

VII. LIQUID PHASE PROCESSES

Possible Atmospheric Lifetimes and Chemical Reaction Mechanisms for Selected HCFCs, HFCs, CH₃CCl₃, and their Degradation Products Against Dissolution and/or Degradation in Seawater and Cloudwater

Paul H. Wine

and

W. L. Chameides

Georgia Tech Research Institute and School of Geophysical Sciences
Georgia Institute of Technology
Atlanta, GA 30332

EXECUTIVE SUMMARY

The rates at which eight potential alternative HCFCs and HFCs and methyl chloroform (CH_3CCl_3) can be removed from the atmosphere by dissolution and reaction in the oceans and in cloudwater have been estimated from the species' thermodynamic and chemical properties using simple mathematical formulations to simulate the transfer of gases from the atmosphere to the aqueous phase. The HCFCs and HFCs considered are CHCl_2CF_3 (HCFC-123), CFCl_2CH_3 (HCFC-141b), CF_2ClCH_3 (HCFC-142b), CHF_2Cl (HCFC-22), CHFClCF_3 (HCFC-124), CH_2FCF_3 (HFC-134a), CHF_2CH_3 (HFC-152a), and CHF_2CF_3 (HFC-125).

Cloudwater is found to be of no importance as an atmospheric sink for any of the above compounds. Best-estimate lifetimes for all eight HCFCs and HFCs toward removal in the oceans are greater than 77 years, with only HCFC-22, HCFC-123, and HCFC-141b having lifetimes shorter than 200 years. The most reactive of the nine species considered toward removal in the oceans is methyl chloroform with a best-estimate lifetime of 42 years and a minimum reasonable lifetime of 22 years. Important removal mechanisms for methyl chloroform, HCFC-22, HCFC-123, and HCFC-141b in seawater are hydrolysis and reaction with hydrated electrons. Improved hydrolysis kinetics data and Henry's law solubility data for methyl chloroform, HCFC-22, HCFC-123, and HCFC-141b would help to reduce the uncertainties in the aqueous phase removal rates of these species, as would improved estimates of the hydrated electron concentration in seawater.

Gas phase degradation products of the eight HCFCs and HFCs include a large variety of halo-substituted carbonyls, acids, peroxyacids, hydroperoxides, alcohols, nitrates, peroxy nitrates, and peroxyacetyl nitrates. Although handicapped by the total absence of Henry's law solubility data for any of the compounds of interest and the limited availability of relevant kinetic data, an assessment of the rates and mechanisms of aqueous phase removal of the gas phase degradation products has been carried out.

The species X_2CO , HXCO , CH_3CXO , CF_3OH , CX_3OONO_2 , and ROOH ($\text{X} = \text{F}$ or Cl , $\text{R} =$ halo-substituted methyl or acetyl) are all expected to be removed from the atmosphere on time scales limited by transport to cloudy regions or the marine boundary layer (i.e. about 1 month); aqueous phase reactions of these species result in the formation of chloride, fluoride, and carbon dioxide, as well as formic, acetic, and oxalic acids. The species CX_3CXO , $\text{CX}_3\text{CX}_2\text{OOH}$, $\text{CX}_3\text{CX}_2\text{OONO}_2$, $\text{CX}_3\text{C(O)OONO}_2$, and $\text{CX}_3\text{C(O)OOH}$ are also expected to be removed from the atmosphere rapidly, and their aqueous phase reactions result in the formation of halo-substituted acetates, $\text{CX}_3\text{C(O)O}^-$.

The species $\text{CX}_3\text{C(O)OH}$ are very acidic and, as a result, are highly soluble in cloudwater. These acids are expected to be rapidly removed from the atmosphere by rainout. However, the aqueous phase species $\text{CX}_3\text{C(O)O}^-$ are expected to be resistant to chemical degradation. Trichloroacetate can thermally decompose on a time scale of 2-10 years to yield carbon dioxide and chloroform. In fresh water, the reaction of $\text{CCl}_3\text{C(O)O}^-$ with the hydrated electron is also expected to occur on a time scale of a few years. The species $\text{CFCl}_2\text{C(O)O}^-$, $\text{CF}_2\text{ClC(O)O}^-$, and $\text{CF}_3\text{C(O)O}^-$ may have very long aqueous phase lifetimes. The longest lived species, $\text{CF}_3\text{C(O)O}^-$, could have a lifetime in natural waters as long as several hundred years. Processes which could possibly degrade $\text{CF}_n\text{Cl}_{3-n}\text{C(O)O}^-$ on shorter time scales than suggested above, but whose rates cannot be estimated with any degree of confidence at this time, include oxidation by photochemically generated valence band holes in semiconductor particles and hydrolysis catalyzed by enzymes

AQUATIC MECHANISMS

in microorganisms and plants; further research aimed at characterizing these processes is needed.

One possible gas phase degradation product about which very little is known is CF_3ONO_2 . This compound has never been observed, and may be thermally unstable. If CF_3ONO_2 is thermally stable, then it may have a long lifetime toward aqueous phase removal. Henry's law solubility data and hydrolysis kinetics data for CF_3ONO_2 are needed before its aqueous phase removal rate can be assessed with any degree of confidence.

N92-15445

**POSSIBLE ATMOSPHERIC LIFETIMES AND CHEMICAL REACTION MECHANISMS FOR
SELECTED HCFCs, HFCs, CH₃CCl₃, AND THEIR DEGRADATION PRODUCTS AGAINST
DISSOLUTION AND/OR DEGRADATION IN SEAWATER AND CLOUDWATER**

P.H. Wine and W.L. Chameides

**Georgia Tech Research Institute and School of Geophysical Sciences
Georgia Institute of Technology
Atlanta, GA 30332**

1. INTRODUCTION

For a wide variety of atmospheric species including CO_2 , HNO_3 , and SO_2 , dissolution in seawater or cloudwater followed by hydrolysis or chemical reaction represents a primary pathway for removal from the atmosphere (Peters, 1983; Liss, 1983; Chameides and Davis, 1982). In order to determine if this mechanism can also remove significant amounts of atmospheric chlorofluorocarbons (HCFCs), fluorocarbons (HFCs), and their degradation products, an investigation was undertaken as part of the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS). In this investigation, the rates at which CHCl_2CF_3 (HCFC-123), CCl_2FCH_3 (HCFC-141b), CClF_2CH_3 (HCFC-142b), CHClF_2 (HCFC-22), CHClFCF_3 (HCFC-124), CH_2FCF_3 (HFC-134a), CHF_2CH_3 (HFC-152a), CHF_2CF_3 (HFC-125), and CH_3CCl_3 can be dissolved in the oceans and in cloudwater were estimated from the species' thermodynamic and chemical properties using simple mathematical formulations to simulate the transfer of gases from the atmosphere to the ocean or cloudwater. The ability of cloudwater and rainwater to remove gas phase degradation products of these compounds was also considered as was the aqueous phase chemistry of the degradation products. The results of this investigation are described below.

2. OCEANIC REMOVAL OF HCFCs AND HFCs

The exchange of gases between the atmosphere and ocean is typically simulated with the "stagnant film" model (Danckwerts, 1970). In this model, transfer from the atmosphere to the ocean is assumed to be limited by the rate at which the gas can diffuse (via molecular diffusion) through a thin film of air residing directly above the ocean-atmosphere boundary and a thin film of seawater residing below the boundary. Under these conditions, ϕ_o , the steady state flux of a species from the atmosphere to the ocean (in molecules $\text{cm}^{-2} \text{s}^{-1}$) is given by (Liss, 1983)

$$\phi_o = \{C_A - [I]_o / (HRT)\} \frac{1}{\left[r_A + r_S / (HRT N_A 10^{-3}) \right]} \quad (1)$$

where r_A and r_S are the transfer resistances (in s cm^{-1}) of the atmospheric and oceanic film, respectively, H is the species Henry's or solubility constant (M atm^{-1}), $R = 1.36 \times 10^{-22} \text{ atm cm}^3/\text{molecule/K}$ is the gas constant, T is temperature (assumed to be 285K), N_A is Avogadro's number, C_A is the species' concentration (in molecules cm^{-3}) at the bottom of the atmospheric mixed layer, and $[I]_o$ is the species concentration (in M or moles per liter) at the top of the oceanic mixed layer. It can be shown by solving the one-dimensional diffusion equation that the transfer resistances in Eqn. [1] are given by the thicknesses of the films divided by the molecular diffusion coefficient; in the case of r_A one would use a gas-phase diffusion coefficient of about $0.01 \text{ cm}^2 \text{ s}^{-1}$, while for r_S an aqueous-phase diffusion coefficient of about $10^{-5} \text{ cm}^2 \text{ s}^{-1}$ would be used (Danckwerts, 1970). For conditions typical of the ocean, r_A is about 1.25 s cm^{-1} , while r_S is about 170 s cm^{-1} (Liss, 1983). For the HCFCs and HFCs under consideration here, $H \leq 0.2 \text{ M atm}^{-1}$ and thus

$$r_S / (HRT N_A 10^{-3}) \approx 7/H > 35 \gg r_A \quad (2)$$

It follows, therefore, that the oceanic resistance, r_S , dominates for these compounds and Eqn. [1] can be represented by

$$\phi_o = \{HRT N_A 10^{-3} / r_S\} \{C_A - [I]_o / (HRT)\} \quad (3)$$

AQUATIC MECHANISMS

In order to evaluate Eqn. [3], the species' concentration, $[I]_0$, at the bottom of the oceanic stagnant layer must be defined. This can be accomplished by considering the downward transport of the species through the wave-mixed surface layer of the ocean, which typically extends from the surface (i.e., the bottom of the stagnant ocean film) to the beginning of the main thermocline at about 80 m depth. Following Johnson (1981), the one-dimensional form of the continuity equation for the species in this mixed layer is given by

$$[I]/t = -k[I] + \frac{1}{z} (D \frac{[I]}{z}) \quad (4)$$

where $[I]$ is the species' concentration in the layer, t is time, k is the species' pseudo first-order loss rate due to hydrolysis or chemical reaction, z is depth below the surface, and D is the eddy diffusion coefficient used to parameterize the effect of turbulence on vertical transport. The value of D assumed in our calculations is $40 \text{ cm}^2 \text{ s}^{-1}$ (Johnson, 1981).

Assuming that $[I]$ tends to zero as z gets large, the steady state solution of [4] yields the following form for ϕ_0 (Johnson, 1981):

$$\phi_0 = (Dk)^{1/2} [I]_0 N_A 10^{-3} \quad (5)$$

Equating [3] and [5], it follows that

$$[I]_0 = (HRT) C_A / \{1 + r_S (Dk)^{1/2}\} \quad (6)$$

and substituting [6] into [5] yields a closed form for ϕ_0 ; i.e.,

$$\phi_0 = (Dk)^{1/2} N_A 10^{-3} HRT C_A / \{1 + r_S (Dk)^{1/2}\} \quad (7)$$

Substituting for R , N_A , and T , Eqn [7] reduces to

$$\phi_0 = (H C_A / 0.04) \{r_S + 1/(Dk)^{1/2}\}^{-1} \quad (8)$$

Table 1. Atmospheric Lifetimes (in years) Against Oceanic Loss as a Function of Solubility (H) and First-Order Loss Coefficient in Ocean (k)

	H (M atm ⁻¹)							
	0.001	0.005	0.01	0.02	0.04	0.06	0.08	0.1
k(s ⁻¹)								
10 ⁻¹¹	73,200	14,600	7,320	3,600	1,830	1,230	916	732
10 ⁻¹⁰	23,300	4,670	2,330	1,170	583	389	292	233
10 ⁻⁹	7,550	1,510	755	377	189	126	94	75
10 ⁻⁸	2,560	511	256	128	64	43	32	25
10 ⁻⁷	978	196	98	49	24.5	16	12	9.8

If the species is well-mixed in the atmosphere, it follows from [8] that τ_o , the species' atmospheric lifetime against dissolution in the ocean, is given by

$$\tau_o = (H_A \cdot 0.04/f/H) \{r_s + 1/(Dk)^{1/2}\} \quad (9)$$

where $H_A = 8$ km is the atmospheric scale height and $f = 0.7$ is the fraction of the earth's surface covered by ocean. Values of τ_o calculated from Eqn. [9] for H varying from 0.001 to 0.1 M atm⁻¹ and k varying from 10⁻¹¹ to 10⁻⁷ s⁻¹ are listed in Table 1. It should be noted that Eqn. [9] is only valid for values of H and k such that $\tau_o > 30 - 60$ days. Once the calculated ϕ_o falls below this value, the assumption used in the above derivation that the species is well-mixed in the atmosphere is no longer valid. In this case, the actual atmospheric lifetime for removal in the oceans will be limited by the time required to transport the species to the marine boundary layer (i.e., about 30 to 60 days).

The values for H and k used to calculate τ_o for the HFCs and HCFCs of interest in this work are listed in Table 2. For all species except CH₃CCl₃, values for H in seawater were assumed to be 80% of their pure water Henry's law coefficient at a temperature of 285K. Pure water values for H (see Figure 1) were taken from McLinden AFEAS, 1989 (this report) for all species considered except CH₃CCl₃. The Henry's law coefficients for CH₃CCl₃ in pure water and seawater were obtained from the results of Gossett (1987). He found that $H = 5.8 \times 10^{-8} \exp(4130/T)$ M atm⁻¹ in pure water and that addition of .75M

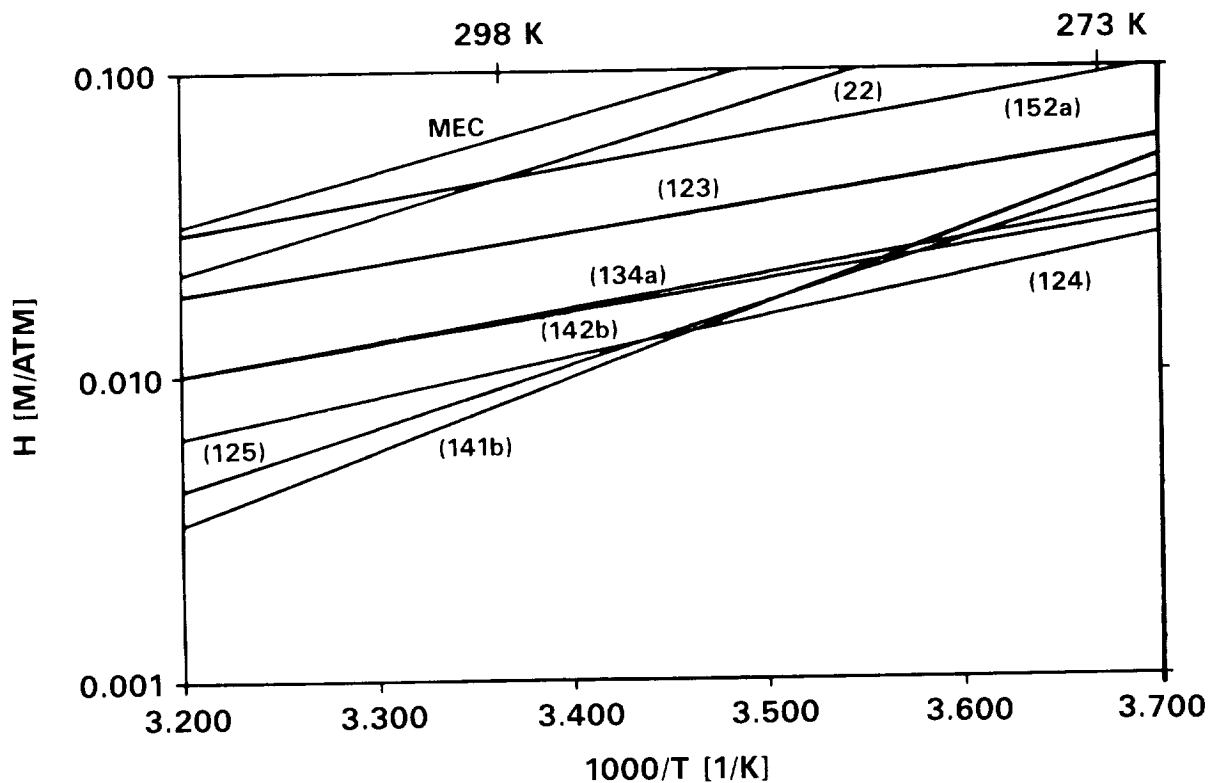


Figure 1. Henry's Law solubilities in pure water for selected HFCs, HCFCs, and CH₃CCl₃ (MEC) as a function of temperature.

AQUATIC MECHANISMS

Table 2. Solubilities, Pseudo First-Order Loss Rates, and Lifetimes Against Oceanic Removal For Selected HFCs and HCFCs

Species	H(M/atm)	Pseudo First Order Loss Rates (s ⁻¹)				Lifetime (years)	
		k _h	k _e	k _{OH}	k	b.e.	min
CH ₂ CCl ₃	0.08	4 x 10 ⁻⁹	1.4 x 10 ⁻⁹	1.6 x 10 ⁻¹¹	5.4 x 10 ⁻⁹	42	22
CF ₃ CHF ₂ (125)	<0.015	<10 ⁻¹⁰	<10 ⁻¹¹	4 x 10 ⁻¹²	<10 ⁻¹⁰	>1500	>700
CF ₃ CH ₂ F(134a)	0.02	<10 ⁻¹⁰	<10 ⁻¹¹	1.2 x 10 ⁻¹¹	<10 ⁻¹⁰	>1100	>530
CH ₃ CHF ₂ (152a)	0.05	<10 ⁻¹⁰	<10 ⁻¹¹	4 x 10 ⁻¹¹	<10 ⁻¹⁰	>460	>210
CF ₃ CHClF(124)	0.015	10 ⁻⁹	10 ⁻⁹	1.6 x 10 ⁻¹¹	2 x 10 ⁻⁹	360	170
CH ₃ CClF ₂ (142b)	0.02	10 ⁻⁹	10 ⁻⁹	4 x 10 ⁻¹²	2 x 10 ⁻⁹	270	130
CF ₃ CHCl ₂ (123)	0.03	10 ⁻⁹	10 ⁻⁹	4 x 10 ⁻¹¹	2 x 10 ⁻⁹	180	85
CH ₃ CFCl ₂ (141b)	0.015 - 0.07	10 ⁻⁹	10 ⁻⁹	1 x 10 ⁻¹¹	2 x 10 ⁻⁹	77-360	36
CHClF ₂ (22)	0.085	3 x 10 ⁻¹⁰	3 x 10 ⁻¹⁰	6 x 10 ⁻¹²	6 x 10 ⁻¹⁰	110	45

T is assumed to be 285K

b.e. = Lifetime calculated with H and k listed in Table

min = Lifetime calculated with maximum H value listed and k enhanced by a factor of 5

KCl resulted in a 40% decrease in H (the ionic strength of seawater is approximately 0.75M). Gossett's result in pure water at 298K is in excellent agreement with an estimate by Lyman (1985) which was based on solubility and vapor pressure data, but a factor of two larger than an earlier measurement reported by Dilling (1977). While the values for the Henry's law solubilities of most of the species were judged to be known to within about 15%, McLinden AFEAS 1989 has noted the possibility of a significant error in the Henry's Law solubilities cited for CF₃CHF₂ and CH₃CFCl₂. To account for this possibility as well as other unknown systematic errors, we have adopted a range of H-values for CF₃CHF₂ and CH₃CFCl₂. (See Table 2).

Three processes were considered to determine the pseudo first-order loss rate, k, for the compounds of interest. These were hydrolysis, indicated by k_h in Table 2, reaction with hydrated electrons, indicated by k_e in Table 2, and reaction with OH, indicated by k_{OH} in Table 2. The total loss rate is thus given by

$$k = k_h + k_e + k_{OH} \quad (10)$$

The hydrolysis rates in Table 2 for CHClF₂ and for CH₃CCl₃ were obtained from McLinden AFEAS, 1989 and Ellenrieder and Reinhard (1988), respectively. New unpublished results (Gerken and Franklin, 1989) verify the CH₃CCl₃ hydrolysis rate in Table 2 and provide improved temperature dependence data.

The other hydrolysis rates were assumed to be intermediate between that of CH_3CCl_3 and CHClF_2 for those species which contain at least one Cl atom (i.e., 10^{-9} s^{-1}) and less than 10^{-10} s^{-1} for those species which do not contain any Cl. It should be noted that the k_h values listed in Table 2 are based on data obtained from fresh water and that the actual hydrolysis rates in seawater may be significantly different. For instance, ionic strength effects have the potential to increase or decrease the hydrolysis rates by as much as 50% (Neely, 1985). In the case of the fluorinated compounds, hydrolysis can be enhanced by perhaps an order of magnitude or more because the large levels of Cl^- ions in seawater can catalyze hydrolysis of fluorocarbons via nucleophilic substitution of Cl for F followed by hydrolysis of the chlorocarbon (Zafiriou, 1975). In order to indicate the possible impact of these effects on our results, sensitivity calculations will be presented in which our estimated values for k are arbitrarily increased by a factor of 5. It should be noted, however, that it does not appear possible for Cl^- catalysis to cause any of the HFCs to have an "effective" hydrolysis rate faster than that of CF_3CHClF , because nucleophilic substitution of OH for Cl is expected to be considerably faster than nucleophilic substitution of Cl for F.

The values for k_e in Table 2 were obtained by assuming an average hydrated electron level in the mixed layer of the ocean of $1 \times 10^{-19} \text{ M}$. This estimate for the concentration of hydrated electrons in the oceans is based on: 1. the observations of Zepp et al. (1987a) which implied a diurnally averaged abundance of free electrons at the surface of fresh water lakes and rivers of about $5 \times 10^{-18} \text{ M}$ from the irradiation of dissolved organic matter; 2. the fact that dissolved organic matter is about 10 times less abundant in the ocean than in fresh water (Stumm and Morgan, 1970); and 3. the assumption that free electrons will decrease with increasing depth with a scale depth of 15m due to the attenuation of sunlight in the ocean. (Note that the upper limit for e^- in seawater of 10^{-15} M reported by Swallow (1969) seems much too high based on current information). Second-order rate constants for the reaction of CH_3CCl_3 and CHClF_2 with hydrated electrons were taken to be $1.4 \times 10^{10} \text{ M}^{-1} \text{ s}^{-1}$ and $3 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$, respectively, based on the observations of Lal et al. (1988) and Salih et al. (1976). Rate constants for the other HFCs and HCFCs which contain Cl atoms were assumed to be intermediate between that of CH_3CCl_3 and CHClF_2 , i.e. $10^{10} \text{ M}^{-1} \text{ s}^{-1}$ for species containing Cl atoms (cf., Balkas et al., 1971; Anbar and Hart, 1965; Balkas, 1972; Afanassiev et al., 1979; Salih, et al., 1976; Hart et al., 1964; Bullock and Cooper, 1970), and less than $10^8 \text{ M}^{-1} \text{ s}^{-1}$ for those species which contain no Cl atoms.

The values of k_{OH} listed in Table 2 were estimated assuming a seawater OH concentration of $4 \times 10^{-19} \text{ M}$ (Zepp et al., 1987b; Zafiriou and True, 1979). For CH_3CCl_3 , a second-order aqueous-phase rate constant for the OH reaction of $4 \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$ (Lal et al., 1988) was adopted. The second-order rate constants for the other HFCs and HCFCs were assigned values based on their gas phase rate constants relative to the gas phase $\text{OH} + \text{CH}_3\text{CCl}_3$ rate constant. Comparison of the aqueous phase rate constants reported by Lal, et al. (1988) with known gas phase rate constants for the same reactions seems to justify this procedure.

The resulting lifetimes obtained from Eqn [9] for each of the HFCs and HCFCs considered here are listed in Table 2. Note that two sets of lifetimes are listed in the Table: the 'best estimate' for the values of H and k obtained in the manner described above, and a minimum lifetime obtained from the maximum value estimated for H and a k enhanced by a factor of 5 over the value listed in the Table. With the exception of CH_3CCl_3 and CH_3CFCl_2 , it appears likely that the lifetimes for HFCs and HCFCs against removal by dissolution in the oceans are of the order of 100 years or more indicating that this process is unlikely

AQUATIC MECHANISMS

to be of significance. In the case of CH_3CCl_3 and CH_3CFCl_2 , however, oceanic removal could be non-negligible depending on the exact Henry's law solubilities and loss rates of these species in seawater. There is also a possibility that the same may be true of CHClF_2 and CF_3CHCl_2 . Further research to better define the Henry's Law coefficients and loss rates for these species in seawater might prove to be a useful endeavor.

3. REMOVAL OF HCFCs AND HFCs IN CLOUDWATER

The removal of HCFCs and HFCs by dissolution and chemical degradation in cloudwater appears to be much smaller than the rate of removal in the oceans. To illustrate this fact, consider the removal by cloudwater of CH_3CCl_3 , probably the most readily removed of all the compounds considered here. As discussed above, CH_3CCl_3 probably has a Henry's law solubility in cloudwater ($T \geq 273\text{K}$) of $\leq 0.2 \text{ M atm}^{-1}$. Its pseudo first-order rate of removal in cloudwater is probably controlled by reaction with aqueous-phase OH radicals; given a second-order, aqueous-phase rate constant against reaction with OH of $4 \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$ (Lal et al., 1988) and a cloudwater OH concentration of about $2 \times 10^{-13} \text{ M}$ (Chameides, 1984; Jacob, 1986), we estimate a k -value for CH_3CCl_3 in cloudwater of about $8 \times 10^{-6} \text{ s}^{-1}$. Assuming an average column content of liquid water in the atmosphere of about $10^{-4} \text{ L cm}^{-2}$ (Junge, 1963) and assuming gas-aqueous-phase equilibration, (appropriate for $H \leq 10^3 \text{ M atm}^{-1}$, cf., Xing and Chameides, 1989) it follows that RC, the rate of loss of the species in cloudwater (in molecules $\text{cm}^{-2} \text{ s}^{-1}$), is given by

$$\text{RC} = X (0.2 \text{ M atm}^{-1}) (10^{-4} \text{ L cm}^{-2}) N_A 8 \times 10^{-6} \text{ s}^{-1} \quad (11)$$

where X is the species volume mixing ratio. If we further assume that the species is well-mixed in the atmosphere, Eqn. [11] implies an atmospheric lifetime, τ_c , against removal by cloudwater of

$$\tau_c = X (2.5 \times 10^{19} \text{ molec cm}^{-3}) H_A / \text{RC} \approx 5,000 \text{ years} \quad (12)$$

Even longer lifetimes are obtained as H and k are decreased for the other HFCs and HCFCs.

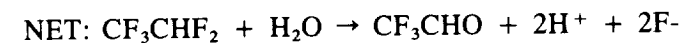
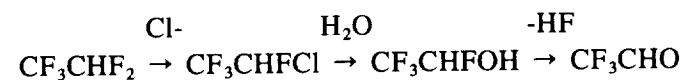
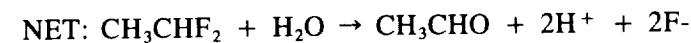
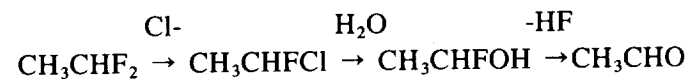
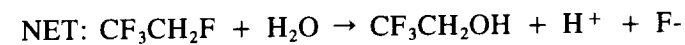
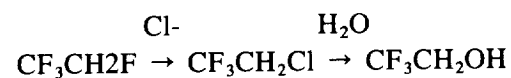
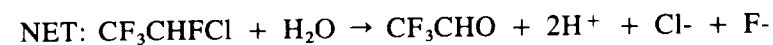
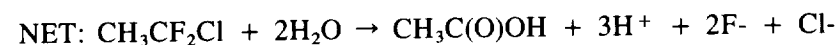
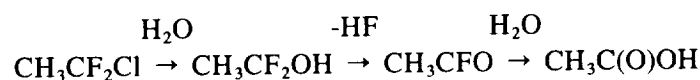
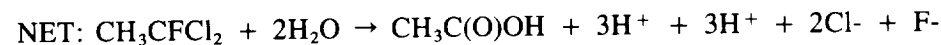
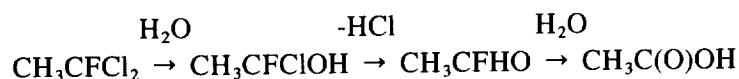
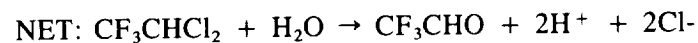
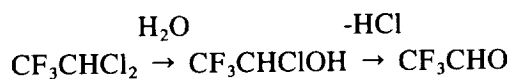
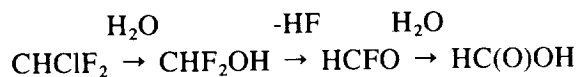
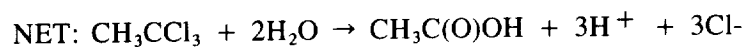
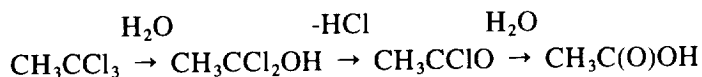
4. DEGRADATION PRODUCTS OF HYDROLYSIS AND HYDRATED ELECTRON REACTIONS

Hydrolysis of C_2 halocarbons can proceed via either substitution or elimination mechanisms, while only the substitution pathway is available for C_1 halocarbons. Primary halocarbons generally hydrolyze predominantly by the substitution pathway, with elimination becoming more important for branched halocarbons (Roberts and Caserio, 1965). For CH_3CCl_3 , hydrolysis is known to yield 70-80% $\text{CH}_3\text{C(O)OH}$ (the substitution product) and 20-30% $\text{H}_2\text{C} = \text{CCl}_2$ (the elimination product) (Ellenrieder and Reinhard, 1988; Gerkens and Franklin, 1989). Product information is not available for the other halocarbons of interest in this assessment.

The haloethylenes formed via elimination are resistant to hydrolysis and relatively insoluble in water (see, for example, Gossett, 1987). Degradation of these compounds is expected to occur rapidly in the gas phase following volatilization from the aqueous phase.

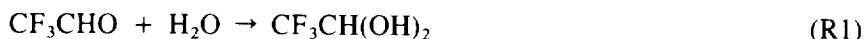
Hydrolysis via the substitution pathway is a multistep process which involves formation of unstable intermediates such as α -haloalcohols and acid halides. Probable intermediate and end products are summarized in Table 3. The expected stable products are: HC(O)OH from CHClF_2 ; $\text{CH}_3\text{C(O)OH}$ from CH_3CFCl_2 and $\text{CH}_3\text{CF}_2\text{Cl}$; CF_3CHO from CF_3CHCl_2 , CF_3CHF_2 and CF_3CHFCl ; $\text{CF}_3\text{CH}_2\text{OH}$ from $\text{CF}_3\text{CH}_2\text{F}$;

Table 3. Probable Reaction Pathways for Hydrolysis of the Halocarbons of Interest via Substitution Mechanisms



AQUATIC MECHANISMS

CH₃CHO from CH₃CHF₂. The fluorine containing end product CF₃CH₂OH is expected to be volatilized from the ocean to the gas phase where it would be oxidized by OH radicals. The recent work of Betterton and Hoffmann (1988) suggests that the other fluorine containing end product, CF₃CHO, will have a large effective Henry's law solubility (10⁵ - 10⁶ M atm⁻¹) due to efficient hydration,



The gem-diol species CF₃CH(OH)₂ is expected to be relatively stable in seawater. The lifetime of CF₃CHO ⇌ CF₃CH(OH)₂ in seawater may be limited by oxidation of the small equilibrium concentration of CF₃CHO(g) via reaction with OH radicals.

The reactions of hydrated electrons with halocarbons result in the formation of halo-substituted peroxy radicals.



As mentioned in an earlier section, (R2) proceeds at a diffusion controlled rate for most chlorocarbons, but is considerably slower for fluorocarbons. Attack of chlorofluorocarbons by e⁻ will always result in removal of a chlorine atom. Haloperoxy radicals are strong oxidizing agents which, in seawater, are expected to undergo electron transfer reactions with resultant production of halohydroperoxides. The aqueous phase chemistries of haloperoxy radicals and halohydroperoxides are considered in some detail in later sections of this report.

5. ALTERNATIVE DEGRADATION PATHWAYS

In addition to hydrolysis and reaction with hydrated electrons, a number of other halocarbon degradation pathways are operative in selected environments such as anoxic contaminant groundwaters, surface waters with high concentrations of metal ion reductants, and regions of high biological activity. These pathways are discussed in a recent review by Vogel, et al. (1987). They include metal catalyzed hydrogenolysis and dihalo-elimination, nucleophilic substitution of SH⁻ for X⁻, and enzyme catalyzed hydrolysis and halogenation reactions. It seems unlikely that the above processes will make significant contributions to the global removal rate of HCFCs, HFCs, and CH₃CCl₃ from the atmosphere, although research aimed at quantifying their contribution would be worthwhile.

6. AQUEOUS PHASE REMOVAL OF GAS PHASE DEGRADATION PRODUCTS

Several assessments of potential gas phase degradation products have been prepared as part of the Alternative Fluorocarbons Environmental Acceptability Study. The degradation products include a large variety of halo-substituted carbonyls, acids, peroxyacids, hydroperoxides, alcohols, nitrates, peroxy nitrates, and peroxyacetylnitrates. Our attempt to assess the lifetimes of the above compounds toward aqueous phase removal is somewhat hampered by the total absence of Henry's law solubilities for any of the compounds of interest. An Appendix is attached to this report which contains tables of Henry's law solubilities for non-halo-substituted analogs, vapor pressure data, acid-base equilibria, and one-electron redox potentials. These data were used extensively in our evaluation. Possible aqueous phase removal rates and degradation mechanisms for each class of gas phase products are considered below.

Acid Halides

Acid halides are known to hydrolyze rapidly. For Cl_2CO , F_2CO , and ClFCO , substitution of OH for X (X = Cl, F) produces a halohydroxycarbonyl which rapidly eliminates HX to yield the end product CO_2 . Hydrolysis of the other acid halides of interest, (i.e., HCXO , CH_3CXO , CX_3CXO) proceeds by a single step substitution route to give the corresponding carboxylic acid.

Kinetic data for acid halide hydrolysis in water solvent are rather sparse. Bunton and Fendler (1966) studied the kinetics of CH_3CFO hydrolysis in water as a function of temperature and pH. They obtained the result $k_h = 2.9 \times 10^7 \exp(-6290/T) \text{ s}^{-1}$ independent of pH over the range 2.8-6.8, i.e. $k_h = 0.0051 \text{ s}^{-1}$ at 280K and 0.023 s^{-1} at 300K. Hudson and Moss (1962) used stop-flow techniques to investigate the kinetics of CH_3CClO hydrolysis at 300K in 75.6% H_2O - 24.4% dioxan; they measured $k_h = 292 \text{ s}^{-1}$, a rate which is expected to be even faster in pure H_2O solvent. Swain and Scott (1953) measured the relative rates of hydrolysis of CH_3CClO and CH_3CFO in 75% acetone - 25% water at 298K and found that CH_3CClO was 7700 times more reactive, in agreement with the reactivity trend suggested by the above-mentioned absolute rate measurements. Ugi and Beck (1961) studied the hydrolysis kinetics of a series of acid chlorides in 10.9 vol % H_2O + 89.1 vol % acetone at 298K and obtained the following rate constants in units of s^{-1} : CH_3CClO , 0.0011; ClCH_2CClO , 0.020; Cl_2CHCClO , 3.1; Cl_3CClO , > 10; Cl_2CO , 1.02. Substitution of Cl for H on the alkyl carbon dramatically increases the rate of hydrolysis, presumably because the electron withdrawing power of Cl results in stabilization of the transition state for water attack on the carbonyl carbon. Substitution of F for H on the alkyl carbon should increase the hydrolysis rate even more dramatically. Based on the above information it seems clear that, with the possible exception of HFCO , all acid halides of interest will hydrolyze more rapidly than CH_3CFO . Hence, the kinetic data of Bunton and Fendler (1966) for CH_3CFO hydrolysis provide a useful lower limit rate coefficient for assessing the maximum lifetime of acid halides toward uptake and hydrolysis in the ocean and in cloudwater.

For temperatures typical of cloudwater and surface seawater, it seems safe to assume that k_h will be greater than 10^{-3} s^{-1} for all acid halides of interest. Using the 285K effective Henry's law solubility for acetaldehyde of 45 M atm^{-1} (Snider and Dawson, 1985; Betterton and Hoffmann, 1988) as a guide, it also seems safe to assume that $\text{H} > 10 \text{ M atm}^{-1}$ for all acid halides of interest, particularly since electron withdrawing substituents such as Cl and F are known to increase the solubility of carbonyls (Betterton and Hoffmann, 1988). On the basis of the formulations described above, these lower limit values for k_h and H imply upper limit lifetimes for the acid halides against removal in the ocean and removal in cloudwater of the order of a month and 2 years, respectively. It should be noted that the maximum lifetime for removal of acid halides by hydrolysis in the ocean is transport limited, and would be only one or two months even if the above lower limits for k_h and H were reduced by a factor of ten each. Hence, there seems to be very little chance that (apparently) important gas phase degradation products such as ClFCO and CF_3CClO (R.A. Cox, AFEAS, 1989 (this report)) will survive in the atmosphere long enough to represent significant sources of stratospheric chlorine.

CF_3OH

In the condensed phase, CF_3OH is known to be unstable toward elimination of HF (Seppelt, 1977),



(R4) probably also occurs in the gas phase. If not, it will occur very rapidly upon uptake of CF_3OH into

AQUATIC MECHANISMS

cloudwater or seawater. Henry's law solubilities for aliphatic alcohols are typically an order of magnitude larger than those of the corresponding aldehydes (Snider and Dawson, 1985). Hence, conversion of CF_3OH to $\text{CO}_2 + 3\text{HF}$ via HF elimination and subsequent hydrolysis of CF_2O will be as fast as CF_2O hydrolysis if HF elimination occurs in the gas phase and faster if HF elimination occurs in the aqueous phase.

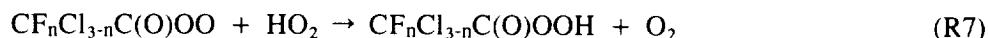
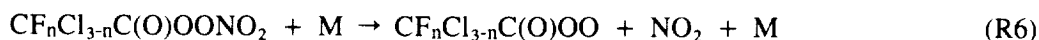
Peroxyacetylnitrates

Both hydrolysis and Henry's law data are available for PAN. At 285K, $H \approx 7 \text{ M atm}^{-1}$ and $k_h \approx 1 \times 10^{-4} \text{ s}^{-1}$ (Lee, 1984; Holdren, et al., 1984). Based on our earlier discussions, these values suggest a lifetime of about 10 years for PAN removal by cloudwater and of the order of a month for removal in the ocean. Holdren, et al. (1984) have shown that the PAN hydrolysis rate is independent of pH over the range 4.0 - 5.6, and that nitrate is produced as a product. Hence, the hydrolysis reaction is probably

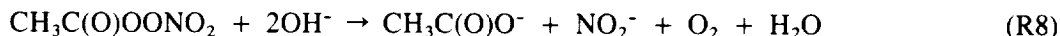


In the absence of experimental data, it seems reasonable to assume that removal of $\text{CF}_n\text{Cl}_{3-n}\text{C}(\text{O})\text{OONO}_2$ by hydrolysis in seawater and cloudwater will proceed at a rate somewhat faster than that for PAN due to stabilization of the transition state for water attack on the carbonyl carbon by the electron withdrawing nature of Cl and F. The hydrolysis products are expected to be halo-substituted peroxy acids and nitrate. Lifetimes toward hydrolysis in seawater and cloudwater on the order of a few weeks and few years, respectively seem likely.

Despite the rapid removal rate estimated above, ocean hydrolysis may not be an important atmospheric removal mechanism for the halogenated peroxyacetylnitrates. The marine boundary layer is typified by relatively warm temperatures, low NO_x levels, and high HO_x levels. Under such conditions, conversion of peroxyacetylnitrates to peroxyacetic acids should occur in the gas phase, i.e.



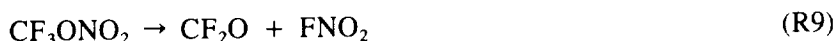
The stoichiometry of PAN hydrolysis in alkaline solution is (Nicksic, et al., 1967; Stephens, 1967)



At a typical seawater pH of 8.1 it is not clear what the relative contributions of (R5) and (R8) to PAN hydrolysis will be. However, since peroxyacetic acid is known to hydrolyze rapidly to acetic acid and H_2O_2 (Lind and Kok, 1986), acetate is produced in either case. Similarly, the long-lived halogen-containing products of $\text{CF}_n\text{Cl}_{3-n}\text{C}(\text{O})\text{OONO}_2$ hydrolysis are expected to be halo-substituted acetates, although halo-substituted peroxyacetates may be produced as intermediates with lifetimes of hours to days. The chemistry of peroxyacetates is discussed in more detail in a later section.

CF₃ONO₂

It has been suggested in the literature (Hohorst and DesMarteau, 1974) that CF₃ONO₂ is thermally unstable in condensed phases.

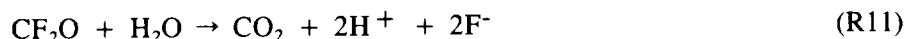
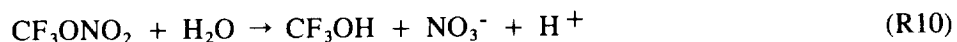


(R9) may also occur in the gas phase.

If CF₃ONO₂ turns out to be thermally stable, then in the absence of Henry's law solubility data and hydrolysis data, we assume that CF₃ONO₂ will behave similarly to CH₃ONO₂ (methyl nitrate). The Henry's law solubility of CH₃ONO₂ is nearly identical to that of PAN (Lee, et al., 1983). Robertson, et al. (1982) studied the hydrolysis kinetics of isopropylnitrate and three other secondary nitrates in water. Because the observed rates were very slow at room temperature, Robertson, et al.'s experiments were carried out at elevated temperature; the temperature range covered for isopropylnitrate was 340-369K. Extrapolation of Robertson, et al.'s results to lower temperatures suggests $k_h \sim 2 \times 10^{-7} \text{ s}^{-1}$ at 300K and $5 \times 10^{-9} \text{ s}^{-1}$ at 280K. Baker and Easty (1952), have studied the kinetics of neutral hydrolysis (H₂O nucleophile) of methyl-, ethyl-, and isopropylnitrate in 60% ethanol/40% water at 60.2°C; they obtain the relative reactivities methyl:ethyl:isopropyl = 2.0:1.1:4.8. Alkaline hydrolysis (OH⁻ nucleophile) was found to be about 100 times faster than neutral hydrolysis, but the neutral reaction is expected to dominate under atmospheric conditions. The above results suggest that at 285K, a typical seawater temperature, k_h for methyl nitrate is about $4 \times 10^{-9} \text{ s}^{-1}$.

Clearly, removal of CF₃ONO₂ by hydrolysis in cloudwater will be of no importance as an atmospheric loss process. For $H = 1 - 10 \text{ M atm}^{-1}$ and $k_h = (1 - 10) \times 10^{-9} \text{ s}^{-1}$, the lifetime of CF₃ONO₂ toward hydrolysis in seawater will be in the range 0.1 - 10 years. Measurements of H and k_h for CF₃ONO₂ in seawater would clearly be worthwhile.

It is well established that neutral hydrolysis of simple primary and secondary alkyl nitrates proceeds via an S_N2 mechanism to yield the corresponding alcohol (Baker and Easty, 1952; Robertson, et al., 1982). Hence, while the CF₃ONO₂ hydrolysis rate is highly uncertain and could be quite long, the degradation mechanism can be predicted with a reasonable degree of certainty:

**Peroxy nitrates**

No quantitative solubility or hydrolysis rate data is available for alkylperoxy nitrates (which are thermally unstable) or the halo-substituted species. The synthesis and characterization of CF₃OONO₂ is reported in the literature (Hohorst and DesMarteau, 1974). Thermal decomposition of CF₃OONO₂ is found to be rather slow in the liquid phase, but hydrolysis to CF₃OOH + NO₃⁻ is rapid. The Henry's law solubilities of the halo-substituted peroxy nitrates are probably similar to those of the peroxyacetyl nitrates and the alkyl nitrates, i.e. $1 - 10 \text{ M atm}^{-1}$.

AQUATIC MECHANISMS

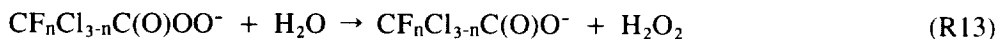
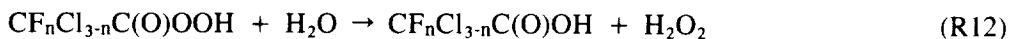
The above information suggests that the lifetime of halo-substituted peroxy nitrates in the atmosphere will be short. In the marine boundary layer, gas phase conversion to halo-substituted alkylhydroperoxides via a mechanism analogous to (R6) and (R7) will occur if the lifetime toward unimolecular decomposition is of the order of 10^6 s or less. Otherwise, removal will be dominated by dissolution and hydrolysis in seawater.

Peroxyacids

Lind and Kok (1986) have determined the Henry's law solubility of peracetic acid to be $\exp(6171/T - 14.55)M \text{ atm}^{-1}$ (i.e. $1790 M \text{ atm}^{-1}$ at 280K). These authors have also observed that peracetic acid hydrolyzes to acetic acid and hydrogen peroxide, with the hydrolysis reaction going to completion in a day or two, (i.e. $k_h \sim 10^{-5} \text{ s}^{-1}$ at 298K). The negative log of the acid dissociation constant (pKa) for peracetic acid is 8.2 (Koubek, et al., 1963). The halogenated peracetic acids will be more acidic than peracetic acid itself. We estimate that the pKa for trichloroperacetic acid will be in the range 6-7, while the pKa for trifluoroperacetic acid will be in the range 5-6. Hence, the halogenated peroxyacids will be partially dissociated in cloudwater, and almost completely dissociated in seawater. For reasons discussed above in conjunction with acid halide and peroxyacetyl nitrate hydrolysis, halogenated peroxyacids are expected to hydrolyze considerably more rapidly than alkylperoxyacids.

Based on the above information, we estimate that under cloudwater conditions, $\text{pH} \sim 5$ and $T \sim 280\text{K}$, reasonable values for H and k_h for the halogenated peroxyacetic acids are $(1-5) \times 10^3 M \text{ atm}^{-1}$ and $(1-100) \times 10^{-5} \text{ s}^{-1}$, respectively, with the fluorinated species expected to be the most reactive. Under seawater conditions, $\text{pH} \sim 8.1$ and $T \sim 285\text{K}$, the effective Henry's law solubilities of the halogenated peroxyacetic acids are expected to be quite large. Reasonable estimates for $\text{CCl}_3\text{C}(\text{O})\text{OOH}$ and $\text{CF}_3\text{C}(\text{O})\text{OOH}$ are $3 \times 10^4 M \text{ atm}^{-1}$ and $3 \times 10^5 M \text{ atm}^{-1}$, respectively. Assuming that the unprotonated acid hydrolyzes about as efficiently as the protonated acid, we estimate that $k_h \sim (2-200) \times 10^{-5} \text{ s}^{-1}$ with $\text{CF}_3\text{C}(\text{O})\text{OO}^-$ expected to be the most reactive species. The above parameters suggest that the lifetimes of the halogenated peroxyacids toward hydrolysis in cloudwater and the ocean are quite short; probably of the order of a week to a month and limited by the rate of transport to cloudy regions and/or the marine boundary layer.

The products of peroxyacid hydrolysis are expected to be the corresponding acids (Lind and Kok, 1986), i.e.,



Acids

The halo-substituted acetic acids are very acidic species. The pKa's for $\text{CF}_3\text{C}(\text{O})\text{OH}$ and $\text{CCl}_3\text{C}(\text{O})\text{OH}$ are 0.25 and 0.64, respectively (Lange, 1979). Hence, these species are almost totally deprotonated in environmental aqueous phase systems. Taking $10^3 M \text{ atm}^{-1}$ as a reasonable lower limit Henry's law solubility for $\text{CF}_n\text{Cl}_{3-n}\text{C}(\text{O})\text{OH}$ at 280 - 285K, effective Henry's law solubilities are $> 10^7 M \text{ atm}^{-1}$ in cloudwater, $> 10^9 M \text{ atm}^{-1}$ in freshwater lakes and rivers, and $> 10^{10} M \text{ atm}^{-1}$ in seawater.

As discussed in detail below, we expect the halo-acids to be resistant to chemical degradation. The combination of low reactivity and high solubility suggests that the principal fate of atmospheric halo-acids

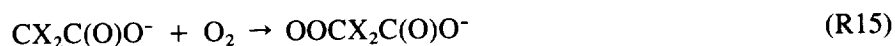
will be rainout. Rainout of highly soluble species has been modelled in some detail by Giorgi and Chameides (1985), who showed that the rainout rate depends not only on the average rainfall, but also on the period of the storm cycle. The difference between rainout rates calculated for continuous light rainfall versus a short period of heavy rain followed by a long dry period is about an order of magnitude with continuous light rainfall resulting in more rapid rainout. A typical rainout rate for $\text{CF}_n\text{Cl}_{3-n}\text{C(O)OH}$ is estimated to be 10^{-6} s^{-1} , or about 12 days.

Once the halo-acids are deposited into freshwater or seawater, they may undergo a number of reactions. These include reaction with hydrated electrons, oxidation-decarboxylation, thermal decarboxylation, hydrolysis, and microbial degradation. Probable rates and mechanisms for these reactions are discussed below.

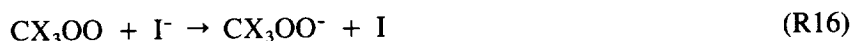
The rate coefficient for the reaction



is known to be $8.5 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$ (Anbar and Hart, 1965). As discussed previously in this report, estimated hydrated electron concentrations in freshwater and seawater are 10^{-18} M and 10^{-19} M , respectively. Hence, the lifetime of $\text{CCl}_3\text{C(O)O}^-$ toward removal via (R14) is estimated to be 3.7 years in freshwater and 37 years in seawater. $\text{CF}_3\text{C(O)O}^-$ is expected to be at least 100 times less reactive with e^- than is $\text{CCl}_3\text{C(O)O}^-$, while $\text{CF}_2\text{ClC(O)O}^-$ and $\text{CFCl}_2\text{C(O)O}^-$ will react at intermediate rates. The radical products of (R14) and its analogs will rapidly add O_2 to form peroxy radicals,

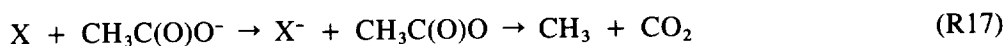


Halo-substituted peroxy radicals are known to be strong oxidizing agents (Packer, et al., 1980; Monig, et al., 1983; Alfassi, et al., 1987; Huie, et al., 1987; Lal et al., 1988). For example, Huie and Neta (private communication) have found that the reactions



proceed rapidly with $k \sim 10^8 \text{ M}^{-1} \text{ s}^{-1}$ for $\text{X} = \text{Cl}$ and F . Kinetics studies of CCl_3OO , $\text{OOCCL}_2(\text{O})\text{O}^-$, and $\text{OOCF}_2\text{C(O)O}^-$ reactions with a number of antioxidants have shown that $\text{OOCCL}_2(\text{O})\text{O}^-$ and $\text{OOCF}_2\text{C(O)O}^-$ are about equally reactive, but both are 3 - 10 times less reactive than CCl_3OO (Packer, et al., 1980). A typical iodide concentration in seawater is 10^{-7} M , suggesting that the lifetime of $\text{OOCX}_2\text{C(O)O}^-$ toward reduction by I^- is about one second. Analogous reactions are also expected to proceed rapidly in freshwater due to the availability of good reducing agents such as, for example, NO_2^- . The probable chemistry of $\text{OOCX}_2\text{C(O)O}^-$ and their protonated species $\text{HOOCX}_2\text{C(O)O}^-$ is discussed in the next section.

It is known that strong oxidizing agents can undergo the following reaction with acetate:



The sulfate radical, for example, is known to react with acetate at a moderate rate ($k = 3.7 \times 10^6 \text{ M}^{-1} \text{ s}^{-1}$ in the zero ionic strength limit) (Wine, et al., 1989) to produce CO_2 (Madhavan, et al., 1978). The

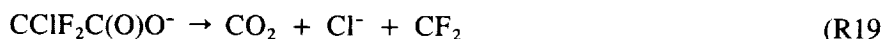
AQUATIC MECHANISMS

one electron redox potential (E^0) is 2.41 volts (versus the normal hydrogen electrode) for the $\text{CH}_3\text{C(O)O}/\text{CH}_3\text{C(O)O}^-$ couple and 2.52 volts for the $\text{SO}_4^-/\text{SO}_4^{2-}$ couple (Ebersson, 1982). Substitution of electron withdrawing substituents such as Cl and F on the alkyl carbon are expected to significantly increase E^0 . Hence, it appears that SO_4^- , one of the strongest oxidizing agents found in environmental aqueous systems, is not capable of oxidizing $\text{CF}_n\text{Cl}_{3-n}\text{C(O)O}^-$. Another possibility worth considering is oxidation of the halo-acetates by valence band holes in colloidal metal oxide particles which can be generated photolytically in surface natural waters. For example, the bandgaps of TiO_2 and ZnO are 3.0 volts (Morrison, 1980) and 3.4 volts (Bahnmann, et al., 1987), respectively. Because the electron donor (i.e. $\text{CF}_n\text{Cl}_{3-n}\text{C(O)O}^-$) must interact with the hole within nanoseconds after the hole is created in order to compete with rapid electron-hole recombination (Rothenberger, et al., 1985), the oxidation process can only occur for donors which are adsorbed to the particle surface. Kormann, et al. (1989), using relatively high concentrations of donor and metal oxide, have found that chloroacetates can be degraded with quantum yields in the range of 3% for TiO_2 and 0.1% for ZnO at $\text{pH} = 5$. Improved knowledge of particle size distributions and concentration profiles in natural waters, rates of adsorption and desorption of the haloacetates to particle surfaces, and degradation quantum yields as a function of wavelength are needed before the potential importance of haloacetate oxidation by valence band holes in semiconductor particles can be assessed with any degree of confidence.

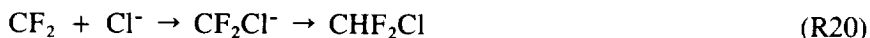
Thermal decarboxylation of halo-substituted acetic acids at elevated temperatures are a well-known set of organic reactions, which are discussed in most undergraduate organic chemistry textbooks (see, for example, Roberts and Caserio, 1965). Verhoek (1934) studied the kinetics of CCl_3COO^- thermal decarboxylation in aqueous solution over the temperature range 50 - 90°C; measured rate coefficients varied from $6.2 \times 10^{-7} \text{ s}^{-1}$ at 50°C to $3.1 \times 10^{-4} \text{ s}^{-1}$ at 90°C. Extrapolation of Verhoek's results to 285K, a typical surface seawater temperature, suggests that $k \sim 3.7 \times 10^{-9} \text{ s}^{-1}$ (lifetime ~ 86 years). At 300K, however, the lifetime of $\text{CCl}_3\text{C(O)O}^-$ toward thermal decarboxylation appears to be only about 2 years. Clearly, thermal decarboxylation in the tropical oceans could be an important removal process for $\text{CCl}_3\text{C(O)O}^-$. The thermal decarboxylation kinetics of $\text{CF}_3\text{C(O)O}^-$ (Auerbach, et al., 1950), $\text{CCl}_2\text{FC(O)O}^-$ (Hine and Duffey, 1959a) and $\text{CF}_2\text{ClC(O)O}^-$ (Hine and Duffey, 1959b) have also been studied in aqueous solution. Extrapolation of available data suggests that at $T \leq 300\text{K}$ all three reactions have rate coefficients of less than 10^{-10} s^{-1} . The more fluorine atoms on the alkyl carbon, the slower the reaction proceeds. For $\text{CCl}_3\text{C(O)O}^-$, $\text{CCl}_2\text{FC(O)O}^-$, and $\text{CF}_3\text{C(O)O}^-$, the mechanism of the thermal decarboxylation reaction is



For $\text{CClF}_2\text{C(O)O}^-$, Hine and Duffey (1959b) have shown that the detailed mechanism is somewhat different

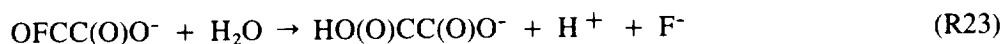
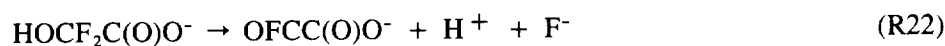
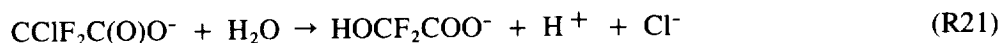


In seawater the CF_2 radical should react with chloride, then protonate to form CHClF_2 :



Very little information is available concerning hydrolysis of trihaloacetic acids. It appears that $\text{S}_{\text{N}}2$ attack by H_2O does not compete with thermal decarboxylation, at least over the temperature regime where the overall reaction rate is convenient for experimental determination. Hine and Duffey (1959b) did ob-

serve oxalic acid as a minor product of $\text{CF}_2\text{ClC(O)O}^-$ degradation in aqueous solution and attributed its production to a hydrolysis reaction:



In seawater oxalic acid exists primarily in the singly protonated form with a smaller but significant concentration of the fully protonated acid.

It is known that enzymes found in soil microorganisms and higher plants can cleave the C-X bonds in a number of haloacetates, including $\text{CH}_2\text{FC(O)O}^-$, $\text{CH}_2\text{ClC(O)O}^-$ and $\text{CHCl}_2\text{C(O)O}^-$, by catalyzing hydrolysis (Goldman, 1969). It seems reasonable to expect that plant and/or microbial enzymes can remove fluorine atoms from $\text{CF}_n\text{Cl}_{3-n}\text{C(O)O}^-$ as well. Further research is needed to establish the rates of $\text{CF}_n\text{Cl}_{3-n}\text{C(O)O}^-$ degradation via biological processes in natural environments such as soils, vegetation, fresh water, and seawater.

In summary, it appears that $\text{CCl}_3\text{C(O)O}^-$ can react at appreciable rates in natural waters with hydrated electrons and by thermal decarboxylation; the lifetime of $\text{CCl}_3\text{C(O)O}^-$ toward removal by these processes is probably a few years. The other chlorofluoroacetates are more stable toward chemical removal. The most stable species, $\text{CF}_3\text{C(O)O}^-$, could have a lifetime in natural waters as long as several hundred years. Processes which could possibly degrade $\text{CF}_n\text{Cl}_{3-n}\text{C(O)O}^-$ on shorter time scales than those suggested above, but whose rates cannot be estimated with any degree of confidence at this time, include oxidation by photochemically generated valence band holes in semiconductor particles and hydrolysis catalyzed by enzymes in microorganisms and plants; further research aimed at characterizing these processes is needed.

Hydroperoxides

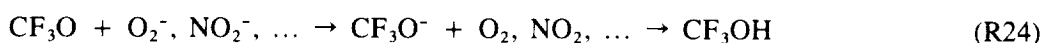
Lind and Kok (1986) have determined the Henry's law solubility of CH_3OOH to be $\exp(5607/T - 13.41)$ M atm⁻¹ (i.e. 746 M atm⁻¹ at 280K). These authors have also observed that CH_3OOH hydrolyzes to methanol and hydrogen peroxide; the lifetime of CH_3OOH toward hydrolysis appeared to be a month or two at 298K. The pKa for CH_3OOH is 11.5 (Lange, 1979). However, the halogenated hydroperoxides are expected to be considerably more acidic. Bernstein, et al., (1971) report a pKa of 6.4 for CF_3OOH , suggesting that this species is > 90% protonated in cloudwater but > 90% unprotonated in seawater. Although no Henry's law data is available for the halogenated hydroperoxides, the vapor pressure of CF_3OOH is known to be about 2 atmospheres at 298K (Bernstein, et al., 1971) whereas the vapor pressure of CH_3OOH is only 54.2 Torr at 298K (G.L. Vaghjiani, private communication). Hence, it seems likely that the Henry's law solubility of CF_3OOH is smaller than that of CH_3OOH .

If photolysis, rates for halogenated hydroperoxides in the gas phase are similar to those of H_2O_2 and CH_3OOH , then gas phase photolysis will be the dominant atmospheric sink for these species ($\tau \approx 1-2$ weeks). However, it is possible that the UV spectra of halogenated hydroperoxides are blue-shifted from the spectra of H_2O_2 and CH_3OOH , in which case gas phase photolysis could be very slow and aqueous phase removal could become important.

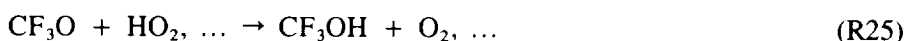
AQUATIC MECHANISMS

The halogenated hydroperoxides' lifetimes against dissolution in cloudwater and photolysis or reaction with OH radicals is likely to be slow. For a Henry's law solubility of 300 M atm⁻¹, a relatively fast photolysis rate in cloudwater of 2 x 10⁻⁶ s⁻¹, and a rate constant for reaction with aqueous-phase OH of 1 x 10⁷ M⁻¹ s⁻¹, we estimate a cloudwater removal lifetime using equations [11] and [12] of the order of years.

With regard to photolysis it is interesting to note that hydroperoxides photolyze via rupture of the O-O bond to give an alkoxy radical and an OH radical. In solution, chlorinated alkoxy radicals are thermally unstable and would be expected to rapidly eliminate a Cl atom to form an acid halide which, as discussed above, would rapidly hydrolyze. Totally fluorinated alkoxy radicals such as CF₃O should react rapidly either by electron transfer, i.e.



or by hydrogen abstraction, i.e.



As discussed above, CF₃OH rapidly eliminates HF to produce CF₂O, which rapidly hydrolyzes to CO₂ + HF. On the other hand, in the case of OH attack on the hydroperoxides, we expect that the products will undergo rapid reactions in solution regenerating hydroperoxide (see above).

In seawater, reactions of the type



can compete with photodissociation as a removal mechanism for hydroperoxides. The species X can be halide ions or transition metal ions. It is worth noting that the reactions where X = I⁻ and Fe²⁺ are used for quantitative analysis of peroxides (Siggia and Hanna, 1979). While quantitative kinetic data for X⁻ + ROOH reactions seem to be available only for hydrogen peroxide (i.e. R = H), it is worth noting that all hydroperoxides are known to react rapidly with iodide (Siggia and Hanna, 1979). Parameters relevant to the assessment of the importance of reactions of I⁻, Br⁻, Cl⁻, Cu(I), and Fe(II) with H₂O₂ as peroxide destruction mechanisms in seawater are given in Table 4. It should be noted that complexation with OH⁻ and Cl⁻ leads to complicated speciation patterns for the transition metal ions. The dominant reacting Cu(I) and Fe(II) species are not the bare metal ions, but CuCl₂⁻ and Fe(OH)⁺ (Moffett and Zika, 1987a). The results presented in Table 4 suggest that reaction with Fe(II) is the dominant sink for H₂O₂ in seawater, since photolysis in surface water and hydrolysis are expected to proceed at rates on the order of 10⁻⁷ s⁻¹ each.

To estimate the lifetime of halogenated hydroperoxides toward chemical or photochemical removal in seawater, we assume that they undergo reactions with X⁻, hydrolysis, and photolysis at rates similar to those observed for H₂O₂, i.e. k ≈ 10⁻⁴ s⁻¹. The Henry's law solubilities for the halogenated hydroperoxides under seawater conditions (T ~ 285K, μ ~ 0.75 M) are estimated to lie in the range 50 - 500 M atm⁻¹. For the above range of values for k and H, it is likely that hydroperoxide removal in seawater will be of the order of 1 month and be limited by transport to the marine boundary layer. Reduction of k by a factor of 100 would have no effect on the (transport limited) lifetime.

Table 4. Sinks for H₂O₂ in Seawater via the Reaction X⁻ + H₂O₂ → X + OH + OH⁻

	k(M ⁻¹ s ⁻¹) ^(a)	[X](M)	k(s ⁻¹)	References
I ⁻	0.26	1 x 10 ⁻⁷	2.6 x 10 ⁻⁸	1
Br ⁻	4.4 x 10 ⁻⁶	8 x 10 ⁻⁴	3.5 x 10 ⁻⁹	2
Cl ⁻	1.7 x 10 ^{-8(b)}	0.54	9.2 x 10 ⁻⁹	2
Cu(I) ^(c)	70	1 x 10 ⁻¹⁰	7.0 x 10 ⁻⁹	3,4
Fe(II) ^(d)	3 x 10 ⁴	5 x 10 ⁻⁹	1.5 x 10 ⁻⁴	5,6

(a) T = 285K

(b) highly uncertain

(c) the reactive species in seawater is thought to be CuCl₂⁻

(d) the reactive species in seawater is thought to be Fe(OH)⁺

1. Liebhafsky and Mohammed, 1933
2. Mohammed and Liebhafsky, 1934
3. Moffett and Zika, 1987a
4. Moffett and Zika, 1987b
5. Hong and Kester, 1986
6. Landing and Westerlund, 1988

X⁻ + ROOH reactions and photolysis lead to the production of haloalkoxy radicals which decay via mechanisms discussed above in conjunction with the cloud chemistry of hydroperoxides. Hydrolysis is expected to produce haloalcohols; these compounds rapidly eliminate HX to form acid halides which, in turn, rapidly hydrolyze via mechanisms discussed earlier.

As discussed in an earlier section, reactions of the hydrated electron with haloacetic acids results in the production of acid hydroperoxides, i.e. HOOCF_nCl_{2-n}C(O)O⁻. These species are expected to be degraded via mechanisms completely analogous to those described above for haloalkyl hydroperoxides. The end products are expected to be oxalic acid (HOCCOOH), HF, and HCl.

7. SUMMARY

The rates at which eight potential alternative HCFCs and HFCs and methyl chloroform (CH₃CCl₃) can be removed from the atmosphere by dissolution and reaction in the oceans and in cloudwater have been estimated from the species' thermodynamic and chemical properties using simple mathematical formulations to simulate the transfer of gases from the atmosphere to the aqueous phase. The HCFCs and HFCs considered are CHCl₂CF₃ (HCFC-123), CFC₂CH₃ (HCFC-141b), CF₂ClCH₃ (HCFC-142b), CHF₂Cl (HCFC-22), CHFClCF₃ (HCFC-124), CH₂FCF₃ (HFC-134a), CHF₂CH₃ (HFC-152a), and CHF₂CF₃ (HFC-125).

AQUATIC MECHANISMS

Cloudwater is found to be of no importance as an atmospheric sink for any of the above compounds. Best-estimate lifetimes for all eight HCFCs and HFCs toward removal in the oceans are greater than 77 years, with only HCFC-22, HCFC-123, and HCFC-141b having lifetimes shorter than 200 years. The most reactive of the nine species, considered toward removal in the oceans is methyl chloroform, with a best-estimate lifetime of 42 years and a minimum reasonable lifetime of 22 years. Important removal mechanisms for methyl chloroform, HCFC-22, HCFC-123, and HCFC-141b in seawater are hydrolysis and reaction with hydrated electrons. Improved hydrolysis kinetics data and Henry's law solubility data for methyl chloroform, HCFC-22, HCFC-123, and HCFC-141b would help to reduce the uncertainties in the aqueous phase removal rates of these species as would improved estimates of the hydrated electron concentration in seawater.

Gas phase degradation products of the eight HCFCs and HFCs include a large variety of halo-substituted carbonyls, acids, peroxyacids, hydroperoxides, alcohols, nitrates, peroxy nitrates, and peroxyacetyl nitrates.

Although handicapped by the total absence of Henry's law solubility data for any of the compounds of interest and the limited availability of relevant kinetic data, an assessment of the rates and mechanisms of aqueous phase removal of the gas phase degradation products has been carried out.

The species X_2CO , $HXCO$, CH_3CXO , CF_3OH , CX_3OONO_2 , and $ROOH$ ($X = F$ or Cl , $R =$ halo-substituted methyl or acetyl) are all expected to be removed from the atmosphere on time scales limited by transport to cloudy regions or the marine boundary layer (i.e. about 1 month); aqueous phase reactions of these species result in the formation of chloride, fluoride, and carbon dioxide, as well as formic, acetic, and oxalic acids. The species CX_3CXO , CX_3CX_2OOH , $CX_3CX_2OONO_2$, $CX_3C(O)OONO_2$, and $CX_3C(O)OOH$ are also expected to be removed from the atmosphere rapidly, and their aqueous phase reactions result in the formation of halo-substituted acetates, $CX_3C(O)O^-$.

The species $CX_3C(O)OH$ are very acidic and, as a result, are highly soluble in cloudwater. These acids are expected to be rapidly removed from the atmosphere by rainout. However, the aqueous phase species $CX_3C(O)O^-$ are expected to be resistant to chemical degradation. Trichloroacetate can thermally decompose on a time scale of 2-10 years to yield carbon dioxide and chloroform. In fresh water, the reaction of $CCl_3C(O)O^-$ with the hydrated electron is also expected to occur on a time scale of a few years. The species $CFCl_2C(O)O^-$, $CF_2ClC(O)O^-$, and $CF_3C(O)O^-$ may have very long aqueous phase lifetimes. The longest lived species, $CF_3C(O)O^-$, could have a lifetime in natural waters as long as several hundred years. Processes which could possibly degrade $CF_nCl_{3-n}C(O)O^-$ on shorter time scales than suggested above, but whose rates cannot be estimated with any degree of confidence at this time, include oxidation by photochemically generated valence band holes in semiconductor particles and hydrolysis catalyzed by enzymes in microorganisms and plants; further research aimed at characterizing these processes is needed.

One possible gas phase degradation product about which very little is known is CF_3ONO_2 . This compound has never been observed, and may be thermally unstable. If CF_3ONO_2 is thermally stable, then it may have a long lifetime toward aqueous phase removal. Henry's law solubility data and hydrolysis kinetics data for CF_3ONO_2 are needed before its aqueous phase removal rate can be assessed with any degree of confidence.

8. ACKNOWLEDGMENTS

The authors would like to thank the reviewers, M.R. Hoffmann and D.D. DesMarteau, for a number of constructive comments which greatly improved the quality of this assessment. They would also like to acknowledge L. Clever, D. Creed, R.E. Huie, E.M. Perdue, A.R. Ravishankara, E.S. Saltzman, G.J. Vaghjiani, O.C. Zafiriou, and R.G. Zepp for helpful discussions concerning various aspects of this work, and R.P. Thorn for assistance with the literature search.

In preparing this assessment the authors made use of information from a number of other AFEAS reports. Authors of these reports were R. Atkinson, R.A. Cox, R.F. Hampson, M.J. Kurylo, R. Lesclaux, D.C. McCune, M.O. McLinden, H. Niki, S.P. Sander, L.H. Weinstein, and R. Zellner.

APPENDIX (R.H. WINE AND W.L. CHAMEIDES)

Tables of Relevant Physical Constants

- AI Henry's law solubilities
- AII Vapor Pressures
- AIII Acid-base equilibrium constants
- AIV One-electron redox potentials

AQUATIC MECHANISMS

Table A1. Henry's Law Solubilities

Species	(M atm ⁻¹)		Reference
	5°C	25°C	
HOOH	360000	74000	1
CH ₃ OOH	850	220	1
CH ₃ C(O)OOH	2100	470	1
HCOOH	1500	3700	2
CH ₃ COOH	41000	8700	3
CH ₃ CHO	49	13	4
CH ₃ OH	720	220	4
CH ₃ ONO ₂		3(22°C)	5
CH ₃ C(O)OONO ₂	12	2.9	6
CH ₂ CCl ₂	0.096	0.039	7

1. Lind and Kok, 1986
2. Latimer, 1952
3. Jacob and Wofsy, 1988
4. Snider and Dawson, 1985
5. Lee, et al., 1983
6. Lee, 1984
7. Gossett, 1987

Table All. Vapor Pressure of Selected Compounds

Species	Vapor Pressure (Torr)		Reference
	0°C	30°C	
HFCO	1590	2420	1
Cl ₂ CO	563	1670	1
CH ₃ CClO	90.4	353	1
CCl ₃ CClO	4.72	27.0	1
CH ₃ OOH	10.9	70	2
CF ₃ OOH	444	1670	3
CF ₃ COOH	2.90	14.3	1
CCl ₃ COOH	0.0043	0.130	1
CH ₃ OH	29.1	162	1
CH ₂ CH ₂ OH	12.2	79.2	1
CF ₃ CH ₂ OH	13.7	93.5	1

1. Lange, 1979
2. G.L. Vaghjiani, private communication
3. Bernstein, et al., 1971

AQUATIC MECHANISMS

Table AIII. Acid-Base Equilibrium Constants

Equilibrated Species	pKa	Reference
$\text{CO}_2\cdot\text{H}_2\text{O}/\text{HCO}_3^-$	6.35	1
$\text{HCO}_3^-/\text{CO}_3^{2-}$	10.33	1
HCl/Cl^-	-6.1	1
HF/F^-	3.18	1
$\text{HC(O)OH}/\text{HC(O)O}^-$	3.75	1
$\text{CH}_3\text{C(O)OH}/\text{CH}_3\text{C(O)O}^-$	4.76	1
$\text{CCl}_3\text{C(O)OH}/\text{CCl}_3\text{C(O)O}^-$	0.64	1
$\text{CF}_3\text{C(O)OH}/\text{CF}_3\text{C(O)O}^-$	0.25	1
$\text{CH}_3\text{C(O)OOH}/\text{CH}_3\text{C(O)OO}^-$	8.20	1
$\text{ClCH}_2\text{C(O)OOH}/\text{ClCH}_2\text{C(O)OO}^-$	7.2	2
$\text{CH}_3\text{OOH}/\text{CH}_3\text{OO}^-$	11.5	2
$\text{CF}_3\text{OOH}/\text{CF}_3\text{OO}^-$	6.4	3
$\text{CH}_3\text{CH}_2\text{OH}/\text{CH}_3\text{CH}_2\text{O}^-$	15	4
$\text{CF}_3\text{CH}_2\text{OH}/\text{CF}_3\text{CH}_2\text{O}^-$	12.37	4
HO_2/O_2^-	4.69	5

1. Lange, 1979
2. Richardson, 1983
3. Bernstein, et al., 1971
4. Ballinger and Long, 1960
5. Bielski, 1978

Table AIV. One-Electron Redox Potentials

Couple	E ⁰ (volts)*	Reference
F/F ⁻	3.6	1
Cl/Cl ⁻	2.41	2
Br/Br ⁻	1.93	2
I/I ⁻	1.33	3
NO ₂ /NO ₂ ⁻	1.03	4
NO ₃ /NO ₃ ⁻	2.3	1
OH/OH ⁻	1.89	2
SO ₄ ⁻ /SO ₄ ²⁻	2.52	5
SO ₃ ⁻ /SO ₃ ²⁻	0.63	6
CH ₃ C(O)O/CH ₃ C(O)O ⁻	2.41	7
HO ₂ /HO ₂ ⁻	0.8	1
O ₂ /O ₂ ⁻	-0.2	1
CO ₃ ⁻ /CO ₃ ²⁻	1.59	8
Fe ³⁺ /Fe ²⁺	0.771	9
Fe(OH) ²⁺ /Fe(OH) ⁺	0.304	9
Cu ²⁺ /Cu ⁺	0.153	9
CuCl ₂ /CuCl ₂ ⁻	0.567	9

*in water, versus the normal hydrogen electrode

1. Berdnikov and Bazhin, 1970
2. Schwarz and Dodson, 1984
3. Stanbury, et al., 1980
4. Wilmarth, et al., 1983
5. Ebersson, 1982
6. Huie and Neta, 1984
7. Ebersson, 1963
8. R.E. Huie, private communication
9. Moffett and Zika, 1987a

