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Chemical Evolution. 31. Mechanism of the Condensation of Cyanide to HCN Oligomers[1]

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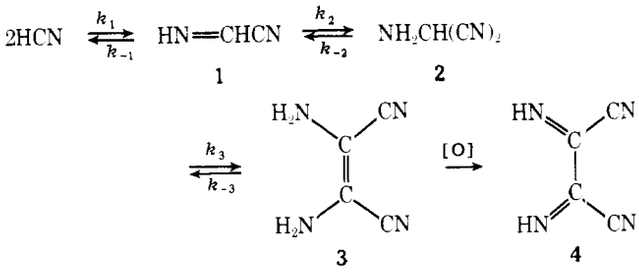
Diaminomaleonitrile undergoes a rapid Ni(II)-catalyzed or a much slower uncatalyzed decomposition to yield 2 equiv of cyanide. This is not an equilibration between diaminomaleonitrile and the dimer and trimer of HCN as shown by the absence of incorporation of $H^{13}CN$ when incubated with diaminomaleonitrile. The formation of urea and oxalic acid is enhanced and the steady-state concentration of diaminomaleonitrile is decreased when the oligomerization of HCN is performed in the presence of oxygen as compared to a pure nitrogen atmosphere. Small but significant yields of oxalic acid and urea were observed when oxygen was eliminated from the reaction solution. An oligomerization pathway is proposed which is consistent with these data. These findings are not consistent with the proposal that HCN condenses to heteropolypeptides via azacyclopropenylidene imine.

Hydrogen cyanide oligomers are believed to have had a significant role in the prebiotic synthesis of purines, pyrimidines, and amino acids.[1,3] HCN condenses in a stepwise fashion to the dimer **1**, trimer **2**, and tetramer **3**. It was postulated that one or more of these simple HCN derivatives condenses further to yield HCN oligomers, a complex mixture of substances with a molecular weight of 500–1000. Purines, pyrimidines, and amino acids are released on hydrolysis of these oligomers. The oligomerization reaction is dependent only on the pH of the reaction mixture and is independent of added nucleophile.[4] Urea and oxalic acid are also products of the oligomerization reaction. An investigation of the mechanism of formation of the oligomers was undertaken because these substances may have had a central role in the formation of biomolecules on the primitive earth.



Results and Discussion

The Proposed Equilibrium between Diaminomaleonitrile (3) and Aminomalononitrile (2). We proposed previously that the monomer, dimer (**1**), trimer (**2**), and tetramer (**3**) of HCN readily equilibrate in aqueous solution.[4] The formation of a precipitate of AgCN when Ag^+ is added to an aqueous solution of **3** provided support for this hypothesis.[5] The observation that diaminomaleonitrile releases cyanide rapidly when treated with Ni^{2+} in NH_4OH solution, a method for the determination of cyanide ion, prompted a reinvestigation of the equilibrium proposed between **1**, **2**, and **3**. The catalyzed decomposition of diaminomaleonitrile requires the presence of both Ni^{2+} and NH_3 if it is to proceed at a rapid rate. Approximately 2 equiv of cyanide are released per mole of diaminomaleonitrile. If diaminomaleonitrile is in equilibrium with HCN, 4 equiv of cyanide would be detected as the $Ni(CN)_4^{2-}$ complex. The same yield of cyanide is obtained when the hydrolysis proceeds 4×10^{-3} times slower in the absence of Ni^{2+}. The similar yields of HCN in the catalyzed and uncatalyzed reactions suggest that overall decomposition pathways are the same in both reactions.

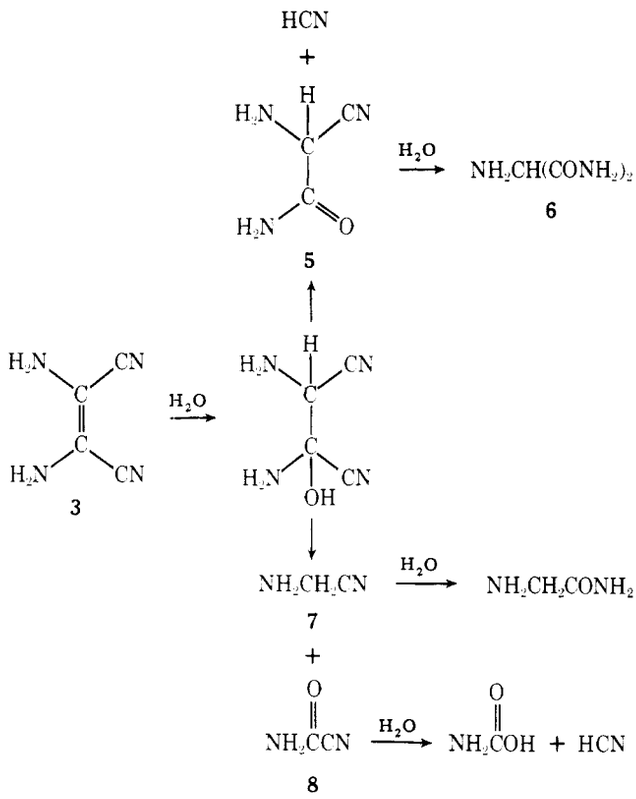
The mechanisms of both the Ni^{2+}-catalyzed and -uncatalyzed decomposition of diaminomaleonitrile are unclear. Hydrolysis of **3** yields either the monoamide of the aminomalononitrile (**5**) and 1 equiv of cyanide or aminoacetonitrile (**7**) and the monoamide of cyanogen (**8**). The monoamide of cyanogen may cleave as does cyanogen to yield 1 equiv of cyanide; however, it appears unlikely that a second equivalent of cyanide will be formed by either reaction pathway. The monoamide of aminomalonitrile is known to hydrolyze to the diamide **6**, and it does not eliminate cyanide.[6] Further work is required to determine the pathway for the decomposition of **3**; however, it is not the stepwise dissociation of **3** to give 4 equiv of HCN. The isotope exchange studies given below eliminate the possibility of the dissociation of **3** to **1** and 2 equiv of HCN.

The proposed equilibrium between cyanide and the dimer, trimer, and tetramer was investigated further by isotope exchange, a technique which has the advantage that the position of the equilibrium is not perturbed as it is by metal ions such as Ag^+ and Ni^{2+}, which form essentially nondissociating cyanide complexes. None of the added $^{13}CN^-$ will condense to

Table I. Reaction of Diaminomaleonitrile and Potassium [^{13}C]Cyanide at pH 7–8

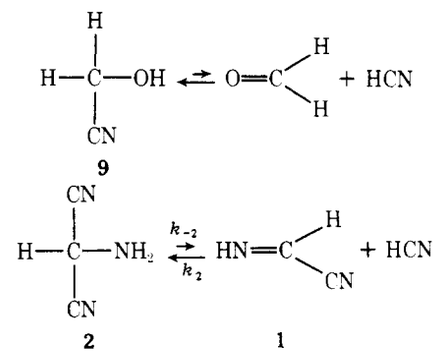
reaction time, days	yield of product, mg	number of scans	area ratio (peak 2/peak 1)[c]	mean ratio ± standard deviation
0[a]		4 000	0.3418	0.3129 ± 0.0743
			0.3967	
			0.2909	
			0.2223	
0.17	246	4 000	0.2417	0.3425 ± 0.0968
			0.3510	
			0.4347	
1.0	230	4 000	0.4223	0.3205 ± 0.0709
			0.3251	
			0.2338	
			0.3007	
4.0	210	6 000	0.3500	0.2857 ± 0.0511
		7 000	0.2329	
		8 000	0.2594	
		8 000	0.3006	
10.0	173.2	10 000	0.3478	0.3666 ± 0.0702
		10 000	0.4426	
		10 000	0.2788	
		20 000	0.3973	
31.0	53.4	20 000	0.7861[b]	

[a]Control solution: 250 mg of diaminomaleonitrile in 2 mL of dimethyl-d_6 sulfoxide. [b]After 31 days, the concentration of diaminomaleonitrile was too low to obtain reliable data. With 20 000 scans, the signal/noise ratio was less than 2. [c]Mean shifts: peak 1, 117.80 ppm; peak 2, 106.90 ppm.



form [^{13}C]diaminomaleonitrile if the $^{13}CN^-$ concentration is less than 0.01 M.[6] The exchange of $^{13}CN^-$ with diaminomaleonitrile was monitored by ^{13}C NMR. Diaminomaleonitrile exhibits two peaks at 106.49 and 117.71 ppm when its ^{13}C NMR spectrum is determined in dimethyl sulfoxide solution. If the proposed equilibrium between the trimer and tetramer exists, then the addition of $^{13}CN^-$ to an aqueous solution of diaminomaleonitrile should result in an increase in the relative intensity of the ^{13}C NMR signal at 117.71 ppm due to the nitrile carbons of diaminomaleonitrile.[7,8] If the equilibrium resulted in appreciable concentrations of the dimer and trimer, then a proportional increase in intensity would be expected in both the nitrile and olefin ^{13}C NMR signals.

When the cyanide exchange experiment was performed in aqueous solution at pH 7 and 9.2 using <0.004 M $^{13}CN^-$, no $^{13}CN^-$ incorporation was observed over a 1- and 3-day time period, respectively, as evidenced by the lack of change of the nitrile/olefin intensity ratios (Tables I and II). These data demonstrate that the equilibrium for the formation of diaminomaleonitrile from aminomalononitrile is so strongly shifted to the side of tetramer in aqueous solution that it is essentially irreversible; i.e., the rate of the reverse reaction (k_{-3}) is very small compared to the rate of the forward reaction (k_3). This conclusion is consistent with the observation that aminomalononitrile (**2**) reacts rapidly with HCN to yield diaminomaleonitrile.[9] It was estimated that there is a steady-state concentration of 10^{-5}–10^{-6} M aminomalononitrile in the presence of 1 M cyanide.[6,9] One might argue that significant amounts of **1** might be present if it were as stable as **3**. But several lines of evidence suggest that k_2 is much greater than k_{-2}. The equilibrium constant for the dissociation of glyconitrile (**9**) to formaldehyde and HCN has been measured, and



it is far on the side of the glyconitrile as shown by the equilibrium constant of 2.1×10^{-6} at 25 °C.[10] This reaction is analogous to the dissociation of aminomalononitrile to iminoacetonitrile; the two reactions would be expected to have similar equilibrium constants. Furthermore, the facile conversion of N-substituted iminoacetonitrile derivatives to N-substituted derivatives of diaminomaleonitrile, a reaction which presumably takes place via the aminomalononitrile derivative, provides added support for k_2 being greater than

Table II. Reaction of Diaminomaleonitrile and Potassium [^{13}C]Cyanide at pH 9.2

reaction time, days	yield of production, mg/mL	number of scans	area ratio (peak 2/peak 1)[c]	mean ratio ± standard deviation
0[a]		1 500	0.2907	0.3787 ± 0.0717
		2 000	0.4530	
		3 000	0.3800	
		4 000	0.3250	
		5 000	0.4450	
0.5	0.9662	5 000	0.2541	0.3711 ± 0.0701
		7 000	0.4415	
		7 500	0.3974	
		8 000	0.3750	
		20 000	0.3878	
3.0	0.3900	15 000	0.3423	0.3578 ± 0.0718
		15 280	0.4472	
		18 000	0.3983	
		25 730	0.3465	
		50 000	0.2547	
10.0[b]	0.0306			

[a]Control solution: 400 mg of diaminomaleonitrile in 2 mL of dimethyl-d_6 sulfoxide. [b]The concentration of diaminomaleonitrile was insufficient to obtain a spectrum. [c]Mean shifts: peak 1, 117.80 ppm; peak 2, 106.90 ppm.

Table III. ^{13}C NMR Study of the Reaction of Diaminomaleonitrile and Potassium [^{13}C]Cyanide in Dimethyl Sulfoxide

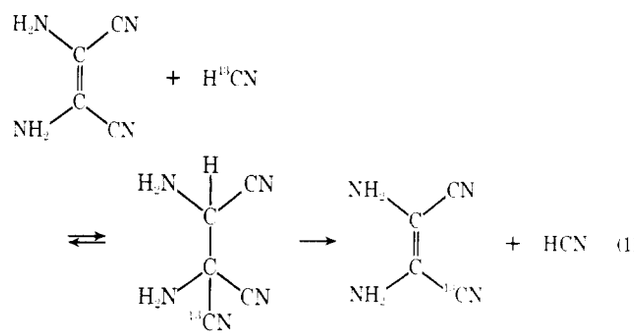
reaction time, days	relative peak area			area ratio (peak 1/peak 2)
	peak 1[a]	peak 2[b]	peak 3[c]	
0[d]	1.18	2.30		0.512
0.67[e]	4.94	4.25	14.26	1.162
1.83[e,f]	7.33	4.71	9.22	1.554
2.67[e,f]	6.40	3.35	5.70	1.910
3.67[e,f]	7.34	4.19	6.07	1.749
10.0	2.56	1.23	7.60	2.151

[a]Average shift, 117.20 ppm. [b]Average shift, 106.50 ppm. [c]Average shift, 158.20 ppm (CN^-). [d]Control solution: 500 mg of diaminomaleonitrile in 2 mL of dimethyl-d_6 sulfoxide. [e]Additional small peak at 145.50–145.79 ppm. [f]Additional small peak at 161.75–161.90 ppm.

k_{-2}.[11,12] Finally, molecular orbital calculations predict that iminoacetonitrile should be more susceptible to a nucleophilic attack than either aminomalononitrile or diaminomaleonitrile.[13] Since we have shown that k_3 is much greater than k_{-3}, it follows from these calculations, as well as from the experimental observations cited above, that k_2 is much greater than k_{-2}.

We conclude from this study that the steady-state concentration of the dimer and trimer of hydrogen cyanide is exceedingly low in dilute aqueous solution. This conclusion is supported by the reported inability to isolate the dimer or trimer from an oligomerizing hydrogen cyanide solution.[6] Diaminomaleonitrile is the predominant species present when cyanide is added to either the dimer or trimer. Consequently, the formation of the HCN oligomers must be via the reaction of diaminomaleonitrile with HCN or less likely by the condensation of two or more diaminomaleonitrile moieties and not via reactions involving the dimer or trimer. This conclusion is supported by the observation that the products released on hydrolysis of HCN oligomers appear to be formed by the condensation of diaminomaleonitrile or its trans isomer with cyanide.[1,3]

We did observe exchange of $^{13}CN^-$ with diaminomaleonitrile in dimethyl sulfoxide solution (Table III). The signal at 117 ppm intensified 2-fold after 16 h and 3–4-fold after 30 days relative to the signal at 106 ppm. This change in peak intensities corresponds to an extent of exchange which is 67% of complete exchange. At the same time, the $^{13}CN^-$ signal at 158 ppm decreased in intensity. The equilibrium between **2** and **3** may be shifted toward **2** in this solvent. On the other hand, these findings may reflect the greater nucleophilicity of cyanide in dimethyl sulfoxide.[14,15] The exchange may proceed via the Michael addition–elimination pathway shown in eq 1 rather than by the dissociation of diaminomaleonitrile.



(1)

The Effect of Oxygen on the Oligomerization of HCN. It was reported by Volker[16] that oxygen has no effect on the oligomerization of hydrogen cyanide. The observation that diaminomaleonitrile is readily air-oxidized[17] prompted a reinvestigation of the oligomerization reaction in the absence of oxygen. It was essential to determine if the cyanide oligomerization proceeds in the absence of oxygen because it is generally agreed that there was little or no molecular oxygen on the primitive earth.[18]

The effect of molecular oxygen was investigated by comparing the loss of cyanide, the formation of urea, and the formation of diaminomaleonitrile in the following 0.1 M cyanide solutions: (1) no precautions were taken to remove air from the solution; (2) the solution was degassed by a freeze–pump–thaw procedure followed by the addition of sufficient nitrogen to give atmospheric pressure in the reaction vessel; (3) the solution was purged with molecular oxygen. The oligomerization reactions were periodically sampled and analyzed over a 6-month period.

The yield of urea was found to be significantly greater in the oxygenated solutions (Figure 1). This is attributed to the oxidation of diaminomaleonitrile to diiminosuccinonitrile (**4**), a compound which is rapidly hydrolyzed to urea by dilute NH_4OH.[17] The observation that the amounts of diaminomaleonitrile are significantly less in the presence of molecular oxygen (Figure 2) is consistent with the above result. The

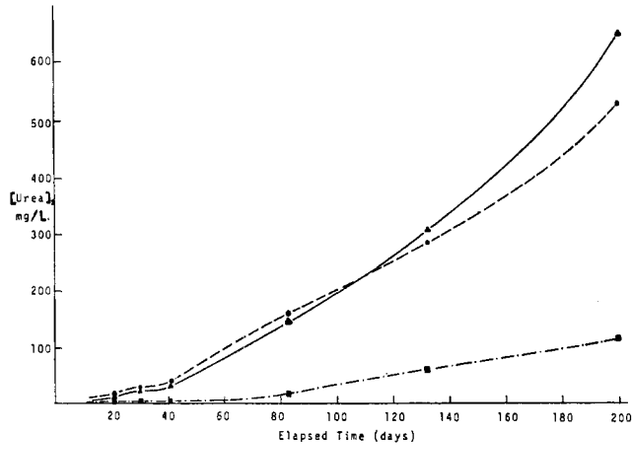


Figure 1. Effect of oxygen on urea formation in HCN oligomerization solutions: solution 1 (control), -▲-; solution 2 (degassed), -■-; solution 3 (oxygenated), -●-.

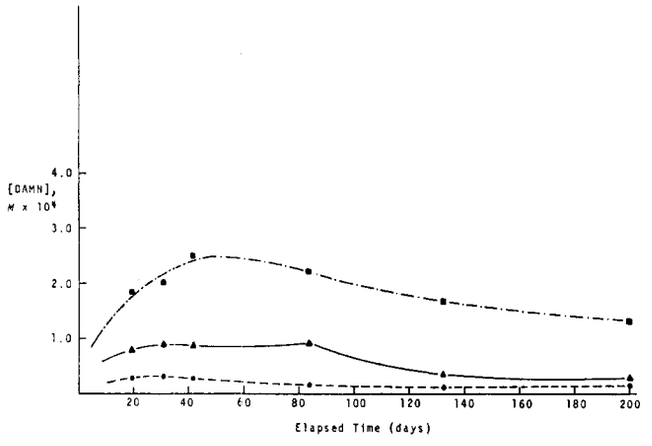


Figure 2. Effect of oxygen on diaminomaleonitrile concentration in HCN oligomerization solutions: solution 1 (control), -▲-; solution 2 (degassed), -■-; solution 3 (oxygenated), -●-.

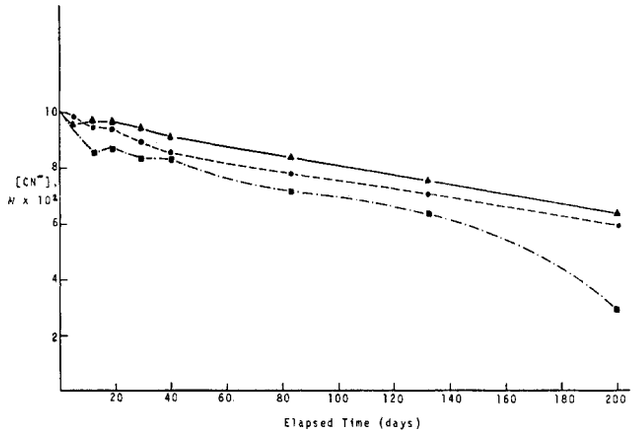


Figure 3. Effect of oxygen on cyanide concentration in HCN oligomerization solutions: solution 1 (control), -▲-; solution 2 (degassed), -■-; solution 3 (oxygenated), -●-.

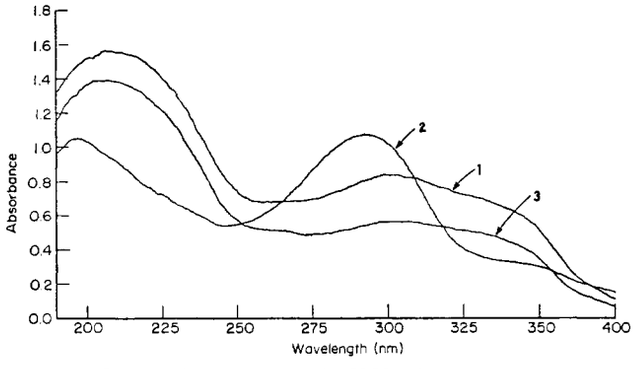


Figure 4. Ultraviolet spectra of the HCN oligomerization mixture after 83 days: (1) solution 1 (control); (2) solution 2 (degassed); (3) solution 3 (oxygenated). Samples were diluted 5× from original concentrations.

principal effect of molecular oxygen is apparently the oxidation of diaminomaleonitrile since the rate of oligomerization of HCN, as monitored by the loss of cyanide, was not significantly different in the absence or presence of oxygen in the early stages of the reaction (Figure 3). The previously reported difference in rate may reflect the differences observed here near the end of the oligomerization.[17]

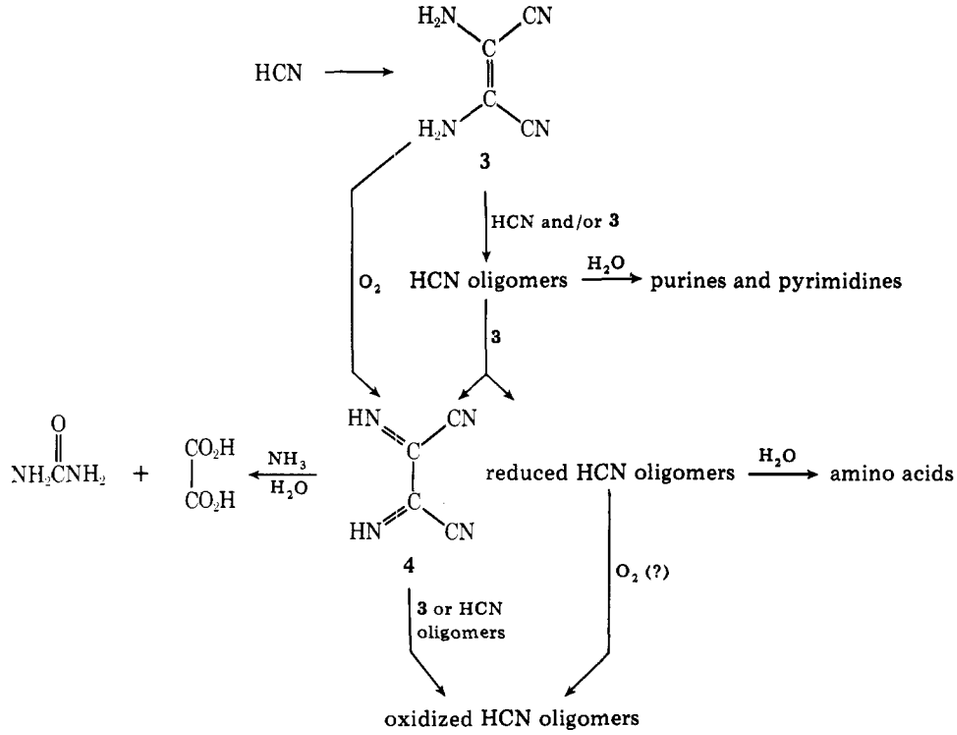
It is significant that urea is formed in the absence of oxygen. This result demonstrates that oxidation reactions are a normal part of the oligomerization reactions in the absence of oxygen. Consistent with this conclusion is the detection in the HCN oligomer hydrolysate of the amino acids glycine, diaminosuccinic acid, aspartic acid, and alanine. A reduction step is required to account for the formation of alanine, diaminosuccinic acid, or aspartic acid from HCN or HCN oligomers such as diaminomaleonitrile.[1,19] The urea may be formed by the oxidation of **3** to **4** by other HCN oligomers. Hydrolysis of **4** yields urea while the hydrolysis of the reduced oligomers yields amino acids. We cannot eliminate the possibility that urea is formed from cyanogen, which is produced by the oxidation of cyanide with aminomalononitrile,[4] but we think that the oxidation of **3** to **4** has more literature precedent.[17]

The ultraviolet spectra of the oligomerization mixtures formed in the absence of oxygen are much simpler than the spectra of those oligomers formed with molecular oxygen present (Figure 4). This suggests that the presence of oxygen may result in the oxidation of the oligomers or their precursors. This is probably a partial oxidation since the general shape of the UV curves is the same; only the intensity of the absorption differs.

Oxalic acid is formed in large amounts during the oligomerization of HCN in the presence of oxygen.[17,20] Since the conversion of hydrogen cyanide to oxalic acid requires an oxidative reaction, the role of oxygen in this oxidation was investigated by measuring the yield of oxalic acid released by hydrolysis of HCN oligomers which had been prepared in the absence of molecular oxygen.[1] The yield of oxalic acid formed by acid hydrolysis was 8.1 mg/L (3% of the HCN oligomer) from the oligomers prepared in a nitrogen atmosphere and 85 mg/L from the oligomers prepared in the presence of molecular oxygen. This dramatic increase in yield demonstrates that molecular oxygen is directly involved in the oxidation of HCN oligomers or a precursor to them. Since it is known that diiminosuccinonitrile (**4**) yields oxalic acid on hydrolysis,[21] compound **4** is the most likely source of free oxalic acid in the oligomerization mixture. The oxalic acid released on hydrolysis is probably formed from **4**, or related structures at the same oxidation state, which became incorporated into the HCN oligomers. The previously discussed differences observed in the ultraviolet spectra of the oligomerization mixtures formed in the presence and absence of oxygen probably reflect a greater percentage of incorporation of these more highly oxidized units when oxygen is present.

The hydrolytic release of oxalic acid from oligomers prepared in a nitrogen atmosphere is further evidence that redox reactions are taking place in the HCN oligomerization reaction. Both the formation of urea and oxalic acid probably

Scheme I



proceed by the oxidation of diaminomaleonitrile (3) to diiminosuccinonitrile (4), which in turn either undergoes hydrolysis to oxalic acid and urea or is incorporated into the HCN oligomers (Scheme I). Of particular interest is the absence of urea on hydrolysis of the HCN oligomers, although it is found in the oligomerization mixture. Ammonia is required for the formation of urea from 4 or its derivatives.[17] Ammonia is present in the oligomerization mixture, but none is used for the hydrolysis of the HCN oligomers. The absence of urea as a hydrolysis product is consistent with the proposed oxidative formation of 4 in the HCN oligomerization. After compound 4 is formed, it either reacts with water or NH_3 to yield simpler hydrolytic products or with other organic compounds to yield HCN oligomers.

Conclusions

The chemical transformations which may take place during HCN oligomerization are summarized in Scheme I. HCN undergoes a rapid, essentially irreversible, condensation to diaminomaleonitrile, which in turn condenses with additional HCN or possibly other diaminomaleonitrile units to give HCN oligomers. Redox reactions take place during the oligomerization to yield reduced HCN oligomers and diiminosuccinonitrile. The diiminosuccinonitrile either hydrolyzes to urea and oxalic acid or reacts with diaminomaleonitrile[22] or HCN oligomers to give oxidized HCN oligomers. Although the oxidized and reduced HCN oliglomers are shown as separate entities in Scheme I, there is no reason to exclude the possibility that there will be both oxidized and reduced units in the same molecule. Diiminosuccinonitrile and the oxidized HCN oligomers may also be formed by oxidation with molecular oxygen.

The amino acids, with the exception of glycine, must be formed by the hydrolyses of reduced oligomers. Glycine may be formed by the hydrolytic cleavage of diaminomaleonitrile[6] or by the hydrolysis of the HCN oligomers. Reduction reactions are not required for the formation of purines or pyrimidines since many of them are at the same oxidation state as HCN. Oxidation by molecular oxygen would be expected to decrease the yields of purines, pyrimidines, and amino acids since they are either at the same oxidation level or at a more reduced state than HCN.

Our findings on the mechanism of HCN oligomerization are not consistent with Matthew's proposal that azacyclopropenylidene imine, a dimer of HCN, is the monomer unit which condenses to give the HCN oligomers.[23,24] First, it seems unlikely that azacyclopropenylidene imine is formed from HCN since recent calculations suggest that the iminoacetonitrile structure is considerably lower in energy.[25] Furthermore, there must only be a low steady-state concentration of the HCN dimer produced since a dimer has never been detected in the presence of HCN. Such a dimer, be it iminoacetonitrile or azacyclopropenylidene imine, will undergo nucleophilic addition reactions with the large excess of cyanide that is present much more rapidly than it will undergo self-condensation reactions. The addition of cyanide to *N*-alkyl derivatives of iminoacetonitrile, yielding N-substituted diaminomaleonitrile derivatives, has been shown to proceed more rapidly than the oligomerization of *N*-alkyliminoacetonitriles.[11]

A modified version of Matthew's proposed mechanisms,[23] the dissociation of diaminomaleonitrile to a dimeric species which undergoes polymerization, was also ruled out in the present study. In this proposal diaminomaleonitrile would be the thermodynamically stable oligomer, but there would still be sufficient amounts of dimer and trimer in equilibrium with it to permit the polymerization of a portion of the dimer, the remainder being reconverted to diaminomaleonitrile in the equilibration process. The lack of incorporation of $H^{13}CN$ in diaminomaleonitrile demonstrates the absence of the equilibrium and eliminates this possibility.

Diaminomaleonitrile, and not the HCN dimer, must be the direct precursor to the HCN oligomers. This work establishes that the formation of diaminomaleonitrile from the HCN dimer and trimer is essentially irreversible. Support for this conclusion is the observation that the structures of the hydrolysis products of the HCN oligomers, glycine, diaminosuccinic acid, aspartic acid, 4,5-dihydroxypyrimidine, and oxalic acid, are readily understood if it is assumed that they are derived from diaminomaleonitrile structural units in the HCN oligomers.[1,3]

Table IV. Reaction of Diaminomaleonitrile with Ni(II) and NH_4OH[a]

reaction time, min	absorbance × 100 (corrected[b])
0	129
1.70	104.4
3.15	89.1
4.33	76.8
5.63	65.6
7.87	51.2
10.13	39.5
12.87	29.75
17.30	18.00
23.33	9.3
42.13	1.6
121.25	0
∞	0

[a] [Diaminomaleonitrile] = 10^{-4} M, [$NiCl_2$] = 9×10^{-4} M, and [NH_4OH] = 0.45 M. [b] Absorbance corrected as discussed in the text.

Experimental Section

General Procedures.[26] Ultraviolet and visible spectra were recorded on a Unicam SP800A spectrophotometer. Carbon-13 NMR spectra were obtained on a Bruker WP-60 spectrometer. Analytical thin-layer chromatography (TLC) was performed on silica gel plates containing a fluorescent indicator (Eastman Chromagram no. 13181), and the compounds were visualized under UV light or with specific color tests. Diaminomaleonitrile (Aldrich) was purified by recrystallizing three times from warm (65 °C) water using a small amount of decolorizing charcoal. Cyanide analyses were performed by silver nitrate titration,[27] the UV absorption of the tetracyanonickelate(II) complex,[28] and the methods of Schilt[29] and Bark and Higson.[30] Urea was analyzed by the procedure of Ormsby.[31] $K^{13}CN$ (90% ^{13}C) was lot MZ from Stohler Isotope Chemicals.

Oligomerization of Hydrogen Cyanide. Pure hydrogen cyanide was prepared from sodium cyanide using a modification of the method of Ziegler.[26,32] Dilute aqueous solutions (0.1 N) of HCN were prepared and adjusted to pH 9.2 with dilute NH_4OH. The solutions were stored in stoppered glass bottles in the dark for at least 1 year, and then filtered and fractionated by ion-exchange chromatography.[26] The term HCN oligomer in this paper is used synonomously with the acid and amphoteric oligomer fractions[1,26] unless otherwise noted.

Hydrolysis of Diaminomaleonitrile with $NiCl_2$ and NH_4OH. A 10^{-3} M diaminomaleonitrile solution was prepared, and a 1-mL aliquot was mixed with 9 mL of freshly prepared nickel(II) chloride (10^{-3} M) in 0.5 M NH_4OH.[28] The UV spectrum was recorded using a thermostated cell maintained at 25 °C and a solution with the same concentrations of nickel(II) ion and ammonia in the reference cells. The UV spectrum was scanned repeatedly until the absorbance at 296 nm remained constant. The tetracyanonickelate ion which formed during the reaction also had some absorbance at 296 nm. The absorbance of the diaminomaleonitrile at 296 nm was therefore corrected to account for this residual absorbance due to tetracyanonickelate ion. The resulting data (Table IV) were found to conform to a first-order kinetic plot (k = 0.112 min^{-1}, $t_{1/2}$ = 6 min).

Hydrolysis of Diaminomaleonitrile with NH_4OH. The UV spectrum of a 10^{-4} M solution of diaminomaleonitrile in 0.45 M NH_4OH was monitored for a 3-h period in a cell thermostated at 25 °C. The half-life of 3 was approximately 1 day (Table V).

Longer term hydrolyses at pH 9.2 in which the HCN concentration was followed by the method of Bark and Higson[30] and the diaminomaleonitrile concentration was followed by the UV absorption at 296 nm indicated that 2 equiv of HCN were formed for every equivalent of diaminomaleonitrile which was hydrolyzed. The same cyanide yield was observed when the hydrolyses were performed in distilled water.

Hydrolysis of Diaminomaleonitrile with $NiCl_2$. An aliquot (1 mL) of 10^{-3} M diaminomaleonitrile solution was mixed with 9 mL of 10^{-3} M $NiCl_2$ solution. The UV spectrum of the mixture was monitored for 24 h in a cell thermostated at 25 °C. No change was observed in the absorbance at 296 nm. In a control experiment it was observed, from the absorption maximum at 267 nm, that CN^- reacts quantitatively with $NiCl_2$ to form the tetracyanonickelate complex.

Reaction of Diaminomaleonitrile with $K^{13}CN$ in Aqueous Solution at pH 7–8. Diaminomaleonitrile (1.5 g) and potassium [^{13}C]cyanide (150 mg, 0.0023 mol) were dissolved in 1 L of distilled water. The solution was then divided into five 200-mL portions which were shaken at 30 °C in stoppered flasks in a shaker bath. The pH of these solutions was in the 7–8 range. Each solution was filtered and extracted with five 100-mL portions of ethyl acetate, and the ethyl acetate solutions were then combined and evaporated to dryness. The product was dissolved in 2 mL of dimethyl-d_6 sulfoxide and the ^{13}C NMR spectrum recorded. The intensity ratio (peak 2/peak 1) was calculated in each case. Each spectrum was run at least 3 times, and the average intensity ratio for all runs was calculated. Results are shown in Table III.

Table V. Decomposition of Diaminomaleonitrile in Ammonium Hydroxide

reaction time, h	absorbance (A) (296 nm)
0	1.29
0.5	1.19
1.0	1.12
1.5	1.08
2.0	1.04
2.5	1.01
3.0	0.98

Reaction of Diaminomaleonitrile with $K^{13}CN$ in Aqueous Solution at pH 9–9.5. In another study, a solution was prepared containing diaminomaleonitrile (2.5 g) and potassium [^{13}C]cyanide (250 mg, 0.0038 mol) in 2 L of distilled water. The pH was adjusted to 9.2 with sodium hydroxide solution and thereafter maintained at 30 °C and pH 9.2. Aliquots were periodically withdrawn and extracted with ethyl acetate as previously described. The results are given in Table II.

Reaction of Diaminomaleonitrile with $K^{13}CN$ in Dimethyl Sulfoxide. A solution containing diaminomaleonitrile (1 g) and potassium [^{13}C]cyanide (100 mg) in 4 mL of 50% dimethyl sulfoxide–50% dimethyl-d_6 sulfoxide was prepared. The ^{13}C NMR spectrum of the black solution was recorded at time intervals up to 10 days, and the intensity ratio (peak 1/peak 2) was calculated in each case. Results are shown in Table V.

Effect of Oxygen on the Oligomerization of HCN. A 3-L solution of 0.1 M HCN was adjusted to pH 9.2 with NH_4OH and was then divided into three equal parts. Solution 1 was simply stoppered and allowed to stand in the dark. Solution 2 was degassed by four freeze–pump–thaw cycles and then stored in an N_2 atmosphere in the dark. Oxygen was bubbled through solution 3 for 15 min before it was stoppered and stored in the dark. Solutions 1 and 3 were subjected to the same freeze–thaw cycles as was solution 2, but they were not pumped to remove air. Aliquots of each solution were taken for analysis immediately after the preparation of the solutions and at regular intervals thereafter. Oxygen was passed through solution 3 and nitrogen was bubbled through solution 2 after each sample was withdrawn. The rate of darkening and precipitate formation was fastest in solution 2 and slowest in solution 3.

Aliquots of the three solutions were monitored for urea, diaminomaleonitrile, and cyanide. Urea was measured by the method of Ormsby,[31] and the results are given in Figure 1. Diaminomaleonitrile formation was measured by the UV absorption of the oligomerization mixture at 296 nm.[6] These spectra showed the formation of a variety of UV-absorbing compounds, especially in solutions 1 and 3 (Figure 4). It was necessary to separate the diaminomaleonitrile from these other substances by TLC using butanol saturated with water and then determine the UV absorption of the eluted diaminomaleonitrile. The amount of diaminomaleonitrile was calculated from the absorbance of standard samples of pure diaminomaleonitrile which were subjected to the same chromatographic and elution procedure. The yields of diaminomaleonitrile are given in Figure 2. Cyanide loss was monitored by silver nitrate titration[27] and the method of Scoggins.[28] The former method gave more reproducible data, and these are given in Figure 3.

Oxalic Acid Analyses. Oxalic acid is a major product formed by the hydrolysis of the HCN oligomers.[33] This result was confirmed by GC/MS analysis of the trimethylsilyl derivative.[34] The yield of oxalic acid was estimated by converting the oxalic acid in the acidic and neutral fractions[1] of the sublimed oligomer acid hydrolysate to its trimethylsilyl derivative. Quantitation was accomplished by comparing the area of the oxalic acid peak with that of standard samples of oxalic acid which were carried through the same procedures. The yield of oxalic acid from the oligomers prepared in the presence of air

and from the oligomers prepared in the presence of nitrogen was found to be 85 and 8.1 mg/L of the oligomerization mixture, respectively.

Urea Analysis of HCN Oligomer Hydrolyzates. Sublimed HCN oligomers (50 mg) were hydrolyzed with 6 N HCl, and half of the hydrolysate was subjected to paper chromatography on Whatman 3MM paper using ethyl acetate/formic acid/water (7:2:1 by volume) as the developing solvent. One-quarter of the hydrolysate was analyzed by TLC using butanol/acetic acid/water (12:3:5 by volume) as the developing solvent. Both chromatograms were sprayed with the *p*-dimethylaminobenzaldehyde reagent.[35] No urea was detected in either chromatogram above the limit of detection of 2–5 μg. It was determined that urea is stable under the acid hydrolysis conditions used.

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Registry No.—**1**, 1726-32-5; **2**, 5181-05-5; **3**, 1187-42-4; hydrogen cyanide, 74-90-8; cyanide, 57-12-5; urea, 57-13-6.

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Steric Effects. 13. Composition of the Steric Parameter as a Function of Alkyl Branching

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The υ steric parameters for alkyl, alkoxy, thioalkyl, dialkylamino, and oxyalkyl groups and the υ' values of alkyl groups were correlated with equations derived from the relationship $\upsilon = an_\alpha + bn_\beta + cn_\gamma + dn_\delta + i$, with excellent results. The parameters n_α, n_β, n_γ, and n_δ represent the number of α, β, γ, and δ carbon atoms, respectively. The correlation equations make possible the estimation of υ values for a very large number of groups. The $E_S{}^c$ values of Hancock and the $E_S{}^o$ values of Palm are simply steric parameters with different values of a from that obtained for the υ values. Rate constants for nucleophilic substitution of benzyl chloride by alkoxide ions, of allyl bromide and of 1-chloro-2,4-dinitrobenzene by alkylamines, of alkaline hydrolysis of ethyl 4-nitrophenyl alkyl phosphonates, C-substituted amides, O-substituted esters, and dialkylphenylacetonitriles, of acidic hydrolysis of C-substituted amides, and of the reaction of alcohols with 4-nitrobenzoyl chloride have been successfully correlated with the equation $Q_{Ak} = an_\alpha + bn_\beta + cn_\gamma + i$. Evaluation of the effect on branching shows clearly that for alkyl groups which are not symmetric, no one set of steric parameters will be effective in all types of reactions.

We have calculated in our previous work in this series[1–5] υ steric parameters for 232 substituents and υ' steric parameters for nine substituents.[6,7] In this paper we investigate the dependence of the steric parameter, υ, on the degree of branching in the alkyl group. We would also like, if possible, to be able to estimate υ values for many additional groups.

In commencing this work, we note that Bowden and Woolridge[8] have reported a poor but significant correlation of E_S values with the equation

$$E_S = m_1 n_C + m_2 n_H + m_3 \quad (1)$$

where n_C and n_H are the number of carbon and hydrogen atoms in the sixth position (with the carbonyl oxygen atom in the ester used to define E_S being considered atom number 1). Let us define the following quantities: $n_\alpha \equiv$ the number of C atoms bonded to the α carbon atom of an alkyl group; $n_\beta \equiv$ the number of C atoms bonded to the β carbon atoms; $n_\gamma \equiv$ the number of C atoms bonded to the γ carbon atoms; $n_\delta \equiv$ the total number of carbon atoms bonded to the δ carbon atoms. Thus, for example, the group *t*-BuCH(Me(CH(Et)CMe$_2$–has values of 3, 2, 3, 3 for n_α, n_β, n_γ, n_δ, respectively, while for the cyclohexyl group, the corresponding values are 2, 2, 1, 0.

Newman[9] had suggested long before that the "six number", n_6, is the major factor in the steric effect. This quantity is defined by the equation

$$n_6 = 3n_\beta \quad (2)$$

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