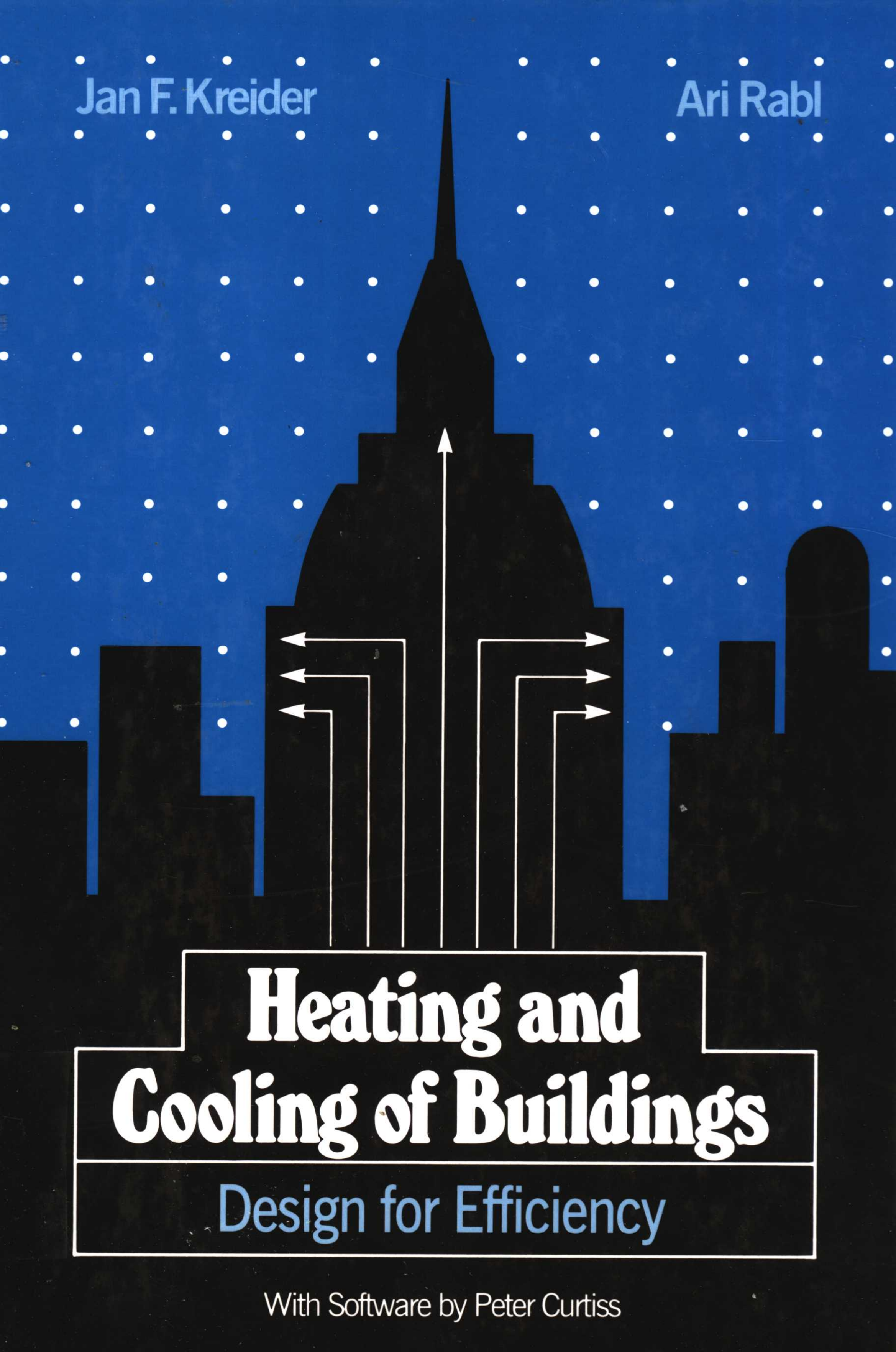
Jan F. Kreider

Ari Rabl



Heating and Cooling of Buildings

Design for Efficiency

With Software by Peter Curtiss

HEATING AND COOLING OF BUILDINGS

Design for Efficiency

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ABOUT THE AUTHORS

Jan F. Kreider is Professor of Engineering and Director of the Joint Center for Energy Management at the University of Colorado at Boulder. He received his BSME (magna cum laude) from Case Institute of Technology and his postgraduate degrees from the University of Colorado. Dr. Kreider is the author of ten engineering textbooks and more than 150 technical articles and reports; he has directed more than $5 million in building-energy-related research during the past decade. He is a Fellow of the ASME, an active member of ASHRAE along with a number of other technical societies, and a winner of ASHRAE's E. K. Campbell Award for excellence in building systems education. He is also the president of a consulting firm specializing in HVAC system design and analysis.

Ari Rabl is Research Scientist at the Centre d'Energétique of the Ecole des Mines in Paris, as well as Adjunct Professor at the University of Colorado at Boulder. He received a Ph.D. in physics from Berkeley, and has worked at Argonne National Laboratory and at the Solar Energy Research Institute. From 1980 to 1989 he was Research Scientist and Lecturer at the Center for Energy and Environmental Studies of Princeton University. His publications on energy-related topics include more than fifty journal articles, numerous review papers, and ten patents. He has also written the book *Active Solar Collectors and Their Applications*. He is a member of the American Physical Society and of ASHRAE.

PREFACE

OVERVIEW

The last two decades have seen an intensive, worldwide research effort on buildings. Sparked by the oil crises of the 1970s, the emphasis was first on energy efficiency, but improved comfort and indoor air quality are emerging as important benefits of proper design. New technologies, from materials to computers, are exerting a profound influence on the design and operation of buildings, and our understanding of buildings has been greatly enriched, including the interaction between the building envelope, the HVAC equipment, and the behavior of occupants and building operators.

Integrating this experience into a comprehensive and modern course on the design of heating and cooling systems has been the main goal of this book. We also intend the book to be useful as a reference for practicing engineers. Another goal has been to benefit from the opportunities offered by the computer revolution by including software to illustrate the text and to foster an intuitive understanding of the physics of buildings and their mechanical systems.

Using the most recent results of building research from all over the world, we have attempted to cover the fundamentals of HVAC analysis and design while pointing the way toward solutions that achieve the required conditions of comfort and convenience for the lowest life cycle cost. In many, if not most, of the decisions of the HVAC engineer, the life cycle cost is dominated by energy costs. Therefore, we try to make the student aware of energy costs and of ways to reduce them. For instance, we highlight the effects of the part-load performance of primary and secondary systems on annual energy consumption. Many of the examples are supplemented by a discussion of energy savings that could be achieved by alternative designs. An entire chapter (Chap. 14) is devoted to strategies for energy-efficient design, with rules of thumb, simulation results, and measured data; this chapter addresses both the envelope and the equipment of a building. The topic of lighting deserves a place because of its importance in the energy budget and its effect on heating and cooling loads. We also include a supplementary monograph (in the Solutions Manual) on economic analysis of building design and HVAC equipment, including a section on optimization.

The student is encouraged to view things in context and to ask whether claims or results make sense. For instance, when there are two different methods for solving a problem, the results are compared or rules of thumb are noted where available for checking calculations. Where appropriate, simple consistency checks are pointed out (e.g., sum of daily energy input and sum of daily loads for the CLTD/CLF method must be equal).

Many of the calculations, in particular the analysis of loads, require so much numerical input that lengthy tables tend to obscure the presentation of the method. Also the calculations are slow and tedious if done by hand. But now almost all readers enjoy easy access to a personal computer. Therefore, we have reduced the amount of tabular data in the printed text, presenting only illustrative excerpts or graphs and referring to the accompanying diskette for complete details and tables of design data. However, there are sufficient tabular data in the appendixes for complete problem solution and for teaching without computers for those instructors who decide not to use computers in the course.

While there are many good computer simulation programs for buildings, the programs are not designed as tools for instruction; also they require much disk space and extensive documentation. Therefore, we have developed short programs for each of the topics that require tedious calculations or copious input data:

- Psychrometric chart and psychrometric process calculations
- Refrigerant properties—saturated and superheated
- CLTD/CLF method for cooling loads
- Transfer function method for heating and cooling loads
- Bin method for annual consumption of various HVAC systems
- Thermodynamic cycle calculations
- Design of lighting systems
- Engineering economics

The book presents the methods of the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), with an explanation of the underlying physical principles. Tabular data for design calculations are based on ASHRAE handbooks, supplemented in some cases by additional material. Numerous examples are presented and solved in a uniform format, which students are encouraged to use for the end-of-chapter problems and for calculations encountered in their professional careers. Comments at the end of each example generalize the results or provide additional insight.

The book is written in dual units: USCS (U.S. Customary System) and SI (Système International d'Unités). Most dimensional equations are stated in both units. Examples are solved in one set or the other, but in most cases the statement and the result show the other units in parentheses. Many graphs have been specially prepared for this book with dual units. Tables and graphs in a single set of units show the conversion factors in the caption. The accompanying software works in either set of units, as specified by the user. There is a table of conversion factors inside the front cover for easy access. The nomenclature follows that recommended by the American Society of Mechanical Engineers (ASME).

SUGGESTED CURRICULA

Students entering the course will have varying backgrounds at different universities. Different instructors will have different goals and will use different parts of this book in their courses. The level of presentation assumes that the reader has a background in basic thermodynamics, heat transfer, and fluid mechanics along with calculus and differential equations. However, Chaps. 2–5 reinforce the fundamentals that are needed for the loads, equipment, and design sections which are the heart of this book (Chaps. 6–14). By judicious choice of the material from the introductory chapters, the instructor can ensure adequate coverage of the fundamentals without repeating topics from previous courses. The table accompanying this preface lists three suggested topic arrangements for three different uses of this book: the first HVAC systems course at a four-year engineering college, a second (probably graduate) course in building heating and cooling systems, and a sequence in HVAC engineering technology at a two-year college.

Suggested usage of "Heating and Cooling of Buildings" in various engineering courses

Course:	**First HVAC Course**	**Advanced HVAC Course**	**HVAC Technology Sequence**
School:	Four-year Engineering College	Engineering Graduate School	Technical College
Notes:	1. Building limited to residential (with optional cooling system) 2. Analysis emphasis 3. Assumes basic fluids, heat transfer, and thermo courses	1. Commercial building focus 2. Design emphasis 3. Assumes first HVAC course taken	1. Envisioned as a two- to three-course sequence 2. Minimal prior courses in the thermal and fluid sciences
Chapter			
1	All sections	Quick review	All sections
2	One-day review	Secs. 2.2.3 & 2.4.6	All except Secs. 2.2.3 & 2.4.6
3	One-day review	—	All sections
4	All psychrometric sections	Secs. 4.5 & 4.6	All sections
5	Two-day review	One-day review	Secs. 5.1–5.4
6	All sections	One-day review	All sections
7	Secs. 7.1–7.2 & 7.5	Secs. 7.3, 7.4, 7.6–7.8	Secs. 7.1–7.2 & 7.5
8	Sec. 8.1	Secs. 8.2–8.6	Sec. 8.1
9	Secs. 9.1, 9.2.1, 9.3, & 9.4	Secs. 9.4–9.8	Secs. 9.1, 9.2.1, 9.3, & 9.4
10	(Secs. 10.1–10.2, 10.7 optional)	All sections	Secs. 10.1–10.4
11	—	All sections	Secs. 11.1–11.3
12	—	Secs. 12.1–12.4, optional 12.5	Secs. 12.1–12.4 survey
13	—	All sections	Secs. 13.1 & 13.2
14	Secs. 14.1 & 14.2	All sections	Secs. 14.1, 14.2, 14.5
Economics supplement	—	All sections	(Optional Sec. 1)

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A book of this magnitude and scope represents the work of many in addition to the authors. First we thank our students who have given us the luxury of testing the book in class. Their comments and ideas were essential in finalizing the organization and coverage of the book.

A number of reviewers took considerable time to examine the book closely, finding errors that the authors missed and suggesting improvements in the presentation. The review process began with helpful comments on the original outline by Louis Burmeister, University of Kansas; Thomas Hellman, New Mexico State University; Doug Hittle, Colorado State University; Ronald Howell, University of South Florida; Dennis O'Neal, Texas A&M University; Maurice Wildin, University of New Mexico; and Byron Winn, Colorado State University, and continued with reviews of the draft by John Lloyd, Michigan State University; and Trilochan Singh, Wayne State University. The exceptionally detailed and constructive comments by Prof. Wildin on the entire manuscript are especially appreciated. Likewise, Wendy Hawthorne made a careful reading of the text and checked most of the examples, and Bill Shurcliff contributed a thorough review of several chapters. Various colleagues offered comments on parts of the book: Mike Brandemuehl (who also contributed novel end-of-chapter problems in the first half of the book), Manuel Collares-Pereira, Jeff Haberl, J. Y. Kao, John Littler, John Mitchell, Leslie K. Nordford, Mike Riley, Gideon Shavit, and Mike Scofield. Of course, any remaining errors are the sole responsibility of the authors.

Peter Curtiss wrote the software that accompanies this book. The thousands of lines of code that he wrote in producing the final product set a new standard for instructional software used in building systems education. Wendy Hawthorne prepared the solutions manual for the end-of-chapter problems.

Our book called on the work of many others. We are grateful to several people who generously provided material or data: R. Boehm, S. Burek, J. Harris, M. A. Piette, and R. Sullivan. We have tried to give credit to original sources wherever possible and have included complete reference lists in each chapter. Permissions were given liberally, and we thank the numerous original sources for their generosity.

Jan F. Kreider would like to express his personal thanks to Dottie for her patience during the apparently endless process of writing this book. Her good nature and support are very much appreciated. Kennon Stewart generously provided practical advice from his decades of HVAC design experience. The University of Colorado's College of Engineering provided the facilities used for preparing the book and for some of the experimental results contained within. Denis Clodic, director of the Centre d'Energetique of the Ecole des Mines de Paris, and Flavio Conti at the Joint Research Center of the European Community provided a gracious environment during his sabbatical for the final tasks needed to finish the book.

Ari Rabl would like to express his personal gratitude to several institutions and individuals. The Ecole des Mines offered a propitious setting for the writing, thanks to the encouragement of Jerome Adnot. The Joint Center for Energy Management of the University of Colorado provided support for summer visits. Robert H. Socolow invited him to join the Center for Energy and Environmental Studies of Princeton University

and to focus on energy use of buildings. The work with colleagues at Princeton was a uniquely stimulating and productive experience to which this book is a tribute. And, of course, his most heartfelt thanks go to Brigitte for her moral support.

Jan F. Kreider
Ari Rabl

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Appendixes for Chapters

CHAPTER
1

INTRODUCTION

1.1 A BIT OF HISTORY

The quest for a safe and comfortable environment is older than the human species. Birds build nests, rabbits dig holes. Early human societies succeeded, in some cases, in creating remarkably pleasant accommodations. The cliff dwellings of the Pueblo Indians at Mesa Verde, Colorado, are an eminent example: Carved under an overhang to block the summer heat, yet accessible to the warming rays of the winter sun, with the massive heat capacity of the surrounding rocks, they are an early realization of the principles of passive solar architecture.

The ancient Greeks were quite conscious of the benefits to be obtained by good orientation of a building with respect to the sun, and they laid out entire settlements facing south (Butti and Perlin 1980). Already in classical antiquity, fuel wood was scarce around the Mediterranean (our generation is not the first to be confronted with an energy shortage). The height of comfort in the classical world was achieved in some villas of the Roman Empire: The people who built them pioneered central heating, with a double floor through whose cavity the fumes of a fire were passed. Also in Roman times, the first translucent or transparent window coverings were introduced, made of materials such as mica or glass. Thus it became possible to admit light into a building without letting in wind, rain, or snow.

But it took a long time before buildings reached what we would consider comfortable conditions. When visiting castles built in Europe as late as the sixteenth century and looking at their heating arrangements, one shivers to think how cold winter must have been even for the wealthiest. In an antique store, one of the authors happened upon an old thermometer with a scale where 60.8°F (16°C) was marked as "room temperature." The comfort of heating to 68°F (20°C) or more is fairly recent.

Cooling is more difficult than heating. In the past the principal method was to ward off the sun, coupled with the use of heavy stonework for thermal inertia—actually quite effective in climates with cool nights. During the Middle Ages, architects of castles like the Alhambra supplemented that approach with skillful use of running water, providing some evaporative cooling. In certain parts of the world, some buildings take advantage of cool breezes that blow regularly from the same direction.

Nights used to be dim because candles and oil lamps were expensive, to say nothing of the quality of the light. In fact before the invention of electric lights, access to daylight was a primary criterion for the design of buildings. Daylight does not penetrate well into the interior; as a rule of thumb, adequate illumination on cloudy days cannot be provided to depths beyond 1.5 to 2 times the height of the upper window edge. This, together with the need for fresh air before the days of mechanical ventilation, explains the shape of buildings well into the first half of the twentieth century: No room could be far from the perimeter. Total disregard for this constraint did not become practical until the availability of fluorescent lighting (with incandescent lamps the cost of air conditioning would have been excessive).

Effective air conditioning had to await the development of mechanical refrigeration during the first decades of the twentieth century. Routine installation of central air conditioning systems dates from the 1960s. The oil crises of the 1970s stimulated intensive research on ways of reducing energy costs. The efficiency of existing technologies is being improved, and "new" technologies such as solar energy and daylighting are being tried. Some approaches are turning out to be more successful than others. This evolution is continuing at full speed, aided by advances in materials and computers. Elucidating these developments is one of the goals of this book.

1.2 IMPORTANCE OF BUILDINGS IN THE U.S. ECONOMY

People in modern times spend most of their time in buildings, and expend much of their wealth on these buildings. Even without trying for an accurate appraisal of the total real estate in the United States, we can get an idea by looking at the floor area, approximately 150×10^9 ft^2 ($\approx 15 \times 10^9$ m^2) in the residential and 50×10^9 ft^2 ($\approx 5 \times 10^9$ m^2) in the commercial sector (USDOC, 1987). Construction costs vary a great deal, of course, with the type and quality of building, but very roughly they are in the range of \$50 to \$100 per square foot (\$500 to \$1000 per square meter). Based on the replacement cost, the total value of the buildings in the U.S. is on the order of \$10 to \$20 $\times 10^{12}$; the GNP, by comparison, was only \$4 $\times 10^{12}$ per year during the mid 1980s.

Obviously one cannot afford to replace the building stock very often. This ensures a certain continuity with the future: However little we may be able to foresee the future of our society, we can expect most of the buildings to last for decades, if not centuries. Rather than replace an building entirely, one may revamp its interior [currently each year some 2% of commercial buildings undergo a major retrofit

(Brambley et al., 1988)]. This implies an awesome responsibility for city planners, architects and engineers: *Do it well or the mistakes will haunt us for a long time.*

The demand for new construction was vigorous during the 1980s. Annual construction rates were around 1.5×10^9 ft^2 ($\approx 0.15 \times 10^9$ m^2) of residential and 1.2×10^9 ft^2 ($\approx 0.12 \times 10^9$) m^2 of commercial floor area; the residential stock was growing at about 1%, the commercial stock at about 2.5% per year. Single family houses have accounted for about two-thirds of recent residential construction. Forecasting of trends is difficult, especially in a sector that is as cyclical as the construction industry and as sensitive to the state of the economy. The residential market may have seen its peak of growth with the passing of the postwar baby boom, although there may be a continuing push for new and better housing as general living standards improve (a likely trend over the long term). The growing shift from industry to services implies an increasing need for commercial floor space.

It is interesting to consider the importance of cost components involved in a building, from design to operation. Brambley et al. (1988) state that one-time costs (design and construction) represent only about one-fifth of the total life cycle cost, with the remaining four-fifths being ongoing costs (operation and maintenance). Such a comparison is not without ambiguity, involving a choice of weights for present and future expenses (via the discount rate, as discussed in the chapter on economic analysis, included in the Solutions Manual), to say nothing about differences between different types of buildings. We cite this figure merely to point out the dominant role of the cost of operation and maintenance. Of the latter, energy represents the lion's share, as can be seen from Fig. 1.1, where the ongoing costs, in dollars per unit floor

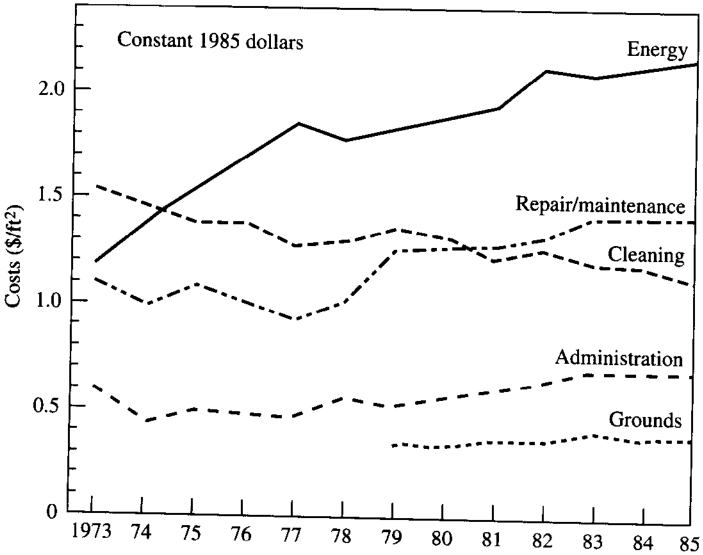

FIGURE 1.1

Average operating costs by component, per unit floor area, for office buildings, corrected for inflation. (*Adapted from Brambley et al., 1988.*) \$1/ft^2 = \$10.76/m^2.

area, are disaggregated according to the categories of administration, cleaning, repair and maintenance, security and grounds, and utilities (i.e., energy, since the cost of water does not amount to much). Since 1973 the importance of energy expenditures has increased in both relative and absolute terms. In the residential sector, energy expenditures tend to be smaller, somewhat less than the construction cost, but clearly they are an important item here, too. There is an important lesson: *Pay attention to energy costs at the design stage.*

To place the energy consumption of buildings in perspective, we show in Fig. 1.2 the evolution since 1960 of the primary energy consumption of the United States, broken down into the principal sectors: transportation, industry, commercial, and residential. Buildings, i.e., the commercial and the residential sectors together, account for 36% of the total.

Several factors have contributed to the growth of energy use in buildings: The population has increased (from 180 million in 1960 to 240 million in 1986), comfort levels have improved, and there are more energy-using devices in the buildings. Figure 1.3 provides a more detailed view of this evolution. Part *a* shows the number of households and the consumption of primary energy per household; part *b* gives the analogous information for commercial buildings, in terms of floor area. Both follow the same pattern. While the number of households and the commercial floor area have grown steadily, the energy consumption per unit peaked in the early 1970s. Part of that may be due to population shifts to warmer climates, but most of it reflects gains in efficiency in response to the oil shocks.

A breakdown of energy consumption by end use is shown in Fig. 1.4. Space heating dominates, in both the residential and the commercial sector. Next in line are water heating in the residential sector, and lighting in the commercial sector.

To highlight once more the importance of buildings and their energy consumption in the U.S. economy, we show in Fig. 1.5 the cost of constructing new buildings

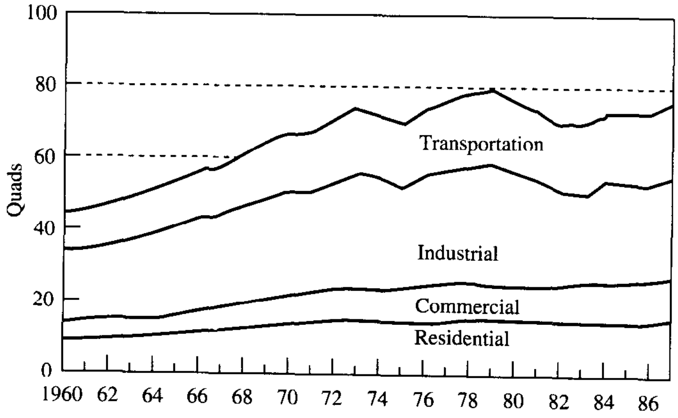

FIGURE 1.2
U.S. consumption of primary energy, by sector. (*From USDOE, 1989.*) 1 quad = 1.055×10^{18} J.