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Calculations of Maximum Allowable Heat Losses for Various Shallow Trench Heat Distribution Systems

Jin B. Fang

U.S. DEPARTMENT OF COMMERCE
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Center for Building Technology
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Prepared for:

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Headquarters, U.S. Army Corps of Engineers
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U.S. DEPARTMENT OF COMMERCE, C. William Verity, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

The calculation of heat losses for shallow trench underground heat distribution systems was performed using a finite element computer program. The finite element analysis solved a two-dimensional steady-state heat transfer problem for two insulated pipes in a rectangular trench with surrounding soil. A life-cycle cost analysis was performed to determine the cost of construction and annual energy cost associated with pipe heat loss for underground concrete trench systems of different trench dimensions and insulated pipe sizes. Procedures for determining the pipe heat losses associated with the minimum life-cycle cost and the corresponding optimum insulation thickness for shallow trench distribution systems are presented. Based on the results of the economic analysis, the maximum allowable heat losses and the insulation thickness for underground pipes were determined and tabulated for a range of pipe sizes and fluid temperatures, various levels of fuel costs, and for a known undisturbed earth temperature and soil thermal conductivity.

Keywords: district heating and cooling; finite element method; fuel energy cost; heat loss; life-cycle cost analysis; pipe insulation thickness; shallow trench; underground heat distribution system.

TABLE OF CONTENTS

		Page
1.	Introduction	1
2.	Pipe Heat Loss Calculations	3
3.	Comparison Between Finite Element and Thermal Analyzer Programs	6
4.	Life-Cycle Cost	8
5.	Conclusions	14
6.	Acknowledgment	16
7.	References	16

LIST OF TABLES

Table 1	A Comparison of the Pipe Heat Losses Calculated from Temperature Dependent Thermal Conductivity with those Obtained from Constant Thermal Conductivity of Calcium Silicate Insulation	18
Table 2	Comparisons of Calculated Results from Finite Element Computer Program with Those by the Thermal Analyzer Program for Various Concrete Trench Systems	19
Table 3	Effect of Trench Dimension on Pipe Heat Losses	20
Tables A-1 through A-13	Maximum Allowable Heat Losses and Economic Insulation Thickness for Hot Water Supply and 150 F Return Pipes and for Energy Cost of $3 through $15/MBtu	35
Tables B-1 through B-13	Maximum Allowable Heat Losses and Economic Insulation Thickness for Steam Supply and 150 F Condensate Pipes and for Energy Cost of $3 through $15/MBtu	61
Tables C-1 through C-13	Maximum Allowable Heat Losses and Economic Insulation Thickness for Hot Water Supply and 250 F Return Pipes and for Energy Cost of $3 through $15/MBtu	87

LIST OF FIGURES

		Page
Figure 1.	Concrete Shallow Trench Underground Heat Distribution System	21
Figure 2.	Thermal Conductivity Variation with Temperature for Calcium Silicate Insulation	22
Figures 3 through 14.	Construction Cost for a Shallow Trench System Containing Two 1-inch through 18-inch Insulated Pipes	23
Figures 15 through 25.	Construction Cost for a Shallow Trench System Containing a 2-inch through 18-inch Supply and a 1-inch through 10-inch Return Insulated Pipes	29

1. Introduction

The production and supply of hot water, chilled water, or steam by a centralized plant is more efficient and economical than production and supply using a number of smaller units. However, this advantage is not possible unless the cost of delivering the working fluid through pipe-lines to the point of use is low. The cost of constructing a distribution pipe-line network generally accounts for the major portion of the total cost of acquiring a district heating and cooling system. In addition, the operating characteristics of the piping system, such as pipe heat loss, operation reliability and maintenance expense, are of major consideration. An extensive financial loss and intensive labor cost will be involved if a system outage occurs. The heat loss through the underground distribution system consumes a large portion of the system fuel energy cost, and the unavoidable escalation in future fuel prices will make such losses more important. Knowledge of pipe heat loss conditions is essential for initial planning and detailed design, choice of materials, and estimated cost of an underground heat distribution system.

The military installations currently maintain approximately 6,000 miles (11,110km) of heat distribution systems [1]. Some of these systems have required repair or replacement due to excessive heat loss resulting from deteriorating thermal pipe-insulation and/or corroding pipes and conduits. Recently, Pan Am [1] and Parsons [2] conducted comparisons of directly buried conduit versus shallow concrete trench heat distribution systems for delivering steam and hot water using life-cycle cost analysis to assess their relative merits. The findings of both studies did not agree with each other, especially for the distribution pipe-lines involving large diameter pipes. The discrepancy was probably due to the estimated cost data. However, continued construction of shallow concrete trench systems is anticipated because of their reduced maintenance and repair costs, easy access for inspection and testing, and relatively dry conditions for minimizing possible based on life-cycle cost analysis was developed at NBS for calculating the maximum allowable heat loss for directly buried conduit underground systems [3], and the results were included in the guide specification for military construction, CEGS-15705 [4]. The methods of determining the minimum life-cycle cost heat loss and the optimum insulation thickness for shallow trench systems will complement the procedure already developed for directly buried conduit systems.

This report presents the procedures to calculate the fuel energy cost associated with pipe heat loss, a set of tables listing the maximum allowable heat loss per unit length of piping section, and the corresponding economic insulation thickness for heat supply and return pipes installed in shallow trench distribution systems. The minimum life-cycle cost heat loss data are prepared based on a range of pipe sizes, insulation thicknesses, energy prices, soil and insulation thermal conductivities and a known undisturbed earth temperature. This report also presents the estimated material and installation costs for constructing various distribution systems of different trench dimensions and insulated pipe sizes.

2. Pipe Heat Loss Calculations

The heat transfer process in a rectangular concrete trench containing a pair of insulated circular pipes and the surrounding soil is quite complex due to the involvements of complicated geometries, composite materials, and at least two modes of heat transfer - conduction and convection. Therefore, the solution of this non-linear type of heat transfer problem by exact methods is not possible.

The heat loss per unit length in a concrete shallow trench underground heat distribution system was calculated using a recently developed computer simulation program [5, 6]. This program has applied the finite element method to a steady-state, two-dimensional, rectangular concrete trench containing two insulated pipes as shown in Figure 1. A twin pipe system comprised of a heat supply and a return line is modelled in the computer program since it is the most commonly used shallow trench heat distribution system. The heat loss calculations are based on a two-dimensional heat flow and account for heat transfer from the pipe fluid through the pipe insulation, the air space, and the concrete trench walls to the surrounding soil and ambient air. Convective heat transfer in the air space between the pipe and trench wall surfaces is treated by assuming an effective conductance for natural convection in the trench. The surface resistance to convective heat transfer between the ambient air and the ground surface in the vicinity of the shallow trench is treated as being contained in an equivalent soil layer [6]. The effect of radiant exchange between the pipes and trench walls is assumed to be negligible due to low emissivity of the aluminum jacket surface. The boundary conditions are the average temperatures of working fluids flowing inside the circular pipes, and the undisturbed earth temperatures along the perimeter of the earth region.

The computer program contains a predesigned finite element mesh with 80 nodal points and 130 triangular elements representing the outer boundary earth region, concrete trench walls, top concrete cover, pipe insulation, and the air space between the insulated pipes and the trench walls. The external boundary temperatures including the nodal points around the outer surfaces of the circular pipes and along the outermost perimeter of the outer earth region surrounding the shallow trench system are prescribed from the data input for computer runs. The system of simultaneous equations solves for the remaining nodal point temperatures using the Gaussian elimination method. The computer code is written in FORTRAN 77 programming language and implemented on an IBM personal computer.

The rate of heat loss from an insulated pipe can be obtained using the following equation derived from one-dimensional, steady-state, radial heat conduction in a composite pipe, based on the average temperature difference across a circular cylindrical shell of pipe insulation layer:

$$q = \frac{(2\pi)\ k_I\ (T_i - T_o)}{(12)\ \ln\ (\gamma_o/\gamma_i)} \tag{1}$$

where q = the heat loss rate per unit length of the insulated pipe, Btu/h·ft (W/m)

k_I = the thermal conductivity of insulation material, Btu·in/h·ft^2·F (W/m·K)

γ_o = outside radius of the insulation layer, ft (m)

γ_i = inside radius of the insulation layer, ft (m)

T_i and T_o = the surface temperature of the insulation layer at inner and outer radii, respectively, F (C)

The pipe insulation is the major resistance to heat transfer for an insulated the pipe, the thermal resistance of the pipe wall, and that of the metal jacket are small and can be assumed negligible. A detailed description and the input data required for executing the computer program, along with the results of some sample calculations, were summarized in previous studies [6].

In order to obtain a more realistic prediction of the pipe heat losses, especially at higher pipe fluid temperatures, a subprogram was added to this finite element computer program to account for the temperature dependency of the pipe-insulation thermal conductivity. The thermal conductivity of calcium silicate, which is resistant to aging during periodical wetting and drying and commonly used for pipe insulation, as a function of the speciment mean temperature [7] is shown in Figure 2. In this figure, the thermal conductivity increases with increasing temperature. The data used to generate the curve in Figure 2 are stored in a computer subprogram, which is formulated based on the table look-up procedure to provide the temperature dependent thermal conductivity value to be used for each triangular element of pipe-insulation. Since the mean temperatures of the earth surrounding the trench and the pipe insulation are dependent upon the rates of heat transfer through them, an iterative procedure is used along with adjustment of soil and insulation thermal conductivities until the heat loss from the underground pipes achieves a steady-state condition.

Computer calculations were performed to determine the effect of thermal conductivity variations with temperature on pipe heat loss for two 6-inch (150 mm) steel pipes installed side by side in a 4.08 ft (1.24 m) wide by 2.92 ft (0.89 m) high concrete trench having 6 in. (152 mm) thick walls and cover. The top cover was laid flush with ground level. The temperature of hot water flowing in the heat supply pipe was 385 F (196 C) and the return pipe temperature was 210 F (99 C). The pipes were insulated with 3.5 in. (89 mm) thick calcium silicate encased in an aluminum jacket, allowing 4 in. (102 mm) of separation between outer surfaces of the carrier pipes. The earth in the vicinity of the shallow trench had annual average temperature of 56 F (13 C) and thermal conductivity of 15 $Btu \cdot in/h \cdot ft^2 \cdot F$ (2.16 $W/m \cdot K$). A comparison of the heat loss values calculated from temperature dependent insulation thermal conductivity with those obtained from the constant thermal conductivity of 0.44 $Btu \cdot in/h \cdot ft^2 \cdot F$ (0.063 $W/m \cdot K$) for various insulation thicknesses is given in Table 1. For this sample case, the temperature dependent thermal conductivity gave approximately 3 to 4% greater total heat loss values compared to the constant thermal conductivity.

3. Comparison Between Finite Element and Thermal Analyzer Programs

The thermal analyzer computer program, TASTAP, developed based on the application of finite difference technique was recently employed for calculating the pipe heat losses of shallow trench and directly buried conduit heat distribution systems [2]. The capabilities of this finite difference computer simulation program were described briefly in Parsons' report [2]. There is a lack of field data on pipe heat loss, temperature distributions of trench air, concrete walls, and soil in the vicinity of underground systems, which are available to be utilized for validation of the predictive methods. Some calculations using the finite element computer program were carried out on typical shallow trench systems with different pipe sizes and fluid temperatures, and the results were compared with the predictions made from the thermal analyzer program TASTAP. An average ground temperature of 55 F (12.8 C), a 6 in. (152 mm) thick trench walls and cover, and the thermal conductivities of soil, concrete and pipe insulation equal to 15, 8, and 0.444 $Btu \cdot in/h \cdot ft^2 \cdot F$ (2.16, 1.15, and 0.064 $W/m \cdot C$), respectively, were used in these calculations.

The heat losses predicted by the finite element and the finite difference computer programs for the carrier pipes installed in various concrete trench systems for hot water and steam distributions are shown in Table 2. In general, for the heat supply pipes the calculated heat loss values from the finite element model are consistently about 6 percent smaller compared to the results of the thermal analyzer. The differences in heat loss values tend to be greatest for the largest pipe diameter. With the exception of one case involving a 12 in. (305 mm) pipe carrying hot water, the finite element model used in this study gives approximately 11 percent greater heat loss values for the return pipes in comparison to the finite difference technique. The total pipe heat losses predicted by the finite element program agree within 4 percent from the thermal analyzer predictions.

The effect of trench size on pipe heat losses using the finite element computer program was studied by systematically varying the inner dimension of the concrete trench containing the two 6-in. (152-mm) insulated pipes. The pipes are wrapped in a 3 in. (76.2 mm) thick insulation and aluminum jacket, and transport hot water at 350 F (177 C) and 285 F (141 C), respectively. The centers of these pipes are located at 2.75 ft (0.84 m) and 3.08 ft (094 m) below the ground surface and are separated by a horizontal distance of 1.90 ft (0.58 m). The results of this parameter analysis are shown in Table 3. The trench dimension has little effect on pipe heat loss predictions as illustrated in the table. For example, doubling the trench dimensions from 3 x 3 ft (0.91 x 0.91 m) to 6 x 6 ft (1.83 x 1.83 m), causes only a 1.5% increase for the pipe heat loss.

4. Life-Cycle Cost

The total life-cycle cost of an underground heat distribution system is the sum of the cost of acquisition, yearly maintenance and repair cost, and yearly fuel energy cost including adjustment for future escalation in fuel prices over the life of the system. The total life-cycle cost (LCC) can be expressed as follows:

$$LCC = MIC + 8760 * Q * EC * UPW + MRC \tag{2}$$

where MIC = the material and installation costs, (\$/ft of the underground system)

Q = the system heat loss rate, which is equal to the sum of the heat loss rates of two pipes, (Btu/h·ft); and 8760 is a conversion factor

EC = the equivalent fuel energy cost, (\$/MBtu)

= 100 (FC/EF), in which FC is fuel cost, (\$/MBtu), and EF is plant fuel conversion efficiency, (%)

UPW = the modified uniform present worth factor adjusted for future escalation in fuel prices

MRC = the maintenance and repair costs, (\$/ft of the system)

The concrete trench had different overall dimensions to accommodate various pipe sizes and insulation thicknesses and to maintain specified clearances such as at least 4 inches (102 mm) of space existing between the insulated pipes, a minimum of 3 inches (76 mm) between the piping and adjoining trench walls, and at least 6 inches (152 mm) from the bottom surface of the pipe to the trench floor as specified in the design guide [8] and shown in Figure 1. A minimum inside width of 2 ft (0.61 m) was used for all concrete trenches since the trenches smaller than this were difficult to work with during the stage of construction. In district heating and cooling, high temperature hot water and pressurized steam are recognized as the most effective and economical working media. For hot water distribution in a twin pipe system, both the heat supply and the return lines generally have the same pipe size. However, the return condensate line for steam distribution is usually a smaller diameter pipe than the supply line due to the volume reduction of the steam condensing to hot water.

The cost of materials and labor employed for constructing shallow trench heat distribution systems of various pipe sizes and trench dimensions can be calculated using the cost data and estimate procedures presented in references [2, 3, 9, 10]. Construction costs for shallow trench underground heat distribution systems are estimated and shown as a function of insulation thickness for nominal pipe sizes ranging from 1 to 18 inches (25 to 457 mm) for hot water and steam distributions in Figures 3 to 25. As illustrated in the figures, the construction costs for both the concrete trench and the insulated pipes increase with thicker pipe insulation. The estimated construction costs for some concrete trench and distribution piping systems were compared with those developed in the sample cases treated in the life-cycle cost analysis of underground heat distribution systems [2], and found to be in good agreement with those reported capital cost data.

The equivalent energy cost per unit length, or the yearly cost of lost energy considered as an operating expenditure, of the shallow trench system was calculated using the computed pipe heat losses obtained as the outputs from the computer program, and the fuel energy cost adjusted over the life of the system by taking projected energy price changes into account. The plant fuel conversion efficiency ranges between 50 and 90% depending on the type of boiler utilized. In all life-cycle cost calculations, the fuel to heat conversion efficiency at the plant is assumed to be 80%.

The energy price is assumed to escalate annually in accordance with the data on the inflation rate of natural gas prices for the period 1985 to 2010 as projected by the U.S. Energy Information Administration [11]:

Escalation Period (Year)	Fuel Price Inflation Rate (%)
1-5	4.11
6-10	6.12
11-15	4.85
16-20	4.11
21-25	4.24

The modified uniform present worth factor (UPW) was calculated based on a 10% discount rate over a 25 year life for the underground shallow trench distribution system, and the fuel price escalation rate project by the U.S. Energy Information Administration for 1985 through 2010, using the following equation [12]:

$$
\begin{aligned}
UPW = & \sum_{j=1}^{N_1} \left(\frac{1+e_1}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{N_1} \sum_{j=1}^{N_2} \left(\frac{1+e_2}{1+d}\right)^j \\
& + \left(\frac{1+e_1}{1+d}\right)^{N_1} \left(\frac{1+e_2}{1+d}\right)^{N_2} \sum_{j=1}^{N_3} \left(\frac{1+e_3}{1+d}\right)^j \\
& + \left(\frac{1+e_1}{1+d}\right)^{N_1} \left(\frac{1+e_2}{1+d}\right)^{N_2} \left(\frac{1+e_3}{1+d}\right)^{N_3} \sum_{j=1}^{N_4} \left(\frac{1+e_4}{1+d}\right)^j \\
& + \left(\frac{1+e_1}{1+d}\right)^{N_1} \left(\frac{1+e_2}{1+d}\right)^{N_2} \left(\frac{1+e_3}{1+d}\right)^{N_3} \left(\frac{1+e_4}{1+d}\right)^{N_4} \sum_{j=1}^{N_5} \left(\frac{1+e_5}{1+d}\right)^j
\end{aligned}
\qquad (3)
$$

where $\sum_{j=1}^{N_k} \left(\frac{1+e_k}{1+d}\right)^j = \left(\frac{1+e_k}{d-e_k}\right) \left[1 - \left(\frac{1+e_k}{1+d}\right)^{N_k}\right]$

N_k = the length of the period for a given escalation rate in a given period, (year)

d = the discount rate, (%)

e_k = the rate of escalation in each of N_k period.

Assuming no salvage value for the underground shallow trench system at the end of a 25 year life-cycle, the modified uniform present worth factor, UPW is found to be 14.16%.

Based on the cost data of a recent survey of field installations [1], the present values over the 25 year life-cycle of annually recurring routine maintenance and nonannually recurring repair costs for a typical shallow trench system were computed and found to be $1.72 per foot ($5.64 per meter) and $0.09 per foot ($0.30 per meter), respectively. These maintenance and repair costs were low compared to the system construction cost and operational cost due to pipe heat losses and therefore neglected in life-cycle cost analysis.

For minimum life-cycle cost or maximum allowable heat loss calculations, the working fluid temperatures for the heat supply pipe were varied between 150 tand 500 F (66 to 260 C) with an increment of 50 F (27.8 C), and temperature levels of either 150 F (66 C) or 250 F (121 C) were selected for the return pipe fluid temperatures. Different pipe sizes ranging from 1 to 18 inches (25 to 457 mm) in nominal diameter and insulation thicknesses varying from 1 to 6 inches (25 to 152 mm) in increments of 0.5 in. (12.7 mm) were selected for heat loss calculations and cost analysis. In order to reflect a variety of fuel energy costs, the selected values of fuel cost ranged from $3.00 to $15.00 per million Btu ($2.84 to $14.22 per giga joule). All calculations were carried out based on an annual average earth temperature of 55 F (12.8 C), a soil thermal conductivity of 10 Btu.in/h.ft2.F (1.44 W/m.C), a 6 in. (152 mm) thick trench wall, a concrete thermal conductivity of 9.7 Btu.in/h.ft2.F (1.4 W/m.C), an annual amplitude of the monthly average temperature cycle of 23 F (-5 C) [6, 13], and heat losses determined for the month of January. The extreme seasonal temperatures were selected as the external temperatures for buried piping design considerations, and the choice of January resulted in the computed pipe heat loss to be approximately 5% greater than annual heat loss.

Computer calculations of the life-cycle cost for the cost of capital investment and the yearly energy cost associated with the heat lost from the pipes were carried out for each pipe size and specified fluid temperatures, and for various insulation thicknesses starting from 1 in. (25 mm) with an increment of 0.5 in. (12.7 mm). From a set of life-cycle costs derived for a range of insulation thickness, the maximum allowable heat losses for the supply and the return lines were selected as those heat losses for which the life-cycle cost was at a minimum for a specified fuel cost and pipe size. The pipe insulation thickness corresponding to these maximum allowable heat losses is the economic insulation thickness. This optimum insulation thickness is equivalent to the best economic balance between the total cost for constructing the shallow trench system and insulating the distribution piping, and the resulting energy saving over the life time of the underground system.

Tables A-1 through C-13 present the maximum allowable heat losses (MAHL) and the corresponding economic insulation thickness (EIT) of the insulated pipes for shallow trench heat distribution systems at selected pipe temperatures and fuel cost. These tables are divided into three sets: the "A" tables present the MAHL and EIT values derived based on a 150 F (66 C) return pipe temperature for a high temperature hot water distribution system, the "B" tables contain MAHL and EIT data based on a 150 F (66 C) condensate return pipe temperature for a pressurized steam system, and the "C" tables present the MAHL and EIT values based on a 250 F (121 C) return pipe fluid temperature for a hot water distribution system.

As illustrated in the tables, the heat loss from the heat supply pipe increases as the temperature of the working medium flowing inside the supply

pipe increases, causing a larger temperature gradient between the inner and outer surfaces of the pipe insulation. However, the heat loss of the return pipe decreases as the supply pipe fluid temperature increases due to two factors; the increased insulation thickness and heat gain by convection heat transfer from the adjoining supply pipe. The effect of temperature variations of the return pipe on the maximum allowable heat losses can be determined by comparing the heat loss values in "A" table and those in "C" table for a given pipe size and fuel cost, and a selected working medium temperature of the supply pipe. The results indicate that a noticeable increase in the return pipe temperature does not cause any significant decrease in the heat loss value of the supply pipe. The heat loss of the return pipe at a temperature greater than 150 F (66 C) for a given pipe size, supply pipe fluid temperature and fuel cost can be found from one of the "A" tables, and is equal to the heat loss value for the supply pipe at specific return pipe temperature. Using equation 1 and assuming a constant temperature for the outer surface of the insulation layer, this heat loss value is then revised to account for the reduction in pipe heat loss due to increased insulation thickness for specific return and supply pipe fluid temperatures. It should be noted that the maximum allowable heat loss and the corresponding economic insulation thickness data presented in the tables would change for different insulation materials, trench configurations and design conditions.

5. Conclusions

The heat losses from two insulated pipes installed in a shallow trench underground heat distribution system were calculated using a computer simulation program developed based on the application of the finite element method to two-dimensional, steady state heat conduction problem. A more accurate prediction of heat flows in an underground system and surrounding soil can be obtained using temperature-dependent, variable thermal conductivities for the pipe insulation. In general, the pipe heat losses predicted from the finite element model used in this study are in reasonably good agreement with the predictions of the finite difference computer model TASTAP. The effect of trench dimension on pipe heat losses was studied numerically using the finite element computer program and found to be insignificant. The material and labor costs for construction of concrete trenches distribution systems including insulated piping of various pipe sizes and insulation thicknesses, and concrete trench of different dimensions are developed, and these cost data are presented graphically.

Life-cycle cost analysis was performed for shallow trench systems to obtain the pipe heat loss and the insulation optimum balance between the costs of capital investment including the costs of constructing distribution piping and installing additional insulation, and the resulting energy saving, calculated over the expected life of the underground system for projected growth of the fuel price. The procedures for calculating the energy cost attributed to the pipe heat loss and for determining the maximum allowable heat loss, which is defined as that heat loss rate for which the total owning and operating cost of the system is at a minimum, for an underground concrete trench system are described. Based on the results of the cost analysis, the maximum allowable heat losses and the most economic insulation thickness for underground pipes distributing steam and hot water, were determined and tabulated for a range of fluid temperatures and pipe sizes, various levels of fuel cost, for fixed values of earth temperature and soil thermal conductivity.

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7. References

1. Pan Am World Services, Inc., "Heat Distribution Systems Life-Cycle Cost Analysis-Comparison Between Direct Buried and Shallow Trench Systems," Report 130319, July 1985.

2. Parsons Corporation, "Life-Cycle Cost Analysis - Comparison Between Direct Buried Conduit and Shallow Concrete Trench Underground Heat Distribution Systems," February 1986.

3. Kusuda, T., "Maximum Allowable Heat Losses for Underground Heat Distribution Systems Based Upon Life-Cycle Cost Analysis," a report for Tri-Service Committee on Underground Heat Distribution Systems, April 1984.

4. U. S. Army Corps of Engineers, Guide Specification Military Construction, Underground Heat Distribution System and Condensate

Return System - Prefabricated or Pre-Engineered Types', CEGS-15705, May 1986.

5. Kusuda, T., "FEMTKE - Finite Element Method Computer Program for Underground Heat Distribution System Heat Loss Calculations," a report for Tri-Service Committee on Underground Heat Distribution Systems, January 1984.

6. Fang, J. B., "Minimum Life-Cycle Cost Heat Losses for Shallow Trench Underground Heat Distribution Systems," NBSIR 86-3381, May 1986.

7. U.S. Department of Energy, 'Economic Thickness for Industrial Insulation,' The Fairmont Press Inc., Atlanta, GA, 1983.

8. U.S. Army Corps of Engineers, Guide Specification Military Construction, 'Heat Distribution Systems Outside of Buildings - Concrete Shallow Trench Systems,' CEGS - 15709, June 1986.

9. Means Mechanical Cost Data, 7th Annual Edition, Robert Snow Means Co., Kingston, MA, 1984.

10. Building Construction Cost Data 1985, 43rd Annual Edition, Robert Snow Means Co., Kingston, MA, 1985.

11. Lippiatt, B. C., Weber, S. F. and Ruegg, R. T., "Energy Prices and Discount Factors for Life-Cycle Cost Analysis," NBSIR 85-3273, November 1985.

12. Ruegg, R. T., "Life-Cycle Costing Manual for the Federal Energy Management Programs," National Bureau of Standards Handbook 135, (Rev.), May 1982.

13. Kusuda, T. and Achenbach, P. R., "Earth Temperature and Thermal Diffusivity at Selected Stations in the United States," ASHRAE Transactions, Vol. 71, Part 1, pp. 61-75, 1965.

TABLE 1

A Comparison of the Pipe Heat Losses Calculated from Temperature Dependent Thermal Conductivity with Those Obtained from Constant Thermal Conductivity of Calcium Silicate Insulation

Insulation Thickness (inch)	Heat Loss Rate (Btu/h-ft) Constant K Pipe 1	Pipe 2	Total	Temp. Dependent K Pipe 1	Pipe 2	Total	Diff. (%)
1.0	238	94	332	251	94	345	3.8
1.5	177	74	251	187	74	260	3.5
2.0	144	62	206	151	62	213	3.3
2.5	124	54	178	129	54	183	2.7
3.0	109	48	157	114	48	162	3.1
3.5	98	44	142	103	43	146	2.7
4.0	90	40	130	94	40	134	3.0
5.0	79	35	114	82	35	117	2.6
6.0	70	32	102	73	32	105	2.9

TABLE 2

Comparisons of Pipe Heat Loss Values Calculated by Finite Element Computer Program with Those by the Thermal Analyzer Program for Various Concrete Trench Systems

1. High temperature hot water systems with pipe temperatures of 350 F and 285 F:

Nominal Pipe Diameter (Inch)	1	6	12
Insulation Thickness (Inch)	2	3	3
Heat Loss (Btu/h·ft)			
Supply Pipe (350 F)	46.57 (47.30)	96.84 (97.00)	154.06 (171.97)
Return Pipe (285 F)	35.85 (34.75)	73.74 (71.69)	115.61 (126.80)
Total	82.42 (82.05)	170.58 (168.69)	269.67 (298.77)

2. Pressurized steam systems with pipe temperatures of 350 F and 160 F:

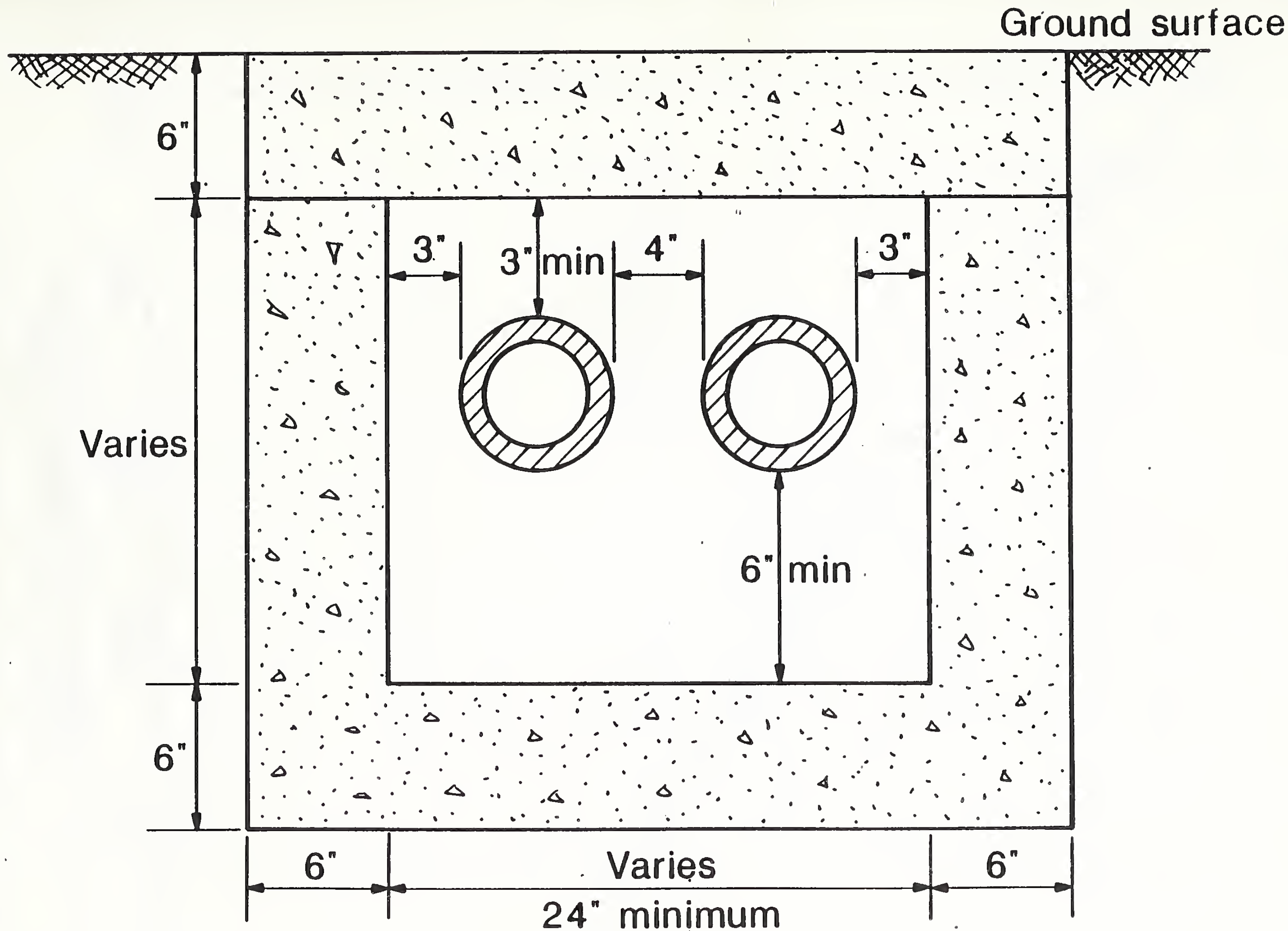
Nominal Pipe Diameter (Inch)			
Supply Pipe	1	6	12
Return Pipe	3/4	3	6
Insulation Thickness (Inch)			
Supply Pipe	2	3	3
Return Pipe	2	2.5	3
Heat Loss (Btu/h·ft)			
Supply Pipe (350 F)	47.05 (49.68)	98.97 (101.68)	159.98 (181.28)
Return Pipe (160 F)	14.08 (10.94)	23.10 (19.16)	29.01 (25.01)
Total	61.13 (60.62)	122.07 (120.84)	188.99 (206.29)

Note: The pipe heat loss values in brackets are predicted by the finite difference thermal analyzer program TASTAP.

TABLE 3

Effect of Trench Dimension on Pipe Heat Losses

Concrete Trench Inner Dimension (width x height)	Pipe Heat Loss (Btu/h-ft)		
	Supply Pipe	Return Pipe	Total
3 ft x 3 ft	97.02	73.35	170.37
4 ft x 4 ft	96.84	73.74	170.58
5 ft x 5 ft	97.19	74.08	171.27
6 ft x 6 ft	97.57	74.44	172.01



Two hot water pipes with calcium silicate insulation/aluminum jacket

Figure 1. Concrete Shallow Trench Underground Heat Distribution System

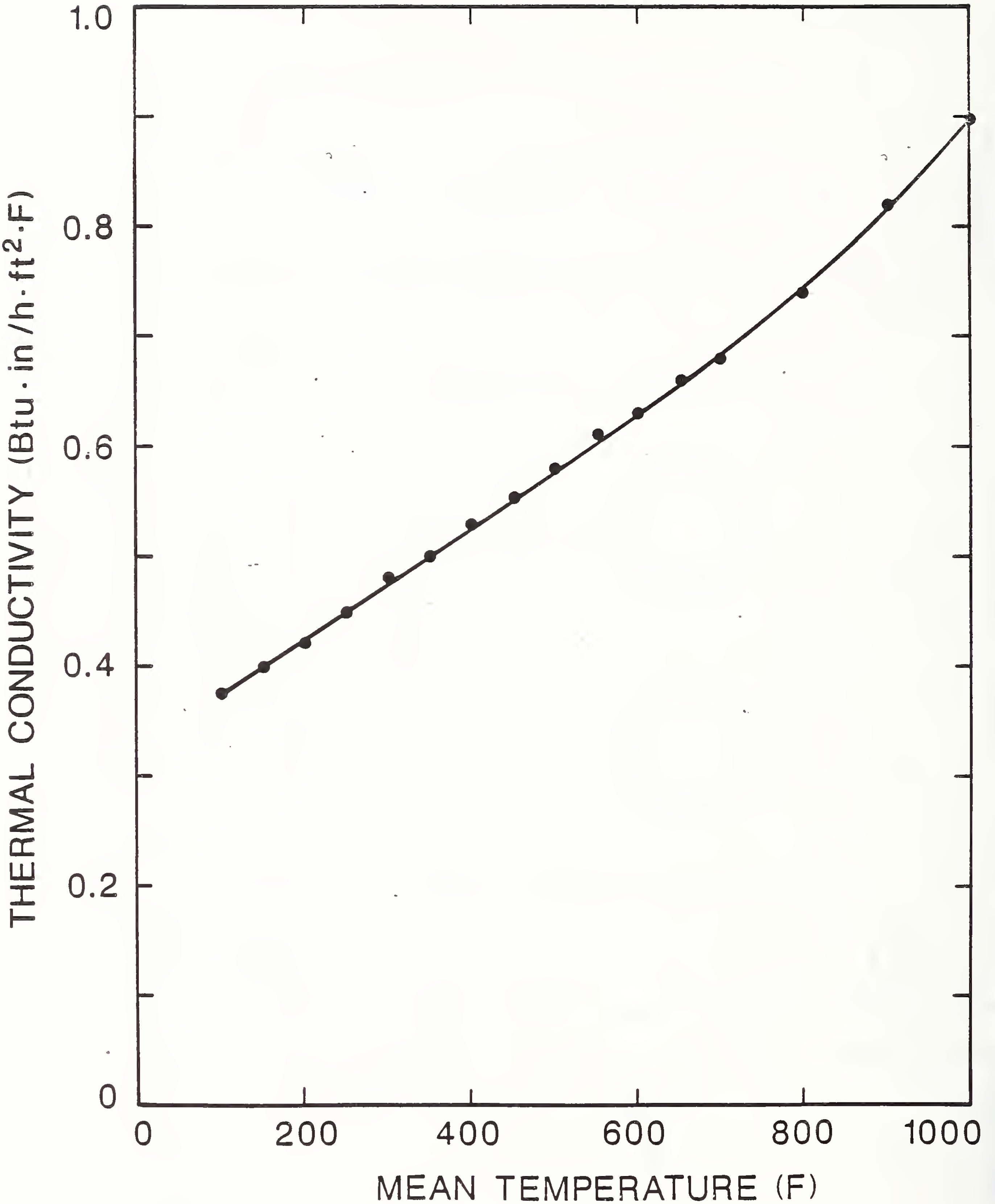


Figure 2. Thermal Conductivity Variation With Temperature for Calcium Silicate Insulation

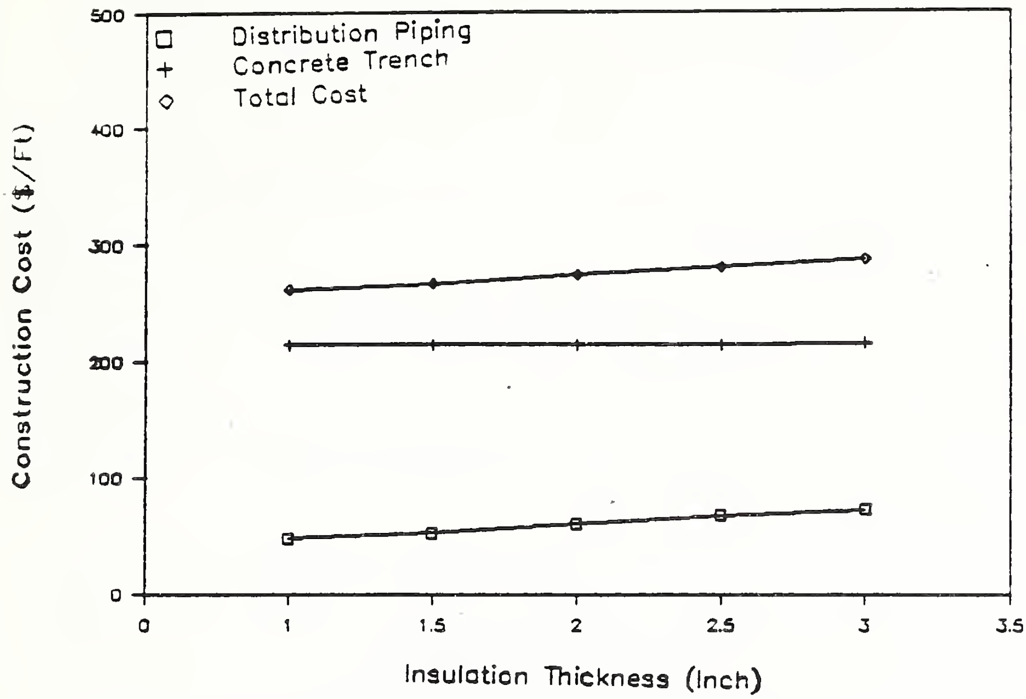


Figure 3. Construction Cost for a Shallow Trench System Containing Two 1-inch Insulated Pipes

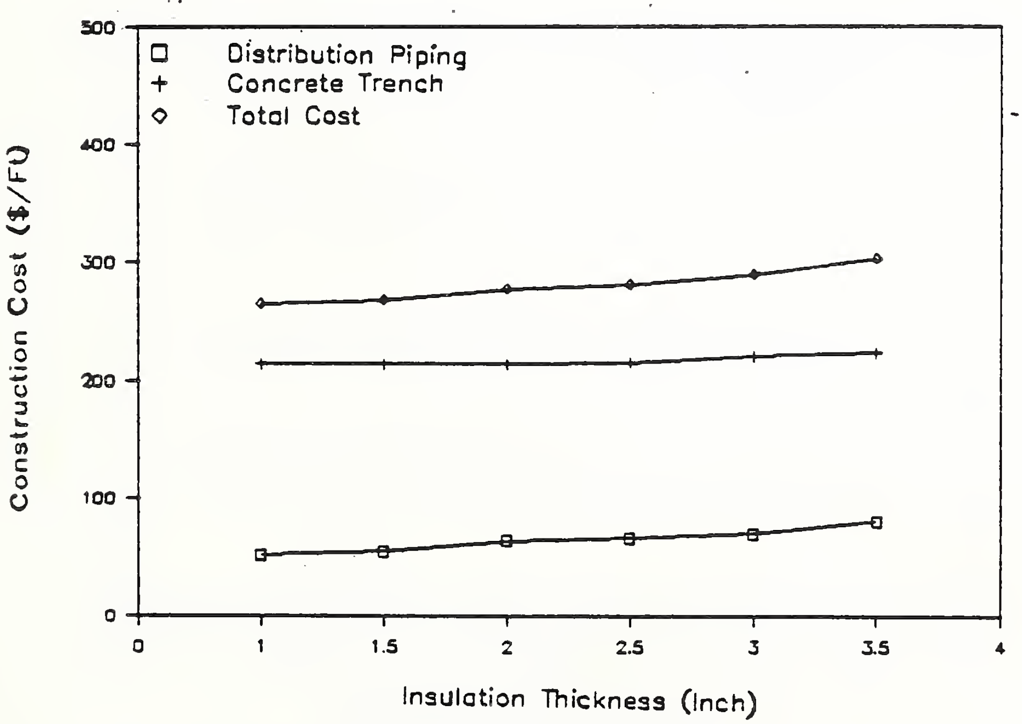


Figure 4. Construction Cost for a Shallow Trench System Containing Two 2-inch Insulated Pipes

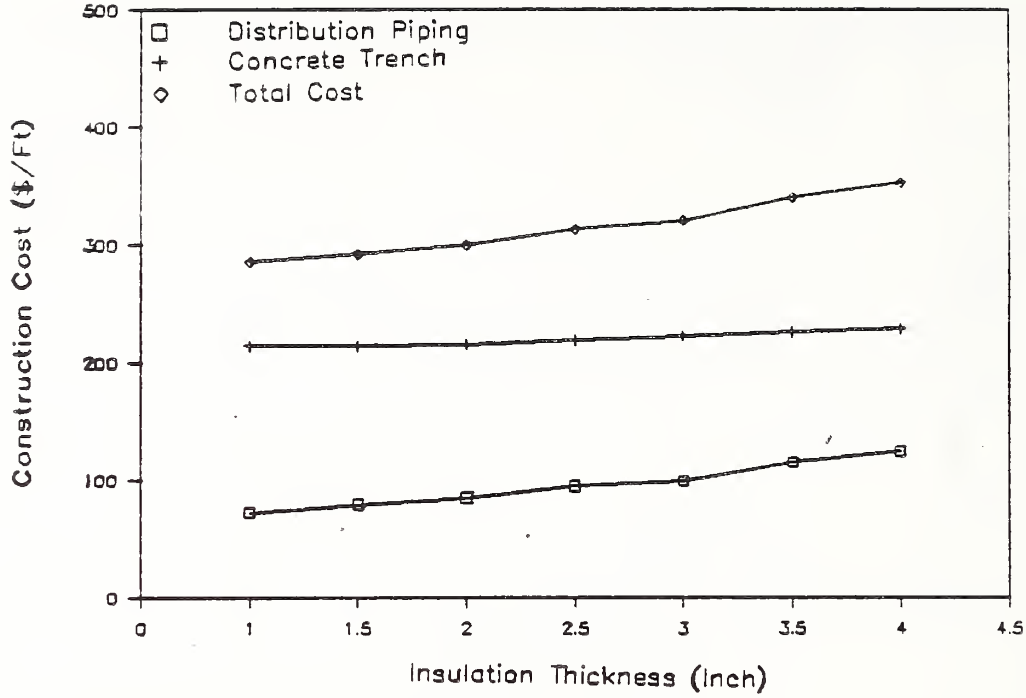


Figure 5. Construction Cost for a Shallow Trench System Containing Two 3-inch Insulated Pipes

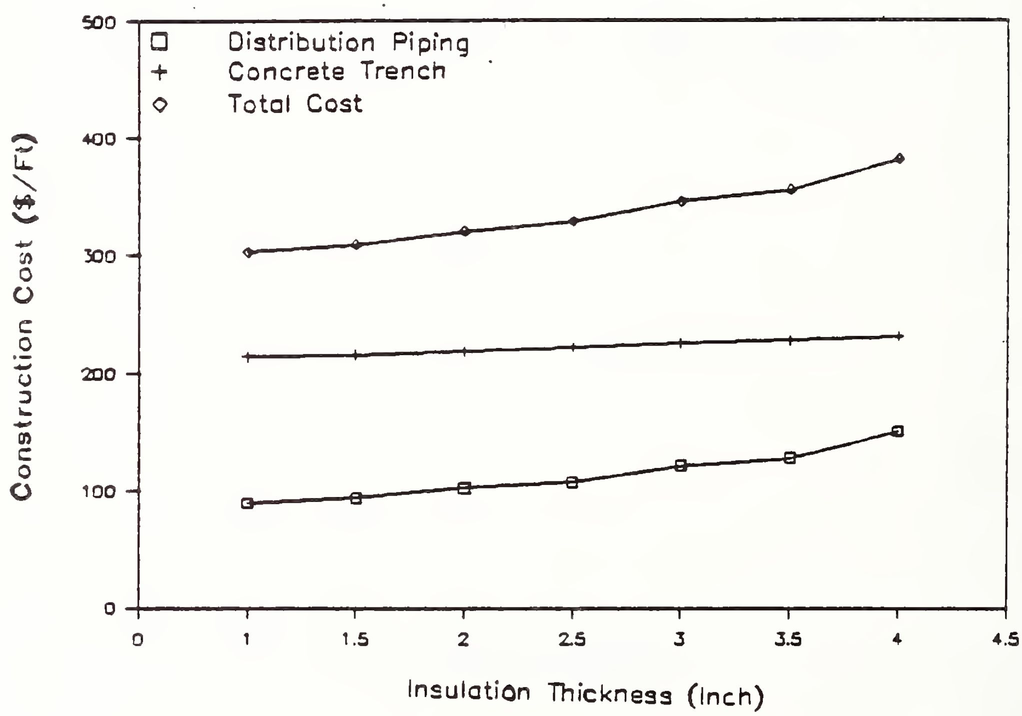


Figure 6. Construction Cost for a Shallow Trench System Containing Two 4-inch Insulated Pipes

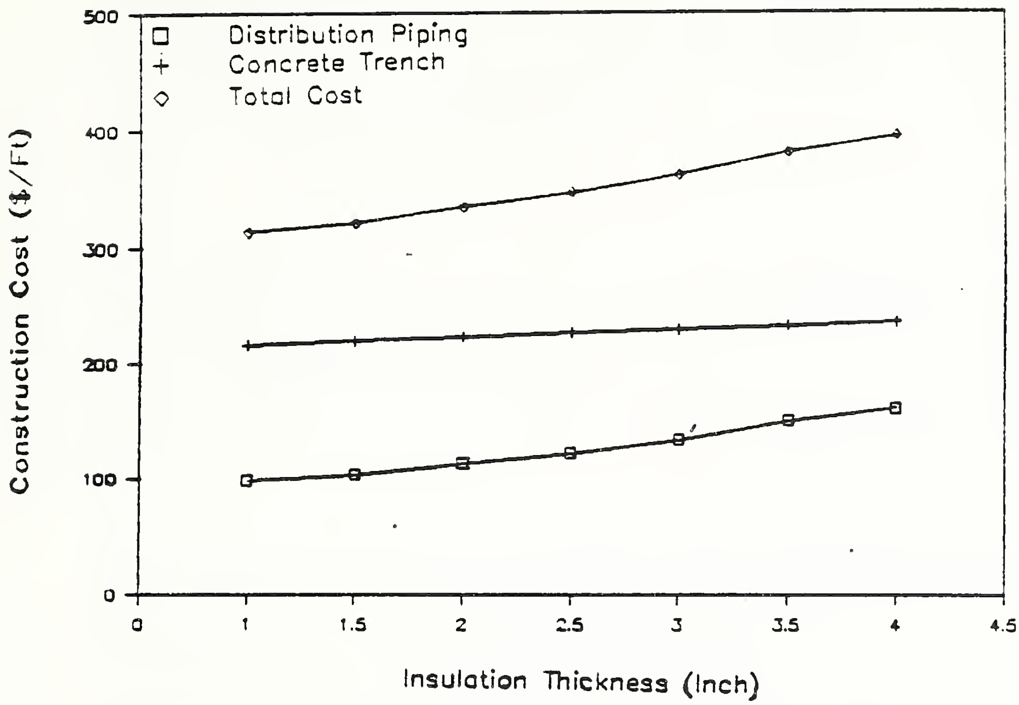


Figure 7. Construction Cost for a Shallow Trench System Containing Two 5-inch Insulated Pipes

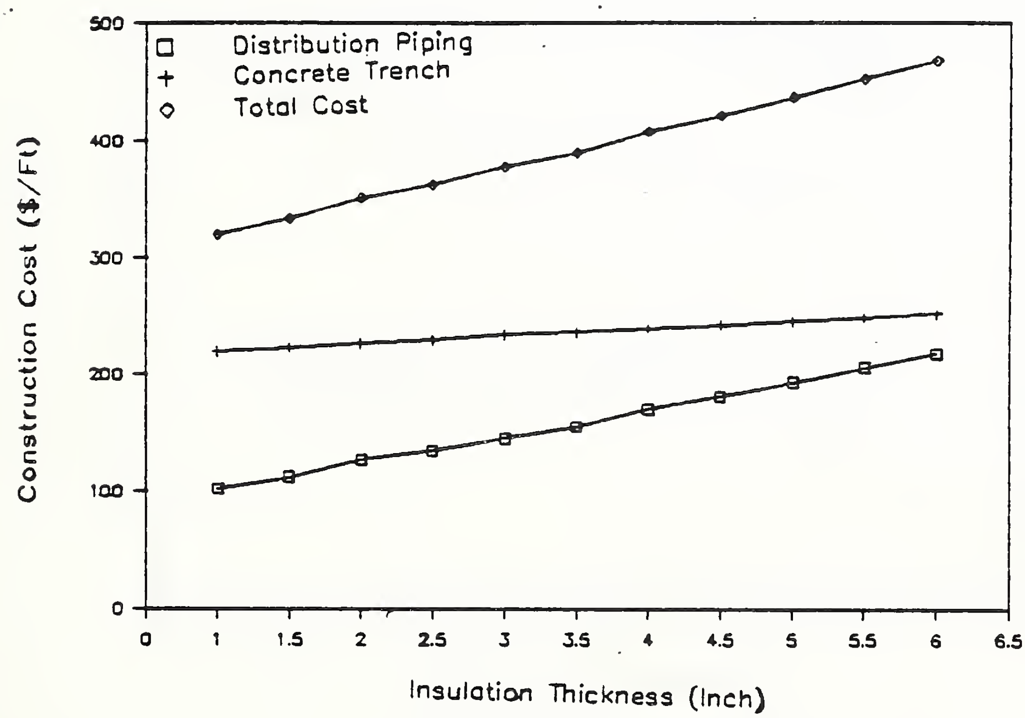


Figure 8. Construction Cost for a Shallow Trench System Containing Two 6-inch Insulated Pipes

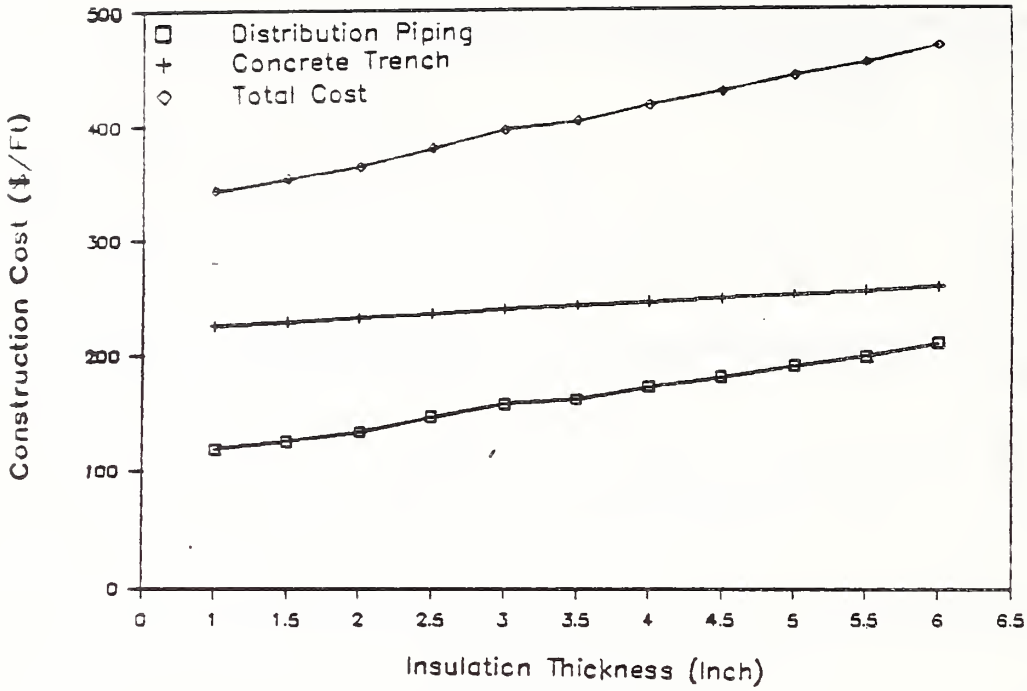


Figure 9. Construction Cost for a Shallow Trench System Containing Two 8-inch Insulated Pipes

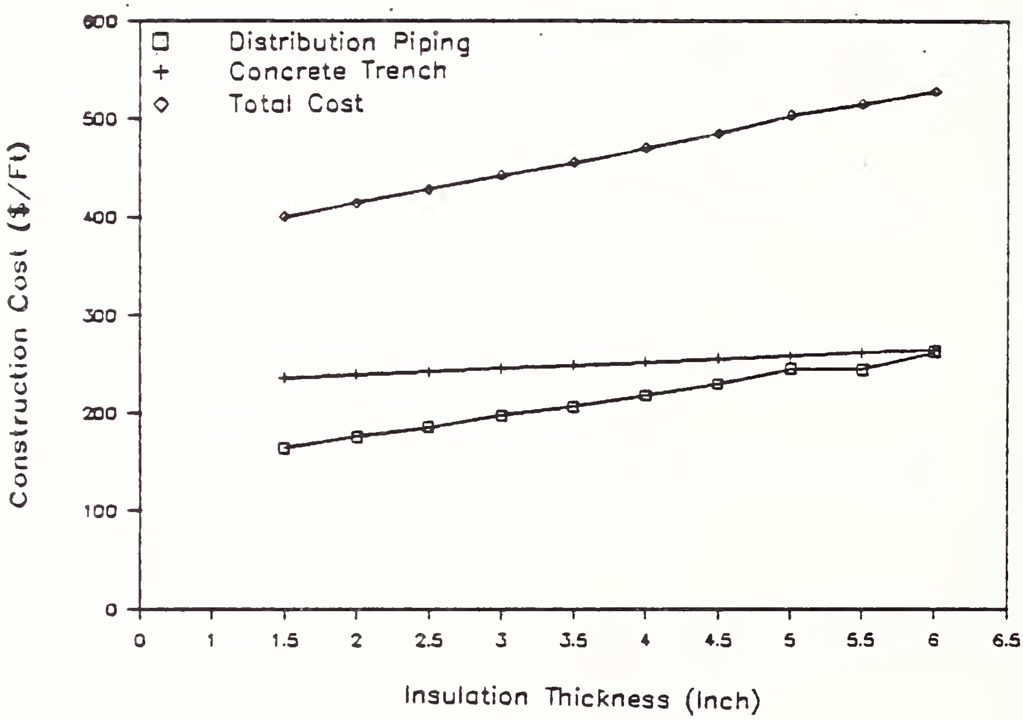


Figure 10. Construction Cost for a Shallow Trench System Containing Two 10-inch Insulated Pipes

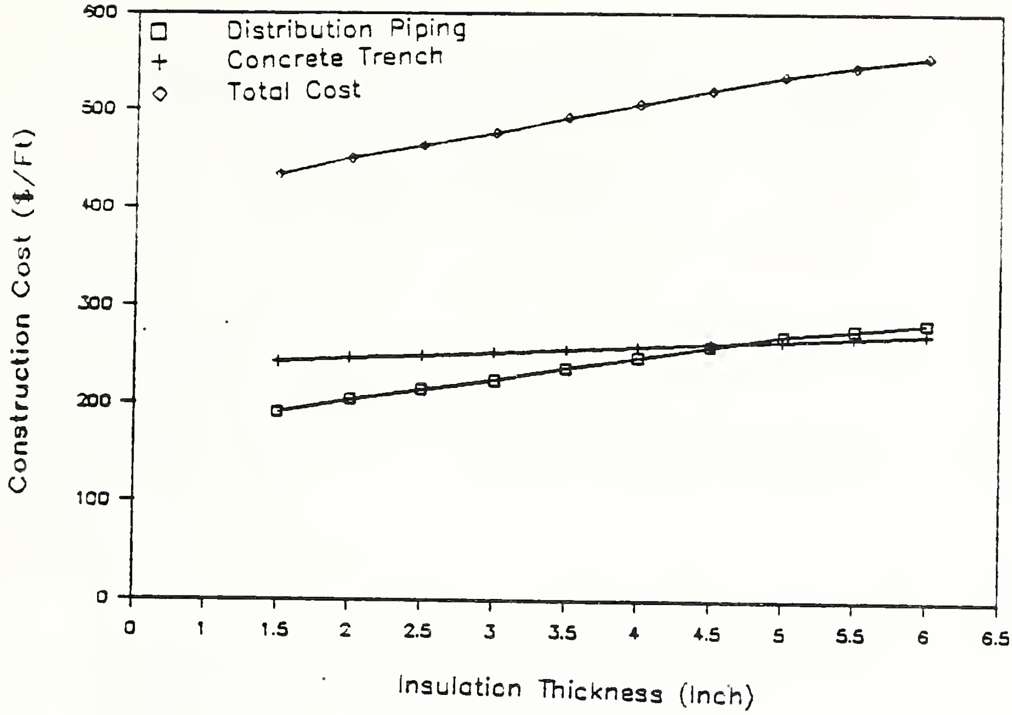


Figure 11. Construction Cost for a Shallow Trench System Containing Two 12-inch Insulated Pipes

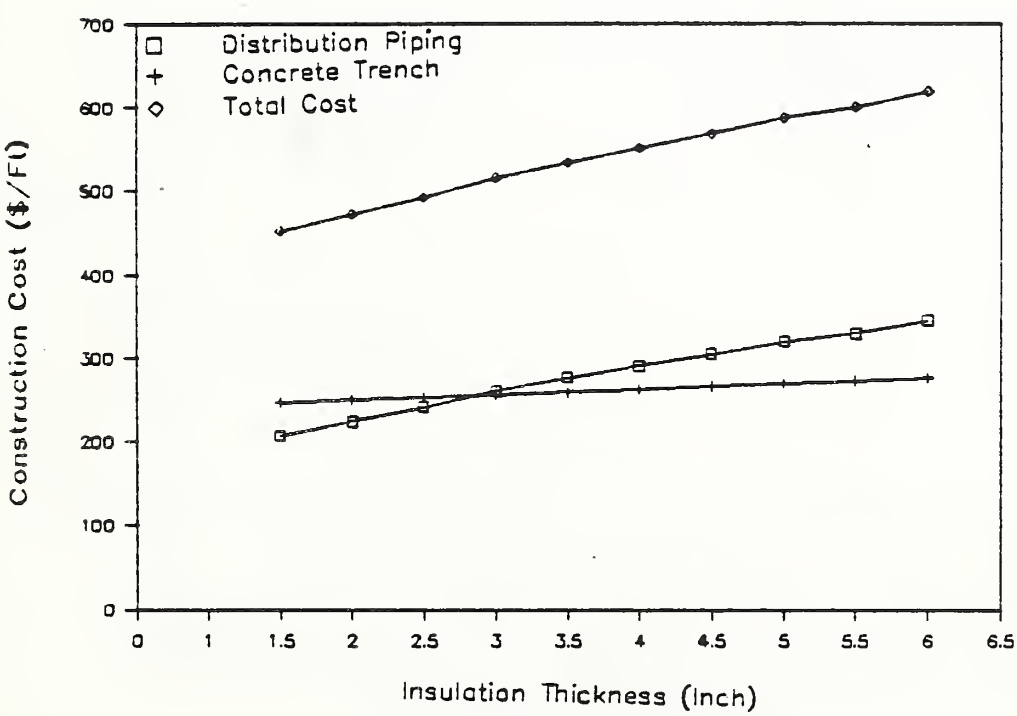


Figure 12. Construction Cost for a Shallow Trench System Containing Two 14-inch Insulated Pipes

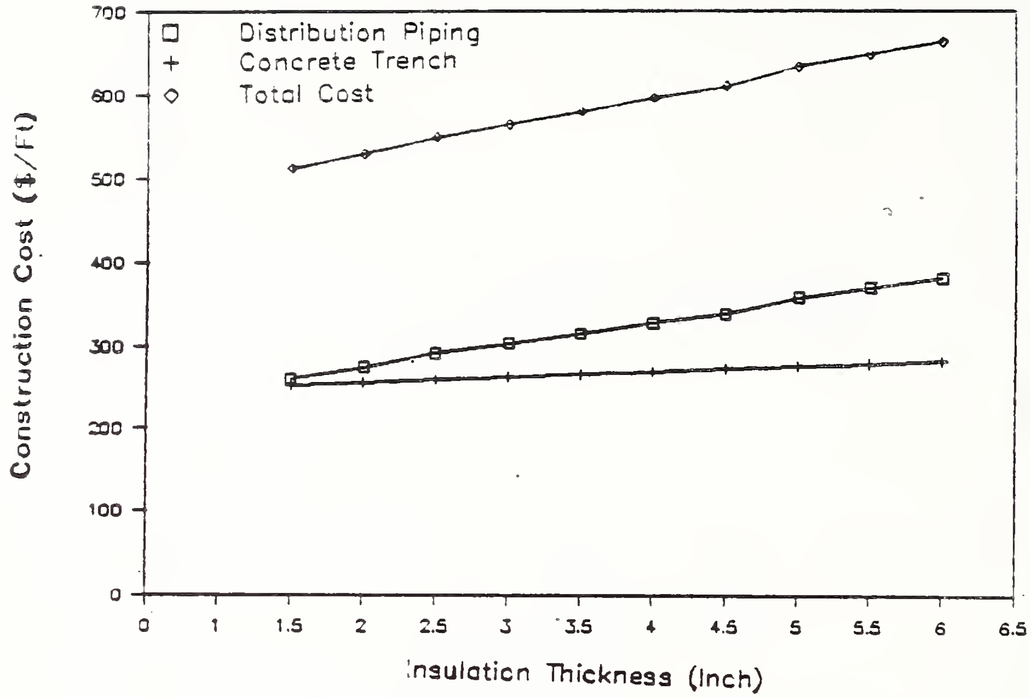


Figure 13. Construction Cost for a Shallow Trench System Containing Two 16-inch Insulated Pipes

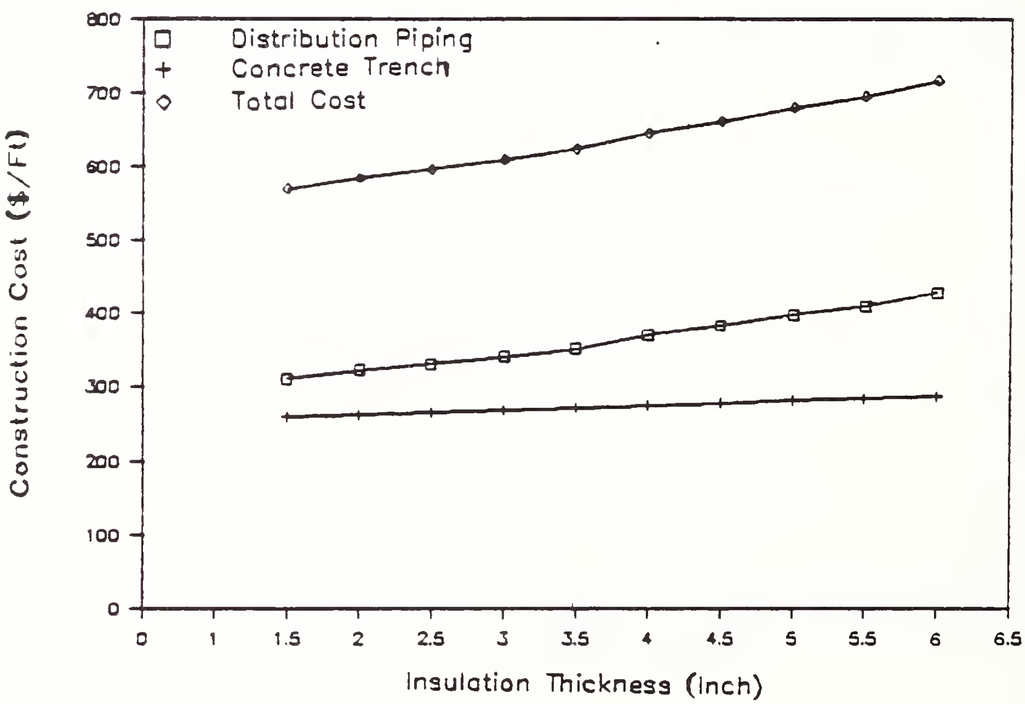


Figure 14. Construction Cost for a Shallow Trench System Containing Two 18-inch Insulated Pipes

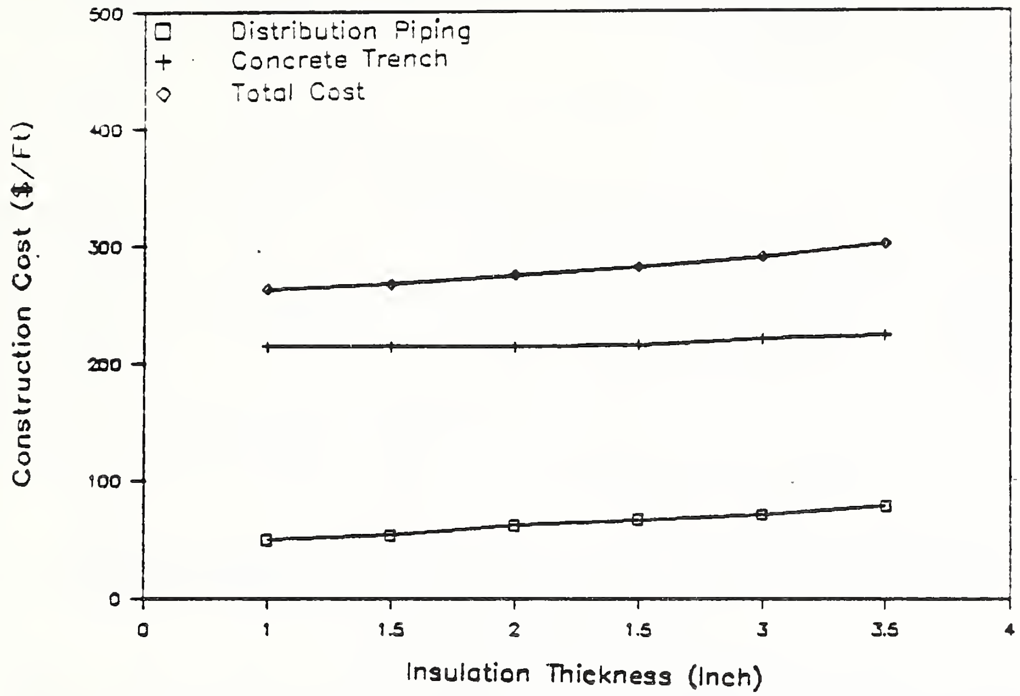


Figure 15. Construction Cost for a Shallow Trench System Containing a 2-inch Supply and a 1-inch Return Insulated Pipes

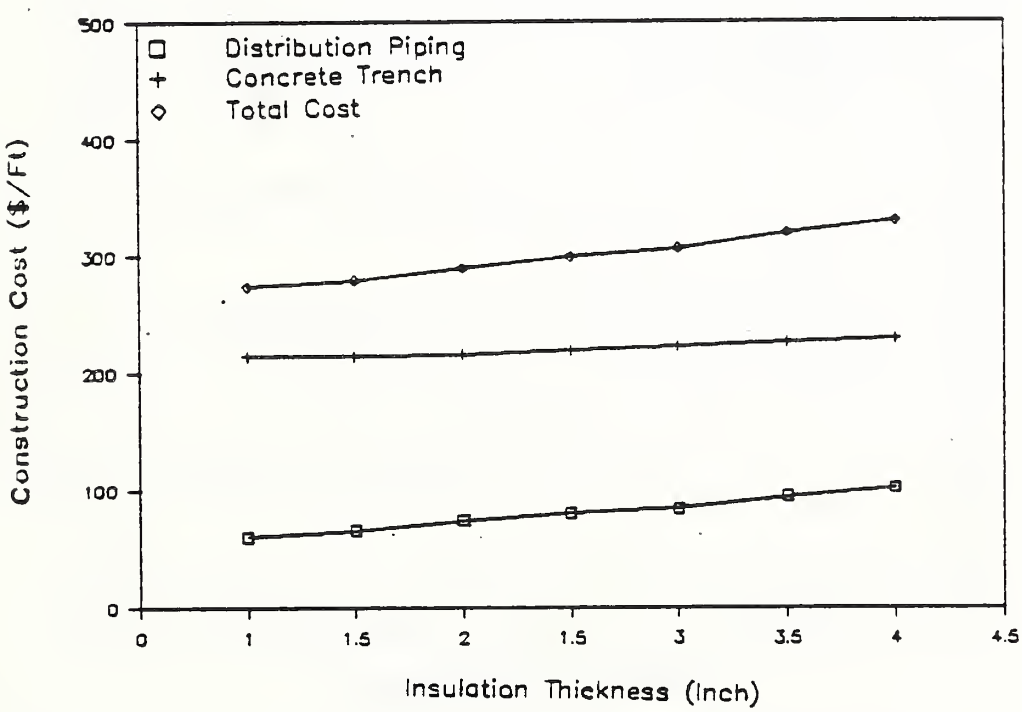


Figure 16. Construction Cost for A Shallow Trench System Containing a 3-inch Supply and a 1.5-inch Return Insulated Pipes

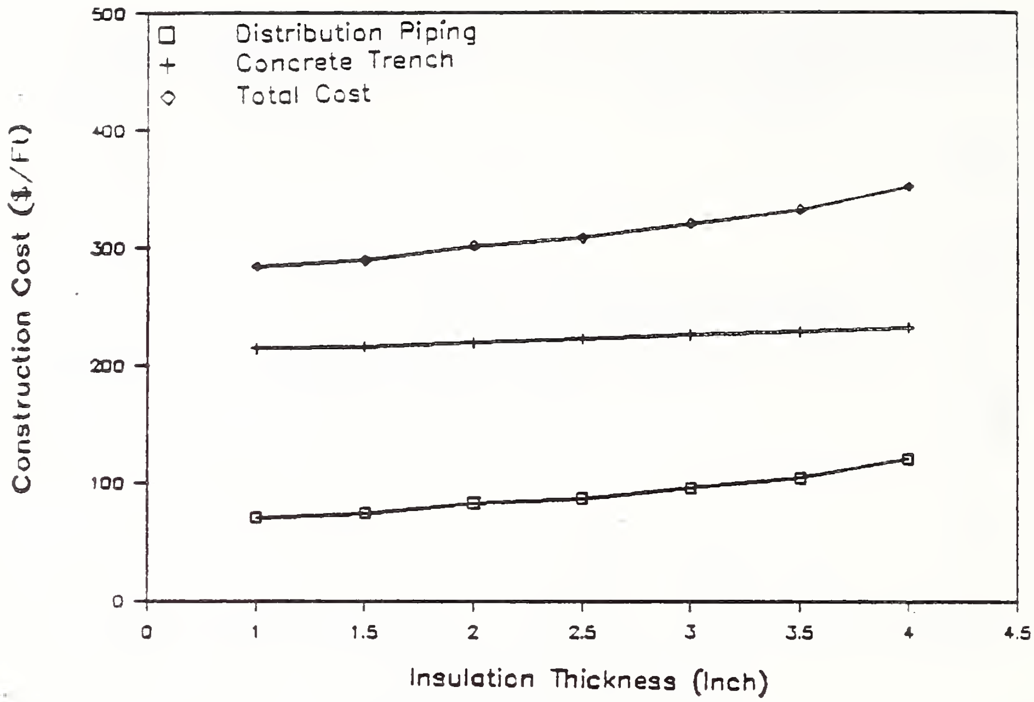


Figure 17. Construction Cost of a Shallow Trench System Containing a 4-inch Supply and a 2-inch Return Insulated Pipes

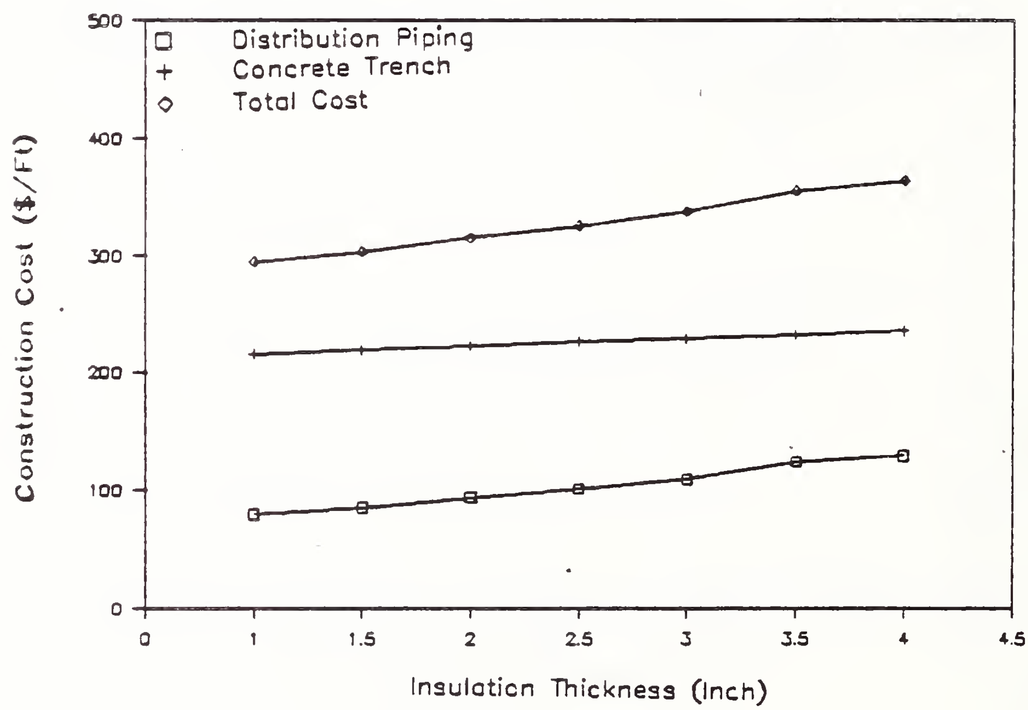


Figure 18. Construct Cost for a Shallow Trench System Containing a 5-inch Supply and a 2.5-inch Return Insulated Pipes

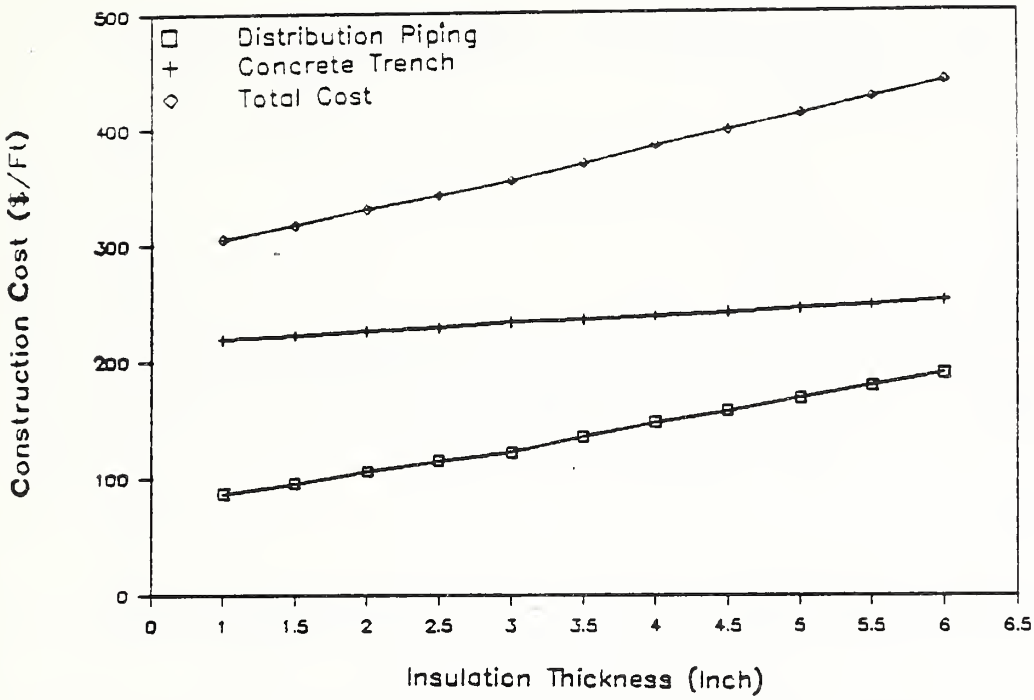


Figure 19. Construction Cost for a Shallow Trench System Containing a 6-inch Supply and a 3-inch Return Insulated Pipes

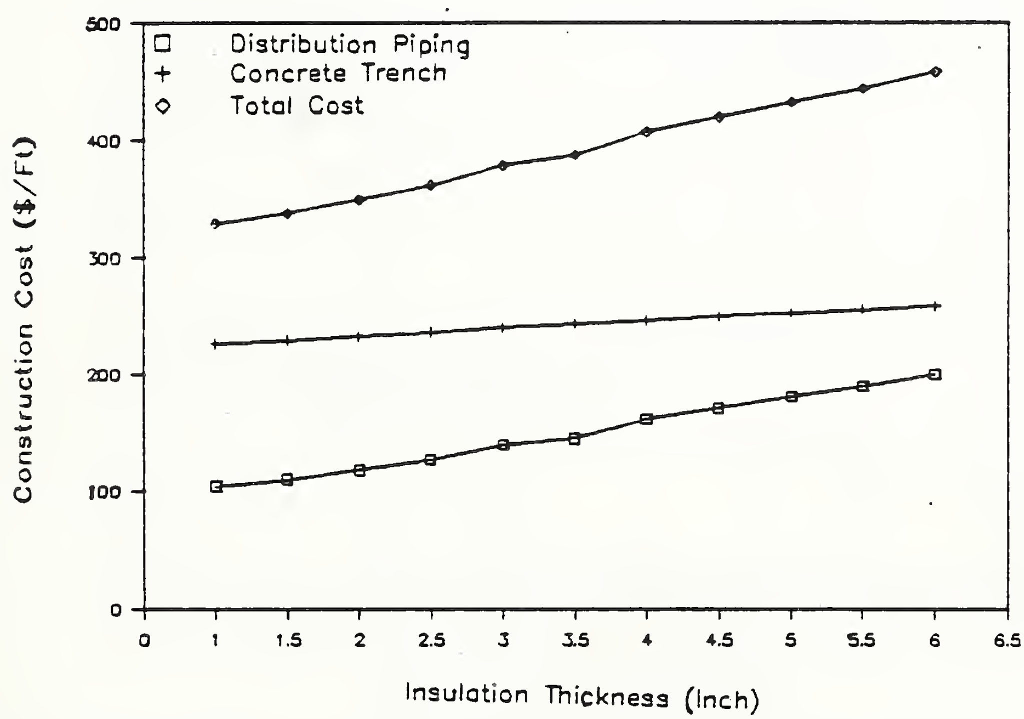


Figure 20. Construction Cost for a Shallow Trench System Containing a 8-inch Supply and a 4-inch Return Insulated Pipes

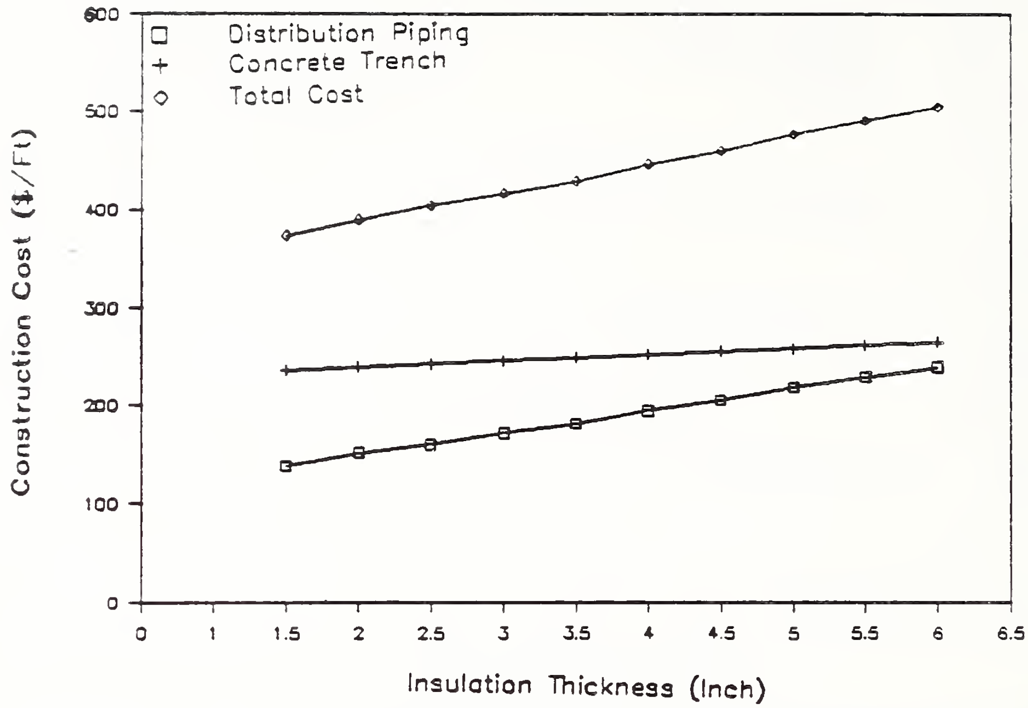


Figure 21. Construction Cost for a Shallow Trench System Containing a 10-inch Supply and a 6-inch Return Insulated Pipes

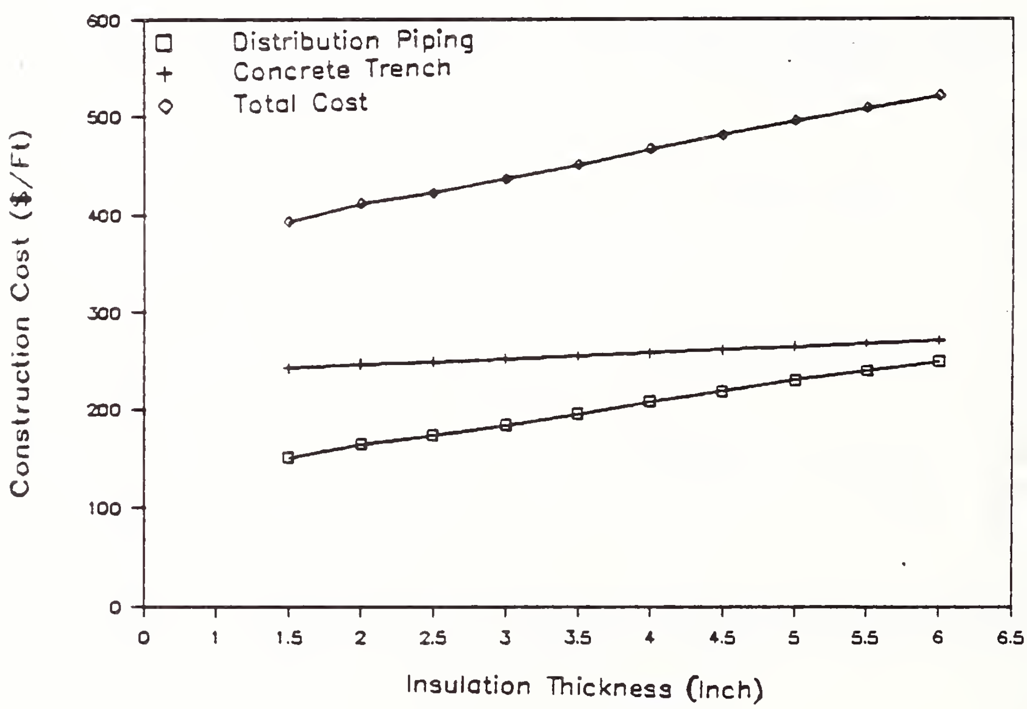


Figure 22. Construction Cost for a Shallow Trench System Containing a 12-inch Supply and a 6-inch Return Insulated Pipes

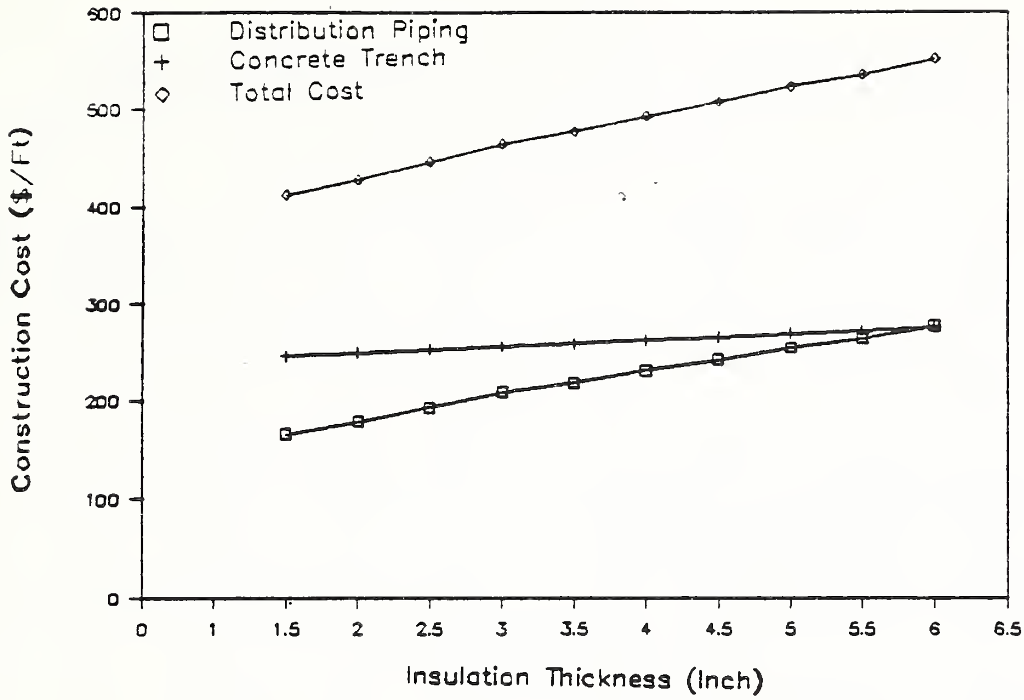


Figure 23. Construction Cost for a Shallow Trench System Containing a 14-inch Supply and a 8-inch Return Insulated Pipes

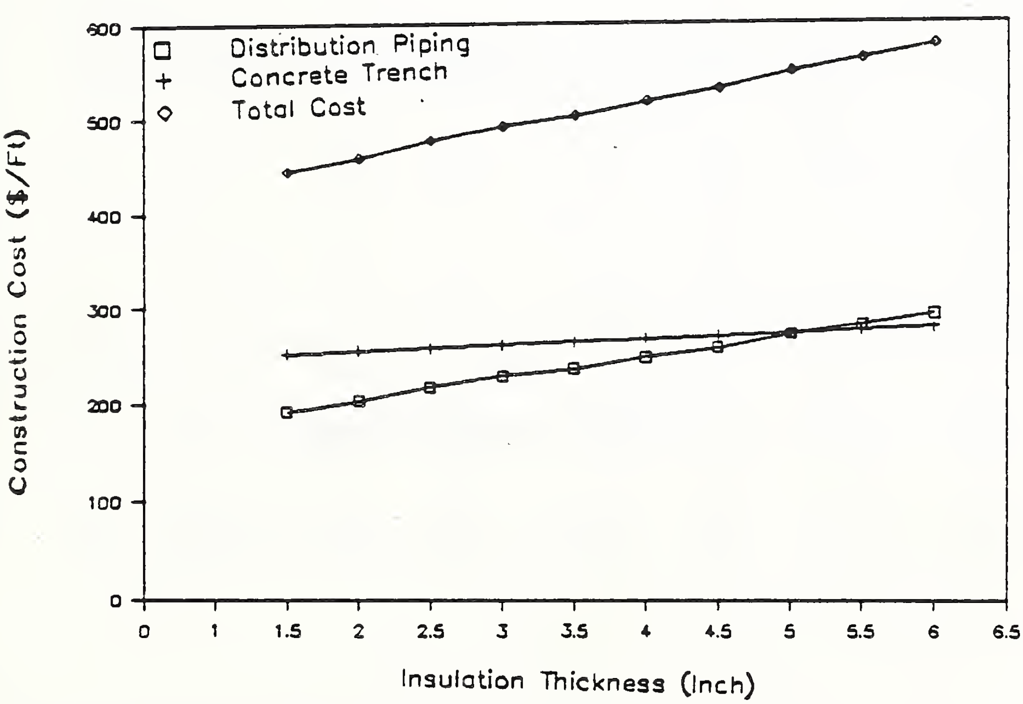


Figure 24. Construction Cost for a Shallow Trench System Containing a 16-inch Supplv and a 8-inch Return Insulated Pipes

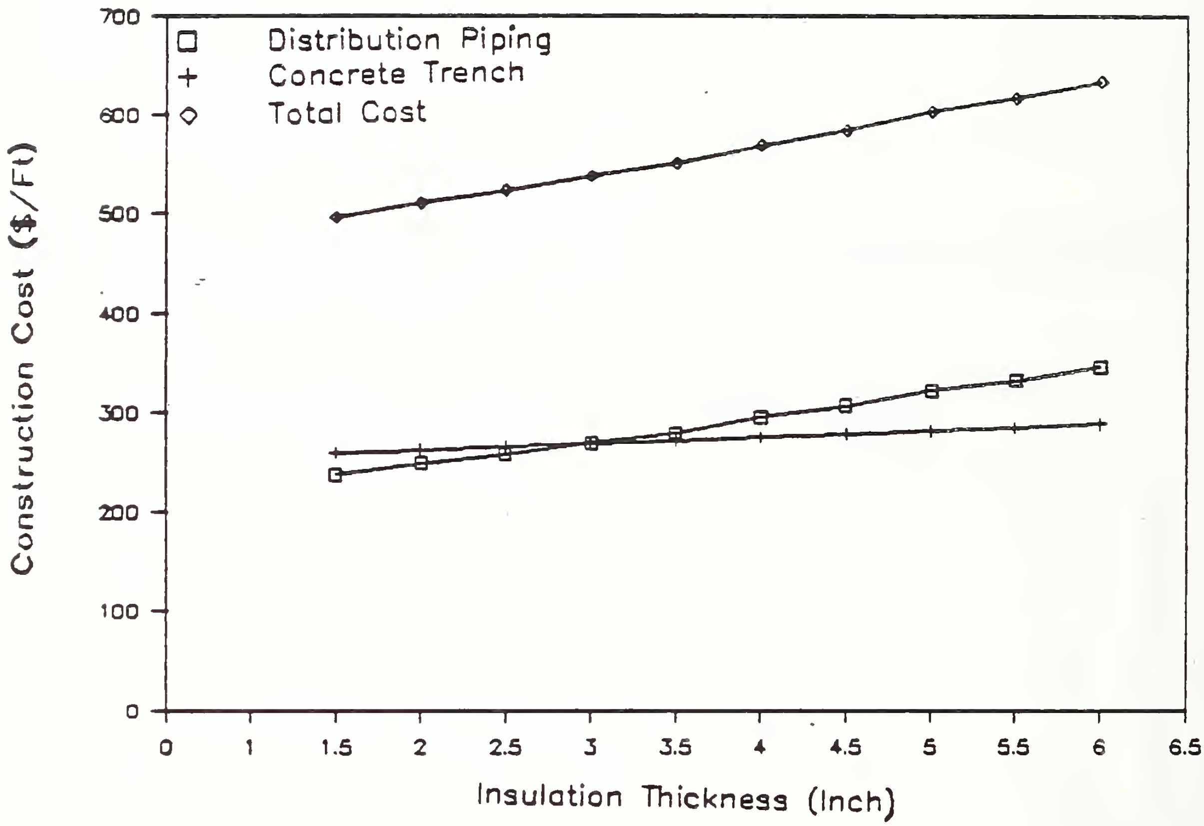


Figure 25. Construction Cost for a Shallow Trench System Containing a 18-inch Supply and a 10-inch Return Insulated Pipes

TABLE A-1.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $3/M Btu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
1	S	22.2	26.2	35.3	45.1	55.6	66.6	77.8	89.5
	R	22.2	17.3	17.1	16.8	16.5	16.2	15.9	15.6
2	S	25.0	37.3	50.5	54.0	66.6	70.0	81.8	94.0
	R	25.0	24.6	24.1	20.0	19.6	17.2	16.9	16.6
3	S	32.3	48.4	54.1	69.2	85.3	88.6	92.6	106.5
	R	32.3	31.6	25.8	25.3	24.7	21.4	19.0	18.7
4	S	38.5	57.8	64.2	70.7	87.3	104.6	108.6	124.9
	R	38.5	37.4	30.4	26.0	25.4	24.8	22.0	21.5
5	S	44.8	67.5	74.6	81.8	101.0	121.0	125.0	144.0
	R	44.8	43.5	35.0	29.8	29.0	28.3	25.0	24.4
6	S	51.0	77.0	84.9	92.7	114.4	137.2	141.1	162.6
	R	51.0	49.3	39.5	33.4	32.5	31.6	27.8	27.0
8	S	62.1	76.4	103.6	112.8	139.2	146.2	153.1	176.4
	R	62.1	49.2	47.7	40.0	38.8	33.8	30.2	29.4
10	S	73.6	90.6	104.2	133.6	144.0	172.6	180.1	207.7
	R	73.6	58.0	48.3	46.7	40.4	39.2	34.8	33.7
12	S	84.0	103.6	119.1	152.8	164.3	197.1	204.8	236.3
	R	84.0	66.0	54.8	52.8	45.6	44.0	38.8	37.4
14	S	90.3	111.7	128.6	165.0	176.5	211.7	219.7	253.7
	R	90.3	70.8	58.8	56.6	48.3	46.5	40.9	39.3
16	S	100.9	123.9	142.0	158.4	195.5	208.2	243.3	253.6
	R	100.9	95.5	64.1	54.6	52.5	45.9	44.2	39.4
18	S	108.8	135.3	155.5	173.5	214.2	228.0	266.6	277.8
	R	108.8	84.5	69.4	59.0	56.5	49.3	47.2	42.1

Note: Energy Cost = $3.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-1.b

Economic Insulation Thickness (inch) for Hot Water Supply and Return Pipes for Energy Cost of $3/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
1	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
2	1.5	1.5	1.5	2.0	2.0	2.5	2.5	2.5
3	1.5	1.5	2.0	2.0	2.0	2.5	3.0	3.0
4	1.5	1.5	2.0	2.5	2.5	2.5	3.0	3.0
5	1.5	1.5	2.0	2.5	2.5	2.5	3.0	3.0
6	1.5	1.5	2.0	2.5	2.5	2.5	3.0	3.0
8	1.5	2.0	2.0	2.5	2.5	3.0	3.5	3.5
10	1.5	2.0	2.5	2.5	3.0	3.0	3.5	3.5
12	1.5	2.0	2.5	2.5	3.0	3.0	3.5	3.5
14	1.5	2.0	2.5	2.5	3.0	3.0	3.5	3.5
16	1.5	2.0	2.5	3.0	3.0	3.5	3.5	4.0
18	1.5	2.0	2.5	3.0	3.0	3.5	3.5	4.0

Note: Energy Cost = $3.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-2.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $4/M Btu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F)							
		150	200	250	300	350	400	450	500
1	S	17.6	26.2	35.3	45.1	55.6	57.0	66.7	76.6
	R	17.6	17.3	17.1	16.8	16.5	14.1	13.9	13.7
2	S	25.0	37.3	42.2	54.0	66.6	70.0	81.8	94.0
	R	25.0	24.6	20.4	20.0	19.6	17.2	16.9	16.6
3	S	32.3	40.0	54.1	69.2	85.3	88.6	92.6	106.5
	R	32.3	26.3	25.8	25.3	24.7	21.4	19.0	18.7
4	S	38.5	47.4	55.3	70.7	87.3	104.6	108.6	124.9
	R	38.5	31.1	26.5	26.0	25.4	24.8	22.0	21.5
5	S	44.8	55.1	64.0	81.8	101.0	121.0	125.0	144.0
	R	44.8	35.9	30.4	29.8	29.0	28.3	25.0	24.4
6	S	51.0	62.6	72.4	92.7	114.4	137.2	141.1	146.4
	R	51.0	40.7	34.3	33.4	32.5	31.6	27.8	25.0
8	S	50.7	76.4	88.0	112.8	122.0	146.2	153.1	176.4
	R	50.7	49.2	41.2	40.0	34.8	33.8	30.2	29.4
10	S	59.9	90.6	104.2	133.6	144.0	154.1	180.1	188.5
	R	59.9	58.0	48.3	46.7	40.4	35.8	34.8	31.5
12	S	68.4	103.4	119.1	133.2	146.2	175.3	185.3	213.7
	R	68.4	66.0	54.8	47.1	41.4	40.0	35.8	34.7
14	S	73.6	111.7	128.6	143.0	156.8	188.0	198.6	229.2
	R	73.6	70.8	58.8	50.1	43.8	42.4	37.8	36.5
16	S	81.4	104.5	123.4	158.4	173.6	188.0	219.7	231.9
	R	81.4	66.6	56.6	54.6	47.7	42.4	40.9	37.0
18	S	88.6	114.2	135.1	154.0	190.1	205.7	240.5	253.7
	R	88.6	72.4	61.4	53.4	51.4	45.6	43.9	39.6

Note: Energy Cost = $4.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-2.b

Economic Insulation Thickness (inch) for Hot Water Supply and Return Pipes for Energy Cost of $4/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
1	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0
2	1.5	1.5	2.0	2.0	2.0	2.5	2.5	2.5
3	1.5	2.0	2.0	2.0	2.0	2.5	3.0	3.0
4	1.5	2.0	2.5	2.5	2.5	2.5	3.0	3.0
5	1.5	2.0	2.5	2.5	2.5	2.5	3.0	3.0
6	1.5	2.0	2.5	2.5	2.5	2.5	3.0	3.5
8	2.0	2.0	2.5	2.5	3.0	3.0	3.5	3.5
10	2.0	2.0	2.5	2.5	3.0	3.5	3.5	4.0
12	2.0	2.0	2.5	3.0	3.5	3.5	4.0	4.0
14	2.0	2.0	2.5	3.0	3.5	3.5	4.0	4.0
16	2.0	2.5	3.0	3.0	3.5	4.0	4.0	4.5
18	2.0	2.5	3.0	3.5	3.5	4.0	4.0	4.5

Note: Energy Cost = $4.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-3.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $5/M Btu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F)							
		150	200	250	300	350	400	450	500
1	S	17.6	26.2	35.3	38.6	47.6	57.0	66.7	68.4
	R	17.6	17.3	17.1	14.5	14.3	14.1	13.9	12.4
2	S	25.0	37.3	42.2	47.4	58.4	70.0	81.8	84.9
	R	25.0	24.6	20.4	17.7	17.5	17.2	16.9	15.2
3	S	26.8	40.0	54.1	60.0	74.0	79.3	92.6	106.5
	R	26.8	26.3	25.8	22.2	21.8	19.4	19.0	18.7
4	S	31.7	47.4	55.3	70.7	87.3	92.9	108.6	124.9
	R	31.7	31.1	26.5	26.0	25.4	22.5	22.0	21.5
5	S	36.8	55.1	64.0	81.8	101.0	107.0	125.0	144.0
	R	36.8	35.9	30.4	29.8	29.0	25.6	25.0	24.4
6	S	41.7	62.6	72.4	92.7	114.4	120.8	127.1	146.4
	R	41.7	40.7	34.3	33.4	32.5	28.5	25.6	25.0
8	S	50.7	76.4	77.2	98.8	122.0	131.0	139.5	160.7
	R	50.7	49.2	36.6	35.7	34.8	30.9	28.0	27.4
10	S	59.9	76.8	91.1	116.7	128.6	154.1	163.6	173.1
	R	59.9	49.7	42.8	41.7	36.8	35.8	32.3	29.4
12	S	68.4	87.8	103.9	118.5	146.2	158.6	185.3	195.8
	R	68.4	56.6	48.5	42.5	41.3	36.8	35.8	32.4
14	S	73.6	94.7	111.5	127.1	156.8	170.0	198.6	209.8
	R	73.6	60.8	51.7	45.2	43.8	39.0	37.8	34.2
16	S	81.4	90.9	109.7	140.6	156.8	172.0	201.0	231.9
	R	81.4	58.5	50.9	49.3	43.8	39.4	38.2	37.0
18	S	88.6	99.4	120.0	154.0	171.5	188.1	219.8	234.2
	R	88.6	63.6	55.3	53.4	47.3	42.5	41.1	37.4

Note: Energy Cost = $5.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-3.b

Economic Insulation Thickness (inch) for Hot Water Supply and Return Pipes for Energy Cost of $5/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
1	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.5
2	1.5	1.5	2.0	2.5	2.5	2.5	2.5	3.0
3	2.0	2.0	2.0	2.5	2.5	3.0	3.0	3.0
4	2.0	2.0	2.5	2.5	2.5	3.0	3.0	3.0
5	2.0	2.0	2.5	2.5	2.5	3.0	3.0	3.0
6	2.0	2.0	2.5	2.5	2.5	3.0	3.5	3.5
8	2.0	2.0	3.0	3.0	3.0	3.5	4.0	4.0
10	2.0	2.5	3.0	3.0	3.5	3.5	4.0	4.5
12	2.0	2.5	3.0	3.5	3.5	4.0	4.0	4.5
14	2.0	2.5	3.0	3.5	3.5	4.0	4.0	4.5
16	2.0	3.0	3.5	3.5	4.0	4.5	4.5	4.5
18	2.0	3.0	3.5	3.5	4.0	4.5	4.5	5.0

Note: Energy Cost = $5.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-4.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $6/M Btu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
1	S	17.6	26.2	35.3	38.6	47.6	51.0	59.6	68.4
	R	17.6	17.3	17.1	14.5	14.3	12.7	12.6	12.4
2	S	25.0	31.3	37.1	47.4	58.4	63.2	73.9	84.9
	R	25.0	20.7	18.0	17.7	17.5	15.7	15.5	15.2
3	S	26.8	40.0	46.9	60.0	66.2	79.3	92.6	106.5
	R	26.8	26.3	22.6	22.2	19.7	19.4	19.0	18.7
4	S	31.7	40.9	55.3	70.7	77.5	92.9	108.6	113.4
	R	31.7	27.0	26.5	26.0	22.9	22.5	22.0	19.9
5	S	36.8	47.3	64.0	81.8	89.3	107.0	125.0	130.0
	R	36.8	31.1	30.4	29.8	26.1	25.6	25.0	22.5
6	S	41.7	53.5	72.4	81.7	100.8	120.8	127.1	146.4
	R	41.7	35.1	34.3	29.9	29.2	28.5	25.6	25.0
8	S	50.7	65.0	77.2	88.6	109.3	131.0	139.5	160.7
	R	50.7	42.3	36.6	32.4	31.7	30.9	28.0	27.4
10	S	51.1	76.8	91.1	104.2	128.6	140.0	150.3	173.1
	R	51.1	49.7	42.8	37.8	36.8	33.1	30.1	29.4
12	S	58.2	76.7	92.5	118.5	132.3	158.6	169.9	181.3
	R	58.2	49.8	43.6	42.5	37.8	36.8	33.3	30.5
14	S	62.7	82.2	99.2	127.1	141.8	170.0	181.9	194.1
	R	62.7	53.2	46.4	45.2	40.2	39.0	35.3	32.2
16	S	69.0	90.9	109.7	127.0	143.5	172.0	201.0	214.3
	R	69.0	58.5	50.9	45.1	40.6	39.4	38.2	34.8
18	S	75.2	99.4	120.0	139.0	156.8	173.7	203.0	218.0
	R	75.2	63.6	55.3	48.9	43.9	39.9	38.7	35.4

Note: Energy Cost = $6.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-4.b

Economic Insulation Thickness (inch) for Hot Water Supply and Return Pipes for Energy Cost of $6/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
1	1.5	1.5	1.5	2.0	2.0	2.5	2.5	2.5
2	1.5	2.0	2.5	2.5	2.5	3.0	3.0	3.0
3	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.0
4	2.0	2.5	2.5	2.5	3.0	3.0	3.0	3.5
5	2.0	2.5	2.5	2.5	3.0	3.0	3.0	3.5
6	2.0	2.5	2.5	3.0	3.0	3.0	3.5	3.5
8	2.0	2.5	3.0	3.5	3.5	3.5	4.0	4.0
10	2.5	2.5	3.0	3.5	3.5	4.0	4.5	4.5
12	2.5	3.0	3.5	3.5	4.0	4.0	4.5	5.0
14	2.5	3.0	3.5	3.5	4.0	4.0	4.5	5.0
16	2.5	3.0	3.5	4.0	4.5	4.5	4.5	5.0
18	2.5	3.0	3.5	4.0	4.5	5.0	5.0	5.5

Note: Energy Cost = $6.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-5.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $7/M Btu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
1	S	17.6	26.2	30.2	38.6	47.6	51.0	59.6	62.7
	R	17.6	17.3	14.7	14.5	14.3	12.7	12.6	11.5
2	S	21.0	31.3	37.1	47.4	58.4	63.2	73.9	84.9
	R	21.0	20.7	18.0	17.7	17.5	15.7	15.5	15.2
3	S	26.8	40.0	46.9	53.6	66.2	79.3	92.6	106.5
	R	26.8	26.3	22.6	20.1	19.7	19.4	19.0	18.7
4	S	27.4	40.9	55.3	62.9	77.5	92.9	98.6	113.4
	R	27.4	27.0	26.5	23.3	22.9	22.5	20.3	19.9
5	S	31.7	47.3	64.0	72.4	89.3	107.0	113.0	130.0
	R	31.7	31.1	30.4	26.7	26.1	25.6	23.0	22.5
6	S	35.8	53.5	72.4	81.7	100.8	108.8	116.4	133.9
	R	35.8	35.1	34.3	29.9	29.2	26.1	23.8	23.3
8	S	43.3	65.0	77.2	88.6	109.3	119.4	128.8	148.2
	R	43.3	42.3	36.6	32.4	31.7	28.6	26.2	25.7
10	S	44.9	67.2	81.4	104.2	116.8	128.6	150.3	160.6
	R	44.9	43.9	38.6	37.8	33.9	30.8	30.1	27.6
12	S	51.1	68.3	83.7	107.2	132.3	145.4	157.4	169.3
	R	51.1	44.6	39.7	38.8	37.8	34.2	31.3	28.8
14	S	54.7	73.2	89.7	114.9	141.8	155.7	168.4	181.1
	R	54.7	47.7	42.3	41.3	40.2	36.2	33.1	30.5
16	S	60.3	80.9	99.1	116.3	143.5	172.0	185.8	199.7
	R	60.3	52.4	46.4	41.7	40.6	39.4	35.9	33.0
18	S	65.8	88.4	108.4	127.1	144.9	173.7	189.0	218.0
	R	65.8	57.0	50.4	45.2	41.0	39.9	36.6	35.4

Note: Energy Cost = $7.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-5.b

Economic Insulation Thickness (inch) for Hot Water Supply and Return Pipes for Energy Cost of $7/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
1	1.5	1.5	2.0	2.0	2.0	2.5	2.5	3.0
2	2.0	2.0	2.5	2.5	2.5	3.0	3.0	3.0
3	2.0	2.0	2.5	3.0	3.0	3.0	3.0	3.0
4	2.5	2.5	2.5	3.0	3.0	3.0	3.5	3.5
5	2.5	2.5	2.5	3.0	3.0	3.0	3.5	3.5
6	2.5	2.5	2.5	3.0	3.0	3.5	4.0	4.0
8	2.5	2.5	3.0	3.5	3.5	4.0	4.5	4.5
10	3.0	3.0	3.5	3.5	4.0	4.5	4.5	5.0
12	3.0	3.5	4.0	4.0	4.0	4.5	5.0	5.5
14	3.0	3.5	4.0	4.0	4.0	4.5	5.0	5.5
16	3.0	3.5	4.0	4.5	4.5	4.5	5.0	5.5
18	3.0	3.5	4.0	4.5	5.0	5.0	5.5	5.5

Note: Energy Cost = $7.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-6.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $8/M Btu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
1	S	17.6	22.4	30.2	34.5	42.5	51.0	59.6	62.7
	R	17.6	14.9	14.7	13.1	12.9	12.7	12.6	11.5
2	S	18.5	27.5	37.1	42.8	52.8	63.2	73.9	84.9
	R	18.5	18.3	18.0	16.1	15.9	15.7	15.5	15.2
3	S	23.3	34.8	42.0	53.6	66.2	79.3	92.6	106.5
	R	23.3	23.0	20.4	20.1	19.7	19.4	19.0	18.7
4	S	27.4	40.9	49.2	62.9	70.4	84.4	98.6	113.4
	R	27.4	27.0	23.7	23.3	21.0	20.7	20.3	19.9
5	S	31.7	47.3	56.6	72.4	80.7	96.7	113.0	119.4
	R	31.7	31.1	27.2	26.7	23.9	23.4	23.0	21.0
6	S	35.8	53.5	63.9	73.6	90.8	108.8	116.4	133.9
	R	35.8	35.1	30.5	27.2	26.7	26.1	23.8	23.3
8	S	43.3	57.1	69.3	80.8	99.6	119.4	128.8	148.2
	R	43.3	37.4	33.1	29.8	29.2	28.6	26.2	25.7
10	S	44.9	67.2	81.4	94.7	107.3	128.6	150.3	160.6
	R	44.9	43.9	38.6	34.7	31.4	30.8	30.1	27.6
12	S	51.1	68.3	83.7	107.2	121.3	134.7	157.4	169.3
	R	51.1	44.6	39.7	38.8	35.0	32.0	31.3	28.8
14	S	54.7	73.2	89.7	114.9	129.9	144.1	157.2	181.1
	R	54.7	47.7	42.3	41.3	37.2	33.9	31.3	30.5
16	S	53.8	73.1	90.8	116.3	132.6	159.0	173.2	199.7
	R	53.8	47.6	42.8	41.7	38.0	37.0	34.0	33.0
18	S	58.7	79.9	99.2	127.1	134.9	161.8	189.0	218.0
	R	58.7	51.8	46.5	45.2	38.6	37.6	36.6	35.4

Note: Energy Cost = $8.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-6.b

Economic Insulation Thickness (inch) for Hot Water Supply and Return Pipes for Energy Cost of $8/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
1	1.5	2.0	2.0	2.5	2.5	2.5	2.5	3.0
2	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.0
3	2.5	2.5	3.0	3.0	3.0	3.0	3.0	3.0
4	2.5	2.5	3.0	3.0	3.5	3.5	3.5	3.5
5	2.5	2.5	3.0	3.0	3.5	3.5	3.5	4.0
6	2.5	2.5	3.0	3.5	3.5	3.5	4.0	4.0
8	2.5	3.0	3.5	4.0	4.0	4.0	4.5	4.5
10	3.0	3.0	3.5	4.0	4.5	4.5	4.5	5.0
12	3.0	3.5	4.0	4.0	4.5	5.0	5.0	5.5
14	3.0	3.5	4.0	4.0	4.5	5.0	5.5	5.5
16	3.5	4.0	4.5	4.5	5.0	5.0	5.5	5.5
18	3.5	4.0	4.5	4.5	5.5	5.5	5.5	5.5

Note: Energy Cost = $8.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-7.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $9/M Btu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
1	S	17.6	22.4	30.2	34.5	42.5	46.7	54.6	62.7
	R	17.6	14.9	14.7	13.1	12.9	11.8	11.6	11.5
2	S	18.5	27.5	37.1	42.8	52.8	63.2	73.9	84.9
	R	18.5	18.3	18.0	16.1	15.9	15.7	15.5	15.2
3	S	23.3	34.8	42.0	53.6	66.2	79.3	84.6	97.2
	R	23.3	23.0	20.4	20.1	19.7	19.4	17.6	17.3
4	S	27.4	40.9	49.2	62.9	70.4	84.4	98.6	113.4
	R	27.4	27.0	23.7	23.3	21.0	20.7	20.3	19.9
5	S	31.7	47.3	56.6	72.4	80.7	96.7	103.8	119.4
	R	31.7	31.1	27.2	26.7	23.9	23.4	21.4	21.0
6	S	35.8	53.5	63.9	73.6	90.8	108.8	116.4	124.1
	R	35.8	35.1	30.5	27.2	26.7	26.1	23.8	21.9
8	S	43.3	57.1	69.3	80.8	99.6	110.2	128.8	138.1
	R	43.3	37.4	33.1	29.8	29.2	26.7	26.2	24.3
10	S	44.9	60.2	74.0	94.7	107.3	128.6	139.5	150.3
	R	44.9	39.5	35.4	34.7	31.4	30.8	28.2	26.1
12	S	51.1	68.3	83.7	98.3	112.4	134.7	147.1	169.3
	R	51.1	44.6	39.7	35.9	32.7	32.0	29.5	28.8
14	S	54.7	73.2	89.7	105.3	120.2	134.5	157.2	170.2
	R	54.7	47.7	42.3	38.2	34.8	32.0	31.3	29.0
16	S	53.8	73.1	90.8	116.3	132.6	148.2	173.2	187.4
	R	53.8	47.6	42.8	41.7	38.0	34.8	34.0	31.4
18	S	58.7	79.9	99.2	117.4	134.9	161.8	189.0	218.0
	R	58.7	51.8	46.5	42.2	38.6	37.6	36.6	35.4

Note: Energy Cost = $9.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-7.b

Economic Insulation Thickness (inch) for Hot Water Supply and Return Pipes for Energy Cost of $9/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
1	1.5	2.0	2.0	2.5	2.5	3.0	3.0	3.0
2	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.0
3	2.5	2.5	3.0	3.0	3.0	3.0	3.5	3.5
4	2.5	2.5	3.0	3.0	3.5	3.5	3.5	3.5
5	2.5	2.5	3.0	3.0	3.5	3.5	4.0	4.0
6	2.5	2.5	3.0	3.5	3.5	3.5	4.0	4.5
8	2.5	3.0	3.5	4.0	4.0	4.5	4.5	5.0
10	3.0	3.5	4.0	4.0	4.5	4.5	5.0	5.5
12	3.0	3.5	4.0	4.5	5.0	5.0	5.5	5.5
14	3.0	3.5	4.0	4.5	5.0	5.5	5.5	6.0
16	3.5	4.0	4.5	4.5	5.0	5.5	5.5	6.0
18	3.5	4.0	4.5	5.0	5.5	5.5	5.5	6.0

Note: Energy Cost = $9.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-8.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $10/M Btu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
1	S	17.6	22.4	27.0	34.5	39.0	46.7	54.6	62.7
	R	17.6	14.9	13.2	13.1	11.9	11.8	11.6	11.5
2	S	18.5	27.5	37.1	42.8	52.8	63.2	73.9	84.9
	R	18.5	18.3	18.0	16.1	15.9	15.7	15.5	15.2
3	S	23.3	34.8	42.0	53.6	66.2	79.3	84.6	97.2
	R	23.3	23.0	20.4	20.1	19.7	19.4	17.6	17.3
4	S	27.4	40.9	49.2	57.1	70.4	84.4	98.6	113.4
	R	27.4	27.0	23.7	21.4	21.0	20.7	20.3	19.9
5	S	31.7	47.3	56.6	65.4	80.7	88.8	103.8	119.4
	R	31.7	31.1	27.2	24.3	23.9	21.8	21.4	21.0
6	S	35.8	47.2	57.6	73.6	90.8	99.6	107.9	124.1
	R	35.8	31.1	27.7	27.2	26.7	24.2	22.3	21.9
8	S	38.2	51.2	63.2	74.6	92.0	110.2	120.1	138.1
	R	38.2	33.7	30.4	27.7	27.3	26.7	24.7	24.3
10	S	44.9	60.2	74.0	87.0	99.6	119.4	130.6	150.3
	R	44.9	39.5	35.4	32.1	29.4	28.8	26.6	26.1
12	S	45.6	61.9	76.8	98.3	112.4	125.8	147.1	159.3
	R	45.6	40.6	36.6	35.9	32.7	30.2	29.5	27.4
14	S	48.8	66.3	82.2	105.3	120.2	134.5	157.2	170.2
	R	48.8	43.3	39.0	38.2	34.8	32.0	31.3	29.0
16	S	53.8	73.1	90.8	116.3	132.6	148.2	162.6	187.4
	R	53.8	47.6	42.8	41.7	38.0	34.8	32.2	31.4
18	S	58.7	73.2	91.6	117.4	134.9	161.8	177.3	204.4
	R	58.7	47.7	43.2	42.2	38.6	37.6	34.7	33.7

Note: Energy Cost = $10.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-8.b

Economic Insulation Thickness (inch) for Hot Water Supply and Return Pipes for Energy Cost of $10/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
1	1.5	2.0	2.5	2.5	3.0	3.0	3.0	3.0
2	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.0
3	2.5	2.5	3.0	3.0	3.0	3.0	3.5	3.5
4	2.5	2.5	3.0	3.5	3.5	3.5	3.5	3.5
5	2.5	2.5	3.0	3.5	3.5	4.0	4.0	4.0
6	2.5	3.0	3.5	3.5	3.5	4.0	4.5	4.5
8	3.0	3.5	4.0	4.5	4.5	4.5	5.0	5.0
10	3.0	3.5	4.0	4.5	5.0	5.0	5.5	5.5
12	3.5	4.0	4.5	4.5	5.0	5.5	5.5	6.0
14	3.5	4.0	4.5	4.5	5.0	5.5	5.5	6.0
16	3.5	4.0	4.5	4.5	5.0	5.5	6.0	6.0
18	3.5	4.5	5.0	5.0	5.5	5.5	6.0	6.0

Note: Energy Cost = $10.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-9.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $11/M Btu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
1	S	15.1	22.4	27.0	34.5	39.0	46.7	54.6	62.7
	R	15.1	14.9	13.2	13.1	11.9	11.8	11.6	11.5
2	S	18.5	27.5	33.5	42.8	52.8	63.2	73.9	78.2
	R	18.5	18.3	16.4	16.1	15.9	15.7	15.5	14.2
3	S	23.3	34.8	42.0	53.6	66.2	79.3	84.6	97.2
	R	23.3	23.0	20.4	20.1	19.7	19.4	17.6	17.3
4	S	27.4	40.9	44.7	57.1	70.4	84.4	98.6	113.4
	R	27.4	27.0	21.7	21.4	21.0	20.7	20.3	19.9
5	S	31.7	41.9	51.2	65.4	74.1	88.8	103.8	119.4
	R	31.7	27.7	24.7	24.3	22.2	21.8	21.4	21.0
6	S	35.8	47.2	57.6	73.6	83.1	99.6	107.9	124.1
	R	35.8	31.1	27.7	27.2	24.7	24.2	22.3	21.9
8	S	38.2	51.2	63.2	74.6	92.0	102.7	120.1	129.6
	R	38.2	33.7	30.4	27.7	27.3	25.2	24.7	23.0
10	S	44.9	60.2	74.0	87.0	99.6	111.8	130.6	141.6
	R	44.9	39.5	35.4	32.1	29.4	27.1	26.6	24.8
12	S	45.6	61.9	76.8	91.1	105.0	125.8	138.4	159.3
	R	45.6	40.6	36.6	33.4	30.8	30.2	28.0	27.4
14	S	48.8	66.3	82.2	97.4	112.2	134.5	147.8	170.2
	R	48.8	43.3	39.0	35.6	32.7	32.0	29.7	29.0
16	S	48.7	67.0	84.0	107.5	123.7	139.2	162.6	187.4
	R	48.7	43.8	39.8	38.9	35.7	33.0	32.2	31.4
18	S	53.2	73.2	85.4	109.3	134.9	151.7	177.3	204.4
	R	53.2	47.7	40.5	39.6	38.6	35.6	34.7	33.7

Note: Energy Cost = $11.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-9.b

Economic Insulation Thickness (inch) for Hot Water Supply and Return Pipes for Energy Cost of $11/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
1	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.0
2	2.5	2.5	3.0	3.0	3.0	3.0	3.0	3.5
3	2.5	2.5	3.0	3.0	3.0	3.0	3.5	3.5
4	2.5	2.5	3.5	3.5	3.5	3.5	3.5	3.5
5	2.5	3.0	3.5	3.5	4.0	4.0	4.0	4.0
6	2.5	3.0	3.5	3.5	4.0	4.0	4.5	4.5
8	3.0	3.5	4.0	4.5	4.5	5.0	5.0	5.5
10	3.0	3.5	4.0	4.5	5.0	5.5	5.5	6.0
12	3.5	4.0	4.5	5.0	5.5	5.5	6.0	6.0
14	3.5	4.0	4.5	5.0	5.5	5.5	6.0	6.0
16	4.0	4.5	5.0	5.0	5.5	6.0	6.0	6.0
18	4.0	4.5	5.5	5.5	5.5	6.0	6.0	6.0

Note: Energy Cost = $11.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-10.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $12/M Btu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
1	S	15.1	20.1	27.0	31.6	39.0	46.7	54.6	62.7
	R	15.1	13.4	13.2	12.1	11.9	11.8	11.6	11.5
2	S	18.5	27.5	33.5	42.8	52.8	63.2	68.1	78.2
	R	18.5	18.3	16.4	16.1	15.9	15.7	14.4	14.2
3	S	23.3	31.1	42.0	53.6	66.2	72.4	84.6	90.1
	R	23.3	20.7	20.4	20.1	19.7	17.4	17.6	16.2
4	S	27.4	36.4	44.7	57.1	70.4	84.4	98.6	104.5
	R	27.4	24.1	21.7	21.4	21.0	20.7	20.3	18.6
5	S	31.7	41.9	51.2	65.4	74.1	88.8	103.8	119.4
	R	31.7	27.7	24.7	24.3	22.2	21.8	21.4	21.0
6	S	35.8	47.2	57.6	67.4	83.1	92.3	107.9	116.0
	R	35.8	31.1	27.7	25.1	24.7	22.7	22.3	20.7
8	S	38.2	51.2	63.2	74.6	92.0	102.7	120.1	129.6
	R	38.2	33.7	30.4	27.7	27.3	25.2	24.7	23.0
10	S	40.3	54.8	68.0	80.8	99.6	111.8	130.6	141.6
	R	40.3	36.1	32.7	29.9	29.4	27.1	26.6	24.8
12	S	41.1	56.8	71.2	91.1	105.0	118.4	138.4	159.3
	R	41.1	37.3	34.1	33.4	30.8	28.6	28.0	27.4
14	S	44.2	60.8	76.1	97.4	112.2	126.4	147.8	170.2
	R	44.2	39.9	36.3	35.6	32.7	30.3	29.7	29.0
16	S	48.7	67.0	84.0	100.2	123.7	139.2	162.6	187.4
	R	48.7	43.8	39.8	36.5	35.7	33.0	32.2	31.4
18	S	53.2	67.7	85.4	109.3	134.9	151.7	177.3	204.4
	R	53.2	44.2	40.5	39.6	38.6	35.6	34.7	33.7

Note: Energy Cost = $12.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-10.b

Economic Insulation Thickness (inch) for Hot Water Supply and Return Pipes for Energy Cost of $12/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
1	2.0	2.5	2.5	3.0	3.0	3.0	3.0	3.0
2	2.5	2.5	3.0	3.0	3.0	3.0	3.5	3.5
3	2.5	3.0	3.0	3.0	3.0	3.5	3.5	4.0
4	2.5	3.0	3.5	3.5	3.5	3.5	3.5	4.0
5	2.5	3.0	3.5	3.5	4.0	4.0	4.0	4.0
6	2.5	3.0	3.5	4.0	4.0	4.5	4.5	5.0
8	3.0	3.5	4.0	4.5	4.5	5.0	5.0	5.5
10	3.5	4.0	4.5	5.0	5.0	5.5	5.5	6.0
12	4.0	4.5	5.0	5.0	5.5	6.0	6.0	6.0
14	4.0	4.5	5.0	5.0	5.5	6.0	6.0	6.0
16	4.0	4.5	5.0	5.5	5.5	6.0	6.0	6.0
18	4.5	5.0	5.5	5.5	5.5	6.0	6.0	6.0

Note: Energy Cost = $12.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-11.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $13/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
1	S	15.1	20.1	24.8	31.6	39.0	46.7	54.6	62.7
	R	15.1	13.4	12.2	12.1	11.9	11.8	11.6	11.5
2	S	18.5	24.9	33.5	42.8	52.8	58.2	68.1	78.2
	R	18.5	16.6	16.4	16.1	15.9	14.6	14.4	14.2
3	S	20.9	31.1	42.0	53.6	66.2	72.4	84.6	90.1
	R	20.9	20.7	20.4	20.1	19.7	17.9	17.6	16.2
4	S	24.5	36.4	44.7	57.1	70.4	84.4	98.6	104.5
	R	24.5	24.1	21.7	21.4	21.0	20.7	20.3	18.6
5	S	28.1	41.9	51.2	60.1	74.1	88.8	103.8	119.4
	R	28.1	27.7	24.7	22.5	22.2	21.8	21.4	21.0
6	S	31.7	42.6	57.6	67.4	77.1	92.3	107.9	116.0
	R	31.7	28.2	27.7	25.1	23.1	22.7	22.3	20.7
8	S	38.2	51.2	63.2	74.6	85.7	102.7	112.7	129.6
	R	38.2	33.7	30.4	27.7	25.6	25.2	23.4	23.0
10	S	40.3	54.8	68.0	80.8	93.3	111.8	123.1	141.6
	R	40.3	36.1	32.7	29.9	27.6	27.1	25.3	24.8
12	S	41.4	56.8	71.2	85.1	105.0	118.4	138.4	159.3
	R	41.4	37.3	34.1	31.4	30.8	28.6	28.0	27.4
14	S	44.2	60.8	76.1	91.0	105.5	126.4	147.8	170.2
	R	44.2	39.9	36.3	33.4	30.9	30.3	29.7	29.0
16	S	44.7	62.0	78.3	100.2	116.1	139.2	162.6	187.4
	R	44.7	40.7	37.3	36.5	33.8	33.0	32.2	31.4
18	S	48.8	67.7	85.4	109.3	126.6	151.7	177.3	204.4
	R	48.8	44.2	40.5	39.6	36.5	35.6	34.7	33.7

Note: Energy Cost = $13.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-11.b

Economic Insulation Thickness (inch) for Hot Water Supply and Return Pipes for Energy Cost of $13/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
1	2.0	2.5	3.0	3.0	3.0	3.0	3.0	3.0
2	2.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5
3	3.0	3.0	3.0	3.0	3.0	3.5	3.5	4.0
4	3.0	3.0	3.5	3.5	3.5	3.5	3.5	4.0
5	3.0	3.0	3.5	4.0	4.0	4.0	4.0	4.0
6	3.0	3.5	3.5	4.0	4.5	4.5	4.5	5.0
8	3.0	3.5	4.0	4.5	5.0	5.0	5.5	5.5
10	3.5	4.0	4.5	5.0	5.5	5.5	6.0	6.0
12	4.0	4.5	5.0	5.5	5.5	6.0	6.0	6.0
14	4.0	4.5	5.0	5.5	6.0	6.0	6.0	6.0
16	4.5	5.0	5.5	5.5	6.0	6.0	6.0	6.0
18	4.5	5.0	5.5	5.5	6.0	6.0	6.0	6.0

Note: Energy Cost = $13.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-12.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $14/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
1	S	15.1	20.1	24.8	31.6	39.0	46.7	54.6	62.7
	R	15.1	13.4	12.2	12.1	11.9	11.8	11.6	11.5
2	S	18.5	24.9	33.5	42.8	52.8	58.2	68.1	78.2
	R	18.5	16.6	16.4	16.1	15.9	14.6	14.4	14.2
3	S	20.9	31.1	42.0	53.6	60.4	67.1	78.4	90.1
	R	20.9	20.7	20.4	20.1	18.2	16.7	16.5	16.2
4	S	24.5	36.4	44.7	57.1	70.4	77.8	90.9	104.5
	R	24.5	24.1	21.7	21.4	21.0	19.2	18.9	18.6
5	S	28.1	41.9	51.2	60.1	74.1	88.8	103.8	119.4
	R	28.1	27.7	24.7	22.5	22.2	21.8	21.4	21.0
6	S	31.7	42.6	52.7	62.5	77.1	92.3	107.9	116.0
	R	31.7	28.2	25.5	23.4	23.1	22.7	22.3	20.7
8	S	34.3	46.8	58.3	69.5	85.7	96.4	112.7	122.4
	R	34.3	30.9	28.2	26.0	25.6	23.8	23.4	21.8
10	S	36.7	50.4	63.2	75.6	93.3	105.3	123.1	141.6
	R	36.7	33.2	30.4	28.1	27.6	25.7	25.3	24.8
12	S	38.0	52.7	66.5	85.1	98.8	118.4	138.4	159.3
	R	38.0	34.7	32.0	31.4	29.1	28.6	28.0	27.4
14	S	40.6	56.3	71.1	91.0	105.5	126.4	147.8	170.2
	R	40.6	37.0	34.1	33.4	30.9	30.3	29.7	29.0
16	S	44.7	62.0	78.3	94.1	116.1	139.2	162.6	187.4
	R	44.7	40.7	37.3	34.5	33.8	33.0	32.2	31.4
18	S	48.8	67.7	85.4	102.6	126.6	151.7	177.3	204.4
	R	48.8	44.2	40.5	37.3	36.5	35.6	34.7	33.7

Note: Energy Cost = $14.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-12.b

Economic Insulation Thickness (inch) for Hot Water Supply and Return Pipes for Energy Cost of $14/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
1	2.0	2.5	3.0	3.0	3.0	3.0	3.0	3.0
2	2.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5
3	3.0	3.0	3.0	3.0	3.5	4.0	4.0	4.0
4	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0
5	3.0	3.0	3.5	4.0	4.0	4.0	4.0	4.0
6	3.0	3.5	4.0	4.5	4.5	4.5	4.5	5.0
8	3.5	4.0	4.5	5.0	5.0	5.5	5.5	6.0
10	4.0	4.5	5.0	5.5	5.5	6.0	6.0	6.0
12	4.5	5.0	5.5	5.5	6.0	6.0	6.0	6.0
14	4.5	5.0	5.5	5.5	6.0	6.0	6.0	6.0
16	4.5	5.0	5.5	6.0	6.0	6.0	6.0	6.0
18	4.5	5.0	5.5	6.0	6.0	6.0	6.0	6.0

Note: Energy Cost = $14.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-13.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $15/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F)							
		150	200	250	300	350	400	450	500
1	S	13.5	20.1	24.8	31.6	39.0	46.7	54.6	62.7
	R	13.5	13.4	12.2	12.1	11.9	11.8	11.6	11.5
2	S	18.5	24.9	33.5	42.8	48.6	58.2	68.1	78.2
	R	18.5	16.6	16.4	16.1	14.8	14.6	14.4	14.2
3	S	20.9	31.1	42.0	53.6	60.4	67.1	78.4	90.1
	R	20.9	20.7	20.4	20.1	18.2	16.7	16.5	16.2
4	S	24.5	36.4	44.7	57.1	70.4	77.8	90.9	104.5
	R	24.5	24.1	21.7	21.4	21.0	19.2	18.9	18.6
5	S	28.1	41.9	51.2	60.1	74.1	88.8	103.8	119.4
	R	28.1	27.7	24.7	22.5	22.2	21.8	21.4	21.0
6	S	31.7	42.6	52.7	62.5	77.1	92.3	107.9	116.0
	R	31.7	28.2	25.5	23.4	23.1	22.7	22.3	20.7
8	S	34.3	46.8	58.3	69.5	85.7	96.4	112.7	122.4
	R	34.3	30.9	28.2	26.0	25.6	23.8	23.4	21.8
10	S	36.7	50.4	63.2	75.6	93.3	105.3	123.1	141.6
	R	36.7	33.2	30.4	28.1	27.6	25.7	25.3	24.8
12	S	38.0	52.7	66.5	85.1	98.8	118.4	138.4	159.3
	R	38.0	34.7	32.0	31.4	29.1	28.6	28.0	27.4
14	S	40.6	56.3	71.1	91.0	105.5	126.4	147.8	170.2
	R	40.6	37.0	34.1	33.4	30.9	30.3	29.7	29.0
16	S	44.7	62.0	78.3	94.1	116.1	139.2	162.6	187.4
	R	44.7	40.7	37.3	34.5	33.8	33.0	32.2	31.4
18	S	48.8	67.7	85.4	102.6	126.6	151.7	177.3	204.4
	R	48.8	44.2	40.5	37.3	36.5	35.6	34.7	33.7

Note: Energy Cost = $15.00/MBtu
Return Pipe Temperature = 150 F

TABLE A-13.b

Economic Insulation Thickness (inch) for Hot Water Supply and Return Pipes for Energy Cost of $15/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
1	2.5	2.5	3.0	3.0	3.0	3.0	3.0	3.0
2	2.5	3.0	3.0	3.0	3.5	3.5	3.5	3.5
3	3.0	3.0	3.0	3.0	3.5	4.0	4.0	4.0
4	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0
5	3.0	3.0	3.5	4.0	4.0	4.0	4.0	4.0
6	3.0	3.5	4.0	4.5	4.5	4.5	4.5	5.0
8	3.5	4.0	4.5	5.0	5.0	5.5	5.5	6.0
10	4.0	4.5	5.0	5.5	5.5	6.0	6.0	6.0
12	4.5	5.0	5.5	5.5	6.0	6.0	6.0	6.0
14	4.5	5.0	5.5	5.5	6.0	6.0	6.0	6.0
16	4.5	5.0	5.5	6.0	6.0	6.0	6.0	6.0
18	4.5	5.0	5.5	6.0	6.0	6.0	6.0	6.0

Note: Energy Cost = $15.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-1.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $3/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
2	S	25.3	37.6	50.7	31.6	64.8	95.7	93.4	107.4
1	R	17.4	17.1	16.7	16.4	16.0	15.6	13.4	13.1
3	S	32.8	48.8	65.9	84.3	85.6	102.5	119.8	137.9
1.5	R	21.5	21.0	20.4	19.8	16.7	16.3	15.9	15.4
4	S	39.1	58.4	79.0	101.0	101.7	104.8	122.4	141.0
2	R	24.5	23.9	23.1	22.4	18.7	16.4	16.0	15.6
5	S	45.7	68.3	92.4	96.1	118.5	121.4	141.8	163.3
2.5	R	27.6	26.8	25.8	21.4	20.7	18.1	17.6	17.0
6	S	52.1	78.0	105.6	109.4	134.8	137.6	160.7	185.2
3	R	31.5	30.4	29.2	24.0	23.1	20.1	19.4	18.7
8	S	63.7	95.8	104.6	133.9	139.8	167.5	195.6	225.7
4	R	37.3	35.7	28.9	27.8	23.8	23.0	22.1	21.1
10	S	75.2	113.6	124.1	134.3	165.6	198.4	201.2	233.3
6	R	49.5	47.2	37.8	31.9	30.7	29.4	25.9	24.9
12	S	86.7	130.8	142.6	153.9	189.8	227.4	231.1	266.8
6	R	48.9	46.3	37.0	31.2	29.8	28.4	25.1	23.9
14	S	92.7	113.1	153.5	165.7	204.4	245.0	248.8	254.9
8	R	60.0	47.3	45.1	37.8	36.1	34.3	30.1	26.8
16	S	104.6	126.5	171.6	185.0	197.4	236.6	245.0	282.8
8	R	59.6	46.6	44.2	37.0	31.8	30.3	26.8	25.5
18	S	113.5	138.3	157.7	202.3	216.1	259.0	268.2	309.8
10	R	70.4	54.7	45.1	42.7	36.6	34.7	30.6	29.0

Note: Energy Cost = $3.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-1.b

Economic Insulation Thickness (inch) for Steam Supply and Return Pipes for Energy Cost of $3/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
2 & 1	1.5	1.5	1.5	1.5	1.5	1.5	2.0	2.0
3 & 1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0
4 & 2	1.5	1.5	1.5	1.5	2.0	2.5	2.5	2.5
5 & 2.5	1.5	1.5	1.5	1.5	2.0	2.0	2.5	2.5
6 & 3	1.5	1.5	1.5	2.0	2.0	2.5	2.5	2.5
8 & 4	1.5	1.5	2.0	2.0	2.5	2.5	2.5	2.5
10 & 6	1.5	1.5	2.0	2.5	2.5	2.5	3.0	3.0
12 & 6	1.5	1.5	2.0	2.5	2.5	2.5	3.0	3.0
14 & 8	1.5	2.0	2.0	2.5	2.5	2.5	3.0	3.5
16 & 8	1.5	2.0	2.0	1.5	3.0	3.0	3.5	3.5
18 & 10	1.5	2.0	2.5	2.5	3.0	3.0	3.5	3.5

Note: Energy Cost = $3.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-2.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $4/MBtu

Pipe Size (inch)	Pipe Type	150	200	250	300	350	400	450	500
		Process Fluid Temperature (F)							
2	S	25.3	37.6	50.7	64.8	66.7	79.9	81.9	94.1
1	R	17.4	17.1	16.7	16.4	14.0	13.7	12.2	12.0
3	S	32.8	48.8	65.9	69.4	85.6	88.8	103.8	119.4
1.5	R	21.5	21.0	20.4	17.1	16.7	14.8	14.4	14.1
4	S	39.1	58.4	79.0	82.5	87.5	104.8	122.4	141.0
2	R	24.5	23.9	23.1	19.3	16.9	16.4	16.0	15.6
5	S	45.7	68.3	75.1	96.1	101.3	121.4	141.8	144.2
2.5	R	27.6	26.8	22.1	21.4	18.6	18.1	17.6	15.8
6	S	52.1	78.0	85.5	109.4	114.9	137.6	141.5	162.9
3	R	31.5	30.4	24.8	24.0	20.7	20.1	18.0	17.4
8	S	63.7	77.3	104.6	113.4	139.8	146.7	171.3	197.4
4	R	37.3	30.0	28.9	24.7	23.8	21.1	20.4	19.7
10	S	75.2	91.6	104.9	134.3	144.5	173.1	180.5	208.1
6	R	49.5	39.3	33.0	31.9	27.8	26.9	24.1	23.3
12	S	86.7	105.2	120.2	153.9	165.2	197.9	205.8	237.3
6	R	48.9	38.7	32.5	31.2	27.2	26.2	23.5	22.6
14	S	92.7	113.1	129.4	165.7	177.7	213.0	220.9	230.1
8	R	60.0	47.3	39.4	37.8	32.8	31.5	27.9	25.1
16	S	104.3	126.5	144.4	160.1	175.0	209.7	245.0	254.9
8	R	59.6	46.6	38.8	33.3	29.2	28.0	26.8	24.1
18	S	91.5	116.3	136.7	175.2	191.5	229.5	241.7	279.0
10	R	57.6	47.2	40.2	38.5	33.7	32.2	28.8	27.4

Note: Energy Cost = $4.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-2.b

Economic Insulation Thickness (inch) for Steam Supply and Return Pipes for Energy Cost of $4/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
2 & 1	1.5	1.5	1.5	1.5	2.0	2.0	2.5	2.5
3 & 1.5	1.5	1.5	1.5	2.0	2.0	2.5	2.5	2.5
4 & 2	1.5	1.5	1.5	2.0	2.5	2.5	2.5	2.5
5 & 2.5	1.5	1.5	2.0	2.0	2.5	2.5	2.5	3.0
6 & 3	1.5	1.5	2.0	2.0	2.5	2.5	3.0	3.0
8 & 4	1.5	2.0	2.0	2.5	2.5	3.0	3.0	3.0
10 & 6	1.5	2.0	2.5	2.5	3.0	3.0	3.5	3.5
12 & 6	1.5	2.0	2.5	2.5	3.0	3.0	3.5	3.5
14 & 8	1.5	2.0	2.5	2.5	3.0	3.0	3.5	4.0
16 & 8	1.5	2.0	2.5	3.0	3.5	3.5	3.5	4.0
18 & 10	2.0	2.5	3.0	3.0	3.5	3.5	4.0	4.0

Note: Energy Cost = $4.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-3.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $5/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
2	S	25.3	37.6	50.7	54.1	58.5	70.1	81.9	94.1
1	R	17.4	17.1	16.7	14.3	12.7	12.5	12.2	12.0
3	S	32.8	48.8	54.3	69.4	74.1	79.4	92.8	106.4
1.5	R	21.5	21.0	17.5	17.1	15.1	13.6	13.4	13.1
4	S	39.1	58.4	64.5	71.0	87.5	93.1	108.8	125.1
2	R	24.5	23.9	19.8	17.2	16.9	15.2	14.8	14.5
5	S	45.7	55.6	75.1	82.2	101.3	107.3	125.3	144.2
2.5	R	27.6	22.7	22.1	19.1	18.6	16.6	16.2	15.8
6	S	52.1	63.2	85.5	93.2	114.9	121.1	141.5	162.9
3	R	31.5	25.6	24.8	21.4	20.7	18.5	18.0	17.4
8	S	51.7	77.3	88.7	113.4	122.4	146.7	153.5	176.8
4	R	31.0	30.0	25.5	24.7	21.8	21.1	19.1	18.5
10	S	61.0	77.5	104.9	117.2	144.5	154.6	180.5	208.1
6	R	40.8	34.1	33.0	28.7	27.8	24.9	24.1	23.3
12	S	70.1	88.9	120.2	134.0	147.1	176.2	205.8	214.7
6	R	40.4	33.7	32.5	28.2	25.1	24.3	23.5	21.3
14	S	75.1	95.5	129.4	144.1	157.9	189.2	199.5	210.5
8	R	49.3	40.9	39.4	34.1	30.0	29.0	26.0	23.7
16	S	84.0	106.6	125.1	141.9	175.0	189.2	220.9	232.9
8	R	48.9	40.5	34.6	30.4	29.2	26.2	25.2	22.9
18	S	77.2	100.9	136.7	155.3	191.5	206.9	220.8	254.8
10	R	49.2	41.8	40.2	35.1	33.7	30.0	27.2	26.1

Note: Energy Cost = $5.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-3.b

Economic Insulation Thickness (inch) for Steam Supply and Return Pipes for Energy Cost of $5/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
2 & 1	1.5	1.5	1.5	2.0	2.5	2.5	2.5	2.5
3 & 1.5	1.5	1.5	2.0	2.0	2.5	3.0	3.0	3.0
4 & 2	1.5	1.5	2.0	2.5	2.5	3.0	3.0	3.0
5 & 2.5	1.5	2.0	2.0	2.5	2.5	3.0	3.0	3.0
6 & 3	1.5	2.0	2.0	2.5	2.5	3.0	3.0	3.0
8 & 4	2.0	2.0	2.5	2.5	3.0	3.0	3.5	3.5
10 & 6	2.0	2.5	2.5	3.0	3.0	3.5	3.5	3.5
12 & 6	2.0	2.5	2.5	3.0	3.5	3.5	3.5	4.0
14 & 8	2.0	2.5	2.5	3.0	3.5	3.5	4.0	4.5
16 & 8	2.0	2.5	3.0	3.5	3.5	4.0	4.0	4.5
18 & 10	2.5	3.0	3.0	3.5	3.5	4.0	4.5	4.5

Note: Energy Cost = $5.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-4.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $6/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F)							
		150	200	250	300	350	400	450	500
2	S	25.3	37.6	42.4	54.1	58.5	70.1	81.9	85.0
1	R	17.4	17.1	14.5	14.3	12.7	12.5	12.2	11.2
3	S	32.8	40.3	54.3	60.1	74.1	79.4	92.8	106.4
1.5	R	21.5	17.9	17.5	15.4	15.1	13.6	13.4	13.1
4	S	39.1	47.8	55.5	71.0	87.5	93.1	108.8	125.1
2	R	24.5	20.3	17.6	17.2	16.9	15.2	14.8	14.5
5	S	37.3	55.6	64.3	82.2	89.5	107.3	125.3	144.2
2.5	R	23.2	22.7	19.6	19.1	17.0	16.6	16.2	15.8
6	S	42.4	63.2	72.9	93.2	101.1	121.1	141.5	146.6
3	R	26.3	25.6	21.9	21.4	19.0	18.5	18.0	16.4
8	S	51.7	65.6	88.7	99.3	109.7	131.4	153.5	160.9
4	R	31.0	26.2	25.5	22.4	20.1	19.6	19.1	17.5
10	S	61.0	77.5	91.6	117.2	129.0	154.6	163.9	188.8
6	R	40.8	34.1	29.6	28.7	25.6	24.9	22.6	22.0
12	S	70.1	88.9	104.7	119.3	147.1	159.5	186.4	196.6
6	R	40.4	33.7	29.2	25.9	25.1	22.8	22.1	20.1
14	S	75.1	95.5	112.6	128.0	157.9	170.8	182.7	194.7
8	R	49.3	40.9	35.3	31.0	30.0	26.9	24.5	22.5
16	S	84.0	106.6	110.9	141.9	157.9	172.9	202.0	215.1
8	R	48.9	40.5	31.4	30.4	27.1	24.6	23.8	21.8
18	S	77.2	100.9	121.2	155.3	172.7	189.0	220.8	235.0
10	R	49.2	41.8	40.2	35.1	33.7	30.0	27.2	26.1

Note: Energy Cost = $6.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-4.b

Economic Insulation Thickness (inch) for Steam Supply and Return Pipes for Energy Cost of $6/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
2 & 1	1.5	1.5	2.0	2.0	2.5	2.5	2.5	3.0
3 & 1.5	1.5	2.0	2.0	2.5	2.5	3.0	3.0	3.0
4 & 2	1.5	2.0	2.5	2.5	2.5	3.0	3.0	3.0
5 & 2.5	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.0
6 & 3	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.5
8 & 4	2.0	2.5	2.5	3.0	3.5	3.5	3.5	4.0
10 & 6	2.0	2.5	3.0	3.0	3.5	3.5	4.0	4.0
12 & 6	2.0	2.5	3.0	3.5	3.5	4.0	4.0	4.5
14 & 8	2.0	2.5	3.0	3.5	3.5	4.0	4.5	5.0
16 & 8	2.0	2.5	3.5	3.5	4.0	4.5	4.5	5.0
18 & 10	2.5	3.0	3.5	3.5	4.0	4.5	4.5	5.0

Note: Energy Cost = $6.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-5.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $7/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
2	S	25.3	31.5	42.4	47.4	58.5	70.1	74.0	85.0
1	R	17.4	14.8	14.5	12.9	12.7	12.5	11.4	11.2
3	S	32.8	40.3	47.1	60.1	66.3	79.4	92.8	106.6
1.5	R	21.5	17.9	15.7	15.4	13.9	13.6	13.4	13.1
4	S	39.1	47.8	55.5	71.0	77.7	93.1	108.8	113.5
2	R	24.5	20.3	17.6	17.2	15.5	15.2	14.8	13.6
5	S	37.3	47.6	64.3	72.6	89.5	107.3	125.3	130.2
2.5	R	23.2	20.0	19.6	17.4	17.0	16.6	16.2	14.9
6	S	42.4	54.0	72.9	82.0	101.1	121.1	127.4	146.6
3	R	26.3	22.5	21.9	19.4	19.0	18.5	16.8	16.4
8	S	44.0	65.6	88.7	99.3	109.7	131.4	139.9	160.9
4	R	26.9	26.2	25.5	22.4	20.1	19.6	18.0	17.5
10	S	51.8	67.7	91.6	104.6	129.0	140.3	163.9	173.6
6	R	35.1	30.4	29.6	26.3	25.6	23.2	22.6	20.8
12	S	59.4	77.5	104.7	119.3	133.2	146.1	170.7	182.0
6	R	34.8	30.1	29.2	25.9	23.4	21.4	20.8	19.1
14	S	63.7	83.2	100.0	128.0	142.6	156.4	169.0	181.6
8	R	42.4	36.4	32.0	31.0	27.8	25.2	23.1	21.4
16	S	71.1	92.4	110.9	128.0	144.3	172.9	186.6	200.3
8	R	42.0	35.9	31.4	28.1	25.4	24.6	22.6	20.9
18	S	67.2	89.5	121.2	140.0	157.7	189.0	203.8	218.7
10	R	43.3	37.8	36.5	32.4	29.2	28.2	25.8	23.8

Note: Energy Cost = $7.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-5.b

Economic Insulation Thickness (inch) for Steam Supply and Return Pipes for Energy Cost of $7/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
2 & 1	1.5	2.0	2.0	2.5	2.5	2.5	3.0	3.0
3 & 1.5	1.5	2.0	2.5	2.5	3.0	3.0	3.0	3.0
4 & 2	1.5	2.0	2.5	2.5	3.0	3.0	3.0	3.5
5 & 2.5	2.0	2.5	2.5	3.0	3.0	3.0	3.0	3.5
6 & 3	2.0	2.5	2.5	3.0	3.0	3.0	3.5	3.5
8 & 4	2.5	2.5	2.5	3.0	3.5	3.5	4.0	4.0
10 & 6	2.5	3.0	3.0	3.5	3.5	4.0	4.0	4.5
12 & 6	2.5	3.0	3.0	3.5	4.0	4.5	4.5	5.0
14 & 8	2.5	3.0	3.5	3.5	4.0	4.5	5.0	5.5
16 & 8	2.5	3.0	3.5	4.0	4.5	4.5	5.0	5.5
18 & 10	3.0	3.5	3.5	4.0	4.5	4.5	5.0	5.5

Note: Energy Cost = $7.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-6.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $8/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
2	S	25.3	31.5	37.2	47.4	58.5	63.3	74.0	85.0
1	R	17.4	14.8	13.1	12.9	12.7	11.6	11.4	11.2
3	S	27.1	40.3	47.1	60.1	66.3	79.4	92.8	106.6
1.5	R	18.2	17.9	15.7	15.4	13.9	13.6	13.4	13.1
4	S	32.1	41.2	55.5	71.0	77.7	93.1	98.7	113.5
2	R	20.7	18.0	17.6	17.2	15.5	15.2	13.9	13.6
5	S	37.3	47.6	64.3	72.6	89.5	107.3	113.2	130.2
2.5	R	23.2	20.0	19.6	17.4	17.0	16.6	15.2	14.9
6	S	42.4	54.0	64.2	82.0	101.1	109.0	127.4	134.1
3	R	26.3	22.5	19.9	19.4	19.0	17.2	16.8	15.5
8	S	44.0	65.6	77.7	89.0	109.7	119.7	139.9	148.4
4	R	26.9	26.2	23.0	20.6	20.1	18.4	18.0	16.7
10	S	51.8	67.7	81.8	104.6	117.1	140.3	150.8	173.6
6	R	35.1	30.4	27.0	26.3	23.8	23.2	21.4	20.8
12	S	59.4	77.5	93.3	108.0	122.0	146.1	158.1	182.0
6	R	34.8	30.1	26.7	24.1	21.9	21.4	19.7	19.1
14	S	63.7	83.2	100.0	115.6	130.5	156.4	169.0	181.6
8	R	42.4	36.4	32.0	28.6	25.9	25.2	23.1	21.4
16	S	61.7	82.0	110.1	117.1	144.3	172.9	186.6	200.3
8	R	37.0	32.4	28.9	26.2	25.4	24.6	22.6	20.9
18	S	67.2	89.5	109.4	127.9	157.7	174.5	189.7	218.7
10	R	43.3	37.8	33.5	30.2	29.2	26.7	24.6	23.8

Note: Energy Cost = $8.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-6.b

Economic Insulation Thickness (inch) for Steam Supply and Return Pipes for Energy Cost of $8/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
2 & 1	1.5	2.0	2.5	2.5	2.5	3.0	3.0	3.0
3 & 1.5	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.0
4 & 2	2.0	2.5	2.5	2.5	3.0	3.0	3.5	3.5
5 & 2.5	2.0	2.5	2.5	3.0	3.0	3.0	3.5	3.5
6 & 3	2.0	2.5	3.0	3.0	3.0	3.5	3.5	4.0
8 & 4	2.5	2.5	3.0	3.5	3.5	4.0	4.0	4.5
10 & 6	2.5	3.0	3.5	3.5	4.0	4.0	4.5	4.5
12 & 6	2.5	3.0	3.5	4.0	4.5	4.5	5.0	5.0
14 & 8	2.5	3.0	3.5	4.0	4.5	4.5	5.0	5.5
16 & 8	3.0	3.5	4.0	4.5	4.5	4.5	5.0	5.5
18 & 10	3.0	3.5	4.0	4.5	4.5	5.0	5.5	5.5

Note: Energy Cost = $8.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-7.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $9/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F)							
		150	200	250	300	350	400	450	500
2	S	21.2	27.6	37.2	47.4	58.5	63.3	74.0	85.0
1	R	15.0	13.3	13.1	12.9	12.7	11.6	11.4	11.2
3	S	27.1	34.9	47.1	53.8	66.3	79.4	92.8	97.3
1.5	R	18.2	15.9	15.7	14.1	13.9	13.6	13.4	12.3
4	S	32.1	41.2	55.5	63.0	77.7	84.5	98.7	113.5
2	R	20.7	18.0	17.6	15.8	15.5	14.2	13.9	13.6
5	S	37.3	47.6	56.9	72.6	89.5	96.9	113.2	119.5
2.5	R	23.2	20.0	17.8	17.4	17.0	15.5	15.2	14.1
6	S	36.2	54.0	64.2	82.0	91.0	109.0	116.6	124.2
3	R	23.0	22.5	19.9	19.4	17.6	17.2	15.8	14.7
8	S	38.6	57.5	77.7	89.0	109.7	119.7	129.1	138.3
4	R	24.1	23.5	23.0	20.6	20.1	18.4	17.0	15.9
10	S	45.4	60.6	81.8	104.6	117.1	129.1	150.8	161.0
6	R	31.2	27.6	27.0	26.3	23.8	21.9	21.4	19.7
12	S	51.9	69.1	93.3	108.0	122.0	135.3	158.1	169.9
6	R	30.9	27.4	26.7	24.1	21.9	20.2	19.7	18.3
14	S	55.6	74.0	90.4	105.8	130.5	144.7	157.7	181.6
8	R	37.4	32.9	29.4	26.6	25.9	23.8	22.0	21.4
16	S	61.7	82.0	100.1	117.1	144.3	159.8	173.9	200.3
8	R	37.0	32.4	28.9	26.2	25.4	23.3	21.5	20.9
18	S	59.8	89.5	109.4	127.9	157.7	174.5	189.7	205.0
10	R	39.0	37.8	33.5	30.2	29.2	26.7	24.6	22.8

Note: Energy Cost = $9.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-7.b

Economic Insulation Thickness (inch) for Steam Supply and Return Pipes for Energy Cost of $9/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
2 & 1	2.0	2.5	2.5	2.5	2.5	3.0	3.0	3.0
3 & 1.5	2.0	2.5	2.5	3.0	3.0	3.0	3.0	3.5
4 & 2	2.0	2.5	2.5	3.0	3.0	3.5	3.5	3.5
5 & 2.5	2.0	2.5	3.0	3.0	3.0	3.5	3.5	4.0
6 & 3	2.5	2.5	3.0	3.0	3.5	3.5	4.0	4.5
8 & 4	3.0	3.0	3.0	3.5	3.5	4.0	4.5	5.0
10 & 6	3.0	3.5	3.5	3.5	4.0	4.5	4.5	5.0
12 & 6	3.0	3.5	3.5	4.0	4.5	5.0	5.0	5.5
14 & 8	3.0	3.5	4.0	4.5	4.5	5.0	5.5	5.5
16 & 8	3.0	3.5	4.0	4.5	4.5	5.0	5.5	5.5
18 & 10	3.5	3.5	4.0	4.5	4.5	5.0	5.5	6.0

Note: Energy Cost = $9.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-8.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $10/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
2	S	21.2	27.6	37.2	47.4	52.8	63.3	74.0	78.2
1	R	15.0	13.3	13.1	12.9	11.7	11.6	11.4	10.6
3	S	27.1	34.9	47.1	53.8	66.3	79.4	84.7	97.3
1.5	R	18.2	15.9	15.7	14.1	13.9	13.6	12.6	12.3
4	S	27.7	41.2	55.5	63.0	77.7	84.5	98.7	113.5
2	R	18.3	18.0	17.6	15.8	15.5	14.2	13.9	13.6
5	S	32.0	47.6	56.9	72.6	89.5	96.9	113.2	119.5
2.5	R	20.4	20.0	17.8	17.4	17.0	15.5	15.2	14.1
6	S	36.2	54.0	64.2	82.0	91.0	109.0	116.6	124.2
3	R	23.0	22.5	19.9	19.4	17.6	17.2	15.8	14.7
8	S	38.6	57.5	69.6	89.0	99.9	110.5	129.1	138.3
4	R	24.1	23.5	21.1	20.6	18.8	17.4	17.0	15.9
10	S	45.4	60.6	81.8	95.0	107.8	129.1	140.0	150.6
6	R	31.2	27.6	27.0	24.4	22.4	21.9	20.2	18.8
12	S	51.9	69.1	84.5	98.9	112.9	135.3	147.6	159.7
6	R	30.9	27.4	24.7	22.5	20.7	20.2	18.8	17.5
14	S	55.6	74.0	90.4	105.8	120.7	135.0	157.7	170.5
8	R	37.4	32.9	29.4	26.6	24.4	22.6	22.0	20.5
16	S	54.9	74.0	91.5	117.1	133.4	148.9	173.9	187.9
8	R	33.4	29.8	26.9	26.2	24.0	22.1	21.5	20.0
18	S	59.8	80.8	99.9	127.9	145.6	162.4	177.9	205.0
10	R	39.0	34.6	31.2	30.2	27.2	25.4	23.5	22.8

Note: Energy Cost = $10.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-8.b

Economic Insulation Thickness (inch) for Steam Supply and Return Pipes for Energy Cost of $10/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
2 & 1	2.0	2.5	2.5	2.5	3.0	3.0	3.0	3.5
3 & 1.5	2.0	2.5	2.5	3.0	3.0	3.0	3.5	3.5
4 & 2	2.5	2.5	2.5	3.0	3.0	3.5	3.5	3.5
5 & 2.5	2.5	2.5	3.0	3.0	3.0	3.5	3.5	4.0
6 & 3	2.5	2.5	3.0	3.0	3.5	3.5	4.0	4.5
8 & 4	3.0	3.0	3.5	3.5	4.0	4.5	4.5	5.0
10 & 6	3.0	3.5	3.5	4.0	4.5	4.5	5.0	5.5
12 & 6	3.0	3.5	4.0	4.5	5.0	5.0	5.5	6.0
14 & 8	3.0	3.5	4.0	4.5	5.0	5.5	5.5	6.0
16 & 8	3.5	4.0	4.5	4.5	5.0	5.5	5.5	6.0
18 & 10	3.5	4.0	4.5	4.5	5.0	5.5	6.0	6.0

Note: Energy Cost = $10.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-9.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $11/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
2	S	18.6	27.6	37.2	42.8	52.8	63.3	68.1	78.2
1	R	13.4	13.3	13.1	11.9	11.7	11.6	10.7	10.6
3	S	23.5	34.9	42.1	53.8	66.3	72.5	84.7	97.3
1.5	R	18.2	15.9	14.4	14.1	13.9	12.8	12.6	12.3
4	S	27.7	41.2	49.4	63.0	70.6	84.5	98.7	113.5
2	R	18.3	18.0	16.1	15.8	14.4	14.2	13.9	13.6
5	S	32.0	42.2	56.9	72.6	80.9	96.9	104.0	119.5
2.5	R	20.4	18.1	17.8	17.4	15.8	15.5	14.4	14.1
6	S	36.2	47.6	64.2	73.8	91.0	99.8	108.1	116.2
3	R	23.0	20.3	19.9	17.9	17.6	16.2	15.0	14.1
8	S	38.6	57.5	69.6	89.0	99.9	110.5	120.3	129.9
4	R	24.1	23.5	21.1	20.6	18.8	17.4	16.2	15.3
10	S	45.4	60.6	74.3	95.0	107.8	119.8	140.0	150.6
6	R	31.2	27.6	25.0	24.4	22.4	20.6	20.2	18.8
12	S	46.4	69.1	84.5	98.9	112.9	126.3	147.6	159.7
6	R	28.0	27.4	24.7	22.5	20.7	19.2	18.8	17.5
14	S	49.5	74.0	90.4	105.8	120.7	135.0	157.7	170.5
8	R	33.7	32.9	29.4	26.6	24.4	22.6	22.0	20.5
16	S	54.9	74.0	91.5	117.1	133.4	148.9	163.2	187.9
8	R	33.4	29.8	26.9	26.2	24.0	22.1	20.6	20.0
18	S	59.8	80.8	99.9	118.1	135.6	162.4	177.9	205.0
10	R	39.0	34.6	31.2	28.4	26.1	25.4	23.5	22.8

Note: Energy Cost = $11.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-9.b

Economic Insulation Thickness (inch) for Steam Supply and Return Pipes for Energy Cost of $11/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
2 & 1	2.5	2.5	2.5	3.0	3.0	3.0	3.5	3.5
3 & 1.5	2.5	2.5	3.0	3.0	3.0	3.5	3.5	3.5
4 & 2	2.5	2.5	3.0	3.0	3.5	3.5	3.5	3.5
5 & 2.5	2.5	3.0	3.0	3.0	3.5	3.5	4.0	4.0
6 & 3	2.5	3.0	3.0	3.5	3.5	4.0	4.5	5.0
8 & 4	3.0	3.0	3.5	3.5	4.0	4.5	5.0	5.5
10 & 6	3.0	3.5	4.0	4.0	4.5	5.0	5.0	5.5
12 & 6	3.5	3.5	4.0	4.5	5.0	5.5	5.5	6.0
14 & 8	3.5	3.5	4.0	4.5	5.0	5.5	5.5	6.0
16 & 8	3.5	4.0	4.5	4.5	5.0	5.5	6.0	6.0
18 & 10	3.5	4.0	4.5	5.0	5.5	5.5	6.0	6.0

Note: Energy Cost = $11.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-10.a

Maximum Allowable Heat Losses (Btu/h°ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $12/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
2	S	18.6	27.6	37.2	42.8	52.8	63.3	68.1	78.2
1	R	13.4	13.3	13.1	11.9	11.7	11.6	10.7	10.6
3	S	23.5	34.9	42.1	53.8	66.3	72.5	84.7	90.1
1.5	R	16.2	15.9	14.4	14.1	13.9	12.8	12.6	11.7
4	S	27.7	41.2	49.4	63.0	70.6	84.5	98.7	104.6
2	R	18.3	18.0	16.1	15.8	14.4	14.2	13.9	12.9
5	S	32.0	42.2	56.9	72.6	80.9	96.9	104.0	119.5
2.5	R	20.4	18.1	17.8	17.4	15.8	15.5	14.4	14.1
6	S	36.2	47.6	64.2	73.8	91.0	99.8	108.1	116.2
3	R	23.0	20.3	19.9	17.9	17.6	16.2	15.0	14.1
8	S	34.7	51.6	69.6	81.1	92.2	102.9	120.3	129.9
4	R	22.0	21.5	21.1	19.2	17.8	16.6	16.2	15.3
10	S	40.6	60.6	74.3	87.4	107.8	119.8	131.0	150.6
6	R	28.2	27.6	25.0	22.8	22.4	20.6	19.2	18.8
12	S	46.4	62.6	77.4	91.6	112.9	126.3	138.8	159.7
6	R	28.0	25.3	23.0	21.2	20.7	19.2	18.0	17.5
14	S	49.5	66.9	82.8	97.9	112.7	135.0	148.2	170.5
8	R	33.7	30.1	27.3	25.0	23.1	22.6	21.0	20.5
16	S	54.9	74.0	91.5	108.1	124.3	148.9	163.2	187.9
8	R	33.4	29.8	26.9	24.6	22.7	22.1	20.6	20.0
18	S	59.8	80.8	99.9	118.1	135.6	152.3	177.9	205.0
10	R	39.0	34.6	31.2	28.4	26.1	24.2	23.5	22.8

Note: Energy Cost = $12.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-10.b

Economic Insulation Thickness (inch) for Steam Supply and Return Pipes for Energy Cost of $12/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
2 & 1	2.5	2.5	2.5	3.0	3.0	3.0	3.5	3.5
3 & 1.5	2.5	2.5	3.0	3.0	3.0	3.5	3.5	4.0
4 & 2	2.5	2.5	3.0	3.0	3.5	3.5	3.5	4.0
5 & 2.5	2.5	3.0	3.0	3.0	3.5	3.5	4.0	4.0
6 & 3	2.5	3.0	3.0	3.5	3.5	4.0	4.5	5.0
8 & 4	3.5	3.5	3.5	4.0	4.5	5.0	5.0	5.5
10 & 6	3.5	3.5	4.0	4.5	4.5	5.0	5.5	5.5
12 & 6	3.5	4.0	4.5	5.0	5.0	5.5	6.0	6.0
14 & 8	3.5	4.0	4.5	5.0	5.5	5.5	6.0	6.0
16 & 8	3.5	4.0	4.5	5.0	5.5	5.5	6.0	6.0
18 & 10	3.5	4.0	4.5	5.0	5.5	6.0	6.0	6.0

Note: Energy Cost = $12.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-11.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $13/MBtu

Pipe Size (inch)	Pipe Type	150	200	250	300	350	400	450	500
		Process Fluid Temperature (F)							
2	S	18.6	27.6	33.6	42.8	52.8	58.3	68.1	78.2
1	R	13.4	13.3	12.1	11.9	11.7	10.9	10.7	10.6
3	S	23.5	31.3	42.1	53.8	60.5	72.5	84.7	90.1
1.5	R	16.2	14.6	14.4	14.1	13.0	12.8	12.6	11.7
4	S	27.7	36.6	49.4	57.2	70.6	84.5	98.7	104.6
2	R	18.3	16.3	16.1	14.7	14.4	14.2	13.9	12.9
5	S	32.0	42.2	56.9	65.6	80.9	96.9	104.0	119.5
2.5	R	20.4	18.1	17.8	16.1	15.8	15.5	14.4	14.1
6	S	32.0	47.6	57.8	73.8	83.3	99.8	108.1	116.2
3	R	20.7	20.3	18.3	17.9	16.5	16.2	15.0	14.1
8	S	34.7	51.6	69.6	81.1	92.2	102.9	113.0	129.9
4	R	22.0	21.5	21.1	19.2	17.8	16.6	15.6	15.3
10	S	40.6	60.6	74.3	87.4	100.0	112.1	131.0	141.9
6	R	28.2	27.6	25.0	22.8	21.1	19.6	19.2	18.0
12	S	46.4	62.6	77.4	91.6	105.5	118.8	138.8	159.7
6	R	28.0	25.3	23.0	21.2	19.6	18.4	18.0	17.5
14	S	49.5	66.9	82.8	97.9	112.7	126.8	148.2	170.5
8	R	33.7	30.1	27.3	25.0	23.1	21.5	21.0	20.5
16	S	49.6	67.7	91.5	108.1	124.3	139.7	163.2	187.9
8	R	30.5	27.6	26.9	24.6	22.7	21.2	20.6	20.0
18	S	54.0	73.9	92.3	109.9	127.1	152.3	177.9	205.0
10	R	35.5	32.0	29.2	26.8	24.9	24.2	23.5	22.8

Note: Energy Cost = $13.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-11.b

Economic Insulation Thickness (inch) for Steam Supply and Return Pipes for Energy Cost of $13/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
2 & 1	2.5	2.5	3.0	3.0	3.0	3.5	3.5	3.5
3 & 1.5	2.5	3.0	3.0	3.0	3.5	3.5	3.5	4.0
4 & 2	2.5	3.0	3.0	3.5	3.5	3.5	3.5	4.0
5 & 2.5	2.5	3.0	3.0	3.5	3.5	3.5	4.0	4.0
6 & 3	3.0	3.0	3.5	3.5	4.0	4.0	4.5	5.0
8 & 4	3.5	3.5	3.5	4.0	4.5	5.0	5.5	5.5
10 & 6	3.5	3.5	4.0	4.5	5.0	5.5	5.5	6.0
12 & 6	3.5	4.0	4.5	5.0	5.5	6.0	6.0	6.0
14 & 8	3.5	4.0	4.5	5.0	5.5	6.0	6.0	6.0
16 & 8	4.0	4.5	4.5	5.0	5.5	6.0	6.0	6.0
18 & 10	4.0	4.5	5.0	5.5	6.0	6.0	6.0	6.0

Note: Energy Cost = $13.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-12.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $14/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
2	S	18.6	27.6	33.6	42.8	52.8	58.3	68.1	78.2
1	R	13.4	13.3	12.1	11.9	11.7	10.9	10.7	10.6
3	S	21.1	31.3	42.1	53.8	60.5	72.5	78.5	90.1
1.5	R	14.8	14.6	14.4	14.1	13.0	12.8	11.9	11.7
4	S	27.7	36.6	49.4	57.2	70.6	84.5	91.0	104.6
2	R	18.3	16.3	16.1	14.7	14.4	14.2	13.1	12.9
5	S	32.0	42.2	56.9	65.6	80.9	89.0	104.0	119.5
2.5	R	20.4	18.1	17.8	16.1	15.8	14.6	14.4	14.1
6	S	32.0	47.6	57.8	73.8	83.3	92.5	101.1	109.5
3	R	20.7	20.3	18.3	17.9	16.5	15.3	14.4	13.6
8	S	34.7	51.6	69.6	81.1	92.2	102.9	113.0	122.7
4	R	22.0	21.5	21.1	19.2	17.8	16.6	15.6	14.7
10	S	40.6	55.1	68.4	87.4	100.0	112.1	123.4	141.9
6	R	28.2	25.5	23.3	22.8	21.1	19.6	18.3	18.0
12	S	46.4	62.6	77.4	91.6	105.5	118.8	138.8	159.7
6	R	28.0	25.3	23.0	21.2	19.6	18.4	18.0	17.5
14	S	49.5	66.9	82.8	91.3	112.7	126.8	148.2	170.5
8	R	33.7	30.1	27.3	23.6	23.1	21.5	21.0	20.5
16	S	49.6	67.7	91.5	100.8	116.6	139.7	163.2	187.9
8	R	30.5	27.6	26.9	23.3	21.7	21.2	20.6	20.0
18	S	54.0	73.9	92.3	109.9	127.1	152.3	177.9	205.0
10	R	35.5	32.0	29.2	26.8	24.9	24.2	23.5	22.8

Note: Energy Cost = $14.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-12.b

Economic Insulation Thickness (inch) for Steam Supply and Return Pipes for Energy Cost of $14/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
2 & 1	2.5	2.5	3.0	3.0	3.0	3.5	3.5	3.5
3 & 1.5	3.0	3.0	3.0	3.0	3.5	3.5	4.0	4.0
4 & 2	2.5	3.0	3.0	3.5	3.5	3.5	4.0	4.0
5 & 2.5	2.5	3.0	3.0	3.5	3.5	4.0	4.0	4.0
6 & 3	3.0	3.0	3.5	3.5	4.0	4.5	5.0	5.5
8 & 4	3.5	3.5	3.5	4.0	4.5	5.0	5.5	6.0
10 & 6	3.5	4.0	4.5	4.5	5.0	5.5	6.0	6.0
12 & 6	3.5	4.0	4.5	5.0	5.5	6.0	6.0	6.0
14 & 8	3.5	4.0	4.5	5.5	5.5	6.0	6.0	6.0
16 & 8	4.0	4.5	4.5	5.5	6.0	6.0	6.0	6.0
18 & 10	4.0	4.5	5.0	5.5	6.0	6.0	6.0	6.0

Note: Energy Cost = $14.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-13.a

Maximum Allowable Heat Losses (Btu/h·ft) from the Supply Pipe (S) and the Return Pipe (R) for Energy Cost of $15/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 150	200	250	300	350	400	450	500
2	S	18.6	27.6	33.6	42.8	52.8	58.3	68.1	78.2
1	R	13.4	13.3	12.1	11.9	11.7	10.9	10.7	10.6
3	S	21.1	31.3	42.1	53.8	60.5	72.5	78.5	90.1
1.5	R	14.8	14.6	14.4	14.1	13.0	12.8	11.9	11.7
4	S	27.7	36.6	49.4	57.2	70.6	84.5	91.0	104.6
2	R	18.3	16.3	16.1	14.7	14.4	14.2	13.1	12.9
5	S	32.0	42.2	56.9	65.6	80.9	89.0	104.0	119.5
2.5	R	20.4	18.1	17.8	16.1	15.8	14.6	14.4	14.1
6	S	32.0	47.6	57.8	67.6	77.2	86.5	95.3	103.9
3	R	20.7	20.3	18.3	16.8	15.6	14.6	13.8	13.1
8	S	34.7	51.6	69.6	81.1	92.2	102.9	113.0	122.7
4	R	22.0	21.5	21.1	19.2	17.8	16.6	15.6	14.7
10	S	40.6	55.1	68.4	87.4	100.0	112.1	123.4	141.9
6	R	28.2	25.5	23.3	22.8	21.1	19.6	18.3	18.0
12	S	46.4	62.6	77.4	91.6	105.5	118.8	138.8	159.7
6	R	28.0	25.3	23.0	21.2	19.6	18.4	18.0	17.5
14	S	49.5	66.9	82.8	91.3	112.7	126.8	148.2	170.5
8	R	33.7	30.1	27.3	23.6	23.1	21.5	21.0	20.5
16	S	49.6	67.7	91.5	100.8	116.6	139.7	163.2	187.9
8	R	30.5	27.6	26.9	23.3	21.7	21.2	20.6	20.0
18	S	54.0	73.9	92.3	109.9	127.1	152.3	177.9	205.0
10	R	35.5	32.0	29.2	26.8	24.9	24.2	23.5	22.8

Note: Energy Cost = $15.00/MBtu
Return Pipe Temperature = 150 F

TABLE B-13.b

Economic Insulation Thickness (inch) for Steam Supply and Return Pipes for Energy Cost of $15/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
2 & 1	2.5	2.5	3.0	3.0	3.0	3.5	3.5	3.5
3 & 1.5	3.0	3.0	3.0	3.0	3.5	3.5	4.0	4.0
4 & 2	2.5	3.0	3.0	3.5	3.5	3.5	4.0	4.0
5 & 2.5	2.5	3.0	3.0	3.5	3.5	4.0	4.0	4.0
6 & 3	3.0	3.0	3.5	4.0	4.5	5.0	5.5	6.0
8 & 4	3.5	3.5	3.5	4.0	4.5	5.0	5.5	6.0
10 & 6	3.5	4.0	4.5	4.5	5.0	5.5	6.0	6.0
12 & 6	3.5	4.0	4.5	5.0	5.5	6.0	6.0	6.0
14 & 8	3.5	4.0	4.5	5.5	5.5	6.0	6.0	6.0
16 & 8	4.0	4.5	4.5	5.5	6.0	6.0	6.0	6.0
18 & 10	4.0	4.5	5.0	5.5	6.0	6.0	6.0	6.0

Note: Energy Cost = $15.00/MBtu
Return Pipe Temperature = 150 F

TABLE C-1.a

Maximum Allowable Heat Losses (Btu/h·ft) from Hot Water Supply Pipe (S) and Return Pipe (R) for Energy Cost of $3/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 250	300	350	400	450	500
1	S	34.8	44.6	55.1	66.1	77.3	89.1
	R	34.8	34.5	34.3	34.0	33.7	33.4
2	S	49.6	53.4	65.9	69.5	81.3	93.6
	R	49.6	41.3	40.9	35.8	35.5	35.2
3	S	53.1	68.2	84.3	87.9	92.1	106.0
	R	53.1	52.6	52.0	45.0	40.2	39.8
4	S	62.9	69.8	86.3	103.6	107.8	124.3
	R	62.9	53.9	53.3	52.8	46.8	46.3
5	S	73.0	80.7	99.8	119.8	124.1	143.1
	R	73.0	62.1	61.4	60.7	53.6	53.0
6	S	82.8	91.3	112.9	135.6	140.0	161.5
	R	82.8	70.2	69.3	68.4	60.1	59.4
8	S	100.7	110.7	137.1	144.6	151.8	175.3
	R	100.7	84.8	73.0	66.3	65.3	64.5
10	S	101.5	130.9	141.9	170.5	178.5	206.2
	R	101.5	100.0	86.8	85.6	76.2	75.1
12	S	115.7	149.5	161.8	194.5	202.8	234.4
	R	115.7	113.8	98.6	97.1	85.9	84.6
14	S	124.7	161.2	173.5	208.7	217.4	251.5
	R	124.7	122.6	105.4	103.6	91.5	90.0
16	S	137.3	154.8	191.8	205.3	240.5	251.4
	R	137.3	117.9	115.8	102.1	100.3	90.0
18	S	149.7	169.2	186.7	224.6	263.2	275.2
	R	149.7	128.5	113.0	110.9	108.8	97.6

Note: Energy Cost = $3.00/MBtu
Return Pipe Temperature = 250 F

TABLE B-13.b

Economic Insulation Thickness (inch) for Steam Supply and Return Pipes for Energy Cost of $15/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)							
	150	200	250	300	350	400	450	500
2 & 1	2.5	2.5	3.0	3.0	3.0	3.5	3.5	3.5
3 & 1.5	3.0	3.0	3.0	3.0	3.5	3.5	4.0	4.0
4 & 2	2.5	3.0	3.0	3.5	3.5	3.5	4.0	4.0
5 & 2.5	2.5	3.0	3.0	3.5	3.5	4.0	4.0	4.0
6 & 3	3.0	3.0	3.5	4.0	4.5	5.0	5.5	6.0
8 & 4	3.5	3.5	3.5	4.0	4.5	5.0	5.5	6.0
10 & 6	3.5	4.0	4.5	4.5	5.0	5.5	6.0	6.0
12 & 6	3.5	4.0	4.5	5.0	5.5	6.0	6.0	6.0
14 & 8	3.5	4.0	4.5	5.5	5.5	6.0	6.0	6.0
16 & 8	4.0	4.5	4.5	5.5	6.0	6.0	6.0	6.0
18 & 10	4.0	4.5	5.0	5.5	6.0	6.0	6.0	6.0

Note: Energy Cost = $15.00/MBtu
Return Pipe Temperature = 150 F

TABLE C-1.a

Maximum Allowable Heat Losses (Btu/h·ft) from Hot Water Supply Pipe (S) and Return Pipe (R) for Energy Cost of $3/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 250	300	350	400	450	500
1	S	34.8	44.6	55.1	66.1	77.3	89.1
	R	34.8	34.5	34.3	34.0	33.7	33.4
2	S	49.6	53.4	65.9	69.5	81.3	93.6
	R	49.6	41.3	40.9	35.8	35.5	35.2
3	S	53.1	68.2	84.3	87.9	92.1	106.0
	R	53.1	52.6	52.0	45.0	40.2	39.8
4	S	62.9	69.8	86.3	103.6	107.8	124.3
	R	62.9	53.9	53.3	52.8	46.8	46.3
5	S	73.0	80.7	99.8	119.8	124.1	143.1
	R	73.0	62.1	61.4	60.7	53.6	53.0
6	S	82.8	91.3	112.9	135.6	140.0	161.5
	R	82.8	70.2	69.3	68.4	60.1	59.4
8	S	100.7	110.7	137.1	144.6	151.8	175.3
	R	100.7	84.8	73.0	66.3	65.3	64.5
10	S	101.5	130.9	141.9	170.5	178.5	206.2
	R	101.5	100.0	86.8	85.6	76.2	75.1
12	S	115.7	149.5	161.8	194.5	202.8	234.4
	R	115.7	113.8	98.6	97.1	85.9	84.6
14	S	124.7	161.2	173.5	208.7	217.4	251.5
	R	124.7	122.6	105.4	103.6	91.5	90.0
16	S	137.3	154.8	191.8	205.3	240.5	251.4
	R	137.3	117.9	115.8	102.1	100.3	90.0
18	S	149.7	169.2	186.7	224.6	263.2	275.2
	R	149.7	128.5	113.0	110.9	108.8	97.6

Note: Energy Cost = $3.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-1.b

Economic Insulation Thickness (inch) for Supply and Return Pipes for Energy Cost of $3/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)					
	250	300	350	400	450	500
1	1.5	1.5	1.5	1.5	1.5	1.5
2	1.5	2.0	2.0	2.5	2.5	2.5
3	2.0	2.0	2.0	2.5	3.0	3.0
4	2.0	2.5	2.5	2.5	3.0	3.0
5	2.0	2.5	2.5	2.5	3.0	3.0
6	2.0	2.5	2.5	2.5	3.0	3.0
8	2.0	2.5	2.5	3.0	3.5	3.5
10	2.5	2.5	3.0	3.0	3.5	3.5
12	2.5	2.5	3.0	3.0	3.5	3.5
14	2.5	2.5	3.0	3.0	3.5	3.5
16	2.5	3.0	3.0	3.5	3.5	4.0
18	2.5	3.0	3.0	3.5	3.5	4.0

Note: Energy Cost = $3.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-2.a

Maximum Allowable Heat Losses (Btu/h·ft) from Hot Water Supply Pipe (S) and Return Pipe (R) for Energy Cost of $4/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F)					
		250	300	350	400	450	500
1	S	34.8	44.6	55.1	56.7	66.3	76.3
	R	34.8	34.5	34.3	29.3	29.1	28.8
2	S	41.6	53.4	65.9	69.5	81.3	93.6
	R	41.6	41.3	40.9	35.8	35.5	35.2
3	S	53.1	68.2	84.3	87.9	92.1	106.0
	R	53.1	52.6	52.0	45.0	40.2	39.8
4	S	54.4	69.8	86.3	103.6	107.8	124.3
	R	54.4	53.9	53.3	52.8	46.8	46.3
5	S	62.8	80.7	99.8	119.8	124.1	143.1
	R	62.8	62.1	61.4	60.7	53.6	53.0
6	S	71.0	91.3	112.9	135.6	140.0	161.5
	R	71.0	70.2	69.3	68.4	60.1	59.4
8	S	86.0	110.7	120.4	144.6	151.8	175.3
	R	86.0	84.8	74.0	73.0	65.3	64.5
10	S	101.5	130.9	141.9	152.5	178.5	187.3
	R	101.5	100.0	86.8	77.2	76.2	69.0
12	S	115.7	130.7	144.2	173.3	183.6	212.1
	R	115.7	100.0	88.3	87.1	78.3	77.3
14	S	124.7	140.2	154.5	185.7	196.7	227.4
	R	124.7	107.1	94.3	92.9	83.5	82.2
16	S	119.9	154.8	170.7	185.7	217.4	230.1
	R	119.9	117.9	103.8	93.0	91.6	83.2
18	S	130.8	150.7	186.7	203.0	237.8	251.6
	R	130.8	114.9	113.0	101.1	99.4	90.2

Note: Energy Cost = $4.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-2.b

Economic Insulation Thickness (inch) for Supply and Return Pipes for Energy Cost of $4/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)					
	250	300	350	400	450	500
1	1.5	1.5	1.5	2.0	2.0	2.0
2	2.0	2.0	2.0	2.5	2.5	2.5
3	2.0	2.0	2.0	2.5	3.0	3.0
4	2.5	2.5	2.5	2.5	3.0	3.0
5	2.5	2.5	2.5	2.5	3.0	3.0
6	2.5	2.5	2.5	2.5	3.0	3.0
8	2.5	2.5	3.0	3.0	3.5	3.5
10	2.5	2.5	3.0	3.5	3.5	4.0
12	2.5	3.0	3.5	3.5	4.0	4.0
14	2.5	3.0	3.5	3.5	4.0	4.0
16	3.0	3.0	3.5	4.0	4.0	4.5
18	3.0	3.5	3.5	4.0	4.0	4.5

Note: Energy Cost = $4.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-3.a

Maximum Allowable Heat Losses (Btu/h·ft) from Hot Water Supply Pipe (S) and Return Pipe (R) for Energy Cost of $5/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F)					
		250	300	350	400	450	500
1	S	34.8	38.3	47.3	56.7	66.3	68.2
	R	34.8	29.7	29.5	29.3	29.1	25.9
2	S	41.6	46.9	57.9	69.5	81.3	84.5
	R	41.6	36.3	36.1	35.8	35.5	32.0
3	S	53.1	59.3	73.3	78.7	92.1	106.0
	R	53.1	45.8	45.4	40.5	40.2	39.8
4	S	54.4	69.8	86.3	92.2	107.8	124.3
	R	54.4	53.9	53.3	47.2	46.8	46.3
5	S	62.8	80.7	99.8	106.1	124.1	143.1
	R	62.8	62.1	61.4	54.1	53.6	53.0
6	S	71.0	91.3	112.9	119.6	126.2	145.5
	R	71.0	70.2	69.3	60.8	54.6	54.1
8	S	75.7	97.3	120.4	129.8	138.5	159.7
	R	75.7	74.9	74.0	66.0	59.9	59.3
10	S	89.1	114.7	127.0	152.5	162.5	172.1
	R	89.1	88.0	78.1	77.2	69.8	63.8
12	S	101.4	116.6	144.2	156.9	183.6	194.5
	R	101.4	89.5	88.3	79.3	78.3	71.4
14	S	108.6	124.8	154.5	168.1	196.7	208.3
	R	108.6	95.7	94.3	84.7	83.5	76.0
16	S	106.9	137.9	154.5	170.1	199.1	230.1
	R	106.9	105.4	94.3	85.6	84.5	83.2
18	S	116.7	150.7	168.8	185.8	217.5	232.4
	R	116.7	114.9	102.7	93.1	91.7	84.1

Note: Energy Cost = $5.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-3.b

Economic Insulation Thickness (inch) for Supply and Return Pipes for Energy Cost of $5/MBtu

Pipe Size (inch)	Process Fluid Temperature (F) 250	300	350	400	450	500
1	1.5	2.0	2.0	2.0	2.0	2.5
2	2.0	2.5	2.5	2.5	2.5	3.0
3	2.0	2.5	2.5	3.0	3.0	3.0
4	2.5	2.5	2.5	3.0	3.0	3.0
5	2.5	2.5	2.5	3.0	3.0	3.0
6	2.5	2.5	2.5	3.0	3.5	3.5
8	3.0	3.0	3.0	3.5	4.0	4.0
10	3.0	3.0	3.5	3.5	4.0	4.5
12	3.0	3.5	3.5	4.0	4.0	4.5
14	3.0	3.5	3.5	4.0	4.0	4.5
16	3.5	3.5	4.0	4.5	4.5	4.5
18	3.5	3.5	4.0	4.5	4.5	5.0

Note: Energy Cost = $5.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-4.a

Maximum Allowable Heat Losses (Btu/h·ft) from Hot Water Supply Pipe (S) and Return Pipe (R) for Energy Cost of $6/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 250	300	350	400	450	500
1	S	29.9	38.3	47.3	50.7	59.3	68.2
	R	29.9	29.7	29.5	26.3	26.1	25.9
2	S	36.6	46.9	57.9	62.8	73.5	84.5
	R	36.6	36.3	36.1	32.5	32.3	32.0
3	S	46.2	59.3	65.6	78.7	92.1	106.0
	R	46.2	45.8	40.8	40.5	40.2	39.8
4	S	54.4	69.8	76.8	92.2	107.8	112.8
	R	54.4	53.9	47.7	47.2	46.8	42.4
5	S	62.8	71.5	88.4	106.1	124.1	129.4
	R	62.8	55.2	54.7	54.1	53.6	48.3
6	S	71.0	80.6	99.7	119.6	126.2	145.1
	R	71.0	62.2	61.5	60.8	54.6	54.1
8	S	75.7	87.4	108.1	129.8	138.5	159.7
	R	75.7	67.4	66.7	66.0	59.9	59.3
10	S	89.1	102.7	127.0	138.7	149.2	172.1
	R	89.1	79.0	78.1	70.6	64.5	63.8
12	S	90.6	116.6	130.7	156.9	168.5	180.2
	R	90.6	89.5	80.3	79.3	72.3	66.6
14	S	96.9	124.8	139.9	168.1	180.3	192.8
	R	96.9	95.7	85.8	84.7	77.0	70.9
16	S	106.9	124.8	141.6	170.1	199.1	212.7
	R	106.9	95.7	86.8	85.6	84.5	77.6
18	S	116.7	136.4	154.6	171.8	201.1	216.5
	R	116.7	104.3	94.5	86.5	85.4	78.9

Note: Energy Cost = $6.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-4.b

Economic Insulation Thickness (inch) for Supply and Return Pipes for Energy Cost of $6/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)					
	250	300	350	400	450	500
1	2.0	2.0	2.0	2.5	2.5	2.5
2	2.5	2.5	2.5	3.0	3.0	3.0
3	2.5	2.5	3.0	3.0	3.0	3.0
4	2.5	2.5	3.0	3.0	3.0	3.5
5	2.5	3.0	3.0	3.0	3.0	3.5
6	2.5	3.0	3.0	3.0	3.5	3.5
8	3.0	3.5	3.5	3.5	4.0	4.0
10	3.0	3.5	3.5	4.0	4.5	4.5
12	3.5	3.5	4.0	4.0	4.5	5.0
14	3.5	3.5	4.0	4.0	4.5	5.0
16	3.5	4.0	4.5	4.5	4.5	5.0
18	3.5	4.0	4.5	5.0	5.0	5.5

Note: Energy Cost = $6.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-5.a

Maximum Allowable Heat Losses (Btu/h·ft) from Hot Water Supply Pipe (S) and Return Pipe (R) for Energy Cost of $7/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F)					
		250	300	350	400	450	500
1	S	29.9	38.3	47.3	50.7	59.3	68.2
	R	29.9	29.7	29.5	26.3	26.1	25.9
2	S	36.6	46.9	57.9	62.8	73.5	84.5
	R	36.6	36.3	36.1	32.5	32.3	32.0
3	S	46.2	53.1	65.6	78.7	92.1	106.0
	R	46.2	41.1	40.8	40.5	40.2	39.8
4	S	54.4	62.2	76.8	92.2	98.0	112.8
	R	54.4	48.1	47.7	47.2	42.8	42.4
5	S	62.8	71.5	88.4	106.1	112.3	129.4
	R	62.8	55.2	54.7	54.1	48.8	48.3
6	S	71.0	80.6	99.7	107.9	115.6	133.2
	R	71.0	62.2	61.5	55.2	50.3	49.9
8	S	75.7	87.4	108.1	118.4	127.9	147.4
	R	75.7	67.4	66.7	66.5	55.7	55.1
10	S	79.9	102.7	115.5	127.6	149.2	159.7
	R	79.9	79.0	71.4	65.2	64.5	59.5
12	S	82.1	105.6	130.7	144.0	156.2	168.4
	R	82.1	81.3	80.3	73.1	67.3	62.5
14	S	87.9	113.1	139.9	154.1	167.0	180.0
	R	87.9	86.9	85.8	78.0	71.7	66.5
16	S	96.9	114.4	141.6	170.1	184.1	198.4
	R	96.9	87.9	86.8	85.6	78.6	72.8
18	S	105.7	124.9	143.0	171.8	187.4	216.5
	R	105.7	95.8	87.7	86.5	80.0	78.9

Note: Energy Cost = $7.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-5.b

Economic Insulation Thickness (inch) for Supply and Return Pipes for Energy Cost of $7/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)					
	250	300	350	400	450	500
1	2.0	2.0	2.0	2.5	2.5	2.5
2	2.5	2.5	2.5	3.0	3.0	3.0
3	2.5	3.0	3.0	3.0	3.0	3.0
4	2.5	3.0	3.0	3.0	3.5	3.5
5	2.5	3.0	3.0	3.0	3.5	3.5
6	2.5	3.0	3.0	3.5	4.0	4.0
8	3.0	3.5	3.5	4.0	4.5	4.5
10	3.5	3.5	4.0	4.5	4.5	5.0
12	4.0	4.0	4.0	4.5	5.0	5.5
14	4.0	4.0	4.0	4.5	5.0	5.5
16	4.0	4.5	4.5	4.5	5.0	5.5
18	4.0	4.5	5.0	5.0	5.5	5.5

Note: Energy Cost = $7.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-6.a

Maximum Allowable Heat Losses (Btu/h·ft) from Hot Water Supply Pipe (S) and Return Pipe (R) for Energy Cost of $8/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 250	300	350	400	450	500
1	S	29.9	34.2	42.3	50.7	59.3	62.5
	R	29.9	26.6	26.4	26.3	26.1	23.9
2	S	36.6	42.4	52.4	62.8	73.5	84.5
	R	36.6	32.9	32.7	32.5	32.3	32.0
3	S	41.4	53.1	65.6	78.7	92.1	106.0
	R	41.4	41.1	40.8	40.5	40.2	39.8
4	S	48.5	62.2	69.8	83.8	98.0	112.8
	R	48.5	48.1	43.5	43.1	42.8	42.4
5	S	55.7	71.5	80.0	96.0	112.3	118.8
	R	55.7	55.2	49.7	49.2	48.8	44.7
6	S	62.8	72.7	89.9	107.9	115.6	133.2
	R	62.8	56.2	55.7	55.2	50.3	49.9
8	S	68.1	79.8	98.7	118.4	127.9	147.4
	R	68.1	61.7	61.1	60.5	55.7	55.1
10	S	79.9	93.5	106.3	127.6	149.2	159.7
	R	79.9	72.1	65.8	65.2	64.5	59.5
12	S	82.1	105.6	119.9	133.5	156.2	168.4
	R	82.1	81.3	74.0	68.0	67.3	62.5
14	S	87.9	113.1	128.3	142.8	156.0	180.0
	R	87.9	86.9	78.9	72.6	67.3	66.5
16	S	88.9	114.4	131.0	157.4	171.8	186.2
	R	88.9	87.9	80.6	79.6	73.7	68.7
18	S	97.0	115.6	133.3	160.1	187.4	203.0
	R	97.0	88.8	82.0	81.0	80.0	74.5

Note: Energy Cost = $8.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-6.b

Economic Insulation Thickness (inch) for Supply and Return Pipes for Energy Cost of $8/MBtu

Pipe Size (inch)	Process Fluid Temperature (F) 250	300	350	400	450	500
1	2.0	2.5	2.5	2.5	2.5	3.0
2	2.5	3.0	3.0	3.0	3.0	3.0
3	3.0	3.0	3.0	3.0	3.0	3.0
4	3.0	3.0	3.5	3.5	3.5	3.5
5	3.0	3.0	3.5	3.5	3.5	4.0
6	3.0	3.5	3.5	3.5	4.0	4.0
8	3.5	4.0	4.0	4.0	4.5	4.5
10	3.5	4.0	4.5	4.5	4.5	5.0
12	4.0	4.0	4.5	5.0	5.0	5.5
14	4.0	4.0	4.5	5.0	5.5	5.5
16	4.5	4.5	5.0	5.0	5.5	6.0
18	4.5	5.0	5.5	5.5	5.5	6.0

Note: Energy Cost = $8.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-7.a

Maximum Allowable Heat Losses (Btu/h·ft) from Hot Water Supply Pipe (S) and Return Pipe (R) for Energy Cost of $9/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 250	300	350	400	450	500
1	S	26.8	34.2	42.3	46.5	54.4	62.5
	R	26.8	26.6	26.4	24.2	24.0	23.9
2	S	36.6	42.4	52.4	62.8	73.5	84.5
	R	36.6	32.9	32.7	32.5	32.3	32.0
3	S	41.4	53.1	65.6	78.7	84.1	96.8
	R	41.4	41.1	40.8	40.5	36.9	36.6
4	S	48.5	62.2	69.8	83.8	98.0	112.8
	R	48.5	48.1	43.5	43.1	42.8	42.4
5	S	55.7	71.5	80.0	96.0	103.2	118.8
	R	55.7	55.2	49.7	49.2	45.1	44.7
6	S	62.8	72.7	89.9	107.9	115.6	123.5
	R	62.8	56.2	55.7	55.2	50.3	46.5
8	S	68.1	79.8	98.7	109.4	127.9	137.4
	R	68.1	61.7	61.1	56.2	55.7	55.7
10	S	72.8	93.5	106.3	127.6	138.6	149.5
	R	72.8	72.1	65.8	65.2	60.1	55.9
12	S	82.1	97.0	111.2	133.5	146.0	168.4
	R	82.1	74.7	68.7	68.0	63.2	62.5
14	S	87.9	103.7	118.9	133.4	156.0	169.2
	R	87.9	79.8	73.4	68.0	67.3	62.8
16	S	88.9	114.4	131.0	146.8	171.8	186.2
	R	88.9	87.9	80.6	74.6	73.7	68.7
18	S	97.0	115.6	133.3	160.1	187.4	203.0
	R	97.0	88.8	82.0	81.0	80.0	74.5

Note: Energy Cost = $9.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-7.b

Economic Insulation Thickness (inch) for Supply and Return Pipes for Energy Cost of $9/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)					
	250	300	350	400	450	500
1	2.5	2.5	2.5	3.0	3.0	3.0
2	2.5	3.0	3.0	3.0	3.0	3.0
3	3.0	3.0	3.0	3.0	3.5	3.5
4	3.0	3.0	3.5	3.5	3.5	3.5
5	3.0	3.0	3.5	3.5	4.0	4.0
6	3.0	3.5	3.5	3.5	4.0	4.5
8	3.5	4.0	4.0	4.5	4.5	5.0
10	4.0	4.0	4.5	4.5	5.0	5.5
12	4.0	4.5	5.0	5.0	5.5	5.5
14	4.0	4.5	5.0	5.5	5.5	6.0
16	4.5	4.5	5.0	5.5	5.5	6.0
18	4.5	5.0	5.5	5.5	5.5	6.0

Note: Energy Cost = $9.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-8.a

Maximum Allowable Heat Losses (Btu/h·ft) from Hot Water Supply Pipe (S) and Return Pipe (R) for Energy Cost of $10/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 250	300	350	400	450	500
1	S	26.8	34.2	38.8	46.5	54.4	62.5
	R	26.8	26.6	24.3	24.2	24.0	23.9
2	S	36.6	42.4	52.4	62.8	73.5	77.9
	R	36.6	32.9	32.7	32.5	32.3	29.7
3	S	41.4	53.1	65.6	78.7	84.1	96.8
	R	41.4	41.1	40.8	40.5	36.9	36.6
4	S	48.5	56.5	69.8	83.8	98.0	112.8
	R	48.5	43.8	43.5	43.1	42.8	42.4
5	S	55.7	64.7	80.0	88.2	103.2	118.8
	R	55.7	50.1	49.7	45.4	45.1	44.7
6	S	56.7	72.7	89.9	98.9	107.3	123.5
	R	56.7	56.2	55.7	50.8	46.9	46.5
8	S	62.2	73.8	91.2	109.4	119.3	137.4
	R	62.2	57.1	56.6	56.2	52.1	51.7
10	S	72.8	86.0	98.7	118.5	129.8	149.5
	R	72.8	66.4	61.2	60.7	56.5	55.9
12	S	75.5	97.0	111.2	124.8	146.0	158.4
	R	75.5	74.7	68.7	63.8	63.2	59.1
14	S	80.7	103.7	118.9	133.4	156.0	169.2
	R	80.7	79.8	73.4	68.0	67.3	62.8
16	S	88.9	114.4	131.0	146.8	161.3	186.2
	R	88.9	87.9	80.6	74.6	69.5	68.7
18	S	89.8	115.6	133.3	150.3	175.8	203.0
	R	89.8	88.8	82.0	76.3	75.4	74.5

Note: Energy Cost = $10.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-8.b

Economic Insulation Thickness (inch) for Supply and Return Pipes for Energy Cost of $10/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)					
	250	300	350	400	450	500
1	2.5	2.5	3.0	3.0	3.0	3.0
2	2.5	3.0	3.0	3.0	3.0	3.5
3	3.0	3.0	3.0	3.0	3.5	3.5
4	3.0	3.5	3.5	3.5	3.5	3.5
5	3.0	3.5	3.5	4.0	4.0	4.0
6	3.5	3.5	3.5	4.0	4.5	4.5
8	4.0	4.5	4.5	4.5	5.0	5.0
10	4.0	4.5	5.0	5.0	5.5	5.5
12	4.5	4.5	5.0	5.5	5.5	6.0
14	4.5	4.5	5.0	5.5	5.5	6.0
16	4.5	4.5	5.0	5.5	6.0	6.0
18	5.0	5.5	5.5	6.0	6.0	6.0

Note: Energy Cost = $10.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-9.a

Maximum Allowable Heat Losses (Btu/h·ft) from Hot Water Supply Pipe (S) and Return Pipe (R) for Energy Cost of $11/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 250	300	350	400	450	500
1	S	26.8	34.2	38.8	46.5	54.4	62.5
	R	26.8	26.6	24.3	24.2	24.0	23.9
2	S	33.1	42.4	52.4	62.8	67.7	77.9
	R	33.1	32.9	32.7	32.5	29.9	29.7
3	S	41.4	53.1	65.6	78.7	84.1	96.8
	R	41.4	41.1	40.8	40.5	36.9	36.6
4	S	44.1	56.5	69.8	83.8	92.8	112.8
	R	44.1	43.8	43.5	43.1	42.8	42.4
5	S	50.5	64.7	73.5	88.2	103.2	118.8
	R	50.5	50.1	45.8	45.4	45.1	44.7
6	S	56.7	72.7	82.4	98.9	107.3	123.5
	R	56.7	56.2	51.2	50.8	46.9	46.5
8	S	62.2	73.8	91.2	102.0	119.3	129.0
	R	62.2	57.1	56.6	52.5	52.1	48.7
10	S	72.8	86.0	98.7	110.9	129.8	140.9
	R	72.8	66.4	61.2	57.0	56.5	52.9
12	S	75.5	90.0	104.0	124.8	137.4	158.4
	R	75.5	69.4	64.4	63.8	59.7	59.1
14	S	80.7	96.2	111.1	133.4	146.7	169.2
	R	80.7	74.1	68.7	68.0	63.5	62.8
16	S	82.4	105.9	122.3	137.9	161.3	186.2
	R	82.4	81.5	75.4	70.3	69.5	68.7
18	S	83.8	107.8	133.3	150.3	175.8	203.0
	R	83.8	82.9	82.0	76.3	75.4	74.5

Note: Energy Cost = $11.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-9.b

Economic Insulation Thickness (inch) for Supply
and Return Pipes for Energy Cost of $11/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)					
	250	300	350	400	450	500
1	2.5	2.5	3.0	3.0	3.0	3.0
2	3.0	3.0	3.0	3.0	3.5	3.5
3	3.0	3.0	3.0	3.0	3.5	3.5
4	3.5	3.5	3.5	3.5	3.5	3.5
5	3.5	3.5	4.0	4.0	4.0	4.0
6	3.5	3.5	4.0	4.0	4.5	4.5
8	4.0	4.5	4.5	5.0	5.0	5.5
10	4.0	4.5	5.0	5.5	5.5	6.0
12	4.5	5.0	5.5	5.5	6.0	6.0
14	4.5	5.0	5.5	5.5	6.0	6.0
16	5.0	5.0	5.5	6.0	6.0	6.0
18	5.5	5.5	5.5	6.0	6.0	6.0

Note: Energy Cost = $11.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-10.a

Maximum Allowable Heat Losses (Btu/h·ft) from Hot Water Supply Pipe (S) and Return Pipe (R) for Energy Cost of $12/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 250	300	350	400	450	500
1	S	24.6	31.4	38.8	46.5	54.4	62.5
	R	24.6	24.4	24.3	24.2	24.0	23.9
2	S	33.1	42.4	52.4	57.9	67.7	77.9
	R	33.1	32.9	32.7	30.0	29.9	29.7
3	S	41.4	53.1	65.6	71.9	84.1	89.7
	R	41.4	41.1	40.8	37.2	36.9	34.1
4	S	44.1	56.5	69.8	83.8	98.0	104.0
	R	44.1	43.8	43.5	43.1	42.8	39.3
5	S	50.5	64.7	73.5	88.2	103.2	118.8
	R	50.5	50.1	45.8	45.4	45.1	44.7
6	S	56.7	66.7	82.4	91.7	107.3	115.6
	R	56.7	51.6	51.2	47.3	46.9	43.7
8	S	62.2	73.8	91.2	102.0	119.3	129.0
	R	62.2	57.1	56.6	52.5	52.1	48.7
10	S	67.0	79.9	98.7	110.9	129.8	140.9
	R	67.0	61.8	61.2	57.0	56.5	52.9
12	S	70.1	90.0	104.0	117.5	137.4	158.4
	R	70.1	69.4	64.4	60.2	59.7	59.1
14	S	74.8	96.2	111.1	125.4	146.7	169.2
	R	74.8	74.1	68.7	64.1	63.5	62.8
16	S	82.4	98.9	122.3	137.9	161.3	186.2
	R	82.4	76.2	75.4	70.3	69.5	68.7
18	S	83.8	107.8	133.3	150.3	175.8	203.0
	R	83.8	82.9	82.0	76.3	75.4	74.5

Note: Energy Cost = $12.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-10.b

Economic Insulation Thickness (inch) for Supply and Return Pipes for Energy Cost of $12/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)					
	250	300	350	400	450	500
1	3.0	3.0	3.0	3.0	3.0	3.0
2	3.0	3.0	3.0	3.5	3.5	3.5
3	3.0	3.0	3.0	3.5	3.5	4.0
4	3.5	3.5	3.5	3.5	3.5	4.0
5	3.5	3.5	4.0	4.0	4.0	4.0
6	3.5	4.0	4.0	4.5	4.5	5.0
8	4.0	4.5	4.5	5.0	5.0	5.5
10	4.5	5.0	5.0	5.5	5.5	6.0
12	5.0	5.0	5.5	6.0	6.0	6.0
14	5.0	5.0	5.5	6.0	6.0	6.0
16	5.0	5.5	5.5	6.0	6.0	6.0
18	5.5	5.5	5.5	6.0	6.0	6.0

Note: Energy Cost = $12.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-11.a

Maximum Allowable Heat Losses (Btu/h·ft) from Hot Water Supply Pipe (S) and Return Pipe (R) for Energy Cost of $13/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 250	300	350	400	450	500
1	S	24.6	31.4	38.8	46.5	54.4	62.5
	R	24.6	24.4	24.3	24.2	24.0	23.9
2	S	33.1	42.4	52.4	57.9	67.7	77.9
	R	33.1	32.9	32.7	30.0	29.9	29.7
3	S	41.4	53.1	65.6	71.9	84.1	89.7
	R	41.4	41.1	40.8	37.2	36.9	34.1
4	S	44.1	56.5	69.8	83.8	98.0	104.0
	R	44.1	43.8	43.5	43.1	42.8	39.3
5	S	50.5	59.5	73.5	88.2	103.2	118.8
	R	50.5	46.1	45.8	45.4	45.1	44.7
6	S	56.7	66.7	76.4	91.7	107.3	115.6
	R	56.7	51.6	47.6	47.3	46.9	43.7
8	S	62.2	73.8	85.1	102.0	112.1	129.0
	R	62.2	57.1	53.0	52.5	49.1	48.7
10	S	67.0	79.9	92.5	110.9	122.3	140.9
	R	67.0	61.8	57.4	57.0	53.4	52.9
12	S	70.1	84.1	104.0	117.5	137.4	158.4
	R	70.1	65.0	64.4	60.2	59.7	59.1
14	S	74.8	89.8	104.5	125.4	146.7	169.2
	R	74.8	69.3	64.7	64.1	63.5	62.8
16	S	76.9	98.9	114.9	137.9	161.3	186.2
	R	76.9	76.2	71.0	70.3	69.5	68.7
18	S	83.8	107.8	125.1	150.3	175.8	203.0
	R	83.8	82.9	77.1	76.3	75.4	74.5

Note: Energy Cost = $13.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-11.b

Economic Insulation Thickness (inch) for Supply and Return Pipes for Energy Cost of $13/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)					
	250	300	350	400	450	500
1	3.0	3.0	3.0	3.0	3.0	3.0
2	3.0	3.0	3.0	3.5	3.5	3.5
3	3.0	3.0	3.0	3.5	3.5	4.0
4	3.5	3.5	3.5	3.5	3.5	4.0
5	3.5	4.0	4.0	4.0	4.0	4.0
6	3.5	4.0	4.5	4.5	4.5	5.0
8	4.0	4.5	5.0	5.0	5.5	5.5
10	4.5	5.0	5.5	5.5	6.0	6.0
12	5.0	5.5	5.5	6.0	6.0	6.0
14	5.0	5.5	6.0	6.0	6.0	6.0
16	5.5	5.5	6.0	6.0	6.0	6.0
18	5.5	5.5	6.0	6.0	6.0	6.0

Note: Energy Cost = $13.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-12.a

Maximum Allowable Heat Losses (Btu/h·ft) from Hot Water Supply Pipe (S) and Return Pipe (R) for Energy Cost of $14/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F) 250	300	350	400	450	500
1	S	24.6	31.4	38.8	46.5	54.4	62.5
	R	24.6	24.4	24.3	24.2	24.0	23.9
2	S	33.1	42.4	48.3	57.9	67.7	77.9
	R	33.1	32.9	30.2	30.0	29.9	29.7
3	S	41.4	53.1	60.0	66.7	78.0	89.7
	R	41.4	41.1	37.4	34.6	34.3	34.1
4	S	44.1	56.5	69.8	77.3	90.4	104.0
	R	44.1	43.8	43.5	39.9	39.6	39.3
5	S	50.5	59.5	73.5	88.2	103.2	118.8
	R	50.5	46.1	45.8	45.4	45.1	44.7
6	S	52.0	61.9	76.4	91.7	107.3	115.6
	R	52.0	48.0	47.6	47.3	46.9	43.7
8	S	57.5	68.8	85.1	95.8	112.1	121.9
	R	57.5	53.4	53.0	49.5	49.1	46.1
10	S	62.3	74.8	92.5	104.6	122.3	140.9
	R	62.3	57.9	57.4	53.8	53.4	52.9
12	S	65.5	84.1	97.9	117.5	137.4	158.4
	R	65.5	65.0	60.7	60.2	59.7	59.1
14	S	70.0	89.8	104.5	125.4	146.7	169.2
	R	70.0	69.3	64.7	64.1	63.5	62.8
16	S	76.9	98.9	114.9	137.9	161.3	186.2
	R	76.9	76.2	71.0	70.3	69.5	68.7
18	S	83.8	107.8	125.1	150.3	175.8	203.0
	R	83.8	82.9	77.1	76.3	75.4	74.5

Note: Energy Cost = $14.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-12.b

Economic Insulation Thickness (inch) for Supply and Return Pipes for Energy Cost of $14/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)					
	250	300	350	400	450	500
1	3.0	3.0	3.0	3.0	3.0	3.0
2	3.0	3.0	3.5	3.5	3.5	3.5
3	3.0	3.0	3.5	4.0	4.0	4.0
4	3.5	3.5	3.5	4.0	4.0	4.0
5	3.5	4.0	4.0	4.0	4.0	4.0
6	4.0	4.5	4.5	4.5	4.5	5.0
8	4.5	5.0	5.0	5.5	5.5	6.0
10	5.0	5.5	5.5	6.0	6.0	6.0
12	5.5	5.5	6.0	6.0	6.0	6.0
14	5.5	5.5	6.0	6.0	6.0	6.0
16	5.5	5.5	6.0	6.0	6.0	6.0
18	5.5	5.5	6.0	6.0	6.0	6.0

Note: Energy Cost = $14.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-13.a

Maximum Allowable Heat Losses (Btu/h·ft) from Hot Water Supply Pipe (S) and Return Pipe (R) for Energy Cost of $15/MBtu

Pipe Size (inch)	Pipe Type	Process Fluid Temperature (F)					
		250	300	350	400	450	500
1	S	24.6	31.4	38.8	46.5	54.4	62.5
	R	24.6	24.4	24.3	24.2	24.0	23.9
2	S	33.1	42.4	48.3	57.9	67.7	77.9
	R	33.1	32.9	30.2	30.0	29.9	29.7
3	S	41.4	53.1	60.0	66.7	78.0	89.7
	R	41.4	41.1	37.4	34.6	34.3	34.1
4	S	44.1	56.5	69.8	77.3	90.4	104.0
	R	44.1	43.8	43.5	39.9	39.6	39.3
5	S	50.5	59.5	73.5	88.2	103.2	118.8
	R	50.5	46.1	45.8	45.4	45.1	44.7
6	S	52.0	61.9	76.4	91.7	107.3	115.6
	R	52.0	48.0	47.6	47.3	46.9	43.7
8	S	57.5	68.8	85.1	95.8	112.1	121.9
	R	57.5	53.4	53.0	49.5	49.1	46.1
10	S	62.3	74.8	92.5	104.6	122.3	140.9
	R	62.3	57.9	57.4	53.8	53.4	52.9
12	S	65.5	84.1	97.9	117.5	137.4	158.4
	R	65.5	65.0	60.7	60.2	59.7	59.1
14	S	70.0	89.8	104.5	125.4	146.7	169.2
	R	70.0	69.3	64.7	64.1	63.5	62.8
16	S	76.9	92.9	114.9	137.9	161.3	186.2
	R	76.9	71.7	71.0	70.3	69.5	68.7
18	S	83.8	101.2	125.1	150.3	175.8	203.0
	R	83.8	78.0	77.1	76.3	75.4	74.5

Note: Energy Cost = $15.00/MBtu
Return Pipe Temperature = 250 F

TABLE C-13.b

Economic Insulation Thickness (inch) for Supply and Return Pipes for Energy Cost of $15/MBtu

Pipe Size (inch)	Process Fluid Temperature (F)					
	250	300	350	400	450	500
1	3.0	3.0	3.0	3.0	3.0	3.0
2	3.0	3.0	3.5	3.5	3.5	3.5
3	3.0	3.0	3.5	4.0	4.0	4.0
4	3.5	3.5	3.5	4.0	4.0	4.0
5	3.5	4.0	4.0	4.0	4.0	4.0
6	4.0	4.5	4.5	4.5	4.5	5.0
8	4.5	5.0	5.0	5.5	5.5	6.0
10	5.0	5.5	5.5	6.0	6.0	6.0
12	5.5	5.5	6.0	6.0	6.0	6.0
14	5.5	5.5	6.0	6.0	6.0	6.0
16	5.5	6.0	6.0	6.0	6.0	6.0
18	5.5	6.0	6.0	6.0	6.0	6.0

Note: Energy Cost = $15.00/MBtu
Return Pipe Temperature = 250 F

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The calculation of heat losses for shallow trench underground heat distribution systems was performed using a finite element computer program. The finite element analysis solved a two-dimensional steady-state heat transfer problem for two insulated pipes in a rectangular trench with surrounding soil. A life-cycle cost analysis was performed to determine the cost of construction and annual energy cost associated with pipe heat loss for underground concrete trench systems of different trench dimensions and insulated pipe sizes. Procedures for determining the pipe heat losses associated with the minimum life-cycle cost and the corresponding optimum insulation thickness for shallow trench distribution systems are presented. Based on the results of the economic analysis, the maximum allowable heat losses and the insulation thickness for underground pipes were determined and tabulated for a range of pipe sizes and fluid temperatures, various levels of fuel costs, and for a known undisturbed earth temperature and soil thermal conductivity.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

district heating and cooling; finite element method; fuel energy cost; heat loss; life-cycle cost analysis; pipe insulation thickness; shallow trench; underground heat distribution system.

13. AVAILABILITY

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