STANDARD HANDBOOK OF ENGINEERING CALCULATIONS

SECOND EDITION

Tyler G. Hicks

Step-by-step calculation procedures for:

- Aeronautical and Astronautical Engineering
- Architectural Engineering
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- Control Engineering
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SECOND EDITION

STANDARD HANDBOOK OF ENGINEERING CALCULATIONS

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A Note about This Handbook

The *Standard Handbook of Engineering Calculations*, 2nd edition, is designed to present accurate and authoritative information on engineering calculation procedures in a variety of fields. The editors, advisers, and contributors used every effort possible to assure the accuracy of the procedures, formulas, and constants presented in the handbook. Further, the handbook is written with the understanding that the publisher, the editors, and the contributors are supplying guidelines and not attempting to render professional engineering, legal, accounting, or other professional services. If such services are required, the assistance of a qualified professional should be sought.

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In preparing the various sections of this handbook, the following individuals either contributed sections, or portions of sections, or advised the editor or contributors, or both, on the optimum content of specific sections. The affiliations shown are those prevailing at the time of the preparation of the contributed material or the recommendations as to section content.

In choosing the procedures and worked-out problems, these specialists used a number of guidelines, including: (1) What are the most common applied problems that must be solved in this discipline? (2) What are the most accurate methods for solving these problems? (3) What other problems might be met in this discipline? When the answers to these and other related questions were obtained, the procedures and worked-out problems were chosen. Thus, the handbook represents a cross section of the thinking of a large number of experienced practicing engineers, project directors, and educators.

To those who might claim that the use of step-by-step solution procedures and worked-out examples makes engineering "too easy," the editor points out that for many years engineering educators have recognized the importance and value of problem solving in the development of engineering judgment and experience. Problems courses have been popular in numerous engineering schools for many years and are still given in many schools. However, with the greater emphasis on engineering science in most engineering schools, there is less time for the problems courses. The result is that many of today's graduates can benefit from a more extensive study of specific problem-solving procedures.

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PREFACE

This is a handbook of specific engineering calculation procedures that presents to its users more than five thousand direct and related calculation procedures for solving almost all routine, and many nonroutine, problems met in everyday engineering practice in twelve important technical fields. These fields of engineering are: aeronautical and astronautical, architectural, chemical and process plant, civil, control, electrical, electronic, economic, marine, mechanical, nuclear, and sanitary. Having this handbook on the desk or bench, the engineer or scientist will be able to solve most of the applied problems met in daily activities of design, operation, analysis, or economic evaluation anywhere in the world.

The step-by-step *practical and applied* calculation procedures in this handbook are arranged so they can be followed by anyone with an engineering or scientific background. Each worked-out procedure presents *fully explained and illustrated steps* for solving similar problems in design, industrial, research, government, academic, or license-examination situations. For any applied problem, all the handbook user need do is place his or her calculation sheets alongside this handbook and follow the step-by-step procedure line for line to obtain the desired solution for the actual, real-life problem. By following the calculation procedures in this handbook, the engineer, scientist, or technician will obtain accurate results in minimum time with least effort. And the approach and solutions are modern throughout.

The purpose of this handbook is to provide engineers everywhere with specific step-by-step calculation procedures for the most common design and operating problems met in daily practice. While specialists in a given discipline may know of and use more advanced methods, the procedures given in this handbook will produce safe and usable results for the majority of situations met by practicing engineers.

Spanning twelve separate disciplines from aeronautical and astronautical engineering to sanitary engineering, the handbook is useful to these engineers and to architectural, chemical, civil, control, electrical, electronics, marine, mechanical, and nuclear engineers as well. The editors and contributors endeavored to present calculation procedures that are the most important and useful in each branch of engineering, and which will give practitioners the greatest help in their daily work.

Besides being highly useful in the daily practice of engineering, the handbook is valuable to candidates for professional engineering licenses, marine engineering licenses, and a variety of civil service examinations. Many open-book license examinations contain problems that closely resemble those in this handbook.

Further, the handbook is particularly valuable to engineers asked to work outside their area of specialty. Thus, the electrical engineer who has to size a beam to support a motor or a transformer will find a specific calculation procedure for such a choice in

Section 1, Civil Engineering. And the mechanical engineer asked to design a lightning protection system for an industrial plant will find the solution in Section 4, Electrical Engineering. The same is true for all the other engineering disciplines covered by this handbook. Each procedure is accompanied by a worked-out design or operating situation, showing each step to take and the reasons for the step. Thus, to the design or operating engineer, this is the one handbook he or she should not be without. This is particularly so for this second edition of the handbook because it covers the major changes and developments that took place since publication of the first edition.

Three major developments occurred in engineering since publication of the first edition of this handbook. These are: (1) worldwide adoption of the System International (SI) units in all types of engineering activities; (2) widespread use of microcomputers in engineering, superseding the handheld calculator, which replaced the slide rule; and (3) the energy crises that focused much greater attention on energy conservation throughout the world. This second edition of the handbook reflects these changes on every one of its pages.

All calculation procedures in this new edition use both systems of units—the United States Customary System (USCS) and SI. Thus, the engineer unfamiliar with SI can learn this worldwide system quickly and easily simply by reviewing pertinent calculation procedures in this handbook using both systems of units. Such a review will give the engineer a better sense of the "size" of particular SI units much more rapidly than isolated study of a listing of conversion factors. In each calculation procedure the SI unit is indicated in parentheses or brackets after the USCS unit. Thus, a 100-ft span is presented as a 100-ft (30.5-m) span, while a 1000-lb/in^2 pressure is presented as a 1000-lb/in^2 (6894-kPa) pressure. The engineer can use the handbook calculation procedure either solely in USCS units, solely in SI units, or a combination of them. Thus, overseas users will find the handbook compatible with their local practice and a valuable tool in helping them save time, money, and effort.

To make the calculation procedures more amenable to microcomputer solution (while maintaining ease of solution with a handheld calculator or slide rule), a number of the algorithms in the handbook have been revised to permit faster programming in a micro environment. Likewise, all the new calculation procedures—of which there are many in this second edition—have their algorithms in programmable form. This enhances ease of solution for any method used—micro, calculator, or slide rule.

To help engineers cope with the on-again off-again energy crises—which the editor believes will be with us for many years—a new subsection on energy conservation has been added to Section 3, Mechanical Engineering, in this edition. Also, calculation procedures on energy conservation have been added to a variety of other sections, where appropriate. Thus, Section 2, Architectural Engineering, contains a completely new collection of solar-energy design procedures. These, and other new procedures that have been added to the handbook, will allow engineers to handle energy-conservation computations easily and quickly. So this is the one handbook every engineer needs today.

Many other changes are reflected in this new edition of the handbook. Here are a few. These will give you a flavor of the major updating that the handbook has received: A completely new and comprehensive section on solar-energy design methods for a variety of applications; a new section on optics; a completely new section on energy conservation covering—among many other topics—wind-energy generating plants, fuel savings possible with high-temperature hot-water heating, cogeneration energy economics, small hydro power considerations and analyses, waste-heat boiler fuel savings, conversion of steam generators from oil to coal, and many other key energy-conservation topics; new calculation procedures in the electronics engineering area covering operational amplifiers, a variety of filter designs, satellite communications, microwave transmitters; a much-expanded major section on control engineering covering servo systems of many types, transfer functions, advanced feedback control; a completely new section on process-plant engineering has been added covering steam tracing of pipes and vessels, sizing lines for flashing condensate, stack heights for disposing plant gases and vapors, and estimating costs of plant equipment; new procedures for using energy-efficient electric motors, permanent-magnet motors, and flywheels have been added; in the machine-design section many new procedures are included covering plastic gears, robots of various types, and hollow-shaft designs; in Section 12, Engineering Economics, a total of 41 new key calculation pro-

cedures were added covering—among other subjects—benefit-cost analysis through probability and statistics with many applications to real-life engineering situations, methods for Pascal and Poisson probability distribution, failure probabilities, analysis of failure in systems with safeguards, linear regression and Monte Carlo techniques, short- and long-term forecasting with a Markov process.

So—with the addition of the many new calculation procedures, the full metrication of every procedure in the book, and the revision of the procedure algorithms to permit faster micro programming—this is an entirely new handbook. Users will find the handbook in keeping with today's engineering practice throughout the world.

In a work of this size—some 1500 pages—with nearly half of every page comprised of mathematical material, errors can occur. For this reason, the editor asks each user of the handbook to call to his attention any errors that are found. The errors will be corrected in the next printing of the handbook.

Further, if a reader feels that one or more important calculation procedures have been excluded from the handbook, the editor would like to have these called to his attention. And if a reader would like to submit a favorite calculation procedure for possible inclusion in the next edition, the editor will be glad to receive the procedure and evaluate it. All accepted procedures will be fully acknowledged as to source and contributor in the next edition. To have a procedure considered, just send the name of the procedure to the editor in care of the publisher, McGraw-Hill Book Company, 1221 Avenue of the Americas, New York, NY 10020, Attn. P & RD Division. The editor will respond, indicating if he is interested in seeing the full procedure. Please do *not* send the full procedure unless requested to do so by the editor.

Lastly, thank you for using this handbook in your work. I hope it helps you in all fields of modern engineering practice.

TYLER G. HICKS, P.E.

ACKNOWLEDGMENTS

The contributors and advisers consulted hundreds of sources when preparing the material for inclusion in this handbook. Besides using the books and other publications listed as references at the beginning of each major section of the handbook, the contributors and advisers consulted and drew material from technical magazines and journals, trade-association standards, engineering and scientific papers, industrial and engineering catalogs, and a variety of similar publications. Most of these are noted in appropriate places throughout the handbook. Additional acknowledgments, listed in the order received, are given below.

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Specific firms, trade associations, and publications that were extremely helpful in supplying data for various sections of the handbook include Martin Marietta Corporation; *Electronic Design* magazine; Dresser Industries Inc.—Dresser Industrial Valve and Instrument Division; Ingersoll-Rand Company; Anaconda American Brass Company; Waterloo Register Division—Dynamics Corporation of America; ITT Hammel-Dahl; *Mechanical Engineering*, a monthly publication of The American Society of Mechanical Engineers; McQuay, Inc.; The G. C. Breidert Co.; Modine Manufacturing Company; Rubber Manufacturers Association; Condenser Service & Engineering Co., Inc.; Armstrong Machine Works; American Air Filter Company; Crane Company; *Machine Design* magazine; The RAND Corporation; Texas Instruments Incorporated; McGraw-Hill Publications Company, McGraw-Hill, Inc.; Morse Chain Company; Grinnell Corporation; General Electric Company; The B. F. Goodrich Company; American Standard Inc.; the American Society of Heating, Refrigerating and Air-Conditioning Engineers; International Engineering Associates; Taylor Instrument Process Control Division of Sybron Corporation; Clark-Reliance Corporation; American Society for Testing and Materials; Acoustical and Insulating Materials Association; W. S. Dickey Clay Manufacturing Co.; Flexonics Division, Universal Oil Products Co.; Dunham-Bush, Inc.; Carrier Air Conditioning Company; National Industrial Leather Association; Worthington Corporation; Goulds Pumps, Inc. Illustrations and problems credited to Carrier Air Conditioning Company are copyrighted by Carrier Air Conditioning Company.

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HOW TO USE THIS HANDBOOK

There are two ways to enter this handbook to obtain the maximum benefit from the time invested. The first entry is through the index; the second is through the table of contents of the section covering the discipline, or related discipline, concerned. Each method is discussed in detail below.

Index. Great care and considerable time were expended on preparation of the index of this handbook so that it would be of maximum use to every reader. As a general guide, enter the index using the generic term for the type of calculation procedure being considered. Thus, for the design of a beam, enter at *beam(s)*. From here, progress to the specific type of beam being considered—such as *continuous, of steel.* Once the page number or numbers of the appropriate calculation procedure are determined, turn to them to find the step-by-step instructions and worked-out example that can be followed to solve the problem quickly and accurately.

Contents. The contents of each section lists the titles of the calculation procedures contained in that section. Where extensive use of any section is contemplated, the editor suggests that the reader might benefit from an occasional glance at the table of contents of that section. Such a glance will give the user of this handbook an understanding of the breadth and coverage of a given section, or a series of sections. Then, when he or she turns to this handbook for assistance, the reader will be able more rapidly to find the calculation procedure he or she seeks.

Calculation Procedures. Each calculation procedure is a unit in itself. However, any given calculation procedure will contain subprocedures that might be useful to the reader. Thus, a calculation procedure on pump selection will contain subprocedures on pipe friction loss, pump static and dynamic heads, etc. Should the reader of this handbook wish to make a computation using any of such subprocedures, he or she will find the worked-out steps that are presented both useful and precise. Hence, the handbook contains numerous valuable procedures that are useful in solving a variety of applied engineering problems.

One other important point that should be noted about the calculation procedures presented in this handbook is that many of the calculation procedures are equally applicable in a variety of disciplines. Thus, a beam-selection procedure can be used for civil-, chemical-, mechanical-, electrical-, and nuclear-engineering activities, as well as some others. Hence, the reader might consider a temporary neutrality for his or her particular specialty when using the handbook because the calculation procedures are designed for universal use.

Any of the calculation procedures presented can be programmed on a computer. Such programming permits rapid solution of a variety of design problems. With the growing use of low-cost time sharing, more engineering design problems are being solved using a remote terminal in the engineering office. The editor hopes that engineers throughout the world will make greater use of desk calculators and digital and analog computers in solving applied engineering problems. This modern equipment promises greater speed and accuracy for nearly all the complex design problems that must be solved in today's world of engineering.

To make the calculation procedures more amenable to microcomputer solution (while maintaining ease of solution with a handheld calculator or slide rule), a number of the algorithms in the handbook have been revised to permit faster programming in a micro environment. Likewise, all the new calculation procedures—of which there are many in this second edition—have their algorithms in programmable form. This enhances ease of solution for any method used—micro, calculator, or slide rule.

In the microcomputer field there are a number of applications programs available for performing specific, repetitive engineering calculations. These cover topics such as beam design, electronic filter selection, pipeline flow analysis, spring design, air-conditioning requirements, etc. While helpful, such applications programs have not yet become popular with design engineers because they do not permit as much calculation flexibility as engineers like to have.

A general design applications program, TK!Solver®, is a software product designed to allow people unfamiliar with computers to use the power of the microcomputer while giving complete calculation flexibility. Any of the calculation procedures in this handbook can be entered on TK!Solver and quickly solved.* This type of engineering applications program allows the engineer to see—quickly—and judge rapidly the effect of changing the values of variables in a given algorithm. Such programs are growing in popularity in the engineering field. The reason for this is that engineers want to know and understand *every* step in every calculation procedure they use. This handbook provides exactly that information to all its users—regardless of the solution method used—mainframe computer, micro, handheld calculator, slide rule, or mental analysis.

SI Usage. The technical and scientific community throughout the world accepts the SI (System International) for use in both applied and theoretical calculations. With such widespread acceptance of SI, every engineer must become proficient in the use of this system of units if he or she is to remain up-to-date. For this reason, every calculation procedure in this handbook is given in both the United States Customary System (USCS) and SI. This will help all engineers become proficient in using both systems of units. In this handbook the USCS unit is generally given first, followed by the SI value in parentheses or brackets. Thus, if the USCS unit is 10 ft, it will be expressed as 10 ft (3 m).

Engineers accustomed to working in USCS are often timid about using SI. There really aren't any sound reasons for these fears. SI is a logical, easily understood, and readily manipulated group of units. Most engineers grow to prefer SI, once they become familiar with it and overcome their fears. This handbook should do much to "convert" USCS-user engineers to SI because it presents all calculation procedures in both the known and unknown units.

Overseas engineers who must work in USCS because they have a job requiring its usage will find the dual-unit presentation of calculation procedures most helpful. Knowing SI, they can easily convert to USCS because all procedures, tables, and illustrations are presented in dual units.

Learning SI. An efficient way for the USCS-conversant engineer to learn SI follows these steps:

1. List the units of measurement commonly used in your daily work.
2. Insert, opposite each USCS unit, the usual SI unit used; Table 1 shows a variety of commonly used quantities and the corresponding SI units.

*A highly useful companion work, published by McGraw-Hill Book Company, is *McGraw-Hill's TK!SOLVERPACK® to accompany Hicks: Standard Handbook of Engineering Calculations*, by Steven S. Ross. The Ross work presents more than 600 equations grouped into forty models. Each model contains between two and fifty-two separate equations. The procedures that are presented can be solved in both USCS and SI and are drawn from the current handbook. They include topics in civil, mechanical, electrical, electronics, marine, aeronautical, sanitary, nuclear, chemical, architectural, control engineering, and engineering economics. Any user of this handbook interested in using a microcomputer in his or her engineering work should have a copy of the Ross work at the computer keyboard.

TABLE 1 Commonly Used USCS and SI Units*

USCS unit	SI unit	SI symbol	Conversion factor—multiply USCS unit by this factor to obtain the SI unit
square feet	square meters	m^2	0.0929
cubic feet	cubic meters	m^3	0.2831
pounds per square inch	kilopascal	kPa	6.894
pound force	newton	N	4.448
foot pound torque	newton-meter	N·m	1.356
Btu per pound	kilojoule per kilogram	kJ/kg	2.326
gallons per minute	liters per second	L/s	0.06309
Btu per cubic foot	kilojoule per cubic meter	kJ/m^3	37.26

*Because of space limitations this table is abbreviated. For a typical engineering practice an actual table would be many times this length.

3. Find, from a table of conversion factors, such as Table 2, the value to use to convert the USCS unit to SI, and insert it in your list. (Most engineers prefer a conversion factor that can be used as a multiplier of the USCS unit to give the SI unit.)
4. Apply the conversion factors whenever you have an opportunity. Think in terms of SI when you encounter a USCS unit.
5. Recognize—here and now—that the most difficult aspect of SI is becoming comfortable with the names and magnitude of the units. Numerical conversion is simple, once you've set up *your own* conversion table. So think pascal whenever you encounter pounds per square inch pressure, newton whenever you deal with a force in pounds, etc.

TABLE 2 Typical Conversion Table*

To convert from	To	Multiply by
square feet	square meters	9.290304 E − 02
foot per second squared	meter per second squared	3.048 E − 01
cubic feet	cubic meters	2.831685 E − 02
pound per cubic inch	kilogram per cubic meter	2.767990 E + 04
gallon per minute	liters per second	6.309 E − 02
pound per square inch	kilopascal	6.894757
pound force	newton	4.448222
British thermal unit per square foot	joule per square meter	1.135653 E + 04
British thermal unit per hour	Watt	2.930711 E − 01
British thermal unit per cubic foot	kilojoule per cubic meter	3.725697 E + 01
foot-pound torque	newton-meter	1.355818
British thermal unit per pound	joule per kilogram	2.326 E + 03

Note: The E indicates an exponent, as in scientific notation, followed by a positive or negative number, representing the power of 10 by which the given conversion factor is to be multiplied before use. Thus, for the square feet conversion factor, 9.290304 × 1/100 = 0.09290304, the factor to be used to convert square feet to square meters. For a positive exponent, as in converting British thermal units per cubic foot to kilojoule per cubic meter, 3.725697 × 10 = 37.25697.

Where a conversion factor cannot be found, simply use the dimensional substitution. Thus, to convert pounds per cubic inch to kilograms per cubic meter, find 1 lb = 0.4535924 kg, and 1 in^3 = 0.00001638706 m^3. Then, 1 lb/in^3 = 0.4535924 kg/0.00001638706 m^3 = 27,67990, or 2.767990 E + 04.

*This table contains only selected values. See the U.S. Department of the Interior *Metric Manual*, or National Bureau of Standards, *The International System of Units* (*SI*), both available from the U.S. Government Printing Office (GPO), for far more comprehensive listings of conversion factors.

SI Table for a Mechanical Engineer. Let's say you're a mechanical engineer and you wish to construct a conversion table and SI literacy document for yourself. List the units you commonly meet in your daily work; Table 1 is the list compiled by one mechanical engineer. Next, list the SI unit equivalent for the USCS unit. Obtain the equivalent from Table 2. Then, using Table 2 again, insert the conversion multiplier in Table 1.

Keep Table 1 handy at your desk and add new units to it as you encounter them in your work. Over a period of time you will build a personal conversion table that will be valuable to you whenever you must use SI units. Further, since *you* compiled the table, it will have a familiar and nonfrightening look, which will give you greater confidence in using SI.

Units Used. In preparing the calculation procedures in this handbook, the editors and contributors used standard SI units throughout. In a few cases, however, certain units are still in a state of development. For example, the unit *tonne* is used in certain industries, such as metalworking. This unit is therefore used in the metalworking section of this handbook because it represents current practice. However, only a few SI units are still under development. Hence, users of this handbook face little difficulty from this situation.

Computer-aided Calculations. Widespread availability of programmable pocket calculators and low-cost microcomputers allows engineers and designers to save thousands of hours of calculation time. Yet each calculation procedure must be programmed, unless the engineer is willing to use off-the-shelf software. The editor—observing thousands of engineers over the years—detects reluctance among technical personnel to use untested and unproven software programs in their daily calculations. Hence, the tested and proven procedures in this handbook form excellent programming input for programmable pocket calculators, microcomputers, minicomputers, and mainframes.

A variety of software application programs can be used to put the procedures in this handbook on computer. Typical of these are VisiCalc, SuperCalc, TK!Solver®, etc.

There are a number of advantages for the engineer who programs his or her own calculation procedures, namely: (1) The engineer knows, understands, and approves *every* step in the procedure; (2) there are *no* questionable, unknown, or legally worrisome steps in the procedure; (3) the engineer has complete faith in the result because he or she knows every component of it; and (4) if a variation of the procedure is desired, it is relatively easy for the engineer to make the needed changes in the program, using this handbook as the source of the steps and equations to apply.

Modern computer equipment provides greater speed and accuracy for almost all complex design calculations. The editor hopes that engineers throughout the world will make greater use of available computing equipment in solving applied engineering problems. Becoming computer literate is a necessity for every engineer, no matter which field he or she chooses as a specialty. The procedures in this handbook simplify every engineer's task of becoming computer literate because the steps given comprise—to a great extent—the steps in the computer program that can be written.

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SECTION 1

CIVIL ENGINEERING

MAX KURTZ, P.E.
CONSULTING ENGINEER

METRICATED BY

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