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UNPUBLISHED PRELIMINARY DATA

~~LIQUID METALS~~ (Revised)

~~for~~

~~Space and Nuclear Applications~~

B. ~~Corrosion by Liquid Metals Under~~ Isothermal Conditions

~~Appendix~~

Diffusion Coefficients in Liquid Metals — ~~Table~~

A Compilation of Published Literature

by

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PREFACE

For many important cases corrosion by liquid metals is a rate process, determined by the diffusion of a solute through the liquid phase. Based on this mechanism, it is possible to predict corrosion rates and their variation with pertinent system parameters. The body of experimental coefficients in liquid metals is quite extensive, perhaps much larger than is generally recognized.

In order to apply diffusion theory concepts to the corrosion phenomenon, one of the authors surveyed the literature available on this subject up through 1955; these results were published the following year.** This report is intended to update that study. The abstract and survey journals were examined for the period January, 1956 to May, 1964 in the preparation of this revision. The number of new references found during this period is not great, but this document should now be reasonably complete.

The attention of the authors should be directed to any omissions or corrections to this table, and these will be most gratefully appreciated.

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DIFFUSION COEFFICIENTS IN LIQUID METALS-TABLE

A. Liquid Aluminum (MP 660°C)

All data due to K. Uemura (35,41) except as noted. In this work the aluminum solvent was 99.7% pure (Si - 0.12%, Fe - 0.12%, Cu - 0.05%).

Solute	Temperature °C	$D \times 10^{+5}$ cm^2/sec	References	Notes
Cu	700	7.2		From $CuAl_2$ containing 33 atom % Cu
Cu	800	11.0		
Cu	900	14		
Cu	1000	15		
Cu	700	2.4		From $CuAl_2$ alloy - 33 atom % Cu
Cu	800	6.1		1.6 atom % Si added to solvent
Cu	900	8.2		
Cu	1000	9.6		
Cu	700	7.3		Initial Cu concentration, 11.5 atom %
Cu	800	11.5		Solvent contained 19 atom % Zn
Cu	900	15		
Fe	700	1.4		From alloy containing 8 atom % Fe
Fe	800	2.1		
Fe	900	6.9		
Fe	1000	20		

A. Liquid Aluminum (MP 660°C) (Continued)

Solute	Temperature °C	$D \times 10^{+5}$ cm^2/sec	References	Notes
Fe	900	5.1		From alloy containing 4 atom % Fe.
Fe	1000	6.4		3.1 atom % Ni in solvent.
Mg	700	2.7		
Mg	800	6.4		
Mg	700	3.7		From alloy containing 21 atom % Hg
Mg	800	14		8 atom % Si in solvent
Mg	670	6.1	1	
Mg	700	7.5	1	
Mn	700	0.6		From alloy containing about 13 atom % Mn
Mn	800	2.9		
Mn	900	5.5		
Mn	1000	10		
Ni	700	1.5		From alloy containing 10 atom % Ni
Ni	800	3.9		
Ni	900	5.1		
Ni	1000	7.0		

A. Liquid Aluminum (MP 660°C) (Continued)

Solute	Temperature °C	$D \times 10^{+5}$ cm^2/sec	References	Notes
Ni	900	5.2		From 3.1 atom % Ni alloy
Ni	1000	10		Solvent contained 4 atom % Fe
Si	700	81		From alloy containing 20 atom % Si
Si	800	92		
Si	900	106		
Si	1000	130		
Si	700	26		From alloy containing 8 atom % Si and 21 atom % Mg in Al
Si	800	51		
U	500	2.3	13	
U	600	2.9	13	
U	700	3.6	13	
U	800	4.2	13	
Zn	700	6.2		Pure Zn
Zn	800	14		Pure Zn
Zn	700	6.6		From alloy containing 65 atom % Zn
Zn	800	10.1		From alloy containing 65 atom % Zn

A. Liquid Aluminum (MP 660°C) (Continued)

Solute	Temperature °C	$D \times 10^{+5}$ cm^2/sec	References	Notes
Zn	700	6.7		From alloy containing 19 atom % Zn, 11.5 atom % Cu added to Al
Zn	800	8.9		
Zn	900	11.7		

B. Liquid Bismuth (MP 271.3°C)***

Solute	Temperature °C	D x 10^{+5} cm^2/sec	References	Notes
Al	300-600	$5.7 \times 10^{+2} \exp[-8800/RT]$	6	
Au	500	5.23	29a, 29b	
Bi	281-414	$(4.65 \pm 0.01) \times 10^{+3} \times \exp[-(8100 \pm 466)/RT]$	30	Self-diffusion in Bi containing 0.255 atom % Pb
Pb	281-414	$(1.20 \pm 0.09) \times 10^{+4} \times \exp[-(9680 \pm 1070)/RT]$	30	In Bi containing 0.255 atom % Pb
Sn	450-600	$52 \exp[-3200/RT]$	23	
U	700	0.65	13	
U	800	2.5	13	

Also, see Tables F and J below.

C. Liquid Gallium (MP 29.8°C)

Solute	Temperature °C	$D \times 10^{+5}$ cm^2/sec	References	Notes
Ga	30-98	10.7 exp [-1122/RT]	28	Self-diffusion.
Ga	30	$\log_{10} D = -4.7793 - 9.529 \times 10^{-6} P$	28	P is pressure in kg/cm^2. Measurements carried to 10,008 atm.

D. Liquid Indium (MP 157°C)

Solute	Temperature °C	$D \times 10^{+5}$ cm^2/sec	References	Notes
In	160-480	17.6 exp [-1350/RT]	3	Self-diffusion
In	170-750	(28.9 ± 2.5) exp [-(2430 ± 50)/RT]	14	Self-diffusion
In	200-450	(42.5 ± 5.7) exp [-(2771 ± 158)/RT]	24	In eutectic mixture, containing 53 weight % In, 47 weight % Sn
In	200-450	(33.5 ± 3.6) exp [-(2606 ± 127)/RT]		In In containing 1 weight % Sn
In	200-600	(24.4 ± 1.7) exp [-(2284 ± 83)/RT]	24	In In containing 10 weight % Sn
In	200-600	(32.6 ± 2.8) exp [-(2832 ± 111)/RT]	24	In In containing 20 weight % Sn
In	200-600	(31.5 ± 2.2) exp [-(2602 ± 103)/RT]	24	In In containing 34 weight % Sn
Sn	200-450	(31.9 ± 3.5) exp [-(2473 ± 129)/RT]	24, 25	In In containing 1 weight % Sn
Sn	200-600	(33.4 ± 4.0) exp [-(2698 ± 140)/RT]	24	In In containing 20% Sn
Sn	200-600	(23.9 ± 1.9) exp [-(2297 ± 101)/RT]	24	In In containing 34% Sn
Sn	200-600	(16.0 ± 1.1) exp [-(1816 ± 109)/RT]	24	In In containing 40% Sn

E. Liquid Iron (MP 1539°C)

Solute	Temperature °C	D x 10^{+5} cm^2/sec.	References	Notes
C	1550	7.9	21	0.03 weight % C
C	1570	7.2	21	0.03 weight % C
C	1590	7.2	21	0.03 weight % C
C	1450	6.7	21	2.1 weight % C
C	1500	5.5	21	2.1 weight % C
C	1550	7.8	21	2.1 weight % C
C	1450	6.4	21	3.5 weight % C
C	1500	5.6	21	3.5 weight % C
C	1550	6.7	21	3.5 weight % C
C	Liquid Fe	4 - 19.2	11	
Co	1568	4.7	21	
Co	1638	5.3	21	
Fe	1240-1360	430 exp [-12,200/RT]	44	Self-diffusion in Fe melt containing 4.6 weight % C
Fe	1340-1400	1600 exp [-15,700/RT]	44	Self-diffusion in Fe melt containing 2.5 weight % C

E. Liquid Iron (MP 1539°C) (Continued)

Solute	Temperature °C	$D \times 10^{+5}$ $cm^2/sec.$	References	Notes
Mn	1580	13	26	
Mn	1660	22	26	
Mn	1680	63	36	0 to 1.28 weight % Mn
Mn	1725	17.0	36	0 to 4.5 weight % Mn
Mn	1400-1600	20 exp [-11,500/RT]	30a	Fe saturated with C, 2.5 weight % Mn in alloy
N	1600	3.77	31	
O	Liquid Fe	300-780	11	
P	1550	4.7	16a	
S	1390-1560	24 exp [-3,800/T]	10	0.18 weight % S; in Fe saturated with C, containing 2.2 weight % Si.
S	1560-1670	49 exp [-17,090/RT]	10	0.96 to 1.25 weight % S
Si	1730	280	36	0 to 4.5 weight % Si
Si	1480	2.4	26	0 to 2.5 weight % Si
Si	1525	3.5	26	0 to 1.5 weight % Si
Si	1540	3.8	26	0 to 1.5 weight % Si
Si	1560	10.8	26	0 to 1.5 weight % Si
Si	1400-1600	24 exp [-16,300/RT]	30a	In Fe saturated with C, 1.5 weight % Si.

F. Liquid Lead (MP 327.4°C)

Solute	Temperature °C	$D \times 10^{+5}$ $cm^2/sec.$	References	Notes
Ag	327	5.3	39	
Ag	326-530	8.26 exp [-1925/RT]	29	Estimated accuracy ± 0.8% 0 to 16.5 weight % Ag.
Au	490	3.5	12,29a,29b	
Au	500	3.7	12,29a,29b	
Au	327	2.1	39	
Bi(RaE)	333-657	(96.3 ± 5.0) exp [-(4070 ± 546)/RT]	30	"Trace amounts"
Bi	450-600	96 exp [-4,200/RT]	23	
Bi	510	3.9	23	10 atom % Sn in Pb. Solutions very dilute in Bi
Bi	510	3.4	23	10 atom % Sn in Pb 10 weight % Bi
Bi	510	2.4	23	10 atom % Sn in Pb 20 weight % Bi
Bi	500	6.1	23	10 atom % Bi
Bi	500	6.7	23	20 atom % Bi
Bi	500	7.1	23	30 atom % Bi
Bi	500	7.4	23	40 atom % Bi
Bi	500	7.9	23	50 atom % Bi
Bi	500	8.5	23	60 atom % Bi
Bi	500	8.4	23	70 atom % Bi
Bi	500	7.6	23	80 atom % Bi

F. Liquid Lead (MP 327.4°C) (Continued)

Solute	Temperature °C	$D \times 10^{+5}$ $cm^2/sec.$	References	Notes
Cd	450-600	110 exp [-4800/RT]	23	
Pb(ThB)	343	2.5	12	Self-diffusion
Pb(RaD)	333-657	(91.3 ± 3.0) exp [-(4450 ± 330)/RT]	27	"Trace amounts"
Pt	490	2.0	12,29a,29b	
Rh	500	3.5	12,29a,29b	
Sb	450-600	250 exp [-6400/RT]	23	
Sn	327	7.0	39	
Sn	450-600	120 exp [-5900/RT]	23	
Sn	510	4.0	23	10 atom % Sn
Sn	510	3.7	23	20 atom % Sn
Sn	510	3.2	23	30 atom % Sn
Sn	510	2.4	23	40 atom % Sn
Sn	510	1.7	23	50 atom % Sn
Sn	510	1.8	23	60 atom % Sn
Sn	510	2.2	23	70 atom % Sn

F. Liquid Lead (MP 327.4°C) (Continued)

Solute	Temperature °C	$D \times 10^{+5}$ $cm^2/sec.$	References	Notes
Zn	400-550	$(0.40 \pm 0.01) \times 10^{+2}$ $\times \exp[-(3200 \pm 730)/RT]$	6	0.1 weight % Zn
Zn	400-550	$(1.1 \pm 0.03) \times 10^{+2}$ $\times \exp[-(4600 \pm 470)/RT]$	6	0.5 weight % Zn
Zn	400-550	$(1.9 \pm 0.1) \times 10^{+2}$ $\times \exp[-(4900 \pm 1400)/RT]$	6	1.0 weight % Zn
Zn	400-550	$(1.3 \pm 0.1) \times 10^{+2}$ $\times \exp[-(4000 \pm 740)/RT]$	6	1.5 weight % Zn

Also, see Ref. 27.

G. Liquid Mercury (MP -38.9°C)

Solute	Temperature °C	D x 10^{+5} cm^2/sec.	References	Notes
Ag	25	1.0	33	
Ag	16	1.11	33	
Au	11	0.83	12	
Au	25	0.7	12	
Ba	7.8	0.60	12	
Bi	25	1.5	33	
Bi	25 ± 0.1	0.99	5	Amalgam concentration 0.00075-0.00575 weight %
Ca	10.2	0.62	12	
Cd	8.7	1.68	12	
Cd	15.0	1.80	12	
Cd	20.0	1.53	12	0.9 to 1.5 weight %
Cd	20.00	1.520-1.528	4	1 atm.
Cd	20.00	1.446	4	1500 atm.
Cd	22.0	1.66 ± 0.03	37	0.010 to 0.014 mole Cd/liter Hg
Cd	25.0	1.9	33	
Cd	25.0	1.63	38	
Cd	99.1	3.42	12	
Cd	25.00 ± 0.02	1.52	40	0.0012 mole Cd/liter Hg

G. Liquid Mercury (MP -38.9°C) (Continued)

Solute	Temperature °C	$D \times 10^{+5}$ $cm^2/sec.$	References	Notes
Cs	7.3	0.52	30	
Cs	25.0	0.6	30	
Cu	25.0 ± 0.5	1.06	5	0.0003 to 0.0019 weight %
Hg	2.5-91.2	12.6 exp [-1160/RT]	7	Self-diffusion. Data fit Einstein-Stokes equation with r = 0.80 Å
Hg	10-60	60 exp [-2400/RT]	32	Self-diffusion
Hg	0-98	8.5 exp [-1005/RT]	22	Self-diffusion
Hg	30	$\log_{10} D = -4.7889 - 9.637 \times 10^{-6} \underline{P}$	22	$\underline{P}$ is pressure in kg/cm^2. For $\underline{P} < 8366\ kg/cm^2$. Self-diffusion.
Hg	0-239	$\log_{10} D = (1.854 \pm 0.018) \log_{10} T - (9.349 \pm 0.045)$	17	Self-diffusion
Hg	30	$-2.73\ N_{Zn} + 1.17$	32	In zinc amalgams. N_{Zn} is mole fraction Zn in solution. $N_{Zn} < 0.0484$
Hg	20	700	6a	Self-diffusion
Hg	10-60	78 exp [-2500/RT]	32	In Zn amalgam containing 0.104 weight % Zn
Hg	10-60	27 exp [-1900/RT]	32	In Zn amalgam containing 0.473 weight % Zn
Hg	10-60	15 exp [-1600/RT]	32	In Zn amalgam containing 1.456 weight % Zn

G. Liquid Mercury (MP -38.9°C) (Continued)

Solute	Temperature °C	$D \times 10^{+5}$ $cm^2/sec.$	References	Notes
In	18.1-18.2	1.42	16	
In	19.0	1.48	16	
In	22.0	1.47 ± 0.03	37	0.0075 to 0.0103 mole In/liter Hg
K	10.5	0.61	12	
K	25.0	0.7	33	
Li	8.2	0.76	12	
Li	25.0	0.9	33	
Na	9.6	0.74	12	
Na	22.0	0.80 ± 0.04	37	0.0063 to 0.0095 mole Na/liter Hg
Na	25.0	0.9	33	
Pb	9.4	1.74	12	
Pb	15.0	1.58	12	
Pb	22.0	1.41 ± 0.05	37	0.010 mole Pb/liter Hg
Pb	25.0	2.1	33	
Pb	99.2	2.22	12	
Pb	25.0 ± 0.5	1.16	5	0.0016 to 0.0030 weight % Pb
Pb	25.0 ± 0.02	1.28	40	0.00069 mole Pb/liter Hg
Rb	7.3	0.53	12	

G. Liquid Mercury (MP -38.9°C) (Continued)

Solute	Temperature °C	$D \times 10^{+5}$ $cm^2/sec.$	References	Notes
Sn	25	2.1	33	
Sn	10.7	1.77	34,42	
Sn	25.0 ± 0.1	1.68	5	0.0004 to 0.0040 weight % Sn
Sr	9.4	0.54	12	
Tl	11.5	1.03	12	
Tl	25	1.2	12	
Tl	25.0 ± 0.05	0.99	5	0.0022 to 0.0029 weight % Tl
Zn	10.7	1.77	12	
Zn	11.5	2.52	12	
Zn	15.0	2.42	12	
Zn	20.0	1.67	12	0.2345 weight % Zn
Zn	20.0	1.61	12	0.475 weight % Zn
Zn	20.0	1.56	12	0.675 weight % Zn
Zn	20.0	1.522	12	0.850 weight % Zn
Zn	20.0	1.464	12	0.900 weight % Zn
Zn	25	2.4	33	
Zn	99.2	3.3	33	
Zn	10-60	11 exp [-1000/RT]	32	0.103 weight % Zn
Zn	10-60	18 exp [-1500/RT]	32	0.488 weight % Zn
Zn	10-60	34 exp [-1900/RT]	32	1.630 weight % Zn

H. Liquid Silver (MP 960.8°C)

Solute	Temperature °C	$D \times 10^{+5}$ cm^2/sec	References	Notes
Ag	1002-1105	$(71.0 \pm 0.6) \exp[-(8150 \pm 1130)/RT]$	43	Self diffusion in liquid silver
O	1000-1200	$(147 \pm 10) \exp[-(7100 \pm 3200)/RT]$	20	

I. Liquid Sodium (MP 97.8°C)

Solute	Temperature °C	D x 10^{+5} cm^2/sec.	References	Notes
Na	98-227	110 exp [-2430/RT]	19	Self-diffusion. Measurements fit Einstein-Stokes equation with r = 0.93 Å
Na	98-226	110 exp [-2450/RT]	18	Self-diffusion.

J. Liquid Tin (MP 231.9°C)

Solute	Temperature °C	$D \times 10^{+5}$ $cm^2/sec.$	References	Notes
Ag	500	4.8	12,29a,29b	
Ag	240-480	26 exp [-8346/RT]	15	Probable error ± 16%
Al	240-480	190 exp [-10,333/RT]	15	Estimated accuracy ± 18%
Au	500	5.4	12,29a,29b	
Bi	450-600	130 exp [-5000/RT]	23	
Bi	500	$1.44\ X_{Bi} + 4.8$		X_{Bi} is mole fraction Bi in mixture. $0.1 < X_{Bi} < 0.9$. Fitted to data of Niwa *et al* (23)
Cu	240-480	18 exp [-8346/RT]	15	Probable error ± 17%
In	200-450	(42.5 ± 5.7) exp [-(2771 ± 158)/RT]	24	In binary alloy containing 53 weight % In
Ni	240-480	23 exp [-9002/RT]	15	Estimated accuracy ± 12%
Pb	500	3.7	12,29a,29b	
Sb	450-600	33 exp [-2800/RT]	23	

J. Liquid Tin (MP 231.9°C) (Continued)

Solute	Temperature °C	$D \times 10^{+5}$ $cm^2/sec.$	References	Notes
Sn	299	3.74 ± 0.10	2	Self-diffusion
Sn	662	13.5 ± 0.64	2	Self-diffusion
Sn	240-480	22 exp [-9081/RT]	3	Self-diffusion
Sn	200-450	(11.7 ± 1.7) exp [-(1380 ± 156)/RT]	24	In In-Sn eutectic mixture, containing 47 weight % Sn
Sn	200-600	(32.4 ± 1.2) exp [-(2768 ± 80)/RT]	25	Self-diffusion
Sn	200-600	(37.4 ± 5.4) exp [-(2909 ± 172)/RT]	24	In Sn containing 1 weight % In
Zn	240-480	62 exp [-9697/RT]	25	Probable error ± 18%

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*** In this and other tables, R is the gas constant in cal./mole-deg. and the temperature T is in degrees Kelvin unless otherwise indicated.