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HANDBOOK OF CHEMISTRY *and* PHYSICS

W. M. Haynes
Editor-in-Chief

91ST EDITION
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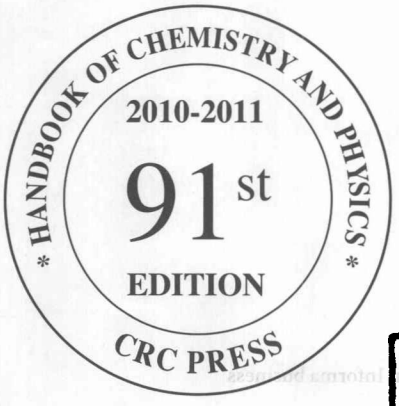
A Ready-Reference Book of Chemical and Physical Data



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FOREWORD

I eoyed being a student in the '1950s,' when my university Physi Department had two copies of the *CRC Handbook of Chemtry and Physics*, but a single subscription to the *Physical Revie*. Professors and students alike had used these bound volumesor years and years. What a joy it was to search for some fact in the pages. In the *Handbook* the actual needed data could usually brecovered efficiently via the indexing, but the real joy was in someoments "lost" in reading some other tables of data that suddenlyad become interesting. Both the *Handbook* and the *Physical Revie* exhibited the spontaneous "snap-open" character imposed by gerations of faculty and young researchers wanting to find the specif heat of bismuth, or the definition of the pascal, or to read the diovery announcement of the deuteron, or nuclear fission or ... . A:w hours spent browsing the *CRC Handbook of Chemistry and Fsics* for me was the more rewarding, in view of its broader doma and focus on the properties of real stuff. And hence the contiing market for well-used copies, even 15 years old.

Butwhat about all the tables of numbers in these *CRC Handoks*? Do we now really need a printed book, when we have the Inrnet available? To me the answer is completely and transparen "YES" we do indeed need *books* of *carefully reviewed data*. The lations of frequently used tables are instantly visible, their organation permanent and unchanging. The carefully reviewed attribe also deserves further comment: Science is a special domain,here we interested little workers are curious to understand how ture works, and perhaps sometimes can use a new insight to desn some new process, or reaction, or chain of equations. For these ta users, while it is helpful to have the data conveniently availae, having the *best* data is critical. In many cases the decisive pnt will come much later: After all our calculations, is this derivequantity just slightly positive or slightly negative? Or even more terestingly, zero within the uncertainty of our evaluation? Eventlly we should be able to rid our work of mathematical errors, t uncertainties in data are intrinsic to the measurement proce And in these days, the progress in some measurement fields pushes against the accuracy/reproducibility limits of the standards with which we quantify our experimental results. Indeed the team of this (now-retired) writer has had this experience — the improved measurement techniques led to challenge the accuracy of realization of the definition of an SI unit, the meter, and ultimately to its replacement definition as a derived quantity, via an adopted value for the speed of light (299,792,458 m/s).

Sometimes we find "quick" and "approximate" results also to be empowering. In "real" life we often just need to know some realistic numbers for preliminary design of some apparatus or process. Or one recent evening after looking at the heating bill, I just really want to have some realistic numbers to try to account for the thermal (in-)efficiency of my new house. Whatever the technical topic, I'll wager reliable information comes faster from the well-known *Handbook* than from the Web. I *do* also love Google and the Web, but the *Handbook* data are created by — and scrutinized by — the expert user community, with any detected errors fully traceable and normally corrected in the next printing. And there is no software start-up time needed!

Another case where serendipity, and unexpected curiosity count is the accidental discovery of interesting "stuff" far from the search topic. For example, in the 90th edition it is wonderful also to have a credible table of the mineral contents – as well as caloric content – of many foods.

In this 91st edition, the traditional (and huge) editing effort and good critical judgment have been brought to this task by Dr. W. M. "Mickey" Haynes of the NIST, who has taken over the helm from long-time editor Dr. David R. Lide. Enjoy!

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March 2010

PREFACE

I am pleased to serve as the fifth Editor-in-Chief of the *CRC Handbook of Chemistry and Physics*. The *Handbook* has been a staple in my library and life during my career, and I am very appreciative to the previous editors for their efforts to ensure the reliability of its information. I thank the publisher for giving me this opportunity, and I hope that my background in properties research will continue to contribute to the level of excellence established for the *Handbook* and to ensure that it remains the first source for data for physical and chemical properties and related topics.

I have been working with David Lide, Editor-in-Chief of the *CRC Handbook of Chemistry and Physics* from 1989–2009, for the past two years during a transition period. I am much indebted to him for his collegial and expert guidance during this period. My main goals, as I take on this project, are to maintain the high standards of quality that have been a hallmark for the *Handbook*, to provide respected sources of documentation for the information published in the *Handbook*, and to expand the coverage of the diverse subject matter in the *Handbook* consistent with advances in science and technology. One cannot overestimate the invaluable contributions that David Lide made to the *Handbook* during his tenure. I would be remiss without noting the most significant of them.

The numerous major changes made to the *Handbook* during the tenure of David Lide were carried out to make it more user friendly, to expand its coverage, and to emphasize quality control, especially in terms of the reliability of the information and its documentation. These major changes include: (a) development of Internet and CD-ROM versions of the *Handbook*; (b) reorganization of the content into 16 sections that bring together related topics; (c) creation of a more systematic index; (d) consistent use of chemical conventions according to IUPAC and ISO recommendations and standards; (e) timely updates of such basic information as fundamental constants, atomic weights, SI units, etc.; (f) major reorganization and expansion of comprehensive, widely used tables for the properties of organic and inorganic compounds, while emphasizing compounds of greatest industrial and research interest; (g) expanded coverage of biochemistry, geophysics, astronomy, and environmental science; and (h) better communication with users through focus groups and other feedback mechanisms.

The 91st Edition of the *Handbook* includes new tables and major expansions and updates, especially in the following areas:

Section 6: Fluid Properties
- New tables on thermophysical properties of selected fluids at saturation and the dependence of liquid density on temperature and pressure
- Major updates for tables on the density of water and properties of ice and D_2O
- Major update and expansion of the table on critical constants of organic compounds

Section 8: Analytical Chemistry
- Major updates for tables on the ionization constants of water and heavy water

Section 9: Molecular Structure and Spectroscopy
- Updates for tables on atomic radii of the elements, bond dissociation energies, and spectroscopic constants of diatomic molecules

Section 10: Atomic, Molecular Structure and Spectroscopy
- Major update for the table on atomic transition probabilities (added new elements) and updates for tables on electron affinities and atomic and molecular polarizabilities

Section 12: Properties of Solids
- New table on electron stopping powers of elements

Section 13: Polymer Properties
- New tables on abbreviations in polymer science and on physical properties of polymers

In order to maintain a manageable number of pages and allow space for growth of the *Handbook*, the indexes for molecular formulae and CAS registry numbers for the Physical Constants of Organic Compounds table and the index for CAS registry numbers for the Physical Constants of Inorganic Compounds table have been removed from the hard-copy edition of the *Handbook*. However, they are available in the electronic versions of the *Handbook* and by email request to the Editor-in-Chief: william.haynes@taylorandfrancis.com

The assistance and cooperation of the Thermodynamics Research Center (TRC) of the National Institute of Standards and Technology (NIST) in updating, expanding, and validating thermophysical properties of organic compounds in the table on critical constants should be recognized. A considerable effort was devoted to this activity for this edition and will be expanded to other tables in the future. TRC specializes in the collection, evaluation, and correlation of thermophysical and thermochemical property data for organic compounds.

The success of the *Handbook* is very dependent on feedback from its users. The Editor-in-Chief will appreciate any suggestions from readers on proposed new topics for the *Handbook* or comments on how the usefulness of the *Handbook* may be improved in future editions. Please send your comments to the Editor-in-Chief: william.haynes@taylorandfrancis.com

Numerous international experts make key contributions to the *Handbook*. These contributors are listed on the pages immediately following the Preface. Their efforts play a significant role in contributing to the wide range of material covered in the *Handbook*. I should also acknowledge the contributions of the Editorial Advisory Board of the *Handbook*, whose members are listed in the front matter. I am much indebted to Fiona Macdonald, Publisher (Chemical & Life Sciences), CRC Press/Taylor & Francis Group for her support and assistance in the preparation of the *Handbook*. Thanks also to Glen Butler, Pam Morrell, Mimi Williams, Theresa Delforn, and James Yanchak for their careful and cooperative work in the production of the *Handbook*.

W. M. Haynes
March 2010

The 91st Edition of the *CRC Handbook of Chemistry and Physics* is dedicated in memory of my parents, William Paul and Nellie Young Haynes

Note on the Ordering of Chemical Compounds: Several different ordering schemes for lists of chemical compounds are used in this book. The long tables, Physical Constants of Organic Compounds and Physical Constants of Inorganic Compounds, are ordered by name (generally the systematic name), but indexes to synonyms, formulas, and CAS Registry Numbers are available. If the table is very short and includes only familiar substances, the listing is usually alphabetical by name or common formula. Many tables of intermediate length are ordered by molecular formula using a modification of the Hill convention. In this convention the molecular formula is written with C first, H second, and then all other elements in alphabetical order of their chemical symbols. For tables with organic compounds only, the sequence of entries is determined by the alphabetical order of elements in the molecular formula and the number of atoms of each element, in ascending order, e.g., C_3H_7Cl, C_3H_7N, C_3H_7NO, $C_3H_7NO_2$, etc. (For organic compounds, a quick way to look up the molecular formula is to use the Physical Constants of Organic Compounds table, which starts on Page **3**-1, and its synonym index on Page **3**-524.) In tables containing non-carbon compounds, those are usually listed first, followed by a separate listing of compounds that do contain carbon. This is a departure from the strict Hill convention as followed by the Chemical Abstracts Service, where the molecular formulas beginning with A and B precede the formulas for carbon-containing compounds, while those beginning with D ... Z follow. For tabular displays, as opposed to an index, it appears more convenient to the user if the non-carbon compounds are listed as a block, rather than being split by the longer list of carbon compounds.

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APPENDIX A: MATHEMATICAL TABLES

Section 1
Basic Constants, Units, and Conversion Factors

CODATA RECOMMENDED VALUES OF THE FUNDAMENTAL PHYSICAL CONSTANTS: 2006

Peter J. Mohr, Barry N. Taylor, and David B. Newell

These tables give the 2006 self-consistent set of values of the basic constants and conversion factors of physics and chemistry recommended by the Committee on Data for Science and Technology (CODATA) for international use. The 2006 adjustment takes into account the data considered in the 2002 adjustment as well as the data that became available between 31 December 2002, the closing date of that adjustment, and 31 December 2006, the closing date of the new adjustment. The new data has led to a significant reduction in the uncertainties of many recommended values. The 2006 set replaces the previously recommended 2002 CODATA set and may also be found on the World Wide Web at physics.nist.gov/constants.

This report was prepared by the authors under the auspices of the CODATA Task Group on Fundamental Constants. The members of the task group are:

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2. Yao, W. M., et al., *J. Phys. G* 33, 1, 2006.

TABLE I: An abbreviated list of the CODATA recommended values of the fundamental constants of physics and chemistry based on the 2006 adjustment.

Quantity	Symbol	Numerical value	Unit	Relative std. uncert. u_r
speed of light in vacuum	c, c_0	299 792 458	m s^{-1}	(exact)
magnetic constant	μ_0	$4\pi \times 10^{-7}$	N A^{-2}	
		$= 12.566\,370\,614... \times 10^{-7}$	N A^{-2}	(exact)
electric constant $1/\mu_0 c^2$	ϵ_0	$8.854\,187\,817... \times 10^{-12}$	F m^{-1}	(exact)
Newtonian constant of gravitation	G	$6.674\,28(67) \times 10^{-11}$	m^3 kg^{-1} s^{-2}	1.0×10^{-4}
Planck constant	h	$6.626\,068\,96(33) \times 10^{-34}$	J s	5.0×10^{-8}
$h/2\pi$	$\hbar$	$1.054\,571\,628(53) \times 10^{-34}$	J s	5.0×10^{-8}
elementary charge	e	$1.602\,176\,487(40) \times 10^{-19}$	C	2.5×10^{-8}
magnetic flux quantum $h/2e$	Φ_0	$2.067\,833\,667(52) \times 10^{-15}$	Wb	2.5×10^{-8}
conductance quantum $2e^2/h$	G_0	$7.748\,091\,7004(53) \times 10^{-5}$	S	6.8×10^{-10}
electron mass	m_e	$9.109\,382\,15(45) \times 10^{-31}$	kg	5.0×10^{-8}
proton mass	m_p	$1.672\,621\,637(83) \times 10^{-27}$	kg	5.0×10^{-8}
proton-electron mass ratio	m_p/m_e	1836.152 672 47(80)		4.3×10^{-10}
fine-structure constant $e^2/4\pi\epsilon_0\hbar c$	α	$7.297\,352\,5376(50) \times 10^{-3}$		6.8×10^{-10}
inverse fine-structure constant	α^{-1}	137.035 999 679(94)		6.8×10^{-10}
Rydberg constant $\alpha^2 m_e c/2h$	R_∞	10 973 731.568 527(73)	m^{-1}	6.6×10^{-12}
Avogadro constant	N_A, L	$6.022\,141\,79(30) \times 10^{23}$	mol^{-1}	5.0×10^{-8}