McGraw-Hill Series in Water Resources and Environmental Engineering

WATER CHEMISTRY

Mark M. Benjamin

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Published by McGraw-Hill, a business unit of The McGraw-Hill Companies, Inc., 1221 Avenue of the Americas, New York, NY 10020.

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 0 QPF/QPF 0 9 8 7 6 5 4 3 2 1

ISBN 0–07–238390–9

Publisher: *Thomas E. Casson*
Executive editor: *Eric M. Munson*
Editorial coordinator: *Zuzanna Borciuch*
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Cover designer: *Pam Verros*
Cover image: © *CSIRO Land and Water/William van Aken 1992*
Senior photo research coordinator: *Carrie K. Burger*
Photo research: *Cheryl DuBois, Feldman & Associates, Inc.*
Supplement producer: *Jodi K. Banowetz*
Compositor: *Interactive Composition Corporation*
Typeface: *10.5/12 Times Roman*
Printer: *Quebecor World Fairfield, Inc.*

Library of Congress Cataloging-in-Publication Data

Benjamin, Mark M.
Water chemistry / Mark M. Benjamin. — 1st ed.
p. cm. — (McGraw-Hill series in water resources and environmental engineering.)
Includes index.
ISBN 0–07–238390–9
1. Water chemistry. I. Title. II. Series.

GB855 .B46 2002
551.46'01'54—dc21 00–048986
CIP

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Periodic Table of Elements

Key

Key	
1	Atomic Number
Hydrogen	Name
H	Symbol
1.0079	Atomic Weight

Period	Group 1A	2A	3B	4B	5B	6B	7B	8B	8B	8B	1B	2B	3A	4A	5A	6A	7A	8A
1	1 Hydrogen **H** 1.0079																	2 Helium **He** 4.0026
2	3 Lithium **Li** 6.941	4 Beryllium **Be** 9.0122											5 Boron **B** 10.811	6 Carbon **C** 12.0112	7 Nitrogen **N** 14.0067	8 Oxygen **O** 15.9994	9 Fluorine **F** 18.9984	10 Neon **Ne** 20.180
3	11 Sodium **Na** 22.989	12 Magnesium **Mg** 24.305											13 Aluminum **Al** 26.9815	14 Silicon **Si** 28.086	15 Phosphorous **P** 30.9738	16 Sulfur **S** 32.066	17 Chlorine **Cl** 35.453	18 Argon **Ar** 39.948
4	19 Potassium **K** 39.098	20 Calcium **Ca** 40.08	21 Scandium **Sc** 44.956	22 Titanium **Ti** 47.87	23 Vanadium **V** 50.942	24 Chromium **Cr** 51.996	25 Manganese **Mn** 54.938	26 Iron **Fe** 55.847	27 Cobalt **Co** 58.933	28 Nickel **Ni** 58.69	29 Copper **Cu** 63.546	30 Zinc **Zn** 65.39	31 Gallium **Ga** 69.723	32 Germanium **Ge** 72.61	33 Arsenic **As** 74.922	34 Selenium **Se** 78.96	35 Bromine **Br** 79.904	36 Krypton **Kr** 83.80
5	37 Rubidium **Rb** 85.468	38 Strontium **Sr** 87.62	39 Yttrium **Y** 88.905	40 Zirconium **Zr** 91.22	41 Niobium **Nb** 92.906	42 Molybdenum **Mo** 95.94	43 Technetium **Tc** (98)	44 Ruthenium **Ru** 101.07	45 Rhodium **Rh** 102.905	46 Palladium **Pd** 106.4	47 Silver **Ag** 107.868	48 Cadmium **Cd** 112.411	49 Indium **In** 114.82	50 Tin **Sn** 118.71	51 Antimony **Sb** 121.75	52 Tellurium **Te** 127.60	53 Iodine **I** 126.904	54 Xenon **Xe** 131.29
6	55 Cesium **Cs** 132.905	56 Barium **Ba** 137.34	*57 Lanthanum **La** 138.91	72 Hafnium **Hf** 178.49	73 Tantalum **Ta** 180.948	74 Tungsten **W** 183.85	75 Rhenium **Re** 186.2	76 Osmium **Os** 190.2	77 Iridium **Ir** 192.2	78 Platinum **Pt** 195.09	79 Gold **Au** 196.967	80 Mercury **Hg** 200.59	81 Thallium **Tl** 204.38	82 Lead **Pb** 207.19	83 Bismuth **Bi** 208.980	84 Polonium **Po** (209)	85 Astatine **At** (210)	86 Radon **Rn** (222)
7	87 Francium **Fr** (223)	88 Radium **Ra** (226)	**89 Actinium **Ac** (227)	104 Rutherfordium **Rf** (261)	105 Dubnium **Db** (262)	106 Seaborgium **Sg** (263)	107 Bohrium **Bh** (262)	108 Hassium **Hs** (265)	109 Meitnerium **Mt** (266)	110 *** (269)	111 *** (272)	112 *** (277)						

	Period														
*Lanthanides	6	58 Cerium **Ce** 140.12	59 Prasedoymium **Pr** 140.907	60 Neodymium **Nd** 144.24	61 Promethium **Pm** 144.913	62 Samarium **Sm** 150.35	63 Europium **Eu** 151.96	64 Gadolinium **Gd** 157.25	65 Terbium **Tb** 158.925	66 Dysprosium **Dy** 162.50	67 Holmium **Ho** 164.930	68 Erbium **Er** 167.26	69 Thulium **Tm** 168.934	70 Ytterbium **Yb** 173.04	71 Lutetium **Lu** 174.97
**Actinides	7	90 Thorium **Th** 232.038	91 Protactinium **Pa** (231)	92 Uranium **U** 238.03	93 Neptunium **Np** (237)	94 Plutonium **Pu** 244.064	95 Americium **Am** (243)	96 Curium **Cm** (247)	97 Berkelium **Bk** (247)	98 Californium **Cf** 242.058	99 Einsteinium **Es** (254)	100 Fermium **Fm** 257.095	101 Mendelevium **Md** 258.10	102 Nobelium **No** 259.101	103 Lawrencium **Lr** 260.105

*** These elements have not yet been named.

I Source: American Chemical Society, *Chemistry in Context: Applying Chemistry to Society,* Third Edition, © 2000 McGraw-Hill Companies, New York, NY.

	Symbol	Atomic No.	Atomic Mass
Actinium	Ac	89	[227]†
Aluminum	Al	13	26.98154
Americium	Am	95	[243]†
Antimony	Sb	51	121.75
Argon	Ar	18	39.948
Arsenic	As	33	74.9216
Astatine	At	85	[210]†
Barium	Ba	56	137.33
Berkelium	Bk	97	[247]†
Beryllium	Be	4	9.0122
Bismuth	Bi	83	208.9804
Bohrium	Bh	107	[262]†
Boron	B	5	10.811
Bromine	Br	35	79.904
Cadmium	Cd	48	112.411
Calcium	Ca	20	40.08
Californium	Cf	98	[251]†
Carbon	C	6	12.011
Cerium	Ce	58	140.12
Cesium	Cs	55	132.9054
Chlorine	Cl	17	35.453
Chromium	Cr	24	51.996
Cobalt	Co	27	58.9332
Copper	Cu	29	63.546
Curium	Cm	96	[247]†
Dubnium	Db	105	[262]†
Dysprosium	Dy	66	162.50
Einsteinium	Es	99	[254]†
Erbium	Er	68	167.26
Europium	Eu	63	151.96
Fermium	Fm	100	[253]†
Fluorine	F	9	18.99840
Francium	Fr	87	[223]
Gadolinium	Gd	64	157.25
Gallium	Ga	31	69.723
Germanium	Ge	32	72.61
Gold	Au	79	196.9665
Hafnium	Hf	72	178.49
Hassium	Hs	108	[265]†
Helium	He	2	4.00260
Holmium	Ho	67	164.9303
Hydrogen	H	1	1.0079
Indium	In	49	114.82
Iodine	I	53	126.9045
Iridium	Ir	77	192.22
Iron	Fe	26	55.847
Krypton	Kr	36	83.80
Lanthanum	La	57	138.9055
Lawrencium	Lr	103	[260]†
Lead	Pb	82	207.2
Lithium	Li	3	6.941
Lutetium	Lu	71	174.97
Magnesium	Mg	12	24.305
Manganese	Mn	25	54.9380
Meitnerium	Mt	109	[266]†

	Symbol	Atomic No.	Atomic Mass
Mendelevium	Md	101	[258]†
Mercury	Hg	80	200.59
Molybdenum	Mo	42	95.94
Neodymium	Nd	60	144.24
Neon	Ne	10	20.180
Neptunium	Np	93	[237]†
Nickel	Ni	28	58.69
Niobium	Nb	41	92.9064
Nitrogen	N	7	14.0067
Nobelium	No	102	[259]†
Osmium	Os	76	190.2
Oxygen	O	8	15.9994
Palladium	Pd	46	106.4
Phosphorus	P	15	30.97376
Platinum	Pt	78	195.08
Plutonium	Pu	94	[244]†
Polonium	Po	84	[209]†
Potassium	K	19	39.098
Praseodymium	Pr	59	140.9077
Promethium	Pm	61	[145]†
Protactinium	Pa	91	[231]†
Radium	Ra	88	[226]†
Radon	Rn	86	[222]†
Rhenium	Re	75	186.21
Rhodium	Rh	45	102.9055
Rubidium	Rb	37	85.4678
Ruthenium	Ru	44	101.07
Rutherfordium	Rf	104	[261]†
Samarium	Sm	62	150.36
Scandium	Sc	21	44.9559
Seaborgium	Sg	106	[263]†
Selenium	Se	34	78.96
Silicon	Si	14	28.086
Silver	Ag	47	107.868
Sodium	Na	11	22.98977
Strontium	Sr	38	87.62
Sulfur	S	16	32.066
Tantalum	Ta	73	180.9479
Technetium	Tc	43	[98]†
Tellurium	Te	52	127.60
Terbium	Tb	65	158.9253
Thallium	Tl	81	204.383
Thorium	Th	90	232.038
Thulium	Tm	69	168.9342
Tin	Sn	50	118.71
Titanium	Ti	22	47.87
Tungsten	W	74	183.85
Uranium	U	92	238.0289
Vanadium	V	23	50.9415
Xenon	Xe	54	131.29
Ytterbium	Yb	70	173.04
Yttrium	Y	39	88.9059
Zinc	Zn	30	65.39
Zirconium	Zr	40	91.22

Only 109 elements are listed. Elements 110–112 have not yet been named.

†Mass number of most stable or best-known isotope.

Source: American Chemical Society, *Chemistry in Context: Applying Chemistry to Society*, Third Edition, © 2000 McGraw-Hill Companies, New York, NY.

WATER CHEMISTRY

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DEDICATION

To those who have nurtured me

Arthur and Hannah Benjamin

Doc and Hune Smith

Judith and Mara Benjamin

PREFACE

OBJECTIVES AND TEXT ORGANIZATION

The past three decades have witnessed a virtual explosion in the range of topics gathered under the umbrella of environmental chemistry. Throughout this period, the basic principles of equilibrium chemistry, particularly as they apply to aquatic systems, have served as indispensable tools for understanding the composition of, and direction of change in, environmental systems. This fact, it seems to me, owes as much to the seminal book that established our current paradigm for studying and interpreting the chemistry of aquatic systems as to the centrality of the equilibrium principles themselves. That book, of course, is *Aquatic Chemistry,* by Stumm and Morgan, first published in 1970 and currently in its third edition. Since the publication of that text, the tools available for solving the equations that define and constrain the equilibrium composition of aquatic systems have been improved significantly, and those tools have been applied to an ever-expanding range of systems, but the basic approach for analyzing the systems has remained largely unaltered.

Though it is unarguably the definitive text in the field, *Aquatic Chemistry* is widely perceived as too advanced for students taking their first course in the subject area, particularly those with little background beyond an introductory course in general chemistry. As a result, over the years, a number of texts have emerged that attempt to convey the key concepts of equilibrium chemistry in a more accessible format. This text follows in that line, covering much of the same material but diverging in a few ways both substantive and stylistic. A brief outline of the text highlights both the similarities and differences.

The text starts with an overview of a few simple, well-known physical/chemical concepts: conservation of mass and energy, and the tendency for any system to change toward a more stable (less reactive) condition. In Chapter 1, a good deal of the vocabulary of equilibrium aquatic chemistry is defined, links between chemical parameters and reactivity are introduced, and the kinetic model for chemical equilibrium is developed.

Chapter 2 provides a more formalized approach to understanding and predicting chemical change, via the concepts of chemical thermodynamics. The presentation and level of coverage in this chapter, particularly the first half, differ substantially from those in most other texts in this field, and a case can be made that the presentation is beyond what is necessary or appropriate in an introductory course. Frankly, at times I have persuaded myself that this assessment is accurate. However, after deliberation, I always returned to the opinion that if I wanted students to understand how thermodynamics applies to aquatic systems, as opposed to simply understanding how to carry out useful thermodynamic calculations, I had to devote substantial space to the topic.

This decision reflects, in large part, my own frustration at having studied thermodynamics so often without quite seeing the connections among the various pieces. For instance, the relationships $\Delta\overline{G} = \Delta\overline{H} - T\,\Delta\overline{S}$ and $\Delta\overline{G} = \Delta\overline{G}^{\circ} + RT\ln a$ make it clear that enthalpy and entropy must be related to chemical activity a, but until recently, I did not understand how. Similarly, I could calculate the redox potential of a solution (E_H) and the surface potential on a suspended colloid (Ψ), but I was never quite sure if, or how, these two electrical potentials were related.

Once I sorted out those issues, I found the insights they provided immensely satisfying, and found that several ideas and principles that I had previously thought disconnected could be interpreted coherently. This cohesiveness is the essential beauty of thermodynamics, and in Chapter 2 I have attempted to convey some of that cohesiveness to students.

In Chapters 3 through 5 and 7 through 10, applications of the chemical principles introduced in Chapters 1 and 2 are presented in the context of specific types of chemical reactions. The first such reactions described focus on acid/base chemistry, in a section that comprises Chapters 3 through 5. This section differs from the discussion of acid/base equilibria in other texts in two ways that are significant. First, in presenting an algorithm for solving for the equilibrium pH of solutions prepared with known inputs, I have chosen to introduce both the proton condition and the *TOT*H equation. In my experience, although students can rapidly master the use of the *TOT*H equation to solve an acid/base problem, they gain a firmer grasp of the qualitative chemistry and the quantitative analysis of equilibrium solutions by writing out the proton condition table. On the other hand, the *TOT*H equation provides an excellent introduction to the development of the tableau that is at the core of numerical solutions to such problems. The essential identity of these two equations for characterizing the proton mass balance is emphasized, so that students understand that both equations provide the same information.

A second skill that is developed in this section is the ability to predict a priori the dominant acid/base species expected to be present at equilibrium, even when a complicated mixture of acids and bases has been used to prepare a solution. I derived this algorithm almost two decades ago, with a good deal of assistance from Dimitri Spyridakis. It has been very gratifying and more than a little surprising to see how enthusiastically other instructors have adopted the algorithm, now that I have begun to publicize what I had assumed was a widespread approach.

Chapter 6 diverges from the preceding and subsequent chapters, being devoted to a presentation of the most common features of some currently available software for solving chemical equilibrium problems. I have emphasized the solution approach taken in the MINEQL family of programs, without tying the discussion to any particular software package. While some instructors may choose to skip this chapter or to have students start using the software packages without going into the solution algorithms, I believe that understanding the basics of those algorithms is valuable, both pedagogically and to ease the learning of the program mechanics when applied to some important systems that are not covered in the manuals.

Chapters 7 through 10 describe, respectively, equilibrium between solutions and a gas phase, reactions of metals in aqueous systems (both complexation and precipitation/dissolution), equilibrium in systems where oxidation-reduction reactions are occurring, and equilibrium between solutions and solid surfaces (adsorption). In each of these chapters, the presentation includes both a formal mathematical analysis of the reactions of interest and a discussion of how those reactions are analyzed by using chemical equilibrium software. All these chapters also refer to the thermodynamic developments in Chapter 2, and the last two chapters rely heavily on that development in the analysis of how the local electrical potential can affect chemical behavior. It is particularly in these latter chapters that, I hope, the detailed discussion of electrical potential and activity coefficients in Chapter 2 pays dividends.

A Comment on the Text Length and a Philosophy of Instruction

One of the most difficult parts of writing this text has been finding the right balance between attention to fundamental concepts and problem-solving techniques. In striking that balance, I have been guided by my experience teaching water chemistry courses over the past 20 years, which has convinced me that students want and can handle more fundamentals than most instructors (including myself) have been providing. Ironically, in my opinion, what frustrates these students and sometimes leads them to believe that water chemistry is overwhelmingly difficult is that, as instructors, we have tried too hard to *simplify* the concepts. Too often, the simplifications we offer provide students the tools to derive correct answers to numerical problems, but only by following algorithms that they do not fully understand. Then, they feel intimidated and lost when faced with a problem for which the algorithm is inapplicable (or worse, they fail to realize that the algorithm is inapplicable and so apply it inappropriately).

I have therefore chosen to write longer and more detailed explanations of both the relevant chemistry and mathematics than are found in most other texts. Undeniably, this decision has lengthened the text, perhaps to the dismay of those who are perusing it for the first time. However, the range of topics covered is no greater than in other water chemistry texts, so the added length does not represent an increase in the conceptual material that readers are asked to master. To the contrary, my belief is that the extra explanatory material will actually *reduce* the time that students need to devote to learning the course content, while simultaneously facilitating a deeper understanding of the subject matter.

Having said that, I recognize that water chemistry courses are taught in many different formats—as semester courses, quarter courses, with and without laboratory components, etc.—and that many instructors will choose to cover only a portion of the text in their courses. In such cases, I believe that a successful course could be taught by omitting coverage of Chapters 10, 9, and 2, in that order, depending on the severity of the time constraints. While an understanding of chemical thermodynamics (Chapter 2) is certainly helpful for interpreting all types of chemical reactions, it is more central to discussions of redox and adsorption reactions (Chapters 9 and 10, respectively) than the reactions covered in earlier chapters. Alternatively, an instructor might consider omitting coverage of chemical equilibrium software packages (Chapter 6 and easily identifiable sections of Chapters 7 through 10).

One of my goals throughout the writing of the text has been to integrate the material within each chapter and between chapters as seamlessly as possible. The benefits of such integration are self-evident, but the integration does impair any effort to fashion a course based on reading of disparate sections. Therefore, my personal preference is not to respond to time constraints by eliminating coverage of selected, isolated sections of the text. I believe that, in the end, students are better served by reading and mastering Chapters 1 and 3 through 8 in their entirety, than by being exposed to all 10 chapters but feeling unsure about their mastery of any of them. However, I realize that different courses have different objectives, and I hope that instructors will experiment freely with various ways to use the text and provide feedback to me on how well those approaches work.

ACKNOWLEDGMENTS

In the end, this book was written because of the encouragement I received from students who flattered me into believing that I could write about water chemistry in a way that made sense to them. The faculty and students who use the book will be the ultimate judges of whether that flattery was merited. But regardless of the verdict, I owe a debt of gratitude to all the students over the years who have suffered through this process with me and who have challenged and rewarded me so.

At the risk of offending the many, I would be remiss if I did not acknowledge by name the few whose support has been so very far above and beyond the call. Paul Anderson has been, first and foremost, a friend for lo these 20 years. That he has been such while simultaneously playing the role of student and later colleague, and always that of gentle but firm critic, surely qualifies him for some sort of award. John Ferguson, Bruce Honeyman, Gregory Korshin, Jim Morgan, Mickey Schurr, John van Benschoten, Ray Simons, and David Waite all contributed generously of their time to help me understand bits of water chemistry that had me confused, and to point out to me portions of the text that needed revision. Desmond Lawler contributed portions of Chapter 7 as part of our joint efforts to write a textbook on physical and chemical water treatment processes. Jill Nordstrom provided student feedback at a level of detail that no author of a textbook deserves, but every author must dream of.

My wife, Judith, has been a source of support and encouragement throughout the years that I devoted to this project. When it seemed that both of our lives were being dominated by the writing effort, I could be reenergized by my fascination with the subject matter and a sense of making progress toward a lifelong dream. Judith shared neither of those sources of inspiration, yet she has remained steadfast throughout, energized by her love and her willingness to share my dream as her own. For that, I will be forever grateful. Finally, I thank my daughter Mara for giving me the joy of fatherhood.

I also gratefully acknowledge the support provided by the University of Washington throughout my career and by the University of New South Wales in Sydney, Australia, during my sabbatical there in 2000.

About the Author

Mark M. Benjamin is the Alan and Ingrid Osberg Professor of Civil and Environmental Engineering at the University of Washington, where he has served on the faculty since 1978. He received his undergraduate degree in chemical engineering at Carnegie-Mellon University and his Master's and Ph.D. degrees in environmental engineering from Stanford University.

Dr. Benjamin has directed and published research on various aspects of water chemistry and water treatment processes. His long-term interests have been in the behavior of metals and their interactions with mineral surfaces, and in the reactions of natural organic matter in water treatment systems. He and his students have received three patents for treatment processes that they have developed. Their publications have won several awards, and three of his students have won awards for best doctoral dissertation in environmental engineering.

Dr. Benjamin is a member of several professional societies and has served on the board of the Association of Environmental Engineering and Science Professors.

The international units

Physical Quantity	Unit	Symbol	Derived Units	Unit	Symbol
Length	meter	m	Force	Newton	N = kg–m/s^2
Mass	kilogram	kg	Energy, work, heat	joule	J = N–m
Time	second	s	Pressure	pascal	Pa = N/m^2
Electric current	ampere	A	Power	watt	W = J/s
Temperature	kelvin	K	Electric charge	coulomb	C = A–s
Luminous intensity	candela	cd	Electric potential	volt	V = W/A = J/C
Amount of material	mole	mol	Electric capacitance	farad	F = A–s/V
			Electric resistance	ohm	Ω = V/A
			Frequency	hertz	Hz = s^{-1}
			Conductance	siemens	S = A/V

Weight-based Concentrations: Unit	Symbol	Volume-based Concentrations: Unit	Symbol
micrograms per kilogram = parts per billion	μg/kg = ppb	micrograms per liter	μg/L
milligrams per kilogram = parts per million	mg/kg = ppm	milligrams per liter	mg/L
milliequivalents per kilogram	meq/kg	micromoles per liter	μmol/L or μM
equivalents per kilogram	equiv/kg	millimoles per liter	mmol/L or mM
moles per kilogram = molal	mol/kg = m	moles per liter	mol/L or *M*
		equivalents per liter	equiv/L or *N*

Dimensions of other parameters

Specific Conductance	microsiemens per centimeter (μS/cm)[= micromhos per centimeter (μmho/cm)]
Dynamic viscosity	Pa–s

Physical and chemical constants

Avogadro's number	$N_A = 6.022045 \times 10^{23}$/mol
Boltzmann's constant	$k_B = 1.3805 \times 10^{-23}$ J/K
Electron mass	$m_e = 9.109 \times 10^{-31}$ kg
Elementary charge	$e_o = 1.60219 \times 10^{-19}$ C
Faraday constant ($F = e_o N_A$)	F = 23.061 kcal/equiv-V = 96.485 kJ/equiv-V = 9.6485×10^4 C/equiv
Gas constant ($R = k_B N_A$)	R = 1.987 cal/mol-K = 8.314 J/mol-K = 0.08206 L atm/mol-K
Ice point	273.15 K
Molar volume of an ideal gas at 273.15 K, 1 atm	22.4138 L/mol
Planck constant	$h = 6.626 \times 10^{-34}$ J s

Mathematical constants and other numbers

$$\pi = 3.1415927$$
$$e = 2.7182818$$
$$\ln x = 2.302585 \log x$$

Useful conversion factors

Energy/Heat/Force/Power

1 J = 1 V–C = 1 N–m
= 1 W–s = 2.7778×10^{-7} kW–h
= 10^{7} erg = 9.9×10^{-3} L–atm
= 0.23901 calorie (cal) = 1.0364×10^{-5} V–F
= 6.242×10^{18} electron volt (eV)
= 9.484×10^{-4} British thermal unit (BTU)
1 cal = 4.184 J (exactly)
1 kcal = 4.184 kJ (exactly)
1 eV = 1.60219×10^{-19} J
1 N = 10^{5} dyne
1 W = 1 kg–m^2/s^3
1 kW h = 3.610×10^{6} J

Mass/Weight

1 atomic mass unit (amu) = 1.661×10^{-27} kg
1 kg = 10^{3} g
1 mg = 10^{-3} g
1 μg = 10^{-6} g
1 ng = 10^{-9} g
1 pg = 10^{-12} g
1 tonne (metric) = 10^{3} kg
1 short ton = 2000 lb = 907.18 kg
1 long ton = 1016 kg
1 lb (avoirdupois) = 453.59 g
1 oz (troy) = 31.103 g

Volume/Flow

1 L = 10^{-3} m^3 = 10^{3} cm^3
1 milliliter (mL) = 10^{-3} L
1 gal (U.S.) = 3.785 L
1 gal (Imperial) = 4.545 L
1 quart (U.S.) = 0.9463 L
1 acre-foot = 325.851 gal (U.S.) = 43.560 ft^3 = 1233.5 m^3
1 ft^3 = 0.028317 m^3
1 gallon per minute (gpm) = 0.06308 L/s
1 cubic foot per second (cfs) = 28.32 L/s = 0.0283 m^3/s = 448.8 gal/min (gpm)

Distance/Length

1 km = 10^{3} m
1 cm = 10^{-2} m
1 mm = 10^{-3} m
1 μm = 10^{-6} m
1 nm = 10^{-9} m
1 angstrom (Å) = 10^{-10} m = 10^{-8} cm
1 statute mile (mi) = 5280 ft
1 mi = 1609.344 m
1 in = 25.4 mm (defined) = 2.54 cm

Pressure

1 atmosphere (atm) = 760 Torr (exactly) = 760 mm Hg = 1.01325 bars = 1.01325×10^{5} Pa = 14.69 lb/in^2
1 Pa = 10^{-5} bar
1 bar = 10^{5} Pa = 0.9869 atm = 10^{6} dyne/cm^2 = 750.06 mm Hg

Values of various expressions involving *R*

R = 1.987 cal/mol-K = 8.314 J/mol-K = 0.08206 L-atm/mol-K
$R \ln 10$ = 4.576 cal/mol-K = 19.14 J/mol-K = 0.1890 L-atm/mol-K
$RT_{298.15\text{K}}$ = 592.5 cal/mol = 2479 J/mol = 24.47 L-atm/mol = 24.15 L-bar/mol
$RT_{298.15\text{K}} \ln x$ = (1364 cal/mol) $\log x$ = (5708 J/mol) $\log x$ = (56.34 L-atm/mol) $\log x$
$RT_{298.15\text{K}}/F$ = 25.69 mV-eq/mol
$RT_{298.15\text{K}}/n_eF = 25.69/n_e$ mV (if n_e is taken as dimensionless)
$(RT_{298.15\text{K}}/F) \ln x$ = (59.157 mV-eq/mol) $\log x$
$(RT_{298.15\text{K}}/n_eF) \ln x = (59.157/n_e$ mV) $\log x$ (if n_e is taken as dimensionless)

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