ORNL/HUD/MIUS-22

MIUS TECHNOLOGY EVALUATION

THERMAL ENERGY CONVEYANCE

J. T. Meador

hudmius

MODULAR INTEGRATED UTILITY SYSTEMS

improving community utility services/ supplying electricity, heating, cooling, and water/ processing liquid and solid wastes/ conserving energy and natural resources/ minimizing environmental impact

U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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J. T. Meador

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FOREWORD

The Department of Housing and Urban Development (HUD) is conducting the Modular Integrated Utility System (MIUS) Program, which is devoted to development and demonstration of the technical, economic, and institutional advantages of integrating the systems for providing all or several of the utility services for a community. The utility services include electric power, heating and cooling, potable water, liquid waste treatment, and solid waste management. The objective of the MIUS concept is to provide the desired utility services consistent with reduced use of critical natural resources, protection of the environment, and minimized cost. The program goal is to foster, by effective development and demonstration, early implementation of the integrated utility system concept by the organization, private or public, selected by a given community to provide its utilities.

Part of the effort undertaken in the Program by the Oak Ridge National Laboratory was an evaluation of the applicability of thermal energy conveyance technology to MIUS. Treatment of subject matter was limited in scope to the interests of the Program. The evaluation stresses those aspects that are most vital to their MIUS application, and it is not intended to be a complete documentation of the technology. MIUS thermal energy distribution systems should utilize low-grade or recoverable heat from exhaust systems that usually produce low-temperature hot water. Emphasis is placed on availability, performance, and cost.

Under HUD direction, several agencies are participating in the HUD-MIUS Program, including the Energy Research and Development Administration, the Department of Defense, the Department of Health, Education and Welfare, the Department of the Interior, the Environmental Protection Agency, the National Aeronautics and Space Administration, and the National Bureau of Standards.

Drafts of technical documents are reviewed by the participating agencies. Comments are assembled by the NBS Team, HUD-MIUS Project, into a Coordinated Technical Review. The draft of this publication received such a review, and all comments were resolved with HUD.

ABSTRACT

Thermal energy produced by a MIUS can be distributed at moderate temperatures, and low-pressure steam or water are most adaptable as energy-transfer media. This report discusses the types, cost, and performance of several types of conduits for thermal energy conveyance. Other aspects of thermal energy conveyance systems are discussed in less detail. Conduits applicable to water conveyance of thermal energy produced in a MIUS are evaluated from data on characteristics and economic factors related to district heating and cooling systems for housing developments.

Many different types of conduit and methods of construction are used in existing thermal energy conveyance systems. Types that are most prevalent, both in older systems that are still in operation and in more recent installations that include improvements in methods and materials, are illustrated and discussed. Information on long-term performance is included, where available, from inspection reports on various types of conduit in existing systems.

Materials of construction are considered according to the demands of the following three major elements of a conduit: (1) the pipe must meet the requirements for conveyance of the heat-transfer media, (2) the insulation must limit thermal losses, and (3) some form of encasement must protect the pipe and insulation from both external loads and the underground environment. Factors such as heat-transfer characteristics, thermal expansion, and creep strength at operating temperature must be considered in the selection of conduit materials. Insulating materials in blanket form and some that are fabricated into preformed shapes to fit steel pipe and fittings are likely to be unsatisfactory in underground service, especially in a damp environment. Some information on the performance of conduits is discussed, and the economics of insulation thickness, based on installed costs in a drainable and dryable conduit, are analyzed.

Commercially available prefabricated conduits with or without insulation are considered with respect to their ability to meet energy conveyance requirements at installed costs that are based on present-day economics. Selection of a preferred type of conduit for a district heating or cooling system requires knowing many factors from detail system design. Illustrative analyses that include most of the design parameters involved in thermal conveyance are presented to put into perspective the most important features of such systems. Another factor that may influence the selection is the installation labor costs. Prefabricated conduits made of mild steel with corrosion-resistant coatings or of fiberglass-reinforced epoxy seem most likely to meet the requirements of a MIUS for low-temperature hot-water (LTHW) service. Conduits made of asbestos-cement or a thermoplastic such as polyvinyl chloride are considered less expensive and adequate for chilled-water service.

1. INTRODUCTION

Selection of a thermal energy distribution system to provide heating or cooling for a MIUS-type facility requires a detailed economic study that incorporates all the factors involved in a specific design for a fixed arrangement of buildings and equipment. However, certain basic considerations have an impact on the overall optimization of integrated, district, onsite thermal energy conveyance systems. Some of the considerations, such as those leading to the choice of heat-transfer media, containment materials, insulation, conduit casing or envelopes, and mechanical aspects of thermal energy distribution, are discussed in this report. Another factor that will influence the selection is the installation labor cost. In this report, the conduit is treated in much greater depth than the other aspects of a thermal energy conveyance system, and special emphasis is placed on estimates of the installed cost of several commercially available types of conduit.

The meaning of the term "conduit," as applied to heat conveyance systems, is not always clear. However, in this report, "conduit" is defined as the complete assembly of pipe, insulation, and casing or envelope.

2. HEAT-TRANSFER MEDIA

Temperature is the primary factor in the selection of a heat-transfer medium. Water and steam are the most widely used media, but other fluids may be used for temperatures below 32° or at temperatures that produce excessively high steam pressure. Relative to district heating and cooling systems, water installations are classified as low-, medium-, or high-temperature systems; whereas, steam installations are classified as low-, intermediate-, or high-pressure systems.

2.1 WATER AND STEAM

For many years, high-temperature water and high-pressure steam have been distributed from central heating plants or steam-power-generating stations to outlying buildings through underground insulated piping systems. Many of the steam systems were built in conjunction with variable-extraction steam turbines where the turbines could be run as fully condensing to meet peak electrical demand, but where steam could be bled at intermediate pressures when warranted by the thermal demand. In the United States, most early developments of direct-fired central heating plants used steam as a heat-supply medium, but, in Europe, high-temperature water has always been most popular.[1] Many medium- to low-temperature systems have been developed for both steam and hot water, and, because of the major increase in these distribution systems over the last decade, the following classifications for water have been established:

1. Chilled-water systems (35 to 55°F);
2. Dual-temperature systems in two ranges (35 to 210°F and 35 to 250°F) so that the distributed water may be either heated or chilled, depending on the season;
3. Low-temperature hot water* (150 to 210°F and 211 to 250°F).

These class ranges were defined by a special advisory committee of the Building Research Advisory Board (BRAB), which included recognized specialists in technical liaison with 18 manufacturer representatives, who met periodically with the committee.[2] Therefore, similar designations for classification of chilled-water (ChW) and low-temperature hot-water (LTHW) systems are used in this report.

Medium-temperature hot water (MTHW), as used in this report, refers to water temperatures from 250 to 300°F. The term "high-temperature hot water" (HTHW) has developed in common usage along with the development of district heating systems. The term usually refers to water temperatures of at least 300°F and in some installations may refer to temperatures as high as 400°F.

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*Although condensate return lines of steam distribution systems are not encompassed in this study, any guidelines for low-temperature hot-water systems should be applicable to such lines.

Steam distribution systems may also be classified according to low-, intermediate-, or high-pressures. (Note: The relationships between saturated steam temperatures and steam pressures are well known.) However, for steam heating systems, ASHRAE[3] classifies a low-pressure system as one with pressures that vary from 0 to 15 psig and a high- (medium) pressure system as one with operating pressures above 15 psig. The high-pressure-steam region, from 15 to 125 psig, includes the usual operating range of MTHW to a temperature of about 350°F.

Before deciding between hot water and steam as a heat-transfer medium, some of the characteristics and properties of both should be considered. When ebullient systems are used to cool internal-combustion piston engines, the recovered heat is contained in low-pressure (∿15 psig) steam, due to limitations on the engine operating temperature. This steam is suitable for use in nearby single-stage absorption chillers and for other nearby low-temperature heating requirements. For district heating purposes, it may be better to transfer this heat to an LTHW system. However, if somewhat higher-temperature water or low- to intermediate-pressure steam is available from other types of prime movers (or heat-recovery equipment), then the performance and economic factors of both water and steam should be evaluated in terms dictated by the demands placed on the system.

Some of the factors that influence the choice of hot water vs steam for heating and cooling systems are as follows:

1. Hot water has a higher heat-storage capacity per unit volume than steam; whereas, steam carries a greater amount of heat per unit weight.

2. In hot-water systems, thermal energy is transferred over a specified temperature range, and the heat flow rate is established by the limiting temperatures and the fluid flow rate. In steam systems, energy is transferred by a constant temperature process, and, when the design pressure (and, thus, condensation temperature) is fixed, the heat supply rate is directly proportional to the fluid flow rate.

3. The high heat-storage capacity of HW is one of the advantages of HW over low-pressure steam. However, consideration of some parameters in item 6 below may be necessary to ensure that the high heat-storage capability of HW is fully utilized. For example, assumed values for fluid (or steam) velocity and the pressure drops used to determine conduit sizes affect the difference between supply and return heat content. All such design factors tend to be appreciably different for HW and low-pressure steam.

4. Hot-water systems will usually require pumps in the return as well as the supply mains; whereas, only a condensate pump is required in the steam system. However, condensate traps add

to the capital and maintenance costs of the steam system and tend to offset the pumping costs of an HW system.

5. A major difference between HW and steam systems is related to the methods of thermal energy production. MTHW or HTHW production as a by-product of steam plant power production has less effect on lowering the efficiency of electrical generation than steam production (or bleed-off) at the same temperature, when an equivalent amount of fuel energy is used in the boiler of the power plant. However, for these conditions, the HW will not deliver as much energy to a district heating system.

6. Many other factors involving both energy and cost, such as heat-transfer parameters, insulation, maximum distance of conveyance, fuel cost, installation requirements, treatment additives and equipment, etc., must be considered before preference between HW or steam can be established for a particular district heating and cooling system. Such comparisons may well depend on the location and distribution pattern of the consumers.

2.2 OTHER HEAT-TRANSFER FLUIDS

Below the freezing point of water, fluids (e.g., brines), solutions of glycol and water, air, and refrigerants (e.g., halogenated hydrocarbons and ammonia) may be used.[4]

Organic fluids have been used in high-temperature heat-transfer systems for many years; among them are the following trademark names: Dowtherm, Humbletherm, Mobiltherm, and Therminol. When high temperatures are required of a system, the cost of high-pressure steam piping can make these fluids economically competitive. For example, at 500°F the vapor pressure of steam is 681 psia, while Dowtherm A, at 500°F, would operate at atmospheric pressure. At 750°F, steam is above its critical temperature, and, even at critical pressure (3206 psia), steam has all the characteristics of a vapor and no characteristics of a liquid.[5] Dowtherm A, at 750°F, has a vapor pressure of 153 psia (Note: the recommended piping material for Dowtherm A systems is stainless steel).*

Certain properties of organic fluids must also be considered in evaluating their applications. The toxicity of the material, if leaked to the environment, should be studied. Also, nonchlorinated organic fluids can burn; Downtherm A has a firepoint temperature of 275°F. Chlorinated compounds will not burn, but, at high enough temperatures, they do have a flash point and explosive range. Degradation of organic fluids sometimes results in corrosive or reactive products.[4]

Chlorinated heat-transfer compounds are generally noncorrosive to mild steel if water does not leak into the system and the fluid is not

*Manufacturer's literature.

overheated. However, if halogenated materials are overheated, hydrogen chloride gas is released. This relatively noncorrosive gas will unite with traces of water to form highly corrosive hydrochloric acid. Chlorides in conjunction with stress can cause failure of some types of stainless steel if water is present. The system must be leak-tight before introducing the media, and welded joints are recommended; where flanges are used, they must be very thick and heavy to maintain tight joints without becoming warped.[4]

Tables D.1 and D.2 of Appendix D (reproduced from ref. 4) show that the usable temperature range of organic fluids includes that of a typical MIUS facility. However, they are economical only if the design temperature is about 350°F (above which steam pressure increases more and more rapidly with temperature rise).

3. PIPING MATERIALS[6,7]

The materials most commonly used in water and steam district heating and cooling systems are iron, steel, concrete, asbestos-cement-fiber, plastic, copper, copper alloys, and aluminum alloys. In order to better understand how materials meet requirements of piping for thermal distribution systems, these materials are grouped into ferrous metal, nonferrous metal, and nonmetal classifications. Since underground piping materials must be capable of withstanding design stresses and remaining relatively unaffected by a harsh environment for long periods of time, they must not only meet pressure code requirements but must resist creep, fatigue, corrosion, and erosion from the heat-transfer fluid. Minimum requirements for district heating systems are prescribed in a standard published by the American National Standards Institute (ANSI).[8] A very good summary of piping information that can be used as a concise guide to understanding most of the parameters involved in the design of a piping system is included in ref. 9. Much of the information in this report is based on an extensive investigation made by BRAB and data included in ref. 10.

3.1 THE FERROUS MATERIALS — IRONS AND STEELS

Cast iron, one of the earliest materials used in metal pipe, is still widely used in water and sewer lines. It has a high resistance to atmospheric and soil corrosion (in most soils) that makes it adaptable to thermal energy conveyance piping. Flanged joints of cast iron pipe meet the code requirements of ANSI Section B31.1,[8] which allows steam pressures up to 250 psi. Cast irons are comparatively brittle but have acceptable strength. Use of cast iron pipe with bell-and-spigot-type joints in underground water or drainage lines can allow for some ground settling without the occurrence of fractures or leaks. A bituminous coating is often applied to improve corrosion resistance.[11]

Wrought iron is practically carbon-free iron containing stringy or platelike inclusions of glasslike slag that deter or reduce corrosion caused by some of the agents (e.g., hot condensate and effluents) found in thermal energy conveyance media. Although wrought iron is highly corrosion resistant, it is rather expensive (particularly the pipe fittings). Smaller sizes (1-1/4 to 2 in.) can be butt- or lap-welded, but sizes greater than 12 in. require fusion welds. Plant experience is usually necessary to determine whether wrought iron can be used economically to solve a corrosion problem in any given application.

Ductile cast iron, sometimes referred to as malleable iron, is a modified form of cast iron in which the graphite (carbon) is in nodules instead of flakes (as seen in the microstructure of the metal). Such modification serves to reduce the brittleness of regular cast (gray) iron. Ductile cast iron pipe is stronger as well as more ductile (10 to 25% elongation for some standard grades) than gray cast iron pipe; however, because welding temperatures may affect its strength, ductile cast iron pipes are usually joined with screwed fittings.[12]

The ferrous material used most extensively, in terms of type of media common to energy conveyance systems and in overall tonnage, is low-carbon steel pipe. This type of pipe is used to carry low- and medium-pressure steam, water, fuel oil, compressed air or gases, condensate, and some effluents. Some significant alloying elements are present in nearly all steels, including low-carbon steels. Many compositions of these steels can be extruded into seamless pipe. Thus, this most economical fabricating process can produce a pipe of low-carbon steel that can be butt welded, resistant welded, or filler welded. Carbon content in low-carbon steel pipe is 0.05% to about 0.25%. In this range, the steel is easily welded and the carbon content, although adding somewhat to strength, is not enough to harden the metal, even with the cold work or heat treatment that is sometimes applied.

The major problem with low-carbon steel pipe is its lack of corrosion resistance. Although this is especially true with hot-water or condensate piping used in thermal energy conveyance, corrosion on the inside pipe wall can be minimized through good makeup-water-treatment practices. Corrosion on the outside of the pipe is not as great on HTHW (over 300°F) lines as on LTHW lines, because any water that tends to seep into or through the insulation is often evaporated without appreciable corrosion of the hot external surfaces of the pipe. Also, in comparing HTHW to steam, the inside of the pipe is not as badly affected, because the HTHW is confined to a closed system that requires minimum makeup water and chemical treatment.[13]

Stainless steels could solve some of the corrosion problems of thermal energy conveyance, but the cost of stainless steel pipe of equal wall thickness is about two to three times that of a good-grade low-carbon steel. Of course, for some organic heat-transfer media, either stainless steel or some type of anticorrosive pipe is virtually essential.

3.2 NONFERROUS METALS

Pipe and tubing made of nonferrous metals is not used extensively in underground mains for thermal conveyance systems. However, they are used extensively in branch connections in apartment buildings, in heating and cooling equipment buildings, and in heat-rejection equipment. Some prefabricated copper tubing (about 2 in. diam) in an insulated conduit casing and with special tubing joints is commercially available for underground service.

Brass, bronze, and other copper-alloy pipe and tubing suitable for low- and medium-temperature service is available in many different chemical compositions. Red brass is used in clean water supplies, admiralty bronze is often used in salt water applications, and copper and brass tubing predominates in heat-exchanger equipment. Copper's corrosion resistance and good workability result in neat, durable piping; but, because of its cost, copper is usually used in small-size (<2 in.) water, steam, and air lines in buildings or around machinery and equipment. Thin-wall copper tubing and brass fittings are used; these have a temperature limit of about 400°F. Aluminum and its alloys are lightweight and are often used in place of copper or copper alloys, especially for condenser tubing. Aluminum-clad alloys resist corrosion better than plain aluminum alloys. Common aluminum alloys can be supplied as pipe in fairly hard tempers at a cost equal to or less than the copper alloys.[6] Copper alloys in small (1/4 to 2 in.) tubing sizes, joints, and fittings are usually connected either by brazing or with socket-type fittings adaptable to soft or hard soldering. Careful joining techniques are necessary because, even at low pressures, joints made of soft solder without good surface adhesion can result in leaks.

Dezincification is a problem with zinc-containing copper alloys — the alloy dissolves and the copper redeposits in a porous pure-metal form.

3.3 NONMETALLIC MATERIALS

The types of nonmetallic materials that have shown continued use or development for thermal energy conveyance include those (a) that have one or more desirable properties, and (b) that can be combined with some other material(s) that tends to offset their weaknesses. One such combination is asbestos-cement pipe material. This type of pipe is pressure-formed from asbestos, cement, and silica, and is then steam-cured for chemical stability. Asbestos-cement pipe is often used in water lines because of its resistance to corrosion and its permanent smoothness and resulting low resistance to flow. Salt water and corrosive soils will not affect asbestos-cement by causing tuburculation or internal pipe roughness that retards fluid flow. The cement and silica combination has the major advantage of corrosion resistance and the asbestos fiber adds to the strength of the combination. An inside-pipe-surface treatment, such as an epoxy lining, is recommended for asbestos-cement pipe when conveying extremely soft water or highly acid solutions.[11]

Asbestos-cement pipe cuts easily and can be drilled and tapped in the field. A disadvantage of asbestos-cement pipe is its relative brittleness and, consequently, it is susceptible to damage from crushing by heavy excavating equipment or heavy trucks. Sizes up to 36 in. that are capable of withstanding pressures up to 200 psi at temperatures up to 150°F are available. Joints can be asbestos-cement couplings that usually use rubber or plastic ring seals.

Concrete pipe has been used for many years in large water mains and sewer lines, and nonpressure-tight concrete pipe is available in sizes ranging down to about 4 in. Pressure-tight concrete pipe (prestressed) is available in sizes down to about 16 in. Concrete has a high flow coefficient, which may actually decrease with use due to the accumulation of deposits in the initially rough concrete surface inside the pipe.

A slick surface with lower flow resistance can be formed by such deposits. Concrete pipe is corrosion-resistant and can withstand significant external loads. Attempts to combine concrete pipe with other materials, such as epoxy (for liners) or steel external reinforcing, have seen only limited application in thermal energy conveyance systems.

Another nonmetallic combination of materials that has been developed and used for thermal energy conveyance systems is fiberglass combined with thermosetting plastics. Epoxies, polyesters, and phenolics are the chief thermosetting materials combined with fiberglass reinforcement, usually in the form of multiple layers of filaments, to add strength. Some reinforced plastics are claimed to be good for temperatures to 300°F in steam or HTHW service. These thermosetting resins should not be confused with the more common plastic materials that have been used in drain and vent piping for more than ten years and are referred to in this report as thermoplastic materials. Major differences exist in the possible methods of pipe fabrication and makeup of field connections with these two types of plastic.

The most common thermoplastic materials used in pipe are acrylonitrile-butadiene-styrene (ABS), polyvinyl-chloride (PVC), polyethylene (PE), and cellulose-acetate-butyrate (CAB).

Under controlled temperatures, these materials can be heated until they are in the plastic temperature range and extruded into a lightweight corrosion-resistant pipe. Also, they can be joined with the thermoweld process using a patented heating device in molded fittings. These thermoplastic pipes are limited to hot-water pressures of less than 100 psia and maximum temperatures of about 200°F. Some of the allowable operating temperatures may be even lower, because thermoplastic materials tend to creep under comparatively low combined stresses from bending loads and internal pressures. This means that the pipe requires even shorter lengths between supports than steel pipe of the same size. An additional factor that must be considered in design is the absorption type of pipe corrosion that results in a weight gain and further adds to the load on the thermoplastic pipe.[14,15]

Epoxies, in various degree[illegible] hardness and strength, are the thermosetting resins that have been most developed in some combination form with fiberglass reinforcement. Two methods of pipe fabrication using multicomponent walls are shown in Fig. 3.1. The diagonally reinforced method with two helical winding directions for the fiberglass filaments is shown in the upper part of the figure. All filaments are embedded in the epoxy matrix and take both hoop and longitudinal stress. The smooth interior that is formed against a mandrel resists corrosion and facilitates flow.

The circumferentially reinforced method, shown in the lower part of Fig. 3.1, is suitable for low-temperature water pipe applications, and its use can reduce costs. The circumferential filament winding accepts hoop stress, and sand mortar or other inexpensive fillers may replace part of the polyester thermosetting resin. A longitudinal group of glass filaments is required for the axial wall stress.

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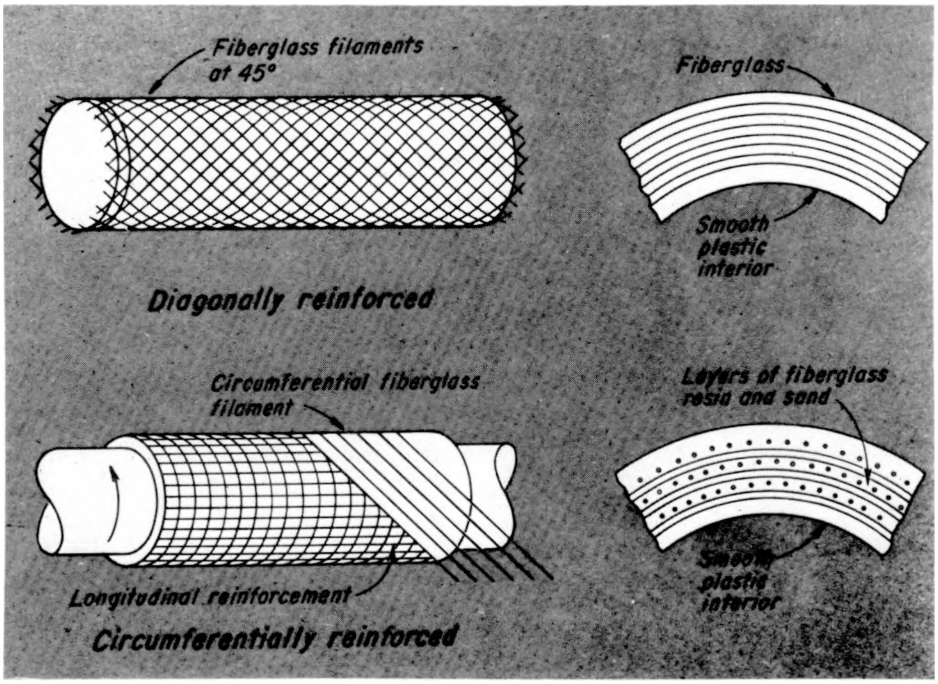

Fig. 3.1. Types of reinforced epoxy pipe. From T. W. Edwards, "Piping," *Power* 104(6): 51-66 (June 1960), with permission from McGraw-Hill.

This filament winding method for production of fiber-reinforced-plastic (FRP) pipe allows a choice of laminates that can give high densities and ultimate strength on the order of 30,000 psi. Fiber-reinforced-plastic pipe requires supports spaced at about half the distance needed for metal piping. Manufacturers claim that smaller sizes of FRP mounted on supports about 12 ft apart have given satisfactory service in use with 300°F steam, steam condensate, or HTHW.

In recent years FRP pipe has been used in underground applications, especially when the nature of the soil is highly corrosive. Though not in use long enough to have data on longevity, the life of FRP pipe is expected to exceed 30 years. Another advantageous feature of FRP pipe is lower installation costs. Because of its light weight, large sections of FRP pipe can be handled more readily and in longer lengths than steel or iron pipe; also, less time is required for assembly.

Joining of most thermosetting plastics is accomplished using various types of bonding cement or mastic in bell-and-spigot or socket-type couplings or fittings. This method of joining sections of FRP pipe can be three to four times faster than welding iron or steel pipe. However, some curing time is usually required. Usually installation requires about 1-1/2 hr from the time of pipe sawing to resin setup. The time for curing is affected by exposure to direct sunlight, and humidity and environmental measures at the site, such as shading for temperature control to about 70 to 80°F, must be considered to optimize setup time.[16]

4. INSULATION

Insulation is usually necessary to minimize heat transfer through the walls of pipe in the energy conveyance system. This is especially true of metallic piping systems, because they have comparatively high heat-transfer coefficients.

Numerous types of insulation are available. The most conventional types include fibrous glass (in bulk or loose fiber form, in preformed shapes, or in matting of uniform thickness), preformed asbestos-fiber-reinforced silica, preformed 85% magnesia, and preformed corrugated asbestos paper. Other insulating materials used in conjunction with some particular type of conduit covering are as follows: insulating concretes, hydrocarbons, cement and rubber concrete, and expanded plastic foams (such as polyurethane).

An ideal material for insulation service should be (1) a nonconductor of electricity, (2) vermin proof, (3) noncorrosive to pipe when wet, (4) capable of withstanding repeated wetting and drying without serious deterioration, and (5) chemically and physically stable at operating temperature.[7,10]

The effectiveness and life of the insulation depends upon how well it is protected by the conduit, or pipe tunnel, both from wetness and from mechanical overloads. An air space should be provided between the carrier pipe and the conduit for drainage of water that may leak in and to permit drying after a leak has been repaired. Insulation should be able to withstand some flexing or movement of the pipe, within a conduit, without cracking, slumping, or taking a permanent set. This is especially important in covering elbows or expansion loops that must accommodate relative expansion.

5. CONDUIT ENVELOPES

Protective coatings and conduit casings that completely enclose and extend the useful life of the insulation should be considered essential in underground systems. Wet or deteriorated insulation is virtually worthless, and many types of conduit have been developed to protect the various types of pipe and their thermal insulation from wetness, corrosion, and mechanical damage. The mechanical damage results from excessive loads caused by earth compaction or heavy traffic, from loads caused by inadequately designed methods of support, insufficient allowance for thermal expansion, or relative movement of pipe sections within the conduit.

A special design report on underground piping systems classified conduit systems into (1) Class A systems which have a built-up outer casing that is verified as watertight by a field air-pressure test, and (2) Class B systems, where a field air-pressure test is not necessary but air space is provided for drying the insulation and the system is sloped for drainage.[7] However, some conduit systems that pass a pressure test at installation have been found to leak only a few months later, and generally, with the passage of time, water can be expected to seep into all conduit systems, including those with pressure-tight welded metal casings. The major weaknesses of conduit systems are as follows:

1. Inadequate provisions for effective sealing of casing joints at installation;

2. The external coatings of sections of conduit can be broken or improperly repaired after suffering mechanical damage during installation or before completion of burial;

3. The external coatings can be adversely affected by soil corrosion (or erosion) or may deteriorate, in only a few years, due to cycling temperatures and/or relative movement of the conduit inside the trench backfill.

The three aforementioned weaknesses are based largely on information acquired from the extensive investigation of district heating systems that was conducted by BRAB.[10] Also, based primarily on the conclusions of ref. 10, conduits have been grouped into the following basic types: (1) non-pressure tight, (2) poured envelopes, and (3) pressure tight. Descriptions and discussions of some of the various conduit envelopes, based largely on information from ref. 10, are included in Sects. 5.1-5.3.

Some major questions to be answered for each of these envelope assemblies are: How well does it protect the pipe from high stresses due to weight and/or thermal expansion and against corrosion due to inadequate waterproofing or provisions for drying? How well does it insulate, and continue to protect the insulation from deformation or deterioration? How impervious is the conduit to internal wetness and external forces or environment due to its state of direct burial? What are the comparative costs? (The cost factor is discussed in Sect. 9.)

5.1 NONPRESSURE-TIGHT ENVELOPES (FIELD CONSTRUCTION)

5.1.1 Concrete trench

One of the earliest effective conduit forms, completely field erected, is the reinforced concrete trench with a concrete slab-type cover. Steel rods or reinforcing mesh wire is used to strengthen the concrete wall and to aid in the pipe-support arrangement. A perforated drain pipe or cover over a groove is added in the bottom of the trench, and the trench is sloped to drain, usually to each manhole. The roller pipe-support mountings are set in the concrete, and, if the pipe is on more than one level, horizontal rods are held in place with the reinforcing steel while the side walls are constructed. Preformed half-round insulation is used, and only that portion of the pipe in contact with the roller supports is left uninsulated. The cover consists of removable, reinforced concrete slabs with joints covered or sealed with bituminous material to minimize seepage into the trench. Where the trench is installed at ground level, the covers can serve the additional function of sidewalks. Of course, heavier sections of reinforced concrete are generally necessary where the conduit is required to cross under roadways. A typical section of a concrete trench and of a reinforced concrete trench is shown in Fig. 5.1. Note that the roller supports are mounted on round rods so that expansion, with relation to 90° bends, may be accommodated by side movement of the rollers along the rod. In some of these conduits, mechanical expansion joints with sliding sleeves and packed seals are used; however, maintenance of such joints is difficult.

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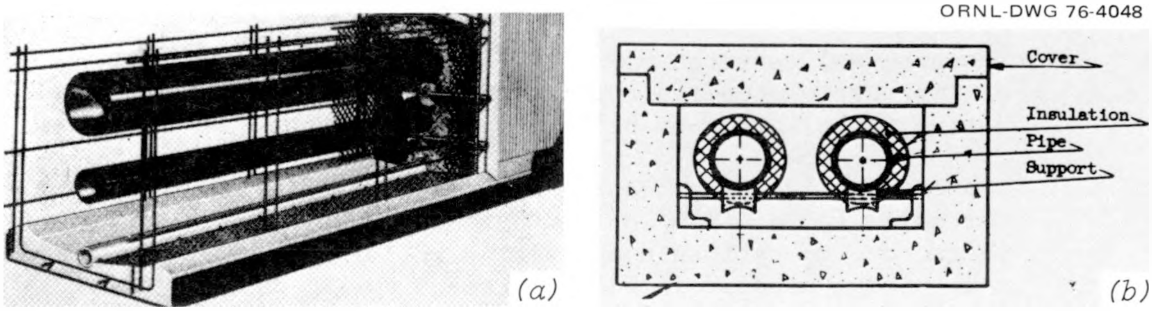

Fig. 5.1. (*a*) Reinforced concrete trench conduit. (*b*) Concrete trench conduit with preformed insulation. (*a*) From S. Elonka, "Underground Piping Systems," *Power* 109(4): 217-224 (April 1965), with permission from McGraw-Hill; (*b*) From *Federal Construction Council Technical Report No. 47 — Field Investigation of Underground Heat Distribution Systems*, Publication 1144, Building Research Advisory Board, National Academy of Sciences — National Research Council, Washington, D.C., 1963.

The main advantages of concrete trenches are strength, durability, and accessibility for maintenance and repair. The primary disadvantage of concrete trenches is their tendency to leak, particularly if cover joints are not sealed properly. The preformed insulation used is usually satisfactory, but dampness penetrating the insulation can cause some pipe corrosion. Loose insulation is seldom satisfactory because it sags or deteriorates in a comparatively short time.

5.1.2 Clay tile on concrete base

These field-erected conduit assemblies are formed by a buildup of sidewalls to support a half-round clay pipe or arch over a continuous concrete slab. The reinforced concrete slab is poured in the bottom of the trench and sloped for drainage. A centered trough is constructed in the slab and covered with a perforated plate to prevent clogging. Mountings for roller pipe supports are set in the base while the concrete is still wet. Short sidewalls made from sections of clay tile (or bricks) are then mounted on the edges of the continuous concrete base to form a support for the half-round lengths of bell-and-spigot or hollow tiles. As an alternate, high-arching tile sections can be used. In either event, before placement of the arch tiles, the pipe lengths are placed on the rollers, field welded, hydrostatically tested, and covered with insulation. The insulation may be in preformed half-round lengths, but in most cases the arched enclosure is simply filled with some loose fibrous type of insulation. The outer covering over the multitude of joints and seams of the tile is usually plastic sheeting or a waterproofed material. A typical section of this type of conduit is shown in Fig. 5.2. The joints of the tile are often sealed with mortar, and a coating of asphalt is usually applied.

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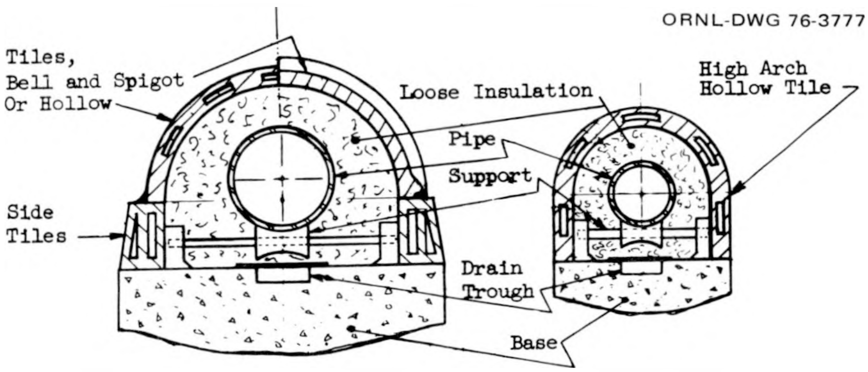

Fig. 5.2. Clay tile on concrete base conduit. From *Federal Construction Council Technical Report No. 47 — Field Investigation of Underground Heat Distribution Systems*, Publication 1144, Building Research Advisory Board, National Academy of Sciences — National Research Council, Washington, D.C., 1963.

Clay tile on concrete base conduit can be constucted to house more than one pipe, but (if U-shaped expansion bends are used in the system) pipe movement inside the conduit may require a very wide section in order to avoid deformation of the insulation. Vitrified tile is impervious to moisture and corrosive soil and has been known to remain essentially unchanged when buried for long periods of time, but adequate sealing of all the joints is very difficult. Slight seepage of groundwater can be tolerated as long as the water can be removed before moisture deteriorates the insulation or piping. Therefore, groundwater levels in the area should be checked before installing a system of this type. These conduits should only be used where groundwater does not rise above the lowest seam in the clay tile. Also, air space for drying insulation in place and provisions for draining the conduit should be provided.

5.1.3 Full-round clay-tile conduit

Full-round clay-tile conduits are field assembled from half-round sections of bell-and-spigot clay-tile pipe; longitudinal and transverse conduit joints are cemented with mortar. The bottom of the lower half-round acts as the drain path. Preformed or loose-fill insulation is used in these conduits, as shown in the two combined half sections in Fig. 5.3. The method of pipe support and allowance for pipe expansion inside the conduit is similar to that for clay tile on a concrete base.

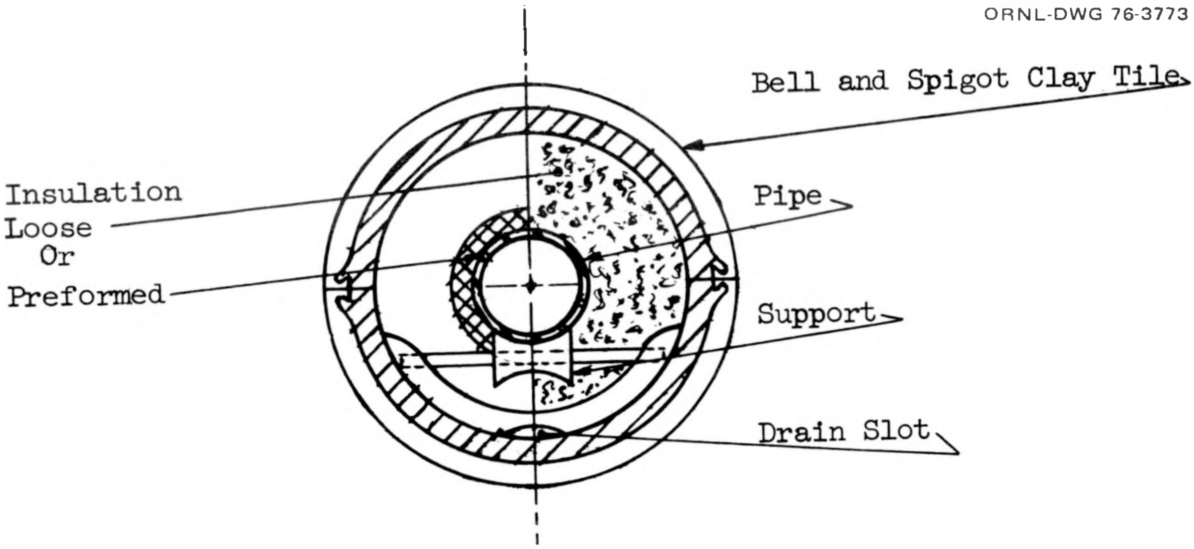

Fig. 5.3. Full-round clay-tile conduit. From *Federal Construction Council Technical Report No. 47 — Field Investigation of Underground Heat Distribution Systems,* Publication 1144, Building Research Advisory Board, National Academy of Sciences — National Research Council, Washington, D.C., 1963.

From inspections of several installations of this type of conduit, the only two installations found to be without damage (to piping or insulation) used preformed insulation and provided water-removal equipment.[10]

The chief disadvantage found was susceptibility to fractures due to the brittleness of both the clay tiles and many mortar joints. A second disadvantage is that repairs to the system are sometimes difficult. Thirdly, because of susceptibility to cracking, these sytems tolerate comparatively little movement underground; consequently, trenching, compaction, and backfilling operations are critical. As for other clay-tile setups, the conduit must be above the groundwater level.

5.1.4 Full-round concrete pipe conduit

These conduits are constructed of two half-round reinforced-concrete pipe sections fitted together in a manner similar to full-round clay-tile conduits. For best results, preformed insulation is used, and the bottom of the conduit is used for drainage.

While the configuration and general construction of concrete pipe conduits are similar to those of full-round clay-tile conduits, concrete pipes have greater strength and resistance to breakage; consequently, they are considered less likely to leak, because of cracks, and less susceptible to breakage resulting from repair work. In all other respects, the systems are comparable and the information on tile conduits is applicable.

5.1.5 Half-round steel on concrete base

This conduit is similar to the "clay tile on concrete base" conduit. The clay-tile arch is replaced by steel sections mounted on a continuous concrete base. The upper section of metal casing that is formed adds strength to the system, and it can be made watertight at installation. The inside and outside of the steel is often corrugated and galvanized. Seams or joints are sealed with bituminous materials. However, in underground installations, the casing is susceptible to accelerated corrosion, and the bituminous seal/coatings were not reliable. Thus far, these systems have not demonstrated satisfactory reliability and, therefore, have not been used extensively.

5.2 POURED ENVELOPES

Poured-envelope conduit is constructed by temporarily supporting pipe in a trench and pouring insulation in the form of a lightweight concrete mix (an aggregate of lightweight materials, such as vermiculite), granular hydrocarbons, or a cement-shredded rubber mixture directly into the trench to form an envelope around the welded pipelines. Any curing process required is incorporated in the methods of field construction. In some instances, concrete pad supports, perforated pipe drains, and plastic trench liners are used. In all these conduits, the combinations of poured insulating materials are intended to provide corrosion and mechanical protection (in addition to insulation) by curing the as-poured materials directly on the steel pipes. Poured-envelope conduit has no specific provision for maintaining dry insulation.

5.2.1 Concrete insulation

The most common existing systems that use concrete-insulation conduit have insulating material made with a mixture of portland cement and vermiculite (expanded mica). The density of the mixture can be varied to be either more firm, for better pipe support, or more yielding, to give or absorb expansion in bends, etc. Protective coverings of asphalt-impregnated felt on either the pipe or the outside of the conduit is used to minimize water infiltration. A typical section is shown in Fig. 5.4.

One attempt at constructing a watertight conduit of this type involved pouring an insulating concrete into an elliptically shaped shell of fiber-reinforced epoxy and sealing a fitted cover to form a complete outer casing,

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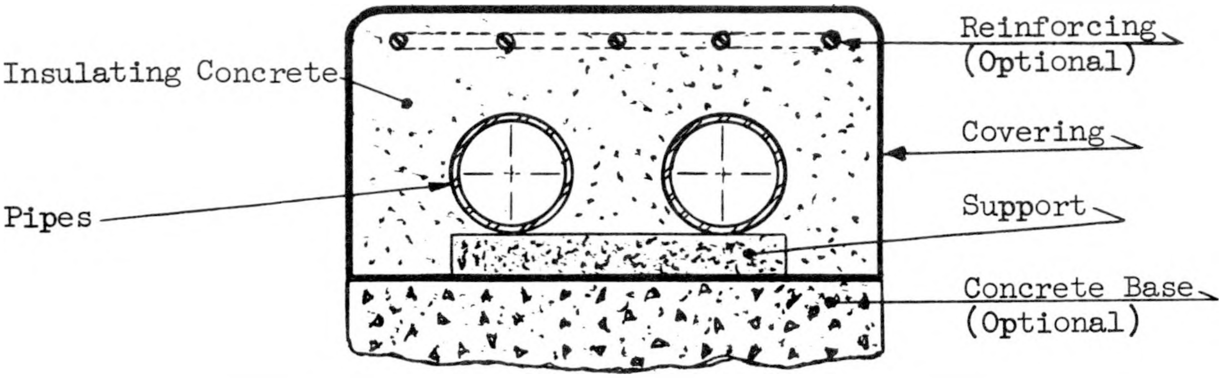

Fig. 5.4. Insulating-concrete envelope. From *Federal Construction Council Technical Report No. 47 — Field Investigation of Underground Heat Distribution Systems*, Publication 1144, Building Research Advisory Board, National Academy of Sciences — National Research Council, Washington, D.C., 1963.

as shown in Fig. 5.5. Support is presumably by the concrete mix, and drains are provided in the bottom of the shell. An installation of this type could not meet the requirements of a pressure test; therefore, it is classified as a poured-in-place arrangement rather than a pressure-tight conduit.

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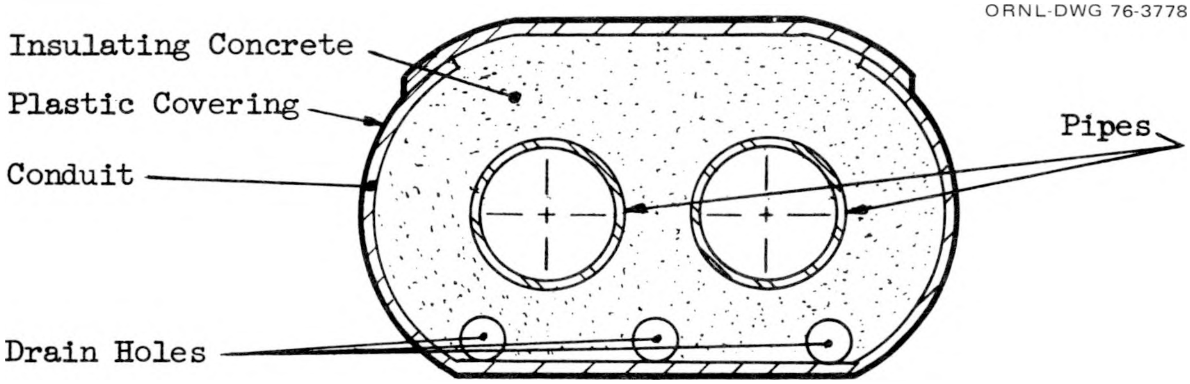

Fig. 5.5. Glass-fiber-reinforced epoxy conduit filled with insulating concrete. From *Federal Construction Council Technical Report No. 47 — Field Investigation of Underground Heat Distribution Systems*, Publication 1144, Building Research Advisory Board, National Academy of Sciences — National Research Council, Washington, D.C., 1963.

A number of the insulating concrete type of conduits inspected by the special committee for BRAB showed signs of infiltrated moisture, pipe corrosion, and evidence of high heat loss. The high heat loss was indicated by high temperatures outside the conduit, excessive temperature drops over the system length, and heat-damaged grass over the installations. Therefore, these envelopes are considered relatively poor in resisting infiltration of normal groundwater and preventing deterioration of the insulating effectiveness.[7,10]

5.2.2 Hydrocarbon insulation

A hydrocarbon envelope is constructed by pouring a natural granular asphaltic material of high resin content[10] around the bare pipes after they have been installed in the trench and hydrostatically tested. The hydrocarbons are then cured by maintaining a controlled temperature in the distribution pipes. The purpose of the curing process is to form a consolidated anticorrosive coating on the pipe, surrounded by a sintered (semiporous) intermediate zone that still has meaningful insulating value, and an outermost zone of loose aggregate (unaffected by the heat) that provides most of the thermal-insulating and load-bearing capabilities. This rather unique method can produce the desired three-zone condition only if the curing temperatures are very carefully controlled. Good overall results can seldom be obtained without adequate supervision by experienced engineers.

An arrangement of the hydrocarbon-insulation envelope is shown in Fig.5.6. Note that some support, at least of a temporary nature, is required to position the pipe in the trench and that there is no positive provision for drainage or drying in the event of leakage through the consolidated zone. Note also that any side movement of the pipes (e.g., due to expansion bends) must deform the hydrocarbons after the cured state is effected. In some cases, a drain pipe outside the unsintered zone is laid in gravel or sand and/or vents can be installed to help release moisture from gravel that surrounds the hydrocarbon envelope.

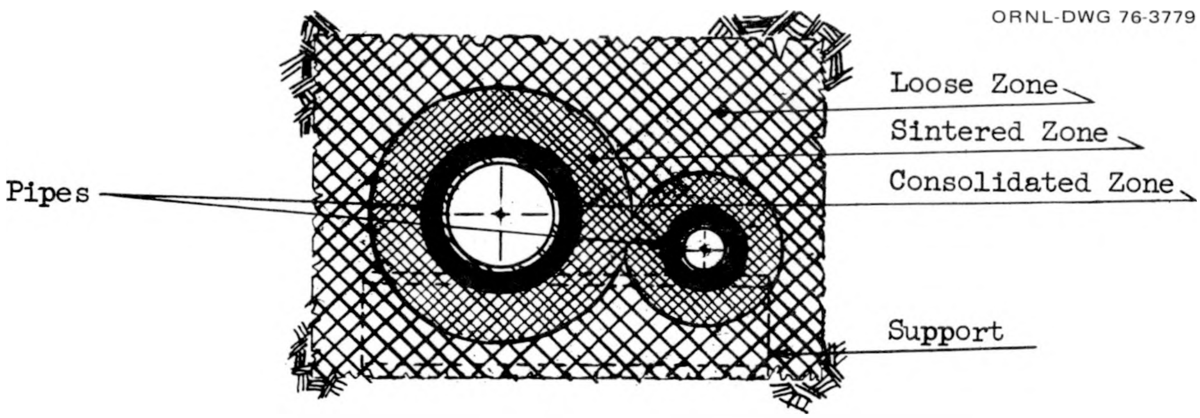

Fig. 5.6. Insulating-hydrocarbon envelope. From *Federal Construction Council Technical Report No. 47 — Field Investigation of Underground Heat Distribution Systems*, Publication 1144, Building Research Advisory Board, National Academy of Sciences — National Research Council, Washington, D.C., 1963.

One of the major problems with this method of installation is that the melting point of asphaltic materials can vary by more than 100°F; therefore, even with carefully graded material, the desired curing may not be uniform. In actual installations, reliable corrosion protection for the pipe was obtained with moderately high-temperature lines. For low temperatures, the consolidated material can become brittle and may crack. Some installations were found to slump (due to overheating at some period of time) and thus were left with almost no loose material to provide good insulation.

5.2.3 Asphalt and insulation

The asphalt and insulation envelope is considered to be a poured envelope but differs from the other envelopes that are poured directly into the trench because predetermined lengths of welded pipe and fittings or bends (often referred to as spool pieces) are factory fabricated. The envelope is constructed by holding a pipe with an asbestos-paper-covered preformed insulation in the center of a sheet metal jacket and filling the annulus with asphalt. A conduit section is shown in Fig. 5.7. The sheet-metal jacket provides a form for containing the asphalt during fabrication, and, after installation, becomes the outer shell or casing of the conduit. Normally, the joints are field constructed in a similar manner.

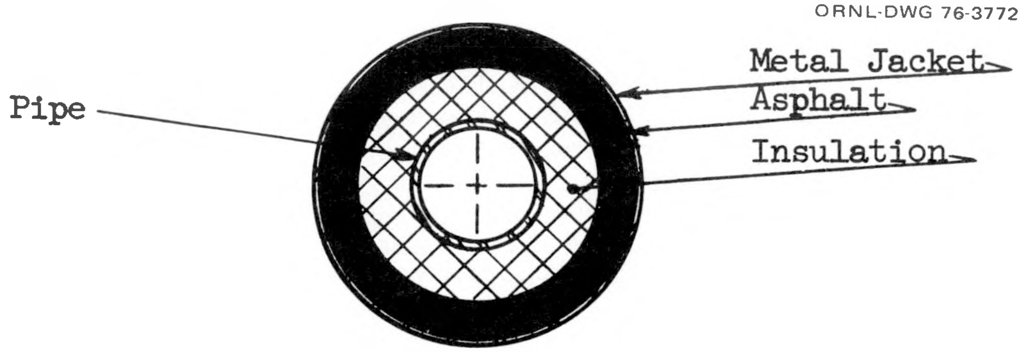

Fig. 5.7. Asphalt and insulation envelope. From *Federal Construction Council Technical Report No. 47 — Field Investigation of Underground Heat Distribution Systems*, Publication 1144, Building Research Advisory Board, National Academy of Sciences — National Research Council, Washington, D.C., 1963.

A lack of provision for drying is obvious. In low-temperature systems with dry insulation, the conduit may be adequate, but, in some cases, temperatures can be sufficiently high to increase heat transfer through sections of the insulation, thereby causing melted asphalt to run into the manholes. Another problem with this type of conduit is the elimination of voids in the asphalt, either in construction or through formation of blow holes due to hot spots in the casing. As with the case in Fig 5.6, a pipe bend undergoing expansion must either deform the insulation or be required to flex the casing.

5.2.4 Cement and rubber

Another poured envelope used in several installations consists of a mixture of portland cement and shredded rubber. With no protective casing and no air space or provision for drying, this type is not considered to be satisfactory.

5.3 PRESSURE-TIGHT ENVELOPES

The use of pressure-testable casing over the insulated pipe provides pressure-tight conduits that are capable of withstanding predictable earth loads and of eliminating entry of water into any section of the conduit. Sections of single pipe inside a conduit are factory fabricated by supporting the pipe in the center of the casing with spiders or rings of insulating concrete. The annulus is either fully or partially filled with insulation, according to whether drying and drainage space is considered necessary. The annular space formed by both the prefabricated sections and the field joints is air-pressure tested at about 15 psia and can be retested periodically as desired. For conduits of this type that house more than one insulated pipe, the casing of the conduit is usually referred to as a carrier pipe. Where even two pipes with preformed insulation are enclosed in a pressure-tight conduit, drainage usually flows in the bottom of the conduit, and relative expansion allowance is provided inside the carrier-type conduit. This type of conduit tends to develop leaks, and, after installation, the exact location of seepage is very difficult to determine.

5.3.1 Prefabricated steel

This type of factory prefabricated conduit can be made of cylindrical or longitudinally corrugated steel with a 16-gage (or heavier) wall. Typical half sections and a field joint are shown in Fig. 5.8. Any ungalvanized joints or welds are given protective coatings of bituminous felt wrap, plastic tape, or enamel. In some cases a gland seal, with an inner ring of packing at the pipe diameter and welded to the conduit at the outer diameter, is used to allow movement of a pipe inside the conduit. Gland seals would be used in pipelines that usually have mechanical expansion joints. Where an insulated annulus is sealed, a vent and drain plug is provided.

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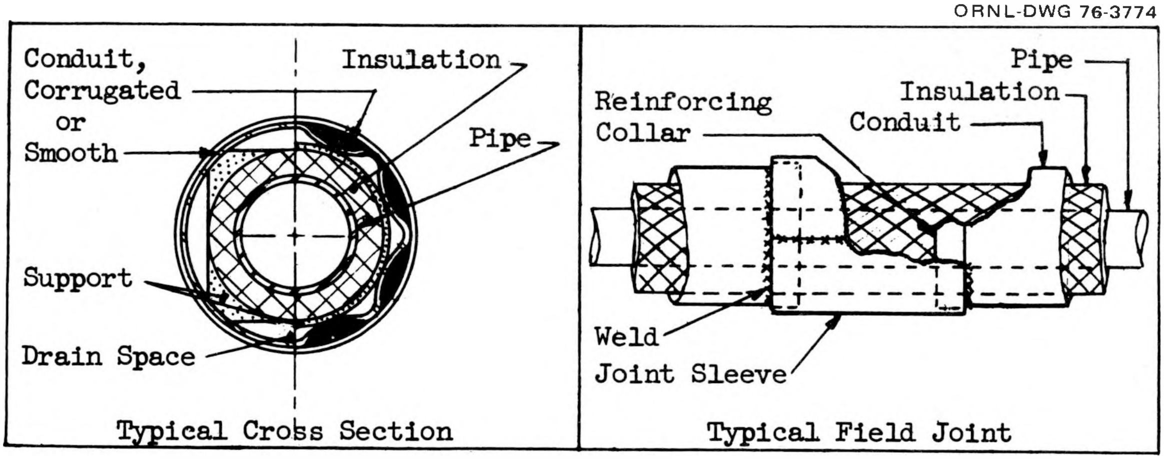

Fig. 5.8. Pressure-tight prefabricated steel conduit. From *Federal Construction Council Technical Report No. 47 — Field Investigation of Underground Heat Distribution Systems*, Publication 1144, Building Research Advisory Board, National Academy of Sciences — National Research Council, Washington, D.C., 1963.

The low-carbon steel conduit is the most popular of the pressure-tested systems and is easily field-welded; therefore, strong joints can be made both pressure-tight and capable of carrying earth loads. Nonetheless, water will evenually enter the conduit. Therefore, the lines should be adequately pitched to drain the air space provided around the insulation. Removable end plugs should be located near the bottom of the conduit end plates. A telltale pipe that extends above the manhole roof is recommended where manhole flooding can occur.[10] A periodic inspection and maintenance progam should be formulated on the basis of pressure-test results.

5.3.2 Sealed asbestos-cement

These conduits are similar in configuration to steel conduit, except they use prefabricated asbestos-cement for both pipe and outer casing. Some of the older conduits were made with gland seals at the end of each section that were bonded to the outer casing with epoxy cement and would allow for expansion by sliding on the pipe diameter. However, pressure tests revealed leaks from areas of poor epoxy adhesion and from delaminations in the base casing material. A more recent design that uses sliding joint couplings fitted with plastic O-ring seals is said to be more dependable. This development also incorporates the use of epoxy linings, polyurethane foam insulation, and plastic end-sealing rings. A typical joint with a detailed coupling section with the more recent seals is shown in Fig. 5.9.[7]

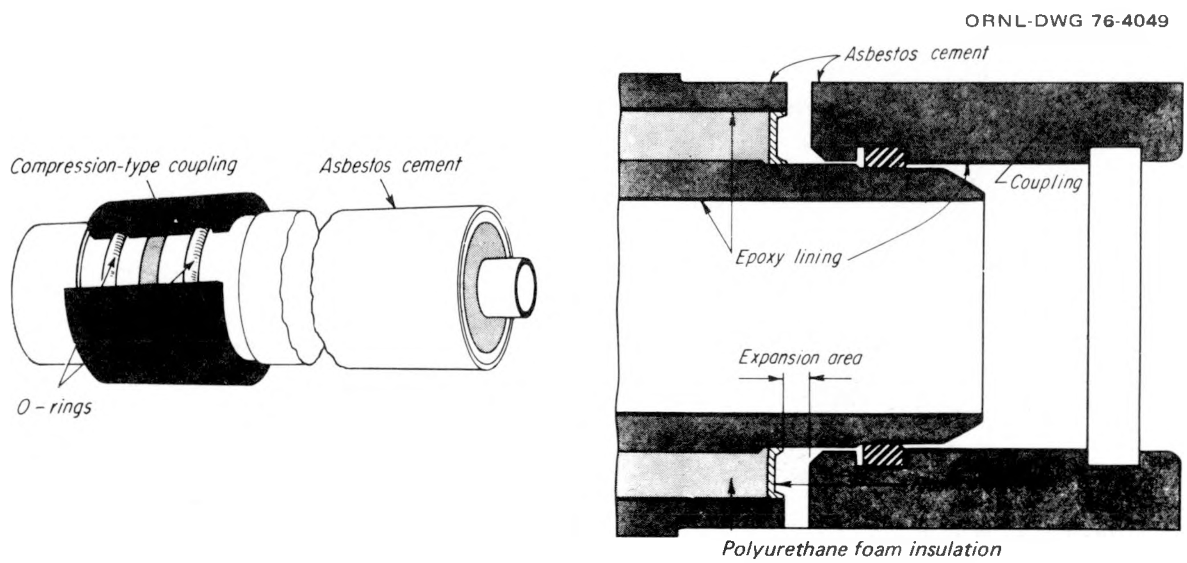

Fig. 5.9. Asbestos-cement conduit coupling and joint section. (Casing and pipe are lined and urethane-foam insulated. Coupling is also expansion joint.) From S. Elonka, "Underground Piping Systems," *Power* 109(4): 217-224 (April 1965), with permission from McGraw-Hill.

Older installations, some of which use preformed insulation and epoxy-coated joints, leaked and were considered by an inspection group from the BRAB to be susceptible to failure from both impact and bearing loads.

The more recently designed system reportedly solves the four major problems encountered with underground direct-buried systems: (1) complete encasement of foam insulation does away with water troubles, (2) asbestos cement eliminates corrosion, (3) coupling replaces expansion loops and joints, and (4) installation costs are lower than any system that requires field-fabricated joints. Since moisture will not harm the system, this type of conduit can be put directly into the trench and back-filled with soil.[7]

Results from recent installations of this type of conduit should be of interest for low-temperature installations to check the expectations of the design.

5.3.3 Fiberglass-reinforced epoxy

One of the most recently developed types of conduit that meets the requirements of a Class A (pressure-tested) system is made with fiber-reinforced plastic (FRP). Factory-fabricated lengths of this type of conduit consist of FRP pipe and a thin-wall FRP casing with the annulus between them completely filled with polyurethane insulation. Field joints of both pipe and casing are made in the manner previously described for FRP pipe. Some type of preformed insulation may be used around pipe fittings, but the outer casing must be made pressure tight.

No detailed sections of FRP conduit are readily available, but detailed specifications for use of FRP at the Jersey City, New Jersey, Operation Breakthrough Project have been written by Gamze-Korobkin-Caloger for HUD. Excerpts from ref. 17 pertaining to some of the FRP conduit and requirements for its installation are presented in Appendix C.

It is uncertain whether this type of conduit will give satisfactory long-term service for thermal energy distribution systems, but several potentially troublesome areas should be considered. Pipe supports inside the casing, or hangers in a culvert, must be spaced at about half the distance needed for low-carbon steel piping. Excessive stress in the piping or compression of the insulation can occur if supports are not properly spaced. The thermal expansion rates of epoxies are greater than low-carbon steel, and, although the modulus of elasticity is lower than metals, thermal gradients and resulting stresses require more attention. Proximity to hot surfaces and high-frequency vibration at high amplitudes are other possible sources of danger.[14]

6. SPECIAL UNDERGROUND PIPING ELEMENTS

Underground piping contracts and expands because of temperature differences between the heat-transfer media and the underground environment. For example, axial expansion of unrestrained low-carbon steel heated from 70 to 180°F is about 1.0 in./100 ft of length. Expansion of most plastics are almost three times this amount (about 3.0 in.). However, some of the thermosetting resins (such as epoxy) have a coefficient of expansion only about 30% higher than mild steel and, under these conditions, will expand about 1.3 in./100 ft. Adequate provision for pipe movement must be made, and the movement must be guided and controlled or the piping and its conduit may be displaced and/or ruptured.

The three major piping elements are as follows: (1) expansion devices; (2) pipe attachments, such as anchors, supports, and guides; and (3) manholes, which allow for drainage and permit the use of various types of connections.

6.1 EXPANSION DEVICES

When properly designed and anchored, expansion loops, in the form of right-angle turns, z-shapes (offsets), or U-bends, allow for expansion and contraction within permissible stress levels.

Bellows and slip joints must be anchored, covered, and protected against misalignment; hence, they usually are installed either in manholes or in the basements of buildings.

Ball joints need not be anchored, since they take advantage of change in piping direction. However, ball joints should be installed in accessible spaces to allow for maintenance.

6.2 ANCHORS, SUPPORTS, AND GUIDES

Since expansion joints must operate within some allowable limit of movement, they will provide only for expansion of a short section of piping. Therefore, anchor points must be established to sectionalize long pipelines, and anchors must be installed so that the expansion of the pipe section between any two anchors is predictable.[11] Anchors (and expansion joints) in mild steel piping, for low-temperature hot-water conveyance, are seldom more than 400 ft apart, but each must be designed for a particular job. They can be attached to the sidewall of a manhole or mounted on a separate concrete footing. When more than one pipe is inside a conduit, the anchors may be located inside and fixed to the casing wall to limit pipe movement within the casing.

Pipe supports are designed to permit the pipe to move by a rolling or sliding action as it expands or contracts. The supports (e.g., steel rollers, steel bars, and concrete blocks) carry the weight of the piping and are designed to allow movement between the support and the pipe.

Pipe guides control both lateral and vertical movement. Their primary function is to guide expansion and contraction along the pipe axis, which prevents bowing that can cause high stresses. Guides are often in the form of sleeves that are attached to some part of the support framework or to the anchors.

6.3 MANHOLES

Manholes can be field-constructed in concrete forms at the job site, but an increasing number of prefabricated manholes made of corrugated galvanized steel are being installed. Manholes should be located in preliminary plot plans in order to establish separate sections of piping that can be engineered to fit the requirements of each particular section.

Manholes provide an enclosure for valves and fittings and for changes of pipe elevation; the walls of their interior surfaces can be used for locating guiding sleeves and for anchoring the fixed section of mechanical expansion joints. Manhole depth is determined by the lowest point of natural drainage between different sections of piping, unless a sump pump is used. Properly designed ventilation for the manhole can materially extend its service life.

7. PIPING SYSTEM LOOPS

District heating-system circuits are often classified into one of four types: single-pipe, two-pipe, three-pipe, or four-pipe circuits or loops.

The single-pipe circuit consists of only a supply line for hot water or steam and does not include a return line. The return water or steam condensate is dumped from the pipe system. Constant makeup of all the dumped water is required to complete the circuit and maintain the supply. An unusual illustration of this type of steam system is found in New York City. The extremely high cost involved in adding a return pipe system to the maze of piping under New York City's streets is estimated to be in excess of the value of the recoverable heat and of the condensate.[1] With a steam heating system, only about 15% of the delivered heat remains in the condensate. Many newer installations (in New York City and elsewhere) include condensate-return lines, and the time may come when older systems will be required to recover condensate in order to conserve energy.

Advantages claimed for a one-pipe circuit in a steam system are (1) reduced piping costs (due to the elimination of the return line), (2) reduced corrosion-treatment costs (because high-temperature steam is reportedly less corrosive than high-temperature water), and (3) the possible savings through economic transport of waste heat from large, remotely located, power stations.

A two-pipe-loop distribution system can be used as either a hot water or chilled water supply or return main, depending on seasonal demands. Such a system may be closed, that is, a primary loop through a heat-exchanger can be used as a heat source for a secondary loop that actually supplies heat to the customer. Use of a secondary loop may be advantageous in supplying potable, domestic hot water to individual customers. An open, two-pipe, domestic hot-water loop would require water treatment that would make potable-quality water of the entire makeup volume of the primary loop and also would need accurate temperature control before the hot water could be sent to the customer. The major advantage of any closed two-pipe system is the reduction in water-treatment cost.[13] Another advantage is the delivery of hot water at design temperature almost instantly on demand (i.e., circulation eliminates significant temperature drops caused by heat losses from the stagnant fluid in the branch pipes).

The three-pipe circuit is usually used in steam systems that supply a large seasonal demand for space heating and domestic hot water. The supply mains consist of one large- and one small-diameter pipe (in order to provide steam at two different supply rates); there is one large common return main. When the demand drops, one of the steam supply lines is shut off. The advantages of using a three-pipe supply system are (1) a reduction in off-season heat losses and (2) more flexibility in meeting the maximum heat demand.

Kennedy Airport in New York has an unusual HTHW three-pipe circuit with equal-size mains, as well as a two-pipe chilled-water system. The third pipe of the HTHW system can be used for the HTHW supply or return and adds dependability to the system, since any two mains can remain in service while the third is being repaired.

Four-pipe systems are used where both steam or hot water and chilled water are supplied by a district system.[18] A system with two complete loops designed for high temperature and two loops for chilled water is more expensive than a two-pipe system that can be used alternately for heating or cooling. The advantages of four-pipe systems are sufficient flexibility, through controls, to meet the entire range of thermal energy demand and the ability to design more dependable performance into each of the two-pipe loops, as required by different operating temperatures.

8. FACTORS AFFECTING PERFORMANCE

The performance of a thermal energy conveyance system is somewhat analogous to that of an electrical transmission system; however, unlike electrical energy systems that are provided with exact metering for all the energy generated and delivered, measurements of thermal energy input vs consumer demand are seldom monitored as accurately as measurements of electrical energy. One of the reasons may be that early district systems were seldom constructed as separate utilities. District heating systems were often interrelated with steam-powered electric generating plants, and only in the last decade have district chilled-water systems received widespread recognition as a new public utility.[19] Definitive data on actual heat loss or gain, which contribute to less efficient thermal conveyance from existing installations, is not often easily applied to new systems. Therefore, approximate percentages of losses are usually estimated.

More important than exact evaluation of initial heat conveyance efficiencies is the consideration of factors that can virtually nullify the effectiveness of insulation and significantly lower the long-term performance of a thermal-distribution system. These factors are briefly discussed in this section.

8.1 ESSENTIAL INSTALLATION PRACTICES

Special care in installation is required to minimize installation errors and poor workmanship. Close inspection by both owner and manufacturer representatives is necessary to obtain quality installation and to ensure against early development of defects. Careful handling must be exercised in the transportation and storage of materials. Problems during installation are usually caused by improper handling, especially for factory-fabricated components. After the pipe has been installed and the back-filling completed, deterioration resulting from installation errors and improper workmanship may go undetected until a pipe failure occurs. Abrasions, broken joints, and improper curing often result from the improper use of equipment. Rough handling of conduit casings or poor masonry work in the trenches can cause deterioration of insulation or pipe corrosion that will go undetected for years and can result in poor efficiency of thermal energy conveyance.

8.2 ENVIRONMENTAL FACTORS

Class A conduits should be used where the bottom of the conduit structure may become subject to saturation conditions. A comprehensive site investigation that covers groundwater level, soil permeability, topography, and precipitation should be made for every installation. Cathodic protection is recommended by BRAB for metal systems situated in soils having a resistivity below 2000 ohms/cm^3.[10] Prevention of conduit failures due to soil movements and other problems associated with soil stability requires that trenching, compaction, and backfilling operations be carefully planned and implemented.

8.3 PREVENTIVE MAINTENANCE

Maintenance problems usually stem from the inadequate training of maintenance personnel. Proper inspection and maintenance procedures performed by well-trained or experienced personnel tend to eliminate the occurrence of serious defects. Regular periodic inspections, if properly conducted, can ensure early detection of defects and thus prevent serious damage. The practice of making repairs to satisfy immediate demands may be necessary; however, many temporary repairs have later been treated as permanent; subsequently additional failures occurred because of the inadequacy of the temporary repair. A typical example is cutting open a conduit to find a pipe leak, without proper repair of the cut in the casing after the leak has been repaired.[10] Such practices can contribute to conditions that will cause an additional failure.

Another serious deficiency that is evident in maintenance criteria for existing systems stems from an irresponsible attitude toward the importance of thermal efficiency. Maintenance personnel will often consider a distribution system to be operating satisfactorily even though the insulation is wet and deteriorated.[10] This attitude may be attributed to the inadequate development or use of simple and accurate methods for measuring heat loss. Measurement techniques, which make use of various forms of heat-flow transducers, are now available for some types of conduit systems but are generally installed only on new systems; and as the cost of energy increases, similar techniques will probably be developed for use with older installations. Also, since most boilers are designed with excess capacity and the ability to overcome most line losses, maintenance personnel tend to ignore the efficiency of the conveyance system until losses become excessive.

8.4 PERFORMANCE TESTS AND PROCEDURES

Tests and procedures for comparing the performance of underground thermal distribution systems have been developed and are discussed extensively in a report by a special advisory committee to BRAB.[2] Recommended tests include simulated environmental conditions of impact loading, thermal stressing under conditions of excessive moisture, failure in the presence of moisture, and surface loading. As an example, using two methods (present worth and annual cost),* an economic comparison was made of a chilled-water distribution system constructed from uninsulated asbestos-cement pipe vs insulated metallic pipe. This example includes a heat-transfer analysis that establishes the steady-state heat gain of the 6-in.-ID metallic pipe with 1-in.-thick insulation at 8 Btu hr^{-1} ft^{-1},

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*See definitions in Appendix D.

as compared to approximately 43 Btu hr^{-1} ft^{-1} for uninsulated class 150 asbestos-cement pipe of the same ID and under the same test conditions. The economic comparisons of the annual costs for the two systems favored the insulated pipe, which cost 3 to 4% less, annually, than the uninsulated system.

Variations in the assumptions made in this example could reverse the results. The relative costs of the two types of pipe are much lower than those obtained from recent prices, especially since no capital cost was included for a conduit casing, which is essential to protect the insulated pipe. The unit conductance of 0.0125 Btu hr^{-1} ft^{-2} $°F^{-1}$ (used in this example) could only apply to an excellent insulating material or should be for a foot of insulation thickness (i.e., for the 0.91-in. thickness used, the thermal conductivity, k_x, equals 0.011 Btu-in. hr^{-1} ft^{-2} $°F^{-1}$). Even a low-density (1.5–2.5 lb/ft^3) polyurethane foam has a thermal conductivity factor of 0.16 to 0.17 Btu-in. hr^{-1} ft^{-2} $°F^{-1}$. Very low-density polyurethane foam could have such a low conductivity, but an outer casing would be required. Present worth and capital recovery factors, based on 6% annual interest for a period of 20 years, will not give comparable results for fixed charges on capital in the current money market. It should also be noted that the example given indicates that use of the insulated pipe system results in a relative energy saving of 35 Btu hr^{-1} ft^{-1} and requires 15 tons less installed cooling capacity. This saving is only about 4% of the full-load capacity (360 tons) of the insulated thermal conveyance system used in this example for chilled-water piping. Therefore, the cost of the thermal energy losses on an annual basis may be less than the difference in cost between an asbestos-cement system and a well-insulated steel system, when 1973 prices of installed systems are factored into a similar analysis.

Data on heat loss or gain from the point of supply to the point of usage should be considered essential to thermal energy conveyance systems. Such data should be collected regularly and included in permanent operational records. Establishment of monitoring procedures that use well-instrumented systems is necessary to detect gradual degradation in the performance of the energy distribution systems. Simple monitoring techniques may be adequate for most systems, but to obtain exact data on elaborate systems over a long period of time may require extensive monitoring in a manner similar to the computerized system in use in San Antonio, Texas.[20]

9. COST FACTORS FOR PREFABRICATED PIPE SYSTEMS

The cost estimates of thermal conveyance pipe and conduit have been determined by using manufacturers' data on the cost of prefabricated pipe conduit sections and estimating the total installation cost for directly buried underground systems as a percentage of the total materials cost. There are many reasons for adopting this method of making the cost estimates. First, every installation differs to such a degree that even a contracting engineer cannot make a good cost estimate without the energy demands of the system, a schematic arrangement, and other detailed information. Pipe material must be chosen that can withstand the anticipated temperature and pressure. Engineering factors such as pipe diameter and piping arrangements must be evaluated relative to noise, vibration, and erosion. Generally, pipe sizes will be chosen to give fluid velocities in the range of 4 to 12 fps (for conceptual purposes, 8 fps may be used for supply and return mains and 4 fps for piping in inhabited areas). A pressure-drop calculation is also required to determine whether a resizing of pipe is necessary from pumping-head or system-pressure considerations. Practically, pump types and sizes should be chosen to allow sharing of reserve pumps and to reduce spare-part requirements. The number and depth of manholes needed to subdivide the system, locate valves, allow for drainage, and possibly enclose some anchors (as determined by system expansion) must be established before approximate system costs can be estimated. Even with the exclusion of manhole costs, data on different conduit assemblies (based on cost per foot of length for the same pipe diameter) will not give comparable costs for an installed distribution system. The number of offsets, branch connections, fabricated connectors of nonstandard lengths, flanged connections, supports, and expansion joints must be considered in a comparative evaluation of total installed cost. Therefore, valid comparisons of cost for different types of conduit, based on estimates in this report, will require considerable engineering judgment for each particular installation.

Furthermore, since most of the systems installed currently are designed to include factory-fabricated components, virtually no data have been obtained on the cost of field-constructed conduits (Sect. 5.1) or poured envelopes (Sect. 5.2). However, to provide at least one basis for comparison of a field-constructed reinforced concrete trench conduit with a prefabricated steel conduit, an estimate was requested of a building contractor for a 4-in.-thick concrete conduit to house two 8-in.-diam pipes with 2-in.-thick insulation. The estimate obtained was about $100 per foot of trench, which is about 30% more than the installed cost of two 8-in. steel conduits with insulated pipe in 14-in. 10-gage casings. No estimate was made on the poured envelopes because accumulation of additional data on installation cost would be required, and a breakdown of total project cost into the costs for various pipe sizes would require additional study.

Some cost data on prefabricated conduit were obtained from American Hydrotherm Corporation[21] and Ameron-Corrosion Control (Bondstrand).[22] These data have been divided into the following categories: (1) cost of assembled materials for conduit, (2) allowance for expansion joints or related costs, and (3) a relative cost for installation as required by each type of conduit.

9.1 PIPE, INSULATION, AND PREFABRICATED CONDUIT

A comparison of the materials cost for an insulated steel pipe enclosed in a coated steel casing with an FRP pipe and casing with an annulus filled with polyurethane foam insulation is shown in Fig. 9.1 (1973 dollars).

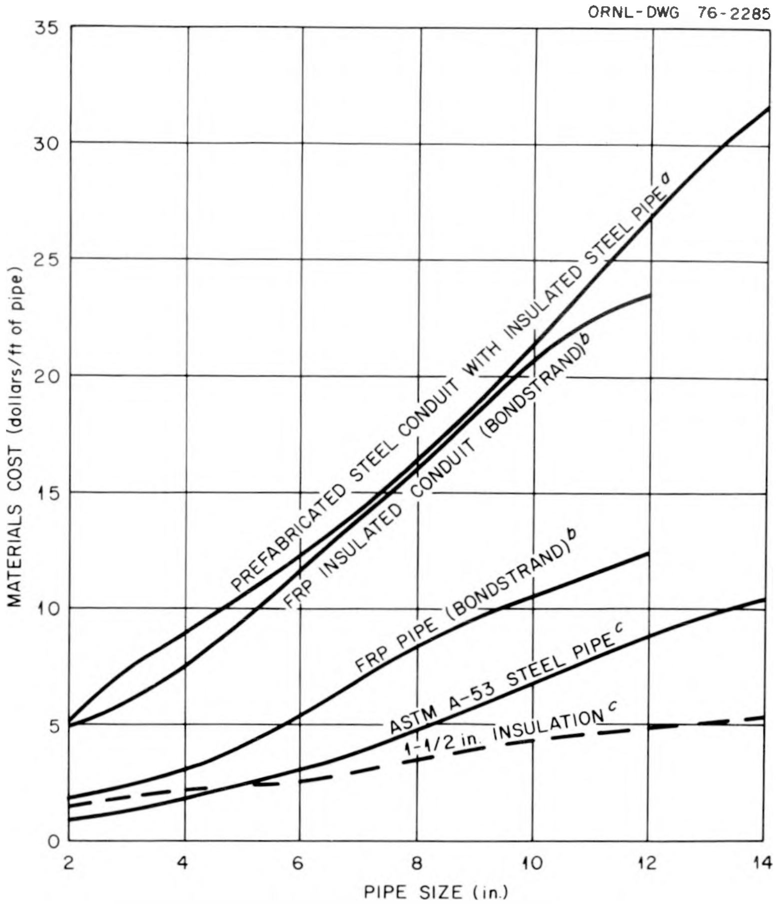

Fig. 9.1. Conduit materials and prefabrication cost for steel and fiber-reinforced plastic (FRP) in 1973 dollars. ([a]W. Diskant, American Hydrotherm Corporation, personal communication to A. J. Miller, Oak Ridge National Laboratory, June 5, 1973. [b]"Engineering Study — Comparison of Installed Costs," Ameron, Corrosion Control Division, Brea, California, 1971. [c]*Commercial-Industrial Estimating and Engineering Standards*, Richardson Engineering Services, Inc., Downey, California, 1972.)

The two lower curves show the cost of insulation and steel pipe as taken from data in ref. 23. The curve for insulation is for 1-1/2-in.-thick preformed fibrous glass insulation with an aluminum foil covering, which is most often used in aboveground installations. These costs are only slightly higher than those for insulation provided in underground conduits, and, when added to the cost of A-53 pipe, will give the approximate cost per foot for an insulated steel pipe. The costs for FRP pipe are for random lengths of Bondstrand bell-and-spigot Quick-lock pipe.[22]

The two top curves in Fig. 9.1 show the comparative materials costs of the insulated pipe and the protective outer casing. The data for insulated FRP pipe is also from catalog data on insulated Quick-lock pipe supplied by Ameron[22] and should meet the specifications included in Sect. 5.3.3. The data for the curve on prefabricated steel conduit were obtained by adding the cost of assembly of a 10-gage steel casing with a protective outer coating to the cost of insulated steel pipe. Data on assembly and coating of the casing with multiple layers of coal tar enamel reinforced with a fiberglass mesh are from American Hydrotherm Corporation estimates. For pipe 6 in. in diameter and larger, the casing diameter provides a minimum of 1 in. for annular drainage space around the insulation. For smaller sizes, two insulated pipes (a supply and a return) are encased in one large-diameter casing that allows for easy drainage. However, this practice does not significantly affect the relative cost of assembled conduit when prorated per foot of pipe.

9.2 INSTALLED COSTS

Estimates of costs (1973 dollars) for installed conduits capable of conveying chilled water and hot water are shown in Fig. 9.2. Also shown in this figure are curves for ChW and LTHW costs of piping conduits derived from ref. 24 (35% has been added to update the data to 1973). Reference 24 costs are averages of contract awards in Florida from 1959 through 1967. The LTHW costs are representative of prefabricated steel pipe and casing with fiberglass insulation. The ChW costs are similar averages for conduit by types shown in Fig. 5.9 or steel pipe insulated with 1-1/2-in. cellular glass wrapped with a vapor barrier. The lowest cost data in Fig. 9.2 are for installed costs of 3-, 6-, and 8-in.-diam Chil-Gard conduit supplied by Ric-Wil, Inc..[25] Chil-Gard conduit consists of a PVC pipe and an outer casing with the annulus of about 1 in. filled with polyurethane foam insulation. The special joints of this piping can be slip-fitted together at installation by using a plastic O-ring seal. This seal permits slippage at the joints to allow for thermal expansion, and, therefore, its installation costs tend to be lower.

The curve for the installed costs of FRP conduit has been evaluated by adding 30% to the materials cost of the insulated FRP conduit to include the cost of expansion loops. The installation cost is then assumed to be 40%* of the total cost of the conduit and expansion joints. This method of estimating installation cost of the Bondstrand piping was checked against the comparable cost of installed FRP pipe at the Jersey City Breakthrough Project with reasonably good agreement.

Three curves are shown in Fig. 9.2 for prefabricated steel conduit. The curve for 240°F hot water is from ref. 21 using the total cost of materials shown in Fig. 9.1, adding 25% for expansion joints, and assuming the cost of installation as 40% of all the material costs (including expansion joints).

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*This percentage is assumed the same as used for steel conduit because the low cost of installing couplings (or fittings) claimed for FRP is not expected to change total installation costs significantly.

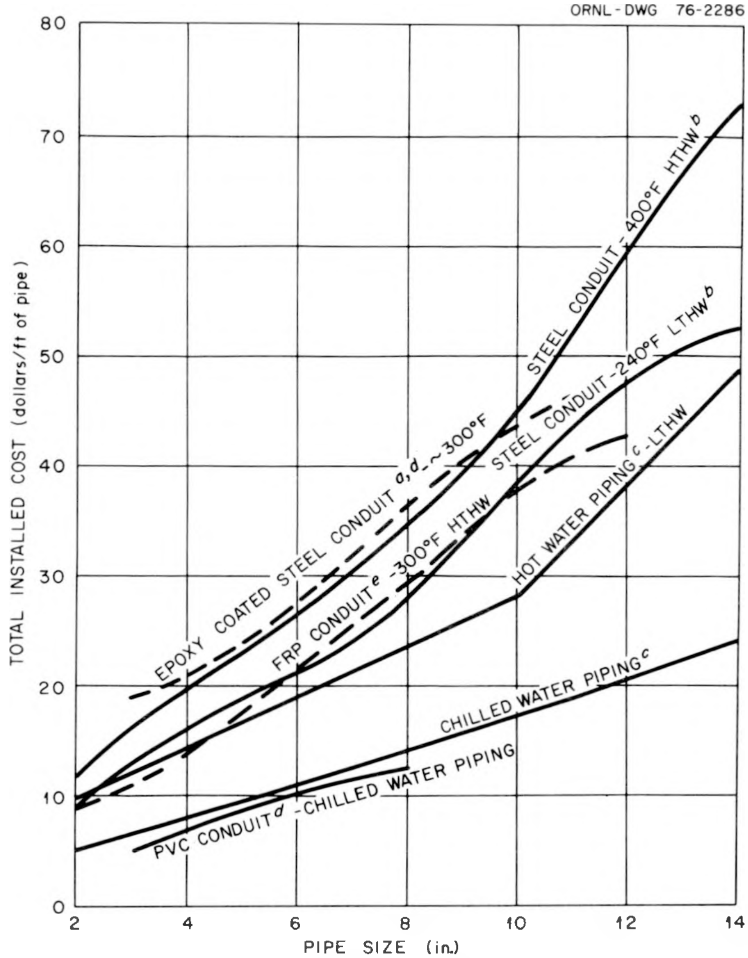

Fig. 9.2. Total installed costs of conduits in 1973 dollars. [[a]Does not include installed cost. [b]W. Diskant, American Hydrotherm Corporation, personal communication to A. J. Miller, Oak Ridge National Laboratory, June 5, 1973. [c]S. P. Goethe, "Central Heating and Refrigeration Systems," *Air Cond. Heat. Vent* 65(10): 45-50 (October 1968). [d]R. H. Wood, manufacturer's representative, Ric-Wil, Inc., personal communication to J. T. Meador, June 1973. [e]"Engineering Study — Comparison of Installed Cost," Ameron, Corrosion Control Division, Brea, California, 1971.]

The 400°F-temperature curve is also from ref. 21. For this example, 35% of the conduit materials cost was added to ref. 21 data to allow for expansion loops, and 40% of all material costs was again used for installation cost. Estimates in ref. 21 are national average values and may vary significantly with soil condition and other regional factors. Data from refs. 23 and 26, based on experience in installing piping, indicate that national average installation costs may be about 15% higher.

The third curve, labeled epoxy-coated-steel conduit, was obtained through a personal communication[25] with a prominent vendor who made estimates on conduit that is considered to be the best available type in production. Cost estimates included an allowance for expansion joints. The conduit consists of steel pipe with 1-1/2 in. of calcium silicate insulation (for all diameters) supported inside a spiral-wound welded-steel casing with an exterior coating of epoxy. Each section of the conduit can be pressure tested, and provision for drains or vents are included for drying the insulation. These data do not include the estimated cost of installation. Although an estimate of installed cost for epoxy-coated-steel conduit shows it to be the most expensive of those estimated, it may represent a better quality system.

9.3 ANNUAL COSTS FOR INSTALLATION AND CONVEYANCE LOSSES

Overall annual costs for owning and operating underground conduit systems are not estimated in this report. The data evaluated include capital costs associated with installation and energy conveyance costs based on losses from the conduit after installation. The costs of trenching and backfilling are assumed as part of the installation cost, because they are nearly proportional to the costs for conduit materials. No estimates of maintenance costs are given, since these costs vary greatly with all factors that affect underground deterioration or system lifetime, and accurate estimates could be derived only from an extensive compilation of data on existing systems.

Monitoring efforts usually include data pertaining to energy production, as required by some predictable demand, rather than providing conveyance costs separate from the total cost of providing energy. Hence, annual owning and operating costs associated only with conveyance of thermal energy are seldom evaluated. Therefore, comparable annual cost data for different types of conduit and complete conveyance systems are considered to be a fertile field for additional study and development. As recommended by BRAB in its discussion of economic considerations, annual owning and operating costs should include capital expenditures, with financing over some reasonable system lifetime, and all operating and maintenance costs directly attributable to the conveyance system. Also, a follow-up study should be undertaken to collect data from operating systems and to evaluate actual heat-transfer conditions in the light of known underground environmental conditions. The results of such a study should be applied in order to assess commonly used methods of treating the heat-transfer problem and to develop recommendations concerning techniques that will ensure realistic results.[2] Moreover, evaluation of such costs is complicated by the dependent relationship between the amortized value of the installed costs for equipment to produce and convey the thermal energy and the value of the energy lost in heat transfer through the installed conduit system. For example, in a hot water system, the value of the heat lost from the distribution system must include both the value of the fuel used in production and the fixed charges on capital for both production and conveyance. Furthermore, the most economical thickness of installation for each conduit size in a conveyance system should be determined, because the more costly the heat energy the greater the improvement in insulation that is warranted to conserve it.

A good basic manual on the economics of insulation for aboveground piping is *How to Determine Economic Thickness of Insulation*, published by the National Insulation Manufacturers Association (NIMA).[27] This manual was developed from a computer study that was sponsored by Union Carbide Chemicals Company, Charleston, West Virginia, through a research agreement with the College of Engineering of West Virginia University. Because of the significant contribution of the first edition to insulation practice, NIMA requested and received permission from Union Carbide Corporation to publish the tables and charts in a slightly revised form to cover practically all the needs of any heat-using industry. Although this manual is primarily for high-temperature process piping and some of the assumptions used are not applicable to MIUS, it illustrates similar variables and a method of analysis that can be applied to underground thermal energy conveyance systems. A graphic representation of the method of determining the minimum cost of insulation is shown in Fig. 9.3. These curves show that the total annual cost is equal to the sum of the amortized annual cost of the insulating materials (curves B) and the cost of the heat lost through the insulation (curves A). It should be noted that the cost of heat should include the amortized annual cost on the capital investment for heat production as well as the cost of fuel and the cost of operation and maintenance of the energy production equipment. The crossover point graphically indicated by the two curves illustrated in Fig. 9.3*b* does not necessarily locate the minimum total cost or the most economical insulation thickness. This assumption is often made in locating the break-even point for such estimates. In order to determine a minimum total cost from these curves, the constantly changing negative slope of the lost-heat-cost curve must be added to the almost constant positive slope of the insulation cost curve. The resulting economical thickness is usually greater than the thickness at the crossover point of the two curves. Only the minimum point of the total cost curve can be used to accurately establish the most economical thickness of insulation. A practice recommended by ref. 28 is the use of the next higher (standard) insulation thickness, above that determined by the minimum point, to compensate for future increases in fuel costs. An exact mathematical solution for evaluating the minimum of the total cost curve is included in the Appendix of the NIMA report.

An analysis similar to the one used in ref. 27 has been made to establish the most economical thickness of insultion that should be used with prefabricated steel conduit in an underground distribution system. This analysis is considered necessary so that the minimum annual costs for installation and conveyance losses can be evaluated for a MIUS; the analysis will exemplify the parameters involved. After establishing the most economical thickness of insulation for each pipe size in a conduit system, the cost of the system can be compared with the cost of a system that is enclosed in a casing with no insulation. This procedure is like comparing the cost for an insulated system with the cost for steel piping that is enclosed in a sealed casing with a specified air gap or with virtually worthless or badly deteriorated insulation.

The heating and cooling losses for nominal pipe sizes from 1-1/2 in. to 14 in. have been evaluated in Appendix A (Tables A.1 and A.2) and are

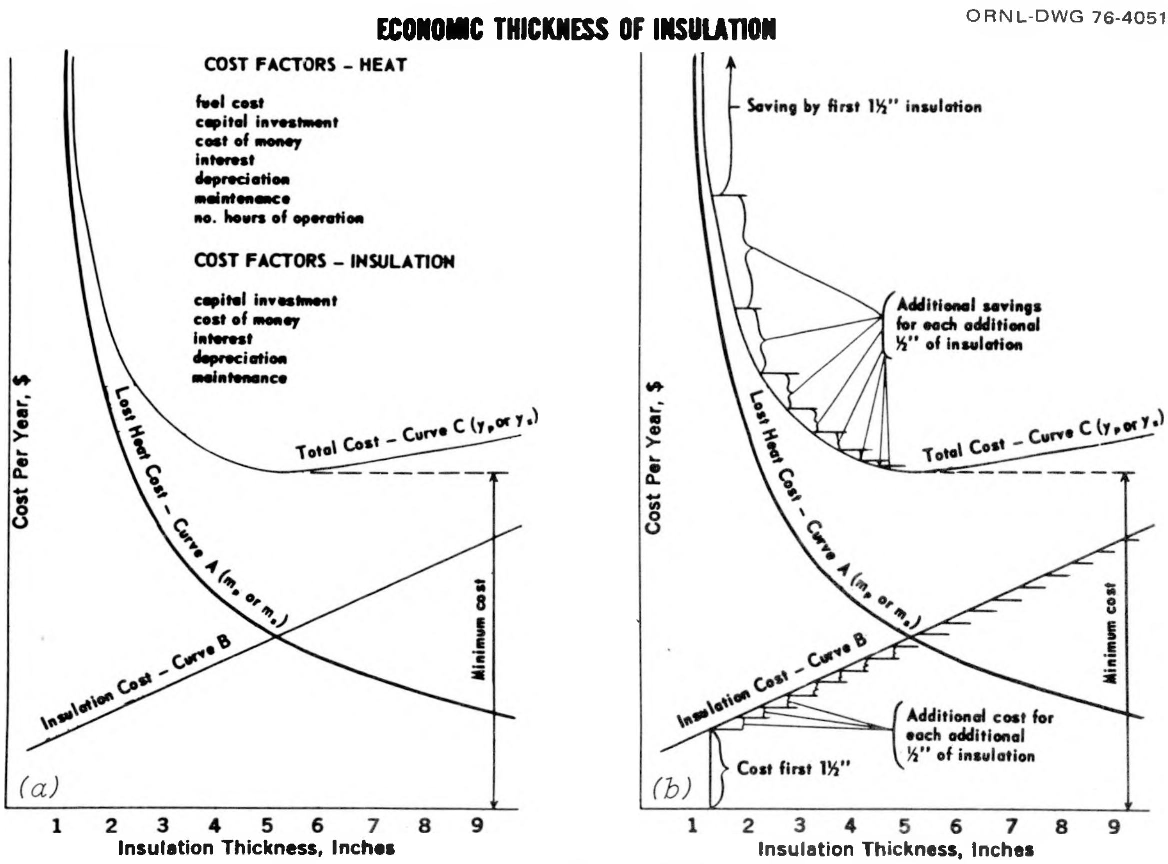

Fig. 9.3. Economics of insulation thickness. From *How to Determine Economic Thickness of Insulation*, National Insulation Manufacturers Association, 441 Lexington Avenue, New York, N.Y. (July 1961).

based on heat-transfer equations similar to those in refs. 29 and 30. The data include underground heating losses from the following: bare pipes; uninsulated pipes that are enclosed in a coated steel casing that provides a 1.0-in. air gap; and conduits that have 0.5, 1.0, 1.5, and 2.0 in. of insulation surrounded by a 1.0-in. air gap. The casings for each of these insulated conduits are sized to provide a 1.0-in. air space outside the diameter of the preformed insulation. Average supply and return temperatures of the hot water (HW) and the chilled water (ChW) have been used. The ground temperature is assumed to be 54°F for evaluating HW losses, and the average earth temperature for summer and fall is assumed to be 62°F for evaluating ChW losses (heat gains). Therefore, the temperature difference for HW is 180° - 54° = 126°F, and the temperature difference for ChW is 62° - 50° = 12°F. The heat-transfer equations used and the resulting heat losses for HW and heat gains for ChW are based on conductivities from refs. 31 and 32 and are included in Appendix A. Curves of these data are shown in Figs. 9.4 and 9.5.

The installed cost of the casing and the series of thicknesses of insulation to be used in this comparative cost analysis have been evaluated separately from the installed cost of the bare pipe. The reason for a separate

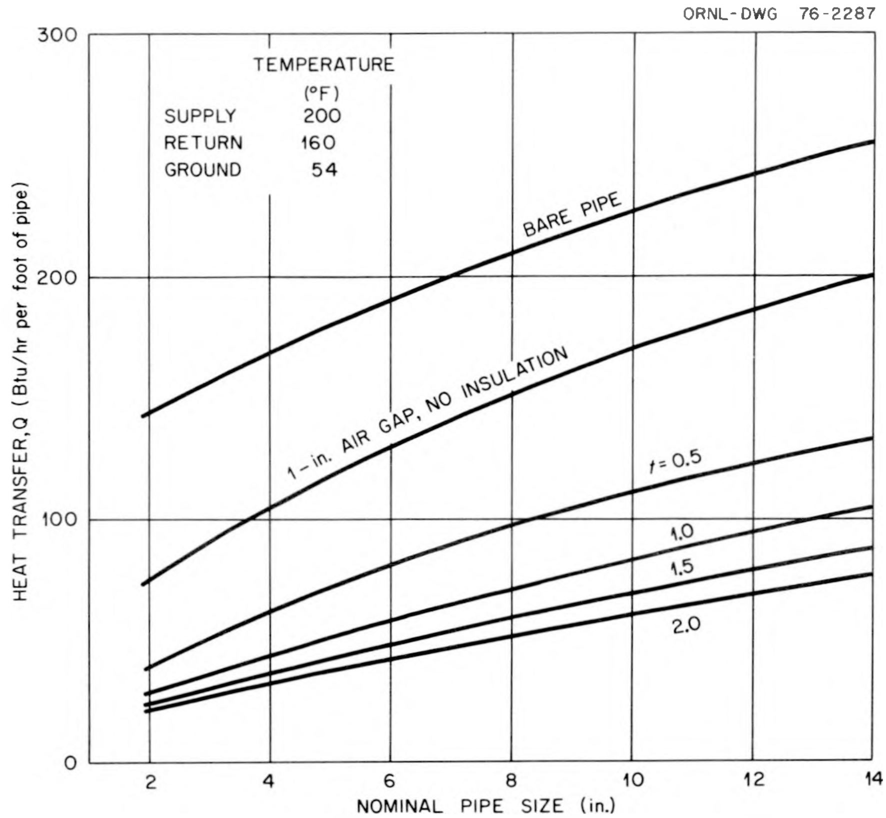

Fig. 9.4. Heat transfer from pipes with a temperature differential (ΔT) of 126°F. (t = insulation thickness, in.)

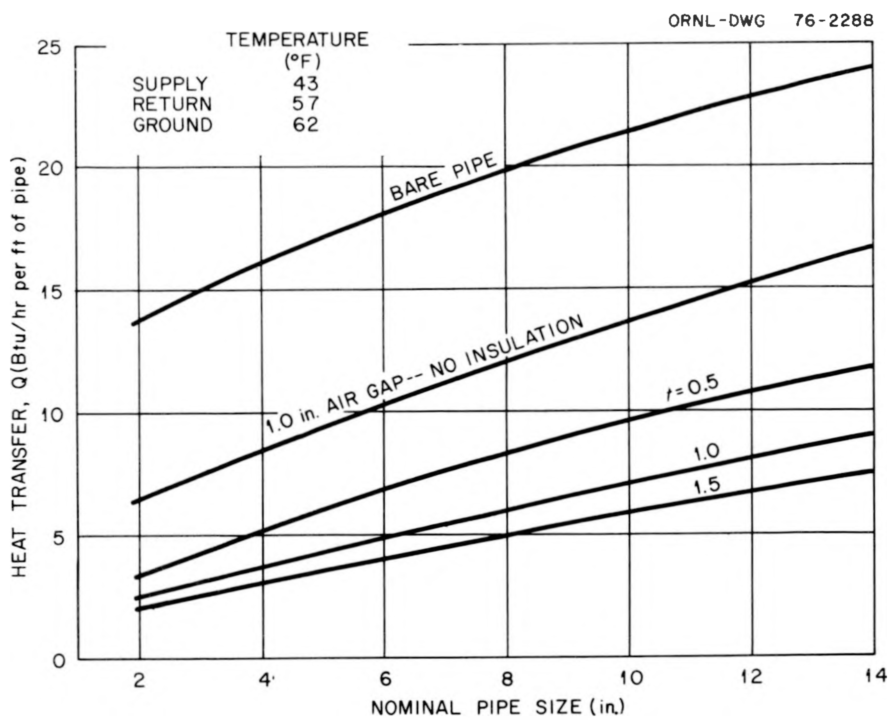

Fig. 9.5. Heat transfer to pipes with a temperature differential (ΔT) of 12°F. (t = insulation thickness, in.)

evaluation is that the installation cost of the casing and various thicknesses of insulation can be estimated as approximately proportional to the cost of materials for all the pipe diameters considered, whereas the installation cost of bare pipe varies to a great extent with pipe diameter. For example, the installed cost of the casing is estimated at 1.75 times the cost of the casing and coating materials for the various casing diameters (the 1.75 for underground installation costs comes from an additional 25% of the materials cost to allow for expansion joints plus 40% of the combined cost of materials, including expansion joints). However, the installed cost of bare pipe does not relate well to material cost. For example, the cost of 1-1/2-in. bare pipe is about $0.65 per foot, but a fair estimate of installed cost is about $4 per foot (more than six times the pipe cost). Comparatively, the material cost of 14-in. bare pipe is estimated to be $11.50 per foot; but, installation cost is about $25 per foot (or about 2.2 times the pipe cost). Therefore, the installed costs of the casing and the casing combined with the various thicknesses of insulation, as shown in Fig. 9.6, are estimated as 1.75 times the cost of casing and insulating materials. The installed cost of pipe must be added to these data to obtain the total installed cost of a conduit assembly.

The cost of preformed insulation that is assembled onto pipe prior to the fabrication of conduit sections is shown in Fig. 9.7. The dashed lines in Fig. 9.7 show the approximate cost of preformed calcium silicate pipe insulation without a covering and without the metal bands required for assembly. The cost data available at Oak Ridge National Laboratory was limited to a few pipe sizes for each insulation thickness; thus, the data were extrapolated to produce the straight dashed lines for cost of the various sizes. A factor of 2.5 times the cost of the preformed insulation was used to obtain the solid lines in Fig. 9.7, which estimate the installed cost (dollar per foot) of insulation on random pipe lengths. These installed costs compare favorably with data from ref. 23. The costs of the casing materials are taken to be the same as for the prefabricated steel conduit materials in Fig. 9.1, with casing sizes varying with insulation thickness. The installed cost of these sizes of pipe and conduit materials are shown to vary linearly with nominal pipe size, since all the costs are increasing linearly.

Insulation thickness, as well as temperature differential, must be considered when comparing the plots of Fig. 9.6 to the installed conduit costs of Fig. 9.2. Manufacturers' costs will usually be based on the insulation thicknesses that they recommend as necessary for good economic service.

Before calculating a lost-heat-cost curve similar to curves A in Fig. 9.3, the cost of production of the thermal energy that will be lost must be established. Since this cost varies for different district heating systems, the value of the heat produced is considered as a variable, and a series of lost-heat-cost curves are evaluated. For MIUS systems, the value of the thermal energy in the water can be expected to be at least $2 per million Btu (MBtu) if fuel cost $1 per MBtu. Therefore, determination of the most economic thickness of insulation for the HW conduits may be defined by lost-heat-cost curves that are based on energy values of about $2 to $3

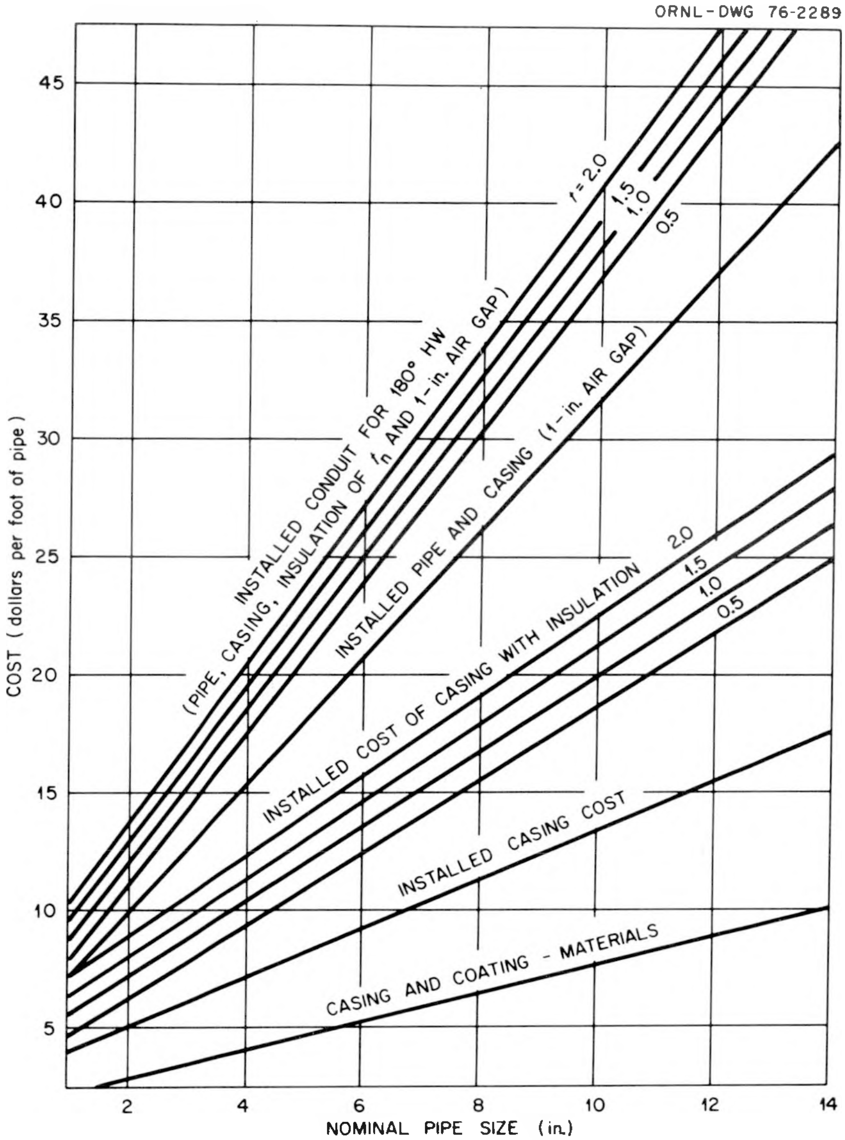

Fig. 9.6. Approximate cost of conduit materials and installation in 1973 dollars. (t = insulation thickness, in.)

per MBtu. To allow for escalating energy costs, an assumed energy value of $4 per MBtu is included. Using these values and the annual heat losses for the pipe sizes shown in Table A.3 of Appendix A, the cost of lost heat can be added to the annual fixed charges on the capital cost of each size and type of conduit to give approximate total cost curves. The minimum value from such total cost data can be used to define the optimum type of conduit if annual maintenance costs do not significantly affect comparative results.

Table B.1 in Appendix B shows the total cost of capital and energy for several sizes of conduit for 1-1/2- to 14-in. pipe sizes. The minimum total annual cost is underlined for energy values of $2, $3, and $4 per

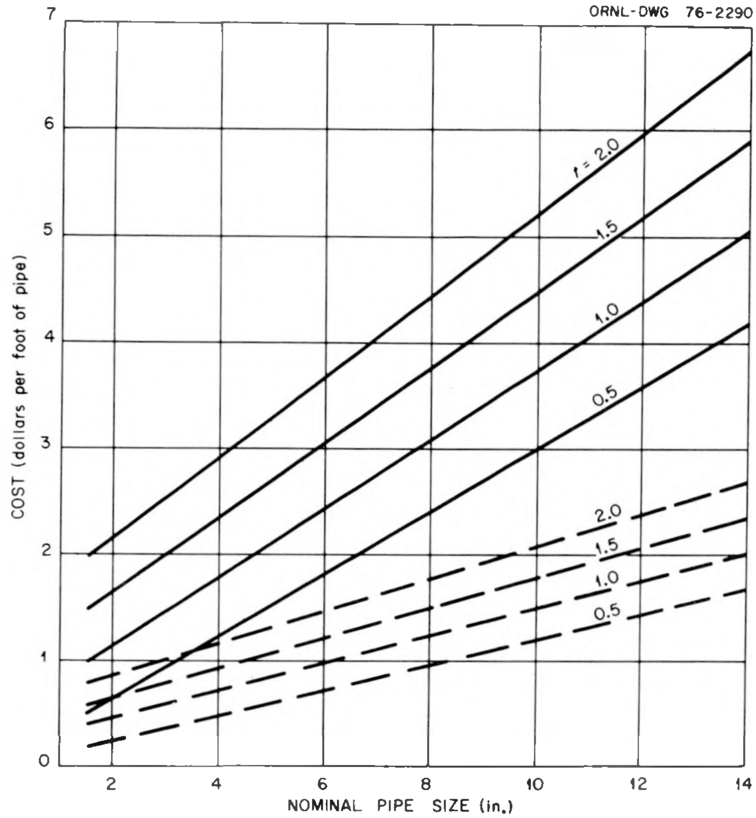

Fig. 9.7. Assembled cost of preformed insulation on random lengths of pipe. (t = insulation thickness, in.)

MBtu. Curves plotted from some of these data are shown in Figs. B.1–B.7. Where the maximum thickness evaluated (2.0 in. of insulation) indicates minimum cost, extending the analysis to thicker insulation will verify the minimum total cost. Since energy costs have been increasing rapidly, and since most insulations tend to deteriorate with age, the next greater (standard) thickness should be used when total cost increases are relatively small. This method of evaluation can be used to determine not only the most economical type of energy conveyance system but also the most significant factors that contribute to annual ownership and operation costs.

The value of the lost-heat-cost curves can be determined from data that include all of the costs required for hot-water production. If hot-water production costs are evaluated realistically, this method should be of assistance in evaluating owning and operating cost and should aid in the selection of economical district heating systems.

Evaluation of chilled-water distribution piping or conduit by methods similar to the method for evaluating the hot-water system produced some rather unusual results. For steel pipe enclosed in a casing (with a 1.0-in. air gap), the capital cost per foot is the same for chilled water as the values shown in Fig. 9.6, which were used in the analysis for hot water. The annual heat gains shown in Table A.4 (Appendix A) are quite low because of the low temperature difference of 12°F and the shorter time (3000 hr/year) that the chilled-water system is in operation. However, the relative value of the thermal energy gain with respect to the amount of cooling energy conveyed may be high.

A representative value for the energy in the chilled-water system is obtained from data included in the example referred to in Sect. 8.4. This example, as presented in ref. 2, uses a capital cost of $300 per ton for chillers and $0.042 per ton-hr as the average operating cost. Therefore, assuming a fixed charge rate of 15% per year, the owning cost related to energy production is $45 per ton-year and $0.015 per ton-hr, assuming 3000 operating hours per year. Thus, the energy production cost is $0.057 per ton-hr or about $4.70 per MBtu.

In applying a value of $5 per MBtu for the energy in chilled water, the additional fixed charges for the casing for any size of conduit is greater than the value of the annual energy saved. For example, the annual heat gains for an 8-in. conduit with a coated-steel casing is 0.038 MBtu $year^{-1}$ ft^{-1} compared to 0.061 MBtu $year^{-1}$ ft^{-1} for a bare pipe. Since the fixed charge on the installed casing is ($11.30)(0.15) = $1.69 per year per ft, energy would have to be worth $1.69/(0.061 - 0.038) = $73.48 per MBtu to justify installation of a coated-steel casing solely on the basis of the value of the energy saved.

These data indicate that use of a coated steel casing with or without insulation is not economical for chilled-water systems unless the amortized capital cost of the casing is much lower, the amount of energy conveyed through the pipe is increased, or the annual hours of operation are greater than previously assumed. The alternative of using other types of pipe or casing must compare the actual installed fixed charges with the relatively low value of energy saved annually, even if improved insulation can virtually eliminate energy loss from the conduit. Since FRP conduit in 4- to 10-in. sizes costs almost the same as the steel conduit for low-temperature service, a similar analysis should show it to be uneconomical. It should be noted (1) that the cost for insulated steel conduit is presently about twice that of the epoxy-lined asbestos-cement conduit and (2) that the energy loss from 6-in.-ID asbestos-cement pipe with a 1-in. wall (as in ref. 2) would be only about one-half of the loss from 6-in. bare steel pipe. Therefore, where mechanical failure due to impact and bearing load is not a problem and if adequate seals can be provided economically, asbestos-cement pipe or conduit might be a likely candidate for chilled-water piping.

Savings in annual cost for underground heating and cooling systems by making installations that utilize common trenching methods have been studied in a companion report for the HUD-MIUS Program.[33] This report indicates that some savings may be possible but will be a comparatively small percentage of the annual cost for installation and conveyance losses in underground systems.

10. SUMMARY AND CONCLUSIONS

The primary design parameter that may well determine the feasibility of a district heating and cooling system that uses water as a heat-transfer medium is the temperature differential between the water at operating conditions and the ambient ground temperature. The temperature differences existing throughout the system influence the amount of thermal energy that can be conveyed and affect many of the design factors directly related to the cost of both the energy production equipment and the conduits required for distribution.

Water is the most common heat-transfer medium used in low-temperature thermal-energy distribution systems, as classified by the special committee for BRAB. The possible alternative of using low-pressure steam instead of LTHW is not expected to offer any major advantages in MIUS installations. Even for low-pressure-steam systems, the capital costs for condensate-return lines are justified on the bases of minimizing steam heat losses, avoiding losses in hot condensate, and reducing water makeup. (Data on steam systems indicate that the combined steam heat losses for district heating systems, using medium-temperature steam, were about 17% of the energy produced, even for comparatively small size systems.)[34] Below the freezing point of water, fluids, such as brines, solutions of glycol and water, and refrigerants, such as halogenated hydrocarbons and ammonia, may be used. For temperatures above that usually associated with HTHW, organic heat-transfer fluids may have properties that can be advantageous in thermal conveyance systems.

The design temperatures of the system will also materially affect the capital cost of both the energy production equipment and the underground conduit. The fixed charges on capital cost for heat-production equipment (amortized over a 20-year period) can be about two times the cost of fuel either used directly or first converted into electricity. Similarly, the fixed charges on capital cost for production equipment to supply chilled water can be five times the value of the fuel. The capital costs of the conduits that can most economically convey thermal energy are also, to a lesser degree, related to the cost of producing the energy.

Selection of the type of conduit installed is usually based on the peak temperature difference, but evaluation of the most economical type of conduit will depend on the difference between average operating temperature and ambient ground temperature during some specified number of hours of annual usage. The minimum temperature difference and maximum operating hours are required, as basic design data, before any reasonably good energy-conserving type of conduit can be selected.

The field-constructed types of conduit are not economically competitive because of high installation costs in this country. However, one exception may exist where four or more mains can be installed in a shallow concrete trench (∿5 ft deep) that may be constructed economically, using common trenching methods, in some soils. In areas with low groundwater levels and gently sloping grades, watertight construction of concrete trenches may not be necessary for adequate performance, and, in these areas, competitive costs are possible.

The example of concrete trench costs included in Sect. 9 indicates that field-constructed conduits are not competitive with prefabricated conduits. Long-term heat-loss data on actual installations of the more economical poured-in-place types of conduit are not available; hence, good performance has not been verified. Therefore, the factory prefabricated conduit sections that can be joined on the job site appear to offer the most promise for meeting current needs.

Mild steel is the most commonly used material in prefabricated pipe and conduit casings, but the current costs of labor for welded joints, anticorrosive coatings, and installation are making nonmetallic materials, with their corrosion-resistant properties and capacity for quick installation, look more promising for thermal energy conveyance systems. Selection of prefabricated conduit can be very temperature dependent. The pipe and casing materials that appear most likely to meet the requirements of a MIUS are galvanized or coated mild steel and fiber-reinforced epoxies, for LTHW service, and asbestos-cement or a thermoplastic such as PVC for ChW service. A combination of two of these materials, such as epoxy-lined asbestos-cement pipe, may prove to be a good candidate for ChW systems. For MTHW systems, assuming that they could be used for MIUS, either the insulated steel conduit or, possibly, the insulated FRP conduit should be satisfactory. In order to determine which of these two would be more economical, each would have to be evaluated in a manner similar to the analysis used in Sect. 9. Special note should be made of the fact that the polyurethane insulation used with FRP conduit can have a heat conductivity factor of about half that of either calcium silicate or the 85% magnesia preformed insulation often used in insulated steel conduit. This means that the heat losses given in Appendix A would be about 20 to 40% lower for the same insulation thickness. Data on the performance of urethane foam insulation in an underground conduit have not been obtained, but systems currently in use that have this type of insulation are expected to provide performance data in the next few years. The thermal resistance of such systems may be adversely affected if the insulation is deformed by forces that develop from thermal expansion. Therefore, performance data and installed costs of this comparatively new type of insulated conduit should be obtained as soon as possible.

The capital cost and cost attributed to lost energy for any particular thermal conveyance system must be considered for both the annual costs of the conveyance system as well as for all costs related to production of the thermal energy to be conveyed. Based on the analysis discussed in Sect. 9, annual owning and operating costs will be minimized when the sum of the fixed charges on capital cost of the conduit system and the value of the energy lost from the system is a minimum. Therefore, determination of the most economical type of conduit must be based on the current costs of both the conveyance system and the energy production equipment as well as on the design parameters of that particular system. Furthermore, some widely used insulation thickness data for process piping design may not be applicable for economic or effective service in underground distribution systems.

From an energy conservation standpoint, better insulation should be used than would be indicated by currently applicable cost estimates. This may be justified by allowing for deterioration of the insulation or conduit casing and using improvements that would extend the assumed 20-year effective lifetime of the insulation.

Finally, the need for monitoring the several classes of HW systems should be emphasized. European countries have accumulated experience in both LTHW and HTHW district heating systems over a period of many years, and their experience should be helpful in performance evaluations. Reference 34 is devoted almost exclusively to steam systems and needs to be updated. Although the International District Heating Association is presently editing a new handbook, very little performance data on HW systems are included in available publications.

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Appendix A

HEAT LOSSES AND HEAT GAINS OF UNDERGROUND PIPING

The heat lost or gained from underground hot- and chilled-water piping was calculated for steady-state conduction for assumed boundary conditions. The cases considered include bare pipe in contact with the earth and pipe with insulation thicknesses from zero to 2 in. with a 1-in. annular air gap outside the insulation and a casing outside the air gap (Fig. A.1).

The temperature of the outside of the pipe was assumed to be 180°F for the hot-water piping and 50°F for the chilled-water piping.

A.1 THERMAL CONDUCTANCE OF INSULATION

The equation for heat conduction per unit of length through a hollow cylinder is[1]

$$Q = \frac{2\pi k(t_p - t_i)}{\ln(r_i/r_p)} , \qquad \text{(A.1)}$$

where

k = thermal conductivity of the insulating material,
r_p = outer radius of cyliner,
r_i = inner radius of air gap,
t_p = temperature at inner surface of insulation,
t_i = temperature at outer surface of insulation (inner surface of air gap).

Dividing both sides of Eq. (A.1) by $(t_p - t_i)$ results in the following expression for the thermal conductance of a hollow cylinder:

$$\frac{q}{t_p - t_i} = \frac{2\pi k}{\ln(r_i/r_p)} . \qquad \text{(A.2)}$$

The insulation material assumed for the study was 85% magnesia. The values of thermal conductivity for the insulation were taken as 0.0367 Btu hr^{-1} ft^{-1} $°F^{-1}$ for the hot-water piping and 0.0333 Btu hr^{-1} ft^{-1} $°F^{-1}$ for the chilled-water piping.

A.2 THERMAL CONDUCTANCE OF AIR GAP

Heat is transferred across an air gap by natural convection and radiation. Both of these effects were accounted for in the heat-loss calculations, and were combined into a single conductance term for the air gap.

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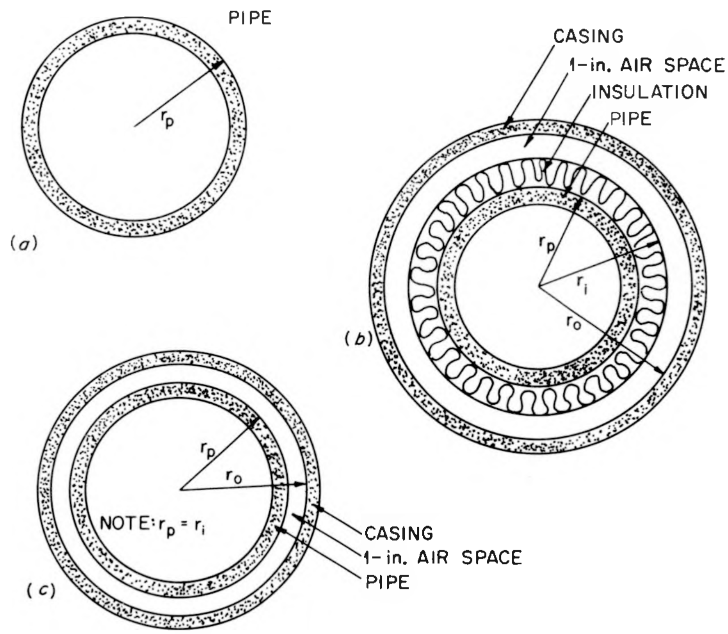

NOTES FOR SIZES AND CONDITIONS EVALUATED

(1) NOMINAL PIPE SIZES: 1.5, 2, 3, 4, 6, 8, 10, 12, 14
(2) INSULATION THICKNESS: 0.5, 1.0, 1.5, 2.0 (FOR HOT WATER)
: 0.5, 1.0, 1.5 (FOR CHILLED WATER)
(3) ASSUMED "AVERAGE" EARTH TEMPERATURE (°F): 54 (ANNUAL FOR HOT WATER)
62 (SUMMER & FALL FOR CHILLED WATER)
180 (FOR HOT WATER), 50 (FOR CHILLED WATER).

Fig. A.1. Conduit configurations for heat-loss analysis. (*a*) Bare pipe. (*b*) Piping conduit (insulated pipe, air gap, and casing). (*c*) Pipe, air space, and casing.

The heat transferred by natural convection was calculated using the results obtained by Grigull and Hauf,[2] who made studies of natural convection in horizontal cylindrical annuli. Using an interferometer, Grigull and Hauf measured the temperature gradient in air at the surface of a heated cylinder with the air enclosed at the outer surface by a cooled cylinder. They reported their results in terms of the mean Nusselt number, Nu_m, which they defined as

$$Nu_m = \left(\frac{\Delta t}{\Delta x}\right)w \frac{\delta}{\Delta T} , \tag{A.3}$$

where

$\left(\frac{\Delta t}{\Delta x}\right)w$ = measured temperature gradient at the heated surface,

δ = air-gap width between the inner and outer cylinder,

ΔT = temperature difference between the inner and outer cylinder.

The heat loss from the inner cylinder to the air gap is given by the equation

$$q = k_g A_i \left(\frac{\Delta t}{\Delta x}\right)w , \tag{A.4}$$

where

k_g = thermal conductivity of air,

A_i = area of inner surface of air gap,

$\left(\frac{\Delta t}{\Delta x}\right)w$ = temperature gradient at the inner surface of the air gap.

Substituting for $\left(\frac{\Delta t}{\Delta x}\right)w$ in Eq. (A.4) in terms of Nu_m from Eq. (A.3) yields

$$q = k_g A_i Nu_m \frac{\Delta T}{\delta} . \tag{A.5}$$

The thermal conductance for natural convection across the air gap may then be expressed as

$$\frac{q}{\Delta T} = \frac{k_g}{\delta} Nu_m A_i . \tag{A.6}$$

Grigull and Hauf found that the mean Nusselt number could be correlated by the equation

$$Nu_m = (0.2 + 0.145 \frac{\delta}{d_i}) \, Gr_\delta^{0.25e^{-0.02(\delta/d_i)}} , \tag{A.7}$$

where

Gr_δ = Grashof number,

$\frac{\delta}{d_i}$ = ratio of air-gap width to inner diameter,

in a regime of Grashof numbers from 30,000 to 716,000 and the ratio δ/d_i from 0.55 to 2.65. In Eq. (A.7), Nu_m is not greatly affected by the value of δ/d_i for ratios of δ/d_i less than 0.55 and becomes nearly a function of Grashof number alone at very small ratios. It should be a fairly good approximation to use Eq. (A.7) for values of δ/d_i less than 0.55 for Grashof numbers above 30,000.

The Grashof number is defined as

$$Gr_\delta = \frac{g\delta^3 \Delta T e_m^{\,2}}{T_m \mu_m^{\,2}} , \tag{A.8}$$

where

g = acceleration of gravity;
T_m = mean temperature in air gap, °R;
δ = air-gap width;
ΔT = temperature difference between the inner and outer cylinder;
e_m = mean air density in gap;
μ_m = mean air viscosity in gap.

The heat transferred by radiation across the air gap may be calculated using the equation

$$q_r = \frac{0.1713 A_i}{1/\varepsilon_i + (A_i/A_o)(1/\varepsilon_o - 1)} \left[\left(\frac{T_i}{100}\right)^4 - \left(\frac{T_o}{100}\right)^4 \right] , \tag{A.9}$$

where (all terms refer to the air gap)

A_i = area of inner surface;
A_o = area of outer surface;
T_i = temperature of inner surface, °R;
T_o = temperature of outer surface, °R;
ε_i = emissivity of inner surface;
ε_o = emissivity of outer surface.

A thermal-conductance term for radiation similar to that for convection may be defined as

$$\frac{q_r}{\Delta T} = \frac{1}{\Delta T} \frac{0.1713 A_i}{1/\varepsilon_i + (A_i/A_o)(1/\varepsilon_o - 1)} \left[\left(\frac{T_i}{100}\right)^4 - \left(\frac{T_o}{100}\right)^4\right] . \quad (A.10)$$

A heat-transfer coefficient for radiation may be defined as

$$h_{r_i} = \frac{1}{\Delta T} \frac{0.1713}{1/\varepsilon_i + (A_i/A_o)(1/\varepsilon_o - 1)} \left[\left(\frac{T_i}{100}\right)^4 - \left(\frac{T_o}{100}\right)^4\right] , \quad (A.11)$$

or, in the case for heat gain by chilled-water lines,

$$h_{r_i} = \frac{1}{\Delta T} \frac{0.1713 A_o/A_i}{1/\varepsilon_o + (A_o/A_i)(1/\varepsilon_i - 1)} \left[\left(\frac{T_o}{100}\right)^4 - \left(\frac{T_i}{100}\right)^4\right] . \quad (A.12)$$

The heat-transfer coefficient, h_{r_i}, varies only slightly for small changes in T_i and T_o, so that the heat loss may be accurately calculated by the first trial for the assumed values of T_i and T_o, if the assumed values are reasonably close (about 10°) to the correct values. The thermal conductance term for radiation may then be written as

$$\frac{q_r}{\Delta T} = h_{r_i} A_i . \quad (A.13)$$

The thermal conductance across the air gap is the sum of the conductance by convection and by radiation

$$\frac{q}{\Delta T} = \left(\frac{k_g}{\delta} Nu_m + h_{r_i}\right) A_i . \quad (A.14)$$

A.3 THERMAL CONDUCTANCE OF EARTH

The heat loss or heat gain by steady-state conduction from a horizontal underground pipe is given by the following equation:[3]

$$q = \frac{2\pi k_e (T_p - T_e)}{\ln\left[d/r + \sqrt{(d/r)^2 - 1}\right]} , \quad (A.15)$$

where

q = heat loss per foot of pipe length,
k_e = thermal conductivity of earth surrounding the pipe,
d = depth of the pipe measured from the ground surface to the centerline of the pipe,

r = outside radius of the pipe (or casing),
T_p = temperature of the pipe (or casing),
T_e = undisturbed earth temperature.

The thermal conductance of the earth, K_e, may then be expressed as follows:

$$K_e = \frac{q}{T_p - T_e} = \frac{2\pi k_e}{\ln\left[d/r + \sqrt{(d/r)^2 - 1}\right]} \quad . \qquad (A.16)$$

For this study, the depth of the centerline of the pipe was assumed to be 4 ft below the ground surface, and the thermal conductivity of the earth was assumed to be 0.833 Btu hr^{-1} ft^{-1} $°F^{-1}$. Thermal conductivity values of earth vary with type and moisture content of soil, and typical values are given in ref. 4. The undistrubed earth temperatures, T_e, were assumed to be the values given[5] for New Brunswick, New Jersey. The heat loss from the hot-water piping was based on the yearly average temperature of the earth of 54°F. The heat gain of the chilled-water piping was based on 62°F, the average earth temperature of the summer and fall, for an assumed thermal diffusivity of the earth of 0.025 ft^2/hr.

A.4 OVERALL THERMAL CONDUCTANCE

The general case considered in this study was for insulated pipe with a 1-in. annular air gap between the insulation and an outer casing. To calculate the heat loss for this case, the resistance to heat flow of the insulation, the air gap, and the earth were added in series. These results are given in the following equation:

$$q = \frac{(T_p - T_e)}{\left[\ln(r_i/r_p)\right]\left[1/2\pi k\right] + \frac{1}{\left[(k_g/\delta)Nu_m + h_{r_i}\right]A_i} + 1/K_e} \quad . \qquad (A.17)$$

For the case of no insulation but with an air gap, the first term of the denominator becomes zero. For the case of the bare pipe in contact with the earth, the first two terms of the denominator become zero.

The calculation procedure that was followed was to evaluate the conductance terms for the air gap, $(k_g/\delta)Nu_m$ and h_r, for assumed temperatures at the surfaces of the air gap and then determine the temperatures that would have to exist for the calculated heat loss. The resulting temperatures were usually close enough to the assumed values that it was not necessary to calculate new values for the conductance terms. Second trials were required in a few cases to obtain closer values of the radiation heat-transfer coefficient (ε_i and ε_o are assumed to be 0.8).

The calculated values for the heat loss from hot-water piping are given in Table A.1. The heat-gain values for the chilled-water piping are listed in Table A.2. These data are plotted in Figs. 9.4 and 9.5 of Sect. 9.3. Annual heat losses and heat gains are listed in Tables A.3 and A.4 respectively.

Table A.1. Hourly hot-water-piping heat loss (Btu hr^{-1} ft^{-1})

Pipe outside diameter (in.)	Bare pipe	Pipe and casing with 1-in. air gap	Conduit with 0.5-in. insulation	Conduit with 1-in. insulation	Conduit with 1.5-in. insulation	Conduit with 2-in. insulation
1.9	142.9	73.8	38.6	28.6	24.0	21.1
2.4	150.4	80.7	43.9	32.7	27.2	23.9
3.5	164.8	99.0	55.8	41.3	34.2	29.7
4.5	175.8	112.3	65.6	48.9	40.0	34.6
6.6	196.1	137.0	84.3	62.7	52.2	44.4
8.6	212.8	155.2	101.8	75.0	61.6	53.5
10.8	229.1	174.6	114.8	89.0	72.4	62.9
12.8	243.7	195.2	128.3	100.0	81.6	70.8
14.0	252.5	199.2	139.0	105.3	88.0	75.2

Table A.2. Hourly chilled-water-piping heat gain (Btu hr^{-1} ft^{-1})

Pipe outside diameter (in.)	Bare pipe	Pipe and casing with 1-in. air gap	Conduit with 0.5-in. insulation	Conduit with 1-in. insulation	Conduit with 1.5-in. insulation
1.9	13.6	6.2	3.3	2.5	2.1
2.4	14.3	6.6	3.7	2.8	2.3
3.5	15.7	8.0	4.7	3.6	2.9
4.5	16.7	9.1	5.6	4.2	3.4
6.6	18.7	11.1	7.1	5.4	4.5
8.6	20.3	12.7	8.6	6.5	5.3
10.8	21.8	14.4	9.8	7.7	6.3
12.8	23.2	16.1	11.0	8.6	7.1
14.0	24.0	16.6	11.9	9.1	7.6

Table A.3. Annual heat losses for underground hot-water pipe and conduits[a] (10^6 Btu $year^{-1}$ ft^{-1})

Nominal pipe size (in.)	Bare pipe	Pipe and casing with 1-in. air gap	Conduit with 0.5-in. insulation	Conduit with 1-in. insulation	Conduit with 1.5-in. insulation	Conduit with 2-in. insulation
1.5	1.25	0.65	0.34	0.25	0.21	0.18
2.0	1.32	0.71	0.38	0.29	0.24	0.21
3.0	1.44	0.87	0.49	0.30	0.30	0.26
4.0	1.54	0.98	0.57	0.43	0.35	0.30
6.0	1.72	1.20	0.74	0.55	0.46	0.39
8.0	1.86	1.36	0.89	0.66	0.54	0.47
10.0	2.01	1.53	1.01	0.78	0.63	0.55
12.0	2.14	1.71	1.12	0.88	0.71	0.62
14.0	2.21	1.74	1.22	0.92	0.77	0.66

[a]Hot water at 180°F and ground temperature at 54°F ($\Delta T = 126$); also assumes constant hot-water temperature for 8760 hr/year.

Table A.4. Annual heat gains for underground chilled-water pipe and conduits[a] (10^3 Btu year^{-1} ft^{-1})

Nominal pipe size (in.)	Bare pipe	Pipe and casing with 1-in. air gap	Conduit with 0.5-in. insulation	Conduit with 1-in. insulation	Conduit with 1.5-in. insulation
1.5	40.8	18.9	9.9	7.5	6.3
2.0	42.9	19.8	11.1	8.4	6.9
3.0	47.1	24.0	14.1	10.8	8.7
4.0	50.1	27.3	16.8	12.6	10.2
6.0	56.1	33.3	21.3	16.2	13.5
8.0	60.9	38.1	25.8	19.5	15.9
10.0	65.4	43.2	29.4	23.1	18.9
12.0	69.6	48.3	33.0	25.8	21.3
14.0	72.0	49.8	35.7	27.3	22.8

[a]Chilled water at 50°F and ground temperature at 62°F ($\Delta T = -12$); also assumes constant chilled-water temperature for 3000 hr/year.

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Appendix B

ANNUAL CAPITAL AND ENERGY COST DATA FOR SELECTION OF OPTIMUM INSULATION THICKNESS

Table B.1 evaluates, for various pipe sizes, the totals of fixed charges on capital cost and the value of the energy lost from HW (ΔT = 126°F) for pipe sizes from 1.5 to 14 in. when the energy is produced at \$2, \$3, or \$4 per MBtu. The values of annual heat losses from bare pipe are included for comparison, but the capital cost of the casing and the several thicknesses of insulation are additional costs (do not include the installed cost of pipe). Then, when plotted as shown in Figs. B.1 through B.9, the total cost determined for an insulated conduit is comparable to the casing costs with no insulation.

The installed costs are from data used in plotting Fig. 9.6, and the values of the annual energy lost are multiples of the annual losses in Table A.3. In Table B.1, the minimum value of the total cost is underlined for each of the two approximate costs for energy production.

The following is an example of the evaluation of total costs per linear foot for each pipe size in Table B.1:

Bare-pipe material cost[1]	= \$0.65
Bare-pipe installed cost[1]	= 4.00
Fixed charges @ 15% of \$4.00	= 0.60
Annual lost energy charge (Table A.1) @ \$2/MBtu	= 2.50
Annual lost energy charge (Table A.1) @ \$3/MBtu	= 3.75
Annual lost energy charge (Table A.1) @ \$4/MBtu	= 5.00
Total cost @ \$2/MBtu = 2.50 + 0.60	= 3.10
Total cost @ \$3/MBtu = 3.75 + 0.60	= 4.35
Total cost @ \$4/MBtu = 5.00 + 0.60	= 5.60
Casing material cost[2]	= 2.60
Casing installed cost[2]	= 4.55
Fixed charges @ 15% of \$4.55	= 0.68
Annual lost energy charge (Table A.1) @ \$2/MBtu	= 1.30
Annual lost energy charge (Table A.1) @ \$3/MBtu	= 1.95
Annual lost energy charge (Table A.1) @ \$4/MBtu	= 2.60
Total cost @ \$2/MBtu = 1.30 + 0.68	= 1.98
Total cost @ \$3/MBtu = 1.95 + 0.68	= 2.63
Total cost @ \$4/MBtu = 2.60 + 0.68	= 3.28
Cost of case plus 1.0 in. insulation[1,2]	= 3.60
Cost of installation @ 175% of \$3.60	= 6.30
Fixed charges @ 15% of \$6.30	= 0.94
Annual lost energy charge (Table A.1) @ \$2/MBtu	= 0.50
Annual lost energy charge (Table A.1) @ \$3/MBtu	= 0.75
Annual lost energy charge (Table A.1) @ \$4/MBtu	= 1.00
Total cost @ \$2/MBtu = 0.50 + 0.94	= 1.44
Total cost @ \$3/MBtu = 0.75 + 0.94	= 1.69
Total cost @ \$4/MBtu = 1.00 + 0.94	= 1.94

Table B.1. Capital and annual costs for various hot-water district-heating conduit sizes

Cost factor	Bare pipe[a]	Conduit casing and coating	Casing with insulation thickness of			
			0.5 in.	1.0 in.	1.5 in.	2.0 in.
1.5-in.-diam pipe						
Material cost (dollars per foot)	0.65	2.60	3.10	3.60	4.10	4.60
Installed cost [b] (dollars per foot)	4.00	4.55	5.42	6.30	7.18	8.05
Fixed charge,[c] dollars $year^{-1}$ ft^{-1}	0.60	0.68	0.81	0.94	1.08	1.21
Annual value of lost energy[d] in dollars $year^{-1}$ ft^{-1} for:						
$2/MBtu energy	2.50	1.30	0.68	0.50	0.42	0.36
$3/MBtu energy	3.75	1.95	1.02	0.75	0.63	0.54
$4/MBtu energy	5.00	2.60	1.36	1.00	0.84	0.72
Total cost, dollars $year^{-1}$ ft^{-1} for:						
$2/MBtu energy	3.10	1.98	1.49	1.44	1.50	1.57
$3/MBtu energy	4.35	2.63	1.83	1.69	1.71	1.75
$4/MBtu energy	5.60	3.28	2.17	1.98	1.92	1.93
2-in.-diam pipe						
Material cost (dollars per foot)	0.75	2.91	3.56	4.08	4.59	5.11
Installed cost [b] (dollars per foot)	4.83	5.09	6.23	7.14	8.03	8.94
Fixed charge,[c] dollars $year^{-1}$ ft^{-1}	0.72	0.76	0.93	1.07	1.20	1.34
Annual value of lost energy[d] in dollars $year^{-1}$ ft^{-1} for:						
$2/MBtu energy	2.64	1.42	0.76	0.58	0.48	0.42
$3/MBtu energy	3.96	2.13	1.14	0.87	0.72	0.63
$4/MBtu energy	5.28	2.84	1.52	1.16	0.96	0.84

Table B.1 (continued)

Cost factor	Bare pipe[a]	Conduit casing and coating	Casing with insulation thickness of			
			0.5 in.	1.0 in.	1.5 in.	2.0 in.
Total cost, dollars $year^{-1}$ ft^{-1} for:						
$2/MBtu energy	3.36	2.18	1.69	1.65	1.68	1.76
$3/MBtu energy	4.68	2.89	2.07	1.94	1.92	1.97
$4/MBtu energy	6.00	3.60	2.45	2.23	2.16	2.18
		3-in.-diam pipe				
Material cost (dollars per foot)	1.40	3.50	4.45	5.00	5.55	6.10
Installed cost [b] (dollars per foot)	6.50	6.12	7.78	8.75	9.71	10.67
Fixed charge,[c] dollars $year^{-1}$ ft^{-1}	0.98	0.92	1.16	1.31	1.46	1.60
Annual value of lost energy[d] in dollars $year^{-1}$ ft^{-1} for:						
$2/MBtu energy	2.88	1.74	0.98	0.72	0.60	0.52
$3/MBtu energy	4.32	2.61	1.47	1.08	0.90	0.78
$4/MBtu energy	5.76	3.48	1.96	1.44	1.20	1.04
Total cost, dollars $year^{-1}$ ft^{-1} for:						
$2/MBtu energy	3.85	2.66	2.14	2.03	2.06	2.12
$3/MBtu energy	5.29	3.53	2.63	2.39	2.36	2.38
$4/MBtu energy	6.73	4.40	3.12	2.75	2.66	2.64
		4-in.-diam pipe				
Material cost (dollars per foot)	1.90	4.10	5.35	5.92	6.50	7.10
Installed cost [b] (dollars per foot)	8.20	7.17	9.36	10.36	11.37	12.42
Fixed charge,[c] dollars $year^{-1}$ ft^{-1}	1.23	1.08	1.40	1.55	1.71	1.86

Table B.1 (continued)

Cost factor	Bare pipe[a]	Conduit casing and coating	Casing with insulation thickness of			
			0.5 in.	1.0 in.	1.5 in.	2.0 in.
Annual value of lost energy[d] in dollars $year^{-1}$ ft^{-1} for:						
\$2/MBtu energy	3.08	1.96	1.14	0.86	0.70	0.60
\$3/MBtu energy	4.62	2.94	1.71	1.29	1.05	0.90
\$4/MBtu energy	6.16	3.92	2.28	1.72	1.40	1.20
Total cost, dollars $year^{-1}$ ft^{-1} for:						
\$2/MBtu energy	4.31	3.04	2.52	2.41	2.40	2.46
\$3/MBtu energy	5.85	4.02	3.11	2.84	2.75	2.76
\$4/MBtu energy	7.39	5.00	3.68	3.27	3.10	3.06
6-in.-diam pipe						
Material cost (dollars per foot)	3.40	5.27	7.10	7.72	8.37	9.02
Installed cost[b] (dollars per foot)	11.50	9.22	12.42	13.51	14.65	15.78
Fixed charge,[c] dollars $year^{-1}$ ft^{-1}	1.72	1.38	1.86	2.03	2.20	2.37
Annual value of lost energy[d] in dollars $year^{-1}$ ft^{-1} for:						
\$2/MBtu energy	3.44	2.40	1.48	1.10	0.92	0.78
\$3/MBtu energy	5.16	3.60	2.22	1.65	1.38	1.17
\$4/MBtu energy	6.88	4.80	2.96	2.20	1.84	1.56
Total cost, dollars $year^{-1}$ ft^{-1} for:						
\$2/MBtu energy	5.17	3.78	3.34	3.13	3.12	3.15
\$3/MBtu energy	6.89	4.98	4.08	3.68	3.58	3.54
\$4/MBtu energy	8.61	6.78	4.82	4.23	4.04	3.93

Table B.1 (continued)

Cost factor	Bare pipe[a]	Conduit casing and coating	Casing with insulation thickness of			
			0.5 in.	1.0 in.	1.5 in.	2.0 in.
		8-in.-diam pipe				
Material cost (dollars per foot)	4.95	6.45	8.87	9.57	10.25	10.95
Installed cost[b] (dollars per foot)	15.00	11.29	15.52	16.75	17.94	19.16
Fixed charge,[c] dollars $year^{-1}$ ft^{-1}	2.25	1.69	2.32	2.51	2.69	2.82
Annual value of lost energy[d] in dollars $year^{-1}$ ft^{-1} for:						
$2/MBtu energy	3.72	2.72	1.78	1.32	1.08	0.94
$3/MBtu energy	5.58	4.08	2.67	1.98	1.62	1.41
$4/MBtu energy	7.44	5.44	3.56	2.64	2.16	1.88
Total cost, dollars $year^{-1}$ ft^{-1} for:						
$2/MBtu energy	5.97	4.41	4.11	3.83	3.77	3.76
$3/MBtu energy	7.83	5.77	5.00	4.49	4.31	4.23
$4/MBtu energy	9.69	7.13	5.89	5.15	4.85	4.70
		10-in.-diam pipe				
Material cost (dollars per foot)	7.05	7.64	10.64	11.39	12.14	12.89
Installed cost[b] (dollars per foot)	18.20	13.37	18.62	19.93	21.24	22.56
Fixed charge,[c] dollars $year^{-1}$ ft^{-1}	2.73	2.01	2.79	2.99	3.19	3.38
Annual value of lost energy[d] in dollars $year^{-1}$ ft^{-1} for:						
$2/MBtu energy	4.02	3.06	2.02	1.56	1.26	1.10
$3/MBtu energy	6.03	4.59	3.03	2.34	1.89	1.65
$4/MBtu energy	8.04	6.12	4.04	3.12	2.52	2.20

Table B.1 (continued)

Cost factor	Bare pipe[a]	Conduit casing and coating	Casing with insulation thickness of			
			0.5 in.	1.0 in.	1.5 in.	2.0 in.
Total cost, dollars $year^{-1}$ ft^{-1} for:						
$2/MBtu energy	6.75	5.07	4.81	4.55	4.45	4.48
$3/MBtu energy	8.76	6.60	5.82	5.33	5.08	5.03
$4/MBtu energy	10.77	8.13	6.83	6.11	5.71	5.58
		12-in.-diam pipe				
Material cost (dollars per foot)	9.85	8.82	12.42	13.22	14.02	14.82
Installed cost[b] (dollars per foot)	21.60	15.43	21.73	23.13	24.53	25.93
Fixed charge,[c] dollars $year^{-1}$ ft^{-1}	3.24	2.31	3.26	3.47	3.68	3.89
Annual value of lost energy[d] in dollars $year^{-1}$ ft^{-1} for:						
$2/MBtu energy	4.27	3.42	2.24	1.76	1.42	1.24
$3/MBtu energy	6.41	5.13	3.36	2.64	2.13	1.86
$4/MBtu energy	8.55	6.84	4.48	3.52	2.84	2.48
Total cost, dollars $year^{-1}$ ft^{-1} for:						
$2/MBtu energy	7.51	5.73	5.50	5.23	5.10	5.13
$3/MBtu energy	9.65	7.44	6.62	6.11	5.81	5.75
$4/MBtu energy	11.79	9.15	7.74	6.99	6.52	6.37
		14-in.-diam pipe				
Material cost (dollars per foot)	11.50	10.00	14.20	15.05	15.90	16.75
Installed cost[b] (dollars per foot)	25.00	17.50	24.85	26.34	27.82	29.31
Fixed charge,[c] dollars $year^{-1}$ ft^{-1}	3.75	2.63	3.73	3.95	4.17	4.40

Table B.1 (continued)

Cost factor	Bare pipe[a]	Conduit casing and coating	Casing with insulation thickness of			
			0.5 in.	1.0 in.	1.5 in.	2.0 in.
Annual value of lost energy[d] in dollars year^{-1} ft^{-1} for:						
\$2/MBtu energy	4.42	3.48	2.44	1.84	1.54	1.32
\$3/MBtu energy	6.63	5.22	3.66	2.76	2.31	1.98
\$4/MBtu energy	8.84	6.96	4.88	3.68	3.08	2.64
Total cost, dollars year^{-1} ft^{-1} for:						
\$2/MBtu energy	8.17	6.11	6.17	5.79	5.71	5.72
\$3/MBtu energy	10.38	7.85	7.39	6.71	6.48	6.38
\$4/MBtu energy	12.59	9.59	8.61	7.63	7.25	7.04

[a] Not included in conduit costs.

[b] Installation of casing or insulation at 1.75 times the cost of materials (1.25 for expansion joints times 1.40 for installation of prefabricated sections), but does not apply to bare pipe.

[c] 15% of capital cost.

[d] Annual heat losses from Table A.3.

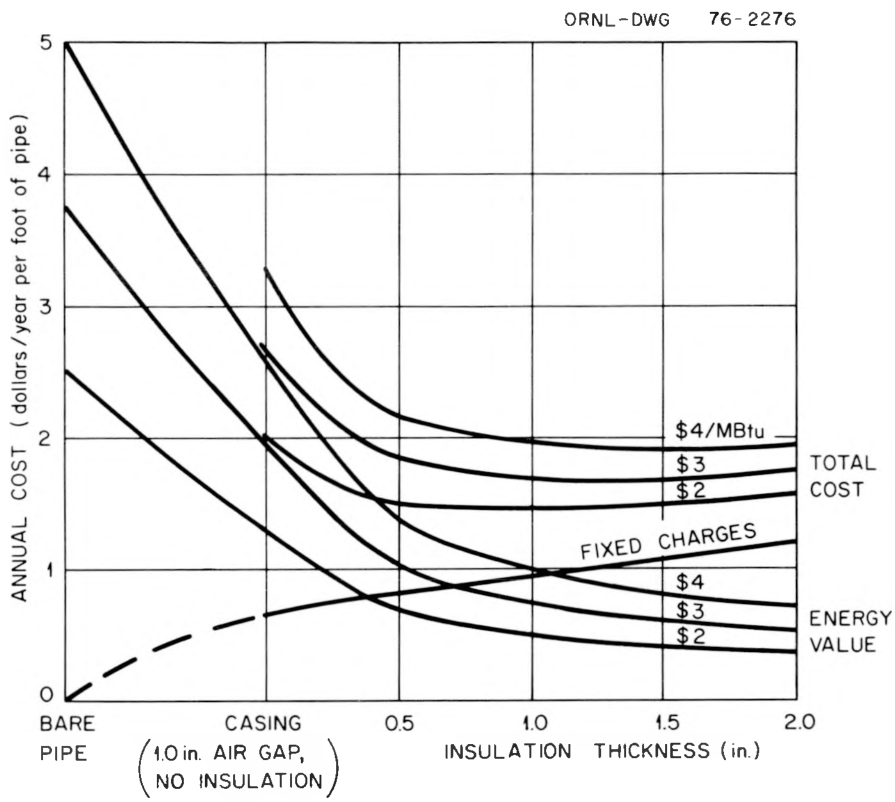

Fig. B.1. Capital and energy cost for 1-½-in. nominal pipe size.

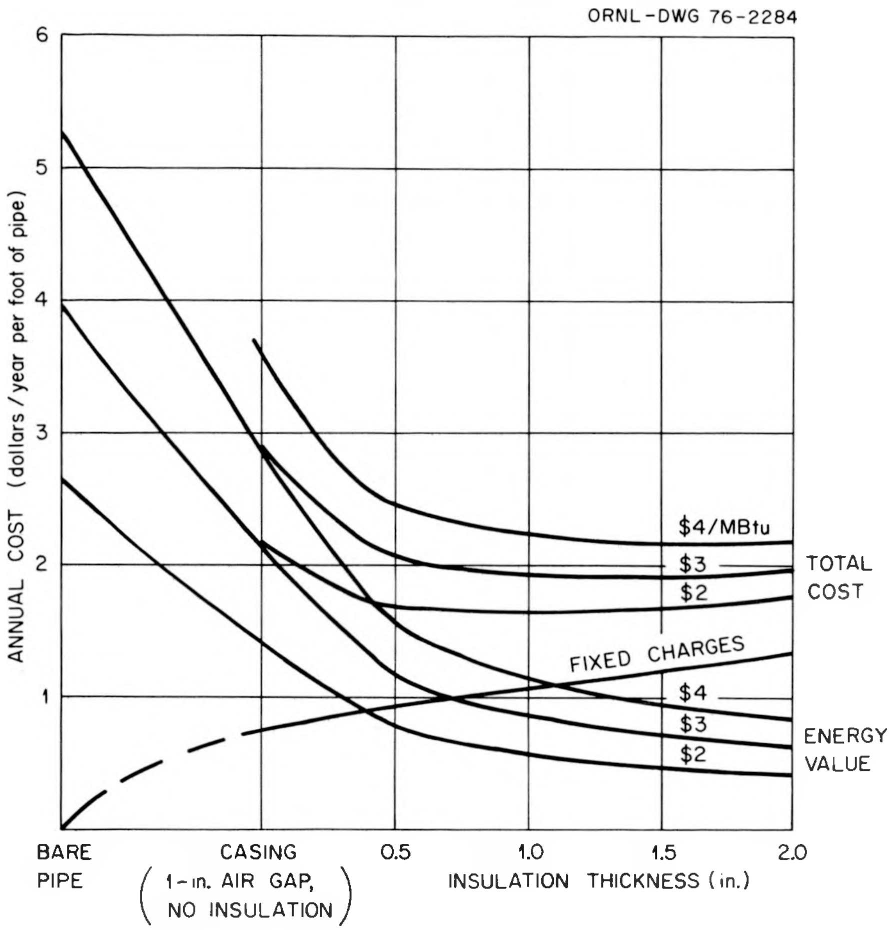

Fig. B.2. Capital and energy cost for 2-in. nominal pipe size.

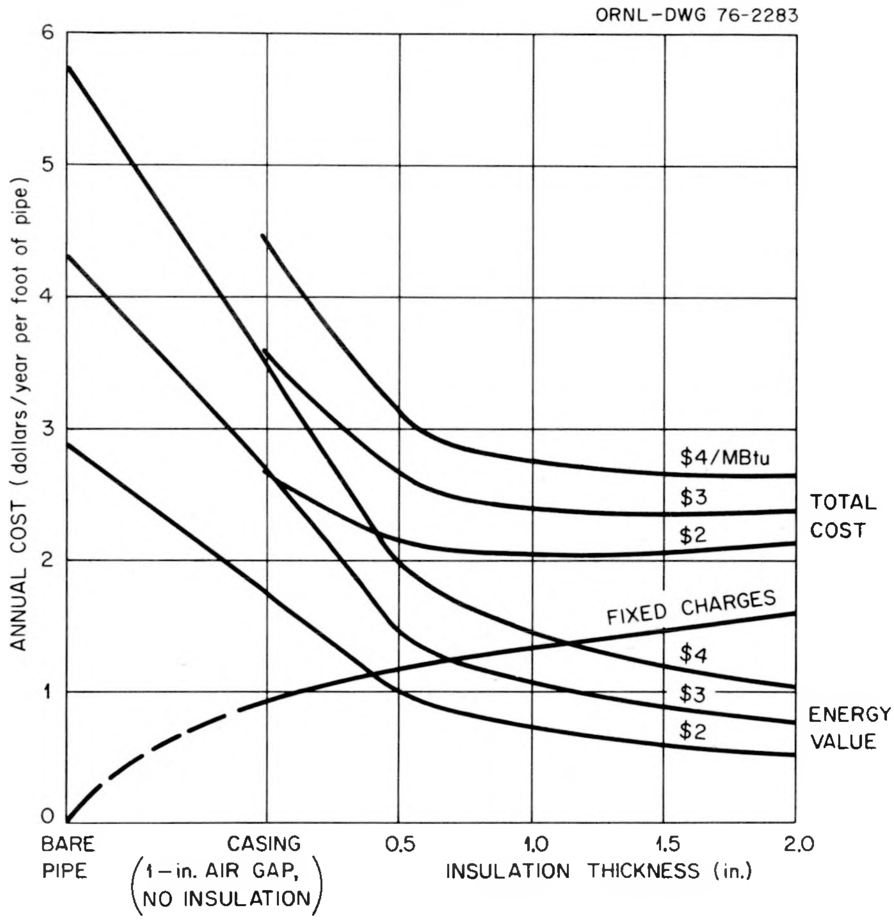

Fig. B.3. Capital and energy cost for 3-in. nominal pipe size.

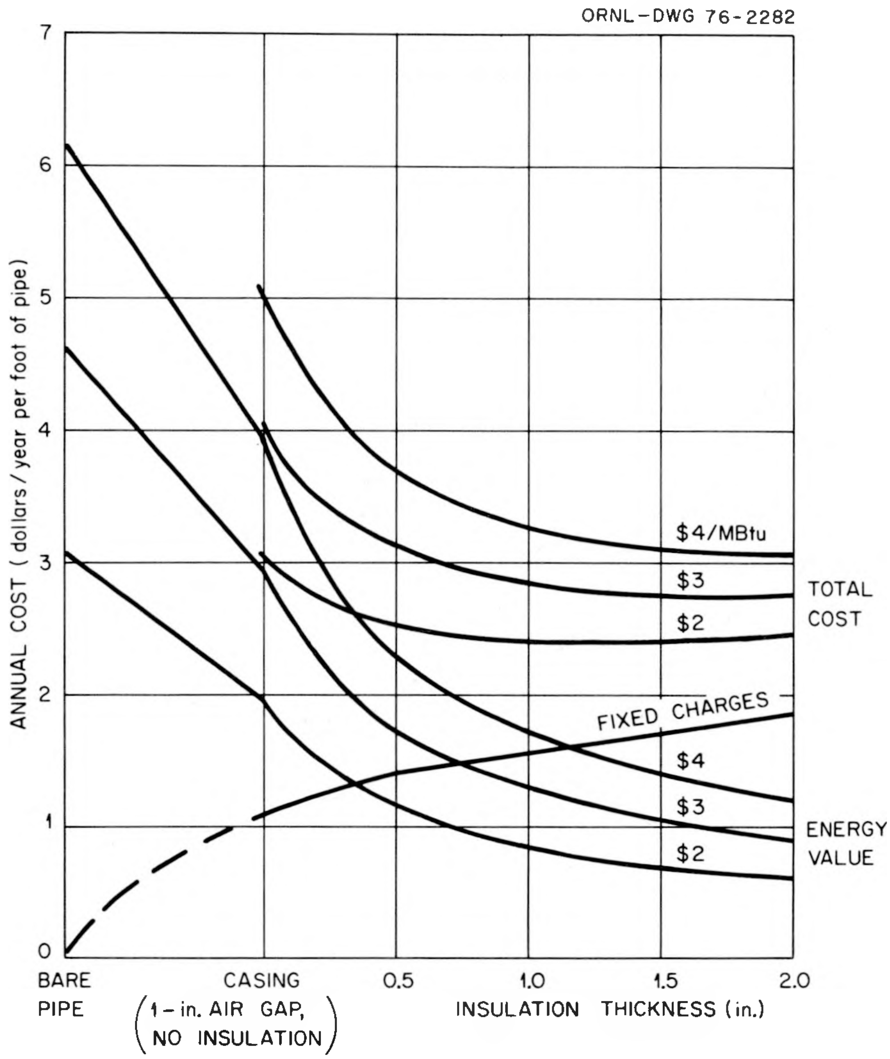

Fig. B.4. Capital and energy cost for 4-in. nominal pipe size.

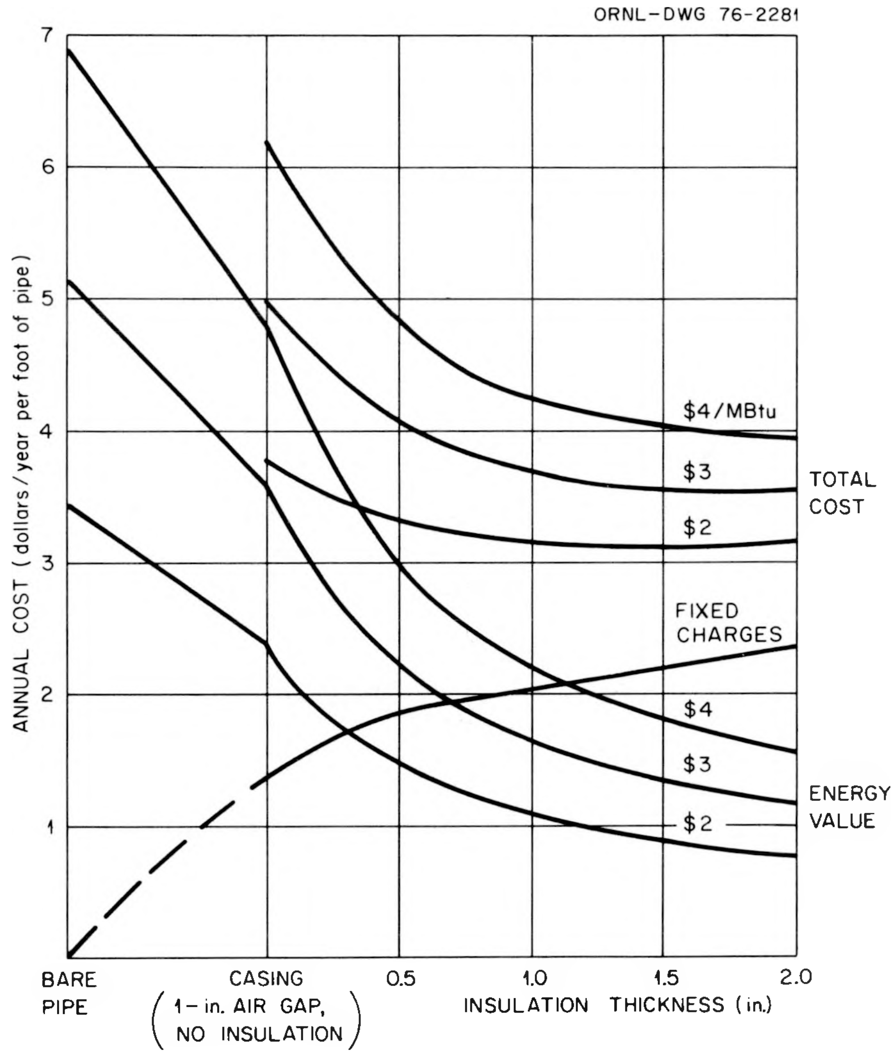

Fig. B.5. Capital and energy cost for 6-in. nominal pipe size.

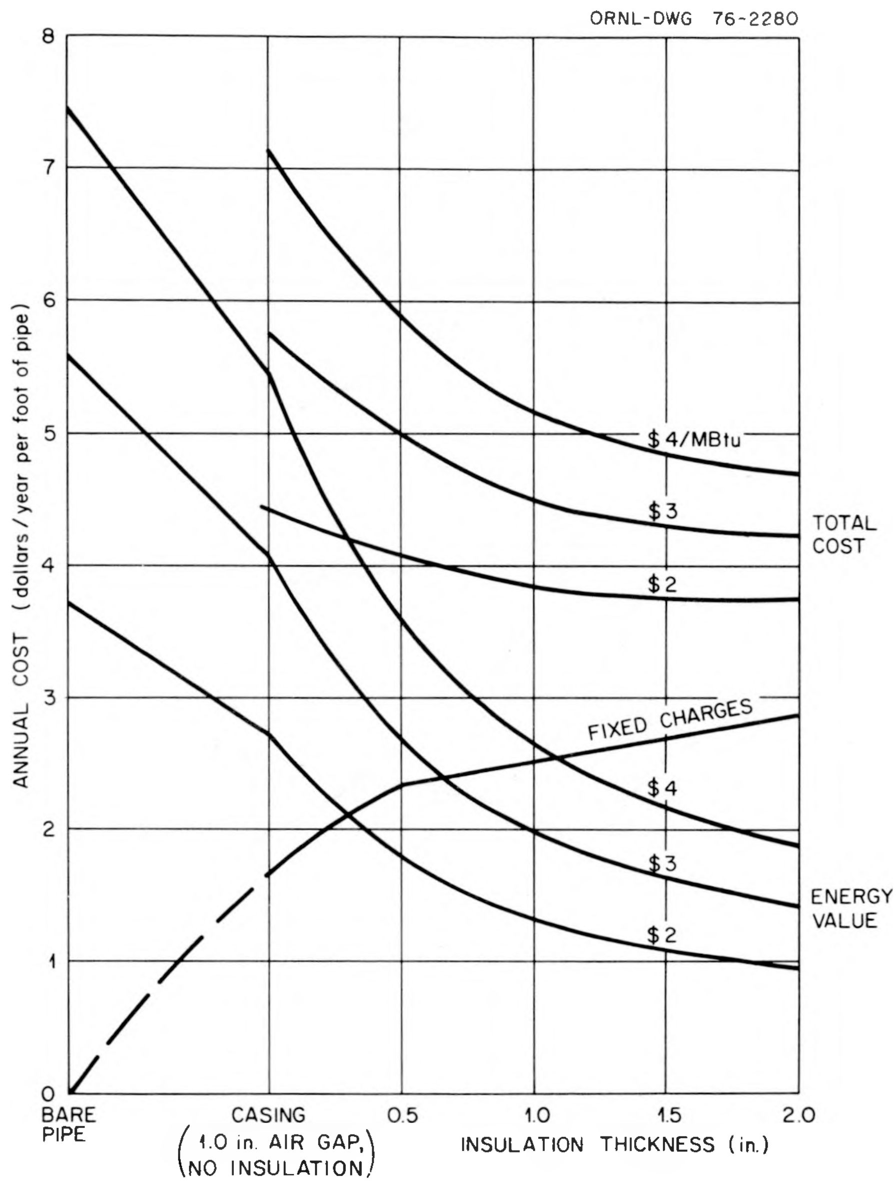

Fig. B.6. Capital and energy cost for 8-in. nominal pipe size.

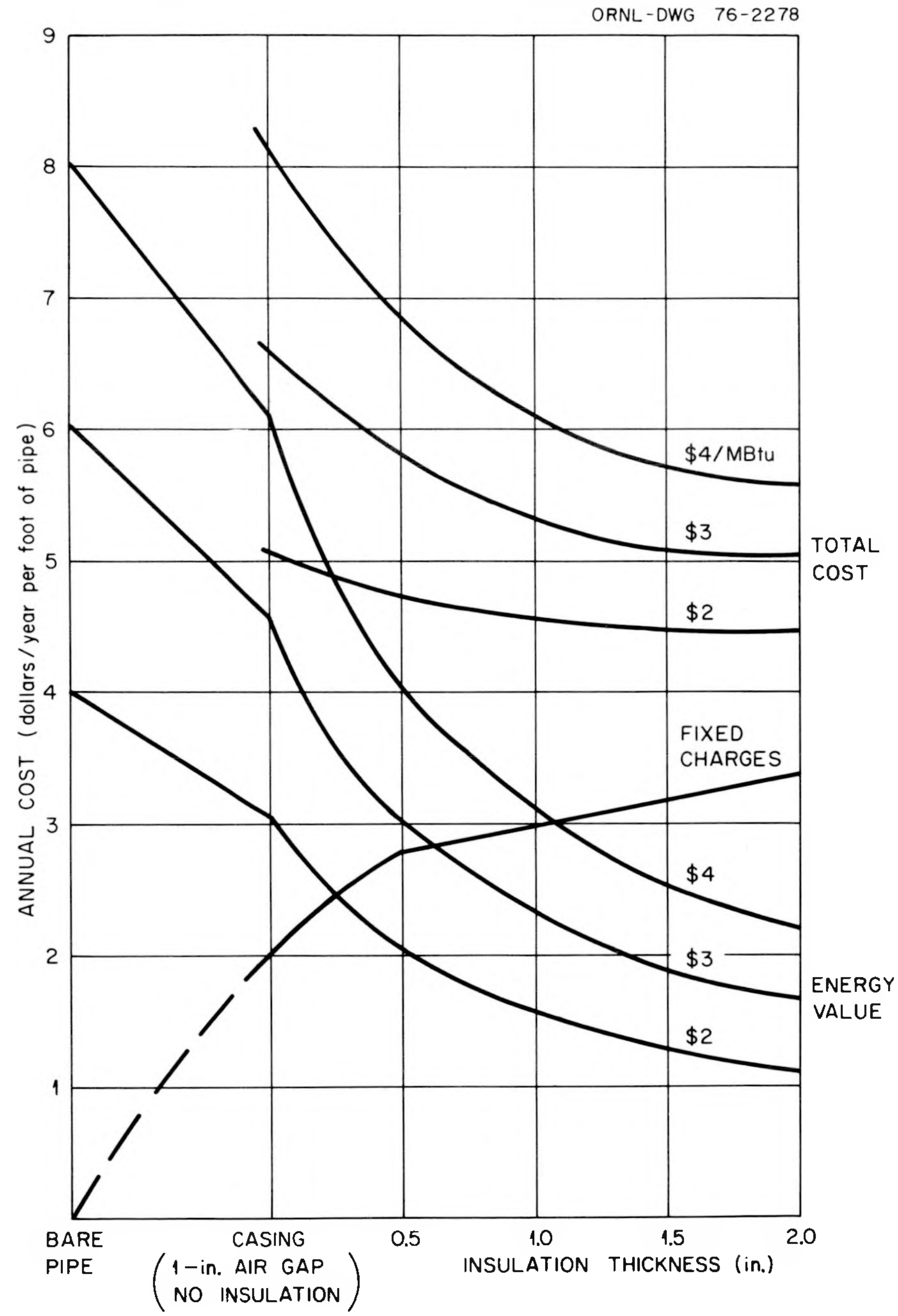

Fig. B.7. Capital and energy cost for 10-in. nominal pipe size.

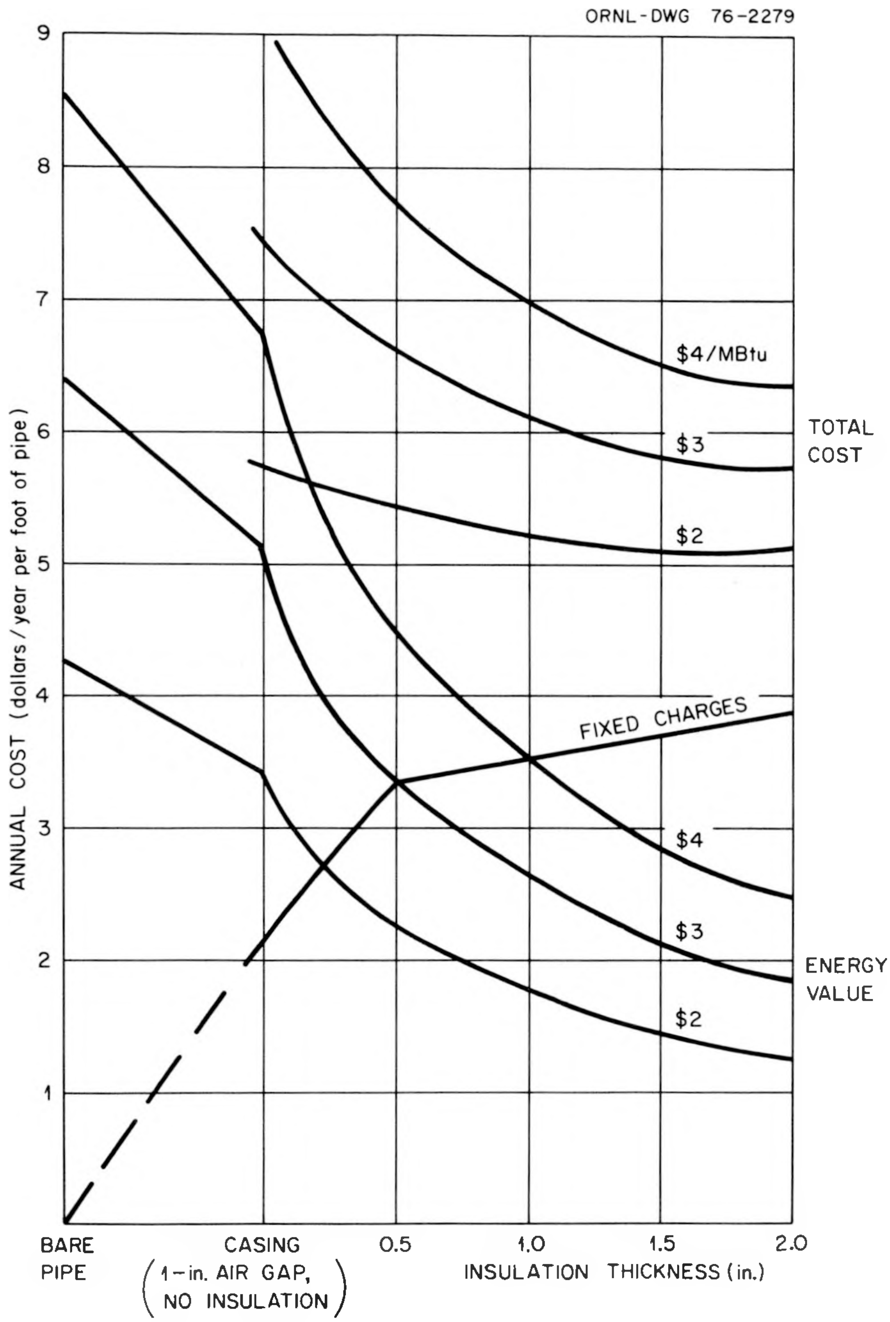

Fig. B.8. Capital and energy cost for 12-in. nominal pipe size.

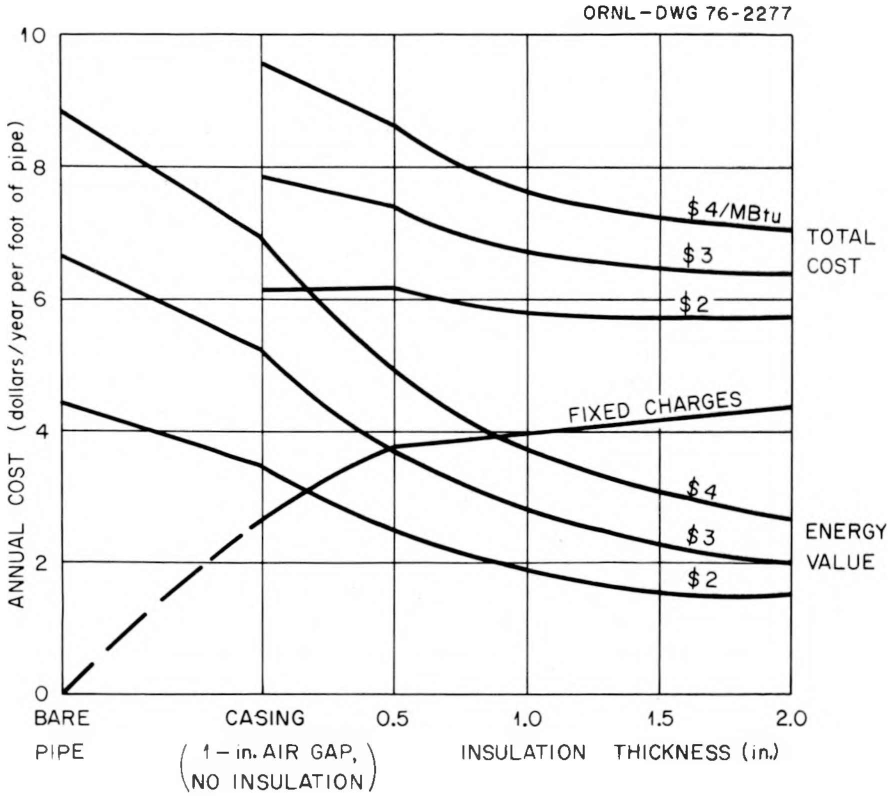

Fig. B.9. Capital and energy cost for 14-in. nominal pipe size.

REFERENCES FOR APPENDIX B

1. *Commercial-Industrial Estimating and Engineering Standards*, Richardson Engineering Services, Inc., Downey, California, 1972.

2. W. Diskant, American Hydrotherm Corp., personal communication to A. J. Miller, Oak Ridge National Laboratory, June 5, 1973.

Appendix C

SPECIFICATIONS FOR FRP AT JERSEY CITY BREAKTHROUGH PROJECT*

Materials: Bondstrand series 2000 — preinsulated, epoxy-reinforced glass-fiber piping.

FRP pipe and fittings: All FRP pipe and fittings shall be helically wound with continuous glass fibers impregnated with epoxy resin. All pipe and fittings shall be designed for handling a maximum fluid temperature of 300°F.

Pipe: The helically wound pipe shall have an outside diameter equal to standard weight steel pipe. The inner surface of the pipe shall have a continuous resin-rich surface layer reinforced with a C-type surfacing veil.

Pipe joints: The pipe shall have bell-and-spigot type couplings and shall be factory sanded on one end as specified by the manufacturer for field-joint installation. Pipe joints having the quick-lock-type joint may be field welded and continuously joined before the joint cement is cured. Joints not having the quick-lock feature shall be fitted with a clamp that will hold the joint rigidly in place until the joint cement has completely cured. A gage shall be used to mark the exterior of the pipe to assure bottoming of the pipe end in the socket.

Curing of field-welded FRP pipe and fittings: All field-welded joints shall be cured with a WatLow self-regulation temperature-controlled electrical heating blanket (or equal) for 25 to 30 min, regardless of ambient temperature.

Insulation: Insulation shall consist of 2- to 2-1/2-lb/cu ft-density rigid polyurethane; it shall be factory applied to the pipe at a minimum thickness, after covering, of 0.875 in. The insulation cover shall be held to the pipe exterior with a factory tension-wound or stressed-fiberglass reinforced polyester or epoxy cover manufactured with the identical filament-wound factory process as the interior of the pipe and shall have a minimum thickness of 0.060 in. The insulation cover shall be bonded to each end of the pipe, with a waterproof seal at a distance, from the end of the pipe, not more than the normal joint overlap plus 1 in. The approximate outside diameter of the insulation cover shall be 2 in. greater than the outside diameter of the pipe.

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*Excerpts from "Specification (Alternate) for Fiberglass-Reinforced Plastic (FRP) Pipe for Underground Heating Hot Water and Chilled Water," transmitted to HUD from Gamze, Korobkin, and Caloger, Oct. 20, 1971.

Notes on tests for insulation cover and waterproof seal: Tests for the cover (casing) seal require watertight integrity after a pipe conduit test section has been cycled alternately with 40°F water and 30 psia steam. These cycling tests and a load-support-hanger test involves considerable detail. Insulation of pipe fittings shall be with a 6-in. envelope of "Gilso-therm-70." Pipe that is buried under roadways shall be laid to a minimum ditch depth as shown on the drawings. Backfill shall not allow large or sharp-edged rocks of any size to directly contact the pipe wall. Compacting shall be done so as to avoid damage to the pipe wall. Where heavy traffic loads are involved, conduit shall be used. Pipe shall not be bent to follow abrupt changes in the contour of the ditch or to change pipe direction. Concrete thrust blocks (not less than 3 cu ft) shall be installed at all elbows or when the piping changes direction.

Hydrostatic testing of the installed FRP piping system shall be made at 1-1/2 times the normal working pressure.

Appendix D

DEFINITIONS AND ORGANIC HEAT-TRANSFER FLUID PROPERTIES

BRAB	Building Research Advisory Board
ChW	Chilled water in the temperature range of 30 to 55°F
Conduit	The complete assembly of pipe, insulation, and casing or envelope
HTHW	High-temperature hot water at temperatures equal to or above 300°F
LTHW	Low-temperature hot water in the temperature range of 150 to 250°F
MTHW	Medium-temperature hot water in the temperature range of 250 to 300°F
Present worth	A method of economic analysis that assumes a present (zero) date for capital cost, with no interest factors applied. Then all future payments (e.g., annual operating and maintenance costs) are estimated, and interest factors are applied to establish their present worth at the zero date. The sum of the capital cost and the investments to be made at present to ensure future payments are equal to the present worth.
Annual cost	A method that translates all costs into comparative annual cost. Capital costs are translated into an annual cost by evaluating the payment required each year to amortize capital over a specific number of years at a prevailing interest rate. The annual costs for operating and maintenance are then added to the amortized capital cost to give the total annual cost.

Table D.1. Frequently used organic heat-transfer fluids[a]

Heat-Transfer Fluid			Usable Temp. Range,* °F.	
Composition	Trade name	Producer	Low	High
Aliphatic petroleum oil	Humbletherm 500	Humble Oil	−5	600
Alkyl-aromatic petroleum oil	Mobiltherm 600	Mobil Oil	−5	600
o-Dichlorobenzene	Dowtherm E	Dow Chemical	0†	500
Diphenyl-diphenyl oxide eutectic	Dowtherm A	Dow Chemical	55†	750
Di -and tri-aryl ethers	Dowtherm G	Dow Chemical	12	650
Hydrogenated terphenyls	Therminol 66	Monsanto	25	650
Polychlorinated biphenyl	Therminol FR-1	Monsanto	25	600
Polyphenyl ether	Therminol 77	Monsanto	60	700

*The low-temperature limit was estimated for each fluid from its minimum pumpability characteristic. This pumping factor has been generally accepted by centrifugal pump manufacturers. It is defined as the temperature where the fluid exhibits a 2,000-cp. viscosity.

†This fluid exhibits a true freezing point below the temperature shown. The viscosity at this temperature is less than 10 cp.

[a]From W. F. Seifert, L. L. Jackson, and C. E. Sech, "Organic Fluids for High-Temperature Heat-Transfer Systems," *Chem. Eng.* 79(24): 96-104 (Oct. 30, 1972), with permission from McGraw-Hill.

Table D.2. Physical properties of frequently used organic heat-transfer fluids[a]

Compound	Freezing Point, °F.	Boiling Point, °F.	Flash Point, °F.	Fire Point, °F.
1,2,4-trichlorobenzene	63	417	210	†
Tetrachlorobenzene (isomer mixture)	170	480	None	†
Chlorinated biphenyl	7‡	515-680	330	>500
Dichlorodiphenyl ether (isomer mixture)	−4	590	335	530
Trichlorodiphenyl ether (isomer mixture)	130	650	400	>600
Octachlorostyrene	210	—	None	None
Diphenyl ether—diphenyl eutectic	54	495	255	275
Biphenylyl phenyl ether (isomer mixture)	99	680	370	410
o-Biphenylyl phenyl ether	122	670	370	410
Di- and triaryl ethers	<0	572	305	315
Dimethyl-diphenyl ether (isomer mixture)	−40†	554	—	—
Tetramethyl diphenyl ether (isomer mixture)	—	590	—	—
Di-sec-butyl diphenyl ether (isomer mixture)	—	705	380	400
Dicyclohexyldiphenyl ether (isomer mixture)	—	785	—	—
Dodecyldiphenylether (isomer mixture)	45‡	>800	410	440
Ethyldiphenyl (isomer mixture)	<−60‡	536	—	—
Partially hydrogenated terphenyl	−15‡	690	335	375
Aliphatic oil	15	720-950	425	475
Alkylaromatic oil	20	~650	350	390

*Cleveland Open Cup method
†None to boiling point
‡Pour point

[a]From W. F. Seifert, L. L. Jackson, and C. E. Sech, "Organic Fluids for High-Temperature Heat-Transfer Systems," *Chem. Eng.* 79(24): 96-104 (Oct. 30, 1972), with permission from McGraw-Hill.

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