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OPTIMAL INSULATION OF PIPES AND TANKS
FOR SOLAR HEATING SYSTEMS

Topical Report

By
Gerard F. Jones
Noam Lior

February 1979

Work Performed Under Contract No. EM-78-C-04-5319

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Philadelphia, Pennsylvania

MASTER

U.S. Department of Energy

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Solar Energy

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OPTIMAL INSULATION OF PIPES AND TANKS
FOR SOLAR HEATING SYSTEMS
with Application Example to Insulation Design
for the University of Pennsylvania SolaRow House

TOPICAL REPORT

Gerard F. Jones and Noam Lior
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PREFACE
COLLECTOR ARRAY STUDIES

by

Noam Lior
Principal Investigator

In the course of studies performed to implement the solar heating retrofit of a Philadelphia row house (SolaRow), and to make recommendations for the design of solar collector arrays in general, it was found that the determination of insulation type and thickness for the solar heating system's piping and thermal storage tanks must receive more serious consideration than that accorded to it at present by most solar system designers.

The major problem to address is the fact that heat losses in solar heating systems could easily amount to 25% or more of the total solar heat collected. This has a seriously adverse effect on solar system economics. Some of the major reasons for high heat losses are:

(1) Selection of insulation values which are optimized based on an economic model which doesn't properly reflect the economics of solar heating systems.

(2) System control strategy which allows excessive heat losses; for example by allowing hot fluid to lose heat to cooler ambients for periods of time which are longer than necessary.

(3) The use of large areas of heat-loss surface, such as long pipes, and thermal storage tanks which have a large surface/volume ratio.

Preface (continued)

The design of solar collector arrays involves the determination of the optimal flow configuration (e.g. series, parallel, parallel-series, etc.) and collector row spacing, both of which are intimately related to the length of insulated piping selected, and hence, to the heat losses from the insulated surface. This report presents specifically the appropriate insulation optimization technique for solar heating systems in which the piping and thermal storage configuration is already known, and provides engineering graphs and tables for design purposes. Separately, in continuing the work beyond this report, the techniques developed are being presently implemented into an overall method for optimizing the design of solar collector arrays, which also includes such items as flow configuration effects on collector performance and on pumping power, row spacing effects on shading and on heat losses due to wind, and overall system cost.

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ABSTRACT

A compact and time effective insulation design procedure for solar heating system piping and water-filled thermal storage tanks was developed. Recognizing the particular sensitivity of solar systems to cost, the economic aspect of the problem is treated by a comprehensive present-value life-cycle cost analysis. In the development of the method, a numerical sensitivity analysis was performed to determine the relative effects of all relevant independent variables (within their pertinent ranges) on piping and tank heat transfer coefficient values. For the acceptable error limits of $\pm 14\%$ for pipes and $\pm 19\%$ for tanks, it was found that one may assume that only the nominal pipe diameter (or tank diameter), the thermal conductivity of the insulation, and the insulation's thickness have an effect on the overall heat transfer coefficient. Based on this result, design graphs and tables are presented which can be used to determine the optimal insulation thickness and type, total annual heat losses, present-value annual costs of insulation and lost heat, and overall insulation R values. The use of the method is illustrated by calculating all the above quantities for all piping and storage tanks for the University of Pennsylvania SolaRow House. Recommendations on installation techniques together with insulation material and labor costs are included. The present method provided insulation thicknesses slightly greater than those obtained by the ETI technique.

A major conclusion of this study is that the cost of insulation in solar systems is not insignificant (e.g., $\sim 15\%$ of total cost in SolaRow), and that heat losses through insulation could amount to an important percentage of the useful solar energy collected (e.g., 24% in SolaRow). This re-emphasizes the need for a careful design of insulation in solar systems and points to methods for reducing these costs and losses, primarily by reducing the length of piping, the surface area of thermal storage tanks, and the residence time of warm fluid in the piping.

1. INTRODUCTION

When compared to the delivered energy costs for a system using conventional heat sources, the collection and use of solar heat is a costly process. Hence, minimization of solar heat lost through solar heating system surfaces (such as pipes, thermal storage tanks, etc.) is required, but only at constrained associated equipment and labor costs. Since economics constitutes probably the major present obstacle to the widespread utilization of solar heating, it is important to include in the design procedure of solar systems the careful optimization of the thermal insulation. This optimization is obtained by selecting principally the insulation material and thickness which give the lowest total cost of insulation material, labor, maintenance, and energy lost through the insulation, over the lifetime of the system. A qualitative illustration of the optimization method is shown in Fig. 1.

For a given insulating material, the amount of lost heat (and thus the cost of lost heat) decreases as the thickness of the insulation increases[†]. On the other hand, the cost of the insulating material and labor increases with thickness. As the sum of these costs passes through a minimum, the optimal insulation thickness is determined. The cost vs. thickness relationship in Fig. 1 is shown in a number of discrete points instead of the customary continuous curve, because commercial insulation is most often purchasable in discrete thicknesses only. In this example, insulating material #1 has an optimal thickness No. 5 which results in a total cost C_{T1} , while material #2 has an optimal thickness No. 4 with cost C_{T2} . It is also noteworthy that when choosing between the two materials, #1 is optimal because $C_{T1} < C_{T2}$.

[†]That is true for above-critical diameters. For below-critical ones, the addition of insulation increases the heat loss. All piping considered here, and which is practical for solar systems, has above-critical diameters.

Fig. 1. Optimization of insulation thickness and material

Note: Insulation thickness increases with the "insulation thickness number".

Least cost optimization as described above does not consider other insulation characteristics such as dimensional stability, flammability, water permeability, etc. These requirements are to be satisfied first before an insulation is considered a candidate for cost optimization.

Several techniques for the determination of optimal insulation thicknesses are presently available (cf [1-3]). These consist primarily of industrial computer programs and nomograms oriented to applications where conventional fuels are used. The recently developed ETI Method [3] optimizes the selection of insulation based on a number of economic criteria, most notably through life-cycle costing, and is thus gaining in popularity due to increasing energy costs and emphasis on industrial energy conservation.

Specifically, typical simplifying assumptions made in these techniques are:

- a. The thermal resistance due to the fluid-to-tube heat transfer coefficients and due to heat conduction through the tube wall is ignored (resistance = 0).

- b. The thermal resistance due to the heat transfer coefficient between the insulation's outer surface (or jacketing) and ambient air is assumed to be a constant, and thermal radiation from that surface is either constant or neglected.
- c. Pipe material and commercial diameters and wall thicknesses as applied to different types of tubes (e.g. steel, copper, plastic) do not enter into the heat loss calculation.

The third assumption not only affects the thermal resistance to heat flow from the tube but, when using design graphs, could lead to incorrect predictions of the heat transfer surface area and thus of the final thickness of insulation.

The purpose of this study is first to analyze through the use of a comprehensive heat transfer model and a numerical perturbation technique the sensitivity of the rate of heat loss coefficient (UA value) to the various independent variables which define it, and secondly to use those variables, which are found in the sensitivity analysis to dominate the rate of heat loss, in a combined heat transfer/economic model to construct convenient insulation design graphs and tables. With these, an optimal insulation material and thickness and the annual heat loss for each pipe and tank size for a given solar system can be determined.

The analysis considers indoor water-filled storage tanks as well as both indoor and outdoor piping for four working fluids and for influence from the following independent variables:

- (1) Ambient temperature and wind velocity.
- (2) Piping or storage tank hot fluid temperature.
- (3) Piping material and nominal size.
- (4) Working fluid type: Water, 50-50% (by wt.) ethylene glycol-water solution, silicone liquid (Dow Corning^R Q2-1132), hydrocarbon heat transfer liquid (Shell Thermia Oil 15).

- (5) Insulation thickness.
- (6) Insulation thermal conductivity.
- (7) Piping design pressure gradient (which determines liquid flow velocity).
- (8) Insulation surface emissivity.
- (9) Annual system usage factor.
- (10) Annual payback on capital.
- (11) Cost of solar heat.
- (12) Cost of insulation material, jacketing, and labor.

2. OPTIMIZATION MODEL DEVELOPMENT

2.1 Heat Transfer Model

Consider the thermal circuit for the case of steady radial heat flow from a hot fluid through a composite circular wall of length ℓ^+ , assuming zero contact resistance between components as shown in Fig. 2 (the neglect of contact resistance results in a conservative estimate of insulation thickness)

where $2r_i = d_i$ $i = 1, 2, 3$

$$R_1 = \frac{1}{\pi d_1 \ell h_i} \quad (1)$$

$$R_5 = \frac{1}{\pi d_3 \ell h_o} \quad (4)$$

$$R_2 = \frac{\ell n(d_2/d_1)}{2\pi \ell k_p} \quad (2)$$

$$R_6 = \frac{1}{\pi d_3 \ell h_r} \quad (5)$$

$$R_3 = \frac{\ell n(d_3/d_2)}{2\pi \ell k_i} \quad (3)$$

$$h_r = 4\epsilon\sigma \left(\frac{T_p + T_r}{2} \right)^3 \quad (6)$$

⁺Other symbols are defined in the Nomenclature, Section 10.

For $T_r = T_a$,

$$R_4 = \frac{1}{1/R_5 + 1/R_6} \quad (7)$$

and the expression for the rate of radial heat flow, per unit length of cylinder is

Fig. 2. The geometry and analog thermal circuit of the insulated pipe heat transfer model

$$Q_l = \frac{T_f - T_a}{\sum_{i=1}^4 R_i} = \frac{\pi(T_f - T_a)}{\frac{1}{d_1 h_i} + \frac{\ln(d_2/d_1)}{2k_p} + \frac{\ln(d_3/d_2)}{2k_i} + \frac{1}{d_3(h_o + h_r)}} = UA\Delta T \quad (8)$$

where $\Delta T \equiv T_f - T_a$

and U is the overall heat transfer coefficient based on surface area A

where A is the surface area selected, per unit length of pipe

$$\text{but } \frac{d_2}{d_1} = 1 + \frac{2t_p}{d_1}, \quad \frac{d_3}{d_2} = 1 + \frac{2t_i}{d_2} \quad (9)$$

$$\text{then } d_3 = \left(1 + 2\frac{t_p}{d_1} + 2\frac{t_i}{d_1}\right) d_1 \equiv \gamma d_1 \quad (10)$$

$$\text{thus } UA = \pi \left[\frac{1}{d_1 h_i} + \frac{\ln(1 + \frac{2t}{d_1})}{2k_p} + \frac{\ln(1 + \frac{2t_i}{d_1 + 2t})}{2k_i} + \frac{1}{\gamma d_1 (h_o + h_r)} \right]^{-1} \quad (11)$$

$\equiv$ rate of heat loss per unit of pipe length per unit of ΔT

The value of h_i for both indoor and outdoor piping can be evaluated for $10000 \leq Re \leq 120000$ from the fully developed turbulent flow heat transfer correlation [4]

$$Nu = 0.023 Re_f^{0.8} Pr_f^{0.4} \quad (12)$$

and the Fanning Equation [4] with:

$$f = 0.184 Re_f^{-0.20} \quad (13)$$

as follows:

$$h_i = 0.31076 k_f d_1^{4/9} \phi^{1/3} Pr_f^{0.4} v_f^{-8/9} (\text{Btu/hr ft}^2 \text{ } ^\circ\text{F}) \quad (14)$$

where $\phi \equiv \frac{\Delta P}{\rho}$, dimensionless pipe pressure gradient. The value of h_o for outdoor piping (forced convection dominant) is determined by [5]

$$h_o = \frac{k_a}{\gamma d_1} (0.4 Re_a^{0.5} + 0.06 Re_a^{0.67}) Pr_a^{0.4} (\mu_a / \mu_{ap})^{0.25} \quad (15)$$

$$\text{where } Re_a = \frac{\gamma d_1 V}{\nu_a}, \quad T_{ap} = \frac{T_a + T_p}{2} \quad (16)$$

For indoor piping where natural convection dominates [2]

$$h_o = 0.27 \left(\frac{T_p - T_a}{\gamma d_1} \right)^{1/4} \quad (17)$$

Generally, the characteristic length used in the calculation of natural convection heat transfer coefficients is the diameter for horizontal cylinders, and the height for vertical ones. A comparison of the optimal insulation thickness

required when using the two lengths shows negligible differences for typical installations. For simplicity, all natural convection heat transfer coefficients were therefore determined in this study based on diameter.

For indoor storage tanks where the internal tank walls are completely wetted by water and no thermal stratification is assumed, the total rate of heat transfer per tank, Q' is:

$$Q' = \ell Q_{\ell} + Q_t + Q_b \quad (18)$$

where ℓ is the tank height.

Q_{ℓ} is determined from (8) with h_i evaluated from [2]:

$$h_i = 0.56 k_f [\rho_f \beta_f c_{p_f} g (T_f - T_t) (d_1 \nu_f k_f)^{-1}]^{0.25} \quad (19)$$

and h_o is determined from (17).

Q_t and Q_b are the heat transfer rates from the top and bottom of the tank respectively. Assuming steady linear heat flow through tank insulation.

$$Q_t \text{ or } Q_b = \frac{\pi d_1^2 \Delta T}{4 \left(\frac{1}{h_{it,b}} + \frac{t_p}{k_p} + \frac{t_i}{k_i} + \frac{1}{h_{ot,b} + h_r} \right)} \quad (20)$$

For vertical tanks with legs, $h_{o,t}$ and $h_{i,t}$ are evaluated from (17) with γd_1 replaced by d_1 , and (19), respectively, and [5]:

$$h_{i,b} = \frac{k_f}{d_1}, \quad h_{o,b} = 0.12 \left(\frac{T_p - T_a}{d_1} \right)^{1/4} \quad (21)$$

2.2 The Economic Model

A minimum present-value life-cycle cost analysis which involves the comparison of the annual average of the sum total costs over an expected lifetime for various alternative schemes is employed in this study. It is an underlying assumption here that insulation is determined by the life-cycle cost consideration to be the minimal life-cycle cost scheme, although alternative schemes for adding the energy lost through system surfaces could have conceivably been employed instead of adding insulation. Such schemes which could include the addition of solar collectors or other heat sources, are assumed a-priori to be more costly than the addition of insulation, thus justifying the assumption.

The average annual costs associated with the minimal, present-value life-cycle cost scheme arise from three sources:

- (1) Average annual present-value of the initial lumped investment which provided insulation labor and material.
- (2) Present-value average annual maintenance costs.
- (3) Present-value average annual energy costs.

The equation expressing this total present-value average cost C_T (\$/ft-yr or \$/m-yr) per unit length of piping insulation is

$$C_T = \frac{E_1(1)}{n} (C_i + C_j + C_\ell) + \frac{E_2(1)}{n} C_m + 8760 \times 10^{-6} F C_S UA (T_f - T_a) \quad (22)$$

where the three terms on its r.h.s. correspond to the above items (1)-(3), respectively. Specifically,

C_i = Base cost of the insulation material, including the cost of fitting and valve insulation prorated over the straight pipe length,
\$/ft (\$/m)

C_j = Base cost of insulation jacketing, \$/ft (\$/m)

C_ℓ = Base cost of insulation labor, \$/ft (\$/m)

C_m = Base cost of maintenance during the first year, \$/ft (\$/m)

F = Annual usage factor ($0 \leq F \leq 1$) of the insulated component.

This is the annual fraction of time during which the solar collection system (or storage tanks) loses heat. Consideration must be given to the working fluid remaining in piping and exposed to ambient temperatures after the solar collection system has stopped.

T_f, T_a = Average annual temperature of working fluid and ambient respectively, constant over the insulation lifetime, °F(°C)

C_s = Present-value annual average cost of solar heat, $\$/ (10^6 \text{ Btu-yr})$ [$\$/ (\text{MJ-yr})$]. C_s may be a given value, or could be calculated by using the equation

$$C_s = \frac{M_i E_1(2) + M_o E_3 + M_m E_2(2)}{n L_B n} + \theta(1-n) C_a \frac{E_4}{n} \quad (23)$$

where,

M_i = initial capital cost of solar heating system including all labor and materials, \$

M_o = first year operating costs of solar heating system, \$

M_m = first year maintenance cost of solar heating system, \$

L_B = total annual space heating and domestic hot water load, 10^6 Btu/year (MJ/year)

n = fraction of annual space heating and domestic hot water load contributed by solar

θ = 1 or 0, 1 corresponding to auxiliary heating of storage tank water directly, 0 corresponding to no direct auxiliary heating of water

C_a = first year cost of auxiliary energy delivered to storage, $\$/ 10^6 \text{ Btu}$ ($\$/ \text{MJ}$)

E are economic coefficients for converting cash flows to present values [6]
denoted as follows:

$$E_{1(j)} = \alpha_{(j)} - \beta_{(j)} - \sigma_{(j)} \left(\frac{1+g}{1+d} \right)^n + [(1-t)p_{(j)} + h_{(j)}] P(d, g, n_{(j)}) + \\ + (1-\alpha_{(j)}) \left[(1-t) \frac{P(d, 0, m_{(j)})}{P(i_{(j)}, 0, m_{(j)})} + t \frac{P(d, i_{(j)}, m_{(j)})}{P(0, i_{(j)}, m_{(j)})} \right] - B \quad (24)$$

$$E_{2(j)} = (1-t_1) P(d, r_{m(j)}, n) \quad (25)$$

$$E_3 = (1-t_1) P(d, r_0, n) \quad (26)$$

$$E_4 = (1-t_1) P(d, r_f, n) \quad (27)$$

where

The index $j \equiv 1$, for the insulation, or

$j \equiv 2$, for the complete solar system

$\alpha_{(j)}$ downpayment fraction of first cost

$\beta_{(j)}$ investment tax credit fraction, if applicable

$\sigma_{(j)}$ fractional salvage value at end of equipment life

g annual general inflation rate, (percent/100)

d annual discount rate, which could be chosen as either that for mere inflation, for an opportunity cost of money, or for a required return on investment; (percent/100).

t annual incremental income tax rate (only applicable in business applications, where the capital expenses are income tax deductible, otherwise $t=0$), (percent/100)

t_1 same as t , but only applicable if maintenance, operating, and fuel expenses are tax deductible, otherwise $t_1 = 0$

p actual annual property tax rate, (percent/100)

h annual insurance cost, as a fraction of the first cost

$$P(d,r,n) \equiv \frac{(1+d)^n - (1+r)^n}{(1+d)^n (d-r)} \quad \text{for } d \neq r \quad (28)$$

and

$$P(d,r,n) \equiv \frac{n}{1+r} \quad \text{for } d = r \quad (29)$$

n period of economic analysis (usually life of system), years

$i_{(j)}$ annual interest rate on loan or mortgage, (percent/100)

$m_{(j)}$ period of loan or mortgage, years

B cumulative present worth of depreciation tax credits per dollar invested:
with straight line depreciation:

$$B_{SL} = \frac{t(1-\sigma)}{k} P(d,0,k) \quad (30)$$

with declining balance:

$$B_{DB} = \frac{t\delta}{k} P(d, -\delta/k, k) \quad (31)$$

and with Sum Of Years Digits

$$B_{SOYD} = \frac{2t(1-\sigma)}{k(k+1)} \left[P(d_{(j)}, 0, k) + \frac{k-1-P(d,0,k-1)}{d} \right] \quad (32)$$

where

k depreciation lifetime

δ declining balance multiplier

$r_{m(j)}$ annual fractional rate of increase in maintenance expense

r_o annual fractional rate of increase in operating expense of
solar system

r_f annual fractional rate of increase in auxiliary fuel expense

Equation (22) can be rearranged to yield

$$C_{TM} = \frac{C_i}{C_s} F(T_f - T_a) = C_R + UA^* \quad (33)$$

where

$$C_R = \frac{E_1(1) (C_i + C_j + C_\ell) + E_2(1) C_m}{nC_s F(T_f - T_a)} \quad \text{and} \quad (34)$$

$$UA^* = 8760 \times 10^{-6} UA \left[\frac{10^6 \text{ Btu}}{\text{foot-year-}^\circ\text{F}} \left(\frac{\text{MJ}}{\text{meter-year-}^\circ\text{C}} \right) \right] \quad (35)$$

For thermal storage tanks, eqn. (22) takes the form

$$C_T' = \frac{E_1(1)}{n} (C_i + C_j + C_\ell) + \frac{E_2(1)}{n} C_m + 8760 \times 10^{-6} C_s \ell (UA)' F(T_f - T_a) \quad (36)$$

and eqns. (33) - (35) become:

$$C_{TM}' = \frac{C_T'}{C_s \ell F(T_f - T_a)} = C_R' + (UA*)' \quad (37)$$

where

$$C_R' = \frac{E_1(1) (C_i + C_j + C_\ell) + E_2(1) C_m}{nC_s \ell F(T_f - T_a)} \quad (38)$$

and

$$(UA*)' = 8760 \times 10^{-6} (UA)' \left[\frac{10^6 \text{ Btu}}{(\text{foot tank height})\text{-year-}^\circ\text{F}} \left(\frac{\text{MJ}}{\text{meter-year-}^\circ\text{C}} \right) \right] \quad (39)$$

It is noteworthy that C_T' , C_i , C_j and C_ℓ in eqn (36) represent total costs, and not costs per unit length as in pipes.

UA, the heat loss coefficient per unit length of insulated surface depends on many variables and its determination complicates the insulation design procedure. Therefore, a numerical sensitivity analysis is performed on UA to possibly reduce the number of independent variables which need to be considered in the design of the insulation.

3. SENSITIVITY ANALYSIS

3.1 General

In the numerical sensitivity analysis, variations in the (UA) value were determined by independently perturbing each variable that describes it, from a base value.[†] If the deviation of (UA) by such a perturbation, for a particular independent variable, falls within acceptable error tolerance, (UA) can then be considered independent of that variable for the range investigated and can for any design purposes be calculated with that variable fixed at its base value.

Upon investigation of (6), (11), (14), (15), and (16), the functional form of (UA) can, in general, be written as:

$$UA = UA(d_i, t_i, f_L, k_p, t_p, T_a, T_f, \phi, \epsilon, k_i, V) \quad (40)$$

where T_a and T_f are included to account for temperature dependent air and working fluid thermophysical properties and for nonlinear effects of thermal radiation and natural convection.

3.2 Piping

Commercially available schedule 40 carbon steel pipe and type L wall copper water tube are considered for piping materials in this analysis because of their common usage in residential and commercial areas. In addition, all results that apply to copper tube can be applied equally to aluminum pipe or tube having the same outside diameter and similar wall thickness since the thermal resistance of the pipe or tube wall in either a forced or natural convection dominant case is expected to be small.

Since commercial piping is considered, d_i , t_p and k_p cannot be specified independently. Instead, two alternate independent variables M_p and D (piping material and nominal diameter) are defined so that the value M_p determines k_p

[†] A base value is defined here as a value which lies midway between the maximal and minimal value in the continuous independent variable's range or an arbitrarily determined value within a continuous variable's range.

and the specification of both M_p and D determines t_p and d_1 . The number of independent variables is thus reduced from eleven to ten. In addition, since a k_i of 0.010 Btu/hr-ft- $^{\circ}$ F (0.017 W/m $^{\circ}$ C) is approximately the lower limit of thermal conductivities for commercially available insulation materials, it is convenient to define:

$$k^* \equiv k_i / 0.010 \text{ Btu/hr-ft-}^{\circ}\text{F} (\equiv k_i / 0.017 \text{ W/m}^{\circ}\text{C}) \quad (41)$$

With this, $k^* = 1.0, 2.0, 3.0$ and 4.0 corresponds approximately to polyurethane foam, fiberglass or a closed cell foam rubber, foamed glass and calcium silicate insulation respectively. Eqn. (40) is now written:

$$UA = UA(D, t_i, f_L, M_p, T_f, T_a, \phi, \epsilon, k^*, V), \text{ for outdoor pipe} \quad (42)$$

and

$$UA = UA(D, t_i, f_L, M_p, T_f, T_a, \phi, \epsilon, k^*), \text{ for indoor pipe} \quad (43)$$

The range of parameters used in the sensitivity analysis is listed below:

Discrete Design Variables

Nominal Commercial Pipe Diameter D : 3/8, 1/2, 3/4, 1, 1-1/4, 1-1/2, 2, 2-1/2, 3, 3-1/2, 4, 4-1/2, 5 in.

$t_i = 3/8$ (0.95), $1/2$ (1.27), $3/4$ (1.91), 1 (2.54), $1-1/2$ (3.81), 2 (5.08), $2-1/2$ (6.35), 3 (7.62), $3-1/2$ (8.89), 4 (10.16), $4-1/2$ (11.43), 5 (12.70), $5-1/2$ (13.97), 6 (15.24), in. (cm.)

Type of fluid, f_L : 1, 2, 3, 4, corresponding to the working fluids listed in table 1 below.

Commercial Pipe Material M_p :

1, 2, 3, corresponding to copper (1), steel (2) and a hypothetical pipe material (3) which has the dimensions and thermal conductivity represented by the mean value of the commercial copper and steel materials.

Property	Fluid No. 1: Water		Fluid No. 2: Aqueous Solution of ethylene-glycol, 50% by weight		Fluid No. 3: Silicone Oil, Dow Corning Q2-1132		Fluid No. 4: Synthetic Hydrocarbon, Shell Thermia Oil 15	
Temperature, °F	150°	200°	150°	200°	150°	200°	150°	200°
k_f , Btu/hr ft °F (W/m°C)	0.384 (0.664)	0.394 (0.681)	0.245 (0.423)	0.241 (0.416)	0.081 (0.140)	0.080 (0.138)	0.075 (0.129)	0.075 (0.129)
ν , ft ² /s (m ² /s)	4.770×10^{-6} (4.431×10^{-7})	3.410×10^{-6} (3.168×10^{-7})	1.132×10^{-5} (1.051×10^{-6})	7.860×10^{-6} (7.302×10^{-7})	1.168×10^{-4} (1.085×10^{-5})	8.221×10^{-5} (7.637×10^{-6})	1.110×10^{-4} (1.031×10^{-5})	8.382×10^{-5} (7.787×10^{-6})
Pr	2.74	1.88	9.18	6.55	111.09	79.24	133.57	105.48
ρ , lbm/ft ³ (kg/m ³)	61.20 (980.3)	60.10 (962.7)	65.30 (1046.0)	64.10 (1026.8)	56.88 (911.1)	55.38 (887.11)	52.17 (835.7)	51.08 (818.2)
c_p , Btu/lbm °F (kJ/kg °C)	1.000 (4.184)	1.000 (4.184)	0.845 (3.535)	0.870 (3.640)	0.378 (1.581)	0.387 (1.619)	0.485 (2.029)	0.510 (2.134)

TABLE 1: Fluid Properties at 150°F(60°C) and 200°F(93°C)

Continuous Value Variables

$$100(39) \leq T_f \leq 300(149), \text{ } ^\circ\text{F} (^\circ\text{C})$$

$$20(-6.7) \leq T_a \leq 80(27), \text{ } ^\circ\text{F} (^\circ\text{C})$$

$$0.05 \leq \phi \leq 0.10, \text{ dimensionless}$$

$$0.10 \leq \epsilon \leq 1.0, \text{ dimensionless}$$

$$0.010(0.017) \leq k_i \leq 0.040(0.069), \text{ Btu/hr ft}^\circ\text{F (W/m}^\circ\text{C)}$$

$$5(2.2) \leq V \leq 15(6.7), \text{ miles per hour (m/s)}$$

The sensitivity analysis was begun by defining seven "base cases"; three each for indoor and outdoor piping and one for indoor water-filled thermal storage tanks. The indoor and outdoor piping base cases are defined in Table 2; the storage tank base case is defined in Table 3. The method proceeds by calculating the (UA) values both for the base cases and the perturbed cases, where the former are determined for each base case from base case variables and evaluated for all D (nominal diameter) and t_i (insulation thickness) combinations (i.e., if the number of D and t_i values considered are seven and six respectively, there are $7 \times 6 = 42$ (UA) values calculated for each base case.). The perturbed case (UA) values are determined by changing each continuous variable (these are T_f , T_a , ϕ , ϵ , k^* , and V) from its base case value independently (the other continuous variables remain fixed at their base case values), evaluating (UA) for several (say five) points within that continuous variable's range and performing this operation for all four fluids, for all D_i and t_i combinations and for $M_p = 1$ and $M_p = 2$. The base case and perturbed case (UA) values are then compared for like D and t_i combinations and the results analyzed. These results indicate the effect of each of the continuous and discrete variables on the (UA) value. Should the effect be small for a particular variable, then (UA) can be considered independent of that variable and calculated for design purposes at that variable's base value.

The above method can be represented analytically with the aid of the following definitions:

$\hat{i}$ = number indicating the location and type of heat loss surface ($\hat{i} = 1$ for outdoor piping, $\hat{i} = 2$ for indoor piping, $\hat{i} = 3$ for indoor water-filled thermal storage tanks)

$\hat{j}$ = base case number ($\hat{j} = 1, 2$ or 3 for $\hat{i} = 1$,
 $\hat{j} = 4, 5$ or 6 for $\hat{i} = 2$,
 $\hat{j} = 7$ for $\hat{i} = 3$)

$\hat{k}$ = number indicating the specific D and t_i combination (for seven D values and six t_i values, $\hat{k} = 1, 2, 3, \dots, 42$)

$\hat{\ell}$ = piping number for $M_p = 1$ and $M_p = 2$ ($\hat{\ell} = 1, 2$)

$\hat{m}$ = fluid number for $f_L = 1, 2, 3, 4$ ($\hat{m} = 1, 2, 3, 4$)

$\hat{n}$ = the number indicating the base case continuous variable ($T_f = 1$,
 $T_a = 2$, $\phi = 3$, etc.)

$\hat{p}$ = index number of a particular value within a continuous variable's ($\hat{n}$) range ($\hat{p} = 1, 5$)

then

$$UA_{\hat{i}, \hat{j}, \hat{k}} \equiv \text{Base case (UA) value} \quad (44)$$

$$UA_{\hat{i}, \hat{k}, \hat{\ell}, \hat{m}, \hat{n}, \hat{p}} \equiv \text{Perturbed case (UA) value} \quad (45)$$

and a comparison variable is defined

$$\hat{B}_{\hat{i}, \hat{j}, \hat{k}, \hat{\ell}, \hat{m}, \hat{n}, \hat{p}} \equiv \left| 1 - \frac{UA_{\hat{i}, \hat{k}, \hat{\ell}, \hat{m}, \hat{n}, \hat{p}}}{UA_{\hat{i}, \hat{j}, \hat{k}}} \right| \quad (46)$$

where all subscripts of $\hat{B}$ are iterated independently beginning with $\hat{p}$ and continuing towards $\hat{i}$ in the sequence indicated. To simplify analysis of the results, the maximal value of $\hat{B}$ with respect to $\hat{k}$ and $\hat{m}$ is determined and

$$\frac{UA_{\max}}{UA_{\text{base}}} \equiv \frac{UA_{\hat{i}, \hat{\ell}, \hat{n}, \hat{p}}}{UA_{\hat{i}, \hat{j}}} \quad (47)$$

defined, where $\hat{k}$ and $\hat{m}$ are those for which $\hat{B}$ is a maximum and have thus been eliminated as variables. In doing this, the maximal possible influence of $\hat{m}(F_L)$ and $\hat{k}$ (D and t_i combinations) on (UA) is exhibited. The calculations in the sensitivity analysis were carried out on a Univac 90-70 computer. Determination of eq. (47), which is the criterion of the sensitivity analysis, involved more than 25000 (UA) value calculations.

Equation (47) can then be plotted for each $\hat{i}$ (location and type of heat loss surface number), $\hat{j}$ (base case), $\hat{\ell}$ (M_p), and $\hat{n}$ (continuous variable number) value against a nondimensional representation of $\hat{p}$ (value of the $\hat{n}$ -th continuous variable). The results are presented as graphs in Figs. 3 and 4 for outdoor and indoor piping respectively, and in Fig. 7 for indoor water-filled thermal storage tanks.

Location of Piping	Base Case No.	M_p	f_L	Value of Base Case Variables					
				$T_f, ^\circ F(^{\circ}C)$	$T_a, ^\circ F(^{\circ}C)$	ϕ	ϵ	k^*	V mph (m/s)
Outdoor	1	1	1	200 (93)	40 (4)	0.075	0.5	2.0	10 (4.5)
	2	2	1	200 (93)	40 (4)	0.075	0.5	2.0	10 (4.5)
	3	3	1	200 (93)	40 (4)	0.075	0.5	2.0	10 (4.5)
Indoor	4	1	1	200 (93)	60 (16)	0.075	0.9	2.0	0
	5	2	1	200 (93)	60 (16)	0.075	0.9	2.0	0
	6	3	1	200 (93)	60 (16)	0.075	0.9	2.0	0

Table 2. Definition of Base Cases for Piping Insulation Sensitivity Analysis

Fig. 3. Sensitivity analysis results for outdoor piping insulation
Upper curves: steel pipe; lower curves: copper tube

Fig. 4. Sensitivity analysis results for indoor piping insulation
Upper curves: steel pipe; lower curves: copper tube

3.3 Indoor Hot Water Storage Tanks

$$\text{Here } (UA)' = (UA)' (d_2, t_i, k_p, t_p, T_f, T_a, \epsilon, k_i) \quad (48)$$

The ranges of the variables T_f , T_a , ϵ , and k_i are the same as for pipes.

Cylindrical steel tanks of outside diameter d_2 , height ℓ , and wall thickness $t_p = 3/16"$ (0.48 cm) are considered (applicability of results to other wall thicknesses is permitted since the effect of t_p on the (UA) value is small), where

$$1.5(0.46) \leq d_2 \leq 9(2.74), \text{ ft (m)}$$

$$5(1.52) \leq \ell \leq 9(2.74), \text{ ft (m), also:}$$

$$t_i: 1/2(1.27), 1(2.54), 2(5.08), 3(7.62), 4(10.16), 5(12.7), 6(15.24), \\ 7(17.78), 8(20.32), 10(25.4), 12(30.48), 14(35.56), \\ 16(40.64), 18(45.72), 20(50.80), 22(55.88), 24(61.96) \text{ in. (cm)}$$

The "base case" here is described in Table 3.

Location	Base Case	Value of Base Case Variables			
		$T_f, ^\circ\text{F}(^\circ\text{C})$	$T_a, ^\circ\text{F}(^\circ\text{C})$	ϵ	k^*
Indoor Storage Tanks	7	150 (66)	60 (16)	0.50	2

Table 3. The base case for storage tank insulation sensitivity analysis

The method of the sensitivity analysis here is the same as for piping.

The results of the analysis are shown in Fig. 5.

Fig. 5. Sensitivity analysis results for indoor hot water storage tank insulation

3.4 Conclusions from the Sensitivity Analysis

As expected, the major influence on (UA) is through the insulation's thermal conductivity and thickness for all cases. The influence of all the other variables is at least an order of magnitude smaller than that of k^* . Specifically, for outdoor piping cases, only the wind velocity influences the (UA) value to any noticeable extent over its range, this effect being only $\pm 3\%$. For the outdoor piping cases the hot fluid temperature T_f and the insulation's emissivity ϵ show an effect of $\pm 3\%$ each on (UA), and for the indoor hot water storage tanks the influence of T_f is $\pm 5\%$ and of ϵ is $\pm 8\%$. The radiative losses become more pronounced for indoor insulation because they are comparable to the natural convection losses, whereas outdoor external surface heat transfer coefficients are dominated by wind-driven forced convection. Also, indoor tanks have a large external surface area.

The type of heated liquid has a very small influence (12%), that is maximal for the silicone oil, which demonstrates smaller (UA) values than the other fluids.

It is noteworthy that both in this method and others for determining optimal insulation thickness, the proper pipe diameter must be selected due to the difference between the numbers describing the nominal diameter for different pipe materials, (e.g. copper, steel), and the actual measured diameter. For example, if the difference between the actual and nominal diameters was neglected, using the same nominal diameter for copper and steel pipe would result here in errors of up to 20% in the UA value, this because of the difference in pipe surface area. Errors like this could easily be made when using the ETI manual [3].

Assuming that a (UA) error of up to $\pm 14\%$ is allowable when determining optimal piping insulation ($\pm 19\%$ for storage tank insulation), the results of the sensitivity analysis for the base cases and the ranges of variables listed, can be summarized by

$$UA = UA(D, t_i, k^*, \text{indoor or outdoor}) \quad (49)$$

and

$$(UA)' = (UA)'(d_2, t_i, k^*) \quad (50)$$

Referring to eq. (33), the effects on C_{TM} due to the above errors in UA^* can be quantified by writing

$$\frac{C_{TM}}{C_R} = 1 + u \left(\frac{UA^*}{C_R} \right) \quad (51)$$

where u is an error coefficient with values of

$0.86 \leq u \leq 1.14$ for piping

$0.81 \leq u \leq 1.19$ for storage tanks

Using (51), two limiting case effects of u on C_{TM} are considered, these being

$$C_R \ll (UA^*) \quad (52)$$

$$C_R \gg (UA^*) \quad (53)$$

For case (52), the second term on the right hand side of (51) becomes the dominant term on that side and C_{TM} is then equal to $u(UA^*)$. For the case of (53) the first term on the right hand side of (51) is dominant and C_{TM} determined independently of u or (UA^*) . Thus, the maximal error in C_{TM} due to an error in the (UA^*) value is realized by case (52) and is the same as that error associated with the (UA^*) value.

4. DESIGN GRAPHS

With equations (49) and (50), and (UA) variables defined from Base Case 3 for outdoor piping, Base Case 6 for indoor piping, and Base Case 7 for indoor storage tanks, eq. (33) is used to generate graphs relating system variables C_R to system costs C_{TM} . These can then become optimal insulation design graphs because C_R can be varied till minimal C_{TM} read from the graphs, is obtained. A natural further step of calculation which would directly indicate the optimal thickness without the trial-and-error procedure (through differentiation of the rate of heat loss with t_i) was not implemented mainly because the cost function is discontinuous due to the discrete values of commercial pipe diameters and insulation thicknesses, but also because the present method provides more information, indicating C_{TM} for a variety of C_R values.

Equation (33) was thus plotted in Figure 6 for outdoor piping insulation, where the different combinations of D and t_i are listed in Table 4, and correspond to the curves in Fig. 6.

Indoor piping insulation design graphs are shown in Fig. 7 with the D and t_i combination legend listed in table 5. A comparison of like combinations of D and t_i from Figs. 6 and 7 indicate that (UA) differences as large as 32% exist, justifying the development of both an indoor and outdoor piping insulation design graph.

Indoor hot water storage tank insulation design graphs are shown in Fig. 8, with the d_2 and t_i combination legend listed in Table 6.

Inspection of Figs. 6, 7 and 8 with tables 4, 5 and 6 shows that the "critical diameter" (the value of d_3 for which the (UA) value is a maximum for all other independent variables fixed) is smaller than d_3 determined from any combination of pipe diameter and insulation thickness used in this analysis. Therefore, for all cases, (UA) for a given pipe diameter decreases with increasing insulation thickness, thus confirming the statement made earlier that all diameters considered in this report are above critical.

The optimal insulation thickness, total annual heat loss, present-value annual average insulation and heat loss costs, and overall insulation R-value, are determined for a particular pipe (or tank) for a given system as follows:

- (1) Obtain insulation material and jacketing costs for each insulation thickness starting from the smallest available thickness for the particular pipe size of interest, and from economic and system design information and labor costs which apply to the project, calculate C_R (or C_R^i) for each thickness using eqn (34).

(2) Knowing whether the pipe to be insulated is indoor or outdoor, find from Table 4 or 5 (or 6) the curve numbers which correspond to the pipe (or tank) size and the insulation thicknesses.

(3) Knowing whether the pipe to be insulated is indoor or outdoor and the value of k^* for the particular insulation under investigation enter the C_R (or C'_R) value to the proper figure (6, 7, or 8).

(4) From the correct curve number read off the value of C_{TM} (or C'_{TM}) that corresponds to each insulation thickness.

(5) The optimal insulation thickness is that which gives the smallest value of C_{TM} (or C'_{TM}). The C_{TM} (or C'_{TM}) axis intercept for this insulation thickness is the value (UA^*) (or (UA^*)).

For the optimal insulation thickness:

The present-value annual average cost per unit length of piping is

$$C_T = C_{TM} C_S F(T_f - T_a), \text{ \$/yr} \quad (54)$$

and the total annual heat loss per unit length of insulated pipe is

$$Q_h = (UA^*) F(T_f - T_a), \quad 10^6 \text{ Btu/yr (MJ/yr)} \quad (55)$$

For each storage tank, the total annual cost is:

$$C'_T = C'_{TM} \ell C_S F(T_f - T_a), \text{ \$/yr} \quad (56)$$

and the total annual heat loss is

$$Q'_h = (UA^*) \ell F(T_f - T_a), \quad 10^6 \text{ Btu/yr (MJ/yr)} \quad (57)$$

Nominal Pipe Size	Curve Number					
	Insulation Thickness in. (cm)					
	3/8" (0.95)	1/2" (1.27)	3/4" (1.91)	1" (2.54)	1-1/2" (3.81)	2" (5.08)
3/8"	5	3	1			
1/2"	7	4	2	1		
3/4"	9	7	3	2		
1"	10	8	5	3	1	
1-1/4"	12	10	7	5	2	1
1-1/2"	14	11	8	6	3	2
2"	15	13	10	8	5	3

Table 4:
Outdoor Piping Insulation Legend
(For use with Fig. 6)

Fig. 6. Outdoor piping insulation design graphs (Base Case 3).
Number legend is given in Table 4.

Nominal Pipe Size	Curve Number					
	Insulation Thickness					
	3/8" (0.95)	1/2" (1.27)	3/4" (1.91)	1" (2.54)	1-1/2" (3.81)	2" (5.08)
3/8"	6	4	1			
1/2"	8	6	3	1		
3/4"	10	8	5	3		
1"	12	10	7	5	2	
1-1/4"	15	12	9	7	4	2
1-1/2"	16	14	11	8	5	3
2"	17	16	13	10	7	5

Table 5:
Indoor Piping Insulation Legend.
(For use with Fig. 7)

Fig. 7. Indoor piping insulation design graphs (Base Case 6)
Number legend is given in Table 5.

Tank Outside Diameter, feet (m)	Insulation Thickness Inches (cm)							
	1/2 (1.27)	1 (2.54)	2 (5.08)	3 (7.62)	4 (10.16)	5 (12.7)	6 (15.24)	7 (17.78)
1 1/2 (0.45)	17	11	5	3	1			
2 (0.61)	20	14	8	5	3	2	1	
3 (0.91)	28	20	13	9	6	5	4	3
4 (1.22)	32	25	16	12	9	7	6	5
5 (1.52)	34	29	20	15	12	10	8	7
6 (1.83)	36	31	23	18	15	12	10	9
7 (2.13)		33	27	21	18	14	13	11
8 (2.44)		35	29	24	20	17	15	13
9 (2.74)		36	30	26	22	19	16	15

Table 6:

Indoor Hot Water Storage Tank
Insulation Legend (For use with
Fig. 8)

Fig. 8. Indoor hot water storage tank insulation graphs (Base Case 7)
Number legend is given in Table 6.

In addition, the overall insulation R-value for a particular insulation thickness of cylindrical pipes and tanks is calculated by[†]

$$R \text{ (or } R') = \frac{8760 \times 10^{-6}}{UA^* \text{ (or } UA^{*'})} \frac{\text{ft length of cylinder } ^\circ\text{F}}{\text{Btu}} \left(\frac{\text{m length of cylinder } ^\circ\text{C}}{\text{W}} \right) \quad (58)$$

The procedure can be repeated for several different insulation materials having different k^* values to determine the economic optimal insulation material for a particular pipe (or tank) size.

The system variables F , C_s , T_f and T_a can be determined by hourly computer simulation or by using annual averages by techniques such as proposed in [7] and [8].

5. DESIGN TABLES

Should more precision be desired in the optimal insulation selection, a method is presented which provides actual numerical (UA^*) values which are listed in Tables 7, 8 and 9 for outdoor (Base Case 3) and indoor (Base Case 6) piping and indoor storage tanks (Base Case 7), respectively.

The optimal insulation thickness and associated information is determined for a particular pipe (or tank) for a given system as follows:

- (1) Same as (1) for Section 4. of the report.
- (2) From the applicable Table 7, 8 or 9 find the value of UA^* (or $UA^{*'}\text{'}$) which corresponds to the particular pipe (or tank) size under consideration for the proper value of k^* and for the range of insulation thicknesses being investigated.

[†]It is noteworthy that this is not the same as the more commonly used R value for flat insulation which is in units of $\text{ft}^2\text{hr}^\circ\text{F}/\text{Btu}$ ($\text{m}^2^\circ\text{C}/\text{W}$).

Nominal Pipe Size	UA* x 10 ³ , Btu/foot-year °F														LEGEND	
															Fixed Nominal Pipe Size	Fixed Insulation Thickness k*=1.0 k*=2.0 k*=3.0 k*=4.0
	INSULATION THICKNESS, inches (cm)															
	0.375(0.95)	0.500(1.27)	0.750(1.91)	1.00(2.54)	1.50(3.81)	2.00(5.08)	2.50(6.35)	3.00(7.62)	3.50(8.89)	4.00(10.16)	4.50(11.43)	5.00(12.70)	5.50(13.97)	6.00(15.24)		
3/8	0.653 1.270 1.860 2.430	0.544 1.070 1.570 2.060	0.429 0.847 1.250 1.650	0.368 0.729 1.080 1.430	0.302 0.601 0.895 1.190	0.267 0.531 0.792 1.050	0.244 0.485 0.725 0.962	0.227 0.453 0.677 0.899	0.215 0.428 0.640 0.851	0.205 0.408 0.611 0.813	0.197 0.393 0.587 0.781	0.190 0.379 0.568 0.755	0.184 0.368 0.551 0.733	0.179 0.358 0.536 0.714		
1/2	0.760 1.480 2.160 2.810	0.627 1.230 1.810 2.360	0.488 0.962 1.420 1.870	0.414 0.820 1.220 1.610	0.336 0.667 0.994 1.320	0.294 0.584 0.872 1.160	0.267 0.531 0.793 1.050	0.248 0.493 0.737 0.979	0.233 0.465 0.695 0.923	0.222 0.442 0.661 0.879	0.212 0.424 0.634 0.843	0.205 0.409 0.612 0.813	0.198 0.396 0.592 0.788	0.193 0.384 0.575 0.766		
3/4	0.927 1.800 2.620 3.390	0.755 1.480 2.170 2.830	0.577 1.140 1.680 2.210	0.484 0.957 1.420 1.870	0.386 0.766 1.140 1.510	0.334 0.664 0.990 1.310	0.301 0.598 0.893 1.190	0.277 0.552 0.825 1.100	0.260 0.518 0.774 1.030	0.246 0.491 0.734 0.975	0.235 0.469 0.701 0.932	0.226 0.451 0.674 0.897	0.218 0.435 0.651 0.866	0.211 0.422 0.631 0.840		
1	1.100 2.120 3.080 3.990	0.886 1.730 2.530 3.290	0.668 1.310 1.940 2.540	0.555 1.100 1.620 2.140	0.436 0.865 1.290 1.700	0.373 0.742 1.110 1.470	0.334 0.664 0.991 1.310	0.306 0.610 0.911 1.210	0.286 0.569 0.850 1.130	0.270 0.537 0.803 1.070	0.257 0.512 0.765 1.020	0.246 0.491 0.734 0.976	0.237 0.473 0.707 0.941	0.229 0.457 0.685 0.911		
1 1/4	1.320 2.550 3.690 4.760	1.060 2.060 3.010 3.910	0.787 1.540 2.280 2.980	0.646 1.270 1.890 2.480	0.500 0.992 1.470 1.950	0.424 0.842 1.250 1.660	0.376 0.748 1.120 1.480	0.343 0.682 1.020 1.350	0.318 0.634 0.947 1.260	0.299 0.596 0.891 1.180	0.284 0.566 0.846 1.120	0.271 0.541 0.809 1.080	0.260 0.519 0.777 1.030	0.251 0.501 0.750 0.998		
1 1/2	1.490 2.870 4.160 5.350	1.190 2.310 3.370 4.370	0.877 1.720 2.530 3.310	0.716 1.410 2.090 2.740	0.549 1.090 1.610 2.130	0.462 0.917 1.360 1.810	0.407 0.810 1.210 1.600	0.370 0.736 1.100 1.460	0.342 0.681 1.020 1.350	0.321 0.639 0.955 1.270	0.303 0.605 0.904 1.200	0.289 0.577 0.863 1.150	0.277 0.553 0.828 1.100	0.267 0.533 0.798 1.060		
2	1.830 3.510 5.060 6.490	1.450 2.810 4.080 5.280	1.050 2.060 3.030 3.960	0.852 1.680 2.470 3.250	0.643 1.270 1.890 2.490	0.535 1.060 1.580 2.090	0.468 0.929 1.380 1.830	0.422 0.839 1.250 1.660	0.388 0.772 1.150 1.530	0.362 0.720 1.080 1.430	0.341 0.679 1.020 1.350	0.324 0.646 0.965 1.280	0.310 0.617 0.924 1.230	0.298 0.593 0.888 1.180		
2 1/2	2.180 4.170 6.000 7.670	1.720 3.320 4.820 6.220	1.240 2.420 3.550 4.630	0.992 1.950 2.880 3.770	0.740 1.460 2.170 2.860	0.609 1.210 1.800 2.380	0.529 1.050 1.570 2.070	0.474 0.943 1.410 1.860	0.434 0.863 1.290 1.710	0.403 0.802 1.200 1.590	0.378 0.754 1.130 1.500	0.358 0.714 1.070 1.420	0.342 0.681 1.020 1.350	0.327 0.653 0.977 1.300		
3	2.560 4.880 6.990 8.930	2.010 3.870 5.600 7.220	1.440 2.800 4.100 5.340	1.140 2.240 3.310 4.330	0.843 1.670 2.470 3.250	0.689 1.360 2.030 2.680	0.594 1.180 1.760 2.320	0.529 1.050 1.570 2.080	0.482 0.960 1.430 1.900	0.446 0.888 1.330 1.760	0.418 0.832 1.240 1.650	0.394 0.786 1.170 1.560	0.375 0.748 1.120 1.490	0.359 0.715 1.070 1.420		
3 1/2	2.900 5.520 7.890 10.000	2.270 4.370 6.310 8.110	1.620 3.150 4.600 5.980	1.280 2.510 3.690 4.830	0.936 1.850 2.740 3.600	0.760 1.500 2.240 2.950	0.652 1.290 1.930 2.550	0.579 1.150 1.710 2.270	0.525 1.040 1.560 2.070	0.485 0.964 1.440 1.910	0.452 0.901 1.350 1.790	0.426 0.849 1.270 1.680	0.404 0.806 1.200 1.600	0.386 0.769 1.150 1.530		
4	3.250 6.150 8.770 11.200	2.530 4.860 7.010 9.000	1.790 3.490 5.100 6.620	1.420 2.770 4.070 5.330	1.030 2.030 3.000 3.950	0.831 1.640 2.440 3.220	0.709 1.410 2.090 2.770	0.627 1.250 1.860 2.460	0.568 1.130 1.680 2.230	0.522 1.040 1.550 2.060	0.486 0.968 1.450 1.920	0.457 0.911 1.360 1.810	0.433 0.863 1.290 1.710	0.413 0.822 1.230 1.630		
5	3.940 7.440 10.60 13.40	3.060 5.860 8.430 10.80	2.160 4.190 6.100 7.910	1.690 3.310 4.860 6.340	1.220 2.400 3.540 4.660	0.974 1.930 2.860 3.770	0.826 1.640 2.430 3.220	0.726 1.440 2.150 2.840	0.654 1.300 1.940 2.570	0.598 1.190 1.780 2.350	0.555 1.100 1.650 2.190	0.520 1.040 1.550 2.050	0.491 0.977 1.460 1.940	0.466 0.929 1.390 1.840		

Table 7: UA* values for nominal pipe size, insulation thickness, and k* combinations for outdoor piping

Nominal Pipe Size	UA* x 10 ³ , Btu/foot-year °F													LEGEND	
	INSULATION THICKNESS, inches (cm)													Fixed Nominal Pipe Size	Fixed Insulation Thickness
	0.375(0.95)	0.500(1.27)	0.750(1.91)	1.00(2.54)	1.50(3.81)	2.00(5.08)	2.50(6.35)	3.00(7.62)	3.50(8.89)	4.00(10.16)	4.50(11.43)	5.00(12.70)	5.50(13.97)	6.00(15.24)	k*=1.0 k*=2.0 k*=3.0 k*=4.0
3/8	0.598 1.100 1.530 1.900	0.509 0.952 1.350 1.700	0.411 0.785 1.130 1.450	0.357 0.689 1.000 1.300	0.296 0.579 0.851 1.110	0.263 0.517 0.763 1.000	0.241 0.475 0.704 0.920	0.225 0.445 0.661 0.873	0.213 0.422 0.628 0.830	0.204 0.404 0.601 0.795	0.196 0.389 0.579 0.767	0.189 0.376 0.560 0.743	0.184 0.365 0.545 0.722	0.179 0.356 0.531 0.704	
1/2	0.694 1.270 1.760 2.190	0.585 1.090 1.540 1.940	0.466 0.888 1.280 1.630	0.401 0.773 1.120 1.450	0.329 0.642 0.942 1.230	0.289 0.568 0.839 1.100	0.264 0.520 0.769 1.010	0.245 0.435 0.719 0.940	0.231 0.458 0.681 0.899	0.220 0.437 0.650 0.860	0.211 0.419 0.625 0.827	0.204 0.405 0.603 0.799	0.197 0.392 0.585 0.766	0.192 0.382 0.569 0.755	
3/4	0.842 1.530 2.110 2.620	0.702 1.300 1.830 2.300	0.550 1.040 1.500 1.910	0.467 0.839 1.300 1.630	0.378 0.736 1.080 1.400	0.328 0.644 0.949 1.240	0.297 0.585 0.865 1.140	0.274 0.542 0.804 1.060	0.258 0.510 0.757 1.000	0.244 0.484 0.720 0.952	0.234 0.463 0.690 0.913	0.225 0.446 0.665 0.880	0.217 0.431 0.643 0.852	0.210 0.418 0.624 0.828	
1	0.993 1.800 2.470 3.060	0.821 1.520 2.130 2.670	0.635 1.200 1.720 2.190	0.534 1.030 1.480 1.910	0.426 0.828 1.210 1.580	0.367 0.719 1.060 1.390	0.329 0.648 0.958 1.260	0.303 0.598 0.886 1.170	0.283 0.560 0.831 1.100	0.266 0.530 0.786 1.040	0.255 0.506 0.752 0.995	0.245 0.485 0.723 0.957	0.236 0.468 0.698 0.925	0.228 0.454 0.676 0.897	
1 1/4	1.190 2.150 2.950 3.630	0.979 1.800 2.520 3.150	0.746 1.410 2.010 2.560	0.621 1.190 1.720 2.200	0.488 0.948 1.380 1.800	0.416 0.814 1.200 1.570	0.371 0.729 1.080 1.410	0.339 0.668 0.989 1.300	0.315 0.623 0.924 1.220	0.297 0.587 0.872 1.150	0.282 0.558 0.830 1.100	0.269 0.534 0.796 1.050	0.259 0.514 0.766 1.010	0.250 0.497 0.741 0.982	
1 1/2	1.350 2.420 3.310 4.070	1.100 2.020 2.810 3.510	0.831 1.570 2.230 2.830	0.688 1.310 1.890 2.430	0.535 1.040 1.510 1.970	0.453 0.886 1.300 1.700	0.401 0.789 1.160 1.530	0.365 0.720 1.070 1.400	0.339 0.669 0.992 1.310	0.318 0.629 0.934 1.230	0.301 0.597 0.887 1.170	0.288 0.570 0.849 1.120	0.276 0.548 0.816 1.080	0.266 0.528 0.787 1.040	
2	1.650 2.950 4.020 4.930	1.330 2.440 3.390 4.220	0.997 1.870 2.660 3.370	0.817 1.560 2.240 2.870	0.625 1.210 1.760 2.290	0.524 1.020 1.500 1.960	0.460 0.903 1.330 1.750	0.416 0.820 1.210 1.590	0.384 0.757 1.120 1.480	0.358 0.709 1.050 1.390	0.338 0.670 0.995 1.310	0.322 0.638 0.948 1.250	0.308 0.611 0.909 1.200	0.296 0.588 0.875 1.160	
2 1/2	1.960 3.500 4.760 5.820	1.580 2.880 4.000 4.960	1.170 2.190 3.100 3.930	0.950 1.810 2.590 3.320	0.719 1.390 2.020 2.620	0.597 1.160 1.700 2.220	0.520 1.020 1.500 1.970	0.468 0.920 1.360 1.790	0.429 0.846 1.250 1.650	0.399 0.789 1.170 1.540	0.375 0.743 1.100 1.460	0.356 0.705 1.050 1.390	0.340 0.673 1.000 1.330	0.326 0.646 0.962 1.270	
3	2.300 4.090 5.550 6.780	1.850 3.360 4.640 5.760	1.360 2.530 3.580 4.530	1.090 2.080 2.970 3.800	0.819 1.580 2.300 2.970	0.674 1.310 1.920 2.500	0.584 1.140 1.680 2.200	0.522 1.030 1.510 1.990	0.477 0.940 1.390 1.830	0.442 0.873 1.293 1.700	0.414 0.819 1.220 1.600	0.392 0.775 1.150 1.520	0.373 0.738 1.100 1.450	0.356 0.707 1.050 1.390	
3 1/2	2.610 4.620 6.260 7.640	2.080 3.790 5.230 6.470	1.520 2.840 4.010 5.060	1.220 2.320 3.320 4.230	0.908 1.750 2.540 3.280	0.743 1.450 2.120 2.750	0.641 1.250 1.840 2.410	0.571 1.120 1.650 2.170	0.519 1.020 1.510 1.990	0.480 0.947 1.400 1.850	0.448 0.886 1.320 1.730	0.423 0.837 1.240 1.640	0.402 0.796 1.180 1.560	0.384 0.761 1.130 1.500	
4	2.910 5.150 6.970 8.490	2.320 4.210 5.810 7.180	1.690 3.150 4.440 5.600	1.350 2.560 3.660 4.660	0.998 1.920 2.790 3.600	0.812 1.580 2.310 3.000	0.697 1.360 2.000 2.620	0.618 1.210 1.790 2.350	0.561 1.100 1.630 2.150	0.517 1.020 1.510 1.990	0.482 0.953 1.410 1.860	0.454 0.898 1.330 1.760	0.430 0.852 1.270 1.670	0.410 0.813 1.210 1.600	
5	3.540 6.240 8.420 10.20	2.810 5.080 6.990 8.640	2.030 3.780 5.320 6.690	1.620 3.050 4.350 5.540	1.180 2.270 3.280 4.240	0.952 1.850 2.700 3.510	0.811 1.580 2.330 3.040	0.715 1.400 2.070 2.710	0.645 1.270 1.870 2.460	0.592 1.170 1.730 2.270	0.550 1.090 1.610 2.120	0.516 1.020 1.510 2.000	0.487 0.964 1.430 1.890	0.463 0.917 1.360 1.800	

Table 8: UA* values for nominal pipe size, insulation thickness, and k* combinations for indoor piping

Tank Outside Diameter feet (m)	(UA*)' x 10 ² , Btu/(foot tank length)-year-°F												LEGEND					
													Fixed Outside Diameter	Fixed Insulation Thickness				
														k*=1.0 k*=2.0 k*=3.0 k*=4.0				
INSULATION THICKNESS, inches (cm)																		
	0.5 (1.27)		1.0 (2.54)		2.0 (5.08)		3.0 (7.62)		4.0 (10.16)		5.0 (12.7)		6.0(15.24)		7.0 (17.78)		8.0 (20.32)	
1.5 (0.45)	0.903 1.990	1.520 2.360	0.516 1.270	0.928 1.570	0.288 0.769	0.541 0.977	0.205 0.566	0.392 0.728	0.162 0.455	0.313 0.590	0.135 0.385	0.263 0.501	0.117 0.336	0.229 0.440	0.104 0.300	0.204 0.394	0.094 0.273	0.185 0.359
2.0 (0.61)	1.210 2.660	2.030 3.150	0.689 1.690	1.230 2.080	0.381 1.010	0.714 1.280	0.269 0.739	0.514 0.949	0.211 0.590	0.406 0.764	0.175 0.496	0.340 0.645	0.151 0.431	0.294 0.562	0.133 0.383	0.260 0.501	0.120 0.346	0.235 0.454
3.0 (0.91)	1.850 4.050	3.100 4.800	1.050 2.560	1.880 3.150	0.579 1.520	1.080 1.930	0.406 1.100	0.770 1.410	0.316 0.875	0.605 1.130	0.260 0.730	0.502 0.947	0.222 0.630	0.431 0.820	0.195 0.557	0.380 0.726	0.174 0.500	0.340 0.654
4.0 (1.22)	2.530 5.520	4.240 6.540	1.440 3.490	2.560 4.290	0.792 2.070	1.470 2.610	0.554 1.490	1.040 1.910	0.429 1.180	0.818 1.520	0.352 0.981	0.677 1.270	0.300 0.844	0.579 1.100	0.262 0.743	0.508 0.967	0.233 0.665	0.454 0.868
5.0 (1.52)	3.250 7.080	5.430 8.370	1.850 4.470	3.280 5.480	1.020 2.640	1.880 3.330	0.711 1.900	1.340 2.430	0.550 1.500	1.040 1.930	0.451 1.250	0.863 1.610	0.383 1.070	0.737 1.390	0.334 0.941	0.646 1.220	0.297 0.841	0.576 1.100
6.0 (1.83)	4.010 8.710	6.690 10.300	2.280 5.490	4.040 6.740	1.260 3.240	2.310 4.090	0.879 2.340	1.640 2.980	0.630 1.840	1.280 2.360	0.557 1.530	1.060 1.970	0.473 1.310	0.905 1.690	0.412 1.150	0.792 1.490	0.366 1.030	0.706 1.340
7.0 (2.13)	4.810 10.400	8.010 12.300	2.740 6.570	4.830 8.050	1.510 3.880	2.770 4.880	1.060 2.790	1.970 3.550	0.817 2.200	1.540 2.820	0.669 1.820	1.270 2.350	0.568 1.560	1.080 2.020	0.494 1.370	0.947 1.780	0.439 1.220	0.843 1.590
8.0 (2.44)	5.640 12.200	9.380 14.400	3.210 7.690	5.660 9.430	1.770 4.540	3.240 5.710	1.240 3.270	2.300 4.160	0.961 2.570	1.800 3.290	0.787 2.130	1.490 2.740	0.668 1.830	1.270 2.360	0.582 1.600	1.110 2.070	0.516 1.430	0.987 1.850
9.0 (2.74)	6.500 14.100	10.800 16.600	3.710 8.870	6.530 10.900	2.050 5.230	3.740 6.580	1.440 3.760	2.660 4.790	1.110 2.960	2.080 3.790	0.911 2.460	1.710 3.150	0.773 2.100	1.460 2.710	0.673 1.840	1.280 2.380	0.597 1.650	1.140 2.130

Table 9: (first page out of two) - (UA*)' values for tank outside diameter, insulation thickness, and k* combinations for indoor water-filled thermal storage tanks

Tank Outside Diameter feet (m)	$(UA^*)' \times 10^2, \quad \text{Btu}/(\text{foot tank length})\text{-year-}^\circ\text{F}$										LEGEND	
											Fixed Outside Diameter	Fixed Insulation Thickness
												k*=1.0 k*=2.0 k*=3.0 k*=4.0
	INSULATION THICKNESS, inches (cm)											
	10 (25.4)	12 (30.48)	14 (35.56)	16 (40.64)	18 (45.72)	20 (50.8)	22 (55.88)	24 (60.96)				
1.5 (0.45)	0.080 0.234 0.308	0.070 0.158 0.207 0.273	0.063 0.126 0.187 0.247	0.058 0.115 0.172 0.227	0.054 0.107 0.160 0.211	0.051 0.100 0.150 0.198	0.048 0.095 0.142 0.188	0.045 0.090 0.135 0.179				
2.0 (0.61)	0.101 0.293 0.386	0.088 0.174 0.257 0.339	0.079 0.155 0.231 0.305	0.072 0.142 0.211 0.279	0.066 0.131 0.195 0.258	0.062 0.122 0.182 0.241	0.058 0.115 0.171 0.227	0.055 0.109 0.162 0.215				
3.0 (0.91)	0.145 0.419 0.551	0.125 0.246 0.364 0.479	0.111 0.219 0.324 0.427	0.100 0.197 0.293 0.387	0.091 0.181 0.269 0.355	0.085 0.168 0.249 0.330	0.079 0.156 0.233 0.308	0.074 0.147 0.219 0.290				
4.0 (1.22)	0.193 0.555 0.726	0.165 0.325 0.479 0.628	0.146 0.286 0.423 0.557	0.131 0.257 0.381 0.502	0.119 0.235 0.348 0.459	0.109 0.216 0.321 0.424	0.102 0.201 0.299 0.395	0.095 0.188 0.280 0.370				
5.0 (1.52)	0.245 0.699 0.913	0.209 0.409 0.601 0.767	0.183 0.359 0.530 0.695	0.164 0.322 0.476 0.625	0.148 0.292 0.433 0.570	0.136 0.269 0.398 0.525	0.126 0.249 0.369 0.487	0.118 0.233 0.345 0.456				
6.0 (1.83)	0.300 0.852 1.110	0.256 0.498 0.731 0.956	0.224 0.437 0.643 0.842	0.199 0.391 0.576 0.756	0.180 0.354 0.523 0.687	0.165 0.325 0.480 0.631	0.152 0.300 0.444 0.585	0.142 0.280 0.415 0.546				
7.0 (2.13)	0.359 1.010 1.320	0.306 0.593 0.868 1.130	0.267 0.520 0.763 0.997	0.237 0.464 0.662 0.893	0.214 0.420 0.618 0.811	0.196 0.384 0.567 0.744	0.181 0.355 0.524 0.689	0.168 0.330 0.488 0.642				
8.0 (2.44)	0.422 1.180 1.540	0.359 0.694 1.010 1.320	0.313 0.607 0.889 1.160	0.278 0.541 0.794 1.040	0.251 0.489 0.719 0.941	0.229 0.447 0.658 0.863	0.210 0.413 0.608 0.798	0.195 0.383 0.566 0.743				
9.0 (2.74)	0.488 1.360 1.770	0.415 0.799 1.160 1.510	0.361 0.699 1.020 1.330	0.321 0.623 0.911 1.190	0.289 0.562 0.825 1.080	0.263 0.514 0.755 0.988	0.242 0.473 0.696 0.913	0.225 0.440 0.647 0.849				

Table 9: (second page out of two) - $(UA^*)'$ values for tank outside diameter, insulation thickness, and k^* combinations for indoor water-filled thermal storage tanks

- (3) Add together the values of UA^* (or $(UA^*)'$) and C_R (or C_R') which correspond to the same pipe size and insulation thickness combination, to get values of C_{TM} (or C_{TM}').
- (4) The optimal insulation thickness is that which gives the smallest value of C_{TM} (or C_{TM}'). The optimum value of UA^* (or $(UA^*)'$) is that which corresponds to the optimal insulation thickness.

Equations to determine the annual heat loss, associated material and heat loss costs, and R-values are the same as those given in section 4. The above procedure can be repeated for several different insulation materials having different k^* values to determine the economic optimal insulation material for a particular pipe (or tank) size.

6. INSULATION DESIGN EXAMPLE: THE UNIVERSITY OF PENNSYLVANIA SOLAROW HOUSE

6.1 Description of System and Design Data

The University of Pennsylvania Solarow house [9] is a three story brick row house located just south of the campus in Philadelphia. Water is circulated from three storage tanks, of three foot diameter (seven foot high (350 gallons) (1325 l) each, located in the basement, to 33 flat-plate solar collectors arranged in five rows and located on the roof. Net collection area is 475 ft^2 (44 m^2). Each row has either five or seven collectors connected in parallel, with the rows being connected in series. The main collector supply and return lines consist of 1-1/2", type L nominal copper water tube and the collector upper and lower distribution headers are 2" nominal tube size. (These close-to-horizontal pipes are larger to minimize frictional resistance during gravity-driven draindown (cf [9])). Nominal 1/2" rubber hose and copper tube connect each collector inlet or outlet (respectively) to the distribution headers. Upon demand for house heating the solar heated water is circulated automatically from the tanks through 1" nominal copper tubes to and from an air-to-water heat exchanger located at the air intake of a fuel-fired

auxiliary furnace where existing ducts distribute the air throughout the house. In addition, a domestic hot water preheat heat exchanger is immersed in two of the three storage tanks to supply preheated city water to the existing gas-fired domestic hot water heater.

Freeze protection is by automatic drain-down into the thermal storage tanks when the water temperature drops below 38°F (3.3°C). To minimize admission of oxygen and startup transients, the water is retained in the pipes at higher temperatures, even when no water circulation is taking place.

The strategy used and estimated costs for insulation of tube fittings, valves, etc., and weatherproofing of insulation, are as follows:

1. Indoor tubing
 - A) For closed-cell foam rubber insulation add 15% to price per linear foot to account for insulation of fittings and valves and painting. Miter cut insulation to fit around valves and fittings (see installation procedures, section 7 below).
 - B) For preformed insulation, miter cut to fit around all valves and fittings.
 - C) Paint all insulation with water base or latex base paint.
2. Outdoor tubing
 - A) Jacket all preformed insulation with 0.006 in. thick corrugated aluminum jacketing with vapor barrier attached and wrap with 3/8 in. wide aluminum bands. Insulate all fittings with plastic preformed insulation fittings. Prorate the cost of these fittings over the length of the tube insulated and add the cost per unit length of jacketing directly to the cost of insulation per unit length.
 - B) Paint all foamed rubber insulation with a weatherproofing paint. Add 15% to the price per unit length.

To determine the optimal insulation, the following data (See Section 2.2) are applied for the University of Pennsylvania SolarRow house:

M_i	= \$20,000	p	= 0.005
$M_o + M_m$	= \$50.00	$h(1) = h(2)$	= 0.003
L_B	= 165×10^6 Btu	$m(1) = m(2)$	= 20 years
n	= 0.47	$i(1) = i(2)$	= 0.09
$n(1) = n(2)$	= 25 years	$r_m(1) = r_m(2) = r_o(1) = r_o(2)$	= 0.06
θ	= 0	B	= 0
$\alpha(1) = \alpha(2)$	= 0.2	$\bar{T}_{f \text{ outdoor}}$	= 110°F (43.3°C)
$\beta(1) = \beta(2)$	= 0	$\bar{T}_{f \text{ indoor}}$	= 90°F (32.2°C)
$\sigma(1) = \sigma(2)$	= 0	For all outdoor piping	$F(T_f - T_a) = 24^\circ\text{F}$
g	= 0.06	For indoor piping	$F(T_f - T_a) = 23^\circ\text{F}$
d	= 0.07	For thermal storage tanks	$F(T_f - T_a) = 63^\circ\text{F}$
t	= 0.18	C_m	= 0.03 \$/ft
t_1	= 0		

$\bar{T}_f$, $F(T_f - T_a)$, and n were determined from estimates supplied by SOLSYS, the University of Pennsylvania solar heating system simulation computer program [10] which used Philadelphia hourly ambient temperatures and insolation values.

6.2. Example

From the above information and from eq. (28):

$$P(d, g, n) = P(0.07, 0.06, 25) = \frac{(1+0.07)^{25} - (1+0.06)^{25}}{(1+0.07)^{25} (0.07 - 0.06)} = 20.9226$$

$$P(d, 0, m) = P(0.07, 0, 20) = \frac{(1+0.07)^{20} - 1}{(1+0.07)^{20} 0.07} = 10.5940$$

$$P(i,0,m) = P(0.09,0,20) = \frac{(1+0.09)^{20} - 1}{(1+0.09)^{20}(0.09)} = 9.1285$$

$$P(d,i,m) = P(0.07, 0.09, 20) = \frac{(1+0.07)^{20} - (1+0.09)^{20}}{(1+0.07)^{20}(0.07-0.09)} = 22.4143$$

$$P(0,i,m) = P(0,0.09,20) = \frac{1 - (1+0.09)^{20}}{1(0-0.09)} = 51.1601$$

From eq. (24) and the above:

$$\begin{aligned} E_1(1) = E_1(2) &= 0.2 - 0 - 0 + [(1-0.18)0.005 + 0.003] 20.9226 + \\ &+ (1-0.2)[(1-0.18) \frac{10.5940}{9.1285} + 0.18 \frac{22.4143}{51.1601}] - 0 = 1.173 \end{aligned}$$

From eq. (25)

$$E_2(1) = E_2(2) = P(d, r_m, n) = P(0.07, 0.06, 25) = 20.9226$$

From eq. (26)

$$E_3 = P(d, r_o, n) = P(0.07, 0.06, 25) = 20.9226$$

The cost of solar heat is obtained from eq. (23) and the above results:

$$C_s = \frac{20000(1.173) + 50(20.9226)}{(0.47)165(25)} + 0 = 12.64 \text{ \$/10}^6 \text{ Btu}$$

It is important to note here that $\eta = 0.47$ used here assumed no heat losses through insulation. Hence, after the optimal insulation values are determined, these heat losses must be calculated, and the value of η

modified. Since η would decrease, it means that C_s would increase, and one or more iterations of the optimal insulation values need to be performed, as described in more detail in Section 6.3 below. Only two iterations were needed in all cases considered here.

For outdoor piping, and from eq. (34), for the first iteration:

$$C_R = \frac{1.173(C_i + C_j + C_\ell) + (20.9226)0.03}{25(12.64)(24)} = (1.1547)10^{-4}(C_i + C_j + C_\ell) + (8.236)10^{-5} \quad (59)$$

Based on specific values of $(C_i + C_j + C_\ell)$, eq. (59) is used to determine the optimal fiberglass insulation ($k^*=2.0$) thickness for an outdoor-located 1 1/2" copper tube used in SolaRow, as demonstrated in Table 10.

By inspection of the last column (first iteration), the minimal value of C_{TM} is 1.628×10^{-3} . Therefore the optimal insulation thickness is 1-1/2" (3.81 cm) with a total annual heat loss per unit length (from (55)) of

$$Q_\ell = (1.09)10^{-3} 24 = (0.0262) 10^6 \text{ Btu/ft-yr (90.6 MJ/m-yr)}$$

The total annual cost of insulation per unit length (from (54)) is:

$$C_T = (1.628)10^{-3}(12.64)24 = \$0.49/\text{ft-yr} (\$1.62 \text{ m/yr})$$

It is interesting to note that of the total present value annual average cost per foot, \$0.33 or 67% is for energy ($C_{TM} = UA^*$ for $C_R = 0$) and the remainder for insulation material and labor.

As shown in Section 6.3 below, the heat losses through the total system's insulation were not negligible, and a second iteration was required, which changed the optimal insulation thickness to 2" (5.08 cm), and correspondingly changed the above values of Q_ℓ and C_T . The second iteration is also shown

Insulation Thickness in. (cm)	C_i Insulation Cost, \$/ft (\$/m)	C_j Jacketing Cost, \$/ft (\$/m)	C_L Labor Cost, (\$/ft) (\$/m)	$C_i + C_j + C_L$ Total Cost, (\$/ft) (\$/m)	$C_R \times 10^3$: 1st iteration 2nd iteration $\frac{10^6 \text{ Btu}}{\text{ft-yr-}^\circ\text{F}}$	Curve No. from Table 4	$(UA^*) \times 10^3$ from Fig. 6 or Table 7, $\frac{10^6 \text{ Btu}}{\text{ft-yr-}^\circ\text{F}}$	$C_{TM} \times 10^3$ from Fig. 6 or Eq. (8) 1st iteration 2nd iteration, $\frac{10^6 \text{ Btu}}{\text{ft-yr-}^\circ\text{F}}$
1/2 (1.27)	0.65 (2.13)	0.51 (1.67)	0.82 (2.69)	1.98 (6.49)	0.389 0.292	11	2.310	2.699 2.602
1 (2.54)	0.78 (2.55)	0.61 (2.00)	0.95 (3.11)	2.34 (7.67)	0.445 0.334	6	1.410	1.855 1.744
1-1/2 (3.81)	1.19 (3.90)	0.71 (2.33)	1.04 (3.41)	2.94 (9.64)	0.538 0.404	3	1.090	1.628 1.494
2 (5.08)	2.24 (7.34)	0.80 (2.62)	1.13 (3.70)	4.17 (13.67)	0.728 0.547	2	0.917	1.645 1.464
2 1/2 (6.35)	3.40 (11.15)	0.90 (2.95)	1.22 (4.00)	5.52 (18.10)	0.937 0.704	-	0.810	1.747 1.514

Table 10: Calculation of the optimal fiberglass insulation thickness for 1-1/2" nominal copper tube, located outdoors

in Table 10.

6.3 Results and Comparison with ETI

Four different commercially available piping insulation materials from six manufacturers, marketed under nine separate trade names, were considered as candidates for this project. The list of these materials, trade names, manufacturers, thermal conductivities and retail prices per foot for all tube sizes and thicknesses investigated is given in Appendix I, and the manufacturers' addresses are given in Appendix II. In addition, considered in the storage tank insulation analysis were various thicknesses of fiberglass batts, these being considered the easiest to remove in the event of a leak or a change in a tank connection.

Also of interest is the range of tubing insulation costs for the same materials but either marketed under different trade names or sold by different dealers. A table of these ranges is presented in Appendix III. Comments on the results are contained in Section 8 of this report.

By following the procedure used in the construction of Table 10, the optimal insulation is determined for all tubing sizes and storage tanks in the SolaRow House solar heating system, as shown in detail in Appendix IV. Table 11 lists major results: the optimal insulation and thicknesses, the associated material and heat loss costs and overall R-values calculated by the present technique for each pipe size and storage tank in the system and also those thickness calculated by the ETI method [3].

Table 11 also shows the percentage of the computed useful solar energy collected which is lost through the optimal insulation thickness (24.9% total for the first iteration) and through the actual insulation thickness (32.3% total) installed in SolaRow. Although the heat escaping through insulated surfaces in the basement doesn't represent a complete loss in winter, the total losses through insulation are significant. They could be reduced if the length of pipe and surface areas of thermal storage tanks can be reduced, and if the residence time of the warm working fluid (water in this case)

Location	Nominal Pipe Diameter, in.	Total Pipe Length, ft (m)	Optimal Insulation Material (k*)	Insulation Thickness in SolaRow, in. (cm)	Present Technique		ETI Method	Total Cost of Insulation $C_1 + C_2 + C_3$, \$/ft (\$/m)	Annual Cost of Heat Loss \$/ft-yr (\$/m-yr)	Total Annual Cost of insulation and Heat Loss, \$/ft-yr (\$/m-yr)	Ratio of Annual Heat Loss to Annual Total Cost, %	Annual Heat Loss From Total Pipe Length, 10^6 Btu/yr (MJ/yr)		Ratio of Annual Insulation Heat Loss to Useful Solar Heat Collected, %	
					Optimal Thickness, in. (cm)	Optimal Insulation R-value, hr ft ² F/Btu (m ² C/W)						For Optimal Thickness	For Thickness Installed in SolaRow	For Optimal Thickness	For Thickness Installed in SolaRow
Outdoor	1-1/2	194 (59.2)	Armstrong Armaglass (2.0)	1-1/2 (3.81)	2 (5.08)	9.6 (5.52)	1-1/2 (3.81)	2.94 (9.64)	0.37 (1.22)	0.59 (1.94)	63	4.27 (4504)	5.08 (5362)	5.5	5.6
	2	245 (74.7)	Armstrong Armaglass (2.0)	1-1/2 (3.81)	2 (5.08)	8.3 (4.78)	1 to 1-1/2 (2.54 - 3.81)	4.52 (14.82)	0.43 (1.40)	0.67 (2.18)	64	6.23 (6573)	7.92 (8351)	8.1	10.3
Indoor	1	60 (18.3)	Armstrong Armaflex (2.0)	3/4 (1.90)	1-1/2 (3.81)	10.5 (6.10)	1 (2.54)	3.12 (10.23)	0.32 (1.05)	0.49 (1.62)	65	1.15 (1208)	1.66 (1754)	1.5	2.3
	1-1/2	146 (44.5)	Armstrong Accotherm (2.0)	1 (2.54)	1-1/2 (3.81)	8.4 (4.87)	1-1/2 (3.81)	2.43 (7.97)	0.40 (0.99)	0.56 (1.49)	71	3.49 (3684)	4.40 (4641)	4.5	5.7
Indoor Thermal Storage Tank	Actual Outside Diameter = 36	7 ft high	Owens-Corning Fiberglass (2.0)	6 (15.24)	14 (35.56)	4.00 [†] (2.32)	10 (2.54)	\$230 per tank	per all three tanks						
									\$53.41	\$81.21	66	2.90 (3057)	5.70 (6016)	3.8	7.4

[†]Based on tank length, not surface area.

Table 11: Optimal insulation thickness, costs, and heat loss implications for SolaRow, determined by present technique and ETI method

can be diminished. Specifically, in the present SolaRow system, the warm water is retained in the collectors and piping even in periods when the water doesn't circulate (see Section 6.1). If the water was drained back into the thermal storage tanks each time when useful solar energy is not collected, this residence time would be reduced significantly, giving $F(T_f - T_a)$ values of 15°F (instead of 24°F) and 14°F (instead of 23°F) for outdoor and indoor piping, respectively. With the present insulation, the heat losses would then be reduced to 22.8% (from the present loss value of 32.3%).

It is noteworthy that an a-priori design for the new $F(T_f - T_a)$ values resulted in optimal insulation thickness which is the same as that calculated for the present $F(T_f - T_a)$ values in the cases of the 1 1/2" outdoor and indoor pipes, but gave thicknesses one step smaller for the 2" outdoor and 1" indoor pipes. This is to be expected, since smaller $F(T_f - T_a)$ values lead to reduced heat losses, a fact which leads to an amount of insulation which is optimally smaller. Such a-priori design for the lower $F(T_f - T_a)$ values results in an insulation heat loss of 18.2%, reduced as compared to the 24.9% loss incurred through insulation optimized on the present $F(T_f - T_a)$ values. Any energy savings achieved by this method must, however, be judged against the disadvantages of frequent draindown, such as accelerated corrosion rates, increased pumping energy during startup, etc.

The cost of useful solar heat (C_s , eqn. (23)) influences the value of the optimal insulation (through eqn. (22)). The value η in eq. (23), representing the fraction of annual space heating and domestic hot water load contributed by solar energy, which was used in the present calculations, did not, however, take into account heat losses through the insulation. This initial assumption of zero heat losses through insulation is typical to most solar system design procedures. It must be noted though that in cases where insulation heat losses are significant, this assumption leads to wrong values

of η , and hence of C_s and of optimal insulation. Generally, the heat losses increase the cost of solar heat, thus economically justifying better insulation. An iterative method can be used in such cases:

- (1) obtain an η value with the assumption of zero insulation heat loss,
- (2) determine the optimal insulation for this η ,
- (3) calculate the insulation heat losses,
- (4) recalculate η based on (3),
- (5) redetermine the optimal insulation for the new value of η ,
- (6) recalculate the heat losses,
- (7) continue the above procedure (4)-(6) till the optimal-insulation values stop changing.

The above-described iterative procedure was conducted for calculating the optimal SolaRow insulation described in Table 11. It was found that only one iteration was required, in addition to the initial calculation, indicating no change in the optimal insulation values, except for the cases of the 1 1/2" outdoor pipe and the thermal storage tank where the optimal insulation thickness increased by one step: from 1 1/2" (3.81 cm) to 2" (5.08 cm), and from 12" (30.5 cm) to 14" (35.56 cm), respectively. The new value of η is $(0.76)(0.47) = 0.36$, and the corrected cost of solar heat is

$$C_s = \frac{\$12.64}{0.76} = \$16.63/10^6 \text{ Btu}$$

The correct value of the total optimal-insulation heat loss is 24% of the collected solar energy.

7. INSTALLATION PROCEDURES

As noted earlier in this report the present method for determining optimal insulation treats commonly available insulation materials, thus the installation techniques described here are conventional.

Armaflex^{R†}, a closed-cell foam rubber, is supplied as unsplit tubes either in three, four or six foot lengths and, if needed, is easily split longitudinally with a razor or a hacksaw blade prior to application. After slipping the split insulation over the tube, the two seams are coated with Armaflex Cement (similar to a contact cement) and allowed to become tacky. After this, they are joined and held in place temporarily with tape until the cement hardens. On straight runs the Armaflex is similarly glued end-to-end. For insulation of elbows and tees, the Armaflex is miter-cut and glued in place. Valves and unions are insulated as shown in Figs. 9 and 10.

All outdoor Armaflex is painted with several coats of Bearn's and Foster 30-35^R weather-proofing coating.

Accotherm^R, a somewhat brittle phenolic resin, is supplied in three foot lengths already split longitudinally in two pieces and attached to an aluminum foil and kraft paper all-purpose jacket with sealing flap. Installation is performed by slipping the insulation on the tube and gluing the sealing flap to the insulation half with Armaflex cement. For indoor tubing Accotherm is mitered to fit around elbows and tees. A continuous fit is ensured by using duct tape on all joints. For oversized fittings and valves, Armaflex is used in accordance with Figs. 9 and 10.

[†]A list of insulation materials manufacturer's addresses is provided in Appendix II.

For outdoor tubing, all large fittings are insulated using Zeston^R pre-molded plastic insulation fittings. To use these, the straight pipe is first insulated up to the copper tube fitting, then the tube fitting is first wrapped with fiberglass to the desired thickness and taped in place with duct tape. The Zeston fitting is then slipped over the fiberglass and secured in place by sticking barbed tacks through the fitting and into the Accotherm insulation. The end of the Zeston fitting and the seam are then weather-proofed by banding and taping.

All outdoor insulation is weatherproofed by covering with 0.006" (0.015 cm) thick corrugated aluminum jacketing overlapping 2" (5.08 cm) between all seams. For horizontal piping runs the longitudinal seam should be on the bottom. The jacketing is held in place using 3/8" (0.95 cm) wide aluminum bands and aluminum clips spaced about 12" (30.48 cm) on centers. If any sloped or vertical piping is to be jacketed, the jacketing should overlap in the proper direction so as to eliminate the drainage of water into the seams.

Before application of storage tank insulation, many insulation clips[†] are cemented to the tank periphery using tile cement. The insulation is then wrapped in a circumferential direction around the tank impaling it on the clips starting from the tank bottom. These rings of insulation are held in place by 3/8" (0.95 cm) aluminum strapping. Taping is unsatisfactory here. The procedure is repeated until as many rings are installed that are necessary to cover the tank. The top and bottom are then insulated by cutting semi-circular pieces from the 23" (58.42 cm) wide batts. In a commercial or residential installation, an outer jacket or "shell" should be added since the fiberglass batts are vulnerable to compression and tearing. In the case described here, outer jacketing was not applied, to allow easier access to the tanks' instrumentation.

[†]A 3" (7.62 cm) long nail protruding through and attached to a 3" (7.62 cm) square perforated thin steel plate comprises an insulation clip.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 The Proposed Method

The above described method for determining optimal insulation is oriented specifically to solar heating systems in their pertinent range of parameters, addressing the particular realistic thermal and economic aspects of this problem. The economic aspect of the problem is treated by a present-value life-cycle cost analysis. Nominal commercial pipe diameters and insulation thicknesses were used in the development of the method to allow more accurate results for practical applications.

The method, assisted by the design graphs (Figs. 6, 7 and 8) or tables (7, 8 and 9), is simple and straightforward to use. Apart from the value of the optimal insulation, the method also provides, when needed, additional information about the insulation system, such as amounts of energy lost through the insulation, annual costs of these energy losses, total annual costs of the insulation material, labor, and lost heat, and the sensitivity of these costs to the proposed insulation.

8.2 Comparison to the ETI Method

Although the ETI method [3] for determining optimal insulation is good and well-accepted, the present method has a few advantages over it for solar heating systems: (1) it is oriented specifically to solar heating system problems and parameters; (2) it is based on a more comprehensive economic model than that of the ETI, which is particularly important here due to the extreme sensitivity of solar heating systems to economics; (3) it provides, when needed, more information about insulation system selection than just optimal thickness; (4) it addresses nominal commercial pipe and insulation size directly. It is slightly more time consuming than the ETI nomographs, but

given the data, it would provide optimal insulation values within 10 to 30 minutes of manual (or hand calculator) calculations.

As indicated in Table 11, the optimal insulation thickness obtained by this method are close to those determined by the ETI method for the same conditions and are either equal, or in most cases, one step higher. This difference most likely arises mainly from the application of the more comprehensive economic model in the present method.

8.3 The Heat Transfer Sensitivity Analysis

It was found that there are three variables which dominate heat loss through insulation, out of the eleven which have some influence on that loss (listed in eqn. (40)), in the range of parameters pertinent to solar heating systems. These three are the nominal pipe diameter (or tank diameter), the thermal conductivity of the insulation, and the insulation's thickness. Neglecting the influence of the other variables by keeping them at constant "base case" values, leads to errors of up to 14% for pipes and $\pm 19\%$ for tanks. These errors were considered acceptable.

Specifically, the largest effects from the other 8 variables were those of wind in the case of outdoor piping ($\pm 3\%$) and of emissivity for indoor piping ($\pm 3\%$) and for the thermal storage tanks ($\pm 8\%$).

The (UA) value is also significantly affected by whether the insulated pipe is located indoors or outdoors, and separate design graphs and tables are hence provided.

8.4 Insulation for the SolaRow House and for Solar Heating Systems in General

A major conclusion from the insulation analysis for SolaRow is that the loss of heat through the solar heating system's insulation is significant, amounting to 32% of the solar energy collected for the presently installed insulation, and 24% for optimal insulation. This arises

mainly due to two reasons: (1) The existence of a large extent of insulated surface: 439 ft (134 m) of 1 1/2" and 2" outdoor pipe, 206 ft (63 m) of 1" and 1 1/2" indoor pipe, and 240 ft² of thermal storage tank surface area; (2) The flow strategy which retains the water in the pipes after the system has stopped collecting useful solar energy, which thus permits heat loss during longer periods of time.

A major recommendation arising from this study is, therefore, that heat losses through insulation must receive careful quantitative consideration during the solar heating system's design process, and that these losses can be reduced by minimizing the length of piping, surface of thermal storage tanks, residence time of hot working fluid in the system in general and in its outdoor portion in particular, and by selecting the optimal insulation thickness to account for the economic constraints. For example, a change in the flow strategy in the SolaRow system by which the water would be allowed to drain into the thermal storage tanks each time when no useful energy is collected, reduces the total heat losses for the optimal insulation from 24% to 18%.

An additional conclusion is that since the quantity $F(T_f - T_a)$ exhibits a large influence on the estimate of the heat loss (and thus on the determination of the optimal insulation thickness), further work is required to provide more accurate design values of these as functions of system design and environmental variables.

Another important observation is the high cost of insulation: \$2944 total (composed of \$1666 for materials and \$1278 for labor) for optimally insulating the SolaRow heating system, or close to 15% of the total system's cost. Again, reduction of the length of pipe and of the surface area of the thermal storage tanks would decrease these costs.

Inspection of the table from Appendix II indicates a wide variation (as great as 75%) in retail prices for the same or similar type of tubing

insulation material, while the table from Appendix I shows a similar variation in cost among dissimilar types of insulation materials. Together, these results emphasize not only the importance of investigating several types of insulation material for a particular application, but more emphatically the necessity of soliciting competitive bids from several vendors once the choice of an insulation material has been made.

Also with respect to the purchase of insulation, the buyer of a small volume of a given size of pre-formed insulation should recognize that many insulation retailers sell this material in pre-set bulk quantities (sometimes 75 to 100 or more feet (22.9 to 30.5 m) per box). In the interest of minimizing insulation costs for a given project, this may necessitate purchasing possibly another type of insulation or the same insulation from a vendor who will sell the quantity that is required.

A less labor and material cost intensive method for weatherproofing outdoor tubing and fitting insulation compared to the method explained here should probably be investigated. Despite the generally good appearance of the finished work and the weather-tightness of the insulation system, the additional cost of \$0.80 to 0.99 per foot for outdoor jacketing material would in some cases be prohibitively high and may force the solar system owner to install a smaller thickness of insulation to reduce the insulation initial costs. Other techniques might include covering the insulation with several layers of tar paper or some weatherproofing substitute.

As a reminder, the mechanical designer should interface with the structural designer at an early stage in any solar collector structural design to ensure that adequate space is provided so that the proper insulation can be applied without great difficulty.

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10. NOMENCLATURE

- A heat transfer area
- B cumulative present worth of depreciation tax credits per dollar invested; with straight line depreciation, eqns. (30)-(32)
- $\hat{B}$ sensitivity analysis comparison variable, eqn. (46), dimensionless
- c_p specific heat, Btu/lbm °F (KJ/kg°K)
- C cost
- C_a first year cost of auxiliary energy delivered to storage, $(\$/10^6 \text{ Btu } (\$/\text{MJ}))$
- C_i Base cost of the insulation material, including the cost of fitting and valve insulation prorated over the straight pipe length, $\$/\text{ft } (\$/\text{m})$
- C_j Base cost of insulation jacketing, $\$/\text{ft } (\$/\text{m})$
- C_ℓ Base cost of insulation labor, $\$/\text{ft } (\$/\text{m})$
- C_m Base cost of maintenance during the first year, $\$/\text{ft } (\$/\text{m})$
- C_s Present value annual average cost of solar heat, defined in eqn. (23), $\$/ (10^6 \text{ Btu-yr}) [\$/ (\text{MJ-yr})]$
- C_R cost ratio defined in eqn. (34), $(\text{Btu/yr-ft}^\circ\text{F}) \times 10^{-6} [(\text{J/yr-m}^\circ\text{C}) \times 10^{-9}]$
- C_T total annual cost of insulation and lost energy defined in eqn. (22) $\$/\text{ft-yr } (\$/\text{m-yr})$
- C_{TM} modified cost defined in eqn. (33), $(\text{Btu/ft-yr}^\circ\text{F}) \times 10^{-6} [(\text{J/yr-m}^\circ\text{C}) \times 10^{-9}]$
- d annual discount rate, which could be chosen as either that for mere inflation, for an opportunity cost of money, or for a required return on investment, $(\%/100)$; or
- d diameter ft (m)
- D nominal pipe diameter, in.
- E economic coefficients defined in eqns. (24)-(27)

f	Moody friction factor, dimensionless
f_L	type of fluid heated in collectors
F	annual usage factor ($0 \leq F \leq 1$) of the insulated component. This is the annual fraction of time which the solar collection system (or storage tanks) loses heat.
g	annual general inflation rate, (%/100), or
g	gravitational constant
h	heat transfer coefficient, Btu/hr°F ft ² (W/m°C), or
h	annual insurance cost, as a fraction of the first cost
$\hat{i}$	number indicating the location and type of heat loss surface
$i_{(j)}$	annual interest rate on loan or mortgage, (%/100)
$\hat{j}$	base case number
k	depreciation lifetime, years, or
k	thermal conductivity, Btu/hr°F (W/m°C)
$\hat{k}$	number indicating the specific D and t_i combination
k^*	k_i (British units)/0.010, nondimensional
$\hat{\ell}$	piping number for $M_p = 1$ and $M_p = 2$ ($\hat{\ell} = 1, 2$)
ℓ	pipe length or tank height, ft(m)
L_B	total annual space heating and domestic hot water load, 10 ⁶ Btu/yr (MJ/yr)
$\hat{m}$	fluid number for $f_L = 1, 2, 3, 4$ ($m = 1, 2, 3, 4$)
$m_{(j)}$	period of loan or mortgage, years
M_i	initial capital cost of solar heating system including all labor and materials, \$
M_O	first year maintenance cost of solar heating system, \$
M_O	first year operating cost of solar heating system, \$
M_p	index indicating type of pipe
n	period of economic analysis (usually life of system), years
$\hat{n}$	the number indicating the base continuous variable
Nu	Nusselt Number, dimensionless
p	actual annual property tax rate, (%/100)
$\hat{p}$	index number of a particular value within a continuous variable's ($\hat{n}$) range

P pressure head, ft (m)
 Pr Prandtl Number
 Q heat flow rate, Btu/hr (W), dimensionless
 Q' total heat flow rate through tank surface, Btu/hr (W)
 r radius, ft (m)
 r_f annual fractional rate of increase in auxiliary fuel expense
 $r_{m(j)}$ annual fractional rate of increase in maintenance expense
 r_o annual fractional rate of increase in operating expense of solar system
 R thermal resistance, ft $^{\circ}$ F hr/Btu (m $^{\circ}$ C/W)
 Re Reynolds number, dimensionless
 t thickness, in. (cm), or
 t annual incremental income tax rate (only applicable in business applications, where the capital expenses are income tax deductible, otherwise $t = 0$), (%/100)
 t_1 same as t , but only applicable if maintenance, operating, and fuel expenses are tax deductible, otherwise $t_1 = 0$
 T temperature, $^{\circ}$ F ($^{\circ}$ C)
 $\bar{T}_f$ annual average of $(T_a + T_f)/2$
 u error coefficient defined in eqn. (51)
 U overall heat transfer coefficient, hr ft $^{\circ}$ F/Btu (m $^{\circ}$ C/w)
 V wind velocity, miles per hour (meters/s)

Greek Symbols

$\alpha_{(j)}$ downpayment fraction of first cost
 β volumetric expansivity $^{\circ}$ F $^{-1}$ ($^{\circ}$ C $^{-1}$)
 $\beta_{(j)}$ investment tax credit fraction
 γ coefficient defined by eqn. (10)
 δ declining balance multiplier
 Δ difference
 ϵ surface emissivity, dimensionless
 η fraction of annual space heating and domestic hot water load contributed by solar

- θ = 1 or 0, corresponding to auxiliary heating of storage tank water directly, 0 corresponding to no direct auxiliary heating of water
 μ dynamic viscosity, lbm/ft s (k/m-s)
 ν kinematic viscosity, ft²/s (m²/s)
 ρ mass density, lbm/ft³ (kg/m³)
 σ Stephan-Boltzman constant
 $\sigma(j)$ fractional salvage value at end of equipment life
 $\phi \equiv \frac{\Delta P}{\ell}$ pressure gradient in pipe, dimensionless

Subscripts

- a air, auxiliary
 ap average between the air and outside insulation surface
 b bottom
 f hot fluid
 i inside, or insulation
 j jacketing
 ℓ length of cylinder, or labor
 m maintenance
 o outside, or optimal
 p outside surface of insulation, or insulation
 r radiative
 t inside surface of pipe or tank wall
 T top

Superscripts

pertains to thermal storage tanks

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APPENDIX I
DESCRIPTION, COST, AND THERMAL CONDUCTIVITY FOR TUBING INSULATION (SUMMER 1977 PRICES)

Nominal Copper Tube Size	Insulation Thickness in. (cm)									
	3/8 (0.95)	1/2 (1.27)		3/4 (1.91)	1 (2.54)		1 1/2 (3.81)		2 (5.08)	
	Material No. (cost \$/foot)									
1/2"	2(0.21)	1(0.594)	5(0.226)	2(0.50)	1(0.71)	6(0.52)	1(1.424)	6(1.11)	1(2.222)	7(2.204)
	3(0.16)	2(0.32)	7(0.443)	3(0.37)	4(0.57)	7(0.691)	4(1.19)	7(1.404)	4(1.85)	
	5(0.155)	3(0.23)	1(0.660)	5(0.354)	7(0.533)		7(1.136)		7(1.811)	
	5(0.22)	4(0.50)	5(0.32)	5(0.50)	1(0.78)		1(1.57)		1(2.46)	
		7(0.59)								
3/4"	2(0.24)	1(0.665)	5(0.251)	2(0.59)	1(0.795)	6(0.59)	1(1.466)	6(1.15)	1(2.304)	7(2.279)
	3(0.18)	2(0.35)	7(0.502)	3(0.44)	4(0.67)	7(0.777)	4(1.22)	7(1.455)	4(1.92)	
	5(0.171)	3(0.27)	1(0.660)	5(0.413)	7(0.604)		7(1.171)		7(1.881)	
	5(0.24)	4(0.55)	5(0.36)	5(0.59)	1(0.78)		1(1.57)		1(2.46)	
		7(0.64)								
1"	2(0.27)	1(0.696)	5(0.279)	2(0.69)	1(0.835)	1(0.87)	1(1.55)	1(1.62)	1(2.430)	7(2.414)
	3(0.21)	2(0.39)	7(0.531)	3(0.53)	4(0.70)	6(0.63)	4(1.30)	6(1.22)	4(2.02)	
	5(0.193)	3(0.30)	1(0.740)	5(0.494)	6(0.534)	7(0.820)	6(1.038)	7(1.53)	7(1.988)	
	5(0.27)	4(0.60)	5(0.40)	5(0.70)	7(0.639)		7(1.242)		1(2.55)	
		7(0.673)								
1 1/2"	2(0.39)	1(0.883)	5(0.359)	2(1.00)	1(1.04)	1(1.02)	1(1.757)	8(1.72)	1(2.724)	1(2.88)
	3(0.29)	2(0.50)	7(0.649)	3(0.94)	4(0.84)	6(0.75)	4(1.47)	1(1.86)	4(2.27)	7(2.714)
	5(0.277)	3(0.39)	1(0.84)	5(0.777)	6(0.643)	7(0.985)	6(1.186)	6(1.39)	7(2.236)	
	5(0.40)	4(0.70)	5(0.52)	5(1.09)	7(0.781)		7(1.420)	7(1.732)	8(2.70)	
		7(0.806)					9(1.186)			
2"	2(0.63)	1(0.902)	5(0.462)	2(1.37)	1(1.088)	1(1.20)	1(1.924)	8(1.89)	1(2.851)	1(3.16)
	3(0.36)	2(0.65)	7(0.708)	3(1.05)	4(0.90)	6(0.84)	4(1.61)	1(2.14)	4(2.37)	7(2.831)
	5(0.449)	3(0.51)	1(0.99)	5(0.971)	6(0.712)	7(1.077)	6(1.304)	6(1.53)	7(2.343)	
	5(0.62)	4(0.76)	5(0.66)	5(1.41)	7(0.852)		7(1.562)	7(1.907)	8(2.83)	
		7(0.872)					9(1.304)			

Legend

Material No.	Thermal Conductivity @ 75°F(24°C)		Manufacturer	Trade Name	Insulation Material
	Btu/hr ft°F	kW/cm°C			
1	0.0187	0.3243	Certain-Teed	ASJ-SSL	Fiberglas
2	0.0210	0.3632	Certain-Teed	Ultra-Foam	Foamed-rubber
3	0.0210	0.3632	Halstead	Insul-Tube	Foamed-rubber
4	0.0200	0.5459	Johns Manville	Micro-Lok 650/AP-T	Fiberglas
5	0.0210	0.3632	Armstrong	Armaflex	Foamed-rubber
6	0.0196	0.3400	Armstrong	Accotherm	Phenolic resin
7	0.0208	0.3597	Owens-Corning	25: ASJ/SSL	Fiberglas
8	0.0316	0.5465	Pittsburgh Corning	Glass foam	Glass foam
9	0.0208	0.3597	Armstrong	Armoglass	Fiberglas

APPENDIX II

Insulation Materials Manufacturers Addresses

<u>Description</u>	<u>Manufacturer</u>
Accotherm	Armstrong Cork Company, Lancaster, Pennsylvania 17604
Armaflex	Armstrong Cork Company, Lancaster, Pennsylvania 17604
ASJ/SSL	CertainTeed Corporation, P. O. Box 860, Valley Forge, Pennsylvania 19481
Foamglass	Pittsburgh Corning Corporation, 800 Presque Isle Drive, Pittsburgh, Pennsylvania 15239
Insul-tube	Halstead Industrial Products, Zelienople, Pennsylvania 16063
Micro-lok 650/AP-T	Johns-Manville, Ken-Caryl Ranch, Denver, Colorado 80202
25: ASJ/SSL	Owens-Corning Fiberglass Corporation, Fiberglas Tower, Toledo, Ohio 43601
30-35 Weatherproof Coating	Bearns and Foster, 5220 Main Street NE, Minneapolis Minnesota 55421
Ultra-foam	CertainTeed Corporation, P. O. Box 860, Valley Forge Pennsylvania 19481
Zeston Insulation Fittings	Zeston, Incorporated, P. O. Box 46, Fords, New Jersey 08863

APPENDIX III

RANGE OF COSTS PER LINEAR FOOT FOR THE SAME TUBING INSULATION MATERIALS QUOTED TO THE UNIVERSITY OF PENNSYLVANIA IN SUMMER 1977

Nominal Copper Tube Size	Insulation Thickness, in. (cm)					
	3/8 (0.95)	1/2 (1.27)	3/4 (1.91)	1 (2.54)	1 1/2 (3.81)	2 (5.08)
	Designation (minimum cost \$/foot / maximum cost \$/foot)					
1/2"	B (0.155/0.22)	A (0.443/0.660) B (0.226/0.32)	B (0.354/0.50)	A (0.533/0.78) C (0.52) [¶]	A (1.136/1.57) C (1.11)	A (1.811/2.46)
3/4"	B (0.171/0.24)	A (0.502/0.665) B (0.251/0.36)	B (0.413/0.59)	A (0.604/0.795) C (0.59)	A (1.171/1.466) C (1.15)	A (1.881/2.46)
1"	B (0.193/0.27)	A (0.53/0.74) B (0.279/0.40)	B (0.494/0.70)	A (0.639/0.87) C (0.534/0.63)	A (1.242/1.62) C (1.038/1.22)	A (1.988/2.55) D (2.50)
1 1/2"	B (0.277/0.40)	A (0.649/0.883) B (0.359/0.52)	B (0.77/1.09)	A (0.781/1.04) C (0.643/0.75)	A (1.186/1.86) C (1.186/1.39) D (1.72)	A (2.236/2.88) D (2.70)
2"	B (0.36/0.63)	A (0.708/0.99) B (0.462/0.66)	B (0.971/1.41)	A (0.852/1.20) C (0.712/0.84)	A (1.304/2.14) C (1.304/1.53) D (1.89)	A (2.343/3.16) D (2.83)

¶ Denotes only one price received for this type of insulation material for this size and thickness.

Legend

Designation	Insulation Material
A	Fiberglass
B	Foamed rubber
C	Phenolic resin
D	Glass foam

APPENDIX IV: Calculation of Optimal Insulation for SolaRow
Final results are shown in Table 11.

Pipe Nominal Diameter And Location	Insulation Thickness in.	$C_R \times 10^3$				$UA^* \times 10^3$	$C_{TM} \times 10^3$
		C_i \$/ft	C_j \$/ft	C_ℓ \$/ft	$C_i + C_j + C_\ell$ \$/ft	First iteration, second iteration, <u>Btu</u> ft-yr-°F	First iteration, second iteration, <u>Btu</u> ft-yr-°F
2" Outdoor	1	0.85	0.80	0.99	2.64	0.495 0.369	1.68 2.049
	1-1/2	1.30	0.90	1.09	3.29	0.591 0.444	1.862 1.714
	2	2.34	0.99	1.19	4.52	0.781 0.587	1.841 1.647
	2-1/2	3.50	1.09	1.29	5.88	0.992 0.745	1.922 1.675
1" Indoor	1/2	0.28	0.12	0.75	1.15	0.272 0.204	1.792 1.724
	3/4	0.49	0.14	0.82	1.45	0.321 0.241	1.521 1.441
	1	0.74	0.16	1.15	2.05	0.417 0.313	1.447 1.343
	1-1/2	1.67	0.20	1.25	3.12	0.591 0.444	1.421 1.274
	2	2.67	0.24	1.35	4.26	0.775 0.582	1.495 1.302
1-1/2" Indoor	1	0.64	0.18	0.95	1.77	0.372 0.279	1.682 1.589
	1-1/2	1.19	0.20	1.04	2.43	0.527 0.396	1.567 1.436
	2	2.24	0.24	1.13	3.61	0.736 0.553	1.626 1.443
	2-1/2	3.40	0.29	1.22	4.91	0.966 0.725	1.760 1.515

Thermal Storage Tanks

All calculations are per one tank

Insulation Thickness in.	C_i \$/ft	C_j \$/ft	C_ℓ \$/ft	$C_i + C_j + C_\ell$ \$/ft	$C'_R \times 10^3$ First iteration, second iteration,	$UA^* \times 10^3$ Btu ft-yr $^{\circ}F$	$C'_{TM} \times 10^3$ First iteration, second iteration,
					Btu ft-yr $^{\circ}F$		Btu ft-yr $^{\circ}F$
3-1/2	14.40	0	90	104.40	0.883 0.663	6.87	7.753 7.533
6	22.00	0	110	132.00	1.994 1.497	4.31	6.304 5.807
9-1/2	33.00	0	130	163.00	1.376 1.033	2.98	4.356 4.013
12	41.00	0	150	191.00	1.613 1.211	2.46	4.073 3.671
14	50.00	0	180	230.00	1.940 1.457	2.19	4.130 3.647

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