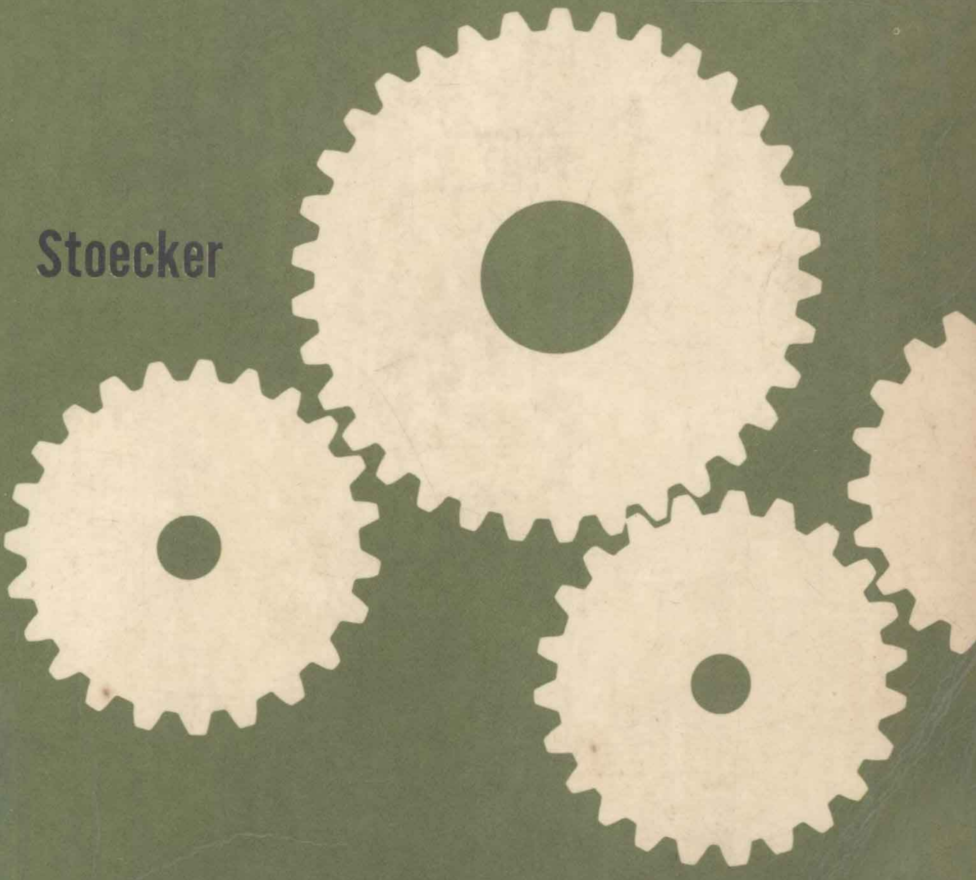
Design of Thermal Systems



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Design of Thermal Systems

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Preface

The title, "Design of Thermal Systems," reflects the three concepts embodied in this book: *design, thermal,* and *systems.*

Design A frequent product of the engineer's efforts is a drawing, a set of calculations, or a report that is an abstraction and description of hardware. Within engineering education, the cookbook approach to design, often practiced during the 1940s, discredited the design effort so that many engineering schools dropped design courses from their curricula in the 1950s. But now design has returned. This reemergence is not a relapse to the earlier procedures; design is reappearing as a creative and highly technical activity.

Thermal Within many mechanical engineering curricula the term *design* is limited to *machine design*. In order to compensate for this frequent lack of recognition of thermal design, some special emphasis on this subject for the next few years is warranted. The designation *thermal* implies calculations and activities based on principles of thermodynamics, heat transfer, and fluid mechanics.

The hardware associated with thermal systems includes fans, pumps, compressors, engines, expanders, turbines, heat and mass exchangers, and reactors, all interconnected with some form of conduits. Generally, the working substances are fluids. These types of systems appear in such industries as power generation, electric and gas utilities, refrigeration, air conditioning and heating, and in the food, chemical, and process industries.

Systems Engineering education is predominantly *process oriented,* while engineering practice is predominantly *system oriented.* Most courses of study in engineering provide the student with an effective exposure to such processes as the flow of a compressible fluid through a nozzle and the behavior of hydrodynamic and thermal boundary layers at solid surfaces. The practicing engineer, however, is likely to be confronted with a task such as designing an economic system that receives natural gas from a pipeline and stores it underground for later usage. There is a big gap between knowledge of individual processes and the integration of these processes in an engineering enterprise.

Closing the gap should not be accomplished by diminishing the emphasis on processes. A faulty knowledge of fundamentals may result in subsequent failure of the system. But within a university environment, it is beneficial for future engineers to begin thinking in terms of systems. Another reason for more emphasis on systems in the university environment, in addition to influencing the thought patterns of students, is that there are some techniques—such as simulation and optimization—which only recently have been applied to thermal systems. These are useful tools and the graduate should have some facility with them.

While the availability of procedures of simulation and optimization is not a new situation, the practical application of these procedures has only recently become widespread because of the availability of the digital computer. Heretofore, the limitation of time did not permit hand calculations, for example, of an optimization of a function that was dependent upon dozens or hundreds of independent variables. This meant that, in designing systems consisting of dozens or hundreds of components, the goal of achieving a *workable* system was a significant accomplishment and the objective of designing an *optimum* system was usually abandoned. The possibility of optimization represents one of the new facets of design.

Outline of this book The goal of this book is the design of optimum thermal systems. Chapters 6 through 11 cover topics and specific procedures in optimization. After Chap. 6 explains the typical statement of the optimization problem and illustrates how this statement derives from the physical situation, the chapters that follow explore optimization procedures such as calculus methods, search methods, geometric programming, dynamic programming, and linear programming. All these methods have applicability to many other types of problems besides thermal ones and, in this sense, are general. On the other hand, the applications are chosen from the thermal field to emphasize the opportunity for optimization in this class of problems.

If the engineer immediately sets out to try to optimize a moderately complex thermal system, he is soon struck by the need for predicting the performance of that system, given certain input conditions and performance characteristics of components. This is the process of *system simulation.* System simulation not only may be a step in the optimization process but may have a usefulness in its own right. A system may be designed on the basis of some maximum load condition but may operate 95 percent of the time at less-than-maximum load. System simulation permits an examination of the operating conditions that may pinpoint possible operating and control problems at nondesign conditions.

Since system simulation and optimization on any but the simplest problems are complex operations, the execution of the problem must be performed on a computer. When using a computer, the equation form of representation of the performance of components and expression of properties of substances is much more convenient than tabular or graphical representations. Chapter 4 on mathematical modeling presents some techniques for equation development for the case where there is and also where there is not some insight into the relationships based in thermal laws.

Chapter 3, on economics, is appropriate because engineering design and economics are inseparable, and because a frequent criterion for optimization is the economic one. Chapter 2, on workable systems, attempts to convey one simple but important distinction—the difference between the design process that results in a workable system in contrast to an optimum system. The first chapter on engineering design emphasizes the importance of design in an engineering undertaking.

The appendix includes some problem statements of several comprehensive projects which may run as part-time assignments during an entire term. These term projects are industrially oriented but require application of some of the topics explained in the text.

The audience for which this book was written includes senior or first-year graduate students in mechanical or chemical engineering, or practicing engineers in the thermal field. The background assumed is a knowledge of thermodynamics, heat transfer, fluid mechanics, and an awareness of the performance characteristics of such thermal equipment as heat exchangers, pumps, and compressors. The now generally accepted facility of engineers to do basic digital computer programming is also a requirement.

Acknowledgments Thermal system design is gradually emerging as an identifiable discipline. Special recognition should be given to the program coordinated by the University of Michigan on Computers in Engineering Design Education, which in 1966 clearly delineated topics and defined directions that have since proved to be productive. Acknowledgment should be given to activities within the chemical engineering field for developments that are closely related, and in some cases identical, to those in the thermal stem of mechanical engineering.

Many faculty members during the past five years have arrived, often independently, at the same conclusion as the author: the time is opportune for developments in thermal design. Many of these faculty members have shared some of their experiences in the thermal design section of *Mechanical Engineering News* and have, thus, directly and indirectly contributed to ideas expressed in this book.

This manuscript is the third edition of text material used in the Design of Thermal Systems course at the University of Illinois at Urbana-Champaign. I thank the students who have worked with me in this course for their suggestions for improvement of the manuscript. The second edition was an attractively printed booklet prepared by my Department Publication Office, George Morris, Director; June Kempka and Dianne Merridith, typists; and Don Anderson, Bruce Breckenfeld, and Paul Stoecker, draftsmen. Special thanks are due to the Engineering Department of Amoco Chemicals Corporation, Chicago, for their interest in engineering education and for their concrete evidence of this interest shown by printing the second edition.

Competent colleagues are invaluable as sounding boards for ideas and as contributors of ideas of their own. Professor L. E. Doyle offered suggestions on the economics chapter and Prof. C. O. Pedersen, a coworker in the development of the thermal systems program at the University of Illinois at Urbana-Champaign, provided advice at many stages. Mr. Donald R. Witt and a class of architectural engineering students at Pennsylvania State University class-tested the manuscript and provided valuable suggestions from

the point of view of a user of the book. Beneficial comments and criticisms also came from the Newark College of Engineering, where Prof. Eugene Stamper and a group of students tested the manuscript in one their classes. Professor Jack P. Holman of Southern Methodist University, consulting editor of McGraw-Hill Book Company, supplied perceptive comments both in terms of pedagogy as well as in the technical features of thermal systems.

The illustrations in this book were prepared by George Morris of Champaign, Illinois.

By being the people that they are, my wife Pat and children Paul, Janet, and Anita have made the work on this book, as well as anything else that I do, seem worthwhile.

W. F. Stoecker

Contents

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Engineering Design

1-1 Introduction Some typical professional activities of engineers are sales, construction, research, development, and design. The last-named activity—design—will be our special concern in this book. The immediate product of the design process is a report, a set of calculations, or a drawing that is an abstraction of hardware. The subject of the design may be a process, an element or component of a larger assembly, or an entire system.

Our emphasis will be on *system* design, wherein a system is defined as a collection of components with interrelated performance. Even this definition often needs interpretation, because a large system sometimes includes subsystems. Furthermore, we shall progressively focus on *thermal* systems where fluids and energy in the form of heat and work are conveyed and converted. Before adjusting this focus, however, this chapter will examine the larger picture into which the technical engineering activity blends. We shall call this larger operation an engineering *undertaking* which implies that engineering plays a decisive role but also dovetails with other considerations. Engineering undertakings include a wide variety of commercial and industrial enterprises as well as municipal-, state-, and federally sponsored projects.

1-2 Decisions in an engineering undertaking In the past 10 years an appreciable amount of attention has been devoted to the "methodology" or the "morphology" of engineering undertakings. Studies on these topics have analyzed the steps and procedures used in reaching decisions. One contribution of these studies has been to stimulate the engineer to reflect on his own thinking processes and on that of others on the project team. Certainly the process and sequence of steps followed in each undertaking is different, and no one sequence, including the one described in this chapter, is universally applicable. The starting point, the goal, and the side conditions differ from one undertaking to the next, so the procedures will vary.

The advantage of analyzing the decision process, especially in complex undertakings, is that it leads to a more logical coordination of the many individual efforts that comprise the entire venture. The flow diagram in Fig. 1-1 shows the typical steps followed in the conception, evaluation, and execution of the plan. The rectangular boxes, which indicate actions, may represent considerable effort and expenditures on large projects. The diamond boxes represent decisions, such as whether to continue the project or to drop it.

The technical engineering occurs mostly in activities 5 and 7—product or system design—and in research and development. Very little will be mentioned in this chapter about product or system design, because it is the subject of the entire study of thermal systems that will be studied in the chapters to follow. The flow diagram only shows how this design procedure fits into the larger pattern of the undertaking. The individual nondesign activities will be discussed next.

1-3 Need or opportunity (step 1) Step 1 in the flow diagram of Fig. 1-1 is to define the need or opportunity. It may seem to be a simple task to state the need or opportunity, but such is not always the case. For example, the officials of a city may think that their need is to enlarge a reservoir for storage of a larger quantity of water for municipal purposes. The officials may not truly have specified the need, but instead have leaped to one possible solution. Perhaps the need would best have been stated as a low-water reserve during certain times of the year. Enlargement of the

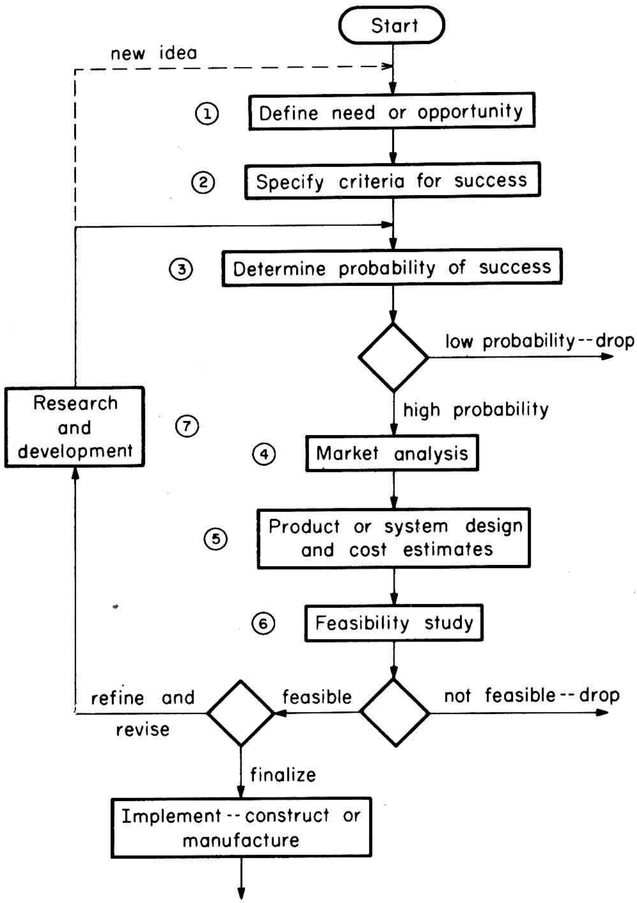

Fig. 1-1 Possible flow diagram in evaluating and planning an engineering undertaking.

reservoir might be one possible solution to consider, but other solutions might be to restrict the consumption of water or to seek other sources such as wells. Sometimes, possible solutions are precluded by not starting at the proper statement of the need.

The word "opportunity" has positive connotations, whereas "need" suggests a defensive action. Sometimes the two cannot be distinguished. For example, an industrial firm may recognize a new product as an opportunity, but if the company does not then expand its line of products, business is likely to decline. The introduction of a new product is, thus, also a need.

In commercial enterprises, typical needs or opportunities lie in the renovation or expansion of facilities to manufacture or distribute a current product. Another form in which an opportunity arises is when the sale of a product not manufactured by the firm is rising and the market potential seems favorable. Still a third form in which an opportunity arises is through research and development within the organization. A new product may be developed intentionally or accidentally. Sometimes a new use can be found by slight modification of an existing product. An organization may know how to manufacture a gummy, sticky substance and assign to the research and development department the task of finding some use for this substance.

Of interest to us at the moment is the need or opportunity that requires engineering design at a subsequent stage.

1-4 Criteria of success (step 2) In commercial enterprises, the usual criterion of success is showing a profit or, more specifically, providing a certain rate of return on the investment. Also, in public projects, the criterion of success is the degree to which the need is satisfied in relation to the cost—monetary or otherwise.

In a profit-and-loss economy, the expected earning power of a proposed commercial project is a dominating influence on the decision to proceed with the project. Strict monetary concerns are always tempered, however, by human, social, and political considerations to a greater or lesser degree. Another way of stating this influence is to say that a price tag is placed on the nonmonetary factors. A factory may be located at a more remote site at a penalty on transportation costs in order that its atmospheric pollution or noise affect fewer people. As an alternate, the plant may spend a large sum of money for superior pollution control in order to be a good neighbor to the surrounding community.

Sometimes a firm will design and manufacture a product that offers little opportunity for profit simply to round out a line of products. The availability of this product, product *A*, permits the sales force to say to a prospective customer, "Yes, we can sell you product *A*, but we recommend product *B*," which is a more profitable item in the company's line and may actually be superior to product *A*.

Often a decision, particularly of an emergency nature, appears out of the realm of economics. If a boiler providing steam for heating a rental office building fails, the decision whether to repair or replace the boiler may seem to be out of the realm of economics. The question could still be considered an economic one, however, with the penalty for not executing the project being an overpowering loss.

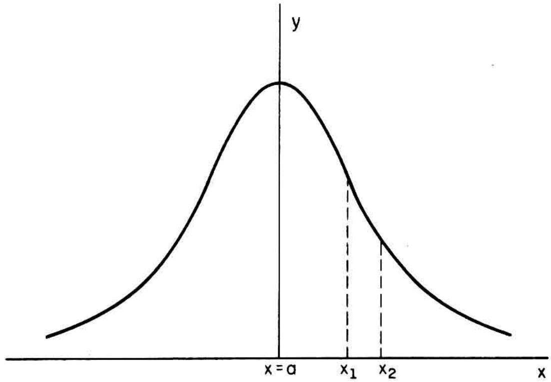

Fig. 1-2 Probability distribution curve.

1-5 Probability of success (step 3) The economic success of engineering projects is not one of the two traditional certainties of life. Along with the opportunity of achieving a profit goes the threat of loss. If the possible construction of a plant to manufacture a product is being considered, there is no absolute assurance that the plant will meet the success criteria discussed in Sec. 1-4. It is preferable, then, to speak of the likelihood or the probability of success, as listed in step 3 of the flow diagram of Fig. 1-1.

The mention of the term *probability* suggests a probability distribution curve, and this curve, as shown in Fig. 1-2, is not without applicability to the decision-making process. The significance of the distribution curve lies particularly in the evaluation of the area beneath the curve. The ordinate y indicates the probability of the event occurring between x and $x + dx$. The area under the curve between x_1 and x_2, for example, represents the probability P of the event occurring between values of x_1 and x_2. Thus,

$$P = \int_{x_1}^{x_2} y\,dx$$

The probability of the event occurring somewhere in the range of x is unity, so the integration over the entire range of x is equal to 1.0:

$$\int_{-\infty}^{\infty} y\,dx = 1$$

The equation for the probability distribution curve is

$$y = \frac{h}{\sqrt{\pi}} e^{-h^2(x-a)^2} \tag{1-1}$$

The maximum value of the ordinate is $h/\sqrt{\pi}$. This fact suggests that increasing the value of h alters the shape of the distribution curve, as shown in Fig. 1-3. If h_1 is greater than h_2, the peak of the h_1 curve rises higher than that of the h_2 curve.

To extend the probability idea to decision making in an engineering undertaking, suppose that a new product or facility is proposed, and the criteria for success is a 10 percent rate of return on the investment for a 5-year life of the plant. After a preliminary design, the probability distribution curve is shown as indicated in Fig. 1-4. Rough figures were used throughout the evaluation, so the distribution curve is flat, indicating no great confidence in an expected percent of return of investment of, let us say, 18 percent. The expected rate of return is attractive enough, however, to proceed further to a complete design, including cost estimates. If the most probable return on investment after this complete design were 16 percent, for example, the confidence in this figure would be greater than the confidence in the 18 percent figure after the preliminary design, because costs have now been analyzed more carefully and marketing studies have been conducted more thoroughly.

The probability distribution curves at two other stages—after construction and after 1 year of operation—show progressively greater degrees of confidence in the rate of return after a 5-year life. After 5 years, the rate of return is known exactly, and the proba-

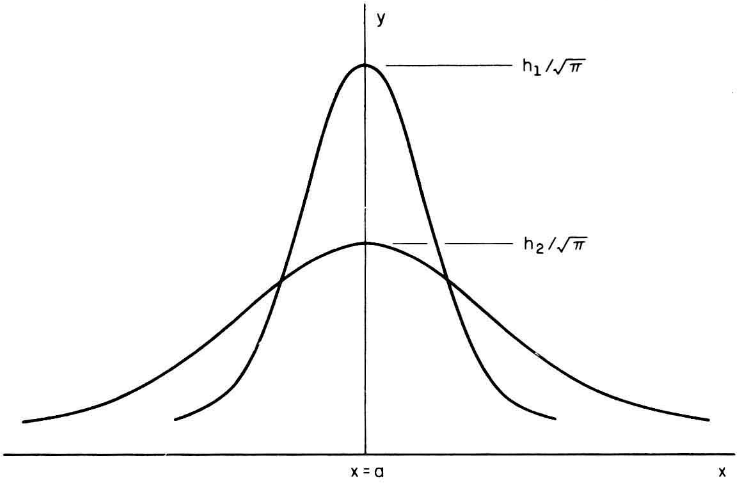

Fig. 1-3 Several different shapes of the probability distribution curve.

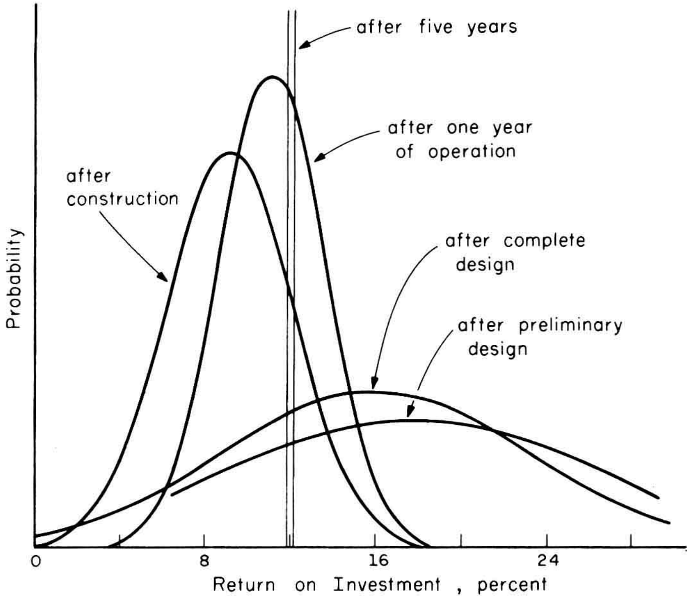

Fig. 1-4 Distribution curves at various stages of decision making.

bility distribution curve degenerates into a curve that is infinitesimally thin and infinitely high.

While decisions made on the basis of probabilities are facts of life, the determination of the probability distribution curves cannot be accomplished with anywhere near the accuracy suggested by Fig. 1-4. To a considerable extent the go-or-no-go decisions are made by management on the basis of "highly likely" or "unlikely" chances of success. The emergence of new developments that would compete with the proposed product, for example, cannot always be anticipated. Marketing surveys are imprecise. Nevertheless, efforts toward quantifying the probability calculation are highly desirable.

1-6 Market analysis (step 4) If the undertaking is one in which a product or service must eventually be sold or leased to customers, there must be some indication of favorable reaction by the potential consumer. An ideal form of the information provided by a market analysis would be a set of curves as shown in Fig. 1-5. With an increase in price, the potential volume of sale decreases until such a high price is reached that no sales can be made. The sales volume-