CARLETON UNIVERSITY

FINAL
EXAMINATION
April 2009

DURATION: **3** HOURS No. of Students: 105

Department Name & Course Number: **Mechanical & Aerospace Engineering** **MAAE2700**
Instructor(s) Ronald E. Miller

AUTHORIZED MEMORANDA

- Answer **multiple choice** questions on the **scantron** sheet.
- Answer all **other** questions directly on the examination paper, using the backs of the sheets if necessary.
- A faculty-approved, non-programmable calculator is allowed.
- No notes, books or other materials are permitted.

Students **MUST** count the number of pages in this examination question paper **before** beginning to write, and report any discrepancy immediately to a proctor. This question paper has **17** pages.

This examination question paper **MAY NOT** be taken from the examination room.

In addition to this question paper, students require:

	an examination booklet	yes ___	no _X_
	a Scantron sheet	yes _X_	no ____

NAME: ____

STUDENT NUMBER:___________________________

Value of each question is indicated for a total of 100 marks.

Questions 1-29 must be answered on the scantron sheet. Anything marked or written on pages 2-4 of this exam paper will not be graded!!!

Questions 1-11 are True/False questions (1 mark each). There is no penalty for guessing.

1) Elements tend to have increasing electronegativity as we move from left to right in the periodic table.
   a) True
   b) False
2) Pearlite is the name for the result of slowly cooling austenite with the eutectoid composition.
   a) True
   b) False
3) Martensitic stainless steel tends to be stronger than austenitic stainless steel, but not as corrosion resistant.
   a) True
   b) False
4) "Sensitized" stainless steel refers to the region of material near a weld where the strength has been significantly reduced.
   a) True
   b) False
5) Generally, as the average degree of polymerization decreases, the strength of a polymer will increase.
   a) True
   b) False
6) Covalent bonding is generally a stronger form of bonding than van der Waals bonding.
   a) True
   b) False
7) Strong ionic bonding leads to materials with excellent electrical conductivity.
   a) True
   b) False
8) Allotropy and Polymorphism are terms used to refer to how some materials exist in different crystal structures at different temperatures.
   a) True
   b) False
9) Because there are so few vacancies in most crystalline solids, they rarely have any effect on the creep behaviour of materials.
   a) True
   b) False
10) At low temperature relative to a metal's melting temperature, a smaller average grain diameter will lead to greater ductility.
    a) True
    b) False
11) In general, increased carbon content will increase the strength and hardness of steel.
    a) True
    b) False

Questions 12-29 are multiple choice (1 mark each). There are no penalties for guessing.

12) Small amounts of carbon can be incorporated into BCC iron as
    a) a graphitic surface layer
    b) a network of dislocations
    c) an interstitial solid solution
    d) a substitutional solid solution

13) The "critical resolved shear stress" is:
   a) The stress required to fracture a material
   b) The stress required to move dislocations and therefore cause slip
   c) The stress at which vacancies begin to shear
   d) The stress above which creep becomes an important deformation mechanism

14) Which of the following is *not* a strengthening mechanism in metals:
   a) strengthening by grain size reduction
   b) strain hardening
   c) solid-solution hardening
   d) precipitation hardening
   e) recrystallization hardening

15) Which value is closest to the Young's modulus of steel:
   a) 70 GPa
   b) 100 GPa
   c) 110 GPa
   d) 200 GPa
   e) 1000 GPa

16) Slowly cooling a 50wt%Mg-50wt%Pb alloy from liquid to room temperature will lead to a microstructure consisting of:
   a) regions of proeutectic α surrounded by regions of a lamellar eutectic structure
   b) a fine mix of approximately equal parts α and Mg_2Pb.
   c) single phase α grains with Mg_2Pb dissolved as an interstitial solid solution
   d) regions of proeutectic α surrounded by hypoeutectic Mg_2Pb.
   e) A "single crystal" similar to that found in gas tubine blades.

17) The reaction $L \rightarrow \alpha + \beta$ (cool) is an example of a:
   a) eutectic reaction
   b) eutectoid reaction
   c) chemical reaction
   d) peritectic reaction
   e) carburization reaction

18) Dislocations are
   a) crystal defects that affect the electrical properties of the material, but have little effect on mechanical properties.
   b) crystal defects that are detrimental to the stiffness of a metal.
   c) crystal defects that give rise to plastic deformation in metals.
   d) tiny cracks in a crystal structure.
   e) capable of rapidly diffusing through a crystal at moderate temperature.

19) If grain boundaries are able to block the motion of dislocations in a polycrystal, it will lead to
   a) higher hardness.
   b) enhanced ductility.
   c) greater stiffness.
   d) lower melting temperatures.
   e) faster recrystallization.

20) In order for the oxidation film on a metal to grow logarithmically, it is necessary that
   a) the metal is aluminum.
   b) the metal is pure and free from alloying elements.
   c) the oxide film is protective.
   d) the oxide film is permeable to gaseous oxygen.
   e) the Pilling-Bedworth ratio is much greater than 2.

21) The Pilling-Bedworth ratio is
   a) the ratio of the volume of oxide produced to the volume of oxygen consumed.
   b) the ratio of the volume of oxide produced to the volume of metal consumed.
   c) the ratio of the area of the anode to the area of the cathode in a galvanic cell.
   d) the ratio of the area of the cathode to the area of the anode in a galvanic cell.
   e) not really a ratio at all.

22) Atomic bonding which takes place through one atom "giving up" a valence electron to another atom is called:
   a) van der Waals bonding
   b) ionic bonding
   c) covalent bonding
   d) adhesive bonding
   e) metallic bonding

23) A copolymer is best described as:
   a) A blend of two polymers where the chains of each polymer type are mixed but remain distinct.
   b) A polymer in which the chains are comprised of a mixture of mers of two or more types.
   c) A blend of two polymers, one of which has a much smaller molecular weight than the other.
   d) A polymer which is "glassy" above a critical temperature.
   e) a cross-linked polymer in which one mer type serves as the cross-linking molecule between chains of another mer type.

24) Which of the following is not one of the Hume-Rothery Rules for determining whether two elements are likely to form a substitutional solid solution:
   a) The two elements have the same crystal structure
   b) The two elements have similar melting temperatures
   c) The two elements have similar electronegativities
   d) The two elements have atomic radii within 15% of each other
   e) The two elements have the same valence

25) Which of the following is not a common method of corrosion prevention:
   a) Cathodic protection
   b) The use of organic coatings
   c) Materials selection
   d) The use of a sacrificial cathode
   e) The use of insulating washers between dissimilar metals

26) A steel component has a Brinell hardness value of 200 while a brass specimen has a Brinell hardness value of 50. What does this tell us about the relative values of Young's Modulus for these materials?
   a) The brass and steel have about the same Young's modulus
   b) The brass has a higher Young's modulus
   c) The steel has a higher Young's modulus
   d) None of the above

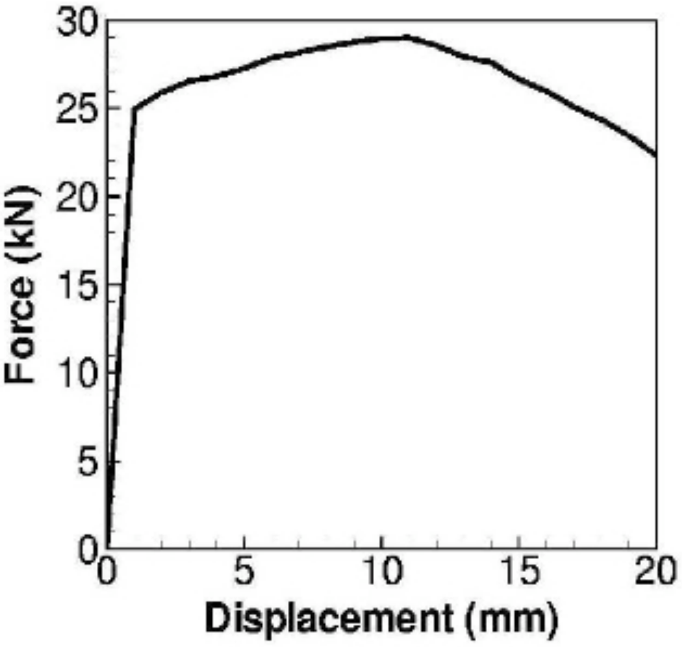
27) Some highly porous materials can be designed to have a negative value of Poisson's ratio. How would the behaviour of these materials be different than conventional metals in a tension test?
   a) They would be more brittle
   b) They would be more ductile
   c) They would have a higher modulus of resilience
   d) They would be better for making springs
   e) They would expand laterally

28) Which of the following will not lead to enhanced strength in polymers:
   a) increased percent-crystallinity
   b) large pendant atom groups
   c) highly polar side groups
   d) increased average length of the polymer chains
   e) solid solution hardening

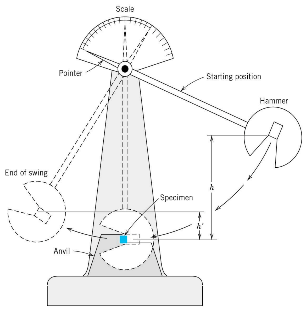
29) Which statement best describes the modulus of resilience:
   a) The area under the stress-strain curve to failure
   b) The area under the stress-strain curve up to the ultimate tensile strength
   c) The area under a tensile loading machine
   d) The cross-sectional area of the sample
   e) The capacity of a material to store elastic energy

Answer the remaining questions in the space provided here on the examination paper. Use the backs of other pages for rough work.

30) (6 marks) A tensile specimen, originally 30 mm long with an initial cross-sectional area of 8.0 x 10^{-5} m^2 exhibits the load vs displacement behaviour shown below (final fracture occurs at 20 mm of displacement). Estimate the following quantities:
   a) Young's Modulus
   b) The percent elongation
   c) The ultimate strength
   d) The true stress at final fracture (assuming no necking occurs in the specimen and the specimen volume is constant during the test)

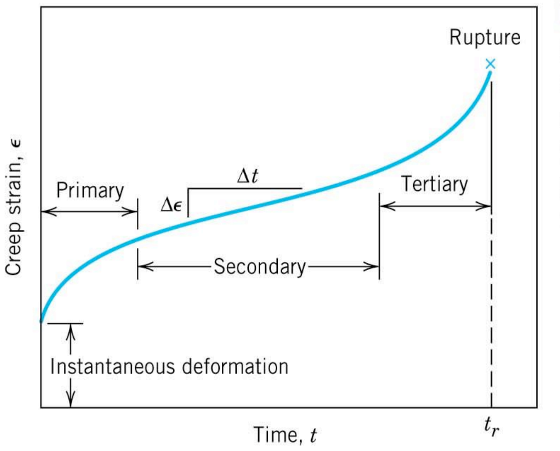


31) (4 marks) The Charpy test is illustrated schematically below. Describe briefly what property this test measures, and how the results of the test would vary as the temperature of the specimen decreases.



32) (3 marks) A particular metal's creep behaviour is such that the primary and tertiary creep regimes are negligible (i.e. there is only instantaneous deformation followed by steady-state creep). Given the material properties below, compute the time it will take for the total strain in a component to reach 3% at a stress of 500 MPa and a temperature of 1000 K.

   i) Young's Modulus, E=100 GPa
   ii) stress exponent, n=3
   iii) creep activation energy, Q_c=186000 J/mol
   iv) Creep constant, $K_2 = 0.5\ \text{hr}^{-1}\text{MPa}^{-3}$



33) (3 marks) Using the information in the table of elemental properties at the end of the exam, compute the theoretical density of Lead and compare it to the density shown in the table.

34) (5 marks) Sketch the following planes or directions in a cubic system:
   a) (210)
   b) (111)
   c) [123]
   d) [301]

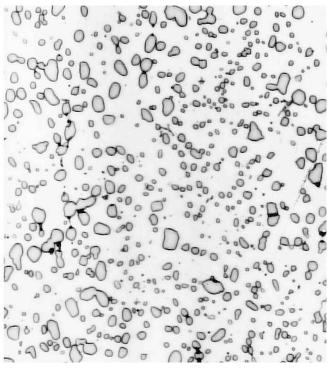
35) (3 marks) Show that in an fcc crystal, the [110] direction has a higher linear density than the [100] direction.

36) (3 marks) A galvanic cell consists of an electrode of magnesium in a 0.03 M solution of Mg^{2+} ions, and an electrode of iron in a 0.09 M solution of Fe^{2+} ions at room temperature. What is the total electric potential of the cell, and which electrode will corrode?

37) (4 marks) A piece of 1020 plain carbon steel (0.2% C) is placed in a carburizing furnace at 1173K. Once the steel is inside the furnace, assume that the surface concentration of C is constant at 0.8%. What is the concentration of C at a depth of 0.5 mm after 3 hours? *(Hint: assume that the steel is essentially FCC iron.)*

38) (2 marks) Slip occurs along the [111] direction on the (101) plane of a BCC metal when a tensile stress of 5 MPa is applied in the [001] direction. What is the critical resolved shear stress for this material?

39) (6 marks) Compare pearlite (on the left, 3000x) to spheroidite (on the right, 1000x).



a) Explain briefly why pearlite tends to have higher strength and hardness than spheroidite.

b) Describe briefly a heat treatment of a eutectoid steel that could be used to produce each structure.

40) (2 marks) This micrograph is of a slow-cooled, hypereutectoid plain carbon steel at approximated 1000x magnification. Label all the phases that are present.

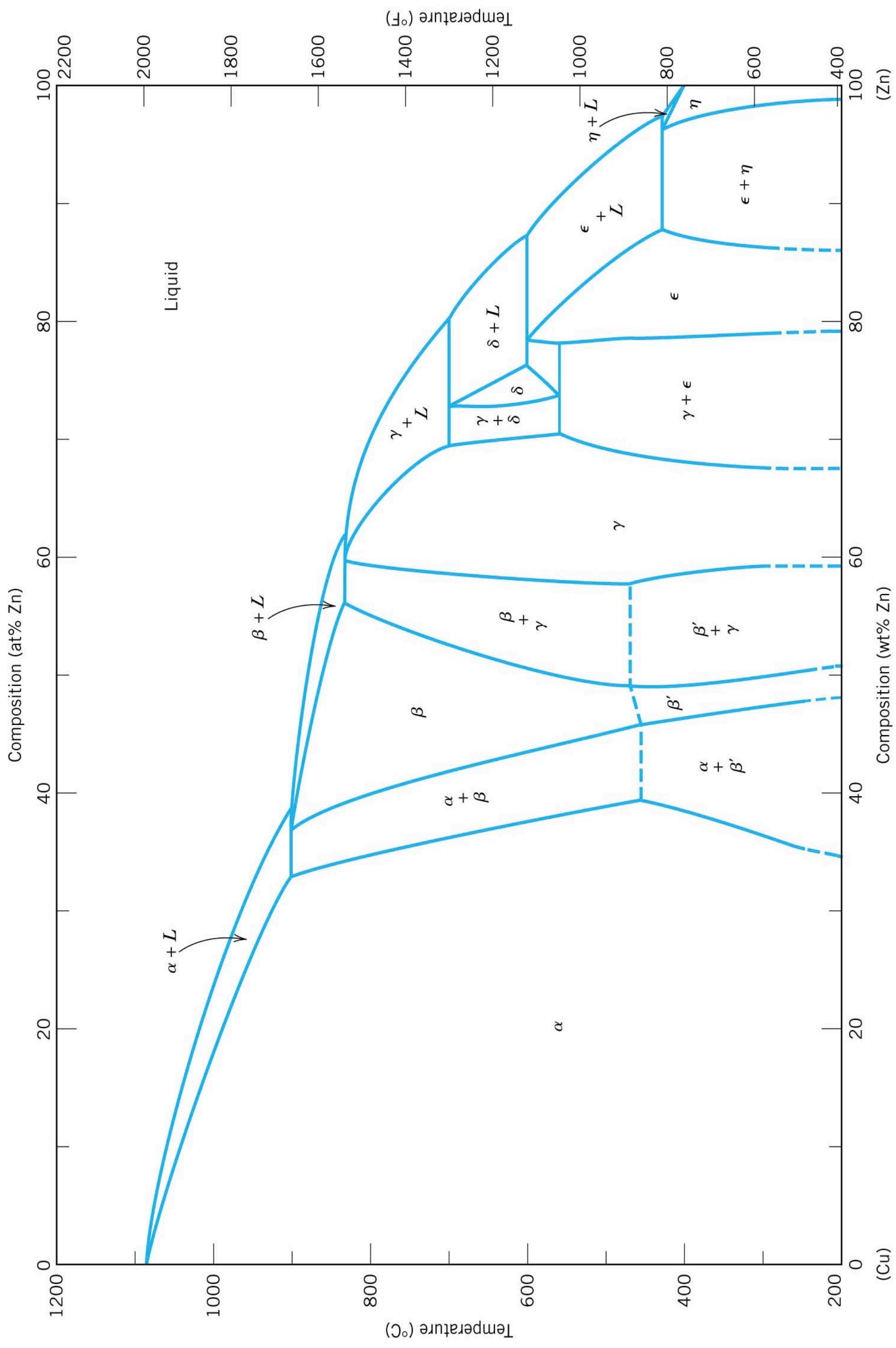


Figure 9.17 The copper–zinc phase diagram. [Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 2, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

41) (1 mark) Cite the composition and temperature coordinates of one peritectic reaction in the Cu-Zn phase diagram above.

42) (1 mark) Cite the composition and temperature coordinates of one eutectoid reaction in the Cu-Zn phase diagram above.

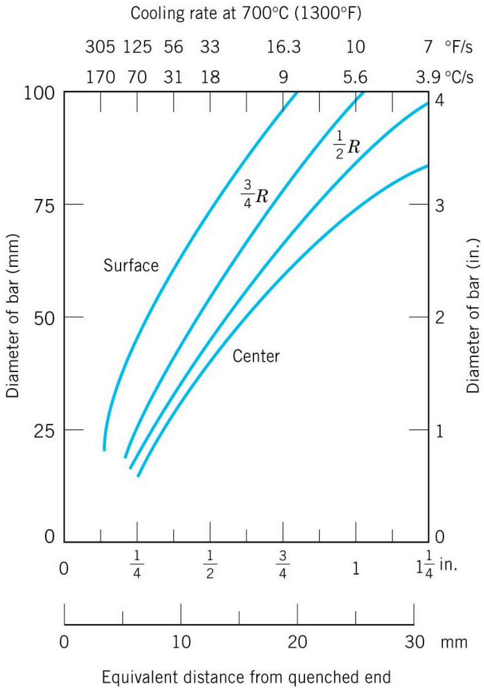
43) (3 marks) Using the Cu-Zn phase diagram above, estimate the compositions and weight fractions of all phases present in an equilibrium mixture at 400 ^{0}C, 70% Zn.

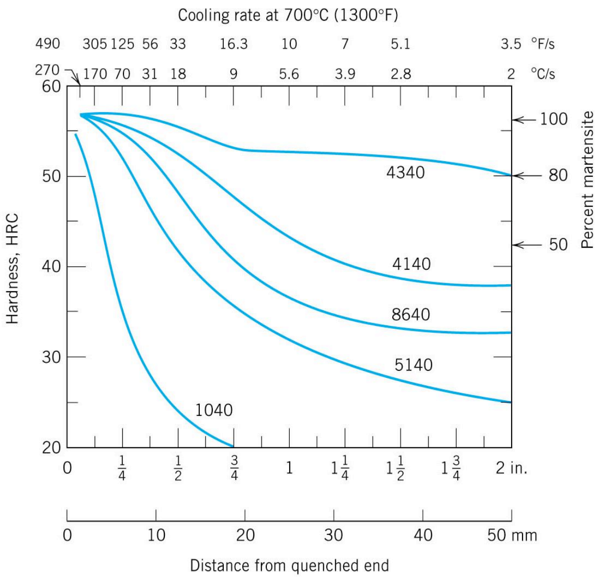
44) (5marks) Estimate the weight fraction of the **eutectoid ferrite only** (not the proeutectoid ferrite) in a slow-cooled 1050 steel (the phase diagram you need is attached at the end of the exam).

45) (6 marks) For this question, you are not expected to remember exact numbers like critical temperatures. Focus on the general shape and features of the Isothermal Transformation (IT) diagram.
   a) Explain, including a sketch, the important information provided by an IT diagram for a eutectoid steel.
   b) Using your sketched IT diagram, sketch a typical heat-treatment to produce martensite.
   c) Using your sketched IT diagram, sketch a typical heat-treatment to produce a mixture of pearlite and martensite.

46) (3 marks) Compute the planar density of atoms on the (100) plane in an FCC aluminum crystal (lattice constant a=0.405 nm).

47) (4 marks) A 75mm diameter bar is to be quenched in agitated oil (data on the left below). It is a requirement that the minimum hardness in the bar be at least 35 HRC, and that the minimum hardness in the bar be at least 80% of the maximum hardness. Which of the 5 alloys shown in the Jominy results on the right are acceptable alloys for this application?

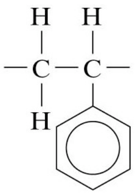




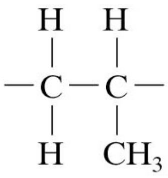
48) (2 marks) Discuss briefly why it would be better to have brass bolts in a steel hull than steel bolts in a brass hull on an ocean-bound ship.

49) (5 marks) A copolymer is 50% PS and 50% PP by weight. The structures for PS and PP are given below.

i. PS



PP



b) What is the mole fraction of PS in the copolymer?

c) If the weight-average molecular weight is 22,000 g/mol, what is the weight-average degree of polymerization?

Constants

Avogadro's number:	$N_0=6.023 \times 10^{23}$
Atomic mass unit:	$u=1.661 \times 10^{-24}$ g
Boltzmann's constant:	$k=8.620 \times 10^{-5}$ eV/K
Gas constant	$R=8.314$ J/(mol K)
Electron Charge:	$e=1.602 \times 10^{-19}$ C
Faraday Constant:	$F=96{,}500$ C/mol

Equations

Ionic Bond Energy

$$E = \frac{-A}{r} + \frac{B}{r^n}$$

ASTM grain size, n

$$N = 2^{n-1}$$

Vacancy concentration

$$\frac{n_v}{N} = Ce^{-Q_v/RT}$$

Arrhenius rate equation

$$rate = Ce^{-Q/RT}$$

Steady-state diffusion

$$J = -D\frac{dC}{dx}$$

Transient diffusion

$$\frac{C_x - C_0}{C_s - C_0} = 1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)$$

Diffusivity

$$D = D_0 e^{-Q/RT}$$

Schmid's Law

$$\tau_R = \sigma \cos\lambda \cos\phi$$

Hall-Petch Relation:

$$\sigma_y = \sigma_0 + k/\sqrt{d}$$

Steady-State Creep Rate

$$\frac{\partial\varepsilon}{\partial t} = K_2\sigma^n \exp\left(\frac{-Q_c}{RT}\right)$$

Nernst Equation

$$\Delta V = (V_2^{\,0} - V_1^{\,0}) - \frac{RT}{nF}\ln\frac{\left[M^{n+}{}_1\right]}{\left[M^{n+}{}_2\right]}$$

$$\Delta V = (V_2^{\,0} - V_1^{\,0}) - \frac{0.0592V}{n}\log_{10}\frac{\left[M^{n+}{}_1\right]}{\left[M^{n+}{}_2\right]}$$

Pilling-Bedworth Ratio

$$\sigma_y = \sigma_0 + k/\sqrt{d}$$

Polymer Tensile Strength

$$TS = TS_\infty - \frac{A}{M_n}$$

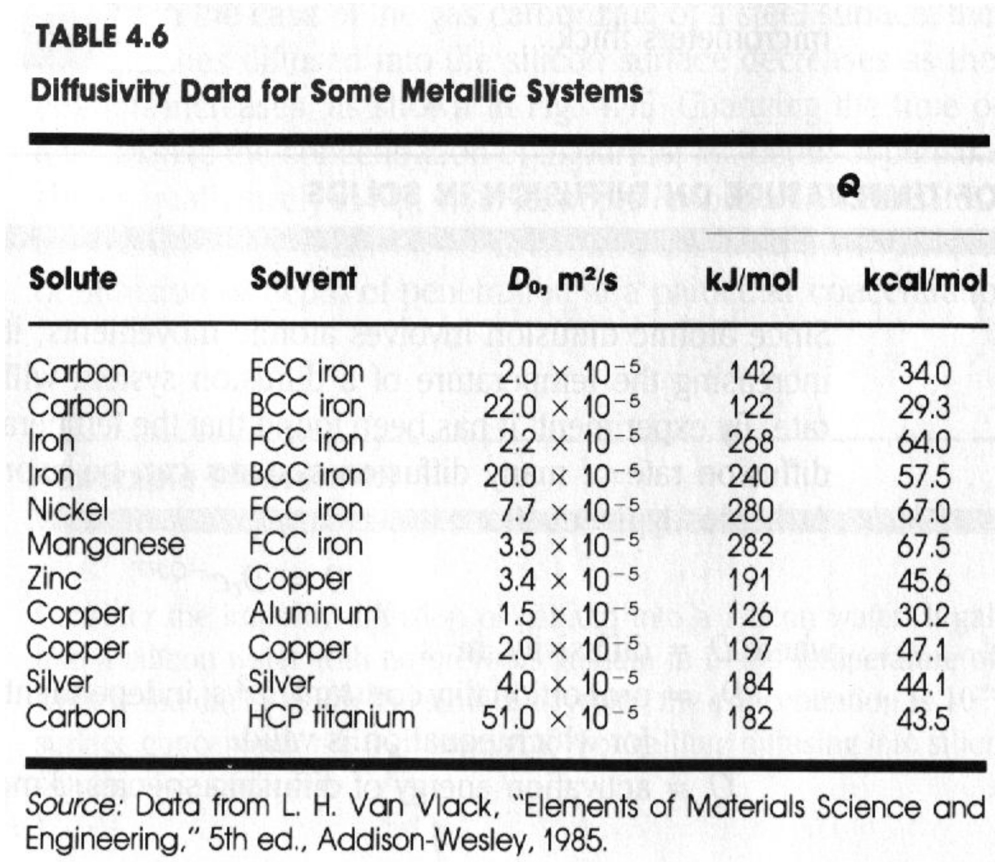


TABLE 4.6

Diffusivity Data for Some Metallic Systems

Solute	**Solvent**	***D_0*, m²/s**	***Q*** kJ/mol	***Q*** kcal/mol
Carbon	FCC iron	2.0×10^{-5}	142	34.0
Carbon	BCC iron	22.0×10^{-5}	122	29.3
Iron	FCC iron	2.2×10^{-5}	268	64.0
Iron	BCC iron	20.0×10^{-5}	240	57.5
Nickel	FCC iron	7.7×10^{-5}	280	67.0
Manganese	FCC iron	3.5×10^{-5}	282	67.5
Zinc	Copper	3.4×10^{-5}	191	45.6
Copper	Aluminum	1.5×10^{-5}	126	30.2
Copper	Copper	2.0×10^{-5}	197	47.1
Silver	Silver	4.0×10^{-5}	184	44.1
Carbon	HCP titanium	51.0×10^{-5}	182	43.5

Source: Data from L. H. Van Vlack, "Elements of Materials Science and Engineering," 5th ed., Addison-Wesley, 1985.

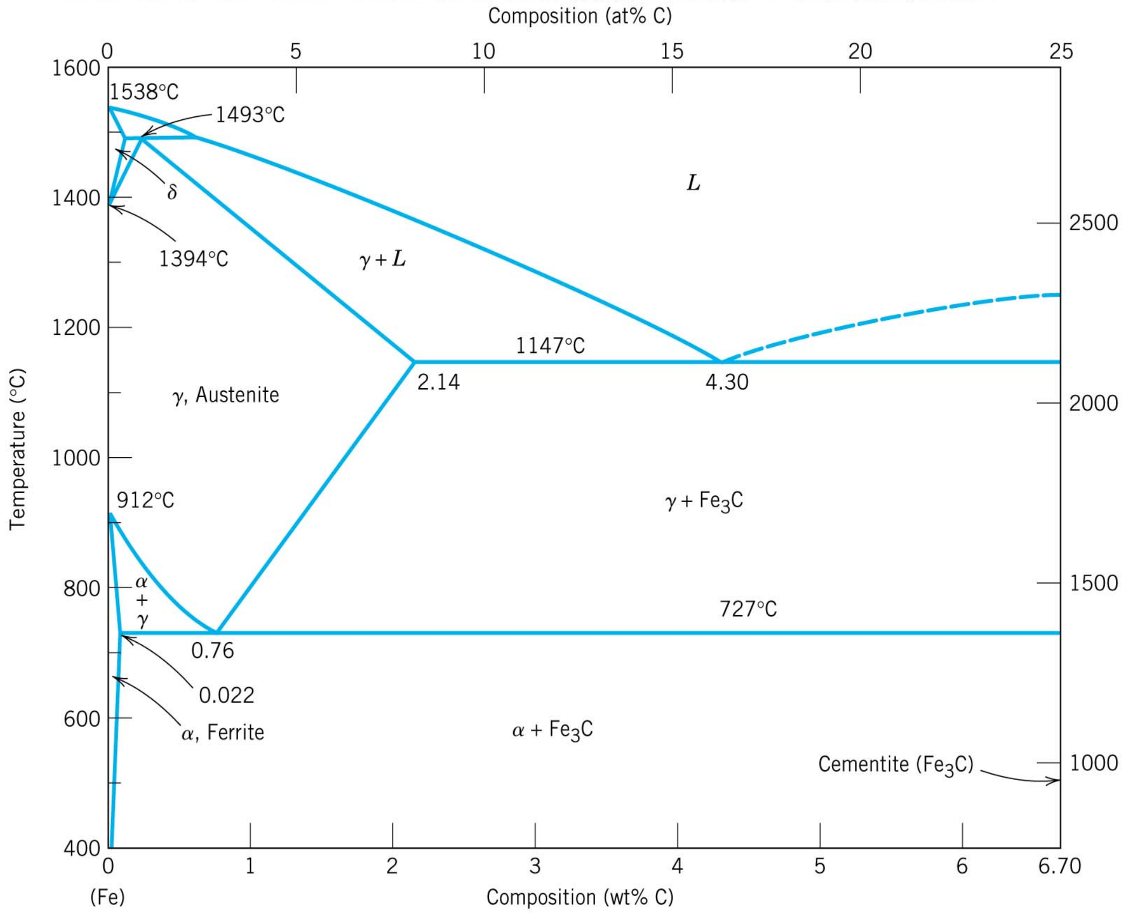


FIGURE 9.21 The iron–iron carbide phase diagram. [Adapted from *Binary Alloy Phase Diagrams,* 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

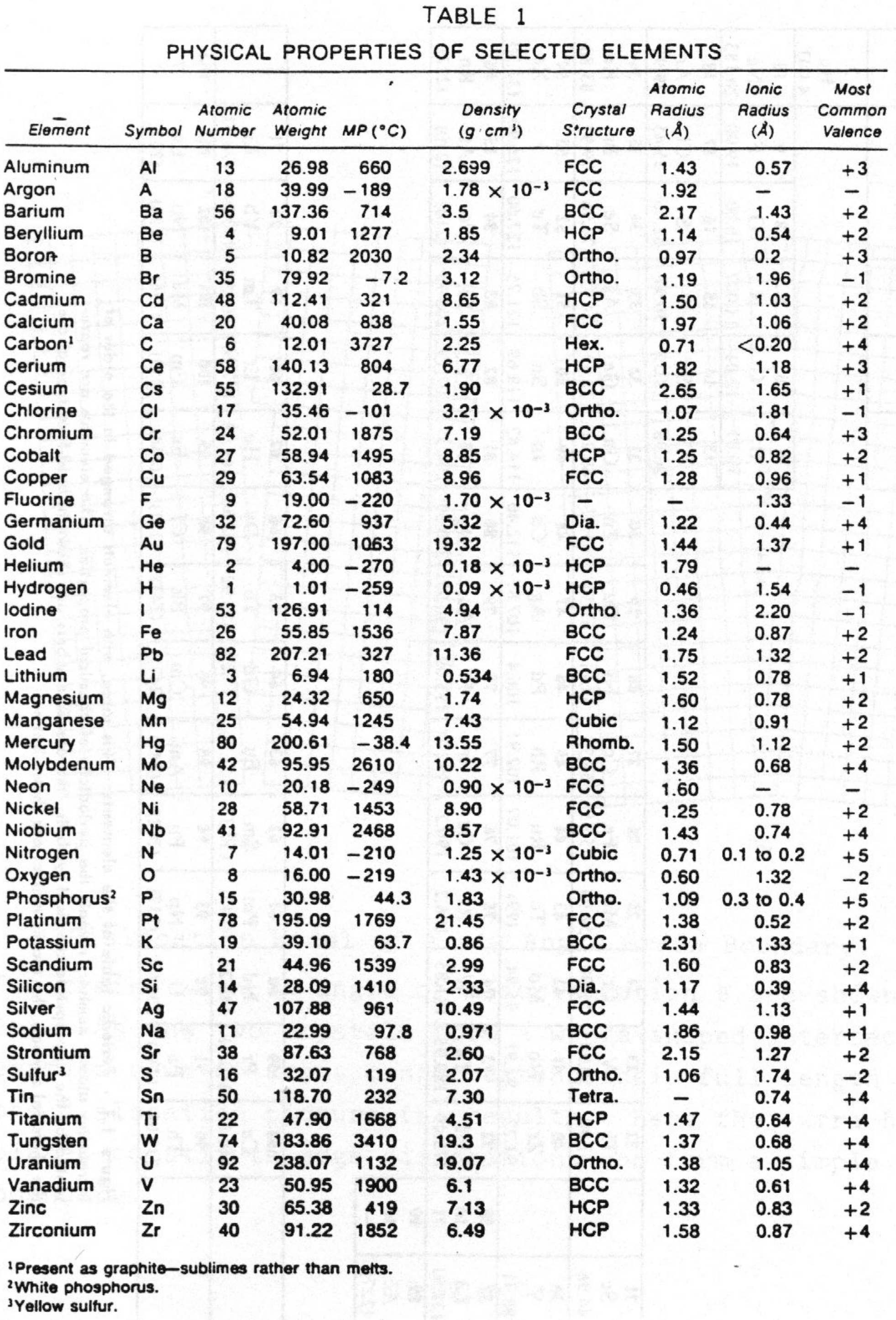


TABLE 1

PHYSICAL PROPERTIES OF SELECTED ELEMENTS

Element	*Symbol*	*Atomic Number*	*Atomic Weight*	*MP (°C)*	*Density* ($g \cdot cm^{-3}$)	*Crystal Structure*	*Atomic Radius* (Å)	*Ionic Radius* (Å)	*Most Common Valence*
Aluminum	Al	13	26.98	660	2.699	FCC	1.43	0.57	+3
Argon	A	18	39.99	−189	1.78 × 10^{-3}	FCC	1.92	—	—
Barium	Ba	56	137.36	714	3.5	BCC	2.17	1.43	+2
Beryllium	Be	4	9.01	1277	1.85	HCP	1.14	0.54	+2
Boron	B	5	10.82	2030	2.34	Ortho.	0.97	0.2	+3
Bromine	Br	35	79.92	−7.2	3.12	Ortho.	1.19	1.96	−1
Cadmium	Cd	48	112.41	321	8.65	HCP	1.50	1.03	+2
Calcium	Ca	20	40.08	838	1.55	FCC	1.97	1.06	+2
Carbon[1]	C	6	12.01	3727	2.25	Hex.	0.71	<0.20	+4
Cerium	Ce	58	140.13	804	6.77	HCP	1.82	1.18	+3
Cesium	Cs	55	132.91	28.7	1.90	BCC	2.65	1.65	+1
Chlorine	Cl	17	35.46	−101	3.21 × 10^{-3}	Ortho.	1.07	1.81	−1
Chromium	Cr	24	52.01	1875	7.19	BCC	1.25	0.64	+3
Cobalt	Co	27	58.94	1495	8.85	HCP	1.25	0.82	+2
Copper	Cu	29	63.54	1083	8.96	FCC	1.28	0.96	+1
Fluorine	F	9	19.00	−220	1.70 × 10^{-3}	—	—	1.33	−1
Germanium	Ge	32	72.60	937	5.32	Dia.	1.22	0.44	+4
Gold	Au	79	197.00	1063	19.32	FCC	1.44	1.37	+1
Helium	He	2	4.00	−270	0.18 × 10^{-3}	HCP	1.79	—	—
Hydrogen	H	1	1.01	−259	0.09 × 10^{-3}	HCP	0.46	1.54	−1
Iodine	I	53	126.91	114	4.94	Ortho.	1.36	2.20	−1
Iron	Fe	26	55.85	1536	7.87	BCC	1.24	0.87	+2
Lead	Pb	82	207.21	327	11.36	FCC	1.75	1.32	+2
Lithium	Li	3	6.94	180	0.534	BCC	1.52	0.78	+1
Magnesium	Mg	12	24.32	650	1.74	HCP	1.60	0.78	+2
Manganese	Mn	25	54.94	1245	7.43	Cubic	1.12	0.91	+2
Mercury	Hg	80	200.61	−38.4	13.55	Rhomb.	1.50	1.12	+2
Molybdenum	Mo	42	95.95	2610	10.22	BCC	1.36	0.68	+4
Neon	Ne	10	20.18	−249	0.90 × 10^{-3}	FCC	1.60	—	—
Nickel	Ni	28	58.71	1453	8.90	FCC	1.25	0.78	+2
Niobium	Nb	41	92.91	2468	8.57	BCC	1.43	0.74	+4
Nitrogen	N	7	14.01	−210	1.25 × 10^{-3}	Cubic	0.71	0.1 to 0.2	+5
Oxygen	O	8	16.00	−219	1.43 × 10^{-3}	Ortho.	0.60	1.32	−2
Phosphorus[2]	P	15	30.98	44.3	1.83	Ortho.	1.09	0.3 to 0.4	+5
Platinum	Pt	78	195.09	1769	21.45	FCC	1.38	0.52	+2
Potassium	K	19	39.10	63.7	0.86	BCC	2.31	1.33	+1
Scandium	Sc	21	44.96	1539	2.99	FCC	1.60	0.83	+2
Silicon	Si	14	28.09	1410	2.33	Dia.	1.17	0.39	+4
Silver	Ag	47	107.88	961	10.49	FCC	1.44	1.13	+1
Sodium	Na	11	22.99	97.8	0.971	BCC	1.86	0.98	+1
Strontium	Sr	38	87.63	768	2.60	FCC	2.15	1.27	+2
Sulfur[3]	S	16	32.07	119	2.07	Ortho.	1.06	1.74	−2
Tin	Sn	50	118.70	232	7.30	Tetra.	—	0.74	+4
Titanium	Ti	22	47.90	1668	4.51	HCP	1.47	0.64	+4
Tungsten	W	74	183.86	3410	19.3	BCC	1.37	0.68	+4
Uranium	U	92	238.07	1132	19.07	Ortho.	1.38	1.05	+4
Vanadium	V	23	50.95	1900	6.1	BCC	1.32	0.61	+4
Zinc	Zn	30	65.38	419	7.13	HCP	1.33	0.83	+2
Zirconium	Zr	40	91.22	1852	6.49	HCP	1.58	0.87	+4

[1] Present as graphite—sublimes rather than melts.

[2] White phosphorus.

[3] Yellow sulfur.

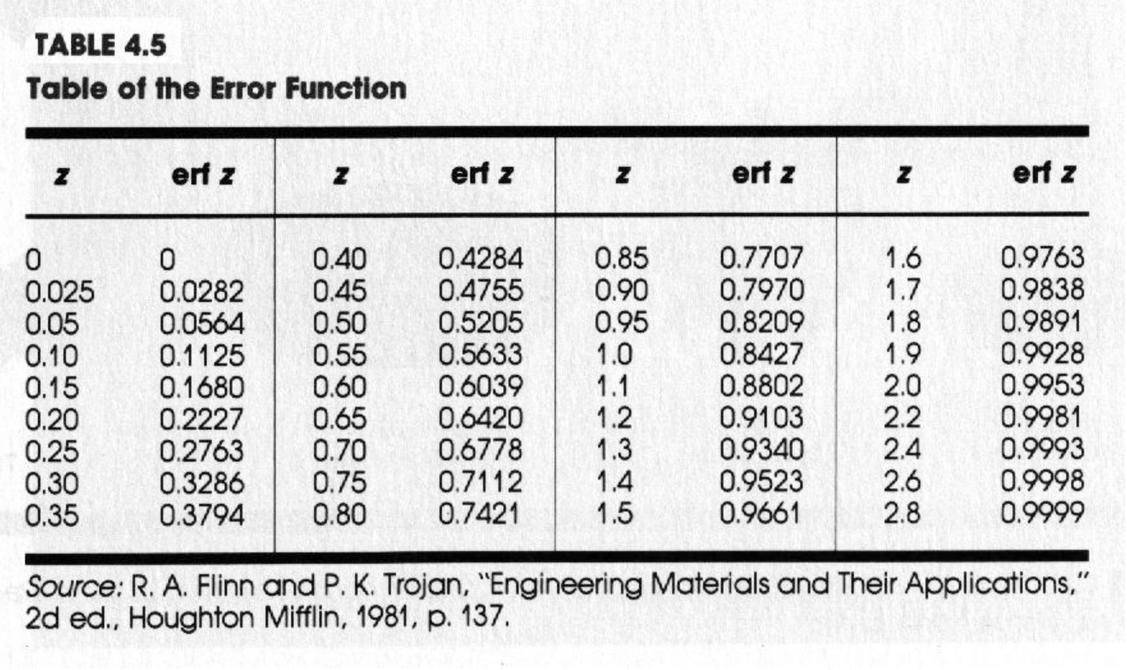


TABLE 4.5

Table of the Error Function

z	erf *z*	*z*	erf *z*	*z*	erf *z*	*z*	erf *z*
0	0	0.40	0.4284	0.85	0.7707	1.6	0.9763
0.025	0.0282	0.45	0.4755	0.90	0.7970	1.7	0.9838
0.05	0.0564	0.50	0.5205	0.95	0.8209	1.8	0.9891
0.10	0.1125	0.55	0.5633	1.0	0.8427	1.9	0.9928
0.15	0.1680	0.60	0.6039	1.1	0.8802	2.0	0.9953
0.20	0.2227	0.65	0.6420	1.2	0.9103	2.2	0.9981
0.25	0.2763	0.70	0.6778	1.3	0.9340	2.4	0.9993
0.30	0.3286	0.75	0.7112	1.4	0.9523	2.6	0.9998
0.35	0.3794	0.80	0.7421	1.5	0.9661	2.8	0.9999

Source: R. A. Flinn and P. K. Trojan, "Engineering Materials and Their Applications," 2d ed., Houghton Mifflin, 1981, p. 137.

Table 17.2 The Galvanic Series

	Platinum
	Gold
	Graphite
	Titanium
	Silver
	316 Stainless steel (passive)
	304 Stainless steel (passive)
↑	Inconel (80Ni–13Cr–7Fe) (passive)
	Nickel (passive)
	Monel (70Ni–30Cu)
Increasingly inert (cathodic)	Copper–nickel alloys
	Bronzes (Cu–Sn alloys)
	Copper
	Brasses (Cu–Zn alloys)
	Inconel (active)
	Nickel (active)
	Tin
	Lead
Increasingly active (anodic)	316 Stainless steel (active)
	304 Stainless steel (active)
	Cast iron
↓	Iron and steel
	Aluminum alloys
	Cadmium
	Commercially pure aluminum
	Zinc
	Magnesium and magnesium alloys

Source: M. G. Fontana, *Corrosion Engineering,* 3rd edition. Copyright 1986 by McGraw-Hill Book Company. Reprinted with permission.

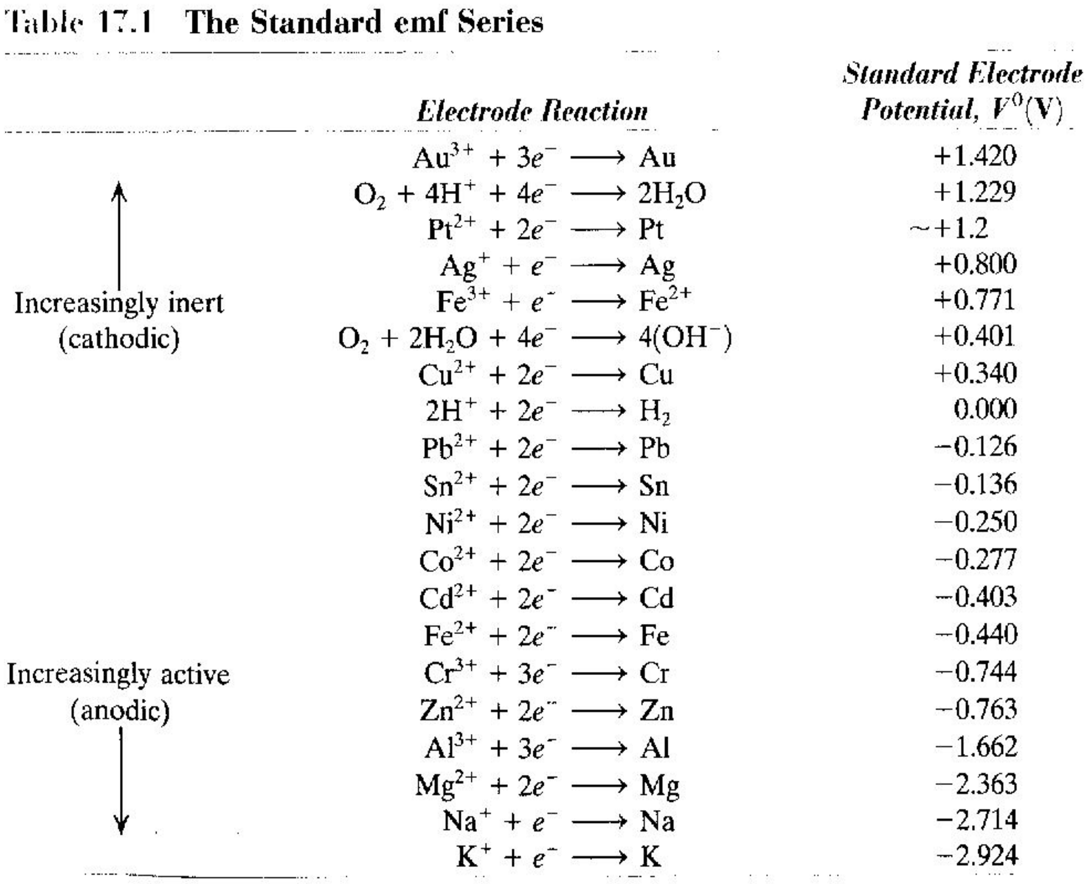


Table 17.1 The Standard emf Series

	Electrode Reaction	*Standard Electrode Potential, V^0(V)*
	$Au^{3+} + 3e^- \longrightarrow Au$	+1.420
↑	$O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O$	+1.229
	$Pt^{2+} + 2e^- \longrightarrow Pt$	~+1.2
	$Ag^+ + e^- \longrightarrow Ag$	+0.800
Increasingly inert	$Fe^{3+} + e^- \longrightarrow Fe^{2+}$	+0.771
(cathodic)	$O_2 + 2H_2O + 4e^- \longrightarrow 4(OH^-)$	+0.401
	$Cu^{2+} + 2e^- \longrightarrow Cu$	+0.340
	$2H^+ + 2e^- \longrightarrow H_2$	0.000
	$Pb^{2+} + 2e^- \longrightarrow Pb$	−0.126
	$Sn^{2+} + 2e^- \longrightarrow Sn$	−0.136
	$Ni^{2+} + 2e^- \longrightarrow Ni$	−0.250
	$Co^{2+} + 2e^- \longrightarrow Co$	−0.277
	$Cd^{2+} + 2e^- \longrightarrow Cd$	−0.403
	$Fe^{2+} + 2e^- \longrightarrow Fe$	−0.440
Increasingly active	$Cr^{3+} + 3e^- \longrightarrow Cr$	−0.744
(anodic)	$Zn^{2+} + 2e^- \longrightarrow Zn$	−0.763
	$Al^{3+} + 3e^- \longrightarrow Al$	−1.662
	$Mg^{2+} + 2e^- \longrightarrow Mg$	−2.363
↓	$Na^+ + e^- \longrightarrow Na$	−2.714
	$K^+ + e^- \longrightarrow K$	−2.924