ECOTHK

AN INTERACTIVE COMPUTER PROGRAM FOR THE DETERMINATION OF THE ECONOMIC THICKNESS OF INSULATION

By

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PREFACE

As energy costs continue to climb, the importance of insulation as a means by which to reduce energy waste becomes increasingly more evident. But, how much insulation is enough? Obviously, the answer to this question is a function of the cost of the insulation, the effectiveness of the insulating material, and the cost savings that result from its ultimate installation. The discussion that follows is presented in response to this very question regarding the degree of insulation.

The purpose of this presentation is three-fold. Foremost among these purposes is a comprehensive development of the concept of economic thickness as it relates to the determination of an optimal amount of insulation for a given circumstance. Second to this is the presentation of a computer algorithm written in Fortran by which the economic thickness of insulation may be determined for flat surfaces or for piping systems. Finally, the application of this computer algorithm is illustrated through a series of practical example problems.

The author would like to take this opportunity to express his sincere appreciation to Dr. Wayne C. Turner for assistance and guidance during this undertaking. Furthermore, a sincere thanks must be expressed to the entire faculty of the

Department of Industrial Engineering and Management at Oklahoma State University for their continued confidence and support in my academic and professional endeavors.

Finally, a heart-felt thanks must go to my wife, Nancy, without whose continued support, encouragement, and patience this project would not have been completed.

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CHAPTER I

INTRODUCTION

The Energy Issue

The energy situation is a multi-dimensional problem that does not lend itself readily to an easily implemented solution. Many factors exist that contribute to the over-all problem and tend to make its ultimate resolution seem all the more unlikely.

Chief among these factors is what has heretofore been a growing reliance by the United States and other energy-consuming countries on the crude oil supply of a relatively small portion of the world. The fast-paced growth of the nineteen sixties and early seventies has pushed our standard of living to the point where we now consume one-third of the world's energy demand. This is phenomenal for a country that represents only one-sixth of the world's total population [21].

Another of the factors contributing to the energy problem in the United States has been a declining interest in domestic oil production. Federal price regulations in combination with spiralling domestic production costs have made exploration and production within the United States almost prohibitive. This trend, however, is reversing as foreign oil prices continue to escalate and tax incentives tend to make domestic oil production more attractive.

The problem is compounded by the fact that we are continuing to place an increased demand on one of our nation's least available resources. The United States depends upon petroleum products to furnish it with approximately three-fourths of its total energy needs. However, petroleum reserves account for only seven percent of the proven economically recoverable resources in the United States [19].

To further illustrate the paradox of the energy problem consider the case for coal. Coal represents roughly 90% of our proven domestic reserves, but yet it accounts for only 18% of the nation's energy consumption [19]. The conversion to coal is occurring at an agonizingly slow pace. Only recently have the economics of the situation and tax incentives made the conversion to coal utilization attractive to the industrial complex. These economic considerations, however, do not lessen the significance of the environmental restrictions which must be observed by coal-fired facilities.

The ultimate solution to our present energy situation, like the problem itself, will not be singular in nature. Rather, the solution, if one exists, must encompass the effective and efficient utilization of all of our energy resources (foreign, domestic, renewable, and non-renewable). This perspective in combination with sound energy management practices and energy planning will aid significantly in our continuing efforts to overcome the energy problem.

The Scope of This Study

The purpose of this paper is not to lament the causes of the energy problem or to admonish our society for its continued utilization of vast amounts of non-renewable energy resources. To the contrary, the American consumer and American industry are to be applauded for the tenacity with which they have battled the current energy problem. Lowered thermostats in the winter, raised thermostats in the summer, car-pooling, more efficient lighting, insulation, mass transit, and waste heat recovery devices are but a few of the tactics which have proven successful in the fight to curb energy consumption.

Equally so, it is not the intention of this study to promote the utilization of one particular energy resource over another, or for that matter, to advocate the establishment or adherence to a particular national energy policy. The point to be made here is that regardless of the form of energy which we have available to us, it is our responsibility, or better yet, our obligation to seek the most efficient manner by which to utilize that energy.

Commitment to this premise both in industry and in the home will yield tangible results. The increased longevity of current energy reserves and real cost savings are two of the primary results of such a commitment. Cost savings due to the reduction in energy waste is, of course, a prospect in which everyone is interested, and as energy costs continue to climb so too will the enthusiasm for reducing energy waste.

Just how does one operationalize his commitment to the energy obligation? As previously mentioned, there are available to us a number of ways by which to combat energy waste. These techniques would include increased insulation, establishment of car-pool systems, installation of industrial waste heat recovery devices, lowered thermostats, reduced excess lighting, and a host of other common sense practices. For further information regarding low-cost and capital intensive energy practices, the reader is referred to references [1, 3, 8, 9, 21, and 24].

One of these tactics in particular is the focus of the discussion that is to follow. More specifically, the topic of insulation is addressed as a means by which to reduce heat transfer and, as such, reduce heat loss or heat gain in a system. This discussion will serve to illustrate how the investment made into insulation may be optimized through the minimization of annual costs. This optimum, referred to as the economic thickness, is fully investigated in this paper. Finally, a computer algorithm by which to determine the economic thickness for insulation will be presented. A comprehensive understanding of the nature and economics of insulation is the end to which this study is devoted.

Outline of the Study

An understanding of the nature just indicated will require a rigorous development of the theory of heat flux, the effect of insulation on heat flow, and the economics of insulation. For this reason, it will prove most helpful to outline the subject material to be presented in subsequent chapters of this study.

Chapter II will concentrate primarily on the thermodynamic theory of heat flux and the retarding affect that insulation produces on this heat flow. The criteria by which to select or compare various types of insulation materials are also presented in this chapter.

The economics of insulation will be the focus of Chapter III. Of particular importance in this chapter is the concept of economic thickness. It is this technique which allows us to optimize the investment that may be made for the insulation of a vessel, piping, or a building.

Chapter IV presents a computer algorithm by which the somewhat tedious calculations required of the economic thickness determination procedure may be executed in an efficient manner. The nature of the information which must be supplied in this program is also outlined in this chapter.

The usefulness of the proposed algorithm is demonstrated in Chapter V thorugh the investigation of a variety of example problems. These examples will encompass both flat surface and piping system analyses.

Chapter VI summarizes the results of this study and reiterates the importance of our energy obligation. A discussion on the utilization of the computer algorithm developed in this study by the Department of Industrial

Engineering and Management at Oklahoma State University will also be presented in this chapter.

Some Basic Assumptions

Fundamental to the discussion that follows are some basic assumptions. These would include:

1) Energy costs will continue to rise and, as such, the need to investigate methods by which to reduce energy waste is evident.
2) The fundamental principles of thermodynamics and the equations representative of heat transfer as developed by J. F. Malloy [17] are valid and relatively accurate.
3) Insulation through the application of various materials onto a system is a means by which to retard the normal heat transfer process.
4) The principles of engineering economics as presented by White, Agee, and Case [28], Fabrycky and Thuesen [12], and Bussey [6] are indicative of valid economic analysis.

CHAPTER II

INSULATION

Theory of Heat Flux

Prequisite to an understanding of how to prevent the flow of heat is a fundamental knowledge of the theory of heat flow or heat flux. The discussion that follows is directed toward the development of this understanding of the basic thermodynamic principles of heat transfer.

John F. Malloy [17] defines heat as energy in transition. Heat is the result of a change in the physical properties of matter. The conversion of potential energy to kinetic energy as displayed by the heating of an object as it falls from a higher elevation to some lower point is indicative of a transition process. Likewise, a change in the internal energy of matter results in the production or consumption of heat. A change in the physical state of matter such as the conversion from gas to liquid or liquid to solid states is typical of this type of heat flow.

Temperature is a comparative assessment of the energy level associated with the state in which a specified amount of matter currently exists. Temperature scales are a convenient means by which to make this assessment of energy. Degrees Fahrenheit and degrees Celsius are probably the temperature scales most familiar to us. These scales are based on commonly observed physical phenomena such as the freezing and boiling points of water. Generally less familiar to the majority of people are those temperature scales which are based on less commonly observed events. These absolute scales as they are referred to are based upon the state of a substance at which no net internal energy is present. This state of matter is typified by no intramolecular motion. Degrees Rankine and degrees Kelvin are terms reflective of the absolute scales and are of critical importance in the study of physics, chemistry, and thermodynamics.

Fundamental thermodynamics [27] tells us that the transfer of heat occurs solely because of the existence of a difference in temperature. This process is reflective of the natural physical tendency for all matter to seek its lowest energy state. That is, heat will flow from an area of high energy concentration (characterized by a comparatively high temperature to an area of lower energy concentration (characterized by a comparatively low temperature). This process will continue until the two areas are in equilibrium.

For purposes of demonstration, let us suppose that we have the simple arrangement shown in Figure II.1. Suppose further that Mass-T_H represents an unspecified amount of a material that exists at some arbitrarily high temperature, T_H. Similarly, Mass-T_L may be thought of as an unspecified amount of a material that exists at some arbitrarily low temperature, T_L, relative to the temperature of Mass-T_H. Remember,

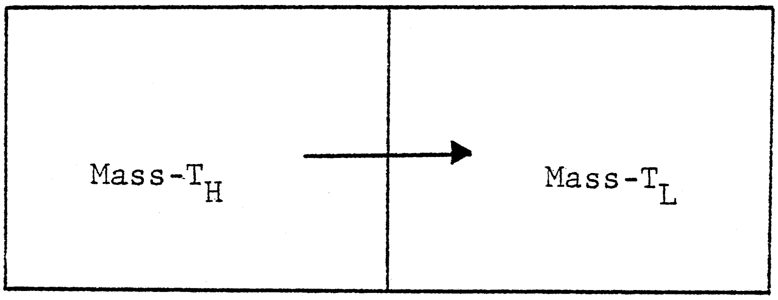


Figure II.1. Illustration of Fundamental Heat Transfer Process

temperature is the convenient comparative assessment of the amount of energy within matter at some specified state. As a result, we can associate Mass-T_H with an amount of material that exists at a higher energy state relative to the state at which Mass-T_L exists.

This difference in temperature will dictate the direction of heat flow that will result in the hypothetical situation depicted. Mass-T_H seeking its lowest possible energy state will expend energy in the form of heat in the direction of Mass-T_L as indicated in Figure II.1. This process will continue until the energy states of the two masses are identical or, more simply, until T_H equals T_L.

This process by which energy is expended is referred to as heat transfer. It is important to note that the direction of natural heat transfer will always be from the higher temperature area to the lower.

While the situation depicted in Figure II.1 is useful for the purpose of introducing the concepts of heat transfer and energy flow, it does represent a rather idealized case. To facilitate a more comprehensive understanding of heat transfer let us now focus on an enhanced model that is more representative of a real-world situation. Figure II.2 depicts a more realistic condition.

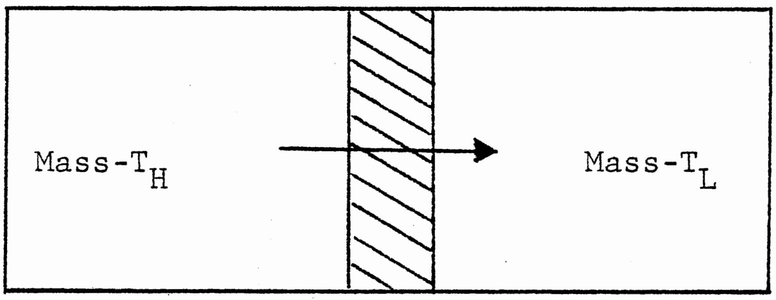


Figure II.2. Illustration of Heat Transfer Across a Homogeneous Boundary

Notice that in this figure we have the same basic arrangement as that of Figure II.1 with only one exception. In this model, a physical boundary of homogeneous construction has been added to separate the areas of temperature extremes.

This depiction is truly more representative of the real world problems regarding energy transfer. For example, the boundary may be thought of as a wall separating indoors from outdoors or any other two areas of extremes in temperature.

From the previous discussion we know that heat will flow from T_H to T_L. However, what will be the effect of the boundary on the heat transfer process? No doubt the boundary will impart a retarding effect on the flow of energy from

T_H to T_L.

The flow of energy through any medium will be directly proportional to the temperature difference under consideration and inversely proportional to the resistance acting to prevent that flow of energy. Stated in algebraic terms this would imply that for Figure II.2 the heat flow that is realized may be assessed by the following relationship.

$$\text{Heat Flow} = \frac{\text{Temperature difference}}{\text{Resistance to heat flow}} \qquad \text{(II.1)}$$

Equation II.1 gives the terms for heat flow expressed as a ratio of the temperature difference to thermal resistance. To further understand the nature of heat flow one should investigate the numerator and the denominator of this ratio individually.

The temperature difference, or simply ΔT, is a relative comparison of the energy levels of the two masses that lie on either side of the boundary or barrier. As such, ΔT may be found be simple subtraction as the difference between T_H and T_L where these two terms are typically expressed in degrees Fahrenheit.

The thermal resistance, R_t, of the boundary is a function of the type of material comprising that barrier and the amount of material, particularly thickness, which is present. Thermal resistance for a particular material is characteristic of that material and is usually expressed as the reciprocal of the thermal conductivity, k, for said material. The thermal conductivity is an assessment of the amount of energy in BTU's which will pass through a one square foot section of a particular material that is one inch thick in one hour. In other words, the units for k are expressed as shown below.

k = BTU/hour/square foot/degree F/inch [22]

K-values for various structural materials are given in Appendix A.1. The reader should note that some of the values so represented are U-values. U-values are expressions of 1/C where C is the overall resistance of a specified thickness of the structural component under consideration. This table is abridged from P. D. Close's text [7] and the ASHRAE Handbook of Fundamentals [13].

As already stated, thermal resistance is dependent on the amount of material present as well as the type of material under consideration. It is relatively obvious that thermal resistance will increase as the thickness of the barrier is increased. These two facts would imply that thermal resistance is directly proportional to the thickness of the material and inversely proportional to the thermal conductivity of the material of which the barrier is composed. That is:

$$\text{Thermal Resistance} = R_t = \frac{\text{Thickness (in inches)}}{\text{Conductivity (k)}}$$

$$= \frac{\text{(degree F)(sq. ft.)(hour)}}{\text{BTU}}$$

Substituting this expression for R_t into Equation II.1, we get the relationship for heat transfer as shown below.

$$\text{Heat Flow} = \frac{\text{Temperature difference}}{\text{Resistance to heat flow}} = Q$$

$$Q = \frac{\Delta T}{R_t} = \frac{T_H - T_L}{\frac{\text{thickness}}{\text{k-value}}} \qquad \text{(II.2)}$$

$$= \text{BTU/(hour)(sq. ft.)}$$

From Equation II.2, we can now easily understand the units for heat flow. This expression gives heat flow, Q, equal to BTU's per hour-square foot. This is an approximation of the number of BTU's which may be transmitted through a barrier of homogeneous composition that is one square foot in surface area for one hour. Had the total surface area for a larger barrier and the number of hours at which such a system operated at the conditions T_H and T_L been specified, it would have been a relatively simple matter to obtain the total amount of heat transferred through the indicated boundary.

$$\text{Heat Loss} = Q \times \text{(surface area)} \times \text{(operating hours)} \qquad \text{(II.3)}$$

$$= \frac{\text{BTU}}{\text{(hr)(sq. ft.)}} \times \text{(sq. ft.)} \times \text{(hrs)} = \text{BTU's}$$

The BTU is an acronym for the British thermal unit. It is a unit of heat or energy. The BTU is defined as the quantity required to raise a one pound mass of water from 59.5 degrees Fahrenheit to 60.5 degrees Fahrenheit [27]. The reader should be aware that more elaborate definitions for the BTU exist. However, this definition is more readily understood by the layperson. Definitions of a more technical nature are found in references [17, 20, and 27].

From the foregoing discussion, one realizes that if the thickness and composition of a flat barrier of singular construction and the existing temperature difference is known that Equation II.2 can be used to determine the heat flux or heat transfer rate, Q.

$$Q = \frac{T_H - T_L}{\frac{\text{thickness}}{\text{k-value}}} = \text{BTU/(hour)(sq. ft.)} \qquad \text{(II.2)}$$

Furthermore, having found the heat flow rate for a single square foot surface area over a time duration of one hour, the total heat loss may be found by evaluation of Equation II.3.

$$\text{Heat Loss} = Q \times \text{(hours)} \times \text{(sq. ft.)} = \text{BTU's} \qquad \text{(II.3)}$$

Equation II.2 has been indicated as the expression which may be employed to evaluate heat flow through a single, flat homogeneous barrier. However, what if the boundary is not singular in composition? For instance, a conventional exterior building wall is usually constructed of some form of masonry, lumber, tar-paper, a modest amount of insulation, and an interior panelling. Obviously, this is not a homogeneous barrier. Equation II.4 indicates that the additive nature of the thermal resistivities of the individual components of construction may be utilized to determine the heat flow through just such a barrier.

$$Q = \frac{T_H - T_L}{\sum_{i=1}^{n} R_i} = \frac{T_H - T_L}{\sum_{i=1}^{n} \frac{\text{thickness}_i}{\text{k-value}_i}} \qquad \text{(II.4)}$$

For example, let us assume that we have a boundary similar to that shown in Figure II.3. In this situation we have assumed that the barrier between Mass-T_H and Mass-T_L is comprised of four layers of differing composition.

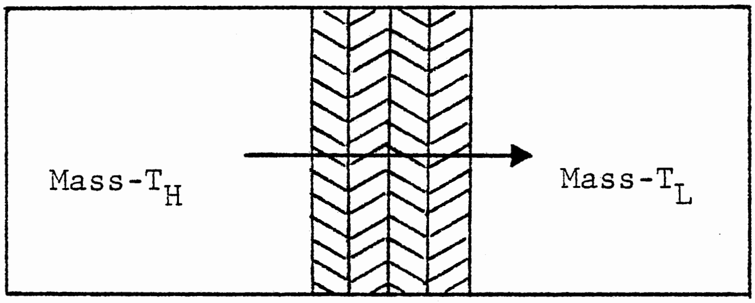


Figure II.3. Illustration of Heat Flow Across a Multi-Layer Boundary

The heat flow through a barrier such as this is determined by dividing the temperature difference by the summation of the various thermal resistances of each respective material layer. That is:

$$Q = \frac{T_H - T_L}{\sum_{i=1}^{n} \frac{thk_i}{k_i}} = \frac{T_H - T_L}{\frac{thk_1}{k_1} + \frac{thk_2}{k_2} + \frac{thk_3}{k_3} + \frac{thk_4}{k_4}}$$

By substitution of the known values into this expression, the heat flow through a multi-layer heterogeneous barrier may be determined.

The interface between a barrier and the gas or fluid it contains typically exhibits a phenomenon known as surface resistance. Surface resistance, R_s, is the retarding effect produced on the natural heat flow process by the surface film of air or fluid in contact with the barrier. Surface resistance, like other thermal resistances, is inversely proportional to the conductivity of the film-barrier interface, f. Simply stated:

$$R_s = \frac{1}{f}$$

The effect of surface resistance may be accounted for in the heat flow expression by simply adding R_s into the denominator of Equation II.4. The result of taking surface resistance into consideration yields Equation II.5.

$$Q = \frac{T_H - T_L}{\sum_{i=1}^{n} R_i + R_s} = \frac{T_H - T_L}{\sum_{i=1}^{n} \frac{thk_i}{k_i} + \frac{1}{f_{T_H}} + \frac{1}{f_{T_L}}} \qquad \text{(II.5)}$$

Surface film conductance, f, is a function of surface emittance, surface air velocity, and the comparative temperatures. As Michael Harrison [14] points out, while volumes of tables are available within which values of R_s are tabulated, these are at best estimates. The parameters which establish R_s typically change over time and as a result so does R_s. Some of the more commonly assumed values for R_s as proported by Harrison are presented in Appendix A.2. Values for surface conductance of various common building materials may be determined from the graph presented in Appendix A.3. This graph is taken from the ASHRAE Handbook of Fundamentals [13].

One other situation needs to be investigated before this introduction to the theory of heat flow is concluded. This final area of interest has to do with a particular type of surface through which heat may be transferred. Up until now our discussion has focused on the transmission of heat through a flat surface. Of critical concern to the industrial complex, however, is the heat flow that may occur through pipes or cylindrical vessels. Due to the radial dispersion of heat through a cylindrical surface, the corresponding heat flow expression is written as shown by Equation II.6.

$$Q = \frac{T_H - T_L}{r_2 \ln \frac{r_2}{r_1}} \qquad [14] \qquad (II.6)$$

In this expression, the term $r_2\ln(r_2/r_1)$ is referred to as the "equivalent thickness." The parameters, r_2 and r_1, represent the outer radius of a single layer of boundary material (or insulation) in inches and the inner radius of the boundary (or the outer radius of the pipe itself), also in inches. Multiplication of Equation II.6 by the quantity $2\pi r_2/12$ will yield an expression which gives the heat loss per hour per linear foot of piping.

Equations II.1 through II.6 represent the expressions by which the physical heat loss for a flat or cylindrical boundary may be determined. These relationships will be used extensively as our investigation concerning thermal insulation continues.

Insulation

Insulation is a means by which to retard the natural heat transfer process. Through the introduction of an insulating material between masses of differing temperature, we can substantially reduce the degree to which heat transfer takes place. The degree to which one reduces this heat transfer process is dependent on the physical characteristics and the amount, or particularly, the thickness of the material so utilized.

Heat transfer may occur by one of three mechanisms. These would include: conduction, convection, and radiation.

Heat transfer via conduction occurs as the result of the contact of two materials that exist at different temperatures. Conduction is the transfer of heat or energy at the molecular level that results in the formation of a temperature gradient along those materials that are in contact. Reduction of heat loss through conduction is accomplished by using insulating materials which are less conductive than the existing boundary. For example, glass is much less conductive than steel or aluminum. As such, it is used extensively as an insulating material particularly in the fiber form.

Convective heat transfer occurs as the result of the heating of the air or vapor in contact with the boundary surface. As this gas or fluid heats it tends to rise and as it rises additional heat is taken with it. Heat losses of this nature can be controlled by the creation of small cells which tend to retard this rising action. As a result, most thermal insulations are porous or cellular in construction.

Radiation is the natural transfer of energy from one surface to another over some distance. Closely related to the emittance of a particular material, this tendency is reduced substantially by utilizing insulations which are opaque in nature or possibly even contain reflective materials.

Figure II.4 illustrates the manner by which insulation functions to reduce these natural heat loss processes. Due to its current popularity and readily understood construction characteristics, this diagram is shown with fiberglass as the insulating material. Figure II.4 is adapted from Malloy's text [17].

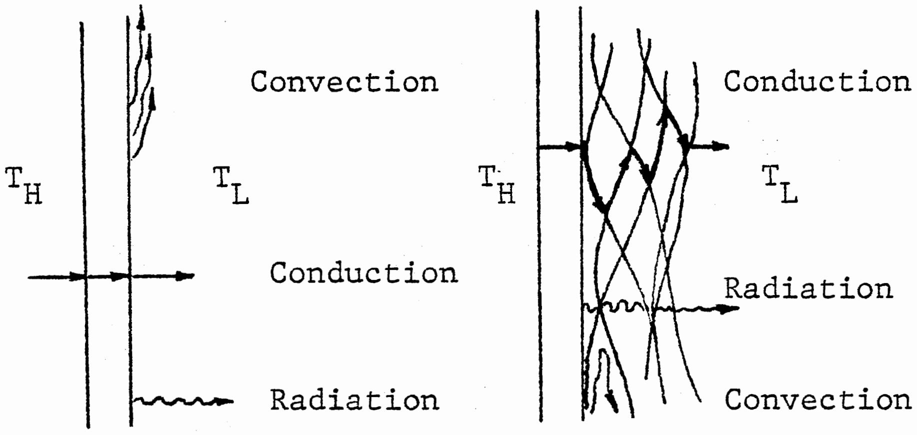


Figure II.4. Illustration of the Three Heat Transfer Mechanisms for an Uninsulated and Insulated Surface

Comparison of Insulating Materials

Comparison of various insulations is typically based on each respective material's resistance to thermal transfer, R_i. For each insulating material the thermal resistance, R_i, is a function of the thickness of the material and the comparative conductivity, k, of that material. That is:

$$R_i = \frac{\text{thickness}}{\text{k-value}}$$

Therefore, R_i is a ratio of thickness to conductivity, k. It is relatively obvious that the thermal resistance may be increased by one of two modes. First, one could increase the thickness of the insulation. That is, more material could be added. Secondly, we could attempt to decrease the conductivity of the insulating material. Thermal conductivity, however, is characteristic of the physical attributes of the material so used. As a result, it is quite common to compare insulations on the basis of their respective k-values. The lower the thermal conductivity, k_i, the more efficient the insulation. Values of k for various common insulating materials are presented in Table II.1. This table is also given in Appendix A.4 for ease of reference. Additional information regarding k-values and R-values for various insulating materials is presented in Appendix A.5.

It is important to realize that the thermal conductivity for an insulating material will vary with temperature. For this reason, the thermal conductivities given in Table II.1

TABLE II.1

INDUSTRIAL INSULATION TYPES AND PROPERTIES

Insulation type and form	Temp. range °F	Thermal Conductivity Btu-in/hr/sq ft/°F @ T Mean °F			Comprehensive strength psi @% deformation	FHC-Fire hazard classification or flame spread-smoke developed	Cell structure (permeability and moisture absorption)
		75	200	500			
Calcium silicate blocks, shapes, P/C	to 1,500	.37	.41	.53	100 to 250@5%	Noncombustible	Open cell
Glass fiber blankets	to 1,200	.24 to .31	.32 to .49	.43 to .73			
Glass fiber boards	to 1,000	.22	.28	.51 to .61	.02 to 3.5@10%	Noncombustible to 25/50	Open cell
Glass fiber pipe covering	to 850	.23	.30	.62			
Mineral fiber blocks and P/C	to 1,900	.23 to .34	.28 to .39	.45 to .82	1 to 18@10%	Noncombustible to 25/50	Open cell
Cellular glass blocks, shapes, P/C	-450 to 900	.38	.45	.72	100 @ 5%	Noncombustible	Closed cell
Expanded perlite blocks, shapes, P/C	to 1,500	-	.46	.63	90 @ 5%	Noncombustible 25 to 75 -	Open cell
Urethane foam blocks and P/C	-100 to -450 to 224	.16 to .18	-	-	16 to 75@10%	140 to 400	95% Closed cell
Isocyanurate foam blocks and P/C	to 350	.15	-	-	17 to 25@10%	25-55 to 100	93% Closed cell
Phenolic foam P/C	-40 to 250	.23	-	-	13 to 22@10%	25/50	Open cell
Elastomeric closed cell sheets and P/C	-40 to 220	.25 to .27	-	-	40 @ 10%	25 tp 75 - 115 to 490	Closed cell
MIN-K® blocks and blankets	to 1,800	.19 to .21	.20 to .23	.21 to .24	100 to 190@8%	Noncombustible	Open cell
Ceramic fiber blankets	to 2,600	-	-	.38 to .54	.5 to 1 @ 10%	Noncombustible	Open cell

and Appendices A.4 and A.5 are presented for the mean temperature at which that insulation is to be used. The mean temperature is the average temperature that will result within the insulation and is determined as shown in Equation II.7.

$$T_{mean} = \frac{T_H + T_L}{2} \qquad \text{(II.7)}$$

Insulating Materials

As has already been eluded to, insulation is not restricted to the use of one specific material. In fact, there exists quite a variety of commercially available insulating materials. Some of the more common insulations will be discussed in the paragraphs that follow.

Glass Fiber--The flexibility of fiberglass insulation makes its utilization over a wide variety of applications possible. It is available in the form of batts, blankets, semi-rigid boards, and pipe moldings. Fiberglass may even be procured for uses over different temperature ranges. This is attributed to the use of different binders within the product. Even if "binder burnout" does occur, the long glass fibers tend to maintain the structural integrity of this insulation. Glass fiber insulation is relatively compressible and, as such, it is not considered to be a load-bearing insulation.

Mineral Wool/Rock Wool--This insulating material is similar in nature to fiberglass. However, the characteristic fibers are formed from molten rock or slag rather than from silica. Typically, mineral wool fibers are more heat resistant than glass fibers and, therefore, may be used at higher temperature ranges. These insulations have fiber lengths that are shorter than glass insulation and for that reason they are not regarded to be as versatile or durable as fiberglass insulations.

Calcium Silicate--Calcium silicate is an insulation of extreme strength and durability. The lime, silica, and fiber construction of this type of insulation makes it popular in applications where physical abuse is normally a problem. Piping systems in plants and refineries and pressure vessels are common applications of calcium silicate. Additionally, the fact that this insulation contains no organic binder eliminates the problem of "binder burnout." This obviously makes calcium silicate applicable to higher temperature situations than glass or rock wool.

Cellular Glass--The thermal conductivity of this type of insulation is somewhat higher than most other insulations. However, it does possess certain qualities which make its utilization very attractive. For instance, cellular glass insulation is composed of millions of completely sealed glass bubbles. This type of construction is completely impervious to liquid and vapors. This fact makes cellular glass insulations extremely popular in exterior and buried applications. Furthermore, this type of insulation is considered load-bearing which increases its versatility that much more.

Plastic Foams--There are basically three types of plastic foams which are used as insulating materials. These would include polyurethane, isocyanurate, and phenolic foams. Polyurethane and isocyanurate foams offer the lowest thermal conductivities relatively speaking. These foams do pose some serious fire safety problems, however. This problem has resulted in the use of these foams primarily as a cold service insulation. On the other hand, phenolic foams do not pose quite the fire safety problem that the other two foams do. However, the k-value of this material is somewhat higher.

Expanded Perlite--Naturally occurring perlite is expanded at a high temperature to produce this type of insulation. Expanded perlite is rigid and load-bearing but has a higher thermal conductivity than calcium silicate and much more brittle. This material is also susceptible to absorption upon oxidation or aging.

Min-K®--Developed for use in the aerospace program, this insulation material has probably the lowest thermal conductivity of all the insulating materials at high temperature ranges. This material is formed of minute air cells within a silica base. It is available in flexible sheets as well as blocks. The drawback to this insulation is its relatively high cost compared to the other available insulations.

Refractories--Refractories are those materials which tend to maintain their chemical and physical integrity when subjected to extremes in temperature. As a means of insulation, there exist basically two types of refractories. These include ceramic fibers and firebrick. Ceramic fibers are woven into "blankets" which may be utilized in high temperature applications. Likewise, firebrick tends to "cure" upon exposure to high temperatures. The result is a highly thermal efficient means of construction.

Selection of an Insulation

The selection of one particular insulation material is not a trivial matter. A lack of concern over the choice of an insulation which is appropriate for a specific situation could lead to a selection which may prove less effective than might otherwise be available. In essence, this could mean wasted dollars. Michael R. Harrison [14] maintains that several factors should be considered when trying to decide on the particular type or form of insulation to be used in a specific situation. These would include: 1) temperature use range, 2) thermal conductivity, 3) compressive strength, 4) fire hazard classification, 5) cell structure, and 6) the available form. Each of these parameters will be discussed subsequently.

All forms of insulation display a temperature range over which their use is relatively more effective. Utilization of a particular type of insulation above its characteristic temperature range may result in degradation of that insulating material. This instability may manifest itself as high temperature shrinkage or cracking of the insulating medium or a phenomenon known as "binder burnout" may be the result.

In this situation the extreme temperatures cause a breakdown of the organic binder that holds the insulation together. In either case, the end result is a rapid degradation of the insulating material. The temperature ranges for a specific insulation are usually available from the manufacturer. Temperature ranges of the more common insulating materials are given in Table II.1 and Appendix A.4.

Thermal conductivity, as has already been pointed out, is characteristic of the type of insulating material and the mean temperature at which it is utilized. The lower the k-value, the more effective the insulation will be. Therefore, it behooves the engineer to select an insulation with as low a thermal conductivity as possible given that additional design parameters have been satisfied.

The situation under consideration may be such that the insulation to be utilized must bear a load. This load may be continuous in nature, such as with a buried pipe or vessel, or intermittent as in the case of foot or light equipment traffic. Specifications with regard to compressibility of various insulating materials are usually available from the respective manufacturers.

Fire hazard classification of insulations relates to each product's contribution to flame spread or smoke development. Red oak has a flame spread/smoke development of 100/100 and all insulating materials are compared to this standard. Typically, a 25/50 fire hazard classification is considered appropriate for situations where fire safety is of concern.

Fire classification for insulating materials are also contained in Table II.1 and Appendix A.4.

The ability of an insulating material to absorb moisture is a direct consequence of the cell structure of that material. Closed cell materials are utilized extensively in situations which warrant that the insulation be impervious to moisture or vapor such as the exterior retrofit insulation of a building envelope.

Insulation is available in a wide variety of forms. These would include batts, blankets, loose fill, rigid boards and blocks, pipe half-soles, full-pipe casings, single-layer, and multiple-layer applications. However, not all insulations are available in all forms. For this reason, the engineer or analyst should seek that insulation form which will prove both cost effective and thermally efficient.

Additional considerations may also exist which are specific to a given insulation application. Density, pH, and specific heat may prove to be critical in certain situations. Consultation with the manufacturer will usually provide additional specifications as needed.

The reader will note that cost has been excluded from the criteria by which to select a specific insulating material. The economics of insulation (both the initial cost and the resulting cost savings) is somewhat intricate in nature. As such, this topic will be fully addressed in Chapter III.

CHAPTER III

THE ECONOMICS OF INSULATION

Just how much insulation is enough? This question, restated here from the preface, is the focus of this chapter. Assuming that additional design parameters such as surface temperature, condensation control, and process heat loss (gain) have been satisfied, the answer to this question is typically a matter of economics. For this reason, a comprehensive discussion on the costs and cost savings associated with the use of an insulating material and the manner by which these cash flows may be evaluated will be developed in the pages that follow.

The Costs of Insulation

Practically speaking, there exist two fundamental costs that are of interest when one undertakes the evaluation of an insulation system. These cost classifications include: 1) the installed cost of the insulation, and 2) the periodically recurring maintenance cost associated with the insulation selected for a specific application. Each of these costs will be discussed subsequently.

The installed cost of insulation consists of several major components. These include: 1) the insulating material costs, 2) jacketing costs, if any is required, 3) securement material costs for wiring or banding, and 4) the labor costs incurred for the actual installation of the proposed materials.

Literature with regard to the economics of insulation is rich with the methods that may be employed to estimate the installed cost of insulation systems [7, 17, and 29]. These methods usually involve the use of nomographs and piping complexity factors and are, at best, estimates based on historical national averages. During periods of extreme inflation historical data such as these methods utilize may prove to be relatively inaccurate as a means by which to estimate the installed cost of insulation. As a result, the engineer or analyst is encouraged to consult with the manufacturer or a local insulation contractor to obtain a more accurate estimate of the initial cost of insulation. The data so obtained is usually expressed in a form such as installed cost per square or linear foot for a specified thickness of the insulating material.

Estimates of installed cost per square or linear foot should be obtained for a range of specific thicknesses of the insulating material; for example, cost per square foot for one inch of insulation, cost per square foot for two inches of insulation, cost per square foot for three inches of the insulating material, etc. In this form, the cost information so obtained will more accurately reflect the non-linear relationship between insulation thickness and installed cost.

That is, a single application of three inch thick insulation does not necessarily cost three times as much as a one inch layer of the same material. This may be attributed to the fact that while the material cost of each application may indeed triple, the labor required to install a single layer of one inch or three inch insulation may remain constant. The end result is a non-linear relationship between thickness and installed cost.

Perhaps less familiar is the concept of a maintenance cost associated with the use of an insulating material. Nonetheless, such a cost does exist and, as such, it should be accounted for when one attempts to economically evaluate a specific insulation proposal.

A periodic (usually annual) expenditure will need to be forecast to allow for the repair or replacement of an estimated portion of the insulating material. These repairs are the result of excessive wear and tear which may be attributed to machine vibration, physical abuse due to unusual loading, or incidental abuse such as that caused by fork lift maneuvering or truck unloading. In an effort to maintain the structural integrity and thermal efficiency of the insulation system it is wise to plan on a modicum of system maintenance. It is usually sufficient to estimate the first year's maintenance cost and assume that repairs of a similar nature will be required on an annual basis.

The Cost Savings

As discussed in Chapter II, insulation is used to retard the natural heat flow process. Respective thicknesses of insulation, therefore, may be evaluated by the degree to which that heat flow process is reduced. Knowledge of the various situational parameters such as operating temperature, ambient temperature, surface resistance, hours of operation, and surface area will allow for the quantification of this reduction in heat loss. Further still, the cost per therm (cost per one hundred thousand BTU's) may be utilized to determine the dollar value associated with this BTU savings.

This reduction in heat loss is, therefore, a cost savings and, as such, may be thought of as an income with respect to the expenditure required to realize this cost savings. The resulting relationship between initial investment and the reduction in annual heat loss (or, gain) will be the focus of the following section.

Probably a less easily understood form of cost savings arises with regard to the capital plant investment required for a heating or cooling system. The reasoning here is that by utilizing an appropriate amount of insulation one may effectively reduce the capital investment required for a specific capacity conversion plant. The premise being that less heat (or, cooling) needs to be generated since less is wasted. While the reasoning here is valid, it pertains primarily to the evaluation of heating and cooling systems that are in the design stage only. The position in this study will be such that the majority of insulation studies are conducted on a retrofit basis and, as a result, the installed insulation will not directly affect the capital investment already made in the heating or cooling plant.

The Total Cost Curve

As has already been indicated, the cost of insulating and the resulting energy cost savings are related. In essence, one could say that we spend some fixed amount of money at the present time in order to realize a recurring cost savings over some number of years in the future. Therefore, it would follow that if one spends a little more money now, he will realize a little larger annual cost savings. This type of rationale, however, can prove to be very misleading. That is, the next increment of insulation installed (hence, the next increment of cost) does not realize the same magnitude of BTU savings (incremental cost savings) as did the previous incremental thickness of insulation under evaluation.

As T. S. Rogers [23] points out this is probably a classic demonstration of the "Law of Diminishing Returns." That is to say that as the capital investment in insulation is increased, a smaller and smaller cost savings per dollar invested is realized. This would imply that there exists some point at which the next dollar invested is just recovered by the subsequent cost savings.

Rogers elaborates further on this basic economic principle to develop what is referred to as the "Law of Maximum Benefits." With respect to the study of insulation, one could say that the maximum benefits associated with the insulation of a system will result when the design parameters such as process temperature, surface temperature, and condensation control are satisfied and the least annual cost associated with the fulfillment of these parameters is realized.

The least annual cost may be found by simply adding the annualized cost of the investment made into the insulation to the costs of the annual energy losses that will occur from its ultimate installation. The end result is a curve-linear relationship as indicated in Figure III.1. This illustration is taken from the ASHRAE Handbook of Fundamentals [13].

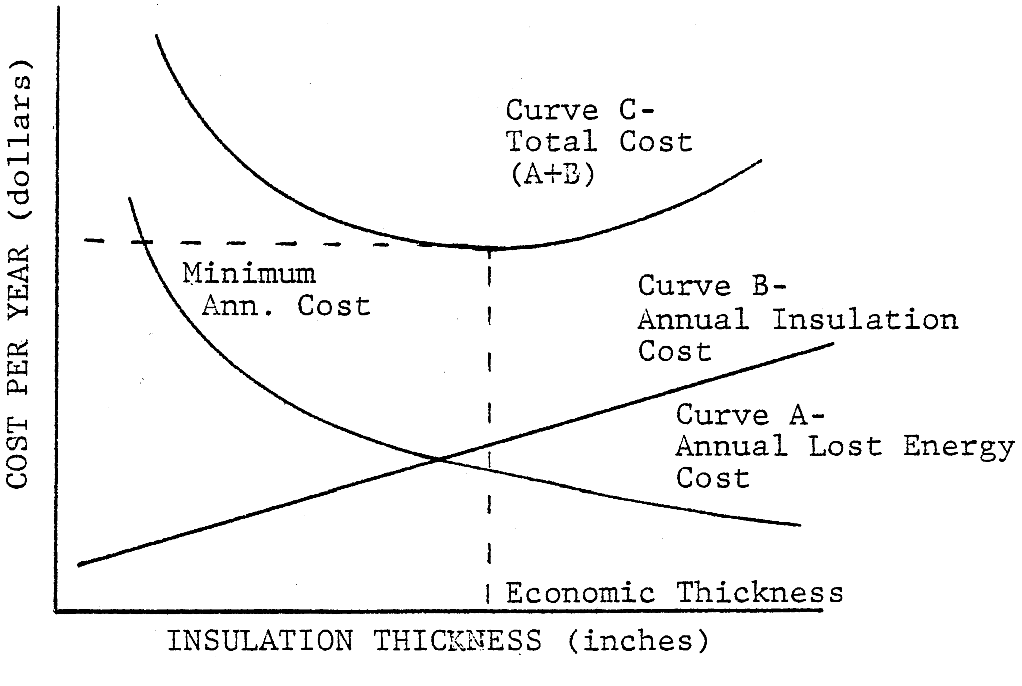


Figure III.1. Total Cost Curve for Insulation

From Figure III.1 one can easily see a graphical demonstration of the law of diminishing returns and the law of maximum benefit about which T. S. Rogers wrote. Notice that as the investment in insulation continues through the application of more material the corresponding reduction in heat loss lessens. Furthermore, when these two respective curves are added the result is a total cost curve as indicated by Curve C. Analysis of this curve indicates that a minimum point with regard to the annualized cost of insulation does indeed exist. This is the point of maximum benefit or minimum annual cost that Rogers refers to.

The total cost curve was later modified by Michael Harrison [14] to reflect the non-linear relationship that is characteristic of increased thicknesses of insulation. The resulting cost curve is depicted in Figure III.2. Notice that this graphical representation of the annualized cost of insulation also accounts for the additional labor that is required for double and triple layer installations.

The Economic Thickness of Insulation

The point of minimum annualized cost of insulation which has been eluded to is referred to as the "economic thickness" of insulation. As such, the economic thickness is that thickness which will prove to be of maximum economic benefit for the situation under study.

The technique by which the economic thickness of insulation is determined may be thought of as an optimization of

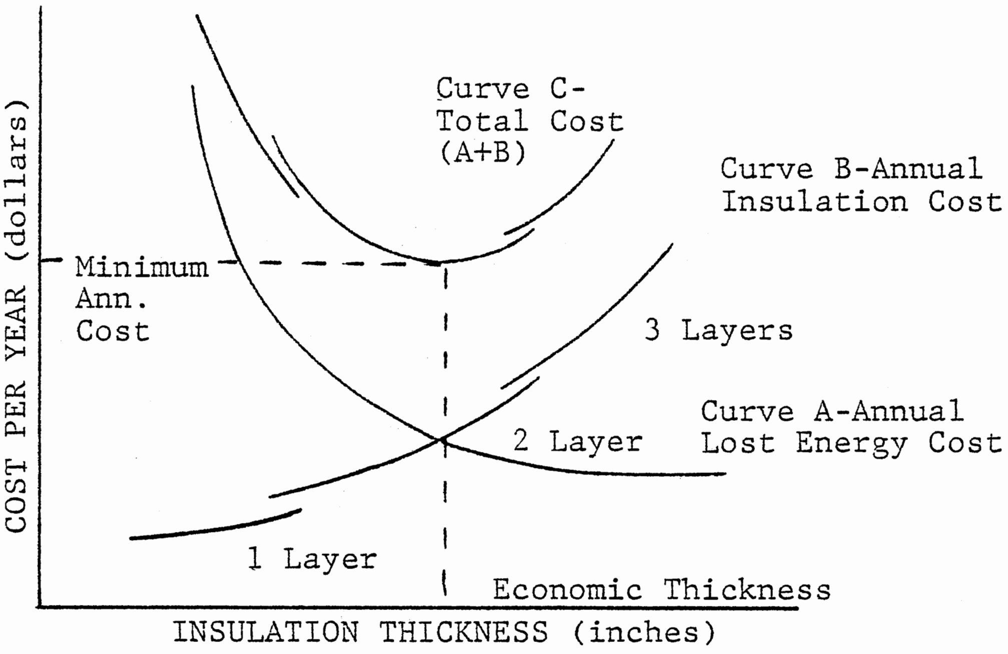


Figure III.2. Modified Total Cost Curve for Insulation

the total cost curve. As indicated in a study by the York Research Corporation [29] there exist two basic approaches to the determination of the economic thickness of insulation. These methods include: 1) the minimum total cost method, and 2) the incremental cost method. While both of these techniques will yield the same economic thickness for a given situation, the former approach will be the one taken in this study.

The minimum total cost method requires that the actual energy losses and insulation costs be calculated for each individual thickness of insulation under consideration. It follows, therefore, that the thickness which yields the lowest annualized total cost would correlate to the economic thickness. For the majority of situations this method has proven to be difficult to perform by hand calculation. However, the reader should keep in mind that the ultimate goal of this study is the development of a computer program by which to determine the economic thickness of insulation via the total cost method.

The Economic Analysis of Insulation

The economic evaluation of insulation may be performed by employing the accepted standard principles of engineering economic analysis. These techniques may be utilized to annualize the total cost of various thicknesses of insulation for a specific situation. Once calculated, these annual dollar amounts may be compared to identify that thickness at which the minimum annual cost may be realized. These economic techniques are discussed in detail in references [12, 16, and 28] and the reader is encouraged to review these sources to increase his familiarity with the evaluation methods soon to be discussed.

To facilitate a comprehensive understanding of the calculation procedure required to determine the economic thickness of insulation, a generic outline of the solution methodology will be presented. The procedure developed in the paragraphs that follow will orient the reader to the technique that will be applied consistently throughout the remainder of this study. Furthermore, each of the steps in the solution procedure will be explained in theory as to what its function is and how it relates to the remaining steps.

Step 1: Scope of Study--This phase of the analysis deals with the specification of the problem to be investigated. Certain parameters characteristic of the situation under investigation should be delineated at this time. A checklist of the questions that need to be researched might include:

a) What is the system to be insulated? Is it a flat surface or is it a piping system?
b) What type of insulation needs to be used in the system under analysis?
c) What is the k-value associated with the insulation under consideration? Can a lower k-value be obtained?
d) What is the feasible range of thicknesses which needs to be analyzed?
e) What is the process temperature and the ambient temperature of the system?
f) What is the efficiency of the conversion plant?

The questions posed above are indicative of the physical aspects of the system which need to be confirmed. These parameters may be measured directly from the system as it presently exists. The selection of a particular type of insulation may then be based on analysis of these conditions. This process was discussed at length in Chapter II.

Additional information of a different kind needs to be sought during this step. The economic parameters appropriate for the evaluation of the proposed insulation need to be established. This data would include the firm's minimum attractive rate of return or it's cut-off rate, the general inflation rate, an estimate of the fuel escalation rate, and, of course, the cost per unit of heat or cooling. The installed cost of the various thicknesses of insulation should also be determined at this time.

The useful life of the selected insulation should be specified at this time. The research literature is somewhat vague with respect to the determination of an insulation's useful life. The analyst is encouraged to consult with a manufacturer's representative concerning this problem.

While this listing of the variables which need to be defined seems somewhat overwhelming, it serves to indicate the complexity one encounters when attempting to analyze insulation systems. The actual determination of these parameters alone may be quite a cumbersome undertaking much less their subsequent evaluation.

Step 2: Determination of Heat Loss (Gain) in BTU's--Utilizing the concepts presented in the discussion on heat flux in Chapter II and the parameters defined in the previous step, the annual BTU loss and/or gain must next be calculated. This step will make use of some form or combination of Equations II.5 and II.6 to determine the annual BTU loss for heating processes or BTU gain for cooling situations for a specific thickness of the insulation. While the equations so mentioned may be used to determine the energy loss for the entire system, it will be the practice of this study to determine this loss in terms of BTU's per foot; either square foot for flat surfaces or per linear foot for piping systems. This is done to keep the numbers reasonable and thereby maintain ease of computation.

Step 3. Annual Energy Cost Determination--Once determined, the annual BTU loss per foot may be multiplied by the cost of producing that heat. In the case of cooling, the annual BTU gain per foot may be multiplied by the cost of providing a unit of cooling. Each of these costs may be obtained from accounting records in the form of dollars per therm of energy consumed. A therm is equivalent to one hundred-thousand BTU's of energy. This step essentially converts the annual BTU loss to an annual dollar amount at the current cost of the fuel so utilized.

Step 4: Net Present Cost of Annual Energy Losses Over the Life of the Insulation--The present value of the annual energy costs that will result over the useful life of the insulation may be found once the annual dollar value that is associated with that energy loss is identified. This is accomplished by compounding the current equivalent dollar value of the energy loss at a modified interest rate, k', over y periods into the future and then discounting each of the subsequent future sums back to the present time at the firm's minimum attractive rate of return. This modified interest rate as developed in an article by K. E. Case and W. C. Turner [26] is favored here as the means by which to account for the effects of both the general inflationary trend and the accelerated rate of increase for a specific component of the economy, such as energy prices. The quantification of k' is shown in Equation III.1.

$$k' = \frac{1 + k}{1 + j} \qquad [26] \qquad \text{(III.1)}$$

In this expression, k is the rate of increase of a specific economic component such as energy costs. The other factor, j, is the interest rate reflective of the general inflationary trend.

Inflating the annual dollar loss attributed to wasted BTU's as found in step two by the factor, $(1 + k')^y$, and then discounting that single sum so generated will accurately yield a present worth amount for any year's energy loss. This procedure is repeated for each year that the insulation is expected to be in service. These present worth amounts may then be summed to find the total present worth of all of the energy losses that will occur over the useful life of the insulation. The end result is a present worth expression of the kind indicated by Equation III.2.

$$PW_{energy} = \sum_{y=1}^{n} \begin{matrix}\text{current value}\\ \text{of energy loss}\end{matrix} \times (1 + k')^y \times (1 + i)^{-y} \qquad \text{(III.2)}$$

Likewise, the maintenance costs should be discounted to the present time by the same factor, $(1 + i)^{-y}$. The maintenance costs, however, are not compounded as were the energy costs since they are assumed to be expressed in terms of "constant worth" dollars [28]. This combined present worth procedure is consistent with that presented by C. B. Estes,

K. E. Case, and W. E. Turner [11].

Utility and maintenance costs are expenses with regard to the income statement. As such, the net effect of these cash flows may be found by multiplying the recurring dollar values by the quantity, (1 - Ti), where Ti is the incremental income tax rate for the firm. This approach is taken in an effort to more accurately reflect the true magnitude of the costs incurred as a result of the installation of the insulation. These facts combined will yield an after tax present worth expression for the annual energy losses and the required maintenance of the specific thickness of insulation under immediate investigation that is of the form indicated by Equation III.3.

$$PW = \sum_{y=1}^{n} \left[\begin{matrix}\text{maintenance}\\ \text{cost}\end{matrix} + \begin{matrix}\text{annual}\\ \text{energy}\\ \text{cost}\end{matrix} \ (1+k')^{y} \right] x\ (1 - Ti)\ x\ (1+i)^{-y} \tag{III.3}$$

Recursive evaluation of this expression for all values of y, the years in the estimated life of the insulation, will yield a single present sum that is equivalent to the cash flow profile generated by the insulation's continued utilization. This single sum will be used in the next step of the analytical procedure to determine the total annual cost of the increment of insulation under consideration.

The reader will note that upon inspection Equation III.3 contains no expression for the depreciation of the insulation. It should be pointed out here that insulation is not depreciable [10] and, as a result, no term incorporating its effect is included in Equation III.3. It is the contention of the Internal Revenue Service that the insulation is regarded as a non-depreciable capital asset whose depreciable value will be accounted for in the expensing of each year's required maintenance. For this reason, depreciation strategies are eliminated from the solution procedure to be utilized throughout the remainder of this text.

Step 5: The Total Annual Cost Determination--Once calculated, the present worth of the annual cash flows due to the energy losses and maintenance costs may be added to the purchase price or installed cost of the respective increment of insulation under analysis. This single sum is representative of the entire cash flow profile associated with the purchase and installation of the insulating system.

This single sum may then be annualized by employing the appropriate capital recovery factor [28]. This factor, shown below, distributes the single sum equivalent cost of the system over the useful life of the insulation. The result is an equivalent uniform annual cost figure which is indicative of the annual cost of the installation and maintenance of the insulation. It is this amount which will be minimized to find the economic thickness of insulation.

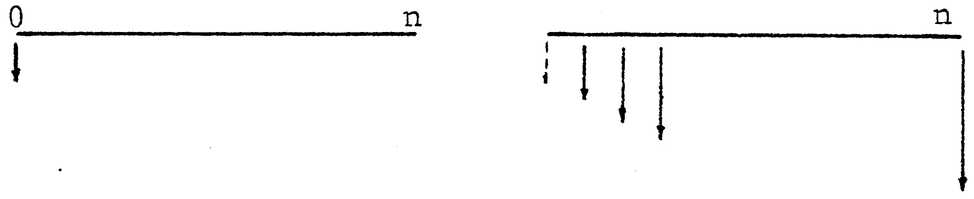
$$\text{Cap. rec. factor} = \frac{i(1+i)^y}{(1+i)^y - 1} \quad [28] \quad (\text{III.4})$$

It should be pointed out here that the purchase price of the insulation should be adjusted to account for the effects of any tax credit that may be available for insulating practices. At the present time, insulation as it is used in industry does not qualify for a tax credit [16]. On the other hand, the individual is entitled to a credit for the installation of insulation within the home. This credit amounts to 15% of the first $2,000 that is spent on insulation or other qualified energy conservation expenditures [10].

Step 6: Repeat Steps 2 Through 5--Having performed the analytical procedure for the initial thickness of insulation to be investigated, it may then be repeated for all subsequent thicknesses of insulation pertinent to the study. Each increase in the thickness of the insulating material will result in a smaller BTU loss and, correspondingly, a smaller annual energy cost. These reduced costs are typically realized at the expense of a slightly higher installed cost which, likewise, gives rise to a somewhat higher annual maintenance cost.

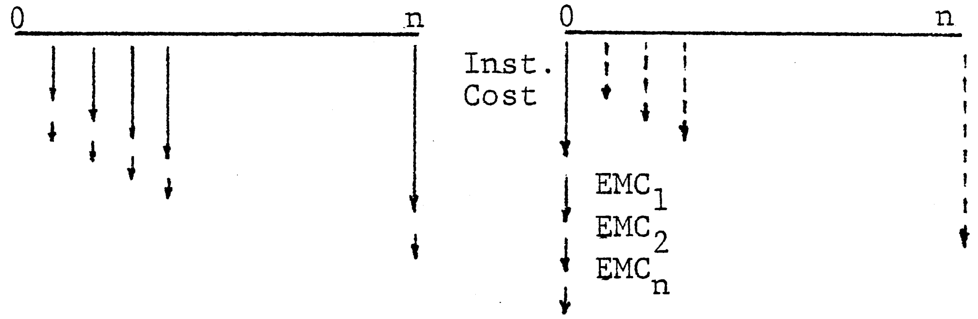
Performing the outlined procedure for all thicknesses of insulation that are under consideration will yield a set of annual cost figures. One annual amount will correlate to each respective thickness that is analyzed. The economic thickness of the insulation under analysis will be that thickness which corresponds to the minimum annual cost figure.

The analytical procedure previously outlined may be demonstrated graphically. Figure III.3 illustrates the methodology that has been proposed as a means by which to determine the total annual cost for a range of thicknesses. This figure makes use of a cash flow diagram approach to



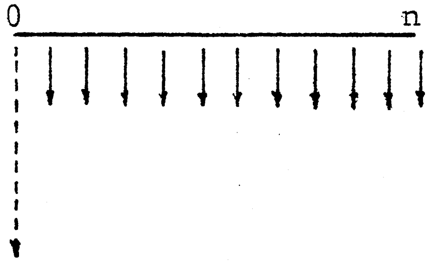
a) Current Cost of BTU Loss at Current Thickness

b) Inflated Energy Costs for Years 1 Through n



c) Constant Value Maintenance Cost Added to Energy Costs

d) Present Worth of Energy and Maintenance Costs and Installed Cost



e) Annualized Cost of Insulation, Maintenance and Energy Losses

Figure III.3. Cash Flow Representation of Proposed Analytical Procedure explain the compounding of BTU losses expressed in terms of current dollars at the modified interest rate, k'.

The annual maintenance costs in constant value dollars are then added to the annual energy losses to obtain cash flow profile C. These cash flows are then discounted one at a time at the minimum attractive rate of return to find the net present equivalent as shown in profile D. The installed cost of the thickness under consideration is then added to this present equivalent to get the total net present value of the insulation system. This amount is then annualized by use of the capital recovery factor as shown in diagram E. Once again, it should be noted that this solution procedure is then repeated for each respective thickness of the proposed insulating material that is to be investigated.

An Example of the Solution Procedure

An example study will be undertaken at this time to further illustrate the analytical procedure that has been developed herein. Suppose, for example, that we are considering the insulation of an eight inch (nominal) iron pipe. Let us assume further that step 1, the scope of the study, has been researched and the following information pertinent to the study has been determined.

Step 1: Scope of Study

Firm: Sandco, Inc.
Contact: S. D. Sandstrum
Insulation Type: Calcium Silicate with jacketing
Process Temperature: 180 degrees F.
Ambient Temperature: 80 degrees F.
Hours of Operation: 8760 hours
Pipe Size: 8 inch nominal, Sch 40

Minimum Attractive Rate of Return: $i = 18\%$
General Inflationary Rate: $j = 15\%$
Fuel Escalation Rate: $k = 20\%$
Heat Plant Efficiency: 70%
Heating Cost: $.35 per 100,000 BTU's
Estimated Useful Life: 10 years
Incremental Tax Rate: 48%
Available Tax Credit: None available
Range to be Analyzed: 1 to 6 inches
Increment: 1 inch

From this information some additional facts of importance to the solution procedure may be calculated as follows. The mean temperature to which the insulation will be exposed may be found by using Equation II.7.

$$T_{mean} = \frac{T_H + T_L}{2}$$

$$= \frac{180 + 80}{2} = 130 \text{ degrees F}$$

Knowing the mean temperature and the type of insulation under analysis, the k-value of that material may be found from Appendix A.4. Reference to this appendix yields an interpolated k-value for the calcium silicate insulation of approximately 0.39 BTU per hour, square foot, degree F.

Furthermore, knowing the operating conditions makes possible the determination of the number of heating degree-hours that is indicative of the system's operation. This quantity may be found on an annual basis as shown below:

$$\text{Heating degree-hours} = \Delta T \times \text{Hours of Operation}$$

$$= (180 - 80) \times 8760 \text{ Hrs}$$

$$= 876{,}000 \text{ degree-hours/year}$$

Reference to Appendix A.2 yields a surface resistance of approximately 0.460 hour, square foot, degree F per BTU for the iron pipe under consideration. Further still, from Appendix A.7, the actual outside radius of the schedule 40 eight inch nominal pipe may be found as 4.3125 inches. This information will prove to be of importance in the determination of the equivalent thickness for this system. This concept was introduced in Chapter II.

The modified inflation rate, k', may also be calculated at this time using Equation III.1.

$$k' = \frac{1 + k}{1 + j} - 1 = \frac{1 + .20}{1 + .15} - 1 = 0.0435$$

The reader should note that k' is not defined for the condition where k equals j. This situation would be indicative of a condition in which the annual energy losses would be assumed to be expressed in constant worth dollars and the analysis would proceed as it would for the case of constant value maintenance costs.

Finally, the installed cost for each respective thickness in the range of insulation to be analyzed must be specified. We will assume for this exemplary study that the cost information indicated in Table III.1 is available. Notice that the maintenance costs are a fixed proportion of the installed costs, namely 1%. This is a relatively common practice.

<u>Step 2: Annual BTU Loss for Initial Thickness</u>--With all of the preliminary information so obtained, we are now ready

TABLE III.1

INSTALLED COST FOR EACH THICKNESS IN EXAMPLE STUDY

Thickness (in inches)	Installed Cost/Linear Ft.	Maintenance Cost/Linear Ft.
1.00	$ 5.06	$0.05
2.00	9.12	0.09
3.00	13.93	0.14
4.00	17.48	0.17
5.00	25.15	0.25
6.00	29.08	0.29

to start the recursive evaluation of each respective thickness of insulation under investigation. Let us begin by calculating the heat loss per linear foot for the first inch of insulation. Using a modified form of Equation II.6 from Chapter II and multiplying by the factor, $2\pi r_2/12$, we can find the heat loss per year per foot of eight inch pipe.

$$Q = \frac{\text{Heating degree-hours}}{\frac{r_2 \ln(r_2/r_1)}{\text{k-value}} + \text{Surface Resistance}} \times \frac{2\pi r_2}{12} \times \frac{1}{\text{Eff.}}$$

$$= \frac{(876{,}000)(2\pi)(5.3125)/12}{\left(\frac{(5.3215)\ \ln(5.3125/4.3125)}{0.39} + 0.460\right)(.70)}$$

$$= 1{,}054{,}609.1 \text{ BTU per year per linear foot.}$$

Step 3: Current Energy Loss Cost--Knowing the annual BTU loss to be realized for only one inch of insulation, the equivalent dollar value of that loss may be determined by multiplying that amount by the current cost per therm of the fuel consumed to generate that heat. The current dollar value of the heat loss may therefore be found as follows:

$$\text{Current Energy Cost} = \text{BTU loss} \times \text{Cost/Therm of Heat}$$

$$= 1{,}054{,}609.1 \text{ BTU} \times \frac{\$\ .35}{100{,}000 \text{ BTU}}$$

$$= \$3.69 \text{ per Linear Foot}$$

Steps 4 and 5: Annual Equivalent Determination--Steps 4 and 5 of the solution procedure may be combined to determine the annual equivalent cost of the current thickness of insulation under evaluation. The cash flow analysis developed as a result of this integration is presented in Table III.2. The result is an equivalent after-tax annual cost of $3.46 per linear foot for a one inch thickness of calcium silicate insulation.

Step 6: Recursive Evaluation of Subsequent Thicknesses--The indicated solution technique may then be repeated for each successive thickness of calcium silicate to be analyzed. The end results of these calculations may be summarized and presented in tabular form as indicated by Table III.3.

The right hand column in Table III.3 is representative of the list of annual cost figures for the respective thicknesses in the range of calcium silicate under analysis. Inspection of this column reveals that a minimum after-tax annual cost figure does indeed exist. The thickness which corresponds to this minimum annual dollar figure is two inches. Thus, two inches is the economic thickness or the thickness of maximum benefit for the situation as described

TABLE III.2

EQUIVALENT ANNUAL COST DETERMINATION FOR A ONE INCH THICKNESS OF CALCIUM SILICATE

End of Year	Inflated Energy Loss	Constant Worth Maintenance Expense	Combined After-Tax Cash Flow	Present Worth Amount
0	$ 5.06*		$ 5.06	$ 5.06
1	3.85	$ 0.05	2.03	1.72
2	4.02	0.05	2.12	1.52
3	4.19	0.05	2.20	1.34
4	4.38	0.05	2.30	1.19
5	4.57	0.05	2.40	1.05
6	4.76	0.05	2.50	0.93
7	4.97	0.05	2.61	0.82
8	5.19	0.05	2.72	0.72
9	5.45	0.05	2.84	0.64
10	5.65	0.05	2.96	0.57
		Total Present Worth	=	$15.56**

*Indicates installed cost of respective thickness.

**

$$\text{Annual Cost} = \$15.56 \times \frac{.18(1.18)^{10}}{(1.18)^{10} - 1}$$

$$= \$15.56 \times (0.2225) = \$3.46 \text{ per Linear Foot.}$$

TABLE III.3

ECONOMIC THICKNESS DETERMINATION FOR CALCIUM SILICATE PROBLEM

Thickness (in inches)	Installed Cost ($/Ln Ft)	Annual Energy Loss (BTU/Ln Ft)	Net Present Cost ($/Ln Ft)	After-Tax Annualized Cost ($/Ln Ft)
1.00	$ 5.06	1,054,609.1	$15.56	$ 3.46
2.00	9.12	624,146.6	15.48	3.44
3.00	13.93	462,443.7	18.82	4.19
4.00	17.48	377,010.1	21.51	4.79
5.00	25.15	323,844.0	28.93	6.44
6.00	29.08	287,378.0	32.61	7.26

for Sandco, Inc., in step 1.

One can easily see from the sample problem considered above that the determination of the economic thickness by hand can be quite a tedious undertaking. However, computer technology may be utilized to effectively reduce the time required to determine the economic thickness of insulation. This prospect will be investigated in Chapter IV.

CHAPTER IV

ECOTHK: A COMPUTER PROGRAM

As indicated by the sample study presented in Chapter III, one can easily see the tedious and time-consuming nature of the solution procedure required for the determination of the economic thickness of insulation. The recursive nature of the proposed analytical algorithm, however, lends itself quite readily to a computerized process.

In the discussion that follows ECOTHK, a computer algorithm by which to determine the economic thickness, will be presented. This computer program will be addressed in the batch form and the interactive mode. User instructions for the interactive mode will also be presented in an effort to help the reader gain access to ECOTHK via the time share option.

ECOTHK -- Batch Form

From the example study of Chapter III it is obvious that the proposed solution procedure is somewhat cumbersome. While the calculations do not require high technology mathematics, they are, nonetheless, consuming when performed by hand. This aspect of insulation economics has, no doubt, hampered the efficiency with which the total cost curve for insulation systems may be optimized.

As previously indicated, the recursive nature of the solution procedure outlined in Chapter III proves to be highly compatible with computerized algorithms. Computer technology, therefore, may be utilized to overcome the tedious aspects of the analytical procedure.

A computer algorithm may be generated by properly coding the expressions used in the economic thickness solution procedure. In this way, the analyst would simply submit the appropriate input data and let the computer execute the coded analytical procedure. As a result, the economic thickness for a specific insulation system may be determined in seconds using the same procedure that required literally hours when attempted by hand.

Just such a computer algorithm has been developed by the author using standard Fortran computer language [4, 25]. This computer program shall be referred to throughout the remainder of this study by the acronym, ECOTHK.

Figure IV.1 is a flowchart of the logic that ECOTHK follows. This figure is presented in an effort to further substantiate the correlation between the proposed computer algorithm and the solution procedure of Chapter III. The reader should also note that an explanation for each respective calculation performed by ECOTHK is indicated by reference to the appropriate equations of Chapters II and III.

Once developed in batch form, ECOTHK was then used to perform the calculations required of the sample problem

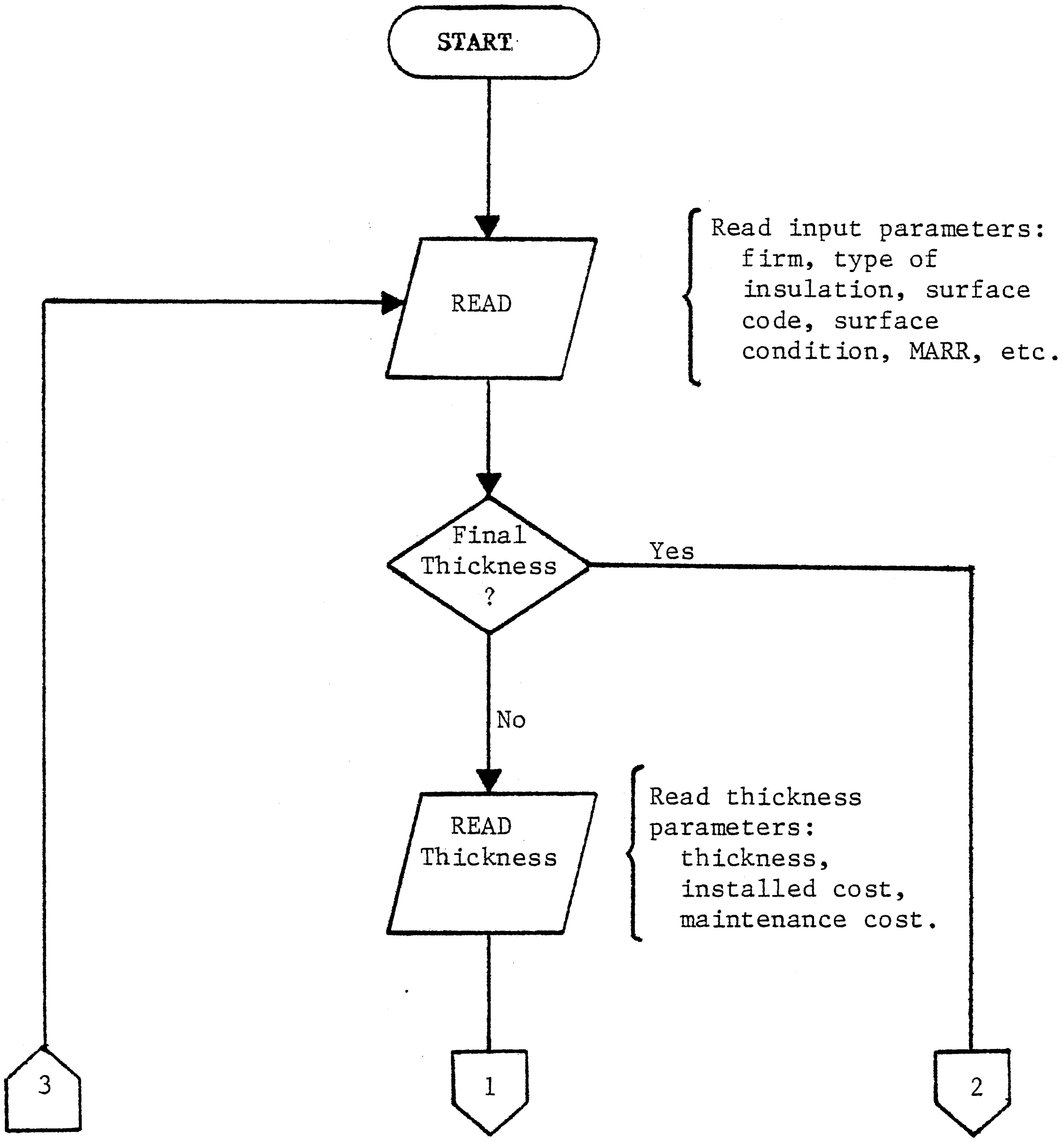


Figure IV.1. ECOTHK Flowchart

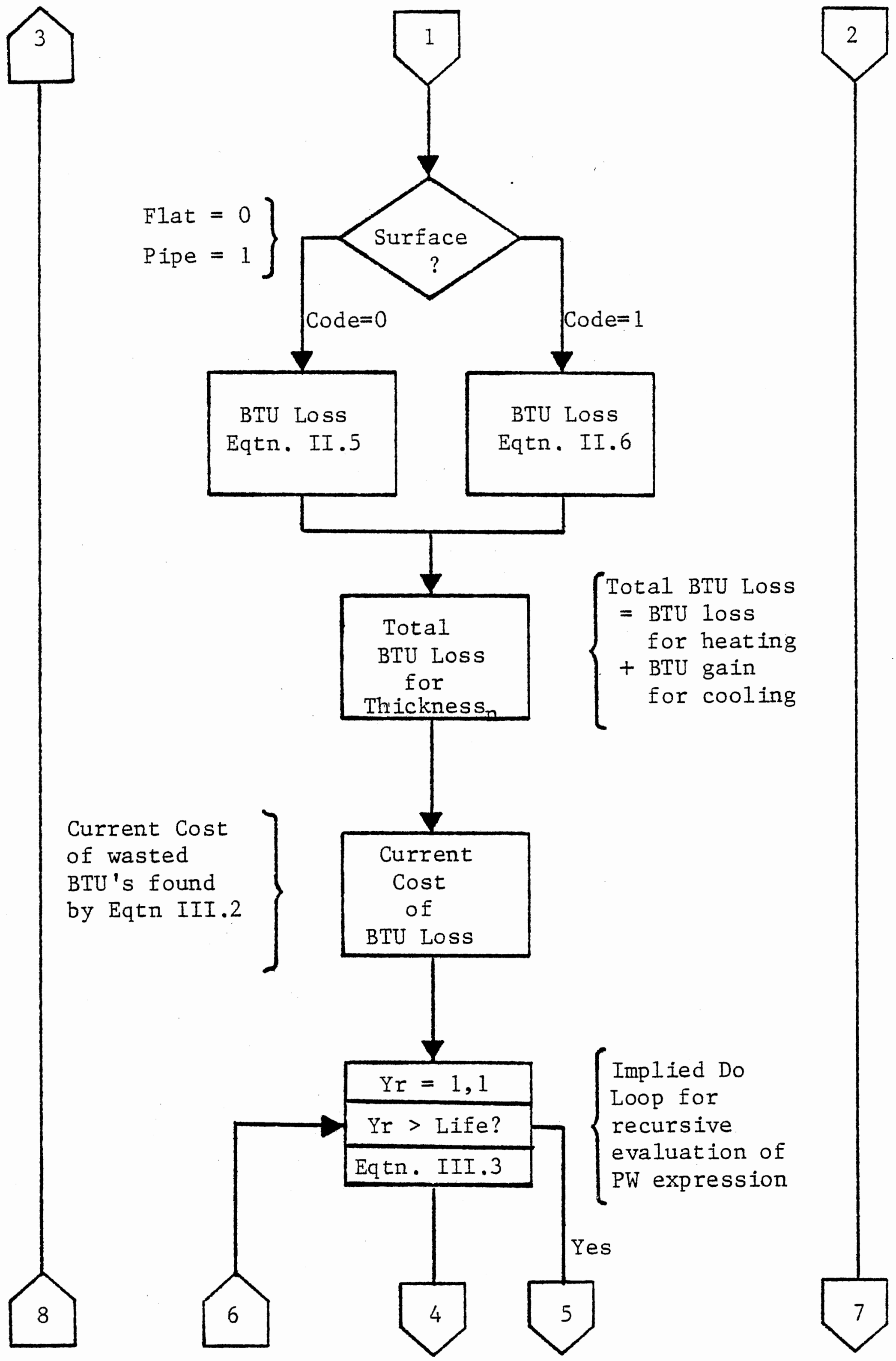


Figure IV.1. Continued

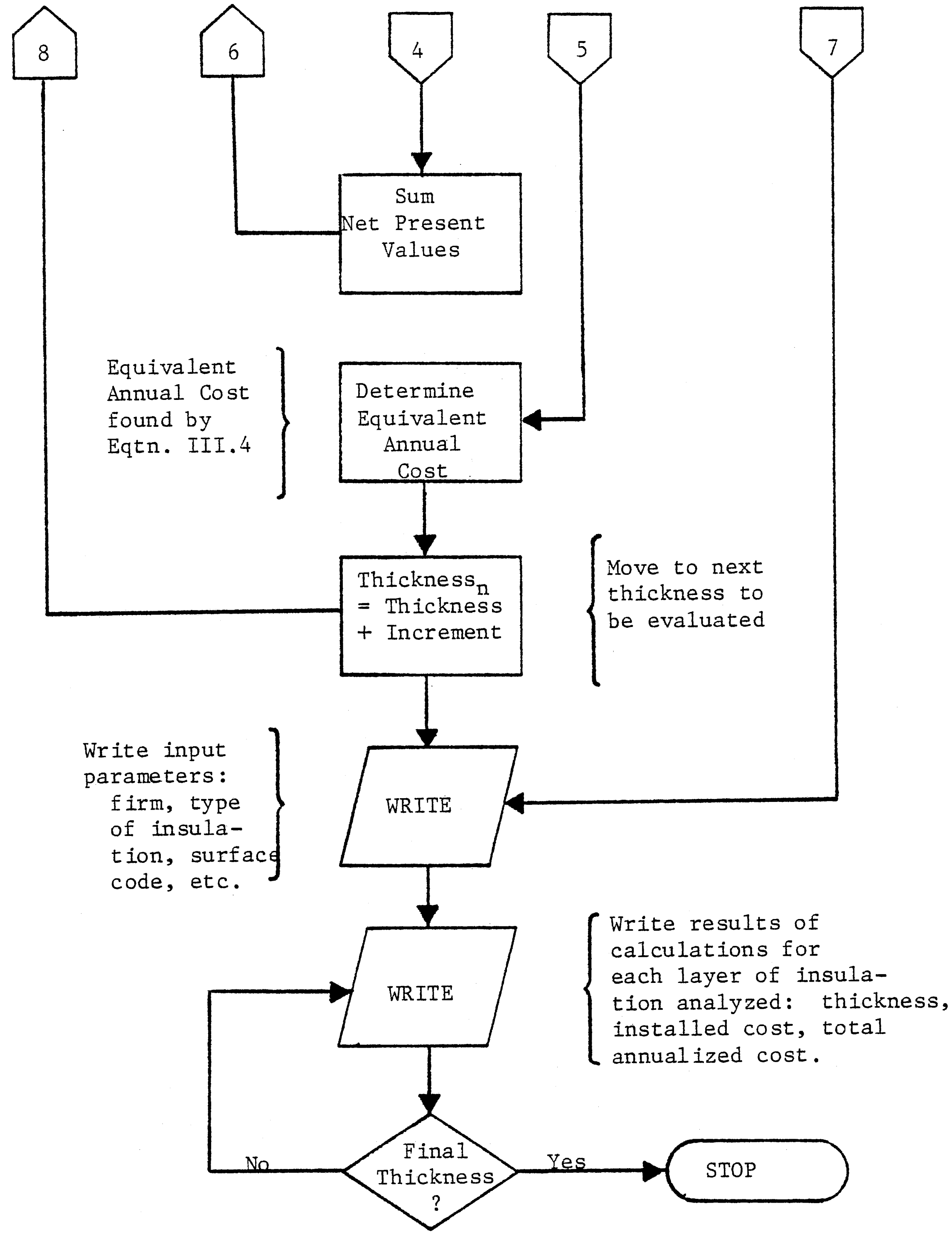


Figure IV.1. Continued

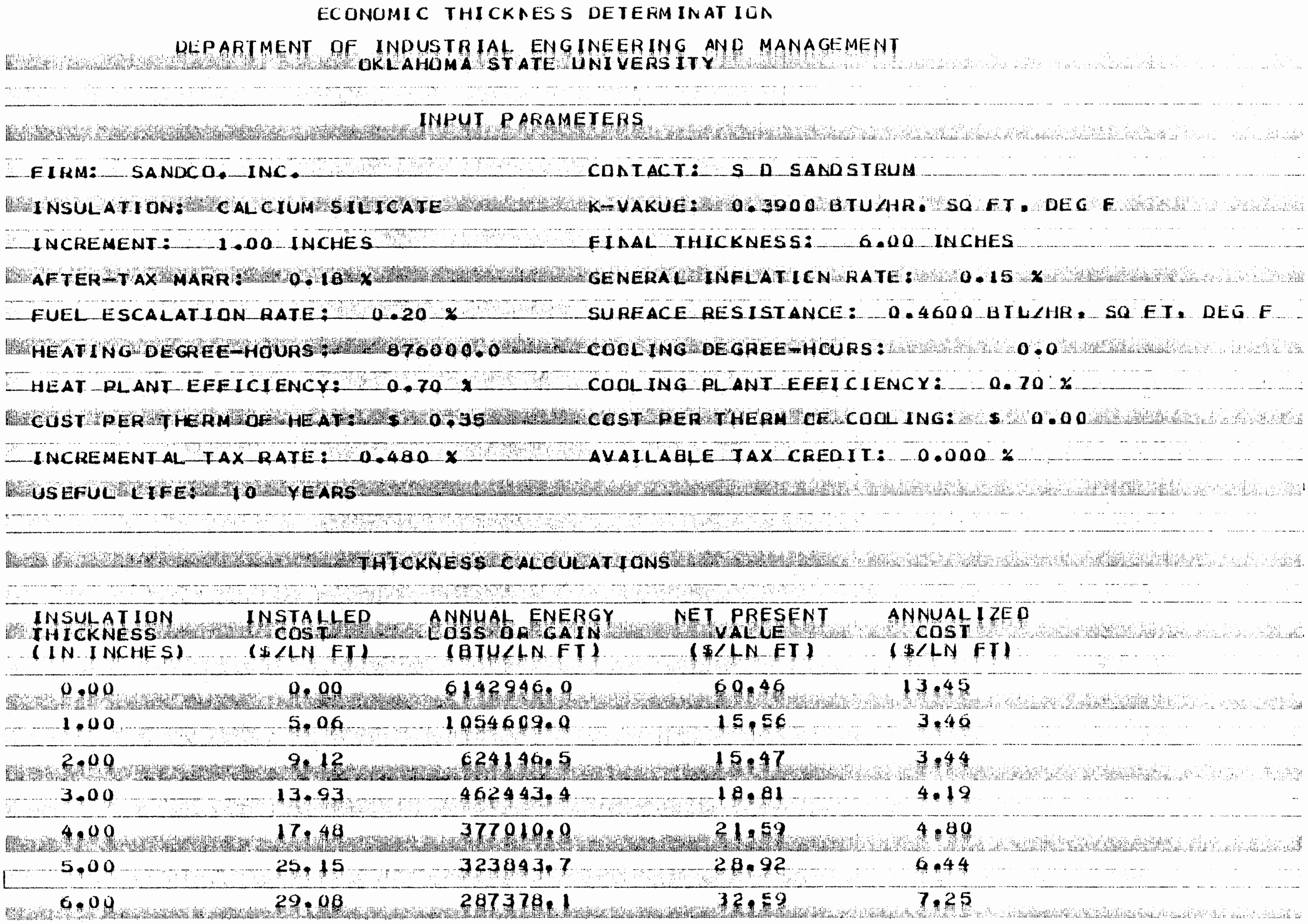
presented in Chapter III. The resulting output of the program is presented in Figure IV.2. The reader should note by inspection of the hard copy that ECOTHK requires essentially the same input data as did the hand calculation procedure. The reader should also note that the output of ECOTHK is similar to the results of the hand procedure and yields the same conclusion with regard to the thickness at which the minimum annual cost will be realized for the example situation under analysis.

For the reader's convenience a complete listing of the batch form of ECOTHK is given in Appendix A.8. This listing includes not only the output of the example study of Chapter III, but also a complete listing of the variables used within the algorithm and the documentation required to follow the logic inherent to the program.

ECOTHK -- Interactive Mode

Having been developed in batch form, ECOTHK was then converted to an interactive mode by use of the appropriate Fortran control language. As a result, ECOTHK is on disk within the OSU Fortran Library and may be accessed through the time share option (TSO). The conversion to an interactive form was performed to make ECOTHK more conveniently accessible, remove the necessity of using punched cards to convey input data, and to allow for the performance of sensitivity analyses on the situation under investigation.

It is important to realize that the interactive form of



```
                    ECONOMIC THICKNESS DETERMINATION

            DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT
                        OKLAHOMA STATE UNIVERSITY

                             INPUT PARAMETERS

FIRM:  SANDCO. INC.                     CONTACT:  S D SANDSTRUM
INSULATION:  CALCIUM SILICATE           K-VAKUE:  0.3900 BTU/HR. SQ FT. DEG F
INCREMENT:  1.00 INCHES                 FINAL THICKNESS:  6.00 INCHES
AFTER-TAX MARR:  0.18 %                 GENERAL INFLATION RATE:  0.15 %
FUEL ESCALATION RATE:  0.20 %           SURFACE RESISTANCE:  0.4600 BTU/HR. SQ FT. DEG F
HEATING DEGREE-HOURS:   876000.0        COOLING DEGREE-HOURS:         0.0
HEAT PLANT EFFICIENCY:   0.70 %         COOLING PLANT EFFICIENCY:   0.70 %
COST PER THERM OF HEAT:  $  0.35        COST PER THERM OF COOLING:  $  0.00
INCREMENTAL TAX RATE:  0.480 %          AVAILABLE TAX CREDIT:  0.000 %
USEFUL LIFE:  10 YEARS

                          THICKNESS CALCULATIONS

INSULATION       INSTALLED     ANNUAL ENERGY      NET PRESENT     ANNUALIZED
THICKNESS          COST        LOSS OR GAIN          VALUE           COST
(IN INCHES)      ($/LN FT)     (BTU/LN FT)        ($/LN FT)       ($/LN FT)

   0.00             0.00        6142946.0            60.46           13.45
   1.00             5.06        1054609.0            15.56            3.46
   2.00             9.12         624146.5            15.47            3.44
   3.00            13.93         462443.4            18.81            4.19
   4.00            17.48         377010.0            21.59            4.80
   5.00            25.15         323843.7            28.92            6.44
   6.00            29.08         287378.1            32.59            7.25
```

Figure IV.2. Batch ECOTHK Output

ECOTHK is essentially no different than the batch form. As such, the logic of this mode may also be illustrated by Figure IV.1. The primary difference in the two modes is that ECOTHK in the interactive mode may be accessed without a key punch and a card reader through the use of a remote computer terminal such as a decwriter or cathode ray tube.

Undoubtedly, it would prove beneficial to discuss the advantages of the interactive mode at this time. The following points serve to substantiate the advantages of this mode.

Foremost among the advantages of the interactive mode is the potential for remote utilization of the ECOTHK algorithm. The improved ease of access that results should guarantee ECOTHK's use within the Department of Industrial Engineering and Management at OSU. This is a topic which will be addressed again in Chapter VI.

ECOTHK in the interactive form eliminates the need to submit the input data via a punched card. This reduces the potential for misapplications of ECOTHK that may result from input that is out of order or due to lost cards. Furthermore, since the majority of the interactive mode is written in free format, exact placement of input data is not critical. These facts combined indicate the improved flexibility of the interactive form.

The improved flexibility and accessibility of the interactive mode of ECOTHK allows for the performance of sensitivity analyses with respect to the evaluation of insulation systems. That is, once the evaluation has been performed under one set of input parameters, the analyst may then repeat the evaluation. During the subsequent analyses, however, the parameters which may be in doubt could be varied or "played with" to determine their true impact on the annual cost calculations for the system under analysis.

The advantages discussed above serve to substantiate the enhanced version of the ECOTHK algorithm. It is the author's contention that this mode will prove to be the most efficient method by which to determine the economic thickness for any given situation under consideration.

User Instructions for ECOTHK

An interactive program for the determination of the economic thickness is the primary purpose of this study. As such, it would prove highly beneficial to discuss the method by which to access and use ECOTHK at this time. The resulting set of user instructions that follows is presented in order to increase the user's familiarity with the interactive mode and the type and form of data which will need to be supplied to ECOTHK in order to determine the economic thickness. With the outlined instructions below, the user should be amply prepared to access and take full advantage of ECOTHK's potential.

1) Gaining Access to the Computer -- ECOTHK may be accessed by a remote terminal via an audio coupler. The analyst should dial 822 on a university extension and wait

for a high-pitched whistle. The whistle indicates that a time-share line is available and at this time the user may connect the audio coupler. Once connected, the analyst is ready to interact with the computer.

2) *Gaining Access to ECOTHK* -- Having gained access to the computer, the analyst is now ready to call the ECOTHK algorithm. This procedure occurs in a stepwise progression with the analyst responding to the requests that the computer makes. The scenario proceeds something like this:

Analyst--LOGON

This is the standard acronym employed to address the computer via the time share option.

Computer--IKJ56700A ENTER USERID

The computer is requesting the analyst to identify himself. The response to this request will determine to which account the subsequent computer time will be charged.

Analyst--U11610A

The user should respond with a current user ID number as issued by the University Computer Center. U11610A is the user ID currently assigned to this research project.

Computer--ENTER CURRENT PASSWORD FOR U11610A

To ensure the security of the university computer system, the computer is requesting additional means of identification.

Analyst--STEV

"STEV" is the current password for this project. Should a new password be assigned to this project, it should be keyed in at this time.

Computer--U11610A LOGON IN PROGRESS AT (TIME) AND (DATE)

The computer has verified the ID and password the analyst has submitted. The analyst now has access to the central processing unit on a time sharing basis. This statement will be followed by any current messages of which the analyst needs to be aware of with regard to the status of the computer system.

Computer--READY

The computer will follow the messages printed above with the term, READY. This indicates that the computer is prepared to accept the commands of the analyst.

Analyst--TERM LINESIZE(130)

The analyst should respond with this command at this time. This statement simply assures a

130 character output line which is critical to the output that is characteristic of ECOTHK's execution.

Computer--READY

The computer has acknowledged the user's request for a longer line of output and is awaiting the next command.

Analyst--CALL ECOTHK.LOAD(ECOTHK)

With this statement, the analyst is actually asking to use the ECOTHK algorithm which is in the University Fortran Library. The computer will now start to request input data specific to the study to be undertaken.

The user should be patient with the computer. At times the computer is extremely busy accommodating the requests of all remote users. As such, there may be a substantial time lag between the command of the analyst and the response of the computer. This characteristic is typical of the time share option.

Another word of warning is in order at this time, also. The analyst should make sure to press the return key after each line of data he enters on the remote terminal. Without this action, the analyst's command is not entered into the execution queue and, as a result, the computer does not know to respond in an interactive manner.

3) Entering Input Data for ECOTHK -- At this time the analyst is ready to supply input data to the ECOTHK algorithm. As previously indicated, ECOTHK will request the data and the analyst should make the appropriate responses. To illustrate this procedure, the data pertinent to the example study of Chapter III will be entered in response to ECOTHK's requests. For example:

Computer--ENTER NAME OF FIRM

Analyst--SANDCO, INC The analyst may enter any acronym indicative of the client for whom he is conducting the study. This acronym may not exceed 16 characters.

Computer--ENTER CLIENT REPRESENTATIVE

Analyst--S D SANDSTRUM

The user may respond with any name not exceeding 16 characters.

Computer--ENTER INSULATION TYPE UNDER ANSLYSIS

Analyst--CALCIUM SILICATE

The specific type of insulation to be analyzed should be entered at this time. Once again, the appropriate entry may not exceed 16 characters in overall length.

Computer--ENTER K-VALUE OF INSULATION

Analyst--0.3900 The k-value of the insulation should be typed in at this time. This figure found in Appendix A.4, may be carried to any number of decimal places. However, it is doubtful that significance beyond four decimal places will have any real impact on the economic thickness determination.

Computer--ENTER INCREMENT AND FINAL THICKNESS

Analyst--1.00 6.00

Respective values for the increment by which each successive thickness will be increased and the final thickness to be analyzed are entered at this time. These values should be in terms of inches. Each value should be entered as a real number with the decimal point included. The two figures should be separated by at least one blank space. No punctuation is required to separate the data so entered.

Computer--ENTER MARR, INFLATION AND FUEL ESCALATION RATES

Analyst--0.18 0.15 0.20

The analyst should respond by entering the appropriate interest rates in decimal form.

Once again, all that is required to separate the data files is a blank space.

Computer--ENTER HEATING AND COOLING DEGREE-HOURS

Analyst--876000.0 00.0

Appropriate values for heating and cooling degree-hours may be determined by using the equations of Chapter II and III. The resulting data should be entered at this time. If one or the other of these processes is not to be considered zeroes should be entered in real form. Do not leave a blank data file. Each of these figures should be entered as real numbers with decimals included.

Computer--ENTER HEATING AND COOLING EFFICIENCIES

Analyst--0.70 0.70

The efficiency of both the heating and cooling system are typed in at this time in decimal form. As before, these values need to be separated by a blank space. A real value other than zero has to be read in each of these data files regardless of whether the specific process (heating or cooling) is not being analyzed. If one of these processes is not being analyzed, simply repeat the known efficiency. The imaginary value will not enter into the calculations for process of interest as long as the corresponding degree-hours has been specified to be zero.

Computer--ENTER EXISTING SURFACE RESISTANCE

Analyst--0.4600 For the eight inch Sch 40 pipe, the surface resistance was found in Appendix A.2 to be 0.4600. This value is entered presently as a real number.

Computer--ENTER HEATING AND COOLING COST PER THERM

Analyst--0.35 0.00 The average dollar cost for 1 x 10^5 BTU's of heating and/or cooling is entered at this time. Once again, a value must be read for each cost. If a specific process is not being investigated, simply record 0.00. These values should be separated by a blank space.

Computer--ENTER INCREMENTAL TAX RATE AND TAX CREDIT

Analyst--0.48 0.00 The appropriate tax rate and and available tax credit should be typed in response at this time. These values should be entered in real form and separated by a blank space. If a tax credit does not apply, simply record 0.00.

Computer--ENTER USEFUL LIFE OF INSULATION

Analyst--10 Once determined, the useful life of the insulation (in years) may be entered as an integer.

Computer--ENTER SURFACE CODE AND OUTSIDE RADIUS

Analyst--1 4.3125 The surface code is an integer value. Flat surfaces correspond to a 0 (zero) and piping systems are represented by a 1 (integer one). It is important to specify which type of system is under investigation so that ECOTHK can employ the appropriate heat flux equations. If a piping system is under analysis, the outside radius of the pipe should be recorded at this time. Data of this type is available from Appendix A.7. If a flat surface is under evaluation, 0.00 should be keyed in for the outside radius. The two values should also be separated by a blank space.

Computer--ENTER THICKNESS, INSTALLED COST, MAINTENANCE COST

Analyst--0.00 0.00 0.00
1.00 5.06 0.05
2.00 9.12 0.09
3.00 13.93 0.14
4.00 17.48 0.17
5.00 25.15 0.25
6.00 29.08 0.29

The thickness, installed cost, and maintenance cost for each respective layer under consideration should be entered in matrix form at this time. Each line should correspond to the data relevant to one thickness. It is very important that the data be entered in real form and in the order indicated. The data files on each line should be separated by at least one blank space. ECOTHK will respond with a question mark each time the return key is pressed to start a line of data for a new layer.

4) Obtaining Output from ECOTHK -- Once all of the pertinent cost data for each thickness has been entered, ECOTHK will respond very quickly with the results of its execution. ECOTHK will yield a hard copy which will identify the study, echo the situational parameters submitted to it, and list the BTU loss (or gain) and the annualized cost of the system at each respective thickness of insulation under evaluation.

Similar to the batch form and hand calculation, inspection of the output will yield the determination of the economic thickness for the particular study at hand. The economic thickness will correlate to that thickness of insulation which will result in the minimized after-tax total annual cost.

Upon completion the computer will be in the "READY" mode once again. The analyst may opt to terminate use by simply typing LOGOFF or, he may want to repeat the run with a change of variables. This is accomplished by restating the line size and calling ECOTHK into an interactive mode once more [see Step #2].

For the reader's convenience, the hard copy resulting from ECOTHK's execution of the sample problem under consideration is presented in Figure IV.3. The various stages of progression for ECOTHK's use are also indicated in this figure. For ease of reference, a copy of this run is also reproduced in Appendix A.8.

Inspection of ECOTHK's output indicates that the results of its execution are consistent with those obtained by the hand calculation procedure. As before, two inches of calcium silicate yields the minimum after-tax total annual cost.

ECOTHK is not limited to the evaluation of piping systems only. In fact, ECOTHK is a very flexible algorithm. A comprehensive understanding of this flexibility may be attained by consideration of a few more sample problems. Additional applications of ECOTHK will be the subject of discussion for Chapter V.

```
LOGON
IKJ56700A ENTER USERID -
U11610A
ENTER CURRENT PASSWORD FOR U11610A-
STEV
U11610A LOGON IN PROGRESS AT 12:50:40 ON DECEMBER 12, 1980
 The remote facility in Engineering South will close for semester
 break at 6:00 p.m. Thursday, Dec. 11, and will reopen at 10:30 a.m.
  Monday, January 12.
READY
TERM LINESIZE (130)
READY
CALL ECOTHK.LOAD(ECOTHK)
ENTER NAME OF FIRM
SANDCO,INC
ENTER CLIENT REPRESENTATIVE
S D SANDSTRUM
ENTER INSULATION TYPE UNDER ANALYSIS
CALCIUM SILICATE
ENTER K-VALUE OF INSULATION
?
0.3900
ENTER INCREMENT AND FINAL THICKNESS
?
1.00 6.00
ENTER MARR, INFLATION AND FUEL ESCALATION RATES
?
0.18 0.15 0.20
ENTER HEATING AND COOLING DEGREE-HOURS
?
876000.0 00.0
```

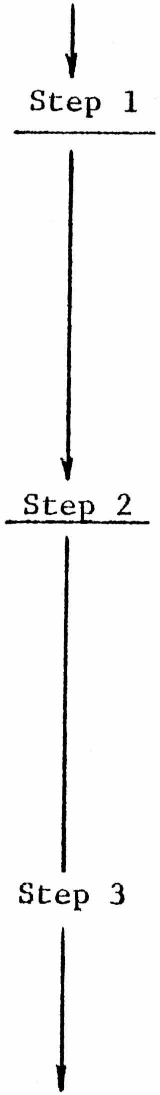


Figure IV.3. Interactive ECOTHK Hard Copy

```
ENTER HEATING AND COOLING EFFICIENCIES
?
0.70 0.709
ENTER EXISTING SURFACE RESISTANCE
?
0.4600
ENTER HEATING AND COOLING COST PER THERM
?
0.35 0.00
ENTER INCREMENTAL TAX RATE AND TAX CREDIT
?
0.48 0.00
ENTER USEFUL LIFE OF INSULATION
?
10
ENTER SURFACE CODE AND OUTSIDE RADIUS
?
1 4.3125
ENTER THICKNESS, INSTALLED COST, MAINTENANCE COST
?
0.00 0.00 0.00
?
1.00 5.06 0.05
?
2.00 9.12 0.09
?
3.00 13.93 0.14
?
4.00 17.48 0.17
?
5.00 25.15 0.25
?
6.00 29.08 0.29
```

Step 3

Figure IV.3. Continued

```
                    ECONOMIC THICKNESS DETERMINATION

          DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT
                       OKLAHOMA STATE UNIVERSITY

                           INPUT PARAMETERS

FIRM:  SANDCO,INC                          CONTACT:  S D SANDSTRUM
INSULATION:  CALCIUM SILICATE              K-VAKUE:  0.3900 BTU/HR, SQ FT, DEG F
INCREMENT:   1.00 INCHES                   FINAL THICKNESS:   6.00 INCHES
AFTER-TAX MARR:    0.18 %                  GENERAL INFLATION RATE:   0.15 %
FUEL ESCALATION RATE:    0.20 %            SURFACE RESISTANCE:  0.4600 BTU/HR, SQ FT, DEG F
HEATING DEGREE-HOURS:    876000.0          COOLING DEGREE-HOURS:         0.0
HEAT PLANT EFFICIENCY:   0.70 %            COOLING PLANT EFFICIENCY:   0.71 %
COST PER THERM OF HEAT:  $  0.35           COST PER THERM OF COOLING:  $  0.0
INCREMENTAL TAX RATE:  0.480 %             AVAILABLE TAX CREDIT:  0.0   %
USEFUL LIFE:  10  YEARS


                       THICKNESS CALCULATIONS

INSULATION      INSTALLED     ANNUAL ENERGY     NET PRESENT     ANNUALIZED
THICKNESS         COST        LOSS OR GAIN         VALUE           COST
(IN INCHES)     ($/LN FT)      (BTU/LN FT)      ($/LN FT)       ($/LN FT)
  0.0              0.0         6142946.0          60.46           13.45
  1.00             5.06        1054609.0          15.56            3.46
  2.00             9.12         624146.5          15.47            3.44
  3.00            13.93         462443.4          18.81            4.19
  4.00            17.48         377010.0          21.59            4.80
  5.00            25.15         323843.7          28.92            6.44
  6.00            29.08         287377.7          32.59            7.25
READY
END
READY
LOGOFF
```

Step 4

Figure IV.3. Continued

CHAPTER V

SAMPLE STUDIES WITH ECOTHK

ECOTHK is a flexible algorithm. The solution procedure inherent to ECOTHK may be used to economically evaluate a wide variety of insulation systems and situations. It is not limited to the consideration of piping systems alone.

To illustrate this fact, a number of sample studies will be presented in this chapter. While these examples do not constitute an exhaustive listing of the potential applications of ECOTHK, they do serve to convey to the reader some of the major insulation situations for which the algorithm was developed.

Insulation of Cold Processes

The example problem of Chapter III dealt with the insulation of a hot process. Quite often, however, the analyst will be concerned with the insulation of a cold process. ECOTHK may be utilized in this type of situation just as it was in the former example.

For instance, let us consider the insulation of a cold water reservoir. Treated cold water used as a coolant in a 24-hour year-round production process must be maintained at 55 degrees F. The reservoir is a 6' x 6' x 8' free-standing steel tank located within the production building where the average ambient temperature is 80 degrees Fahrenheit.

The reader will note that this sample study differs from the example of Chapter III in two respects. First, it is a cold process problem and, secondly, it involves the transfer of heat through a flat surface.

To delineate the scope of this study, the following situational parameters are assumed:

Firm: Plastics, Inc.
Contact: S. D. Sandstrum
Insulation Type: Urethane Foam
Process Temperature: 55 degrees F.
Ambient Temperature: 80 degrees F.
Hours of Operation: 8760 hours
Minimum Attractive Rate of Return: i = 18%
General Inflationary Rate: j = 15%
Fuel Escalation Rate: k = 18%
Useful Life: 10 years
Incremental Tax Rate: 50%
Available Tax Credit: 00%
Range to be Analyzed: 0 to 2 inches
Increment: 0.50 inch
Surface Code: Flat = 0

The insulation to be analyzed is urethane foam in panel form. This insulation was chosen due to its availability, low k-value, and ease of maintenance. Evaluation of this insulation at the mean temperature of 67.5 degrees F. yields a k-value of 0.1700 BTU per hour, foot squared, degree F. This value was found in Appendix A.4.

The surface resistance of the steel tank needs to be specified at this time. An R_s-value of 0.486 may be interpolated from Appendix A.2.

The example problem of Chapter III required the determination of heating degree-hours. In a similar fashion, cooling degree-hours for this cold process may be found as follows:

$$\text{Cooling degree-hours} = \Delta T \times \text{Hours of Operation}$$
$$= (80 - 55) \times 8760 \text{ hrs/yr}$$
$$= 219{,}000 \text{ degree-hours/yr}$$

The cooling of the process water is accomplished via electric heat pumps (heat exchangers). These units are assumed to have a relative efficiency of 85%.

Research of the accounting and utility consumption records indicates that the average annual cost of cooling is approximately $0.53 per 100,000 BTU's.

Consultation with a local insulation contractor yields the appropriate installed cost information. This data is presented in Table V.1.

TABLE V.1

COST DATA FOR THE COLD WATER TANK

Thickness (in inches)	Total Project Cost
0.00	$ 0.00
0.50	643.68
1.00	669.60
1.50	723.60
2.00	784.08

Dividing these total cost figures by the exposed surface area of 216 square feet yields the installed cost per square foot for each respective thickness of urethane under consideration. Table V.2 includes the estimated annual maintenance cost of 5% of the installed cost for each layer of insulation.

TABLE V.2

COSTS PER SQUARE FOOT FOR
THE COLD WATER TANK

Thickness (in inches)	Installed Cost/Square Ft.	Maintenance Cost/Square Ft.
0.00	$ 0.00	$ 0.00
0.50	2.98	0.15
1.00	3.10	0.16
1.50	3.35	0.17
2.00	3.63	0.18

Once determined, these parameters may be submitted to ECOTHK for evaluation. Figure V.1 indicates the manner by which this data was entered into the ECOTHK algorithm via the time share option.

One inch of urethane foam yields the minimum annual after-tax cost of $0.89 per square foot of surface area. The economic thickness for this cold water process, therefore, is one inch of insulation. Multiplying the annual cost figure so obtained by the exposed surface area yields a total after-tax cost of $192.24 per year for maintaining the reservoir at 55 degrees F.

```
                ECONOMIC THICKNESS DETERMINATION

         DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT
                     OKLAHOMA STATE UNIVERSITY

                         INPUT PARAMETERS

FIRM:  PLASTICS, INC                     CONTACT:  S D SANDSTRUM
INSULATION:  URETHANE FOAM               K-VARUE:  0.1700 BTU/HR, SQ FT, DEG F
INCREMENT:   0.50 INCHES                 FINAL THICKNESS:   2.00 INCHES
AFTER-TAX MARR:   0.18 %                 GENERAL INFLATION RATE:   0.15 %
FUEL ESCALATION RATE:   0.18 %           SURFACE RESISTANCE:  0.4860 BTU/HR, SQ FT, DEG F
HEATING DEGREE-HOURS:         0.0        COOLING DEGREE-HOURS:    219000.0
HEAT PLANT EFFICIENCY:   0.85 %          COOLING PLANT EFFICIENCY:    0.85 %
COST PER THERM OF HEAT:  $  0.0          COST PER THERM OF COOLING:  $  0.53
INCREMENTAL TAX RATE:  0.500 %           AVAILABLE TAX CREDIT:  0.0   %
USEFUL LIFE:  10  YEARS


                  THICKNESS CALCULATIONS

INSULATION     INSTALLED     ANNUAL ENERGY     NET PRESENT     ANNUALIZED
THICKNESS        COST        LOSS OR GAIN         VALUE           COST
(IN INCHES)    ($/SQ FT)      (BTU/SQ FT)      ($/SQ FT)       ($/SQ FT)
  0.0             0.0          530137.9           7.05            1.57
  0.50            2.98          75177.7           4.32            0.96
  1.00            3.10          40457.4           4.00            0.89
  1.50            3.35          27675.6           4.10            0.91
  2.00            3.63          21031.2           4.31            0.96
READY
LOGOFF
```

Figure V.1. ECOTHK Output for Cold Process Example

Insulation of Building Walls

Until now, the examples in this study have been concerned with evaluation of process insulation systems. Another area of importance, however, has not yet been considered. This area of interest is the evaluation of building envelope insulation.

ECOTHK may be used to analyze building insulations just as it was employed for other evaluations. The fundamental difference in this type of application has to do with the type of research which must precede the study.

In the previous insulation systems we assumed a definite ambient and process temperature. This fundamental assumption does not hold for building insulation systems. That is, the temperature outside of the building varies with the climactic conditions. The temperature inside of the structure typically varies, also. In fact, we very often refer to the indoor temperature range as a "comfort zone" ranging from 65 to 78 degrees F.

Obviously, these conditions complicate the manner by which heating (or cooling) degree-hours for the system under evaluation may be determined. One approach to the resolution of this problem incorporates the use of standard heating and cooling degree-days.

A heating degree-day is defined as a 24-hour period in which the mean daily temperature is one degree below a base temperature; usually 65 degrees. Similarly, the cooling degree-day is thought to be a 24-hour period in which the mean daily temperature is one degree above a base temperature of 78 degrees F.

Standardized tables of geographical degree-day information exist and are presented in Appendix A.6. The heating or cooling degree-days for a building may be obtained from tables such as these. Degree-hours may then be calculated simply by multiplying the referenced value by the quantity, 24 hours/day. The derived quantity is analogous to the heating or cooling degree-hours found by the product of the temperature difference and the hours of operation.

Degree-hours is the form in which heating or cooling load must be submitted to ECOTHK. Therefore, building insulation systems may be evaluated by using the standard tables presented in the appendices.

To further illustrate this technique, another example study will be undertaken at this time. Let us consider a production building the walls of which are constructed of eight inch concrete blocks. There is currently no insulation on these exterior walls. It is felt that the ceiling of this building is adequately insulated and, as such, our study will deal exclusively with the analysis of the wall insulation.

Suppose further that the following information is indicative of the scope of this study:

Firm: Plastics, Inc.
Contact: S. D. Sandstrum
Insulation Type: Fiberglass Batts
Minimum Attractive Rate of Return: $i = 18\%$
General Inflationary Rate: $j = 14\%$
Fuel Escalation Rate: $k = 20\%$

Useful Life: 15 years
Incremental Rate: 50%
Available Tax Credit: 00%
Range to be Analyzed: 0 to 9 inches
Increment: 1.00 inch
Surface Code: Flat = 0
Average Cost of Heat: 0.37 per therm
Average Cost of Cooling: 0.49 per therm
Heat Plant Efficiency: 75%
Cooling Plant Efficiency: 83%

The indoor temperature for this structure will range from 65 to 78 degrees F. This means that the average annual temperature exposure of the proposed insulation will be about 71.5 degrees F. Evaluating the insulation at this average yields a k-value of 0.36 BTU per hour, square foot, degree F.

Determination of the existing surface resistance for this example will require a little more study than it has in the previous examples. Using Appendices A.1 and A.3, we can find the overall surface resistance as follows:

Outside Air Conductance: $f_o = 6$ @ 15 MPH

Eight Inch Concrete Block: $U = 0.58$

Inside Air Conductance: $f_i = 1.47$

Combining this information gives an R_s-value as shown below:

$$\begin{aligned} R_s &= U + \frac{1}{f_o} + \frac{1}{f_i} \\ &= 0.58 + \frac{1}{6} + \frac{1}{1.47} \\ &= 1.427 \text{ BTU/hr, ft}^2\text{, deg. F.} \end{aligned}$$

Therefore, for the eight inch concrete block walls we may assume a surface resistance of 1.427 BTU per hour, square foot, degree F. It is this value which will need to be submitted to the ECOTHK algorithm for the "existing surface resistance" variable.

Let us assume that the building under analysis is located in Lexington, Kentucky. From Appendix A.6.A, the annual heating degree-days for Lexington is found to be 4683.

The location of interest does not appear in Appendix A.6.B. Therefore, to determine the cooling degree-days for the situation at hand one should search for the site nearest to that area at approximately the same latitude. Cooling degree-days above 78 degrees for St. Louis, Missouri, will be assumed for this sample study. This gives approximately 6400 degree-days for cooling the facility at Lexington, Kentucky.

Multiplying each of these values by 24 hours/day will yield heating and cooling degree-hours per year. The determined values are 112,392 and 153,600, respectively.

Suppose further that consultation with an insulation contractor yields the cost data shown in Table V.3. The indicated maintenance costs are based on 1% of the installed costs.

TABLE V.3

COST DATA FOR FIBERGLASS WALL INSULATION

Thickness (in inches)	Installed Cost/Square Ft.	Maintenance Cost/Square Ft.
0.00	$ 0.00	$ 0.00
1.00	1.31	0.01
2.00	1.53	0.02
3.00	1.65	0.02
4.00	1.84	0.02
5.00	2.01	0.02
6.00	2.15	0.02
7.00	3.27	0.03
8.00	3.43	0.03
9.00	3.57	0.04

The interactive mode of ECOTHK may now be accessed to evaluate the proposed insulation system. Figure V.2 is the hardcopy that results from ECOTHK's execution. Based on the degree-day method proposed here, the economic thickness for this system is found to be three inches of fiberglass batting. This thickness will realize an annual after-tax cost of $0.43 per square foot based on the assumed parameters.

Three example problems have been presented so far within this study. These sample studies should indicate to the reader the comprehensive nature of the ECOTHK algorithm.

One may conclude from these sample problems that ECOTHK is compatible with piping system, flat surface, and building envelope analysis. Furthermore, the evaluation of either hot or cold or both hot and cold processes may be accommodated by the ECOTHK algorithm. As a result, the potential of ECOTHK is such that it should play a major role in energy management practices.

At this time it would prove beneficial to address two areas closely related to the use of the ECOTHK algorithm. These topics include the subject of sensitivity analysis and estimation of the fuel escalation rate. Each of these concepts will be discussed subsequently.

Sensitivity Analysis

Sensitivity analysis involves the variation of one specific input variable while maintaining the other input

```
                    ECONOMIC THICKNESS DETERMINATION

               DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT
                          OKLAHOMA STATE UNIVERSITY

                              INPUT PARAMETERS

FIRM:  PLASTICS, INC                    CONTACT:  S D SANDSTRUM
INSULATION:  FIBREGLASS BATTS           K-VAKUE:  0.3600 BTU/HR, SQ FT, DEG F
INCREMENT:  1.00 INCHES                 FINAL THICKNESS:   9.00 INCHES
AFTER-TAX MARR:   0.18 %                GENERAL INFLATION RATE:   0.14 %
FUEL ESCALATION RATE:   0.20 %          SURFACE RESISTANCE:  1.4270 BTU/HR, SQ FT, DEG F
HEATING DEGREE-HOURS:    112392.0       COOLING DEGREE-HOURS:    153600.0
HEAT PLANT EFFICIENCY:   0.75 %         COOLING PLANT EFFICIENCY:   0.83 %
COST PER THERM OF HEAT:  $  0.37        COST PER THERM OF COOLING:  $  0.49
INCREMENTAL TAX RATE:  0.500 %          AVAILABLE TAX CREDIT:  0.0   %
USEFUL LIFE:  15  YEARS


                           THICKNESS CALCULATIONS

INSULATION      INSTALLED    ANNUAL ENERGY    NET PRESENT    ANNUALIZED
THICKNESS         COST       LOSS OR GAIN        VALUE          COST
(IN INCHES)    ($/SQ FT)     (BTU/SQ FT)      ($/SQ FT)      ($/SQ FT)
  0.0             0.0         234699.6           3.47           0.68
  1.00            1.31         79651.3           2.51           0.49
  2.00            1.53         47964.7           2.29           0.45
  3.00            1.65         34314.0           2.21           0.43
  4.00            1.84         26711.9           2.29           0.45
  5.00            2.01         21867.2           2.38           0.47
  6.00            2.15         18510.2           2.47           0.49
  7.00            3.27         16046.6           3.58           0.70
  8.00            3.43         14161.8           3.72           0.73
  9.00            3.57         12673.3           3.86           0.76
READY
LOGOFF
```

Figure V.2. ECOTHK Output for Building Insulation parameters at their assumed values. In this way, the variation of the parameter so tested may be evaluated in light of its net impact of the overall analysis performed.

As has been indicated, ECOTHK may be used to perform a sensitivity analysis on the evaluation of an insulation system. To demonstrate this fact, let us consider the cold water reservoir presented earlier in this chapter. Let us suppose that the data with regard to the fuel escalation rate is somewhat suspect. For this reason, the analyst is leary of the assumed value of 18% per year.

Using ECOTHK the impact of this parameter on the economic thickness determination may be analyzed. This is accomplished by simply repeating the execution of ECOTHK on the time share option while substituting new values for the fuel escalation rate and maintaining the other input variables as constants.

Figure V.3 shows the output that results from the sensitivity analysis performed on the cold water reservoir. In this analysis, the parameter in question, the fuel escalation rate, was allowed to vary from 16% to 20% per year.

This variance of ± 2% in the assumed value of the fuel escalation rate resulted in no appreciable change in the economic thickness for this sample study. The analyst should rest assured of the thickness at which the minimum annual cost will be realized despite his suspicion of the assumed value for the fuel escalation rate in this situation.

```
                    ECONOMIC THICKNESS DETERMINATION

              DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT
                          OKLAHOMA STATE UNIVERSITY

                              INPUT PARAMETERS

FIRM:  PLASTICS, INC                     CONTACT:  S D SANDSTRUM
INSULATION:  URETHANE FOAM               K-VAKUE:  0.1700 BTU/HR, SQ FT, DEG F
INCREMENT:   0.50 INCHES                 FINAL THICKNESS:   2.00 INCHES
AFTER-TAX MARR:   0.18 %                 GENERAL INFLATION RATE:   0.15 %
FUEL ESCALATION RATE:   0.16 %           SURFACE RESISTANCE:  0.4860 BTU/HR, SQ FT, DEG F
HEATING DEGREE-HOURS:         0.0        COOLING DEGREE-HOURS:    219000.0
HEAT PLANT EFFICIENCY:   0.85 %          COOLING PLANT EFFICIENCY:   0.85 %
COST PER THERM OF HEAT:  $  0.0          COST PER THERM OF COOLING:  $  0.53
INCREMENTAL TAX RATE:  0.500 %           AVAILABLE TAX CREDIT:  0.0   %
USEFUL LIFE:  10  YEARS


                     THICKNESS CALCULATIONS

INSULATION     INSTALLED     ANNUAL ENERGY     NET PRESENT     ANNUALIZED
THICKNESS        COST        LOSS OR GAIN         VALUE           COST
(IN INCHES)   ($/SQ FT)      (BTU/SQ FT)       ($/SQ FT)       ($/SQ FT)
   0.0           0.0          530137.9            6.55            1.46
   0.50          2.98          75177.7            4.25            0.94
   1.00          3.10          40457.4            3.96            0.88
   1.50          3.35          27675.6            4.07            0.91
   2.00          3.63          21031.2            4.29            0.96
READY
```

Figure V.3. Sensitivity Analysis of Cold Water Tank Problem Using ECOTHK

```
                    ECONOMIC THICKNESS DETERMINATION

          DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT
                      OKLAHOMA STATE UNIVERSITY

                          INPUT PARAMETERS

FIRM:  PLASTICS, INC                     CONTACT:  S D SANDSTRUM
INSULATION:  URETHANC FOAM               K-VAKUE:  0.1700 BTU/HR, SQ FT, DEG F
INCREMENT:   0.50 INCHES                 FINAL THICKNESS:   2.00 INCHES
AFTER-TAX MARR:   0.18 %                 GENERAL INFLATION RATE:   0.15 %
FUEL ESCALATION RATE:   0.17 %           SURFACE RESISTANCE:  0.4860 BTU/HR, SQ FT, DEG F
HEATING DEGREE-HOURS:          0.0       COOLING DEGREE-HOURS:    219000.0
HEAT PLANT EFFICIENCY:   0.85 %          COOLING PLANT EFFICIENCY:   0.85 %
COST PER THERM OF HEAT:  $  0.0          COST PER THERM OF COOLING:  $  0.53
INCREMENTAL TAX RATE:  0.500 %           AVAILABLE TAX CREDIT:  0.0   %
USEFUL LIFE:  10  YEARS


                       THICKNESS CALCULATIONS

INSULATION      INSTALLED     ANNUAL ENERGY    NET PRESENT    ANNUALIZED
THICKNESS         COST        LOSS OR GAIN        VALUE          COST
(IN INCHES)     ($/SQ FT)      (BTU/SQ FT)      ($/SQ FT)      ($/SQ FT)
  0.0             0.0          530137.9           6.79           1.51
  0.50            2.98          75177.7           4.28           0.95
  1.00            3.10          40457.4           3.98           0.89
  1.50            3.35          27675.6           4.09           0.91
  2.00            3.63          21031.2           4.30           0.96
READY
```

Figure V.3. Continued

```
                    ECONOMIC THICKNESS DETERMINATION

             DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT
                         OKLAHOMA STATE UNIVERSITY

                            INPUT PARAMETERS

FIRM:  PLASTICS, INC                         CONTACT:  S D SANDSTRUM
INSULATION:  URETHANE FOAM                   K-VAKUE:  0.1700 BTU/HR, SQ FT, DEG F
INCREMENT:    0.50 INCHES                    FINAL THICKNESS:   2.00 INCHES
AFTER-TAX MARR:   0.18 %                     GENERAL INFLATION RATE:   0.15 %
FUEL ESCALATION RATE:   0.18 %               SURFACE RESISTANCE:  0.4860 BTU/HR, SQ FT, DEG F
HEATING DEGREE-HOURS:           0.0          COOLING DEGREE-HOURS:    219000.0
HEAT PLANT EFFICIENCY:   0.85 %              COOLING PLANT EFFICIENCY:   0.85 %
COST PER THERM OF HEAT:  $  0.0              COST PER THERM OF COOLING:  $  0.53
INCREMENTAL TAX RATE:  0.500 %               AVAILABLE TAX CREDIT:  0.0   %
USEFUL LIFE:  10  YEARS


                        THICKNESS CALCULATIONS

INSULATION     INSTALLED     ANNUAL ENERGY    NET PRESENT    ANNUALIZED
THICKNESS        COST        LOSS OR GAIN        VALUE          COST
(IN INCHES)    ($/SQ FT)      (BTU/SQ FT)      ($/SQ FT)      ($/SQ FT)
  0.0            0.0          530137.9           7.05           1.57
  0.50           2.98          75177.7           4.32           0.96
  1.00           3.10          40457.4           4.00           0.89
  1.50           3.35          27675.6           4.10           0.91
  2.00           3.63          21031.2           4.31           0.96
READY
LOGOFF
```

Figure V.3. Continued

```
                    ECONOMIC THICKNESS DETERMINATION

              DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT
                         OKLAHOMA STATE UNIVERSITY

                             INPUT PARAMETERS

FIRM:  PLASTICS, INC                    CONTACT:  S D SANDSTRUM
INSULATION:  URETHANE FOAM              K-VAKUE:  0.1700 BTU/HR, SQ FT, DEG F
INCREMENT:   0.50 INCHES                FINAL THICKNESS:   2.00 INCHES
AFTER-TAX MARR:   0.18 %                GENERAL INFLATION RATE:   0.15 %
FUEL ESCALATION RATE:   0.19 %          SURFACE RESISTANCE:  0.4860 BTU/HR, SQ FT, DEG F
HEATING DEGREE-HOURS:          0.0      COOLING DEGREE-HOURS:    219000.0
HEAT PLANT EFFICIENCY:   0.85 %         COOLING PLANT EFFICIENCY:   0.85 %
COST PER THERM OF HEAT:  $  0.0         COST PER THERM OF COOLING:  $  0.53
INCREMENTAL TAX RATE:  0.500 %          AVAILABLE TAX CREDIT:  0.0   %
USEFUL LIFE:  10  YEARS


                      THICKNESS CALCULATIONS

INSULATION      INSTALLED      ANNUAL ENERGY     NET PRESENT     ANNUALIZED
THICKNESS         COST         LOSS OR GAIN         VALUE           COST
(IN INCHES)     ($/SQ FT)       (BTU/SQ FT)      ($/SQ FT)       ($/SQ FT)
  0.0             0.0           530137.9            7.32           1.63
  0.50            2.98           75177.7            4.35           0.97
  1.00            3.10           40457.4            4.02           0.89
  1.50            3.35           27675.6            4.11           0.92
  2.00            3.63           21031.2            4.32           0.96
READY
```

Figure V.3. Continued

```
                    ECONOMIC THICKNESS DETERMINATION

            DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT
                        OKLAHOMA STATE UNIVERSITY

                            INPUT PARAMETERS

FIRM:   PLASTICS, INC                      CONTACT:   S D SANDSTRUM
INSULATION:   URETHANE FOAM                K-VAKUE:   0.1700 BTU/HR, SQ FT, DEG F
INCREMENT:    0.50 INCHES                  FINAL THICKNESS:    2.00 INCHES
AFTER-TAX MARR:    0.18 %                  GENERAL INFLATION RATE:    0.15 %
FUEL ESCALATION RATE:    0.20 %            SURFACE RESISTANCE:  0.4860 BTU/HR, SQ FT, DEG F
HEATING DEGREE-HOURS:          0.0         COOLING DEGREE-HOURS:     219000.0
HEAT PLANT EFFICIENCY:    0.85 %           COOLING PLANT EFFICIENCY:    0.85 %
COST PER THERM OF HEAT:   $   0.0          COST PER THERM OF COOLING:   $   0.53
INCREMENTAL TAX RATE:   0.500 %            AVAILABLE TAX CREDIT:   0.0    %
USEFUL LIFE:   10   YEARS


                      THICKNESS CALCULATIONS

INSULATION      INSTALLED     ANNUAL ENERGY     NET PRESENT      ANNUALIZED
THICKNESS         COST        LOSS OR GAIN         VALUE            COST
(IN INCHES)     ($/SQ FT)      (BTU/SQ FT)      ($/SQ FT)       ($/SQ FT)
   0.0             0.0          530137.9           7.60            1.69
   0.50            2.98          75177.7           4.39            0.98
   1.00            3.10          40457.4           4.04            0.90
   1.50            3.35          27675.6           4.13            0.92
   2.00            3.63          21031.2           4.34            0.96
READY
LOGOFF
```

Figure V.3. Continued

The reader should note that the range of variation for k does not include 15%. Assuming the escalation rate equal to the specified inflation rate would have resulted in default of the ECOTHK algorithm. Therefore, the lower limit of the range over which the fuel escalation rate is analyzed is bounded by the assumed value of the general inflationary trend. This topic was discussed at length in Chapter III.

Determination of the Fuel Escalation Rate

The fuel escalation rate may be thought of as the annual compounding rate at which fuel costs have risen over an assumed period of time. An article by J. A. Bontadelli and W. G. Sullivan in a recent issue of Industrial Engineering [11] outlines the method by which the fuel escalation rate may be estimated. They maintain that the escalation rate, k, may be found by evaluating the single sum compound amount factor indicative of the price increases realized over an unspecified number of years. The relationship to be evaluated is indicated by Equation V.1.

$$\text{Future Price} = \text{Present Price} \times (1 + k)^n \qquad (V.1)$$

To illustrate the methodology involved here, let us assume that we have available the cost data shown in Table V.4. The fuel escalation rate, k, should reflect the overall annual rate of increase in fuel prices over the years for which the data is available.

By substituting the appropriate values into Equation V.1 and solving for k, the fuel escalation rate for the energy costs shown in Table V.4 may be determined. This procedure is indicated below.

$$\text{Future Price} = \text{Present Price} \times (1 + k)^n$$

$$0.53 = 0.10 \times (1 + k)^{10}$$

$$(1 + k)^{10} = 5.30$$

$$k = 0.1815 = 18.15\%$$

TABLE V.4

COST DATA FOR FUEL ESCALATION RATE EVALUATION

Year	Cost per Therm
1970	$ 0.10
1971	0.10
1972	0.15
1973	0.16
1974	0.32
1975	0.42
1976	0.45
1977	0.46
1978	0.49
1979	0.53

Therefore, the escalation rate for the fuel costs depicted in Table V.4 was found to be 18.15%. It should be pointed out that this is an overall rate indicative of the increased costs over the full ten year period. Evaluation of intermediate prices may vary significantly using this interest rate. Another approach would be to estimate the average annual fuel cost increase over the same ten year period.

The purpose of this chapter has been to illustrate some of the concepts characteristic to the application of the ECOTHK algorithm through the consideration of a few new example studies. Furthermore, the use of ECOTHK as a tool by which to perform sensitivity analyses was exemplified. Finally, a method by which to estimate the fuel escalation rate, k, was presented.

At this time the reader is urged to review the user instructions of Chapter IV once again and attempt an evaluation of his own using the ECOTHK algorithm. If an insulation study cannot be readily identified, try running one of the example problems set forth in this study. As a result of this exercise, the ease of evaluation and flexibility afforded by ECOTHK will become self-evident.

CHAPTER VI

CONCLUDING REMARKS

An Overview

From all indications, the energy problem will be with us for quite some time. Sky-rocketing fuel costs, runaway inflation, and record-high interest rates all substantiate the persistence of the energy paradox. These same factors serve to confound the engineer or analyst as he attempts to economically evaluate energy related proposals.

As a result of the foregoing discussion, one may see how each of the economic parameters indicated above may be incorporated into the analysis of energy management projects. While this study was directed to the evaluation of insulation systems, it should be noted here that the same basic analytical approach developed within these pages may be applied to other energy proposals. A comphrehensive understanding of these analytical techniques has been one of the primary purposes of this study.

The inclusion of fuel escalation rates and inflationary indices proved to be quite cumbersome for the evaluation of insulation systems when performed by hand. ECOTHK, a computer program by which to analyze insulation, was developed as a consequence. This algorithm uses the standard principles of heat transfer and engineering economic analysis to make the investigation of insulation proposals in a more efficient manner.

The ECOTHK algorithm was then made interactive via the time share option at Oklahoma State University to increase its accessibility. The reasoning behind this action will become evident in the paragraphs that follow.

Uses of the ECOTHK Algorithm

It is the author's contention that the ultimate resolution of the current energy situation may be facilitated through continued research in the energy area and increased efforts to educate American industry and citizenry with regard to the progress of this research. Only through the cooperative efforts of universities, private research foundations, the industrial complex, and the conservatory actions of the individual citizen will the energy problem be overcome.

Several programs exist at Oklahoma State University which are devoted to the development of sound principles for the efficient and judicious management of the available energy resources. These programs, sponsored by the School of Industrial Engineering and Management, are compatible with the perspective taken in this paper. The degree of compatibility is exemplified by O.S.U.'s three-fold mission: education, research, and extension.

Due to this congruity of purpose, the ECOTHK algorithm is offered to the School of Industrial Engineering and

Management at Oklahoma State University for use in their energy related programs. The potential applications relative to the incorporation of ECOTHK into these programs will now be discussed.

The School of Industrial Engineering and Management has formed a major research thrust in the area of energy management. This commitment is reflected by the courses offered through this school at the graduate and undergraduate level in the areas of economic analysis and energy management.

With respect to these classes, the ECOTHK algorithm should prove useful as a teaching aide. Making ECOTHK accessible to these classes should result in the student's improved understanding of the principles of engineering economic analysis, energy management, and the fundamentals of heat transfer.

The School of Industrial Engineering and Management also supports several programs the primary purposes of which are to educate and consult industry and citizens across the state of Oklahoma. ECOTHK may prove extremely helpful as a tool by which to help these clients evaluate their respective insulation proposals.

The time share capability of the ECOTHK algorithm proves highly beneficial with regard to these programs. This aspect allows efficient utilization of the program by the client as well as by the student. The client's access may be accommodated through a remote computer terminal connection to the O.S.U. Computer Center or by requesting a representative of the department to conduct the study for him. The representative, either a faculty member or a graduate assistant, may then access ECOTHK via one of the terminals in Engineering North 315. The resulting hardcopy and documentation may then be mailed to the client.

The intent of this study was the development of something more than just a report to fulfill the requirements for the Master of Science degree. Rather, the goal has been to develop a potential service in the area of energy management for those who seek advice with regard to insulation practices. If ECOTHK is utilized within the School of Industrial Engineering and Management for the classroom, the energy management programs, or to simply initiate further research with regard to the optimization of the capital invested in energy related proposals, this intent will be realized.

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APPENDICES

APPENDIX A.1.A

CONDUCTIVITIES OF COMMON BUILDING AND INSULATING MATERIALS [7, 13, 17]

Material			Mean Temp. °F	Conductivity k (or U Value)
BUILDING CONSTRUCTION MATERIALS				
Asbestos board		120# Density	68	5.17
Asbestos, compressed		77# Density	59	1.78
Asbestos paper		31# Density	50	0.50
		61# Density	68	1.00
			212	1.09
Asbestos slate		111# Density	122	1.53
Asbestos wood				
Asbestos, cement-compressed, hard, rigid		123# Density	86	2.70
Asphalt, street		132# Density	68	5.28
Beaver board				
Cane fiber		13.8# Density	75	0.33
Spruce fiber		31# Density	75	1.97
Cane fiber board		(Celotex)		
		13.8# Density	75	0.33
			90	0.34
Ebonite		74# Density	68	0.41
Glass				
Flint			59	4.16
Plate			68	5.55
Soda		161# Density	68	4.94
Quartz			212	13.27
Gypsum block		42.7# Density	32	1.69
			68	1.86
			86	1.94
Gypsum board				
Gypsum board covered with paper		62# Density	70	1.44
	1/2" Thick	53.5# Density	68	2.60 (U)
Linoleum			32	1.21
			68	1.29
			75	1.36

Appendix A.1.A Continued

Material		Mean Temp. °F	Conductivity k (or U Value)
BUILDING CONSTRUCTION MATERIALS (continued)			
Masonite	20# Density	75	0.33
Plaster and lath			
Metal lath and plaster	3/4" Thick	70	4.4 (U)
Wood lath and plaster	3/4" Thick	70	2.6 (U)
Plaster board			
Covered with paper	61# Density		
3/8" Thick		70	3.73 (U)
1/2" Thick		70	2.83 (U)
Plaster, gypsum	52.4# Density	68	1.77
	46.2# Density	86	2.32
Porcelain		329	11.30
Quartz		212	13.27
Rubber	68.6# Density	86	1.22
Shingles			
Asbestos	65# Density	75	6.0 (U)
Asphalt	70# Density	75	6.5 (U)
Slate	201# Density	75	10.37 (U)
Wood		75	1.28 (U)
Slate			
Across cleavage		50	9.15 to 10.45
Along cleavage		50	10.00 to 18.9
Strawboard	43# Density	86	0.50
Textan			
Rubber composition	81# Density	86	1.17
Wood pulp board	43# Density	86	0.49
Wood felt	20.6# Density	86	0.37
Wood fiber board	19.8# Density	75	0.33
	11.9# Density	86	0.30
	28.5# Density	75	0.50
MASONRY MATERIALS			
Brick			
Low density		70	5.0
High density		70	9.2
Red building, soft burned		600	4.3
		800	4.6
		1000	4.9
Red building, hard burned		600	7.4
		800	8.2
		1000	9.0
Brick—slag	87.4# Density	59	87.4
Cement plaster		70	8.0
Cinder block			
4 x 8 x 16—Solid		40	1.00 (U)
8 x 8 x 16—With standard hollow spaces		40	0.58 (U)
12 x 8 x 16—With standard hollow spaces		40	0.53 (U)
Concrete			
Typical		40	12.00
Concrete Block			
8 x 8 x 16—Sand and gravel aggregate (hollow)		40	0.9 (U)
8 x 8 x 16—Limestone aggregate (hollow)		40	0.86 (U)
12 x 8 x 16—Sand and gravel aggregate (hollow)		40	0.78 (U)
Solid		88	8.2
Concrete, cellulated			
	40# Density	75	1.06
	50# Density	75	1.44
	60# Density	75	1.80
	70# Density	75	2.18

Appendix A.1.A Continued

Material				Mean Temp. °F	Conductivity k (or U Value)
MASONRY MATERIALS (continued)					
Concrete, cinder					
1:2:2.75 Ratio		104#	Density	75	4.63
1:2.75:4.5 Ratio		99#	Density	75	4.30
1:3.5:5.5 Ratio		92#	Density	75	3.73
Concrete–cork filled					
1 Portland: 2 Sand: 3 Granulated cork		79#	Density	185	1.79
Concrete gypsum					
87.5% Gypsum, 12.5% Wood chips		51#	Density	74	1.66
Concrete, Haydite					
1:2:2.75 Ratio		80#	Density	75	4.15
1:2.75:4.5 Ratio		75#	Density	75	3.78
1:3.5:5.5 Ratio		72#	Density	75	3.67
1:8 Ratio		67#	Density	75	2.90
Concrete, limestone					
1:2:2.7 Ratio		135#	Density	75	11.2
1:2.75:4.5 Ratio		138#	Density	75	12.0
1:3.5:5.5 Ratio		136#	Density	75	11.5
Concrete, sand and gravel					
1:2:2.75 Ratio		145#	Density	75	13.1
1:2.75:4.5 Ratio		146#	Density	75	12.9
1:3.5:5.5 Ratio		145#	Density	75	13.2
Dolomite, compact				70	13.6 to 16.3
Domont brick (Terracotta)		113#	Density	196	4.62
Glagstone					
Across cleavage				70	12.8
Along cleavage				70	18.4
Freestone, sandstone				70	6.1
Glass block				100	0.46 (U)
				200	0.49 (U)
				300	0.53 (U)
				400	0.56 (U)
				500	0.60 (U)
Granite				70	15.0 to 22.0
Gravel					
Fine (0.16" to 0.35")		91#	Density	185	1.63
Dry Stones (1" to 3")		115#	Density	32	2.34
				68	2.58
				104	2.83
Gypsum Board					
Gypsum board					
covered with paper		62#	Density	70	1.44
	1/2" Thick.	53.5#	Density	68	2.6 (U)
Gypsum plaster					
		52.4#	Density	68	1.77
		46.2#	Density	86	2.32
Gypsum tile				50	.46
3 x 3 x 16		67#	Density	40	.50 (U)
Gypsum tile				50	.46
Haydite block					
8 x 8 x 16		67#	Density	40	.50 (U)
8 x 12		77#	Density	40	.46 (U)
Insulux Glass Block				100	.46 (U)
				200	.49 (U)
				300	.53 (U)
				400	.57 (U)
				500	.50 (U)
Lime					
Hard				50	25.57
Limestone					
				32	4.8
				59	4.9
				68	5.1
				77	5.2

Appendix A.1.A Continued

Material			Mean Temp. °F	Conductivity k (or U Value)
	MASONRY MATERIALS (continued)			
Marble			86	14.5 to 19.9
Millstone		78.5# Density	177	3.36
Mortar		107# Density	191	2.24
		117# Density	191	3.71
Onyx			86	16.14
Red Brick			200	5.4
			400	5.7
			600	6.1
			800	6.5
			1000	8.6
Sand				
Fine (less than .08"—Dry)		96# Density	32	2.10
			68	2.26
Fine—common moisture		98# Density	68	8.60
Sandstone				
Fresh cut—natural gray		141# Density	50	10.72
			68	11.62
			104	12.75
Slate				
Across cleavage			50	9.15 to 10.45
Along cleavage			50	16.00 to 18.9
Soapstone		171# Density	158	23.22
Stucco			50	12.00
Terra Cotta		112# Density	196	4.62
Terrazzo			50	12.00
Tile, clay hollow				
4"			50	1.00 (U)
6"			50	0.64 (U)
8"			50	0.60 (U)
10"			50	0.58 (U)
12"			50	0.40 (U)
Tile, gypsum				
4" hollow tile			50	0.46 (U)
	METALS			
Aluminum		168 to 170# Density	−290	1396.0
			32	1396.0
			210	1430.0
			570	1597.0
			930	1855.0
Antimony		413# Density	32	128.35
			212	115.0
Brass	Yellow Brass		32	592.5
			212	738.0
	Red Brass		32	714.0
			212	820.0
Bronze			68	410.0
			210	492.0
Copper			32	2190.0
			212	2324.0
			390	2574.0
Gold			−420	1048.0
			32	2160.0
			390	2145.0
Iron				
Cast			86	432.5
Iron wrought		492# Density	65	417.0
			212	412.0

Appendix A.1.A Continued

Material		Mean Temp. °F	Conductivity k (or U Value)
METALS (continued)			
Lead		−297	313.8
		10.4	276.3
		32	244.5
		64.4	241.0
		210	233.0
Magnesium	108# Density	210	1089.0
Mercury		32	50.2
		212	62.8
Nickel (99%)		−256	374.5
		50	403.0
		930	331.0
		1650	306.0
Platinum		212	485.0
Silver		−256	2900.0
		32	3135.0
		212	2880.0
		644	2920.0
Steel			
Less 0.1% carbon		210	379.0
		570	347.0
		1110	258.0
		1650	234.0
Less than 0.6% carbon		210	290.0
		1110	234.0
		1650	202.0
Approximately 1.5% carbon		210	258.0
		570	249.0
		1110	234.0
		1650	202.0
Steel chromium		86	213.0 to 291.0
Steel, puddled		59	319
Steel wool			
No. 2 Size Fiber	4.74# Density	132	0.63
	6.3# Density	132	0.61
	9.48# Density	132	0.55
Tin		32	443.0
		212	413.0
MISCELLANEOUS			
Air			
(No heat transfer by radiation or convection)		70	0.175
Air spaces and aluminum foil spacers—vertical			
1 1/2" space divided by			
Aluminum foil (bright both sides)		50	0.23 (U)
3/4" space divided by			
Aluminum foil (bright both sides)		50	0.31 (U)
2 1/4" space divided by two curtains			
Aluminum foil (bright both sides)		50	0.15 (U)
3" space divided by three curtains			
Aluminum foil (bright both sides)		50	0.11 (U)
3 3/4" space divided by four curtains			
Aluminum foil (bright both sides)		50	0.09 (U)
Air spaces and aluminum foil spacers			
3 5/8" faced both sides with aluminum foil			
Vertical (heat flow across)		50	0.56 (U)
Horizontal (heat flow up)		50	0.94 (U)
Horizontal (heat flow down)		50	0.41 (U)
Air spaces with ordinary building materials			
3 5/8" face with material of emissivities = .83			

Appendix A.1.A Continued

Material			Mean Temp. °F	Conductivity k (or U Value)
MISCELLANEOUS (continued)				
Vertical (heat flow across)			50	1.17 (U)
Horizontal (heat flow up)			50	1.32 (U)
Horizontal (heat flow down)			50	0.94 (U)
Celluloid, white			86	1.46
Chalk			70	6.48
Charcoal		11.85# Density	32	0.41
			104	0.46
			176	0.51
Clay	Dried		50	3.60
	Wet		50	16.09
Clinkers, from boilers		46.8# Density	32	1.05
			68	1.13
Coal dust	Dry	62.4# Density	32	0.97
			68	1.05
Lamp black		12.05# Density	132	0.22
			316	0.27
			441	0.32
Leather		62# Density	50	1.10
Linen			50	0.61
Paraffin		55# Density	86	1.60
Peat Moss	Dry	11.8# Density	32	0.33
			68	0.34
	Damp	12.17# Density	68	0.57
Plaster of Paris				
Powder			50	7.55
Set			50	2.04
Rubber	Hard	74.3# Density	99	1.11
	Soft	68.6# Density	86	1.22
	Sponge	14# Density	50	1.38
Sawdust				
Various, dry		12# Density	90	0.41
Pine, loose, dry		3.6# Density	166	0.57
Silk Fibers		9.2# Density	32	0.32
			122	0.38
			212	0.42
Soil	Dry		50	0.96
	Including stones— Normal dampness		32	3.47
			68	3.63
			158	4.03
	Wet		50	4.64
Vacuum				
Silvered vacuum jacket				
Residual air pressure 0.001 MM of Hg			77	0.0042 (U)
WOOD				
Balsa				
Across grain		20.6# Density	86	0.59
		7.05# Density	86	0.32
California Redwood (across grain)				
0% Moisture		22# Density	75	0.66
8% Moisture		22# Density	75	0.70
16% Moisture		22# Density	75	0.74
0% Moisture		28# Density	75	0.70
8% Moisture		28# Density	75	0.75
16% Moisture		28# Density	75	0.80
Cypress (across grain)				
0% Moisture		22# Density	75	0.67

Appendix A.1.A Continued

Material		Mean Temp. °F	Conductivity k (Or U Value)
WOOD (continued)			
8% Moisture	22# Density	75	0.71
16% Moisture	22# Density	75	0.79
0% Moisture	32# Density	75	0.79
8% Moisture	32# Density	75	0.84
16% Moisture	32# Density	75	0.90
Elm—Soft (across grain)			
0% Moisture	28# Density	75	0.73
8% Moisture	28# Density	75	0.77
16% Moisture	28# Density	75	0.81
0% Moisture	34# Density	75	0.88
8% Moisture	34# Density	75	0.93
16% Moisture	34# Density	75	0.97
Fir (across grain)			
0% Moisture	26# Density	75	0.61
8% Moisture	26# Density	75	0.66
16% Moisture	26# Density	75	0.76
0% Moisture	34# Density	75	0.67
8% Moisture	34# Density	75	0.75
16% Moisture	34# Density	75	0.82
Hemlock, Eastern (across grain)			
0% Moisture	22# Density	75	0.60
8% Moisture	22# Density	75	0.63
16% Moisture	22# Density	75	0.67
0% Moisture	30# Density	75	0.76
8% Moisture	30# Density	75	0.81
16% Moisture	30# Density	75	0.85
Hemlock, West Coast (across grain)			
0% Moisture	22# Density	75	0.68
8% Moisture	22# Density	75	0.73
16% Moisture	22# Density	75	0.78
0% Moisture	30# Density	75	0.79
8% Moisture	30# Density	75	0.85
16% Moisture	30# Density	75	0.91
Mahogany (across grain)	34# Density	86	0.90
Maple, Hard			
Across Grain	45# Density	127	1.26
Along Grain	45# Density	127	3.02
0% Moisture	40# Density (Across Grain)	75	1.01
8% Moisture	40# Density (Across Grain)	75	1.08
16% Moisture	40# Density (Across Grain)	75	1.15
0% Moisture	46# Density (Across Grain)	75	1.05
8% Moisture	46# Density (Across Grain)	75	1.13
16% Moisture	46# Density (Across Grain)	75	1.21
Maple, Soft (Across grain)			
0% Moisture	36# Density	75	0.89
8% Moisture	36# Density	75	0.96
16% Moisture	36# Density	75	1.01
0% Moisture	42# Density	75	0.95
8% Moisture	42# Density	75	1.02
16% Moisture	42# Density	75	1.09
Oak			
Across grain	51# Density	32	1.38
		59	1.46

Appendix A.1.A Continued

Material		Mean Temp. °F	Conductivity k (or U Value)
WOOD (continued)			
Along grain	51# Density	54	2.42
		60	2.50
		120	2.99
0% Moisture	38# Density (Across Grain)	75	0.98
8% Moisture	38# Density (Across Grain)	75	1.03
16% Moisture	38# Density (Across Grain)	75	1.07
0% Moisture	48# Density (Across Grain)	75	1.18
8% Moisture	48# Density (Across Grain)	75	1.24
16% Moisture	48# Density (Across Grain)	75	1.29
Pine, Norway (across grain)			
0% Moisture	22# Density	75	0.62
8% Moisture	22# Density	75	0.68
16% Moisture	22# Density	75	0.74
0% Moisture	32# Density	75	0.74
8% Moisture	32# Density	75	0.83
16% Moisture	32# Density	75	0.92
Pine, Sugar (across grain)			
0% Moisture	22# Density	75	0.54
8% Moisture	22# Density	75	0.59
16% Moisture	22# Density	75	0.65
0% Moisture	30# Density	75	0.64
8% Moisture	30# Density	75	0.71
16% Moisture	30# Density	75	0.78
Pine, White			
Across Grain	28# Density	167	0.74
Along Grain	28# Density	133	1.78
Across Grain	34# Density	86	0.80
Pine, Yellow, Long Leaf (across grain)			
0% Moisture	30# Density	75	0.76
8% Moisture	30# Density	75	0.83
16% Moisture	30# Density	75	0.89
0% Moisture	40# Density	75	0.86
8% Moisture	40# Density	75	0.95
16% Moisture	40# Density	75	1.03
Pine, Yellow, Short Leaf (across grain)			
0% Moisture	26# Density	75	0.74
8% Moisture	26# Density	75	0.79
16% Moisture	26# Density	75	0.84
0% Moisture	30# Density	75	0.91
8% Moisture	30# Density	75	0.97
16% Moisture	30# Density	75	1.04
Sawdust			
Various, dry	12# Density	90	0.41
Pine, loose, dry	3.6# Density	166	0.57
Shavings—Planer			
Red Wood Bark	3# Density	90	0.31
Red Wood Bark	5# Density	75	0.26
Various	8.75# Density	86	0.41
Beech and Birch	13.2# Density	90	0.36
Teak Wood			
Across grain	40.5# Density	32	1.13
Across grain	40.5# Density	59	1.21
Across grain	40.5# Density	122	1.38
Along grain	40.5# Density	32	2.59
Along grain	40.5# Density	59	2.67
Along grain	40.5# Density	122	2.75

APPENDIX A.1.B

K-VALUE OF SOME COMMON MATERIALS [20]

Non-Metallic Solids

Material	Mean Temp. °F.	K-Value
Acrylic (transparent Plexiglas)	70	0.112
Asbestos (36 lb/ft^3)	70	0.092
Brick (masonry)	70	0.300
Bakelite	70	0.134
Clay	70	0.740
Coal (anthracite)	70	0.150
Concrete	70	0.540
Cork Board	70	0.025
Diatomaceous Earth	70	0.040
Felt, Hair	70	0.025
Fiber Glass Laminates		
Silicone	200	0.085
Polyester	200	0.080
Phenolic	200	0.070
Glass		
Silica	70	0.880
Borosilicate Crown	70	0.720
Soda-lime	70	0.540
Pyrex	70	0.680
Ice	-150	2.040
	32	1.280
Magnesia (85%)	70	0.033
Marble	70	1.600
Nylon	70	0.140
Rock Wool	70	0.023
Rubber		
Hard	70	0.106
Natural	70	0.085
Neoprene	70	0.121
Sandstone (dry)	70	1.100
Santocel	70	0.013
Teflon	70	0.140
Wood (typical)	70	0.100

Appendix A.1.B Continued

Metal Alloys

Material	Mean Temp. °F.	K-value
Aluminum Alloy		
7075-T6	-200	51.0
	+200	79.0
2024-T4	-200	51.0
	+200	78.00
Brass and Bronze		
Commercial Bronze	68	109.0
Red Brass	68	92.0
Cartridge Brass	68	70.0
Free-cutting Brass	68	67.0
Admiralty Metal	68	64.0
Aluminum Bronze	68	48.0
Phosphor Bronze	68	47.0
Bearing Bronze	68	100.0
Constantan	68	12.5
Inconel-X	68	6.9
Iron (cast, 4% carbon)	68	30.0
Steel		
SAE 1095	100	34.0
SAE 1010	68	37.1
Stainless type 301	68	8.6
Stainless type 347	-250	7.1
	200	9.0
	1600	14.9

APPENDIX A.2

ASSUMED R_s-VALUES FOR PIPING SYSTEMS AND FLAT METAL SURFACES [14]

(Still Air)

$t_s - t_a$ °F	Plain, Fabric, Dull Metal $\varepsilon = .95$	Aluminum $\varepsilon = .2$	Stainless Steel $\varepsilon = .4$
10	.53	.90	.81
25	.52	.88	.79
50	.50	.86	.76
75	.48	.84	.75
100	.46	.80	.72

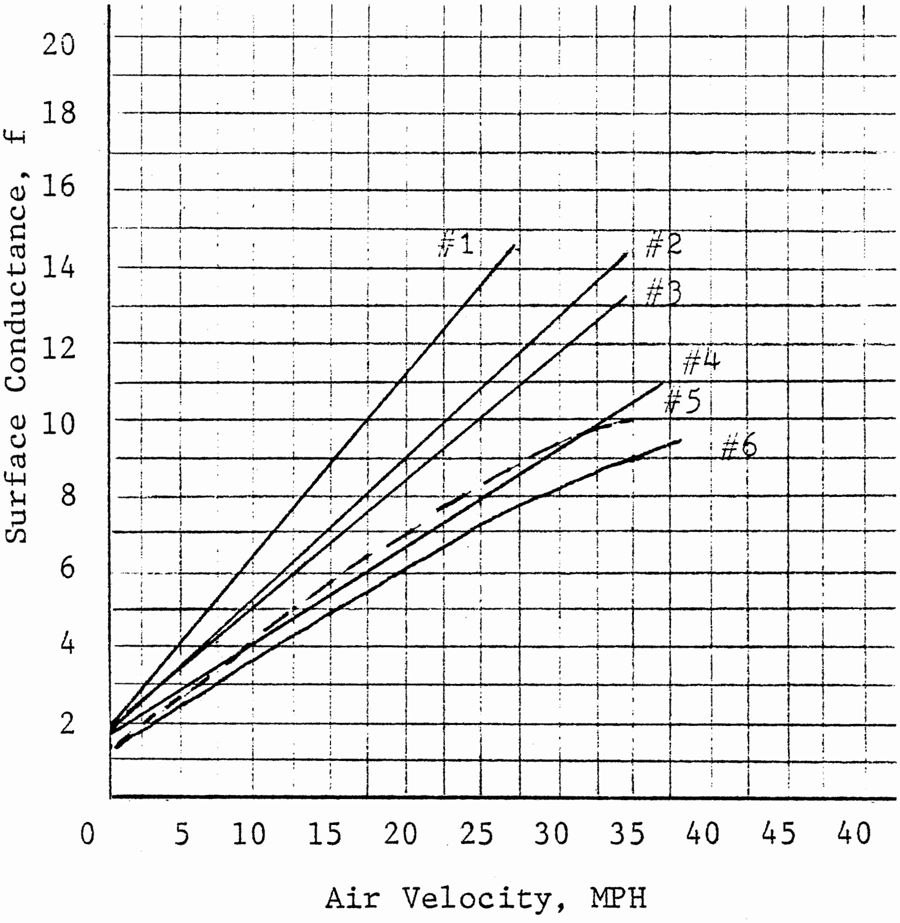
R Values With Wind Velocities

	Plain, Fabric Dull Metal	Aluminum	Stainless Steel
5 mph	.35	.41	.40
10 mph	.30	.35	.34
20 mph	.24	.28	.27

York Corporation recommends 0.70 as a single value to be used when no other value can be determined. This figure is adequate since R_s has very little impact upon the economic thickness determination. That is, a 50% deviation in the assumed R_s-value will result in roughly a 5% variance in the thickness calculations [29].

APPENDIX A.3

SURFACE CONDUCTANCES FOR COMMON STRUCTURAL MATERIALS [13]



Key:

Curve #1--Stucco
#2--Brick and rough plaster
#3--Concrete
#4--Smooth plaster
#5--Clear pine
#6--Glass or white paint on pine

Surface Resistance

$$\text{Surface Resistance} = R_s$$
$$= \frac{1}{f}$$

Appendix A.3 Continued

Commonly Assumed Air Film Surface Conductances [13]

	Air Velocity	f	$R_s = 1/f$
Outdoor	15 MPH	6.0	0.17
	7.5 MPH	4.0	0.25
Indoor	00 MPH	1.47	0.68

APPENDIX A.4

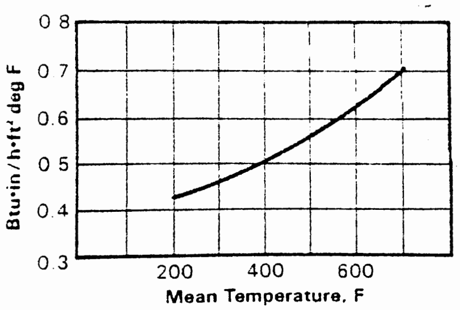
INDUSTRIAL INSULATION TYPES AND PROPERTIES

Insulation type and form	Temp. range °F	Thermal Conductivity Btu-in/hr/sq ft/°F @ T Mean °F			Comprehensive strength psi @% deformation	FHC-Fire hazard classification or flame spread-smoke developed	Cell structure (permeability and moisture absorption)
		75	200	500			
Calcium silicate blocks, shapes, P/C	to 1,500	.37	.41	.53	100 to 250@5%	Noncombustible	Open cell
Glass fiber blankets	to 1,200	.24 to .31	.32 to .49	.43 to .73			
Glass fiber boards	to 1,000	.22	.28	.51 to .61	.02 to 3.5@10%	Noncombustible to 25/50	Open cell
Glass fiber pipe covering	to 850	.23	.30	.62			
Mineral fiber blocks and P/C	to 1,900	.23 to .34	.28 to .39	.45 to .82	1 to 18@10%	Noncombustible to 25/50	Open cell
Cellular glass blocks, shapes, P/C	-450 to 900	.38	.45	.72	100 @ 5%	Noncombustible	Closed cell
Expanded perlite blocks, shapes, P/C	to 1,500	-	.46	.63	90 @ 5%	Noncombustible 25 to 75 -	Open cell
Urethane foam blocks and P/C	-100 to -450 to 224	.16 to .18	-	-	16 to 75@10%	140 to 400	95% Closed cell
Isocyanurate foam blocks and P/C	to 350	.15	-	-	17 to 25@10%	25-55 to 100	93% Closed cell
Phenolic foam P/C	-40 to 250	.23	-	-	13 to 22@10%	25/50	Open cell
Elastomeric closed cell sheets and P/C	-40 to 220	.25 to .27	-	-	40 @ 10%	25 tp 75 - 115 to 490	Closed cell
MIN-K® blocks and blankets	to 1,800	.19 to .21	.20 to .23	.21 to .24	100 to 190@8%	Noncombustible	Open cell
Ceramic fiber blankets	to 2,600	-	-	.38 to .54	.5 to 1 @ 10%	Noncombustible	Open cell

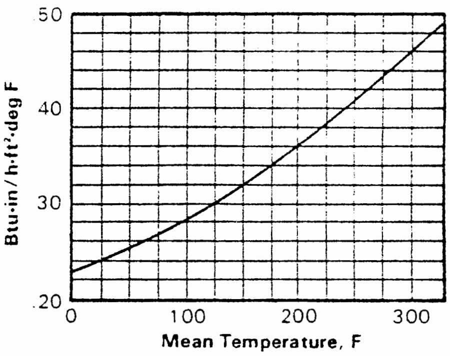
APPENDIX A.5

OWENS-CORNING CONDUCTIVITY CURVES

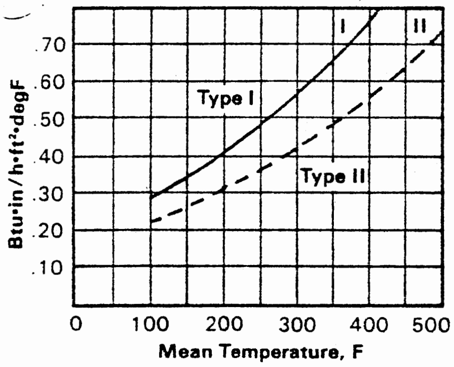
[Ref. Manufacturer's Literature]



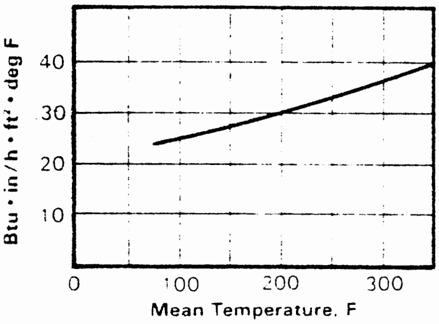
O.C. Kaylo-10
Asbestos-Free Blocks
(Calcium Silicate)



O.C. Fiberglass
Pipe Wrap

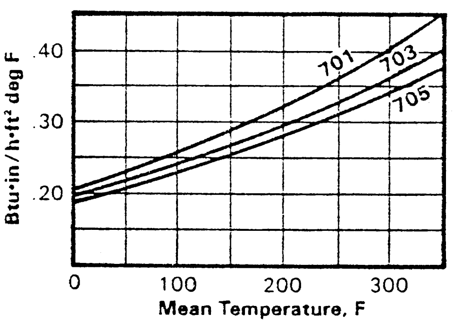


O.C. Fiberglass
Insulating Wool

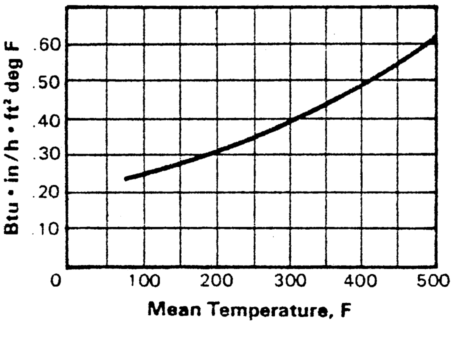


O.C. Fiberglass
Pipe Insulation

Appendix A.5 Continued



O.C. Fiberglass
700 Series
Blocks and Boards



O.C. Fiberglass
Intermediate Service
Boards

APPENDIX A.6.A

HEATING DEGREE-DAY TABLES

(Base 65 deg.F.) [2]

State	Station	Avg. Winter Temp^d	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Yearly Total
Ala.	Birmingham............A	54.2	0	0	6	93	363	555	592	462	363	108	9	0	2551
	Huntsville............A	51.3	0	0	12	127	426	663	694	557	434	138	19	0	3070
	Mobile............A	59.9	0	0	0	22	213	357	415	300	211	42	0	0	1560
	Montgomery............A	55.4	0	0	0	68	330	527	543	417	316	90	0	0	2291
Alaska	Anchorage............A	23.0	245	291	516	930	1284	1572	1631	1316	1293	879	592	315	10864
	Fairbanks............A	6.7	171	332	642	1203	1833	2254	2359	1901	1739	1068	555	222	14279
	Juneau............A	32.1	301	338	483	725	921	1135	1237	1070	1073	810	601	381	9075
	Nome............A	13.1	481	496	693	1094	1455	1820	1879	1666	1770	1314	930	573	14171
Ariz.	Flagstaff............A	35.6	46	68	201	558	867	1073	1169	991	911	651	437	180	7152
	Phoenix............A	58.5	0	0	0	22	234	415	474	328	217	75	0	0	1765
	Tucson............A	58.1	0	0	0	25	231	406	471	344	242	75	6	0	1800
	Winslow............A	43.0	0	0	6	245	711	1008	1054	770	601	291	96	0	4782
	Yuma............A	64.2	0	0	0	0	108	264	307	190	90	15	0	0	974
Ark.	Fort Smith............A	50.3	0	0	12	127	450	704	781	596	456	144	22	0	3292
	Little Rock............A	50.5	0	0	9	127	465	716	756	577	434	126	9	0	3219
	Texarkana............A	54.2	0	0	0	78	345	561	626	468	350	105	0	0	2533
Calif.	Bakersfield............A	55.4	0	0	0	37	282	502	546	364	267	105	19	0	2122
	Bishop............A	46.0	0	0	48	260	576	797	874	680	555	306	143	36	4275
	Blue Canyon............A	42.2	28	37	108	347	594	781	896	795	806	597	412	195	5596
	Burbank............A	58.6	0	0	6	43	177	301	366	277	239	138	81	18	1646
	Eureka............C	49.9	270	257	258	329	414	499	546	470	505	438	372	285	4643
	Fresno............A	53.3	0	0	0	84	354	577	605	426	335	162	62	6	2611
	Long Beach............A	57.8	0	0	9	47	171	316	397	311	264	171	93	24	1803
	Los Angeles............A	57.4	28	28	42	78	180	291	372	302	288	219	158	81	2061
	Los Angeles............C	60.3	0	0	6	31	132	229	310	230	202	123	68	18	1349
	Mt. Shasta............C	41.2	25	34	123	406	696	902	983	784	738	525	347	159	5722
	Oakland............A	53.5	53	50	45	127	309	481	527	400	353	255	180	90	2870
	Red Bluff............A	53.8	0	0	0	53	318	555	605	428	341	168	47	0	2515
	Sacramento............A	53.9	0	0	0	56	321	546	583	414	332	178	72	0	2502
	Sacramento............C	54.4	0	0	0	62	312	533	561	392	310	173	76	0	2419
	Sandberg............C	46.8	0	0	30	202	480	691	778	661	620	426	264	57	4209
	San Diego............A	59.5	9	0	21	43	135	236	298	235	214	135	90	42	1458
	San Francisco............A	53.4	81	78	60	143	306	462	508	395	363	279	214	126	3015
	San Francisco............C	55.1	192	174	102	118	231	388	443	336	319	279	239	180	3001
	Santa Maria............A	54.3	99	93	96	146	270	391	459	370	363	282	233	165	2967
Colo.	Alamosa............A	29.7	65	99	279	639	1065	1420	1476	1162	1020	696	440	168	8529
	Colorado Springs............A	37.3	9	25	132	456	825	1032	1128	938	893	582	319	84	6423
	Denver............A	37.6	6	9	117	428	819	1035	1132	938	887	558	288	66	6283
	Denver............C	40.8	0	0	90	366	714	905	1004	851	800	492	254	48	5524
	Grand Junction............A	39.3	0	0	30	313	786	1113	1209	907	729	387	146	21	5641
	Pueblo............A	40.4	0	0	54	326	750	986	1085	871	772	429	174	15	5462
Conn.	Bridgeport............A	39.9	0	0	66	307	615	986	1079	966	853	510	208	27	5617
	Hartford............A	37.3	0	12	117	394	714	1101	1190	1042	908	519	205	33	6235
	New Haven............A	39.0	0	12	87	347	648	1011	1097	991	871	543	245	45	5897
Del.	Wilmington............A	42.5	0	0	51	270	588	927	980	874	735	387	112	6	4930
D. C.	Washington............A	45.7	0	0	33	217	519	834	871	762	626	288	74	0	4224
Fla.	Apalachicola............C	61.2	0	0	0	16	153	319	347	260	180	33	0	0	1308
	Daytona Beach............A	64.5	0	0	0	0	75	211	248	190	140	15	0	0	879
	Fort Myers............A	68.6	0	0	0	0	24	109	146	101	62	0	0	0	442
	Jacksonville............A	61.9	0	0	0	12	144	310	332	246	174	21	0	0	1239
	Key West............A	73.1	0	0	0	0	0	28	40	31	9	0	0	0	108
	Lakeland............C	66.7	0	0	0	0	57	164	195	146	99	0	0	0	661
	Miami............A	71.1	0	0	0	0	0	65	74	56	19	0	0	0	214

Appendix A.6.A Continued

State	Station	Avg. Winter Temp[d]	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Yearly Total
Fla. (Cont'd)	Miami Beach............C	72.5	0	0	0	0	0	40	56	36	9	0	0	0	141
	Orlando.................A	65.7	0	0	0	0	72	198	220	165	105	6	0	0	766
	Pensacola...............A	60.4	0	0	0	19	195	353	400	277	183	36	0	0	1463
	Tallahassee.............A	60.1	0	0	0	28	198	360	375	286	202	36	0	0	1485
	Tampa...................A	66.4	0	0	0	0	60	171	202	148	102	0	0	0	683
	West Palm Beach.........A	68.4	0	0	0	0	6	65	87	64	31	0	0	0	253
Ga.	Athens..................A	51.8	0	0	12	115	405	632	642	529	431	141	22	0	2929
	Atlanta.................A	51.7	0	0	18	124	417	648	636	518	428	147	25	0	2961
	Augusta.................A	54.5	0	0	0	78	333	552	549	445	350	90	0	0	2397
	Columbus................A	54.8	0	0	0	87	333	543	552	434	338	96	0	0	2383
	Macon...................A	56.2	0	0	0	71	297	502	505	403	295	63	0	0	2136
	Rome....................A	49.9	0	0	24	161	474	701	710	577	468	177	34	0	3326
	Savannah................A	57.8	0	0	0	47	246	437	437	353	254	45	0	0	1819
	Thomasville.............C	60.0	0	0	0	25	198	366	394	305	208	33	0	0	1529
Hawaii	Lihue...................A	72.7	0	0	0	0	0	0	0	0	0	0	0	0	0
	Honolulu................A	74.2	0	0	0	0	0	0	0	0	0	0	0	0	0
	Hilo....................A	71.9	0	0	0	0	0	0	0	0	0	0	0	0	0
Idaho	Boise...................A	39.7	0	0	132	415	792	1017	1113	854	722	438	245	81	5809
	Lewiston................A	41.0	0	0	123	403	756	933	1063	815	694	426	239	90	5542
	Pocatello...............A	34.8	0	0	172	493	900	1166	1324	1058	905	555	319	141	7033
Ill.	Cairo...................C	47.9	0	0	36	164	513	791	856	680	539	195	47	0	3821
	Chicago (O'Hare)........A	35.8	0	12	117	381	807	1166	1265	1086	939	534	260	72	6639
	Chicago (Midway)........A	37.5	0	0	81	326	753	1113	1209	1044	890	480	211	48	6155
	Chicago.................C	38.9	0	0	66	279	705	1051	1150	1000	868	489	226	48	5882
	Moline..................A	36.4	0	9	99	335	774	1181	1314	1100	918	450	189	39	6408
	Peoria..................A	38.1	0	6	87	326	759	1113	1218	1025	849	426	183	33	6025
	Rockford................A	34.8	6	9	114	400	837	1221	1333	1137	961	516	236	60	6830
	Springfield.............A	40.6	0	0	72	291	696	1023	1135	935	769	354	136	18	5429
Ind.	Evansville..............A	45.0	0	0	66	220	606	896	955	767	620	237	68	0	4435
	Fort Wayne..............A	37.3	0	9	105	378	783	1135	1178	1028	890	471	189	39	6205
	Indianapolis............A	39.6	0	0	90	316	723	1051	1113	949	809	432	177	39	5699
	South Bend..............A	36.6	0	6	111	372	777	1125	1221	1070	933	525	239	60	6439
Iowa	Burlington..............A	37.6	0	0	93	322	768	1135	1259	1042	859	426	177	33	6114
	Des Moines..............A	35.5	0	6	96	363	828	1225	1370	1137	915	438	180	30	6588
	Dubuque.................A	32.7	12	31	156	450	906	1287	1420	1204	1026	546	260	78	7376
	Sioux City..............A	34.0	0	9	108	369	867	1240	1435	1198	989	483	214	39	6951
	Waterloo................A	32.6	12	19	138	428	909	1296	1460	1221	1023	531	229	54	7320
Kans.	Concordia...............A	40.4	0	0	57	276	705	1023	1163	935	781	372	149	18	5479
	Dodge City..............A	42.5	0	0	33	251	666	939	1051	840	719	354	124	9	4986
	Goodland................A	37.8	0	6	81	381	810	1073	1166	955	884	507	236	42	6141
	Topeka..................A	41.7	0	0	57	270	672	980	1122	893	722	330	124	12	5182
	Wichita.................A	44.2	0	0	33	229	618	905	1023	804	645	270	87	6	4620
Ky.	Covington...............A	41.4	0	0	75	291	669	983	1035	893	756	390	149	24	5265
	Lexington...............A	43.8	0	0	54	239	609	902	946	818	685	325	105	0	4683
	Louisville..............A	44.0	0	0	54	248	609	890	930	818	682	315	105	9	4660
La.	Alexandria..............A	57.5	0	0	0	56	273	431	471	361	260	69	0	0	1921
	Baton Rouge.............A	59.8	0	0	0	31	216	369	409	294	208	33	0	0	1560
	Lake Charles............A	60.5	0	0	0	19	210	341	381	274	195	39	0	0	1459
	New Orleans.............A	61.0	0	0	0	19	192	322	363	258	192	39	0	0	1385
	New Orleans.............C	61.8	0	0	0	12	165	291	344	241	177	24	0	0	1254
	Shreveport..............A	56.2	0	0	0	47	297	477	552	426	304	81	0	0	2184
Me.	Caribou.................A	24.4	78	115	336	682	1044	1535	1690	1470	1308	858	468	183	9767
	Portland................A	33.0	12	53	195	508	807	1215	1339	1182	1042	675	372	111	7511
Md.	Baltimore...............A	43.7	0	0	48	264	585	905	936	820	679	327	90	0	4654
	Baltimore...............C	46.2	0	0	27	189	486	806	859	762	629	288	65	0	4111
	Frederich...............A	42.0	0	0	66	307	624	955	995	876	741	384	127	12	5087
Mass.	Boston..................A	40.0	0	9	60	316	603	983	1088	972	846	513	208	36	5634
	Nantucket...............A	40.2	12	22	93	332	573	896	992	941	896	621	384	129	5891
	Pittsfield..............A	32.6	25	59	219	524	831	1231	1339	1196	1063	660	326	105	7578
	Worcester...............A	34.7	6	34	147	450	774	1172	1271	1123	998	612	304	78	6969

Appendix A.6.A Continued

State	Station	Avg. Winter Temp[d]	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Yearly Total
Mich.	Alpena.................A	29.7	68	105	273	580	912	1268	1404	1299	1218	777	446	156	8506
	Detroit (City)...........A	37.2	0	0	87	360	738	1088	1181	1058	936	522	220	42	6232
	Detroit (Wayne).........A	37.1	0	0	96	353	738	1088	1194	1061	933	534	239	57	6293
	Detroit (Willow Run)....A	37.2	0	0	90	357	750	1104	1190	1053	921	519	229	45	6258
	Escanaba..............C	29.6	59	87	243	539	924	1293	1445	1296	1203	777	456	159	8481
	Flint..................A	33.1	16	40	159	465	843	1212	1330	1198	1066	639	319	90	7377
	Grand Rapids...........A	34.9	9	28	135	434	804	1147	1259	1134	1011	579	279	75	6894
	Lansing................A	34.8	6	22	138	431	813	1163	1262	1142	1011	579	273	69	6909
	Marquette.............C	30.2	59	81	240	527	936	1268	1411	1268	1187	771	468	177	8393
	Muskegon..............A	36.0	12	28	120	400	762	1088	1209	1100	995	594	310	78	6696
	Sault Ste. Marie.........A	27.7	96	105	279	580	951	1367	1525	1380	1277	810	477	201	9048
Minn.	Duluth.................A	23.4	71	109	330	632	1131	1581	1745	1518	1355	840	490	198	10000
	Minneapolis.............A	28.3	22	31	189	505	1014	1454	1631	1380	1166	621	288	81	8382
	Rochester...............A	28.8	25	34	186	474	1005	1438	1593	1366	1150	630	301	93	8295
Miss.	Jackson................A	55.7	0	0	0	65	315	502	546	414	310	87	0	0	2239
	Meridian...............A	55.4	0	0	0	81	339	518	543	417	310	81	0	0	2289
	Vicksburg..............C	56.9	0	0	0	53	279	462	512	384	282	69	0	0	2041
Mo.	Columbia...............A	42.3	0	0	54	251	651	967	1076	874	716	324	121	12	5046
	Kansas City.............A	43.9	0	0	39	220	612	905	1032	818	682	294	109	0	4711
	St. Joseph..............A	40.3	0	6	60	285	708	1039	1172	949	769	348	133	15	5484
	St. Louis...............A	43.1	0	0	60	251	627	936	1026	848	704	312	121	15	4900
	St. Louis...............C	44.8	0	0	36	202	576	884	977	801	651	270	87	0	4484
	Springfield.............A	44.5	0	0	45	223	600	877	973	781	660	291	105	6	4900
Mont.	Billings................A	34.5	6	15	186	487	897	1135	1296	1100	970	570	285	102	7049
	Glasgow...............A	26.4	31	47	270	608	1104	1466	1711	1439	1187	648	335	150	8996
	Great Falls.............A	32.8	28	53	258	543	921	1169	1349	1154	1063	642	384	186	7750
	Havre..................A	28.1	28	53	306	595	1065	1367	1584	1364	1181	657	338	162	8700
	Havre..................C	29.8	19	37	252	539	1014	1321	1528	1305	1116	612	304	135	8182
	Helena.................A	31.1	31	59	294	601	1002	1265	1438	1170	1042	651	381	195	8129
	Kalispell...............A	31.4	50	99	321	654	1020	1240	1401	1134	1029	639	397	207	8191
	Miles City..............A	31.2	6	6	174	502	972	1296	1504	1252	1057	579	276	99	7723
	Missoula...............A	31.5	34	74	303	651	1035	1287	1420	1120	970	621	391	219	8125
Neb.	Grand Island............A	36.0	0	6	108	381	834	1172	1314	1089	908	462	211	45	6530
	Lincoln.................C	38.8	0	6	75	301	726	1066	1237	1016	834	402	171	30	5864
	Norfolk.................A	34.0	9	0	111	397	873	1234	1414	1179	983	498	233	48	6979
	North Platte............A	35.5	0	6	123	440	885	1166	1271	1039	930	519	248	57	6684
	Omaha.................A	35.6	0	12	105	357	828	1175	1355	1126	939	465	208	42	6612
	Scottsbluff..............A	35.9	0	0	138	459	876	1128	1231	1008	921	552	285	75	6673
	Valentine...............A	32.6	9	12	165	493	942	1237	1395	1176	1045	579	288	84	7425
Nev.	Elko...................A	34.0	9	34	225	561	924	1197	1314	1036	911	621	409	192	7433
	Ely....................A	33.1	28	43	234	592	939	1184	1308	1075	977	672	456	225	7733
	Las Vegas..............A	53.5	0	0	0	78	387	617	688	487	335	111	6	0	2709
	Reno...................A	39.3	43	87	204	490	801	1026	1073	823	729	510	357	189	6332
	Winnemucca............A	36.7	0	34	210	536	876	1091	1172	916	837	573	363	153	6761
N. H.	Concord................A	33.0	6	50	177	505	822	1240	1358	1184	1032	636	298	75	7383
	Mt. Washington Obsv....	15.2	493	536	720	1057	1341	1742	1820	1663	1652	1260	930	603	13817
N. J.	Atlantic City............A	43.2	0	0	39	251	549	880	936	848	741	420	133	15	4812
	Newark.................A	42.8	0	0	30	248	573	921	983	876	729	381	118	0	4589
	Trenton................C	42.4	0	0	57	264	576	924	989	885	753	399	121	12	4980
N. M.	Albuquerque............A	45.0	0	0	12	229	642	868	930	703	595	288	81	0	4348
	Clayton.................A	42.0	0	6	66	310	699	899	986	812	747	429	183	21	5158
	Raton..................A	38.1	9	28	126	431	825	1048	1116	904	834	543	301	63	6228
	Roswell................A	47.5	0	0	18	202	573	806	840	641	481	201	31	0	3793
	Silver City..............A	48.0	0	0	6	183	525	729	791	605	518	261	87	0	3705
N. Y.	Albany.................A	34.6	0	19	138	440	777	1194	1311	1156	992	564	239	45	6875
	Albany.................C	37.2	0	9	102	375	699	1104	1218	1072	908	498	186	30	6201
	Binghamton.............A	33.9	22	65	201	471	810	1184	1277	1154	1045	645	313	99	7286
	Binghamton.............C	36.6	0	28	141	406	732	1107	1190	1081	949	543	229	45	6451
	Buffalo.................A	34.5	19	37	141	440	777	1156	1256	1145	1039	645	329	78	7062
	New York (Cent. Park)..	42.8	0	0	30	233	540	902	986	885	760	408	118	9	4871
	New York (La Guardia)..A	43.1	0	0	27	223	528	887	973	879	750	414	124	6	4811

Appendix A.6.A Continued

State	Station	Avg. Winter Temp^d	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Yearly Total
	New York (Kennedy)....A	41.4	0	0	36	248	564	933	1029	935	815	480	167	12	5219
	Rochester..............A	35.4	9	31	126	415	747	1125	1234	1123	1014	597	279	48	6748
	Schenectady............C	35.4	0	22	123	422	756	1159	1283	1131	970	543	211	30	6650
	Syracuse...............A	35.2	6	28	132	415	744	1153	1271	1140	1004	570	248	45	6756
N. C.	Asheville...............C	46.7	0	0	48	245	555	775	784	683	592	273	87	0	4042
	Cape Hatteras..........	53.3	0	0	0	78	273	521	580	518	440	177	25	0	2612
	Charlotte..............A	50.4	0	0	6	124	438	691	691	582	481	156	22	0	3191
	Greensboro.............A	47.5	0	0	33	192	513	778	784	672	552	234	47	0	3805
	Raleigh................A	49.4	0	0	21	164	450	716	725	616	487	180	34	0	3393
	Wilmington.............A	54.6	0	0	0	74	291	521	546	462	357	96	0	0	2347
	Winston-Salem..........A	48.4	0	0	21	171	483	747	753	652	524	207	37	0	3595
N. D.	Bismarck...............A	26.6	34	28	222	577	1083	1463	1708	1442	1203	645	329	117	8851
	Devils Lake............C	22.4	40	53	273	642	1191	1634	1872	1579	1345	753	381	138	9901
	Fargo..................A	24.8	28	37	219	574	1107	1569	1789	1520	1262	690	332	99	9226
	Williston..............A	25.2	31	43	261	601	1122	1513	1758	1473	1262	681	357	141	9243
Ohio	Akron-Canton...........A	38.1	0	9	96	381	726	1070	1138	1016	871	489	202	39	6037
	Cincinnati.............C	45.1	0	0	39	208	558	862	915	790	642	294	96	6	4410
	Cleveland..............A	37.2	9	25	105	384	738	1088	1159	1047	918	552	260	66	6351
	Columbus...............A	39.7	0	6	84	347	714	1039	1088	949	809	426	171	27	5660
	Columbus...............C	41.5	0	0	57	285	651	977	1032	902	760	396	136	15	5211
	Dayton.................A	39.8	0	6	78	310	696	1045	1097	955	809	429	167	30	5622
	Mansfield..............A	36.9	9	22	114	397	768	1110	1169	1042	924	543	245	60	6403
	Sandusky...............C	39.1	0	6	66	313	684	1032	1107	991	868	495	198	36	5796
	Toledo.................A	36.4	0	16	117	406	792	1138	1200	1056	924	543	242	60	6494
	Youngstown.............A	36.8	6	19	120	412	771	1104	1169	1047	921	540	248	60	6417
Okla.	Oklahoma City..........A	48.3	0	0	15	164	498	766	868	664	527	189	34	0	3725
	Tulsa..................A	47.7	0	0	18	158	522	787	893	683	539	213	47	0	3860
Ore.	Astoria................A	45.6	146	130	210	375	561	679	753	622	636	480	363	231	5186
	Burns..................C	35.9	12	37	210	515	867	1113	1246	988	856	570	366	177	6957
	Eugene.................A	45.6	34	34	129	366	585	719	803	627	589	426	279	135	4726
	Meacham................A	34.2	84	124	288	580	918	1091	1209	1005	983	726	527	339	7874
	Medford................A	43.2	0	0	78	372	678	871	918	697	642	432	242	78	5008
	Pendleton..............A	42.6	0	0	111	350	711	884	1017	773	617	396	205	63	5127
	Portland...............A	45.6	25	28	114	335	597	735	825	644	586	396	245	105	4635
	Portland...............C	47.4	12	16	75	267	534	679	769	594	536	351	198	78	4109
	Roseburg...............A	46.3	22	16	105	329	567	713	766	608	570	405	267	123	4491
	Salem..................A	45.4	37	31	111	338	594	729	822	647	611	417	273	144	4754
Pa.	Allentown..............A	38.9	0	0	90	353	693	1045	1116	1002	849	471	167	24	5810
	Erie...................A	36.8	0	25	102	391	714	1063	1169	1081	973	585	288	60	6451
	Harrisburg.............A	41.2	0	0	63	298	648	992	1045	907	766	396	124	12	5251
	Philadelphia...........A	41.8	0	0	60	297	620	965	1016	889	747	392	118	40	5144
	Philadelphia...........C	44.5	0	0	30	205	513	856	924	823	691	351	93	0	4486
	Pittsburgh.............A	38.4	0	9	105	375	726	1063	1119	1002	874	480	195	39	5987
	Pittsburgh.............C	42.2	0	0	60	291	615	930	983	885	763	390	124	12	5053
	Reading................C	42.4	0	0	54	257	597	939	1001	885	735	372	105	0	4945
	Scranton...............A	37.2	0	19	132	434	762	1104	1156	1028	893	498	195	33	6254
	Williamsport...........A	38.5	0	9	111	375	717	1073	1122	1002	856	468	177	24	5934
R. I.	Block Island...........A	40.1	0	16	78	307	594	902	1020	955	877	612	344	99	5804
	Providence.............A	38.8	0	16	96	372	660	1023	1110	988	868	534	236	51	5954
S. C.	Charleston.............A	56.4	0	0	0	59	282	471	487	389	291	54	0	0	2033
	Charleston.............C	57.9	0	0	0	34	210	425	443	367	273	42	0	0	1794
	Columbia...............A	54.0	0	0	0	84	345	577	570	470	357	81	0	0	2484
	Florence...............A	54.5	0	0	0	78	315	552	552	459	347	84	0	0	2387
	Greenville-Spartenburg...A	51.6	0	0	6	121	399	651	660	546	446	132	19	0	2980
S. D.	Huron..................A	28.8	9	12	165	508	1014	1432	1628	1355	1125	600	288	87	8223
	Rapid City.............A	33.4	22	12	165	481	897	1172	1333	1145	1051	615	326	126	7345
	Sioux Falls............A	30.6	-19	25	168	462	972	1361	1544	1285	1082	573	270	78	7839
Tenn.	Bristol................A	46.2	0	0	51	236	573	828	828	700	598	261	68	0	4143
	Chattanooga............A	50.3	0	0	18	143	468	698	722	577	453	150	25	0	3254
	Knoxville..............A	49.2	0	0	30	171	489	725	732	613	493	198	43	0	3494
	Memphis................A	50.5	0	0	18	130	447	698	729	585	456	147	22	0	3232

Appendix A.6.A Continued

State or Prov.	Station	Avg. Winter Temp^d	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Yearly Total
	Memphis..............C	51.6	0	0	12	102	396	648	710	568	434	129	16	0	3015
	Nashville..............A	48.9	0	0	30	158	495	732	778	644	512	189	40	0	3578
	Oak Ridge.............C	47.7	0	0	39	192	531	772	778	669	552	228	56	0	3817
Tex.	Abilene.................A	53.9	0	0	0	99	366	586	642	470	347	114	0	0	2624
	Amarillo................A	47.0	0	0	18	205	570	797	877	664	546	252	56	0	3985
	Austin..................A	59.1	0	0	0	31	225	388	468	325	223	51	0	0	1711
	Brownsville............A	67.7	0	0	0	0	66	149	205	106	74	0	0	0	600
	Corpus Christi..........A	64.6	0	0	0	0	120	220	291	174	109	0	0	0	914
	Dallas...................A	55.3	0	0	0	62	321	524	601	440	319	90	6	0	2363
	El Paso.................A	52.9	0	0	0	84	414	648	685	445	319	105	0	0	2700
	Fort Worth.............A	55.1	0	0	0	65	324	536	614	448	319	99	0	0	2405
	Galveston..............A	62.2	0	0	0	6	147	276	360	263	189	33	0	0	1274
	Galveston..............C	62.0	0	0	0	0	138	270	350	258	189	30	0	0	1235
	Houston................A	61.0	0	0	0	6	183	307	384	288	192	36	0	0	1396
	Houston................C	62.0	0	0	0	0	165	288	363	258	174	30	0	0	1278
	Laredo..................A	66.0	0	0	0	0	105	217	267	134	74	0	0	0	797
	Lubbock................A	48.8	0	0	18	174	513	744	800	613	484	201	31	0	3578
	Midland................A	53.8	0	0	0	87	381	592	651	468	322	90	0	0	2591
	Port Arthur............A	60.5	0	0	0	22	207	329	384	274	192	39	0	0	1447
	San Angelo.............A	56.0	0	0	0	68	318	536	567	412	288	66	0	0	2255
	San Antonio............A	60.1	0	0	0	31	204	363	428	286	195	39	0	0	1546
	Victoria.................A	62.7	0	0	0	6	150	270	344	230	152	21	0	0	1173
	Waco...................A	57.2	0	0	0	43	270	456	536	389	270	66	0	0	2030
	Wichita Falls...........A	53.0	0	0	0	99	381	632	698	518	378	120	6	0	2832
Utah	Milford.................A	36.5	0	0	99	443	867	1141	1252	988	822	519	279	87	6497
	Salt Lake City..........A	38.4	0	0	81	419	849	1082	1172	910	763	459	233	84	6052
	Wendover...............A	39.1	0	0	48	372	822	1091	1178	902	729	408	177	51	5778
Vt.	Burlington.............A	29.4	28	65	207	539	891	1349	1513	1333	1187	714	353	90	8269
Va.	Cape Henry............C	50.0	0	0	0	112	360	645	694	633	536	246	53	0	3279
	Lynchburg..............A	46.0	0	0	51	223	540	822	849	731	605	267	78	0	4166
	Norfolk.................A	49.2	0	0	0	136	408	698	738	655	533	216	37	0	3421
	Richmond...............A	47.3	0	0	36	214	495	784	815	703	546	219	53	0	3865
	Roanoke................A	46.1	0	0	51	229	549	825	834	722	614	261	65	0	4150
Wash.	Olympia................A	44.2	68	71	198	422	636	753	834	675	645	450	307	177	5236
	Seattle-Tacoma..........A	44.2	56	62	162	391	633	750	828	678	657	474	295	159	5145
	Seattle..................C	46.9	50	47	129	329	543	657	738	599	577	396	242	117	4424
	Spokane................A	36.5	9	25	168	493	879	1082	1231	980	834	531	288	135	6655
	Walla Walla............C	43.8	0	0	87	310	681	843	986	745	589	342	177	45	4805
	Yakima.................A	39.1	0	12	144	450	828	1039	1163	868	713	435	220	69	5941
W. Va.	Charleston.............A	44.8	0	0	63	254	591	865	880	770	648	300	96	9	4476
	Elkins...................A	40.1	9	25	135	400	729	992	1008	896	791	444	198	48	5675
	Huntington.............A	45.0	0	0	63	257	585	856	880	764	636	294	99	12	4446
	Parkersburg............C	43.5	0	0	60	264	606	905	942	826	691	339	115	6	4754
Wisc.	Green Bay.............A	30.3	28	50	174	484	924	1333	1494	1313	1141	654	335	99	8029
	La Crosse..............A	31.5	12	19	153	437	924	1339	1504	1277	1070	540	245	69	7589
	Madison................A	30.9	25	40	174	474	930	1330	1473	1274	1113	618	310	102	7863
	Milwaukee..............A	32.6	43	47	174	471	876	1252	1376	1193	1054	642	372	135	7635
Wyo.	Casper..................A	33.4	6	16	192	524	942	1169	1290	1084	1020	657	381	129	7410
	Cheyenne...............A	34.2	28	37	219	543	909	1085	1212	1042	1026	702	428	150	7381
	Lander.................A	31.4	6	19	204	555	1020	1299	1417	1145	1017	654	381	153	7870
	Sheridan...............A	32.5	25	31	219	539	948	1200	1355	1154	1051	642	366	150	7680

APPENDIX A.6.B

COOLING DEGREE-DAY TABLE

(Base 78 deg F.) [8]

City	*Latitude*	*Solar Radiation, langleys*	*DB Degree-hours above 78°F*
Mineapolis	45°N	325	2,500
Concord, N.H.	43°N	300	1,750
Denver	40°N	425	4,055
Chicago	42°N	350	3,100
St. Louis	39°N	375	6,400
New York	41°N	350	3,000
San Fancisco	38°N	410	3,000
Atlanta	34°N	390	9,400
Los Angeles	34°N	470	2,000
Phoenix	33°N	520	24,448
Houston	30°N	430	11,500
Miami	26°N	451	10,771

APPENDIX A.7

STEEL PIPE DIMENSIONS [20]

Nominal pipe size, in.	Outside diam, in.	Schedule No.	Wall thick-ness, in.	Inside diam, in.	Cross-sectional area metal, sq in.	Inside cross-sectional area, sq ft
¼	0.540	40	0.088	0.364	0.125	0.00072
		80	0.119	0.302	0.157	0.00050
⅜	0.675	40	0.091	0.493	0.167	0.00133
		80	0.126	0.423	0.217	0.00098
½	0.840	40	0.109	0.622	0.250	0.00211
		80	0.147	0.546	0.320	0.00163
¾	1.050	40	0.113	0.824	0.333	0.00371
		80	0.154	0.742	0.433	0.00300
1	1.315	40	0.133	1.049	0.494	0.00600
		80	0.179	0.957	0.639	0.00499
1½	1.900	40	0.145	1.610	0.799	0.01414
		80	0.200	1.500	1.068	0.01225
2	2.375	40	0.154	2.067	1.075	0.02330
		80	0.218	1.939	1.477	0.02050
2½	2.875	40	0.203	2.469	1.704	0.03322
		80	0.276	2.323	2.254	0.02942
3	3.500	40	0.216	3.068	2.228	0.05130
		80	0.300	2.900	3.016	0.04587
4	4.500	40	0.237	4.026	3.173	0.08840
		80	0.337	3.826	4.407	0.07986
5	5.563	40	0.258	5.047	4.304	0.1390
		80	0.375	4.813	6.112	0.1263
6	6.625	40	0.280	6.065	5.584	0.2006
		80	0.432	5.761	8.405	0.1810
8	8.625	40	0.322	7.981	8.396	0.3474
		80	0.500	7.625	12.76	0.3171
10	10.75	40	0.365	10.020	11.90	0.5475
		60	0.500	9.750	16.10	0.5185

* Based on A.S.A. Standards B36.10.

APPENDIX A.8.A

HARDCOPY OF ECOTHK--BATCH FORM

```
$JOB          ,TIME=(,3),PAGES=5,EXT,XREF
C       A COMPUTER PROGRAM WRITTEN IN FORTRAN TO DETERMINE THE
C       ECONOMIC THICKNESS OF INSULATION ON A MINIMUM ANNUAL COST BASIS
C
C       STEVE D SANDSTRUM, INDUSTRIAL ENGINEERING AND MANAGEMENT
C
C       PROGRAM VARIABLES
C       IN        INPUT DEVICE
C       LP        OUTPUT DEVICE
C       CODE      SURFACE CODE, FLAT OR PIPE
C       N         LIFETIME OF INSULATION, IN YEARS
C       KVAL      K-VALUE OF INSULATION BEING INVESTIGATED
C       INC       CONSTANT INCREMENT OF INSULATION
C       FNTHK     FINAL THICKNESS TO BE ANALYZED
C       I         AFTER-TAX MINIMUM ATTRACTIVE RATE OF RETURN
C       J         GENERAL ANNUAL INFLATION RATE
C       K         ANNUAL FUEL ESCALATION RATE
C       HDHR      HEATING DEGREE-HOURS PER YEAR
C       HEFF      HEAT PLANT EFFICIENCY
C       CDHR      COOLING DEGREE-HOURS PER YEAR
C       CEFF      COOLING PLANT EFFICIENCY
C       ORAD      OUTSIDE RADIUS OF PIPE, IN INCHES
C       NPW       NET PRESENT WORTH OF HEAT LOSS PER FOOT
C       NPV       NET PRESENT VALUE OF INSULATION SYSTEM PER FOOT
C       HLOSS     ANNUAL HEAT LOSS, IN BTU'S PER FOOT
C       HGAIN     ANNUAL HEAT GAIN, IN BTU'S PER FOOT
C       TCOST     TOTAL CURRENT LOST ENERGY COST, IN $'S PER FOOT
C       THK       CURRENT THICKNESS OF INSULATION UNDER INVESTIGATION
C       INSCST    INSTALLED COST OF CURRENT THICKNESS, IN $'S PER FOOT
C       MANCST    MAINTENANCE COST OF CURRENT THICKNESS, IN $'S PER FOOT
C       RS        EXISTING SURFACE RESISTANCE, IN BTU/HR,SQ FT, DEGREE F
C       Y         EQUIVALENT THICKNESS FOR PIPING SYSTEMS
C       CCOST     COST OF COOLING, IN $'S PER THERM
C       CHEAT     COST OF HEAT, IN $'S PER THERM
C       TE        INCREMENTAL TAX RATE
C       TCRED     AVAILABLE TAX CREDIT
C       ANCST     ANNUAL COST OF INSULATION SYSTEM, IN $'S PER YR PER FT
C       ANBTU     ANNUAL BTU LOSS FOR BOTH COOLING AND HEATING
C       INUMB     NUMBER OF ITERATIONS TO BE PERFORMED
C       NAM       ARRAY RESERVED FOR NAME OF CLIENT
C       CONT      ARRAY RESERVED FOR NAME OF CLINET'S REPRESENTATIVE
C       INTYP     ARRAY RESERVED FOR THE NAME OF THE INSULATION
```

```
C
C     DECLARE DATA TYPES
C
      INTEGER IN, LP, CODE, N, F, INUMB, L
      REAL KVAL, INC, FNTHK, I, J, K, CDHR, HDHR, HEFF, CEFF , ORAD,
     $NPW, PW, HLOSS, HGAIN, TCOST, THK, INSCST, MANCST, PI, RS, Y,
     $CCOST , HCOST, TE, TCRED, ANCST, ANBTU, NPV
      DIMENSION THK(50), INSCST(50), MANCST(50), HGAIN(50), HLOSS(50),
     *ANBTU(50), TCOST(50), PW(50), NPW(50), NPV(50), ANCST(50)
C
C     INITIALIZE DATA
C
      DATA IN/5/, LP/6/
      PI=3.1416
C
C     READ IN IDENTIFICATION OF STUDY
C
      READ( IN,10) NAM1, NAM2, NAM3, NAM4
   10 FORMAT(4A4)
      READ( IN,11) CONT1, CONT2, CONT3, CONT4
   11 FORMAT(4A4)
      READ( IN,12) INTYP1, INTYP2, INTYP3, INTYP4
   12 FORMAT(4A4)
C
C     READ PROGRAM INPUTS
C
      READ( IN,*) KVAL
      READ( IN,*) INC, FNTHK
      READ( IN,*) I, J, K
      READ( IN,*) HDHR, CDHR
      READ( IN,*) CODE, ORAD
      READ( IN,*) HEFF, CEFF
      READ( IN,*) RS
      READ( IN,*) HCOST, CCOST
      READ( IN,*) TE, TCRED
      READ( IN,*) N
```

```
C
C     DETERMINE NUMBER OF ITERATIONS TO BE RUN
C
      INUMB=IFIX((FNTHK/INC)+1.0)
C
C     LOOP TO READ IN INPUT DATA
C
      DO 70 M=1, INUMB
      READ(IN,*) THK(M), INSCST(M), MANCST(M)
   70 CONTINUE
C
C     DETERMINE ANNUAL ENERGY LOSS FOR SYSTEM
C
      DO 50 L=1, INUMB
      IF (CODE .EQ. 1) GO TO 1
      HLOSS(L)=(HDHR)/((RS+(THK(L)/KVAL))*HEFF)
      HGAIN(L)=(CDHR)/((RS+(THK(L)/KVAL))*CEFF)
      GO TO 2
    1 Y=ALOG(ORAD+THK(L))-ALOG(ORAD)
      HLOSS(L)=(HDHR*((2.0*PI*(ORAD+THK(L)))/12.0)*KVAL)/
     $((((ORAD+THK(L))*Y)+(RS*KVAL))*HEFF)
      HGAIN(L)=(CDHR*((2.0*PI*(ORAD+THK(L)))/12.0)*KVAL)/
     $((((ORAD+THK(L))*Y)+(RS*KVAL))*CEFF)
    2 ANBTU(L)=HLOSS(L)+HGAIN(L)
      TCOST(L)=(((HLOSS(L)/100000.0)*HCOST)*(1.0-TE))+
     $(((HGAIN(L)/100000.0)*CCOST)*(1.0-TE))
C
C     DETERMINE AFTER-TAX PRESENT WORTH OF ENERGY LOSSES
C
      NPW(L)=0.00
      DO 60 F=1, N
      PW(L)=(((MANCST(L))*(1.0-TE))+(TCOST(L)*(((1.0+K)/(1.0+J))**F)))*
     $((1.0+I)**(-F))
      NPW(L)=PW(L)+NPW(L)
   60 CONTINUE
C
C     CALCULATE AFTER-TAX NET PRESENT VALUE OF CURRENT THICKNESS
C
      NPV(L)=NPW(L)+(INSCST(L)*(1.0-TCRED))
```

```
C
C     ANNUALIZE AFTER-TAX COST OF CURRENT THICKNESS
C
```

WRITE(LP,

```
      ANCST(L)=NPV(L)*((I*((1.0+I)**N))/(((1.0+I)**N)-1.0))
   50 CONTINUE
C
C     WRITE RESULTS OF CALCULATIONS
      WRITE(LP,100)
  100 FORMAT(1H1, 20X, 'ECONOMIC THICKNESS DETERMINATION',
     $//1H , 10X, 'DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT',
     $/1H , 23X, 'OKLAHOMA STATE UNIVERSITY',
     $//1H0, 27X, 'INPUT PARAMETERS')
      WRITE(LP,101)NAM1,NAM2,NAM3,NAM4,CONT1,CONT2,CONT3,CONT4
  101 FORMAT(/1H0,'FIRM:', 2X, 4A4, 16X, 'CONTACT:', 2X, 4A4)
      WRITE(LP,102)INTYP1,INTYP2,INTYP3,INTYP4,KVAL
  102 FORMAT(1H0, 'INSULATION:', 2X, 4A4, 10X, 'K-VAKUE:', 2X,
     $F6.4, 1X, 'BTU/HR, SQ FT, DEG F')
      WRITE(LP,103) INC, FNTHK
  103 FORMAT(1H0, 'INCREMENT:', 2X, F5.2, 1X, 'INCHES', 15X,
     $'FINAL THICKNESS:', 2X , F5.2, 1X, 'INCHES')
      WRITE(LP,104) I, J
  104 FORMAT(1H0, 'AFTER-TAX MARR:', 2X, F5.2, 1X, '%', 15X,
     $'GENERAL INFLATION RATE:', 2X, F5.2, 1X, '%')
      WRITE(LP,105) K, RS
  105 FORMAT(1H0, 'FUEL ESCALATION RATE:', 2X, F5.2, 1X, '%', 9X,
     $'SURFACE RESISTANCE:', 2X, F6.4, 1X, 'BTU/HR, SQ FT, DEG F')
      WRITE(LP,106) HDHR, CDHR
  106 FORMAT(1H0, 'HEATING DEGREE-HOURS:', 2X, F10.1, 6X,
     $'COOLING DEGREE-HOURS:', 2X, F10.1)
      WRITE(LP,107) HEFF, CEFF
  107 FORMAT(1H0, 'HEAT PLANT EFFICIENCY:', 2X, F5.2, 1X, '%', 8X,
```

```
     $'COOLING PLANT EFFICIENCY:', 2X, F5.2, 1X, '%')
      WRITE(LP,108) HCOST, CCOST
  108 FORMAT(1HO, 'COST PER THERM OF HEAT:', 2X, '$', F6.2, 7X,
     $'COST PER THERM OF COOLING:', 2X, '$', F6.2)
      WRITE(LP,109) TE, TCRED
  109 FORMAT(1HO, 'INCREMENTAL TAX RATE:', 2X, F5.3, 1X, '%', 9X,
     $'AVAILABLE TAX CREDIT:', 2X, F5.3, 1X, '%')
      WRITE(LP, 114) N
  114 FORMAT(1HO, 'USEFUL LIFE:', 2X, I2, 2X, 'YEARS')
      WRITE(LP,110)
  110 FORMAT(//1HO, 23X, 'THICKNESS CALCULATICNS', //1HO,
     $'INSULATION', 5X, 'INSTALLED', 4X, 'ANNUAL ENERGY', 4X,
     $'NET PRESENT', 4X, 'ANNUALIZED', /1H , 'THICKNESS', 8X,
     $'COST', 7X, 'LOSS CR GAIN', 8X, 'VALUE', 9X, 'COST')
      IF (CODE .EQ. 1) GO TO 4
      WRITE(LP,111)
  111 FORMAT(1H , '(IN INCHES)', 4X, '($/SC FT)', 5X, '(BTU/SQ FT)',
     $6X, '($/SQ FT)', 5X, '($/SQ FT)')
      GO TO 3
    4 WRITE(LP,112)
  112 FORMAT(1H , '(IN INCHES)', 4X, '($/LN FT)', 5X, '(BTU/LN FT)',
     $6X, '($/LN FT)', 5X, '($/LN FT )')
    3 DO 80 M=1, INUME
      WRITE(LP,113) THK(M), INSCST(M), ANBTU(M), NPV(M), ANCST(M)
  113 FORMAT(1HO, 1X, F5.2, 11X, F5.2, 7X, F9.1, 6X, F9.2, 7X, F6.2)
   80 CONTINUE
      STOP
      END
C
C     END OF PROGRAM
```

EADC
INSUL

```
                         ECONOMIC THICKNESS DETERMINATION

              DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT
                            OKLAHOMA STATE UNIVERSITY

                                 INPUT PARAMETERS

 FIRM:  SANDCO, INC.                      CONTACT:  S D SANDSTRUM

 INSULATION:  CALCIUM SILICATE            K-VAKUE:  0.3900 BTU/HR, SQ FT, DEG F

 INCREMENT:  1.00 INCHES                  FINAL THICKNESS:  6.00 INCHES

 AFTER-TAX MARR:  0.18 %                  GENERAL INFLATION RATE:  0.15 %

 FUEL ESCALATION RATE:  0.20 %            SURFACE RESISTANCE:  0.4600 BTU/HR, SQ FT, DEG F

 HEATING DEGREE-HOURS:  876000.0          COOLING DEGREE-HOURS:          0.0

 HEAT PLANT EFFICIENCY:  0.70 %           COOLING PLANT EFFICIENCY:  0.70 %

 COST PER THERM OF HEAT:  $  0.35         COST PER THERM OF COOLING:  $  0.00

 INCREMENTAL TAX RATE:  0.480 %           AVAILABLE TAX CREDIT:  0.000 %

 USEFUL LIFE:  10  YEARS


                           THICKNESS CALCULATIONS

 INSULATION      INSTALLED      ANNUAL ENERGY      NET PRESENT      ANNUALIZED
 THICKNESS         COST         LOSS OR GAIN         VALUE            COST
 (IN INCHES)     ($/LN FT)      (BTU/LN FT)        ($/LN FT)        ($/LN FT)

   0.00            0.00         6142946.0            60.46           13.45

   1.00            5.06         1054669.0            15.56            3.46

   2.00            9.12          624146.5            15.47            3.44

   3.00           13.93          462443.4            18.81            4.19

   4.00           17.48          377010.0            21.59            4.80

   5.00           25.15          323843.7            28.92            6.44

   6.00           29.08          287378.1            32.59            7.25
```

Appendix A.8.B Continued

```
                ECONOMIC THICKNESS DETERMINATION

        DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT
                     OKLAHOMA STATE UNIVERSITY

                          INPUT PARAMETERS

FIRM:  SANDCO, INC                      CONTACT:  S D SANDSTRUM
INSULATION:  CALCIUM SILICATE           K-VAKUE:  0.3900 BTU/HR, SQ FT, DEG F
INCREMENT:    1.00 INCHES               FINAL THICKNESS:   6.00 INCHES
AFTER-TAX MARR:   0.18 %                GENERAL INFLATION RATE:   0.15 %
FUEL ESCALATION RATE:   0.20 %          SURFACE RESISTANCE:  0.4600 BTU/HR, SQ FT, DEG F
HEATING DEGREE-HOURS:    876000.0       COOLING DEGREE-HOURS:          0.0
HEAT PLANT EFFICIENCY:   0.70 %         COOLING PLANT EFFICIENCY:   0.70 %
COST PER THERM OF HEAT:  $  0.35        COST PER THERM OF COOLING:  $  0.0
INCREMENTAL TAX RATE:  0.480 %          AVAILABLE TAX CREDIT:  0.0    %
USEFUL LIFE:  10  YEARS.


                      THICKNESS CALCULATIONS

INSULATION      INSTALLED      ANNUAL ENERGY      NET PRESENT     ANNUALIZED
THICKNESS         COST         LOSS OR GAIN          VALUE           COST
(IN INCHES)     ($/LN FT)       (BTU/LN FT)        ($/LN FT)       ($/LN FT)
  0.0              0.0          6142946.0            60.46           13.45
  1.00             5.06         1054609.0            15.56            3.46
  2.00             9.12          624146.5            15.47            3.44
  3.00            13.93          462443.4            18.81            4.19
  4.00            17.48          377010.0            21.59            4.80
  5.00            25.15          323843.7            28.92            6.44
  6.00            29.08          287377.7            32.59            7.25
READY
END
READY
LOGOFF
```

```
ENTER HEATING AND COOLING EFFICIENCIES
?
0.70 0.70
ENTER EXISTING SURFACE RESISTANCE
?
0.4600
ENTER HEATING AND COOLING COST PER THERM
?
0.35 0.00
ENTER INCREMENTAL TAX RATE AND TAX CREDIT
?
0.48 0.00
ENTER USEFUL LIFE OF INSULATION
?
10
ENTER SURFACE CODE AND OUTSIDE RADIUS
?
1 4.3125
ENTER THICKNESS, INSTALLED COST, MAINTENANCE COST
?
0.00 0.00 0.00
?
1.00 5.06 0.05
?
2.00 9.12 0.09
?
3.00 13.93 0.14
?
4.00 17.48 0.17
?
5.00 25.15 0.25
?
6.00 29.08 0.29
```

APPENDIX A.8.B

HARDCOPY OF ECOTHK--INTERACTIVE MODE

```
LOGON
IKJ56700A ENTER USERID -
U11610A
ENTER CURRENT PASSWORD FOR U11610A-
STEV
U11610A LOGON IN PROGRESS AT 12:43:53 ON DECEMBER 12, 1980
 The remote facility in Engineering South will close for semester
 break at 6:00 p.m. Thursday, Dec. 11, and will reopen at 10:30 a.m.
  Monday, January 12.
READY
TERM LINESIZE (130)
READY
CALL ECOTHK.LOAD(ECOTHK)
ENTER NAME OF FIRM
SANDCO, INC
ENTER CLIENT REPRESENTATIVE
S D SANDSTRUM
ENTER INSULATION TYPE UNDER ANALYSIS
CALCIUM SILICATE
ENTER K-VALUE OF INSULATION
?
0.3900
ENTER INCREMENT AND FINAL THICKNESS
?
1.00 6.00
ENTER MARR, INFLATION AND FUEL ESCALATION RATES
?
0.18 0.15 0.20
ENTER HEATING AND COOLING DEGREE-HOURS
?
876000.0 00.0
```