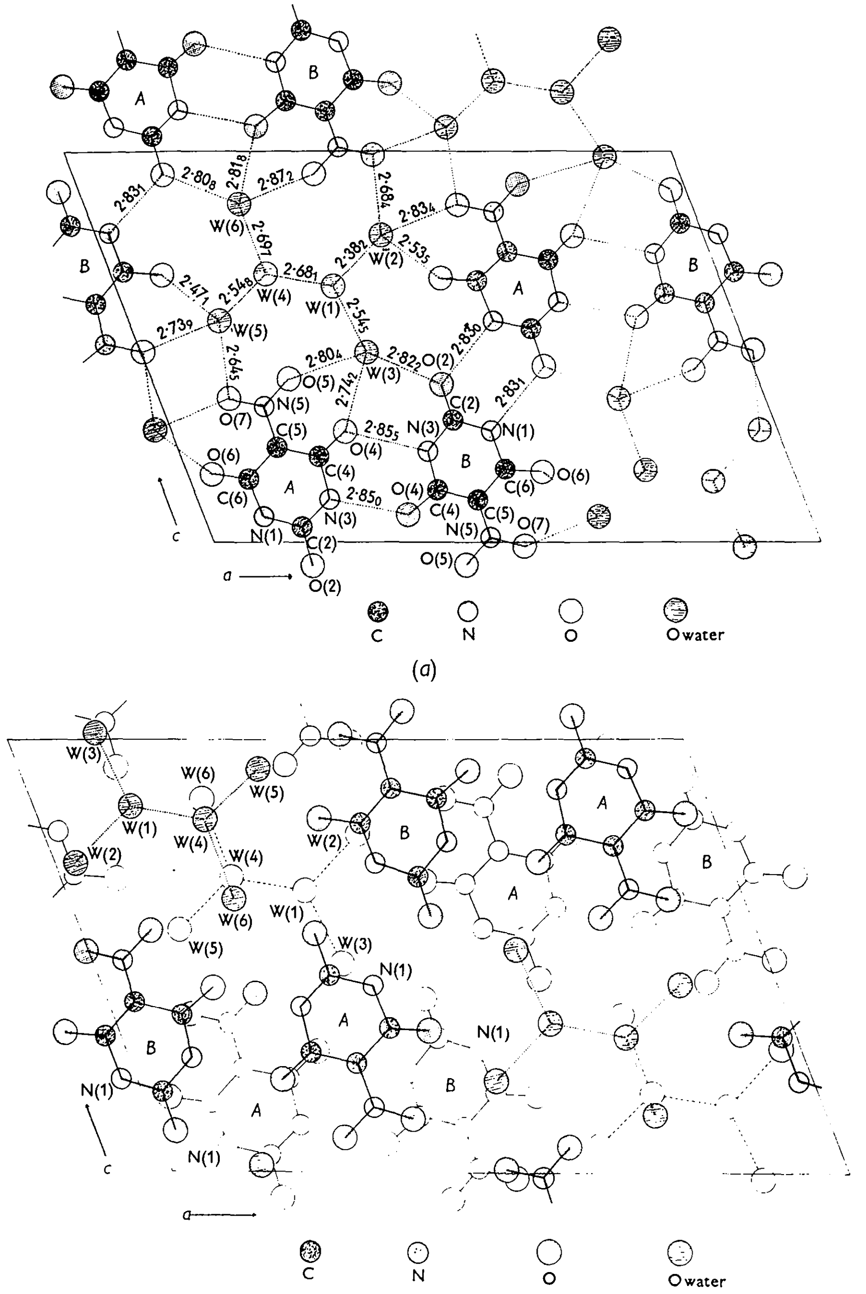
i	*j*	*d(ij)*	*i*	*j*	*d(ij)*
W(1)	W(2)	2·38 Å	W(4)	W(6)	2·70 Å
O(6*B*)	W(5)	2·47	O(7*B*)	W(5)	2·74
W(2)	O(6*A*)	2·54	W(3)	O(4*A*)	2·74
W(4)	W(5)	2·55	O(5*A*)	W(3)	2·80
W(3)	W(1)	2·55	O(2*A*)	W(6)	2·81
O(7*A*)	W(5)	2·65	O(4*B*)	W(6)	2·82
W(1)	W(4)	2·68	W(3)	O(2*B*)	2·82
W(2)	O(7*B*)	2·68	O(7*A*)	W(2)	2·83
W(4)	W(6)	2·69*	W(6)	O(5*B*)	2·87

N · · · O Hydrogen bonding distances

N(1*A*)	O(2*B*)	2·83 Å	N(3*A*)	O(4*B*)	2·85 Å
N(1*B*)	O(2*A*)	2·83	O(4*A*)	N(3*B*)	2·86

A denotes atoms in molecule *A*.
B denotes atoms in molecule *B*.
* Hydrogen-bond between layers.

The chains are then hydrogen-bonded laterally through the water molecules which lie in channels parallel to the [*b*] direction and normal to the layers of the acid molecules. Laterally these channels are hydrogen bonded to the pyrimidine C=O and NO_2H substituents through the water molecules W(2), W(3), W(5), W(6). The hydrogen bonding in the [*b*] direction of the channel is through a single zigzag chain, · · · W(4) · · · W(6) · · · W(4) · · · W(6), as illustrated in Fig. 9. This chain is analogous to the hydrogen-bonding in the hexagonal axial direction of the ice I structure. The nearly planar layers of nitrobarbituric acid and water molecules are therefore comparatively weakly linked in the [*b*] direction by only one hydro-



(*a*)

(*b*)

Fig. 8. (*a*) A single hydrogen-bonded layer, with the shorter intermolecular distances. (*b*) The superposition of adjacent layers.

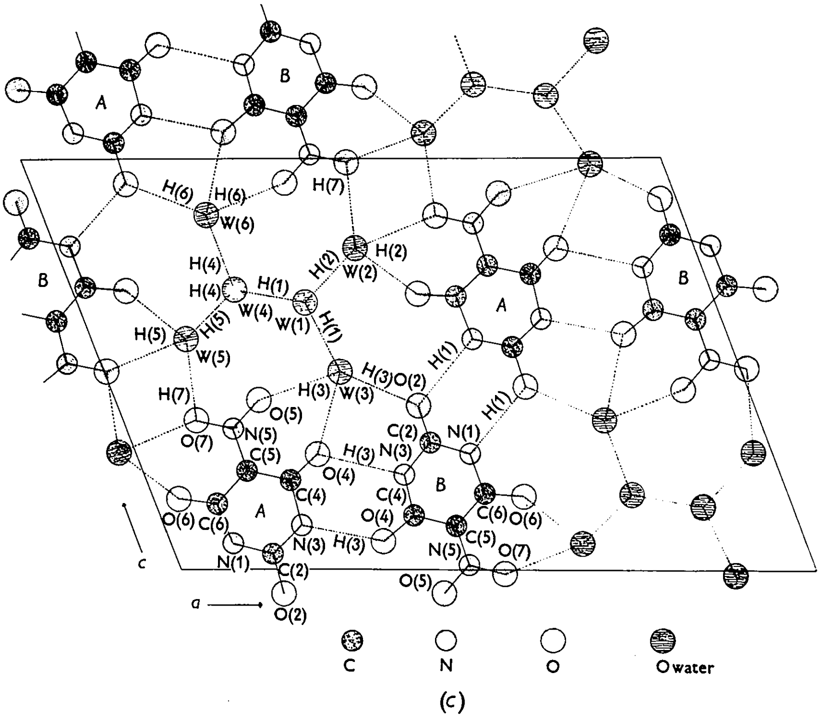
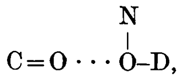


Fig. 8. (c) Proposed bonding scheme in a single layer.

gen bond per asymmetric unit; since all other intra-layer distances are greater than 3·18 Å, as shown in Table 5. This is consistent with the observed cleavage of the crystals.

With one proton associated with the W(4) · · · W(6) interlayer bond, there remain 17 for the hydrogen bonding within the sheets. As shown in Table 4, there are 21 oxygen to oxygen or oxygen to nitrogen distances in the layer which lie in the range of 2·38 to 2·87 Å (Fig. 8(*a*)). It is reasonable to assume from the stereochemistry that the NH · · · O distances correspond to normal hydrogen bonds. There remain, then, 11 water and 2 acinitro group protons to be distributed over 17 intra-layer O · · · O distances per asymmetric unit of structure. In the absence of definite information about the location of the protons, it is only possible to speculate on which of the O · · · O distances less than 2·87 Å corresponds to normal hydrogen bonds, bifurcated hydrogen bonds, or oxygen to oxygen non-bonding contacts. Some guidance can be obtained from the X-ray and neutron diffraction study of perdeuterated violuric acid monohydrate which is a similar type of high density layered pyrimidine structure (Craven & Mascarenhas, 1964; Craven & Takei, 1964). In that structure there are two N–D · · · O bonds and six O · · · O distances less than 3·0 Å with five deuterons. Although the N · · · O distances are long, 2·97 and 3·07 Å, they correspond to normal, nearly linear N–D · · · O bonds. Of the six O · · · O distances, the neutron diffraction analysis revealed that there were

(1) a non-bonded intramolecular distance of 2·64 Å,



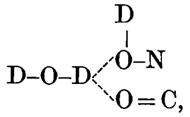
$$\mathrm{C{=}O\cdots \overset{\overset{N}{|}}{O}{-}D},$$

(2) a non-bonded intermolecular distance of 2·79 Å, $\mathrm{C{=}O\cdots O{=}C}$,

(3) a nearly linear, 175°, deuteron bond of 2·56 Å, $\mathrm{N{-}O{-}D\cdots OD_2}$,

(4) a not so linear, 162°, deuteron bond of 2·76 Å, $\mathrm{D{-}O{-}D\cdots O{=}C}$,

(5) a bifurcated deuteron bond



$$\mathrm{D{-}O{-}D}\begin{array}{l}\overset{\mathrm{D}}{\overset{|}{\cdots \mathrm{O{-}N}}}\\ \cdots \mathrm{O{=}C},\end{array}$$

in which the deuteron to oxygen distances are nearly equal at 2·07 to 2·10 Å, and the O · · · O distances are 2·96 and 2·79 Å, with an angle of 55° between them.

It is apparent from the results of this work that O · · · O distances can sometimes be misleading if used as the sole criterion for hydrogen bonding. Non-bonded O · · · O separations and O(H) · · · O bond lengths vary over the same spectrum of distance depending on the stereochemical environment and the special feature of a hydrogen bond is that it permits a proton to be placed between two oxygen atoms without increasing the oxygen to oxygen separation beyond the normal range associated with the non-bonded distances.

A proposed hydrogen bonding scheme for the dilituric acid trihydrate structure is shown in Fig. 8(*c*).

Table 5. *Non-bonding interatomic distances less than 3·5 Å between sheets*

The following roman numbers give the symmetry relationship of the atoms concerned

I	x	y	z
II	$-x$	$-y$	$1-z$
III	$-x$	$1-y$	$1-z$
IV	$1-x$	$-y$	$1-z$
V	$1-x$	$1-y$	$1-z$
VI	$\frac{1}{2}-x$	$\frac{1}{2}+y$	$\frac{3}{2}-z$
VII	$\frac{1}{2}-x$	$-\frac{1}{2}+y$	$\frac{3}{2}-z$
VIII	$\frac{3}{2}-x$	$\frac{1}{2}+y$	$\frac{3}{2}-z$
IX	$\frac{3}{2}-x$	$-\frac{1}{2}+y$	$\frac{3}{2}-z$

Atom *i*		Atom *j*		*d* (*ij*)
O(7)I	*A*	C(4)IX	*B*	3·18 Å
O(6)I	*A*	C(2)VIII	*B*	3·21
C(4)I	*A*	O(4)VIII	*A*	3·21
W(2)I		C(6)VI	*B*	3·21
C(2)I	*A*	W(3)V		3·24
O(7)I	*B*	O(7)III	*B*	3·32
O(2)I	*A*	W(1)IV		3·26
O(5)I	*B*	W(5)IV		3·28
O(7)I	*B*	N(5)IV	*B*	3·30
O(4)I	*B*	O(7)IX	*A*	3·35
O(2)I	*B*	O(6)IX	*A*	3·35
N(1)I	*B*	W(2)VII		3·37
W(1)I		W(6)VII		3·39
O(4)I	*B*	N(5)IX	*A*	3·41
N(3)I	*B*	O(6)IX	*A*	3·42
O(2)I	*A*	W(3)IV		3·43
W(2)I		N(1)VII	*B*	3·43
N(5)I	*A*	O(4)IX	*B*	3·46
O(6)I	*A*	N(3)VIII	*B*	3·42
O(4)I	*B*	O(5)IX	*A*	3·46
W(3)I		N(1)IV	*A*	3·48
N(5)I	*A*	C(4)IX	*B*	3·48
O(6)I	*B*	W(2)VII		3·47
N(3)I	*B*	C(6)IX	*A*	3·49
N(3)I	*A*	O(4)VIII	*A*	3·46
O(7)I	*A*	C(4)VIII	*B*	3·29
O(6)I	*A*	C(2)IX	*B*	3·27
C(4)I	*A*	O(4)IX	*A*	3·25
W(2)I		C(6)VII	*B*	3·28
C(2)I	*A*	W(3)IV		3·28
O(7)I	*B*	O(7)II	*B*	3·22
W(5)I		W(6)VII		3·31
O(5)I	*B*	W(5)V		3·43
O(7)I	*B*	N(5)V	*B*	3·37
O(4)I	*B*	O(7)VIII	*A*	3·45
O(2)I	*B*	O(6)VIII	*A*	3·40
N(1)I	*B*	W(2)VI		3·43
C(4)I	*A*	C(4)IX	*A*	3·42
O(4)I	*B*	N(5)VIII	*A*	3·46
O(4)I	*A*	C(5)IX	*A*	3·43
O(2)I	*A*	W(3)V		3·39
W(2)I		N(1)VI	*B*	3·37
N(5)I	*A*	O(4)VIII	*B*	3·41
C(5)I	*A*	O(4)VIII	*A*	3·43
O(4)I	*A*	N(3)IX	*A*	3·46
W(3)I		N(1)V	*A*	3·40
O(7)I	*A*	N(3)IX	*B*	3·48
O(6)I	*B*	W(2)VI		3·48
C(6)I	*A*	O(2)IX	*B*	3·50

A denotes atoms in molecule *A*.
B denotes atoms in molecule *B*.

Table 6. *Van der Waals distances less than* 4·0 Å *between atoms in the same sheet*

The following roman numbers give the symmetry relationship of the atoms concerned

I	x	y	z
II	$\frac{1}{2}+x$	$\frac{1}{2}-y$	$\frac{1}{2}+z$
III	$-\frac{1}{2}+x$	$\frac{1}{2}-y$	$\frac{1}{2}+z$
IV	$\frac{1}{2}+x$	$\frac{1}{2}-y$	$-\frac{1}{2}+z$
V	$-\frac{1}{2}+x$	$\frac{1}{2}-y$	$-\frac{1}{2}+z$
VI	$-1+x$	y	z

Atom *i*		Atom *j*		*d* (*ij*)
O(5)I	*B*	W(2)IV		3·03 Å
O(7)I	*A*	O(7)II	*B*	3·26
N(5)I	*B*	W(2)IV		3·31
O(2)I	*B*	O(2)V	*A*	3·56
O(5)I	*A*	W(1)II		3·58
O(2)I	*B*	O(6)V	*A*	3·58
O(2)I	*B*	C(2)II	*A*	3·62
N(1)I	*B*	C(2)III	*A*	3·65
O(6)I	*B*	W(6)I		3·66
C(4)I	*B*	O(4)I	*A*	3·68
O(2)I	*A*	O(4)I	*B*	3·68
N(1)I	*B*	N(1)III	*A*	3·69
O(2)I	*B*	C(6)II	*A*	3·70
C(2)I	*B*	O(4)I	*A*	3·72
C(2)I	*B*	W(3)II		3·73
C(2)I	*A*	W(6)III		3·74
O(6)I	*B*	W(4)I		3·74
C(4)I	*A*	N(3)I	*B*	3·75
N(5)I	*B*	W(5)VI		3·84
N(3)I	*B*	W(3)II		3·86
C(4)I	*B*	W(6)III		3·90
N(5)I	*A*	W(2)I		3·96
N(5)I	*B*	W(6)III		3·97
O(5)I	*A*	W(5)II		3·08
N(5)I	*A*	W(5)II		3·29
O(4)I	*B*	O(4)I	*A*	3·50
C(6)I	*B*	W(5)I		3·57
O(2)I	*A*	O(6)IV	*B*	3·58
C(2)I	*B*	O(2)V	*A*	3·62
C(2)I	*B*	N(1)II	*A*	3·64
W(2)I		C(6)I	*A*	3·66
C(4)I	*A*	O(4)I	*B*	3·67
W(3)I		O(6)I	*A*	3·67
O(2)I	*B*	O(4)I	*A*	3·68
W(4)I		O(5)V	*A*	3·70
C(2)I	*A*	O(4)I	*B*	3·71
C(6)I	*B*	O(2)III	*A*	3·72
C(4)I	*B*	N(3)I	*A*	3·73
O(6)I	*A*	W(1)I		3·74
N(3)I	*A*	N(3)I	*B*	3·75
O(5)I	*B*	W(1)IV		3·78
C(4)I	*A*	W(3)II		3·85
N(3)I	*A*	W(6)III		3·89
N(5)I	*A*	W(3)II		3·90
N(5)I	*A*	W(3)I		3·90
O(5)I	*B*	W(4)III		3·97

A denotes atoms in molecule *A*.
B denotes atoms in molecule *B*.

It is based on the two following assumptions, which we believe are stereochemically reasonable; that the N–H · · · O bonds are normal and nearly linear, and that the O · · · H_2O · · · O distances which make angles of 60° or less correspond to bifurcated bonds; *i.e.* those at W(2), W(3), W(5) and W(6) making angles of 58°, 57°, 60° and 55°, respectively. This scheme accounts for all the intermolecular O–O distances less than 3·0 Å, and for all the available protons. It gives an extremely compact layer structure, corresponding to the high crystal density of 1·69 g.cm^{-3}.

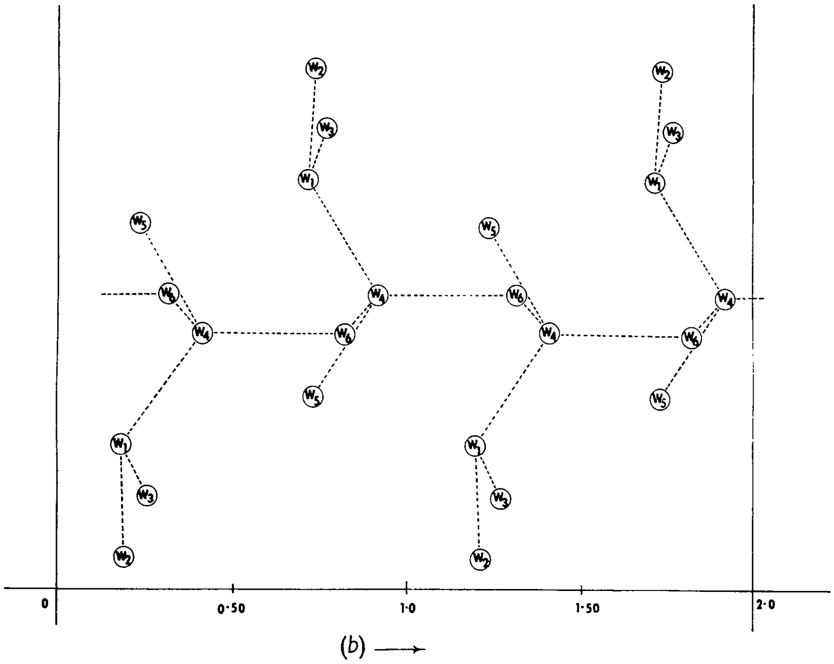


Fig. 9. Hydrogen bonding of the water molecules in the [*b*] direction.

Table 7. *Distances from the least-square planes and equation of the planes in Å units*

Atom	Molecule *A*	Molecule *B*
N(1)	−0·000	−0·012
C(2)	0·002	−0·014
O(2)	−0·014	−0·044
N(3)	0·007	0·014
C(4)	−0·009	−0·001
O(4)	0·012	0·082
C(5)	−0·007	0·016
N(5)	−0·020	−0·036
O(5)	0·018	−0·085
O(7)	−0·019	0·025
C(6)	0·006	0·018
O(6)	0·025	0·036

(*A*) $0{\cdot}0241x+0{\cdot}9995y+0{\cdot}0111z=1{\cdot}8996$
(*B*) $-0{\cdot}0364x+0{\cdot}9993y+0{\cdot}0183z=1{\cdot}7325$

The equation of the plane is of the form, $ax+by+cz=d$, which corresponds to the crystallographic axes.

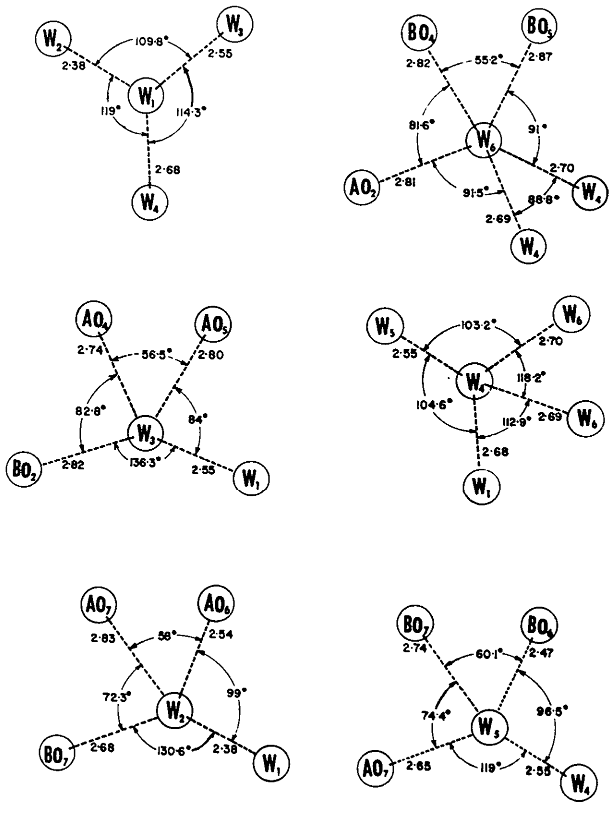


Fig. 10. Nearest-neighbour coordination of the water molecules.

The nearest-neighbour coordination of the water molecules is shown in Fig. 10. W(1) and W(4) are respectively three- and four-hydrogen bonded to other water molecules only. The former is distorted planar trigonal and the latter distorted tetrahedral. This is common in hydrate structures. As pointed out by Clark (1963), in almost one quarter of the hydrated structures which have been studied the water molecules have a planar threefold environment. The water oxygen atoms W(2), W(3) and W(5) have four nearest neighbours approximately in a plane, one of which is another water molecule. According to our assignment of proton positions, the hydrogen bonding is distorted trigonal planar in each case. Oxygen W(6) has five nearest neighbours and four hydrogen bonds in a very distorted tetrahedral arrangement.

The intermolecular O · · · O distances, which are given in Table 4 and Fig. 10, range from 2·38 to 2·87 Å. According to the hydrogen bonding proposed in Fig. 9, they all involve proton interaction either as linear or bifurcated hydrogen-bonds. The N(H) · · · O distances are 2·83 to 2·86 Å. The W(1) · · · W(2) distance of 2·38 Å is exceptionally short, since hydrogen-bond separations less than 2·5 Å are not commonly reported. In oxalic acid dihydrate, the water-oxygen to carbonyl-oxygen distance is 2·491 Å (Ahmed & Cruickshank, 1953), and more recently a short hydrogen bond of 2·393 + 0·018 Å has been reported in di-*p*-chlorophenyl hydrogen phosphate by Calleri & Speakman (1963). In caffeine hydrate (Sutor, 1958) and biuret hydrate (Hughes, Yakel & Freeman, 1961) hydrogen bonds of 2·36 and 2·48 Å respectively occur in structures where there is disorder between occupied and vacant water sites. There was no evidence of a corresponding non-stoichiometry in this structure. Both W(1) and W(2) have normal peak heights and there were no discrepancies at their positions on the difference map. However, W(2) does have a B_{22} thermal parameter about 50% larger than that of the other water oxygen atoms, and its y parameter is very close to 0·25. In order to have a W(1) · · · W(2) distance of 2·50 Å, the y parameter of W(2) would have to be increased to 0·340. Such an arbitrary shift increased the agreement factor by 10%, and the subsequent differential syntheses moved the y parameter back to 0·247. A similar calculation, placing W(2) at exactly 0·2500, gave a shift-back to the original value of 0·2464. We could find no internal evidence from the behaviour of the y and B_{22} parameters of W(2) in refinement to lead us to reject these values. As mentioned above, the matrix correlation factors in the least-squares refinement were quite small, although those for W(1) and W(2) were in fact, the largest observed. We plan to undertake a neutron diffraction study in order to establish the hydrogen positions directly.

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