Table II. Cobalt Extraction Is Unchanged in Presence of Nickel

Metal in Feed, G./L.		Wt. Ratio,	Co after Extraction, G./L.		Co Distribution	Probable Error,
Ni	Co	Co to Ni	Raffinate	Extract	Coeff.	%
30.871	3.024	0.0979	1.514	1.509	1.0	3.2
30.871	1.515	0.0490	0.756	0.756	1.0	5.3
30.871	0.760	0.0246	0.384	0.376	1.0	10.1
30.871	0.377	0.0122	0.177	0.200	1.1	8.6

aqueous extracts or raffinates by precipitation as sulfides. Another approach to metal recovery is electrodeposition.

The calcium chloride solution remaining after deposition of nickel from aqueous raffinates could be recycled to effect necessary process economy.

CONCLUSIONS

Furfural is an effective selective solvent for the separation of cobalt from nickel when present as chlorides in aqueous solutions.

Calcium chloride is an excellent complexing additive. High purity nickel and cobalt may be obtained via a process based on this extraction system.

The general utility of furfural as an extraction solvent for metal separations has been further substantiated.

LITERATURE CITED

(1) Brown, L.H., Cole, F.K. (to The Quaker Oats Co.), U.S. Patent **2,943,912** (July 5, 1960).
(2) Cole, F.K., Brown, L.H., *Ind. Eng. Chem.* **51**, 58 (1959).
(3) Garwin, L., Hixson, A.N., *Ibid.*, **41**, 2298, 2303 (1949).
(4) Kylander, R.L., Garwin, L., *Chem. Eng. Progr.* **47**, 186 (1951).
(5) Lutjen, G.P., *Eng. Mining J.* **155** (6), 81 (1954).
(6) Nicholson, I.W., Brooks, P.T., Clemmer, J.B., Rocky Mountain Minerals Conf., A.I.M.E., Salt Lake City, Utah, Sept. 17, 1958.
(7) Rigamonti, R., Spaccamela-Marchetti, E., *Chim. e ind. (Milan)* **36**, 91 (1954).
(8) Sharp, R.A., Wilkinson, G., *J. Am. Chem. Soc.* **77**, 6519 (1955).

RECEIVED for review September 19, 1960. Accepted December 30, 1960.

Tables of Ozone Properties

A. G. STRENG
The Research Institute of Temple University, Philadelphia 44, Pa.

OZONE is a highly active, allotropic form of oxygen. It has been known since 1785, the year in which van Marum observed the formation of this gas in an electric spark discharge in oxygen. Schoenbein recognized ozone in 1840 as a new substance. Soret showed in 1866 that the chemical composition of ozone is that of triatomic oxygen.

At ordinary temperatures, ozone is a gas, is light blue in color, and has a characteristic pungent odor from which its name was derived from the Greek word ozein, to smell. The odor permits recognition of ozone in concentrations down to about 0.1 p.p.m. Gaseous ozone is a highly active, irritating, oxidizing substance. It is characterized by its strong oxidizing power and by the tendency to revert to molecular oxygen according to the reaction

$$O_3 \rightarrow {}^3\!/_2\, O_2$$

The rate of reaction depends upon the temperature, pressure, and concentration of the ozone. The reaction proceeds slowly at ordinary temperatures, but fairly quickly, even to the velocity of thermal explosion, at elevated temperatures. In addition, the reaction is catalyzed by many sensitizers. Low temperatures contribute to the conservation of ozone.

In the liquid phase, ozone has an indigo-blue color. At temperatures around 90° K. (−183° C.), liquid ozone may be kept without noticeable decomposition for long periods. Fast warming to the boiling point or rapid cooling causes explosions. The liquid ozone must be evaporated or frozen, therefore, very slowly with appropriate precautions. Liquid ozone can be supercooled readily.

Solid ozone has a deep blue-violet color. A layer 0.2 to 0.5 mm. is transparent, but solid ozone in a layer 1 mm. thick is almost opaque. Solid ozone (at 77.35° K.) was compressed to 22.5 atm. without any difficulty. Slight impact and slight friction at that temperature did not cause an explosion.

Gaseous, liquid, or solid ozone explodes easily if exposed to heat, spark, flame, or shock. When working with highly concentrated ozone, improper handling may cause a violent explosion. A knowledge of the properties and safety precautions is very important. Impurities sensitize the ozone vigorously.

In recent years, ozone has attracted attention as a high-energy chemical with a potential use in powerful propellant and explosive systems. Being an endothermic compound and a highly active oxidizer, ozone can burn and detonate by itself and in combination with various fuels. Ozone also represents the simplest combustible and explosive system. When combined with fuels, ozone produces systems with much higher energy content than does oxygen.

Much work has been devoted to the investigation of properties of ozone. Two surveys of ozone literature have been made (*10, 36*), but since then much more has been published. A critical review and compilation of ozone data have become a necessity. Tables of selected data on ozone properties are presented in Tables I, II, and III.

ACKNOWLEDGMENT

The author thanks A.V. Grosse for helpful suggestions and L.V. Streng for help in the systematization of this material.

LITERATURE CITED

(1) Benson, S.W., Axworthy, A.E., Jr., *J. Chem. Phys.* **26**, 1718 (1957).
(2) Birtsall, C.M., Jenkins, A.C., Di Paolo, S.F., *Ibid.*, **23**, 441 (1955).
(3) Brabets, R.I., McDonough, J.M., *Ibid.*, **27**, 880 (1957).
(4) Brabets, R.I., Waterman, T.E., *Ibid.*, **28**, 1212 (1958).
(5) Brinner, E., Porretted, E., *Helv. Chim. Acta* **22**, 397 (1939).
(6) Brown, C., Berger, A.W., Hersh, C.K., *J. Chem. Phys.* **23**, 1340 (1955).
(7) Cook, G.A., Spading, E., Kiffer, A.D., Clumpp, C.V., *Ind. Eng. Chem.* **48**, 736 (1956).
(8) Danti, A., Lord, R.C., *J. Chem. Phys.* **30**, 1310 (1959).
(9) Gill, E.K., Laidler, K.J., *Trans. Faraday Soc.* **55**, 713 (1959).
(10) Grosse, A.V., Streng, A.G., "Study of Ultra High Temperatures," Tech. Note 4, Research Institute, Temple University, Philadelphia, Pa., Aug. 1, 1957; U.S. Dept. of Commerce, Office of Technical Services, Washington, D. C., PB 131732.
(11) Grosse, A.V., Streng, A.G., U.S. Patent **2,298,529** (March 15, 1960).
(12) Guenther, P., Wassmuth, E., Schryver, L.A., - *Z. physik. Chem.* **A158**, 297 (1932).
(13) Harper, S.A., Gordon, W.E., *Advances in Chem. Ser.* No. 21, 28 (1959).
(14) Hersh, C.K., Berger, A.W., Brown, J.R.C., *Ibid.*, p. 22. *Chem. Ser.* **21**, ACS, Washington, D. C., 1959.
(15) Hersh, C.K., Brabets, R.I., Platz, J.M., Swehla, R.J., Kirsh, D.P., *Am. Rocket Soc. J.* **30**, 264 (1960).
(16) Hoslowski, S.A., Ph.D. dissertation, University of Missouri, 1956.
(17) Hughes, R.H., *J. Chem. Phys.* **24**, 131 (1956).
(18) Jenkins, A.C., Birdsall, C.M., *Ibid.*, **20**, 1158 (1952).
(19) Jenkins, A.C., Di Paolo, F.S., Birdsall, C.M., *Ibid.*, **23**, 2049 (1955).
(20) Jenkins, A.C., Di Paolo, F.S., *Ibid.*, **25**, 296 (1956).
(21) Klein, M.J., Klevelent, F.F., Meister, A.G., *Ibid.*, **19**, 1068 (1951).
(22) Miller, R.O., *J. Phys. Chem.* **63**, 1054–7 (1959).

(Continued on page 436)

Table I. Pure Ozone

		Reference
Molecular weight	48.0	
Molecular structure	Triangular, apex angle 116° 49′	(*9, 17*)
Molecular constants	Interatomic distance 1.278 $\times 10^{-8}$ cm.; collision diameter 3.35 $\times 10^{-8}$ cm.; vibration frequency 3.164 $\times 10^{-13}$ sec.$^{-1}$; dipole moment 0.53 Debye unit; asymmetry parameter, $\epsilon = 4.031 \times 10^{-3}$; centrifugal distortion constant, $D_K = 1.96 \times 10^{-4}$ cm.$^{-1}$	(*8, 9, 37, 38*)
Melting point	80.7 ± 0.4° K. (−192.5 ± 0.4° C.)	(*20*)
Boiling point	161.3 ± 0.3° K. (−111.9 ± 0.3° C.)	(*18*)
Vapor pressure		(*18*)
Temp. range 90.2–243.2° K., (−183°–−30° C.), mm. Hg	$\log P = 8.25313 - 814.941587/T - 0.001966943\,T$	
At 80.2° K., −193.0° C. (triple point of ozone)	0.00859 mm. Hg	
At 90.2° K., −183.0° C. (b.p. O_2)	0.10 mm. Hg	
At 195° K., −78.2° C., dry ice temperature	6.18 atm. (90.8 p.s.i.)	
Critical temperature	261.1° K. (−12.1° C.)	(*18*)
Critical pressure, derived from critical temperature	54.6 atm.	(*18*)
Critical volume	147.1 cc./mole	(*36*)
Specific volume of liquid ozone, temp. range 77.4°–174.2° K. (−195.8°–−99.0° C.), cc./g.	$V = 0.551 + (6.25 \times 10^{-4})\,T + (3.35 \times 10^{-6})\,T^2$	(*3*)

Density

			Reference
Gaseous, at NTP		2.1415 g./liter	(*3, 14, 20*)
Liquid			
° K.	° C.		
77.4	−195.8	1.613 (supercooled)	
77.6	−195.6	1.6130 ± 0.0004	
77.8	−195.4	1.614 ± 0.004	
85.2	−188.0	1.595 ± 0.003	
87.6	−185.6	1.5839 ± 0.0011	
90.2	−183.0	1.571 ± 0.003	
90.2	−183.0	1.574	
90.3	−182.9	1.5727 ± 0.0004	
103.2	−170.0	1.536	
123.2	−150.0	1.473	
153.2	−120.0	1.376	
161	−112	1.354 ± 0.001	
Solid			(*31*)
° K.	° C.		
77.4	−195.8	1.728 ± 0.002	

		Reference
Volume expansion on melting	+7.1%	(*31*)

Viscosity (*10, 14, 20*)

° K.	° C.	Poise
Gaseous		
298	25	133×10^{-6}
273	0	127×10^{-6}
195	−78	107×10^{-6}
Liquid		$\eta \cong \dfrac{1}{1549 - 945\,d}$ poise
77.6	−195.6	0.0414 ± 0.0005 (supercooled)
90.2	−183.0	0.0156 ± 0.0002
161.3	−111.9	0.00272

Surface tension (Reference)

At °K.	°C.	Dynes/Cm.	Reference
77.2	−196.0	43.8 ± 0.1	(14)
90.2	−183.0	38.4 ± 0.7	(14)
90.5	−182.7	38.1 ± 0.2	(20)

Heat of formation

	Kcal./Mole	Reference
Gaseous, at 291° K., 18° C.		
Constant volume	34.220 ± 0.180	(12)
Constant pressure	33.923 ± 0.180	
Liquid, at 90.19° K., −183.0° C.	29.83 ± 0.20	(31)
Solid, at 80.7° K., −192.5° C.	29.3	(31)
Heat of vaporization, at b.p.	3.630	(15)
Heat of fusion (estd.)	0.5	

Heat conductivity

°K.	°C.	Cal./(Sec.)(Sq. Cm.)(°C./Cm.)	Reference
Gaseous			
298 (calcd.)	25	3.3 × 10^{-5}	
Liquid			(39)
145.2	−128.0	5.52 × 10^{-4} (±5%)	
108.2	−165.0	5.42 × 10^{-4}	
90.2	−183.0	5.31 × 10^{-4}	
77.4	−195.8	5.21 × 10^{-4}	

Heat capacity Cal./G. °C. (4)

Liquid, temp. range 90°–150° K., (−183° to −123° C.) $C_p = 0.425 + 0.0014(T - 90)$

°K.	°C.	
90	−183	0.425
150	−123	0.509

Thermodynamic quantities of ozone (2, 21)

°K.	Heat Content Function, $(H^\circ - H_0^\circ/T)$	Enthropy, S^0	Free Energy, Function, $-(F - H_0^\circ/T)$	Heat Capacity, C_p^0
As an Ideal Gas in Cal./° Mole				
At 1 atm.				
150	7.961	51.171	43.208	8.059
200	8.022	53.519	45.505	8.374
250	8.138	55.444	47.308	8.847
298.15	8.297	57.046	48.749	9.367
300	8.301	57.105	48.798	9.387
350	8.497	58.590	50.095	9.929
400	8.708	59.949	51.245	10.432
450	8.926	61.219	52.282	10.873
500	9.139	62.375	53.231	11.258
550	9.347	63.460	54.111	11.584
As a Real Gas in Cal./° Mole				
At 1 atm.				(2)
200	7.951	53.474	45.531	8.497
298.15	8.272	57.030	48.757	9.406
350	8.481	58.579	50.100	9.955
At 5 atm.				
200	7.665	50.094	42.436	8.987
298.15	8.173	53.765	45.593	9.564
350	8.415	55.335	46.922	10.059
At 10 atm.				
298.15	8.048	52.305	44.257	9.761
350	8.332	53.901	45.570	10.190

Coefficients of thermal expansion (3)

range 77°–175° K., (−196° to −98° C.) $\alpha = 0.551$, $b = 6.25 \times 10^{-4}$, $\gamma = 3.35 \times 10^{-6}$

Activation energy (1)

of thermal decomposition of gaseous ozone, low pressure

$M + O_3 \rightarrow M + O_2 + 0$ (for $M = O_3$) 24,000 cal.

Rate of energization $K_1 = 4.61 \pm 0.25 \times 10^{12}$ exp.(−24,000/RT), liter $mole^{-1}$ $sec.^{-1}$

Heat capacity Cal./G. °C. (4)

Liquid, temp. range 90°–150° K., (−183° to −123° C.) $C_p = 0.425 + 0.0014(T - 90)$

°K.	°C.	
90	−183	0.425
150	−123	0.509

Minimum ignition energy (35)

1 atm., 298° K., 25° C. 7 × 10^{-5} mjoules (16 × 10^{-9} cal.)

Inflammability limits

Gaseous, 1 atm., 298° K., initiation by shock wave 9.2 mole % O_3 in oxygen (13, 16)

Liquid, 90° K., −183° C., initiation by electrical spark 18.6 mole % O_3 in liquid O_2 (7)

Thermal explosion limits, (1)

mm. Hg. (max. and min., calcd.)

°K.	°C.	Vessel, Liters 0.5	1	2
343	70	535–1020	424–810	336–640
353	80	348–656	275–525	218–416
363	90	222–424	174–332	138–264
373	100	149–285	118–225	94–180
383	110	101–193	80–153	64–122

Burning velocity, (calcd.)

°K.	°C.	Pressure, Atm. 1	2	5	10	100
		Cm./Sec.				
Gaseous (Reference 23, 28, 34)						
298	25	472 ± 12[a]	...	488	504	529
273	0	420	...	...	...	...
233	−40	325	...	...	...	...
195	−78	270 ± 7[a]	282	295	304	317
161	−112	205	...	...	...	...
Liquid (Reference 24)						
		0.361 (161° K., −112° C. initial temp.)	0.738 (172.5° K., −100.7° C.)	...	3.84 (206° K., −67° C.)	...
Solid (Reference 25)						
70	−203	0.301				
63	−210	0.294				
20	−253	0.274				

Flame temperature (calcd.)

Atm.	°K.	°C.	°K.
Gaseous (Reference 23, 28, 34)			
1	298	25	2677
2	298	25	2716
5	298	25	2761
10	298	25	2789
1	195	−78	2648
2	195	−78	2683
5	195	−78	2723
10	195	−78	2748

Table I. Pure Ozone (Continued)

Flame temperature *(continued)* — Reference

Liquid (Reference *24*)

1	161	−112	2400
2	172.5	−100.7	2414
10	206	−67	2436

Solid (Reference *25*)

1	20	−253	2287
1	63	−210	2339
1	70	−203	2346

Flame pressure (calcd.)

1 atm., 298° K., 25° C., 4.1 mm. Hg — *(34)*

Quenching diameter

in cylinder
1 atm., 298° K., 25° C., 90 microns — *(11, 35)*

Quenching diameter vs. pressure

in cylinder at 298° K., 25° C.
$\text{Log } d_c = 1.953 - 1.111 \text{ Log} P$; d_c in microns; P in Atm. — *(35)*

Quenching diameter vs. temperature,

in cylinder at 1 atm. — *(35)*
$d_c = 347.5 - 0.864\ T$; d_c in microns; T in ° K.

Critical boundary

velocity gradient for flash back, at 1 atm., 298° K., 25° C. — $g_f = 2.9 \times 10^5$ sec.$^{-1}$ — *(35)*

Minimum gas flow or flash back flow

at 1 atm., 298° K., 25° C. — *(35)*

Burner Tube, Internal Diameter, Cm.	Min. Flow, Cc./Sec.
0.065	7
0.1	29
0.2	232
0.3	725
0.6	6090
0.8	14500
1.0	29000
2.0	232000

Dielectric constant, at 1 kilocycle/sec. — *(36)*

° K.	° C.	
90	−183	4.75
103	−170	4.33
118	−155	3.85
147	−126	3.33
162	−111	3.01
175	−98	2.91
185	−88	2.78

[a] Experimental.

Detonation velocity — Reference

Gaseous, 1 atm., 298° K., 25° C.	1863 ± 20 meters/sec.	*(32)*
Liquid 96° K., −177° C.	5730 ± 460 meters/sec.	*(22)*

Detonation temperature (calcd.)

Gaseous, 1 atm., 298° K., 25° C.	3340° K.	*(32)*
Liquid, 90° K., −183° C.	3140° K.	

Detonation pressure — *(32)*

Gaseous 1 atm., 298° K., 25° C.	30 atm.
Liquid 90° K., −183° C.	4×10^4 atm.

Magnetic susceptibility — *(36)*

Gaseous ozone	0.002×10^{-6} cgs units
Liquid ozone	0.150×10^{-6} cgs units

Molar extinction coefficients

Gas at 295° K.

3360 cm.$^{-1}$ mole^{-1} lit. at 252 mμ (ultraviolet)
1.32 cm.$^{-1}$ mole^{-1} lit. at 605 mμ (visible)
80.00 cm.$^{-1}$ mole^{-1} lit. at 9.49μ (infrared)

Liquid at 77° K.

2.00 cm.$^{-1}$ mole^{-1} lit. at 600mμ, dissolved in liquid oxygen
3.10 cm.$^{-1}$ mole^{-1} lit. at 600mμ, dissolved in 23 vol. % Freon 12 + 77 vol. % Freon 13 mixture.

Solubility in water — *(5)*

° K.	° C.	G./Liter	Bunsen Coefficient, Liter Gas in 1 Liter Water
273	0	1.13	0.526
283	10	0.875	0.408
293	20	0.688	0.321
303	30	0.563	0.258
313	40	0.450	0.210
323	50	0.369	0.172
333	60	0.307	0.143

Heat of solution

in water at 291° K., 18° C. — 3904 cal./mole — *(5)*

Table II. Mixtures of Ozone with Oxygen

Consolute temp. — Reference

93.3 ± 0.5° K., −179.9 ± 0.5° C. — *(19, 26)*

Ozone concentration in liquid phases (reference *10*)

° K.	° C.	O_3 in Original Mixture, Mole %	O_3 in Original Mixture, Wt. %	In Upper Phase, Wt. %	In Lower Phase, Wt. %
90.2	−183.0	17.6	24.27	24.27	0.00
		18.2	25.0	23.92	1.80
		30.8	40.0	16.8	23.20
		40.0	50.0	12.04	37.96
		50.0	60.0	7.32	52.68
		66.7	75.0	0.21	74.79
		67.2	75.45	0.00	75.45
77.5	−195.7	6.9	10.0	10.0	0.00
		18.2	25.0	8.10	16.90
		30.8	40.0	6.20	33.80
		40.0	50.0	4.93	45.07
		50.0	60.0	3.67	56.33
		66.7	75.0	1.77	73.23
		84.3	89.0	0.00	89.00

Phase boundaries, — Reference

mole % liquid O_3	In Upper Phase	In Lower Phase	Reference
90.0° K., −183.2° C.	17.6	67.2	*(6, 19)*
77.5° K., −195.7° C.	6.9	84.3	

Vapor pressure data, extrapolated to 760 mm.

Mole % O_3	° K.	° C.	
85.0	94.1	−179.1	*(19)*
90.0	97.2	−176.0	
95.0	106.1	−167.1	
98.0	122.3	−150.9	

Density

At 90° K., −183.2° C.

Mole % O_3	G./Cc.	
18.1	1.2334	*(20)*
72.2	1.4596	
81.0	1.5050	
95.2	1.5489	
100.0	1.574	

Table II. Mixture of Ozone with Oxygen *(Continued)*

Viscosity at 90.2° K., −183.0° C. (Reference *20*)

$\text{Log}\ \eta = x_1\ \text{Log}\ \eta\ O_2 + x_2\ \text{Log}\ \eta\ O_3 (\pm 5\%)$
x_1 and x_2 = mole fractions of O_2 and O_3
$\eta\ O_3 = 1.56$ cp.; $\eta\ O_2 = 0.190$ cp.

Latent heat of vaporization (Reference *15*)

Mole % O_3 in $O_3 + O_2$ Mixture	Kcal./Mole
100	3.630
90	1.422
80	1.499
60	1.586
40	1.642
20	1.642
10	1.642
0	1.642

Critical boundary velocity gradient for flash back, at 1 atm., 298° K., 25° C. (Reference *35*)

Mole % O_3	
25	$g_f = 8.0 \times 10^2$ sec.$^{-1}$
40	8.3×10^3
50	2.1×10^4
75	1.1×10^5
100	2.9×10^5

Minimum gas flow or flash back flow (reference *35*) at 1 atm., 298° K., 25° C.

Burner Tube Internal Diameter, Cm.	Minimum Gas Flow, Cc./Sec. 25 Mole %	40	50	75	100
0.065	...	...	...	3	7
0.1	...	...	2	11	29
0.2	...	7	17	88	232
0.3	...	21	53	275	725
0.6	17	174	441	2310	6090
0.8	40	415	1050	5500	14500
1.0	80	830	2100	11000	29000
2.0	640	6640	16800	88000	232000

Minimum ignition energy

Mole % O_3	1 Atm., 25° C. Initial Gas Temp. Mjoules	or Calories
25.0	1.25×10^{-1}	0.3×10^{-4}
50.0	2.9×10^{-3}	0.7×10^{-6}
75.0	3.3×10^{-4}	7.8×10^{-8}
100.0	7×10^{-5}	16×10^{-9}

Burning velocity

Gaseous (Reference *10, 28, 34*)

Mole % O_3	1 Atm., 298° K., 25° C.	1 Atm., 195° K., −78° C.
17	9.2	...
20	18.2	...
24	...	18.0
28	52.2	...
36	...	44.0
40	128.4	...
46	165.9	...
53	210.1	...
58	...	132.0
75	331.2	...
82	...	209.0
100	472 ± 12	270 ± 7

Liquid (calcd.) (Reference *24*)

Mole % O_3	1 Atm. Cm. per sec.	Initial temp., ° K.	2 Atm. Cm. per sec.	Initial temp., ° K.	10 Atm. Cm. per sec.	Initial temp., ° K.
50	0.0774	150.5	0.155	160.5	0.78	187.5
75	0.227	156.5	0.456	167	2.31	198
100	0.361	161	0.738	172.5	3.84	206

Burning velocity *(continued)*

Solid (calcd.) Reference *25*)

Mole % O_3	1 Atm. at ° K. 20	63	70
50	0.0380	0.0505	...
75	0.147	0.170	0.173
100 % O_3	0.274	0.294	0.301

Quenching diameter, in cylinder, 1 atm., 298° K., 25° C. (Reference *11, 35*)

Mole % O_3	Mm.
15.0	5.000
25.0	1.650
50.0	0.390
75.0	0.165
100.0	0.090

Quenching diameter, *vs.* O_3 Concentration in cylinder, 1 atm., 298° K., 25° C. (Reference *35*)

$\text{Log}\ d_c = 6.189 - 2.118\ \text{Log}\ x$; d_c in microns; x in vol. % O_3

In cylinder, 1 atm., 195° K., −78° C.

$\text{Log}\ d_c = 6.403 - 2.113\ \text{Log}\ x$ (Reference *35*)

Flame temperature (calcd.)

Gaseous, 1 Atm., 298° K., 25° C. (Reference *28*)

Mole % O_3	° K.
18.18	1027
40.00	1687
66.67	2277
100.00	2677

Liquid (Reference *24*)

Mole % O_3	1 Atm. Initial temp., ° K.	Flame temp., ° K.	2 Atm. Initial temp., ° K.	Flame temp., ° K.	10 Atm. Initial temp., ° K.	Flame temp., ° K.
50 mole % O_3	150.5	1509	160.5	1508	187.5	1507
75 mole % O_3	156.5	2029	167	2030	198	2031
100 % O_3	161	2400	172.5	2414	206	2436

Solid (Reference *25*)

Mole % O_3		
50 mole % O_3	20	1371
	63	1445
75 mole % O_3	20	1894
	63	1960
	70	1969
100 % O_3	20	2287
	63	2339
	70	2346

Detonation velocity

Gaseous, 1 Atm., 298° K., 25° C. (Reference *32*)

Mole % O_3	Meter/Sec.
25.0	1290
50.0	1633 ± 20
75.0	1782 ± 40
100.0	1863 ± 20

Liquid (Reference *22*)

Mole % O_3	Meter/Sec.
58.0	4160 ± 140
65.1	4500 ± 80
77.6	5100 ± 180
89.5	5600 ± 60
100.0	5730 ± 460

Conversion of mole %, to wt. % O_3

In oxygen $\quad \text{Wt. \% } O_3 = \dfrac{(\text{mole \% } O_3) \times 214.4}{142.9 + 0.715\ (\text{mole \% } O_3)}$

In air $\quad \text{Wt. \% } O_3 = \dfrac{(\text{mole \% } O_3)\ 214.4}{129.3 + 0.851\ (\text{mole \% } O_3)}$

Table III. Mixtures of Ozone with Various Gases

Miscibility and reactivity

	Temperature, °K.	Temperature, °C.	Pressure, Mm. Hg	Time, Hrs.
Gaseous Phase (Reference *29, 33*)				
$H_2 + O_3$ mixtures	195–294	−78–+21	504–1061	3–20[a]
$(CN)_2 + 2/3\ O_3$	273	0	774	. . 2[a]
$(CN)_2\ 2/3\ O_3$	296	+23	557	18[b]
$CH_4 + 4/3\ O_3$	195–294	−78–+21	778–910	1–22[c]
$CO + 1/3\ O_3$	195	−78	752	. . .[d]
$N_2O + O_3$	195–273	−78–0	765	3[a]
$NO + 1/3\ O_3$	195	−78	785	. . .[d]
$NH_3 + 1/2\ O_3$	273	0	765	. . .[d]
$PH_3 + 4/3\ O_3$	195	−78	760	. . .[d]
$SO_2 + 1/3\ O_3$	273	0	760	12[e]

Liquid Phase (Reference *27, 33*)

	Temperature, °K.	Temperature, °C.
$CH_4 + O_3$	90	−183[a,f]
$CO + O_3$	77	−196[b,f]
$F_2 + O_3$	77	−196[a,f]
$OF_2 + O_3$	77	−196[a,f]
$O_3F_2 + O_3$	90	−183[f]
	Slow decomposition of O_3F_2. Upon warming to 116° K., the mixture explodes	
$O_2F_2 + O_3$	116	−157[f]
	At cooling to 90° K., O_2F_2 partially crystallizes out. Upon warming above 195° K., the mixture explodes	
$ClO_3F + O_3$	90	−183[g]
	116	−157[a,f]
$CCl_2F_2 + O_3$	116	−157[f]
$CF_4 + O_3$	90	−183[g]
$CClF_3 + O_3$	116	−157[f]
	Only about 12 wt. % O_3 is soluble in CF_4	
$Ar + O_3$	85	−188[g]
	Only about 10 wt. % O_3 is soluble in Ar	
$N_2 + O_3$	77	−196[g]
	Only 4.41 ± 0.14 mole % O_3 is soluble in liquid N_2	
	81.8	−191.4[g]
	Only 5.1 mole % O_3 is soluble in liquid N_2	
	77	−196[g]
	Only 8.8 ± 0.9 mole % N_2 is soluble in liquid O_3	
$NF_3 + O_3$	90	−183[f]
$ClF_3 + O_3$	133	−140[g]
O_3 liquid + $(CN)_2$ solid	90	−183[a]

Burning velocities

	Mole % O_3	B. Velocity, Cm./Sec.	Reference
$O_3 + H_2$ mixtures, 1 atm., 195° K., −78° C.			(*29*)
	6.0	207 ± 5	
	12.0	664 ± 57	
	18.2	1290 ± 20	
	18.5	1330 ± 30	
	25.0	1680 ± 80	
Mixtures with higher concentration O_3 exploded			
$O_3 + (CN)_2$ mixtures, 1 atm. 273° K., 0° C.	25.0	60 ± 3	(*30*)
	33.3	242 ± 12	
	40.0	285 ± 6	
Mixtures with higher concentration O_3 exploded			

Flame Temperatures

	1 Atm., 14.7 P.S.I.	10 Atm., 147 P.S.I.	40.7 Atm., 600 P.S.I.	
$3(CN)_2 + 2\ O_3$	5208° K.	5506° K.	5657° K.	(*30*)

Solubility of ozone at low partial pressures

Distribution of ozone between air and various solvents

$$D = \frac{\text{concn. in solvent}}{\text{concn. in air}}$$

Solvent	T, °C.	D	
Glacial acetic acid	18.2	2.5	(*40*)
	20	2.8	
	30.2	1.6	
	38.8	1.4	
Dichloroacetic acid	0	1.69	
Acetic anhydride	0	2.15	
Propionic acid	17.3	3.6	
Propionic anhydride	18.2	2.8	
Carbon tetrachloride	0	3.15	
	21	2.95	
Water	20	0.29	
	0	0.49	

[a] No visible reaction. [b] Very slow reaction. [c] Slow reaction. [d] Immediate explosion. [e] SO_3 formation. [f] Mixed homogeneously. [g] Does not mix homogeneously.

(23) Sandri, R., *Can. J. Chem.* **36**, 1210 (1958).
(24) Sandri, R., *Combustion and Flame* **2**, 348 (1958).
(25) Sandri, R., *Combustion and Flame* **4**, 284 (1960).
(26) Schumacher, H.J., *Anales assoc. quím. arg.* **41**, 197–264 (1953).
(27) Streng, A.G., Grosse, A.V., *Advances in Chem. Ser.* No. **21**, 38 (1959).
(28) Streng, A.G., Grosse, A.V., *J. Am. Chem. Soc.* **78**, 1517 (1957).
(29) *Ibid.*, **79**, 3296 (1957).
(30) *Ibid.*, p. 5583.
(31) *Ibid.*, **81**, 805 (1959).
(32) Streng, A.G., Stokes, C.S., Streng, L.A., *J. Chem. Phys.* **29**, 458 (1958).
(33) Streng, A.G., Grosse, A.V., *J. Inorg. & Nuclear Chem.* **9**, 315 (1959).
(34) Streng, A.G., Grosse, A.V., 6th Symposium on Combustion, Reinhold, New York, 1957.
(35) Streng, A.G., Grosse, A.V., "Quenching Diameter of Ozone Flame," 17th Intern. Congr. Pure and Applied Chem., Munich, Germany, 1959.
(36) Thorp, C.E., "Bibliography of Ozone Technology," Vol. 2, Armour Research Foundation, Illinois Institute of Technology, Chicago, Ill., 1955.
(37) Trambarulo, R., Ghorsh, S.N., Burns, C.A., Jr., Gordy, W., *J. Chem. Phys.* **21**, 851 (1953).
(38) Trambarulo, R., Ghorsh, S.N., Burns, C.A., Jr., Gordy, W., *Phys. Rev.* **91**, 222 (A) (1953).
(39) Waterman, T.E., Kirsh, D.P., Brabets, R.I., *J. Chem. Phys.* **29**, 905 (1958); **32**, 304 (1960).
(40) Welsbach Corp., Philadelphia, Pa., "Basic Manual of Applications and Laboratory Ozonization Technique," first rev., 1958.

RECEIVED for review March 24, 1960. Accepted September 19, 1960.