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OPERATED BY
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Energy Division

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## ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| ANSI | American National Standards Institute |
| ASME | American Society of Mechanical Engineers |
| ASTM | American Society for Testing and Materials |
| CPVC | postchlorinated polyvinylchloride |
| DOD | U.S. Department of Defense |
| DOE | U.S. Department of Energy |
| FE | finite element |
| HDPE | high-density polyethylene |
| HDS | hydrostatic design stress |
| IPS | International Pipe Standard |
| LDPE | low-density polyethylene |
| NSF | National Science Foundation |
| PB | polybutylene |
| PE | polyethylene |
| PEX | cross-linked polyethylene |
| PF | urethane foam |
| PPI | Plastics Pipe Institute |
| PR | pressure rated |
| PVC | polyvinylchloride |
| SDR | standard dimension ratio |

## EXECUTIVE SUMMARY

The objectives of this investigation were to characterize and evaluate the potential of nonmetallic piping systems for district heating applications. Nonmetallic systems appear to have the economic potential to greatly expand the service territories of district heating systems. Modern district heating systems are among the more efficient delivery mechanisms and provide a convenient method for using more plentiful domestic fuel such as coal.

Nonmetallic piping materials have been of interest to the district heating industry for many years. Originally, most of the interest stemmed from the possibility of overcoming the corrosion problems experienced with steel piping. While the inherent resistance to corrosion of nonmetallic piping is still attractive, it is not a sufficient feature to justify its adoption. The main focus now has changed to reducing cost. The nonmetallic materials offer a combined material and installation cost that has the potential to be significantly lower than conventional metallic piping systems.

The nonmetallic piping applications for district heating were classified into three categories of nonmetallic materials: (1) currently being used in district heating applications, (2) currently being used in piping applications other than district heating, and (3) not currently being used in any piping applications. The first of these categories includes cross-linked polyethylene and polybutylene. The performance of these two piping systems has been satisfactory, with one important exception: both systems have limited operating temperatures of around 200°F (93.3°C). They are classified as low-temperature systems.

An analysis of the cost components for district heating was performed for currently used metallic district heating piping technology. The analysis separated the cost into civil, mechanical, and material portions of a project. The civil costs are roughly one-third the total, and the material and mechanical costs combined are the other two-thirds of the total. The civil costs include activities such as digging ditches, backfilling, and surface restoration.

While some potential nonmetallic technologies might offer some effect on civil costs, such effects are likely to be minimal. The main potential savings for nonmetallic piping technology are in the mechanical and material costs. An estimate made for the use of plastic piping showed a potential reduction in mechanical costs of about 8% of the total project cost. Material cost savings are possible for small (<4-in. diam.) pipes. For large pipes, the material costs are higher than those for conventional piping systems. Another potential savings is in the engineering costs. In any project, the design of a piping system to accommodate thermal loads and thermal expansion requires careful engineering. Such costs range between 5 and 12% of the project cost. The simpler design of the nonmetallic system could reduce the engineering costs.

Nonmetallic piping offers potential advantages over conventional district heating piping. There are clear opportunities for savings in mechanical installation costs. Among these are fewer joints, less expensive joints, simpler expansion compensation, easier pipe handling, reduced or eliminated pipe cleaning, and simpler testing.

## ABSTRACT

The objectives of this investigation were to characterize and evaluate the potential of nonmetallic piping systems for district heating applications. This investigation considered both currently available products and future products. Analyses of the cost components of district heating systems were performed for current steel heating piping technology. A comparison was then made with hypothetical nonmetallic piping technology, and opportunities where savings might occur were noted.

As a result of these analyses, a conceptual design for a preinsulated, nonmetallic piping was developed to take advantage of likely areas of overall cost reduction. This design, based on low-cost field fabrication and existing materials, used a postchlorinated polyvinylchloride carrier pipe supported structurally by high-density urethane foam and polyethylene jacketing. A structural analysis of this conceptual design was performed using two-dimensional, finite elements. The results are promising for practical operating temperatures.

# 1. INTRODUCTION

The objectives of this investigation were to characterize and evaluate the potential of nonmetallic piping systems for district heating applications. Nonmetallic piping systems appear to have the economic potential to greatly expand the service territories of district heating systems. Modern district heating systems are among the more efficient energy-delivering mechanisms and provide a convenient method for using more plentiful domestic fuels such as coal. For these reasons, research on nonmetallic piping systems is of interest to the U.S. Department of Energy (DOE).

## 1.1 BACKGROUND INFORMATION

A vast number of district heating systems are in use in the United States. There are commercial district heating systems that serve cities; federal government systems that serve military bases, DOE facilities, and Veterans' Administration facilities; systems that serve university campuses; and systems that serve institutional complexes such as hospitals. It is estimated that there are approximately 100 city commercial district heating systems, 400 federal government systems, 1000 university systems, and more than 2000 institutional systems. District heating piping research could help improve the cost-effectiveness and performance of all these systems. However, the ones that have direct drain on the federal treasury are those owned by the government.

A recent study by the Tri-Service Committee[1] estimates that the Department of Defense maintains about 6000 miles (9656 km) of district heating systems. At an installed cost of $300/ft, these systems represent an investment of $9.5 billion. More than three-fourths of these systems were installed during the period 1938–47, and less than 2% were installed after 1963. Consequently, most of these distribution systems will have to undergo extensive retrofit or replacement over the next 20 years, requiring about one-half billion dollars of investment annually.

Although the military is doing applications research to reduce the cost of the systems, its mission does not allow long-term research for the development of new systems. Rather, military efforts focus on using currently available commmercial technology. There is a need for research that is oriented at developing new systems that are less expensive, more reliable, and more efficient. Such research has the potential to save 10–20% of the investment cost of the district heating system on military facilities. It is also estimated that the same 10–20% could also be saved on district heating systems for cities, universities, and institutional complexes. For the military systems, this could mean a savings of between $1 billion and $2 billion. It is much more difficult to estimate the savings on the other types of systems because there is no inventory on the amount or value of network in place. However, it appears that this investment and consequent potential savings are larger than those for military systems. District heating piping research has the potential to save billions of dollars and also reduce the direct drain on the federal treasury for military installations.

## 1.2 APPROACH OF THE INVESTIGATION

This report is a preliminary investigation to determine background information and evaluate the impact of nonmetallic piping systems. The analysis will consider both the technical and economic viability of nonmetallic piping for the overall system. Section 2 categorizes the nonmetallic systems; Sect. 3 reviews the cost components of conventional systems; Sect. 4 discusses opportunities for nonmetallic pipe; and the results of the investigation are presented in Sect. 5.

# 2. DISCUSSION OF NONMETALLIC SYSTEMS

## 2.1 BACKGROUND

Nonmetallic piping materials have been of interest in the district heating industry for many years. Originally, most of this interest stemmed from the corrosion problems experienced with steel piping. Recent examples of such interest are given by Roseen, Schmeling, and Ifwarson[2] and Oliker.[3]

Corrosion of steel piping has been a particular problem in underground steam district heating systems. In these systems, leaks often occur because of corrosion of the outer jacket, which allows groundwater to come in contact with the pipe insulation. Exposure of the insulation to groundwater causes excessively high heat losses and eventually requires replacement of the system.

Condensate return systems associated with steam distribution often have more severe problems. Because the condensate system—or parts of it—typically are vented to air and operated below atmospheric pressure, oxygen concentration in the condensate is high. Many urban condensate return systems were simply abandoned as a result of corrosion.

Hot water systems, although not as susceptible to internal corrosion, also suffered corrosion-induced failures. Early systems were built in concrete culverts that were prone to occasional flooding or leakage. Some of the first pipe-in-pipe systems also experienced jacket failures and consequent groundwater penetration.

This situation has changed over the past few years, and the interest and requirements for successful adoption of nonmetallic piping technology have also changed. Hot water has generally supplanted steam as the system of choice for new district heating installations. While a great deal of steam piping remains in service, with the continuation of the aforementioned corrosion problems, most of the world's new district heating systems are now hot water systems. Currently available piping systems are outlined in Table 2.1 (Summary Information is included in Appendix A).

Fiber-reinforced glass piping has found limited application in steam condensate return systems. It does not suffer corrosion damage, but many installations are sensitive to high-temperature excursions caused by trap failures. Because of their general obsolescence and high temperatures, steam systems would appear to be only of distant interest for nonmetallic technologies. With the general acceptance of hot water for district heating, the concern over internal corrosion has lessened. This is not a significant corrosion problem with properly treated and monitored water in the closed system environment.

Preinsulated hot water piping systems have been developed, tested, and implemented—resulting in reducing the incidence and severity of corrosion caused by groundwater contacting the steel. These systems use a continuous, sealed, high-density polyethylene (HDPE) jacket for protection and often have an internal moisture detection system that can alert operators before widespread corrosion damage occurs.

**Table 2.1. Commercial piping technology for hot water district heating**

| Type or brand | Maximum temperature (°F) | Carrier material | Jacket material | Application |
|---|---|---|---|---|
| Aquawarm | 250 | Copper | Corrugated HDPE[a] | Small users |
| Flexalen | 194 | PB[b] | Corrugated HDPE | Small users |
| Teletherm | 194 | PB | HDPE | Small users |
| VVF[c] specification | 250 | Steel | HDPE | Universal |
| Moller EZbend | 250 | Steel | Corrugated HDPE | Small users |
| Wirsbo | 194 | PEX[d] | Urethane shell | Not in current use because of $O_2$ problems |
| Fiber-reinforced glass | 220 | Glass fiber | Various | Condensate |
| Minitherm | 194 | HDPE/ aluminum foil | PEX foam | Small users |

[a]HDPE = high-density polyethylene.
[b]PB = polybutylene.
[c]VVF = Varne Verks Foreningen.
[d]PEX = cross-linked polyethylene.

These preinsulated systems are also low in cost, relative to both existing steam piping systems and previous concrete culvert hot water systems. Because of these two changes, the competitive environment for nonmetallic piping applications has changed. While the inherent resistance to corrosion of such piping is still attractive, it is not a sufficient feature to justify its adoption. Instead, the focus has changed to cost.

District heating has always faced competition from other energy supply systems. In the United States, the competition includes electricity, oil, and natural gas. In Willmar and St. Paul, Minnesota, current commercial rates for hot water district heating are in the $8–$11/MMBtu range, which includes about $5 and $7/MMBtu, respectively, for the amortization of the piping system. These values indicate that the construction costs of a district heating piping system are relatively high and are a major factor in the attractiveness of nonmetallic piping systems.

Thus, nonmetallic piping materials and technologies of current interest in this study are those that might offer a combined material and installation cost significantly lower than that of conventional metallic piping systems. Materials—such as lined, reinforced concrete—that have been considered primarily as noncorrosive piping have not been evaluated in this study.

## 2.2 CLASSIFICATION FOR NONMETALLIC SYSTEMS

Nonmetallic piping applications for district heating may be separated into three categories of nonmetallic materials: (1) currently being used in district heating piping applications, (2) currently being used in piping applications other than district heating, and (3) not currently being used in any piping applications.

Category 1 includes cross-linked polyethylene (PEX) and polybutylene (PB). While epoxy-resin/glass-fiber pipe is used in some condensate return systems associated with steam district heating systems, it is not used to any appreciable extent as a carrier pipe for the high-temperature side of district heating systems.

PEX has found the most use in Scandinavian hot water district heating systems. The earliest of these systems used separate insulation (usually polyurethane blocks) and were operated at a maximum temperature of about 90°C (194°F). PEX performance was satisfactory, with one important exception: oxygen diffused through the relatively low density pipe walls and increased the oxygen concentration in the water. Because the low-temperature systems were normally expected to provide direct heating service (without an intervening heat exchanger), this water often passed through conventional building heating systems. The high oxygen concentration caused unacceptable corrosion, and most—if not all—of these early PEX systems have been abandoned.

Work has continued to correct the serious corrosion problem associated with PEX piping, and two approaches have been commercialized. In one, a metallic foil is placed between the PEX carrier pipe and the surrounding foamed-in-place urethane insulation. The resulting flexible, preinsulated pipe is marketed as a direct-burial (placed in contact with the soil—not in a tunnel) piping system. Another development involves the placement of an oxygen-diffusion-resistant plastic coating on the outside of the PEX piping. This piping system has been marketed for building systems only.

One difficulty associated with PEX systems is the cost of pipe joining. While continuously extruded pipe will reduce the number of joints required, the problem is still significant because there is no current alternative to metallic compression fittings for PEX joining. Such fittings are relatively simple to use but quite expensive. In addition, creep problems may occur over time at compression fittings. Polyethylene (PE) pipe extruders and others have improved joining techniques under development for other applications. Success in these efforts would also benefit district heating applications.

PB is a more recently adopted piping material that has been used in applications similar to those where PEX has been used. PB carrier piping is used in at least two commercial preinsulated piping systems.[4] PB district heating piping has also been used in geothermal district heating applications in the United States. This piping had polyurethane foam insulation and PE jacketing. It is reported that thermal welding was used in larger sizes. Geothermal applications represent a special case in that the corrosion resistance of the piping is of considerable importance. Unfortunately, there are no hard cost data currently available from these applications.

In other applications, such as potable water systems, PB piping is joined with thermal welding techniques. It is not clear if such a technique can be used in district heating applications (because of higher temperatures and probable higher axial stresses). If thermal welding can be used satisfactorily in district heating, the cost of compression fittings will be eliminated.

Category 2 includes polyvinylchloride (PVC) and postchlorinated polyvinylchloride (CPVC), both of which are used in nondistrict heating applications. Possible applications for CPVC are discussed in Sect. 4.2.

Category 3 includes a variety of newer thermoplastics such as polyphenyloxide and polyetherimide, both of which have attractive high-temperature properties. Neither the cost for large-scale piping production nor the long-term technical suitability, such as resistance to hydration, is known at this time. If these areas are found to be acceptable, polyphenyloxide and/or polyetherimide may be attractive candidates for development.

## 3. REVIEW OF COST COMPONENTS

The material cost for conventional, direct-buried steel systems in the United States is about one-third of the total system construction cost. To further quantify the system cost, two typical sections of a recently constructed hot water district heating system were selected to serve as a cost-estimation base (Figs. 3.1 and 3.2). These sections carry small- and medium-size loads.

This approach will not necessarily yield the highest or lowest impact of piping technology changes. However, it will provide a common ground for the observation of trends and general effects of such changes. Because the primary goal of this work is directive in nature rather than quantitative, the provision of a realistic common comparison base is useful.

The typical sections were originally designed with modern, conventional, direct-buried steel carrier piping (Fig. 3.3). Some service entrances used a direct-buried flexible copper piping system (Aquawarm cost data are provided in Appendix A). Thermal expansion in the steel sections was compensated with bends, including U-bends where necessary. "Friction fixing," which substitutes frictional restraint between the pipe jacket and surrounding soil for conventional anchors, is also used. Soils are typical lean clays, and paving is bituminous asphalt.

An estimate of the installation costs for conventional piping was made using a cost-estimation computer code previously used for engineering estimation for actual projects. This code contains numerous estimation factors and adjustments. The results are summarized in Table 3.1.

The estimations are separated into the civil, mechanical, and material portions of the project. It can be seen from the summary of the estimates for the two portions (Section A and Section B) that the material costs are roughly one-third of the total and that the material and mechanical costs are over one-half of the total (Table 3.1). Thus, for the two sections considered, about \$120,000 of the total \$220,000 is associated with the pipe and its installation.

The value of these estimates is primarily in the relative values shown, not in absolutes. Thus, while factors such as local labor rates and the availability of backfill will change the absolute values considerably, they are not likely to change the general effects and proportion of the estimates.

A way to estimate the maximum impact of nonmetallic piping on construction costs is to consider the costs associated with the civil aspects of construction as the lower bound. If the costs attributed to piping material and mechanical construction are subtracted, the remainder is the civil cost (namely, the cost of digging ditches, backfilling, and surface restoration). While some potential nonmetallic technologies might have some effect on civil work, such effects are likely to be minimal.

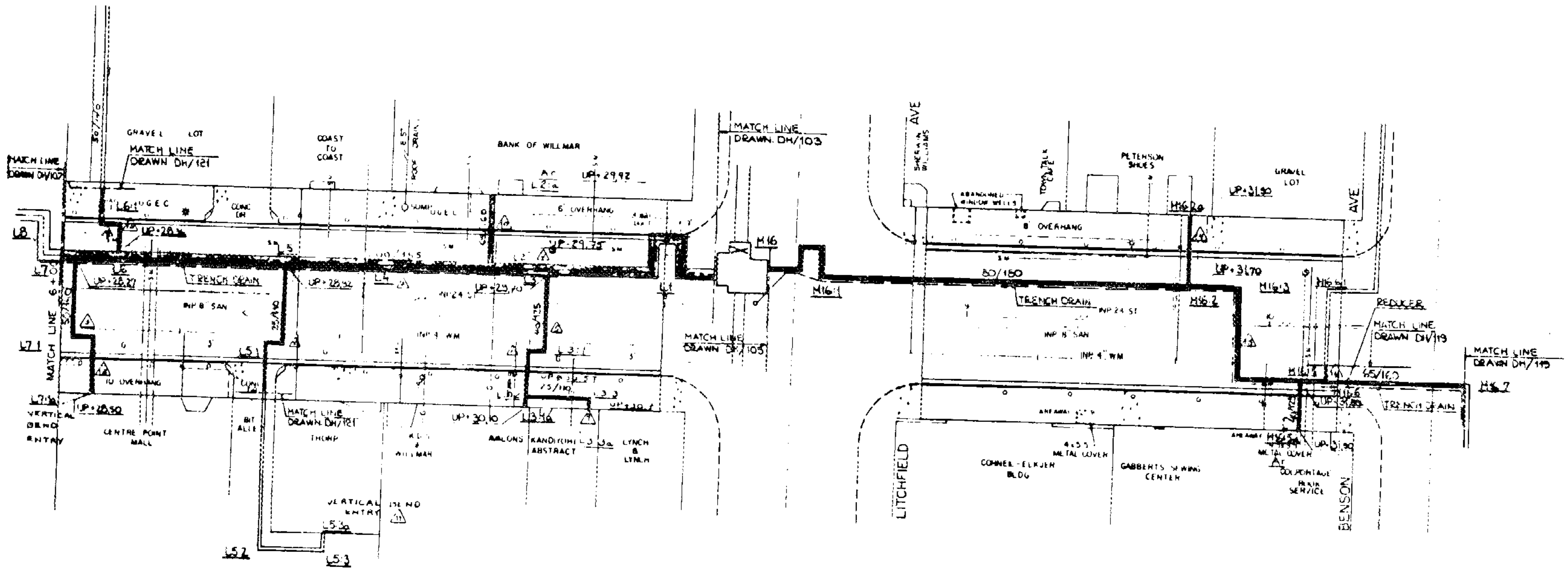



**Fig. 3.1. Section A of a hot water district heating system.**

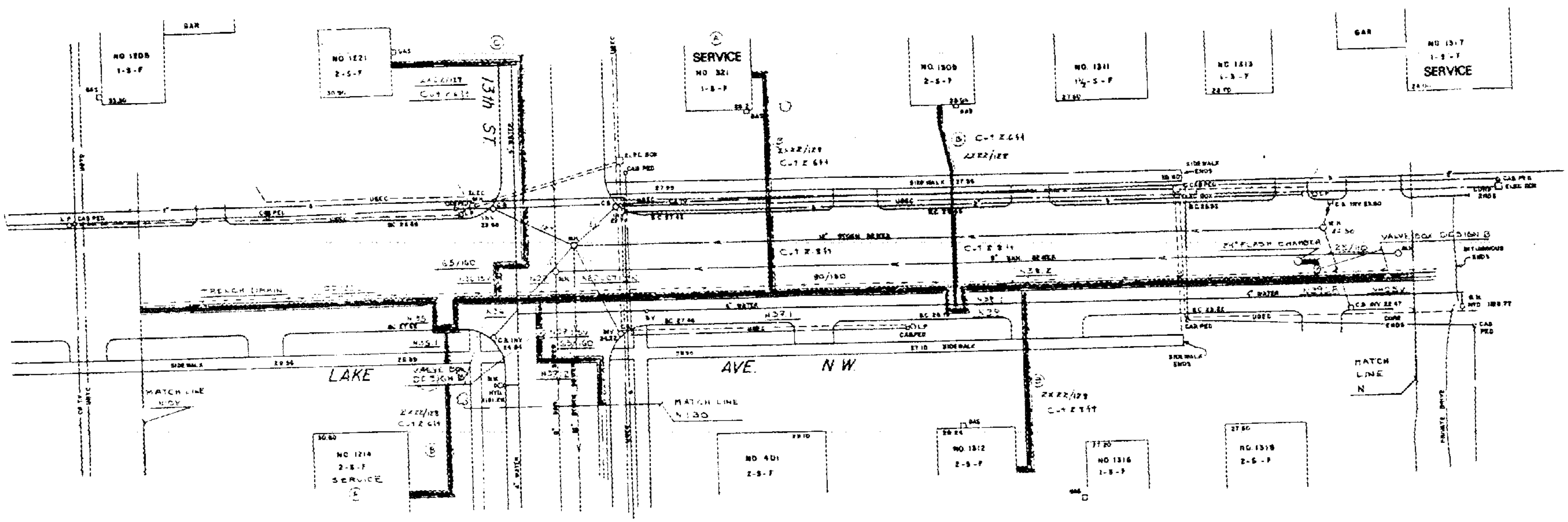
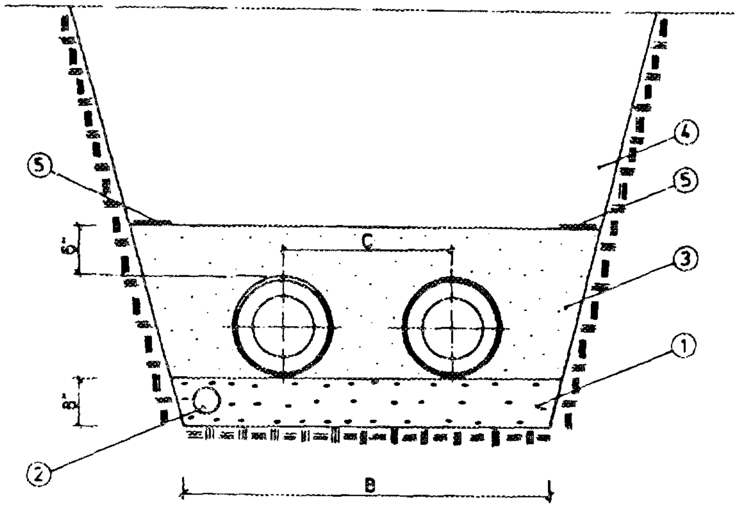



Fig. 3.2. Section B of a hot water district heating system.




TRENCH

| STEEL PIPE / PEH JACKET | | CENTER LINE DISTANCE C | | TRENCH WIDTH B | |
|---|---|---|---|---|---|
| METRIC mm | INCHES | METRIC mm | FOOT | METRIC mm | FOOT |
| 25/110 | 1"/4" | 300 | 1'–0" | 800 | 2'–8" |
| 32/125 | 1¼"/5" | 300 | 1'–0" | 800 | 2'–8" |
| 40/125 | 1¾"/5" | 300 | 1'–0" | 800 | 2'–8" |
| 50/140 | 2"/5½" | 350 | 1'–2" | 900 | 3'–0" |
| 65/160 | 2½"/6" | 350 | 1'–2" | 900 | 3'–0" |
| 80/180 | 3"/7" | 400 | 1'–4" | 1000 | 3'–4" |
| 100/225 | 4"/9" | 400 | 1'–4" | 1000 | 3'–4" |
| 125/250 | 5"/10" | 450 | 1'–6" | 1100 | 3'–8" |
| 150/280 | 6"/11" | 500 | 1'–8" | 1200 | 4'–0" |
| 200/355 | 8"/14" | 550 | 1'–10" | 1300 | 4'–4" |
| 250/450 | 10"/18" | 650 | 2'–2" | 1500 | 4'–11" |
| 300/500 | 12"/20" | 700 | 2'–4" | 1600 | 5'–3" |

1 BASE BACKFILLED WITH GRAVEL, MAXIMUM FRACTION = 4/5 in. (20 mm). MN STANDARD SPECIFICATION 3149 H COARSE FILTER AGGREGATE. STONES WITH SHARP EDGES ARE NOT ALLOWED IN BASE BACKFILL.

2 TRENCH DRAIN, 4-in. PIPE (102-mm), SHALL BE INSTALLED WHERE INDICATED ON PLAN AND PROFILE DRAWINGS. TRENCH DRAIN SHALL BE POROUS CONCRETE PIPE (MN DOT STANDARD SPECIFICATION 3255) OR PERFORATED CORRUGATED POLYETHYLENE TUBING (MN DOT STANDARD SPECIFICATION 3278).

3 ZONE AROUND PIPE SHALL BE BACKFILLED WITH SAND, MAXIMUM FRACTION = 1/3 in. (8 mm). MN STANDARD SPECIFICATION 3149 K SAND COVER.

4 REMAINDER OF TRENCH BACKFILLED WITH MATERIAL ACCORDING TO STREET CONSTRUCTION.

5 WARNING STRIP ABOVE PIPELINE.

**Fig. 3.3. Typical section of conventional direct-buried steel carrier district heating pipe.**

**Table 3.1. Summary of civil, mechanical, and material costs for Sections A and B**

| Item | Adjustment (%) | Cost estimate ($) |
|---|---|---|
| *Distribution piping estimate, Section A* | | |
| Subtotal: pipe | | 32,527.44 |
| Subtotal: mechanical | | 22,795.52 |
| Subtotal: civil | | 49,356.32 |
| Price adjustment: pipe | 1 | 325.27 |
| Price adjustment: mechanical | 0 | 0.00 |
| Price adjustment: civil | 0 | 0.00 |
| Total | | 105,004.55 |
| *Distribution piping estimate, Section B* | | |
| Subtotal: pipe | | 30,328.67 |
| Subtotal: mechanical | | 21,526.34 |
| Subtotal: civil | | 56,408.77 |
| Price adjustment: pipe | 1 | 303.29 |
| Price adjustment: mechanical | 0 | 0.00 |
| Price adjustment: civil | 0 | 0.00 |
| Total | | 108,567.07 |

## 3.1 CIVIL COSTS

For the purposes of this work, civil construction costs are defined as those costs associated with the excavation or replacement of soils and backfills and surface restoration, including curb and gutter replacement, paving, sodding, backfill, and spoil removal.

Civil and mechanical construction costs for modern hot water systems average about two-thirds of the total installation cost. Estimates of the civil cost are given for Sections A and B in Tables 3.2a and 3.2b. Although the two-thirds estimate can vary with different surface and soil conditions, civil construction costs are always a significant factor in total costs.

The techniques and technologies associated with this part of district heating construction are, of course, also a part of many other types of underground construction. It is beyond the scope of this work to consider such technologies, but it is appropriate to consider where the application of nonmetallic piping might allow the use of different technologies and techniques.

There are three basic approaches to underground piping: (1) conventional trench excavation, normally using a backhoe; (2) mechanical trenching; and (3) *knifing* or plowing. The first is used for most utility piping such as sewer and water, as well as for large pipeline installation and conventional district heating systems. Excavation requires considerable disruption of surface materials (paving) and generates an amount of soil equivalent to the volume of the trench. The second approach is commonly employed for

**Table 3.2a. Civil cost estimate for Section A**

| Diameter (mm) | Trench (ft) | Drained (ft) | Excavation cost ($/ft) | Cost estimate ($) |
|---|---|---|---|---|
| 400 | 0 | 0 | | 0.00 |
| 300 | 0 | 0 | | 0.00 |
| 250 | 0 | 0 | | 0.00 |
| 200 | 255.15 | 255.15 | 29 | 7,399.35 |
| 150 | 0 | 0 | 27 | 0.00 |
| 125 | 0 | 0 | 21 | 0.00 |
| 100 | 0 | 0 | 19 | 0.00 |
| 80 | 256.2 | | 16 | 4,099.20 |
| 65 | 63 | | 15 | 945.00 |
| 50 | 75.6 | | 15 | 1,134.00 |
| 40 | 94.5 | | 15 | 1,417.50 |
| 32 | 5.25 | | 14 | 73.50 |
| 25 | 132.3 | | 14 | 1,852.20 |
| | 882 | 255.15 | | |

| | | | |
|---|---|---|---|
| Excavation and backfill | | | 16,920.75 |
| Building penetration and restoration, 14 cst rings, $250/2 | | | 1,750.00 |
| Trench drain ($2/ft) | | | 510.30 |
| Valve box, 0 ($450 each) | | | 0.00 |
| Flash chamber, 1 ($600 each) | | | 600.00 |
| Boring pipe | Diameter (in.) | Casing ($/ft) | |
| | 30 | | 0.00 |
| | 24 | | 0.00 |
| | 18 | 158 | 0.00 |
| | 16 | 145 | 0.00 |
| | 14 | 145 | 0.00 |
| Surveying ($1.75/ft trench) | | | 1,543.50 |
| Removals | Rate ($) | Factor | |
| Curb and gutter | 2.00 | 0.2 | 352.80 |
| Sidewalk | 5.00 | 0.1 | 441.00 |
| Bituminous pave | 3.00 | 0.75 | 1,984.50 |
| Reinforced concrete | 16.00 | 0.1 | 1,411.20 |
| Concrete | 7.00 | 0.1 | 617.40 |
| Restorations | | | |
| Curb and gutter | 12.50 | 0.2 | 2,205.00 |
| Sidewalk | 22.50 | 0.1 | 1,984.50 |
| Bituminous pave | 12.00 | 0.56 | 5,927.04 |
| Reinforced concrete | 34.00 | 0.1 | 2,998.80 |
| Concrete | 28.00 | 0.1 | 2,469.60 |
| Sodding | 2.00 | 0.67 | 1,181.88 |
| General excavation, 220.5 CY | 25.00/CY | | 5,512.50 |
| Concrete chambers, 0 | | | 0.00 |
| Misc. material | | | 700.00 |
| Subtotal | | | 49,110.77 |
| Contingency (0.005) | | | 245.55 |
| Total | | | 49,356.32 |

**Table 3.2b. Civil cost estimate for Section B**

| Diameter (mm) | Trench (ft) | Drained (ft) | Excavation cost ($/ft) | Cost estimate ($) |
|---|---|---|---|---|
| 400 | 0 | 0 | | 0.00 |
| 300 | 0 | 0 | | 0.00 |
| 250 | 0 | 0 | | 0.00 |
| 200 | 0 | 0 | 29 | 0.00 |
| 150 | 0 | 0 | 27 | 0.00 |
| 125 | 0 | 0 | 21 | 0.00 |
| 100 | 127.05 | 127.05 | 19 | 2,413.95 |
| 80 | 353.85 | | 16 | 5,661.60 |
| 65 | 174.3 | | 15 | 2,614.50 |
| 50 | 0 | | 15 | 0.00 |
| 40 | 0 | | 15 | 0.00 |
| 32 | 385.35 | | 14 | 5,394.90 |
| 25 | 10.5 | | 14 | 147.00 |
| | 1,051.05 | 127.05 | | |

| | | | |
|---|---|---|---|
| Excavation and backfill | | | 16,231.95 |
| Building penetration and restoration, 5 cst rings, $250/2 | | | 625.00 |
| Trench drain ($2/ft) | | | 254.10 |
| Valve box, 8 ($450 each) | | | 3,600.00 |
| Flash chamber, 1 ($600 each) | | | 600.00 |
| Boring pipe | Diameter (in.) | Casing ($/ft) | |
| | 30 | | 0.00 |
| | 24 | | 0.00 |
| | 18 | 158 | 0.00 |
| | 16 | 145 | 0.00 |
| | 14 | 145 | 0.00 |
| Surveying ($1.75/ft trench) | | | 1,839.34 |
| Removals | Rate ($) | Factor | |
| Curb and gutter | 2.00 | 0.2 | 420.42 |
| Sidewalk | 5.00 | 0.1 | 525.53 |
| Bituminous Pave | 3.00 | 0.75 | 2,364.86 |
| Reinforced concrete | 16.00 | 0.1 | 1,681.68 |
| Concrete | 7.00 | 0.1 | 735.74 |
| Restorations | | | |
| Curb and gutter | 12.50 | 0.2 | 2,627.63 |
| Sidewalk | 22.50 | 0.1 | 2,364.86 |
| Bituminous pave | 12.00 | 0.56 | 7,063.06 |
| Reinforced concrete | 34.00 | 0.1 | 3,573.57 |
| Concrete | 28.00 | 0.1 | 2,942.94 |
| Sodding | 2.00 | 0.67 | 1,408.41 |
| General excavation, 262.7625 CY | 25.00/CY | | 6,569.06 |
| Concrete chambers, 0 | | | 0.00 |
| Misc. material | | | 700.00 |
| Subtotal | | | 56,128.15 |
| Contingency (0.005) | | | 280.64 |
| Total | | | 56,408.79 |

some types of underground wiring and for gas and water utility piping where flexible piping is used, within the limitations basically determined by the trench width. Mechanical trenching could be of use in district heating where single-casing, flexible piping is used (e.g., Aquawarm). It would be useful if piping were developed that would permit vertical instead of horizontal pairing.

## 3.2 MECHANICAL AND MATERIAL COSTS AND RELATION TO NONMETALLIC PIPING

State-of-the-art preinsulated district heating metallic piping is a highly developed and mass-produced product. The industry currently has an excess of production capacity, and some consolidation of manufacturers has been taking place. Typical metallic material costs are given for Section A in Table 3.3 and for Section B in Table 3.4. Prices for copper piping products (Aquawarm) are provided in Appendix A.

**Table 3.3. Material cost estimate for Section A**

| Diameter (mm) | Pipe | Bend 90° | Tee 400 | Tee 300 | Tee 250 | Tee 200 | Tee 150 |
|---|---|---|---|---|---|---|---|
| | | *Pipe and fittings* | | | | | |
| 400 | 0 | 0 | 0 | | | | |
| 300 | 0 | 0 | 0 | 0 | | | |
| 250 | 0 | 0 | 0 | 0 | 0 | | |
| 200 | 7466 | 2040 | 0 | 0 | 0 | 0 | 0 |
| 150 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 125 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 80 | 2811 | 660 | 0 | 0 | 0 | 0 | 0 |
| 65 | 576 | 0 | 0 | 0 | 0 | 260 | 0 |
| 50 | 553 | 380 | 0 | 0 | 0 | 0 | 0 |
| 40 | 576 | 162 | 0 | 0 | 0 | 240 | 0 |
| 32 | 26 | 0 | 0 | 0 | 0 | 0 | 0 |
| 25 | 565 | 92 | 0 | 0 | 0 | 228 | 0 |

*Cost estimate*

| Item | Cost ($) |
|---|---|
| Pipe and fittings (from above) and other misc. items | 21,941.25 |
| Misc. fittings | 0.00 |
| Warning tape | 107.53 |
| Alarm system | 1,607.53 |
| Technical representative (0 weeks) | 0.00 |
| Subtotal | 23,656.31 |
| Contingency (0.1) | 2,365.63 |
| Subtotal | 26,021.94 |
| Freight and tariff (0.25) | 6,505.49 |
| Total piping | 32,527.43 |

**Table 3.4. Material cost estimate for Section B**

| Diameter (mm) | Pipe | Bend 90° | Tee 400 | Tee 300 | Tee 250 | Tee 200 | Tee 150 | Tee 125 | Tee 100 | Tee 80 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | *Pipe and fittings* | | | | | | |
| 400 | 0 | 0 | 0 | | | | | | | |
| 300 | 0 | 0 | 0 | 0 | | | | | | |
| 250 | 0 | 0 | 0 | 0 | 0 | | | | | |
| 200 | 0 | 0 | 0 | 0 | 0 | 0 | | | | |
| 150 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | |
| 125 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| 100 | 2169 | 600 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| 80 | 3883 | 440 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 65 | 1594 | 352 | 0 | 0 | 0 | 0 | 0 | 0 | 468 | 0 |
| 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 40 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 32 | 4651 | 230 | 0 | 0 | 0 | 0 | 0 | 0 | 299 | 809 |
| 25 | 45 | 46 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

*Cost estimate*

| Item | Cost ($) |
|---|---|
| Pipe and fittings (from above) and other misc. items | 20,300.93 |
| Misc. fittings | 0.00 |
| Warning tape | 128.14 |
| Alarm system | 1,628.14 |
| Technical representative (0 weeks) | 0.00 |
| Subtotal | 22,057.21 |
| Contingency (0.1) | 2,205.72 |
| Subtotal | 24,262.93 |
| Freight and tariff (0.25) | 6,065.73 |
| Total piping | 30,328.66 |

Most recent innovative developments have centered on devices or techniques to reduce the need for expansion-compensation devices (e.g., No-Comp and E-muff). Along with direct-buried valves and compensators, these have tended to reduce the need for concrete vaults, a major source of expense. The net result has been relatively low prices for such products with strong competition between the producers.

Installation techniques are based on conventional welding technologies. However, because welds are structurally important with expansion forces, weld quality must be higher than otherwise required for the temperatures and pressures involved. Radiographic inspection is usually required. Thus, costs for installation have varied considerably from project to project, with apparent differences in welder productivity being significant. Mechanical (installation) estimates for conventional piping in the two sample sections are shown in Tables 3.5 and 3.6.

**Table 3.5. Mechanical cost estimate for Section B (metallic piping)**

| Diameter (mm) | Joints | $/ weld | Weld cost ($) |
|---|---|---|---|
| 400 | 0 | | 0.00 |
| 300 | 0 | | 0.00 |
| 250 | 0 | | 0.00 |
| 200 | 0 | 170 | 0.00 |
| 150 | 0 | 130 | 0.00 |
| 125 | 0 | 105 | 0.00 |
| 100 | 25 | 85 | 2,142.00 |
| 80 | 41 | 62 | 2,529.60 |
| 65 | 30 | 54 | 1,620.00 |
| 50 | 0 | 44 | 0.00 |
| 40 | 0 | 32 | 0.00 |
| 32 | 61 | 30 | 1,836.00 |
| 25 | 7 | 28 | 201.60 |
| Welding | | | 8,329.20 |
| Installation | | | |
| 0.5 h/ft | | | |
| $10/h | | | |
| 2,002 ft pipe | | | 10,010.00 |
| Radiographic | | | |
| $600/1,000 ft | | | 1,201.20 |
| Expansion padding | | | |
| $1/bend | | | |
| Number of bends, 29 | | | 29.00 |
| Misc. materials | | | 0.00 |
| Subtotal | | | 19,569.40 |
| Contingency (0.1) | | | 1,956.94 |
| Total | | | 21,526.34 |

A secondary factor related to installation costs is engineering costs. Engineering costs have also varied considerably in the United States. In any project, the nature of the piping, thermal loads, and thermal expansion requires careful engineering. Such costs have ranged between 5 and 12% of the total project cost.

**Table 3.6. Mechanical cost estimate for Section A**

| Diameter (mm) | Joints | $/ weld | Weld cost ($) |
|---|---|---|---|
| 400 | 0 | | 0.00 |
| 300 | 0 | | 0.00 |
| 250 | 0 | | 0.00 |
| 200 | 32 | 170 | 5,508.00 |
| 150 | 0 | 130 | 0.00 |
| 125 | 0 | 105 | 0.00 |
| 100 | 0 | 85 | 0.00 |
| 80 | 41 | 62 | 2,529.60 |
| 65 | 10 | 54 | 518.40 |
| 50 | 22 | 44 | 950.40 |
| 40 | 29 | 32 | 921.60 |
| 32 | 4 | 30 | 108.00 |
| 25 | 26 | 28 | 739.20 |
| Welding | | | 11,275.20 |
| Installation | | | |
| 0.5 h/ft | | | |
| $10/h | | | |
| 1,680 ft pipe | | | 8,400.00 |
| Radiographic | | | |
| $600/1,000 ft | | | 1,008.00 |
| Expansion padding | | | |
| $1/bend | | | |
| Number of bends, 40 | | | 40.00 |
| Misc. materials | | | 0.00 |
| Subtotal | | | 20,723.20 |
| Contingency (0.1) | | | 2,072.32 |
| Total | | | 22,795.52 |

# 4. OPPORTUNITIES FOR COST REDUCTION

Savings in the cost of systems with nonmetallic piping could occur in any of the three categories involved in construction. As noted, savings in the civil aspects are probably not promising, at least in comparison with flexible metallic piping. Savings in mechanical and material costs are of interest, however.

Because conventional metallic piping systems are mature products, it is difficult to compare material costs with a hypothetical nonmetallic product. A comparison of published prices for Schedule 40 CPVC piping indicates that for sizes over 5 in., preinsulated steel piping is less expensive. Persson[5] provides a comparison of an installed cost between conventional steel piping and an experimental nonmetallic piping system that tends to support this observation, as shown in Fig. 4.1. Note that the savings in civil costs shown relate to conventional steel piping, not flexible piping systems such as Aquawarm.

There are clear opportunities for savings in mechanical installation costs. Among these are fewer joints, less expensive joints, simple expansion compensation, ease of pipe handling, reduced or eliminated pipe cleaning, and simpler testing. Reduction in the number of joints is a clear advantage. With continuously extruded pipe, pipe runs could extend between required fittings such as tees and valves.

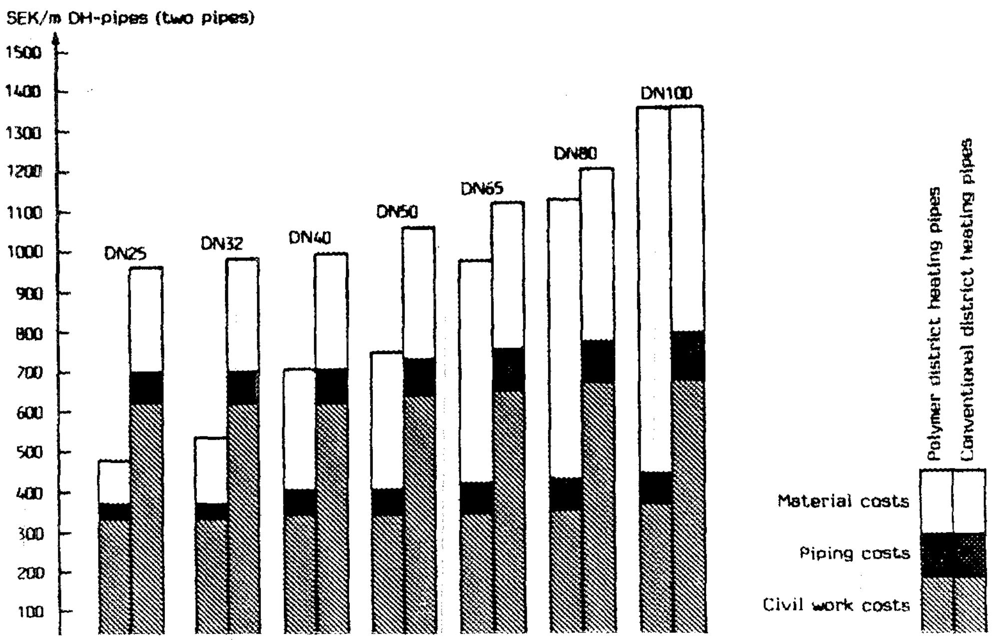



**Fig. 4.1. Total construction costs for the polymer distribution system in Hammerstrand compared with a conventional steel pipe system.**

Joining operations should also be less expensive. Present steel welding technology normally requires at least one welder and one helper. Local codes or union regulations can increase the number of workers. In addition, because welds must be of high quality, skilled welders are required. Such welders often command among the highest wages of the skilled trades. Nonmetallic joining would not require such skilled workers. Solvent welding of CPVC is relatively simple and can be performed by laborers with minimum training.

Compression fittings used for commercial PEX piping systems are also designed for installation by relatively unskilled labor. Although the fittings themselves add to joining costs, the total cost for joining with compression fittings will still be lower than that of welding steel for smaller sizes of piping.

Expansion compensation with steel piping requires considerable engineering and installation skills. Hardware for bellows and bends is usually required, and the piping requires prestressing during installation. Nonmetallic piping requires an understanding of expansion forces because all of the proposed nonmetallic materials expand with increasing temperatures. However, the lower forces involved and the flexibility in pipe routing usually make expansion compensation relatively simple and eliminate the need for additional hardware.

Because the weight of nonmetallic piping is lower than that of metallic piping, the pipe handling, hoisting equipment, and crew requirements at the job site would be reduced. In addition, nonmetallic piping would require less protection against the corrosion of rain and trench water during construction.

After construction, steel piping systems are normally cleaned with water-driven "pigs" to remove the accumulated surface scale and rust on the inside piping surface and to flush out foreign matter. It would be expected that a nonmetallic system would require only a simple flushing after construction.

An estimate for the mechanical (installation) cost of plastic piping for the example Section B is shown in Table 4.1. This estimate is not based on established costs for joining, because such techniques are not well defined for the different types of pipe materials. Nevertheless, this table indicates a reasonable potential for installation savings. In the overall costs for Section B, the use of plastic piping effects mechanical cost savings that represent about 8% of the total project cost.

## 4.1 MAINTENANCE AND OPERATIONS

Maintenance costs for conventional modern district heating systems are quite low, with 1%/year of capital cost often used as a guideline. For the piping sections as described in Sect. 3 as examples, maintenance costs would be about $2200/year. Maintenance may include occasional air bleeding, repairs of leaks, etc. Steel piping systems are sensitive to water chemistry, and this sensitivity would be generally removed with nonmetallic piping systems. The circulating water would still require treatment, however, to protect metallic components of the system (such as heat exchangers). The nonmetallic system would be protected in the event of accidental water chemistry problems.

## 4.2 A PROSPECTIVE NONMETALLIC CONCEPT

It is clear that significant savings in installation costs could be achieved if the potential advantages of nonmetallic piping could be realized. This section describes an effort to

**Table 4.1. Mechanical cost estimate for Section B (plastic piping)**

| Diameter (mm) | Joints | $/ weld | Weld cost ($) |
|---|---|---|---|
| 400 | 0 | | 0.00 |
| 300 | 0 | | 0.00 |
| 250 | 0 | | 0.00 |
| 200 | 0 | 50 | 0.00 |
| 150 | 0 | 45 | 0.00 |
| 125 | 0 | 45 | 0.00 |
| 100 | 25 | 40 | 1,008.00 |
| 80 | 41 | 40 | 1,632.00 |
| 65 | 30 | 30 | 900.00 |
| 50 | 0 | 25 | 0.00 |
| 40 | 0 | 20 | 0.00 |
| 32 | 61 | 10 | 612.00 |
| 25 | 7 | 10 | 72.00 |
| Welding | | | 4,224.00 |
| Installation | | | |
| 0.4 h/ft | | | |
| $10/h | | | |
| 2,002 ft pipe | | | 8,008.00 |
| Radiographic | | | |
| $0/1,000 ft | | | 0.00 |
| Expansion padding | | | |
| $1/bend | | | |
| Number of bends, 29 | | | 29.00 |
| Misc. materials | | | 0.00 |
| Subtotal | | | 12,261.00 |
| Contingency (0.1) | | | 1,226.10 |
| Total | | | 13,487.10 |

integrate these potential advantages with currently available materials and the demands of actual district heating construction and operations.

Of a number of concepts considered, only one was analyzed for structural strength. In this concept, an attempt was made to use the insulation material as a structural support for a nonmetallic carrier pipe. The resulting pipe configuration is similar in appearance to conventional modern preinsulated steel district heating pipe.

CPVC was selected as the concept test material because of its relative ease of joining, commercial availability, oxygen-diffusion resistance, and relative low cost. Conventional urethane foam and HDPE jacket material were selected because of their proven thermal suitability and compatibility with underground conditions. Other materials, especially the more recently developed resins, might prove to be economically attractive.

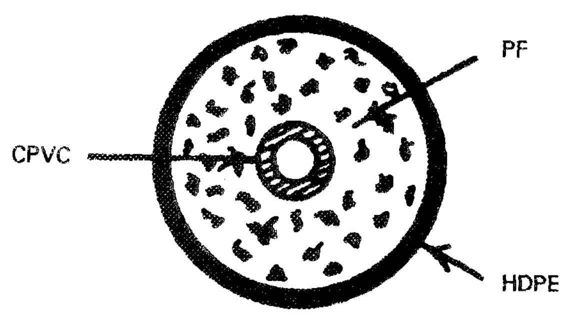
While the strength of the urethane foam insulation material is relatively low, the concentric structure provides for advantages when the thermal situation is considered. In particular, the structural properties of all the included materials improve markedly as the temperature is lowered. Thus, while the carrier pipe material may be operating at temperatures where it would normally have only marginal capacity for withstanding the applied pressure, the jacket and insulation are at lower temperatures and thus assist in resisting the internal pressure of the hot water.

Pressure forces are partially transmitted through the insulation to the jacket. The jacket material, typically HDPE, is at surrounding soil temperatures and better able to withstand these forces. The analytical investigation used the two-pipe geometry shown in Fig. 4.2. Geometries were selected so that they were approximately equivalent to those for steel pipe systems used in conventional modern systems.

The dimensions and materials were selected to provide input to the structural analytical test of the concept. No attempt was made to optimize the dimensions or materials for thermal or structural efficiency, and neither should be considered as the basis for actual piping design.

In addition, no attempt was made to account for creep phenomena, often important in nonmetallic applications, especially in conjunction with fittings. However, the structural system involved in the subject concept provides for restraint of creep in the piping system, and further analysis would be necessary to determine if existing data on unrestrained creep are appropriate.

Two internal pressures, 100 and 225 psia (0.69 and 1.55 MPa), and two thermal environments, 73°F and 200°F (23°C and 93.3°C), were considered for each of the two cases. Material properties for each of the three materials are presented in Table 4.2. Many assumptions had to be made in developing these properties, especially to extrapolate the




| Model number | Pipe geometrics (mm) | | | | | |
|---|---|---|---|---|---|---|
| | CPVC[a] | | PF[b] | | HDPE[c] | |
| | $d_i$ | $d_o$ | $d_i'$ | $d_o'$ | $d_i''$ | $d_o''$ |
| 1 | 20.93 | 26.67 | 26.67 | 77.93 | 77.93 | 88.90 |
| 4 | 154.05 | 168.28 | 168.28 | 254.51 | 254.51 | 273.05 |

[a]CPVC = postchlorinated polyvinylchloride.
[b]PF = urethane foam.
[c]HDPE = high-density polyethylene.

**Fig. 4.2. Pipe geometries investigated.**

**Table 4.2. Material properties**

| Property | Postchlorinated polyvinylchloride | Urethane foam | High-density polyethylene |
|---|---|---|---|
| Compressive strength, MPa | | | |
| Ultimate, 23°C | 75.3[a] | 0.83[b] | 19.4[c] |
| Design, 23°C | 18.9[d] | 0.44[e] | 10.2[e] |
| Design, 93.3°C | 2.1[d] | 0.31[f] | 1.1[g] |
| Tensile strength, MPa | | | |
| Ultimate, 23°C | 55.0[a] | 1.14[b] | 23.4[h] |
| Design, 23°C | 13.8[i] | 0.60[e] | 12.3[e] |
| Design, 93.3°C | 1.5[g] | 0.42[f] | 1.3[g] |
| Modulus of elasticity, MPa | | | |
| 23°C | 2895[i] | 29.0[b] | 827[h] |
| 93.3°C | 315[g] | 20.3[f] | 90[g] |
| Thermal expansion coefficient, $mm^2/°C$ | $63 \times 10^{-6}$ (*i*) | $72 \times 10^{-6}$ (*i*) | $180 \times 10^{-6}$ (*c*) |
| Conductivity, $cal \cdot cm/s \cdot cm^2 \cdot °C$ | $0.35 \times 10^{-3}$ (*a*) | $1.12 \times 10^{-3}$ (*b*) | $1.2 \times 10^{-3}$ (*c*) |
| Specific heat, cal/°C/gm | 0.24[a] | 0.42[c] | 0.55[c] |
| Density, $gm/cm^3$ | 1.55[a] | 0.08[a] | 0.96[c] |
| Poisson's ratio | 0.27[a] | 0.31[j] | 0.35[k] |

[a]*Source:* Data sheet from Michael Barnes.

[b]*Source: Technical Information Bulletin*, Stepanfoam C-605, Stepan Chemical Company, Northfield, Ill.

[c]*Source: Modern Plastics Encyclopedia*, McGraw, New York, 1985–86.

[d]Assumes compressive properties vary same with temperature as design properties in tension presented in *ASME Code for Pressure Piping*, ANSI/ASME B31.3-1984.

[e]Scaled according to ratio of design stress to ultimate stress given in *ASME Code for Pressure Piping*, ANSI/ASME B31.3-1984.

[f]Foam properties vary linearly with temperature between −73°C and 260°C. Values were scaled accordingly. *Source: Structural Design with Plastics*, B. S. Benjamin, Polymer Science and Engineering Series, Society of Plastics Engineers, Inc., Van Nostrand Reinhold, 1969, p. 95.

[g]Assumes property loss varies linearly with temperature as presented in *ASME Code for Pressure Piping*, ANSI/ASME B31.3-1984.

[h]Stress-strain curve high-density polyethylene thermoplastic.

[i]*Source: ASME Code for Pressure Piping*, ANSI/ASME B31.3-1984.

[j]Rough estimate.

[k]*Source: Structural Plastics Design Manual*, FHWA-TS-79-203.

data to the upper temperature level of interest. Design strength values for each of the materials were determined as follows.

**CPVC.** Design tensile stress was obtained from the American National Standards Institute/American Society of Mechanical Engineers' *ASME Code for Pressure Piping*, ANSI/ASME B31.3-1984, which also presented information on the variation of design tensile stress with temperature. Ultimate tensile and compressive strengths were obtained from manufacturers' data sheets (Appendix B). Design tensile strength at the upper temperature level of interest, 200°F (93.3°C), was obtained by extrapolating data presented in the ANSI code on design stress variation with temperature. Design compressive strength values were obtained by assuming that the compressive strength varied with temperature in the same manner as the tensile strength. Room temperature modulus was obtained from the ASME code. Modulus of elasticity also was assumed to vary with temperature in the same manner as the tensile strength. Physical properties were determined from a variety of sources, as noted in Table 4.2.

**HDPE.** Ultimate tensile strength was determined from a stress-strain curve for a material having a density similar to the material addressed in Appendix B. Design tensile stress was then determined by assuming that the stress varied in the same manner as presented in the ASME code for a low-density polyethylene (LDPE): the ultimate tensile strength of HDPE was scaled by the ratio of the design tensile strength of the LDPE [631 psia (4.35 MPa)] presented in the ASME code to the ultimate strength [1200 psia (8.27 MPa)] obtained from the stress-strain curve for LDPE. Variation of tensile strength with temperature was assumed to be the same as for the CPVC material. Ultimate compressive strength was determined from the *Modern Plastics Encyclopedia*.[6] Design compressive strength variation with temperature was then evaluated using the same approach as that used for the design tensile strength determinations. Modulus of elasticity was assumed to vary with temperature in the same manner as the strength values. Physical properties were determined from a variety of sources, as noted in Table 4.2.

**PF.** For high-density isocyanate urethane foam (PF), ultimate tensile and compressive strengths were obtained by using values listed for a foam of density comparable to that described in Appendix B (Stepanfoam C-605, Table B.4). Design tensile and compressive strengths were determined by assuming that the ratio of design stress to ultimate stress is the same as that listed in the ASME code for polyethylene materials. Design values for the strengths at the upper temperature level of interest, 200°F (93.3°C), were determined by applying information presented by B. S. Benjamin.[7] According to the reference, a study of the effect of temperature on the mechanical properties of rigid polyurethane foam indicates that the variation of mechanical properties with temperature is essentially linear between −100°F and 500°F (−73°C and 260°C), with the particular property equal to zero at 500°F (260°F). Because we have the design strengths at room temperature, 73°F (23°C), we can apply this information to estimate the values at 200°F (93.3°C). The modulus of elasticity at room temperature was obtained from information presented in Appendix B. Modulus of elasticity was assumed to vary with temperature in the same manner as the strengths.

A two-dimensional, finite-element (FE) analysis was conducted for the pipe-in-pipe system. Elastic analyses of an infinitely long pipe (plane strain) were performed for the two geometries shown in Fig. 4.3. Both internal pressure (two cases: 100 and 225 psia) and thermal loadings [two cases: 73°F and 200°F (23°C and 93.3°C)] were considered. The thermal loadings represent a steady state analysis, using ADINAT,[8] where the inside surface of the CPVC was given a prescribed constant temperature [T = 73°F or 200°F (23°C or 93.3°C)], while a convective boundary condition simulating heat transfer to the surrounding soil was employed at the outside surface of the composite pipe. The steady state temperature distributions from ADINAT were then input to ADINA,[8] and a stress analysis was performed for each of the two models. The FE models and boundary conditions employed are shown in Figs. 4.3–4.6.

The results presented in Table 4.3 indicate that in smaller pipe sizes, design stress levels are not exceeded or are only slightly exceeded. Because these design levels are

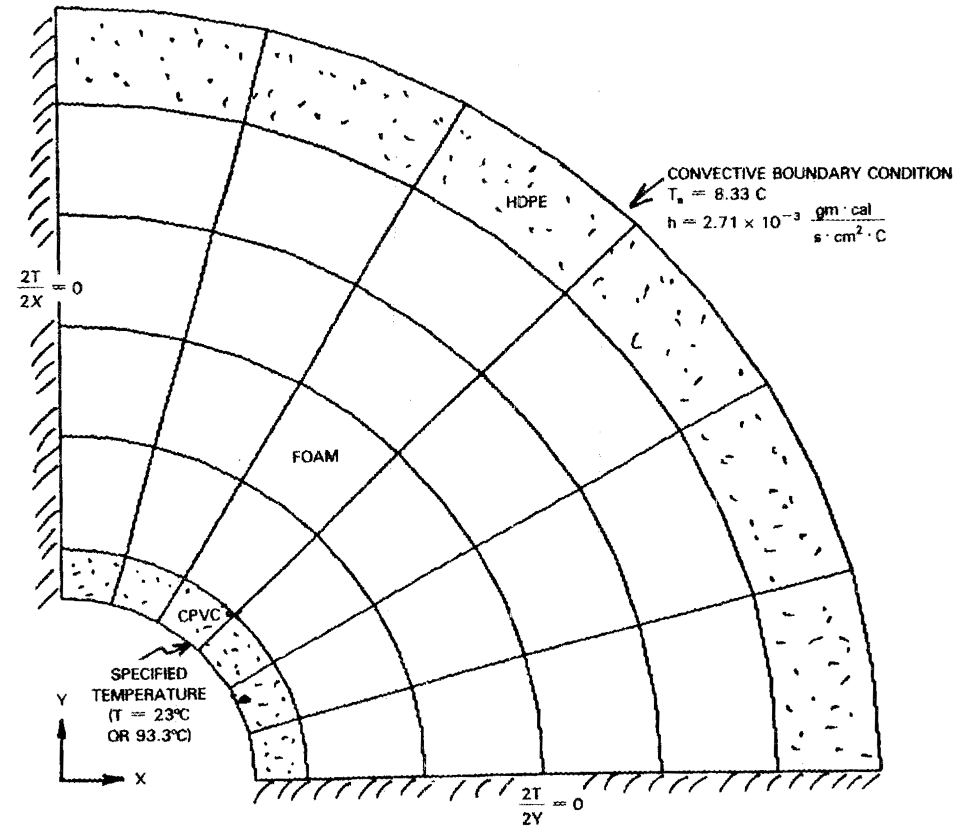



**Fig. 4.3. Finite element model and boundary conditions employed in ADINAT steady state heat transfer analysis for Model No. 1.**

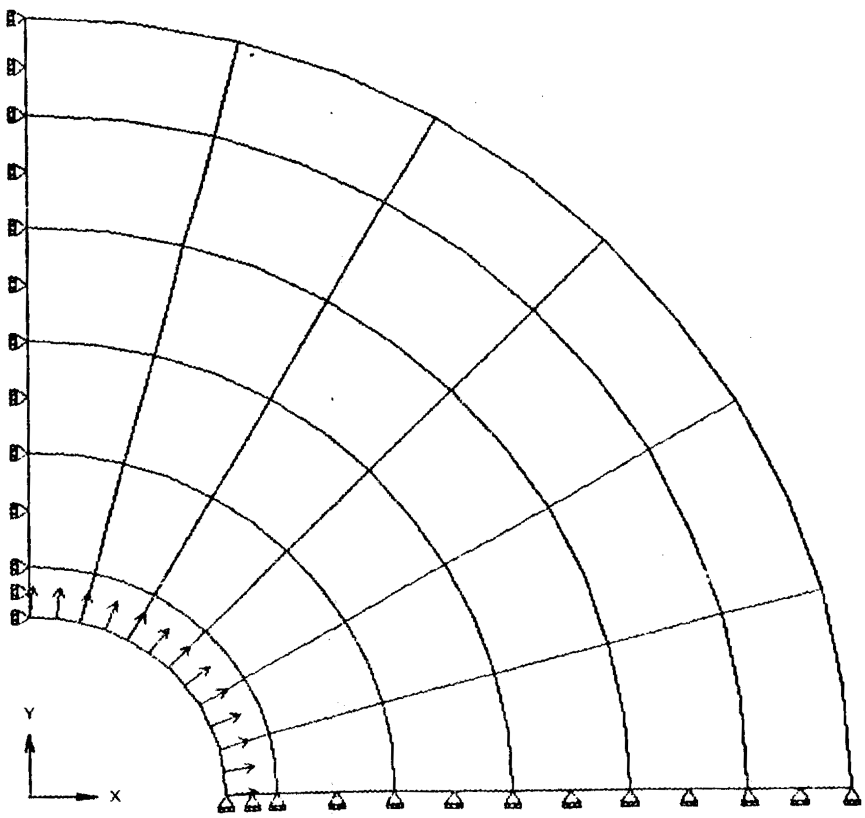



**Fig. 4.4. Finite element model and boundary conditions employed in ADINA stress analysis for Model No. 1.**

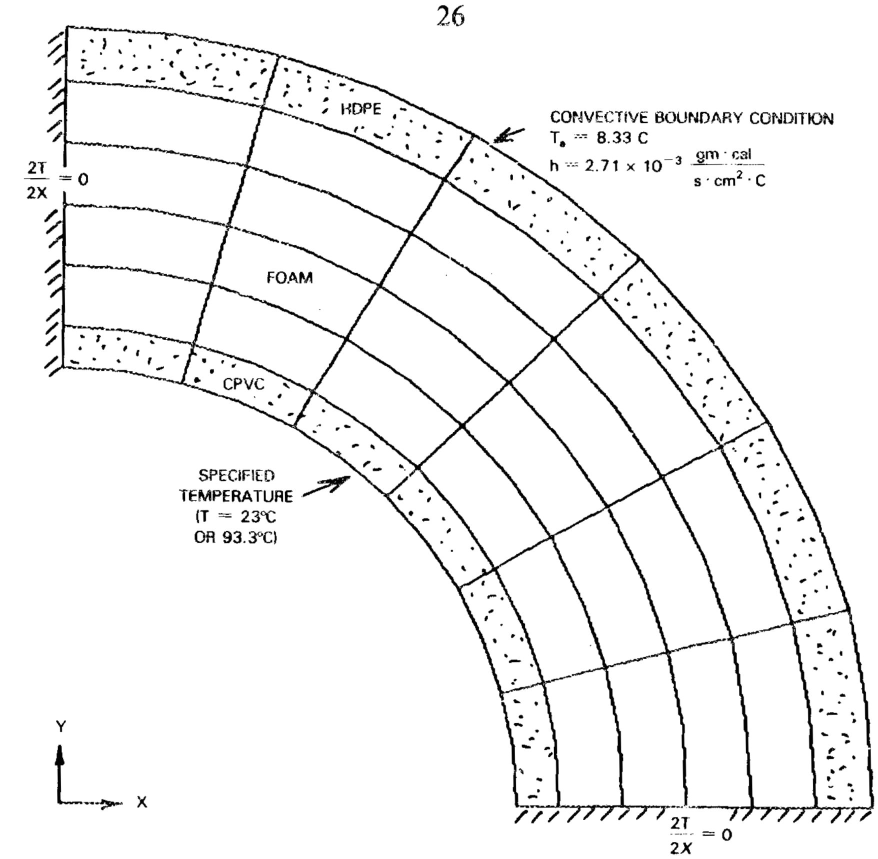



**Fig. 4.5. Finite element model and boundary conditions employed in ADINAT steady state heat transfer analysis for Model No. 4.**

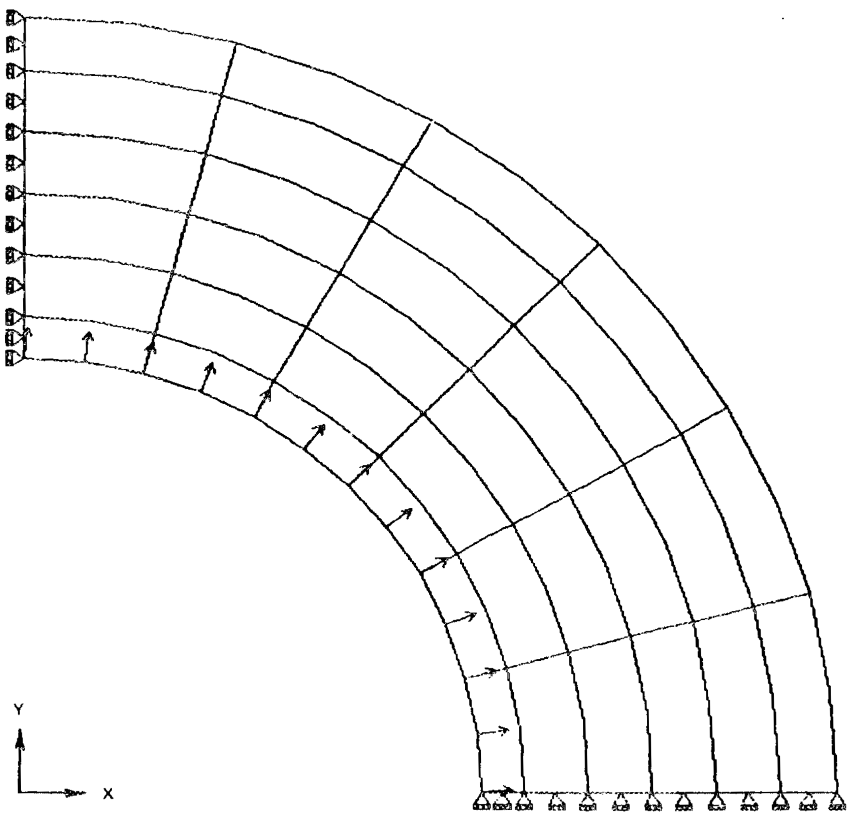



**Fig. 4.6. Finite element model and boundary conditions employed in ADINA stress analysis for Model No. 4.**

**Table 4.3. Maximum stresses at inner surface of postchlorinated polyvinylchloride**

| Loading parameters | | Maximum stresses (MPa) | | | | Design stress limit (MPa) | | |
|---|---|---|---|---|---|---|---|---|
| | | Model No. 1 | | Model No. 4 | | | | |
| Pressure (MPa) | Temperature (°C) | SIGMAX[a] | TAUMAX[b] | SIGMAX | TAUMAX | Tension | Compression | Shear |
| 0.69 | 23 | 2.55 | 2.08 | 6.73 | 4.59 | 13.8 | 18.8 | 16.3 |
| 1.55 | 23 | 5.83 | 4.04 | 15.19 | 9.16 | 13.8 | 18.8 | 16.3 |
| 0.69 | 93.3 | 2.26 | 1.70 | 5.52 | 3.42 | 1.5 | 2.1 | 1.8 |
| 1.55 | 93.3 | 5.13 | 3.47 | 12.45 | 7.25 | 1.5 | 2.1 | 1.8 |

[a]SIGMAX is the largest of $|\sigma_{max}|$, $|\sigma_{min}|$, and $|\sigma_{normal}|$.
[b]TAUMAX is the largest of $|(\sigma_{max} - \sigma_{min})/2|$, $|(\sigma_{max} - \sigma_{normal})/2|$, and $|(\sigma_{min} - \sigma_{normal})/2|$.

extremely conservative and are related to indoor plumbing and piping standards, these levels are most encouraging.*

In addition, because no attempt was made to optimize either insulation foam material or geometries, it is likely that improvements can be made with refinements in both. The unacceptably high stress levels of larger (6-in.) pipe systems are probably of little importance because it appears that in larger sizes, steel piping systems will have fundamental cost advantages in any event.

*Appendix C presents the results of a parametric study in which material properties were varied to determine the effect on the maximum stresses at the inner surface of the CPVC pipe. In this study, design stress levels of 50% of the ultimate strength were utilized as more realistic values for the application.

## 5. SUMMARY AND CONCLUSIONS

The two major objectives of this investigation were to characterize and evaluate the potential of nonmetallic piping systems for district heating applications. There are many district heating systems in the United States, and the total value of the investments for all systems is approximately \$20 billion (the investment in military systems is estimated to be \$9.5 billion). A significant percentage (>20%) of these systems needs extensive retrofit or replacement over the next 20 years. It is estimated that this investment will cost about \$0.5 billion annually. Research and product development are needed to try to reduce the cost of this investment. Nonmetallic piping systems appear to have the potential to greatly reduce the cost. For these reasons, research on nonmetallic piping systems is of interest to DOE.

Nonmetallic piping materials have been of interest to the district heating industry for many years. Originally, most of the interest stemmed from corrosion problems experienced with steel piping. While the inherent resistance to corrosion of such piping is still attractive, it is not a sufficient feature to justify its adoption. The main focus now has changed to reducing cost. The nonmetallic piping materials offer a combined material and installation cost that has the potential to be significantly lower than that of conventional metallic piping systems.

The nonmetallic piping applications for district heating were classified into three categories of nonmetallic materials: (1) currently being used in district heating applications, (2) currently being used in piping applications other than district heating, and (3) not currently being used in any piping applications. The first of these categories include PEX and PB. The performance of these two types of systems has been satisfactory, with one important exception: both systems have limited operating temperatures of around 200°F (93.3°C). They are classified as low-temperature systems.

The difficulty associated with PEX systems is the cost of pipe joining. Currently, extruders and others are improving the joining techniques. PB is a more recently adopted piping material being used in applications similar to those where PEX has been used. It has been reported that thermal welding has been used as a joining technique for the larger sizes. It is not clear that such a technique can be used in district heating applications because of higher temperatures and higher axial stresses. If thermal welding can be used in district heating systems, the cost of compressive fittings, otherwise required, will be eliminated.

An analysis of the cost components for district heating was performed for currently used metallic district heating piping technology. The analysis separated the cost into civil, mechanical, and material portions of a project. The material costs are roughly one-third of the total, and the material and mechanical costs combined are the other two-thirds of the total. The civil cost includes such activities as digging ditches, backfilling, and surface restoration. While some potential nonmetallic technologies might offer some effect on civil cost, such effects are likely to be minimal. The main potential savings for nonmetallic piping technologies are in the mechanical and material costs. An estimate was made for the use of plastic piping and showed a potential reduction in mechanical costs of about 8% of the total project cost. Materials cost savings are possible for small (<4-in.-diam) pipes. For larger pipes, the material costs were higher than those for conventional piping systems. Another potential savings is in engineering costs. In any project, because of thermal loads and thermal expansion, the design of the piping system requires careful engineering. Such costs range between 5 and 12% of the project cost, but the simpler design of nonmetallic systems should reduce the engineering costs.

As a result of the analysis of piping system cost components, a concept for nonmetallic, preinsulated pipe was developed. This concept used the insulation and jacket material to provide some structural support for a piping material with otherwise marginal strength charcteristics at operational temperatures. Properties for commercially available materials were used in an analysis of this nonmetallic, preinsulated pipe concept.

The structural analysis of the concept showed promise for temperatures in the 200°F (93.3°C) range, and it is speculated that temperatures might be elevated to 230°F (110°C). The use of structurally supported nonmetallic piping appears to merit further analysis.

Nonmetallic piping offers potential advantages over conventional district heating piping. There are clear opportunities for savings in mechanical installation costs. Among these are fewer joints, less expensive joints, simpler expansion compensation, ease of pipe handling, reduced or eliminated pipe cleaning, and simpler testing.

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# Appendix A

# SUMMARY OF PIPING MATERIALS AND PRODUCTS

**Table A.1. Summary of piping materials and products**

*Liquid crystal polymers*

Celanese "Vectra," relatively high temperature (melting point 530–635°F) thermoplastic
Cost: Unknown, relatively high
Use: No current piping uses known

*Postchlorinated polyvinylchloride*

B. F. Goodrich and other resin producers
Cost: Schedule 40 piping ranges from $0.74/ft for 1/2-in. pipe to $18.18/ft for 6-in. pipe
Use: Currently extruded for commercial piping

*Poly(amide-imide)*

Amoco "Torlon," very high temperature thermoplastic
Cost: High
Use: Not used for piping

*Cross-linked polyethylene*

Many resin producers
Cost: Low
Use: Currently extruded for commercial piping. Sold commercially for district heating applications by Wirsbo Bruk Ab (Sweden), Oy Termonor Ab (Finland), and others.

*Polybutylene*

Shell Chemical and other resin producers
Cost: Relatively low
Use: Currently extruded for commercial piping. Sold commercially for district heating applications by Wavin Teletherm (Netherlands) and by Salen

*Polycarbonate*

General Electric and other resin producers
Cost: Relatively high

**Table A.2. Cost of postchlorinated polyvinylchloride (CPVC) piping technology, Schedule 80 and Schedule 40**

| | Schedule 40 | | Schedule 80 | |
|---|---|---|---|---|
| Nominal pipe size (in.) | Approx. wt. per 100 ft (lb) | Plain end price per 100 ft ($) | Approx. wt. per 100 ft (lb) | Plain end price per 100 ft ($) |
| | | *Piping*[a] | | |
| 1/4 | | | 11.92 | 73.00 |
| 3/8 | | | 15.40 | 110.40 |
| 1/2 | 19.00 | 74.55 | 24.30 | 87.15 |
| 3/4 | 25.20 | 100.80 | 32.90 | 113.70 |
| 1 | 37.50 | 148.05 | 48.50 | 168.00 |
| 1 1/4 | 50.70 | 193.15 | 66.90 | 217.55 |
| 1 1/2 | 60.70 | 227.20 | 81.10 | 258.80 |
| 2 | 81.50 | 304.75 | 108.50 | 358.30 |
| 2 1/2 | 129.30 | 456.05 | 165.40 | 559.50 |
| 3 | 169.10 | 633.65 | 221.30 | 732.90 |
| 4 | 232.90 | 904.50 | 323.40 | 1073.10 |
| 6 | 409.60 | 1818.60 | 616.80 | 2196.80 |
| 8 | | | 905.80 | 5218.85 |

*Cement and primer*

| | Price each ($) | |
|---|---|---|
| Size | CPVC solvent cement | Primer (purple or clear) |
| Pint | 7.50 | 6.97 |
| Quart | 11.83 | 11.41 |
| Gallon | | 38.72 |

[a]Standard length = 20 ft only.

**Table A.3. Cost of conventional copper piping technology**

| Pipe outside diameter (mm) | Insulation thickness (mm) | HDPE-casing[a] outside diameter (mm) | Length (m) | Cost per meter ($) |
|---|---|---|---|---|
| *Single pipe, standard insulation, one end seal per pipe end* | | | | |
| 1 × 12 | 34 | 93 | 25 | 13.00 |
| 1 × 15 | 33 | 93 | 25 | 15.40 |
| 1 × 18 | 31 | 93 | 25 | 17.80 |
| 1 × 22 | 29 | 93 | 25 | 20.20 |
| 1 × 28 | 26 | 93 | 25 | 23.00 |
| 1 × 35 | 38 | 128 | 12 | 28.00 |
| 1 × 42 | 34 | 128 | 12 | 32.20 |
| 1 × 54 | 42 | 163 | 12 | 39.80 |
| 1 × 70 | 35 | 163 | 12 | 49.40 |
| 1 × 88.9 | 36 | 186 | 9 | 75.80 |
| *Single pipe, extra insulation, one end seal per pipe end* | | | | |
| 1 × 28 | 41 | 128 | 12 | 26.00 |
| 1 × 35 | 53 | 163 | 12 | 32.60 |
| 1 × 42 | 49 | 163 | 12 | 36.20 |
| 1 × 54 | 53 | 186 | 12 | 45.60 |
| 1 × 70 | 45 | 186 | 12 | 56.00 |
| *Double pipe, one end seal per pipe end* | | | | |
| 22/12 | 43 | 128 | 12 | 30.40 |
| 28/15 | 39 | 128 | 12 | 35.20 |
| 35/18 | 50 | 163 | 12 | 41.00 |
| 42/22 | 46 | 163 | 12 | 46.40 |
| 54/28 | 50 | 186 | 12 | 56.00 |
| 2 × 15 | 44 | 128 | 12 | 30.00 |
| 2 × 18 | 42 | 128 | 12 | 35.00 |
| 2 × 22 | 40 | 128 | 12 | 38.60 |
| 2 × 28 | 45 | 163 | 12 | 43.40 |
| 2 × 35 | 50 | 186 | 12 | 51.60 |
| 2 × 42 | 42 | 186 | 12 | 59.20 |

| Pipe outside diameter (mm) 1 × 2 × 3 | Cost each ($) | Pipe outside diameter (mm) 1 × 2 × 3 | Cost each ($) |
|---|---|---|---|
| *T-piece, single pipe, standard insulation* | | | |
| 18 × 18 × 18 | 64.20 | 54 × 54 × 54 | 126.40 |
| 22 × 22 × 22 | 67.00 | 70 × 28 × 70 | 129.20 |
| 28 × 28 × 28 | 70.00 | 70 × 42 × 70 | 137.80 |
| 35 × 28 × 35 | 83.20 | 70 × 70 × 70 | 164.00 |
| 35 × 35 × 35 | 88.40 | 88.9 × 28 × 88.9 | 165.60 |
| 42 × 28 × 42 | 90.20 | 88.9 × 42 × 88.9 | 166.80 |
| 42 × 42 × 42 | 97.40 | 88.9 × 54 × 88.9 | 179.40 |
| 54 × 28 × 54 | 109.20 | 88.9 × 88.9 × 88.9 | 221.20 |

**Table A.3 (continued)**

| Pipe outside diameter (mm) 1 × 2 × 3 | Cost each ($) | Pipe outside diameter (mm) 1 × 2 × 3 | Cost each ($) |
|---|---|---|---|
| *T-piece, single pipe, extra insulation* | | | |
| 28 × 28 × 28 | 80.40 | 54 × 28 × 54 | 125.00 |
| 35 × 28 × 35 | 95.80 | 54 × 54 × 54 | 149.20 |
| 35 × 35 × 35 | 105.40 | 70 × 28 × 70 | 144.60 |
| 42 × 28 × 42 | 101.40 | 70 × 42 × 70 | 159.20 |
| 42 × 42 × 42 | 112.00 | 70 × 70 × 70 | 186.20 |
| *Service T-piece, single pipe, standard insulation* | | | |
| 28 × 2×22 × 28 | 133.80 | 54 × 2×22 × 54 | 201.40 |
| 35 × 2×22 × 35 | 149.20 | 70 × 2×22 × 70 | 240.60 |
| 42 × 2×22 × 42 | 161.20 | 88.9 × 2×22 × 88.9 | 309.40 |
| *Service T-piece, single pipe, extra insulation* | | | |
| 28 × 2×22 × 28 | 133.80 | 35 × 2×28 × 35 | 178.80 |
| 35 × 2×22 × 35 | 172.00 | 42 × 2×28 × 42 | 106.00 |
| 42 × 2×22 × 42 | 184.40 | 54 × 2×42 × 54 | 469.00 |
| 54 × 2×22 × 54 | 227.40 | 70 × 2×42 × 70 | 543.20 |
| 70 × 2×22 × 70 | 261.60 | 88.9 × 2×42 × 88.9 | 547.80 |

| Pipe outside diameter (mm) 1 × 2 × 3 | HDPE-casing[a] outside diameter (mm) | Cost each ($) | Pipe outside diameter (mm) 1 × 2 × 3 | HDPE-casing[a] outside diameter (mm) | Cost each ($) |
|---|---|---|---|---|---|
| *End-service T-piece* | | | | | |
| 28 × 2×22 × 2×22 | 128 | 144.80 | | | |
| *T-piece, double pipe* | | | | | |
| 2×15 × 2×15 × 2×15 | 128 | 86.20 | 28/15 × 28/15 × 28/15 | 128 | 98.20 |
| 2×18 × 2×18 × 2×18 | 128 | 88.60 | 35/18 × 35/18 × 35/18 | 163 | 127.60 |
| 2×22 × 2×22 × 2×22 | 128 | 91.40 | 35/18 × 28/15 × 35/18 | 163/128 | 116.20 |
| 2×28 × 2×28 × 2×28 | 163 | 109.20 | 42/22 × 42/22 × 42/22 | 163 | 135.00 |
| 2×35 × 2×35 × 2×35 | 186 | 136.80 | 42/22 × 28/25 × 42/22 | 163/128 | 119.80 |
| 2×42 × 2×42 × 2×42 | 186 | 154.00 | 54/28 × 54/28 × 54/28 | 186 | 182.80 |
| 2×35 × 2×22 × 2×35 | 186/128 | 123.00 | 54/28 × 28/15 × 54/28 | 186/128 | 147.20 |
| 2×42 × 2×22 × 2×42 | 186/128 | 147.20 | | | |
| *Bend 90°, single pipe, standard insulation* | | | | | |
| 28 | 93 | 53.40 | 54 | 163 | 98.80 |
| 35 | 128 | 70.20 | 70 | 163 | 116.60 |
| 42 | 128 | 72.80 | 88 | 184 | 150.00 |

**Table A.3 (continued)**

| Pipe outside diameter (mm) 1 × 2 × 3 | HDPE-casing[a] outside diameter (mm) | Cost each ($) | Pipe outside diameter (mm) 1 × 2 × 3 | HDPE-casing[a] outside diameter (mm) | Cost each ($) |
|---|---|---|---|---|---|
| | | *Bend 90°, single pipe, extra insulation* | | | |
| 28 | 128 | 64.60 | 54 | 186 | 115.40 |
| 35 | 163 | 90.00 | 70 | 186 | 133.40 |
| 42 | 163 | 92.40 | | | |
| | | *Bend 90°, double pipe* | | | |
| 2 × 28 horizontal | 163 | 155.80 | 35/18 horizontal | 163 | 98.40 |
| 2 × 35 horizontal | 186 | 171.60 | 42/22 horizontal | 163 | 103.60 |
| 2 × 42 horizontal | 186 | 190.60 | 54/28 horizontal | 186 | 126.40 |
| 2 × 28 vertical | 163 | 161.40 | 22/12 vertical | 128 | 84.60 |
| 2 × 35 vertical | 186 | 191.20 | 28/15 vertical | 128 | 96.20 |
| 2 × 42 vertical | 186 | 201.80 | 35/18 vertical | 163 | 108.80 |
| 22/12 horizontal | 128 | 76.60 | 42/22 vertical | 163 | 114.00 |
| 28/15 horizontal | 128 | 87.40 | 54/28 vertical | 186 | 140.20 |
| | | *Bend 45°, standard insulation* | | | |
| 54 | 163 | 64.20 | | | |
| 70 | 163 | 76.60 | | | |
| 88.9 | 186 | 104.20 | | | |
| | | *Bend 45°, extra insulation* | | | |
| 54 | 186 | 77.80 | | | |
| 70 | 186 | 90.00 | | | |

[a]HDPE = high-density polyethylene.

# Appendix B

# TECHNICAL DATA ON NONMETALLIC PIPING MATERIALS

**Table B.1. Technical data on postchlorinated polyvinylchloride (CPVC)**

| Property | PVC[a] | CPVC | Remarks | ASTM[b] test |
|---|---|---|---|---|
| | | **Specific material data** | | |
| | | *Mechanical* | | |
| Tensile strength, 73°F, psi | 7,280 | 8,000 | Same in circumferential direction | D-638 |
| Modulus of elasticity in tension, 73°F, psi | 420,000 | 360,000 | Ratio of stress to elongation (Young's modulus) | D-638 |
| Compressive strength, 73°F, psi | 9,600 | 10,920 | | D-695 |
| Flexural strength, 73°F, psi | 12,700 | 15,100 | Tensile stress on bent sample at failure | D-790 |
| Izod impact, 73°F, ft-lb/in. of notch | 1.6 | 1.5 | Impact resistance of notched sample to a sharp blow | D-256 |
| Relative hardness, 73°F | | | | |
| Durometer "D" | 80 ± 3 | | Equivalent to aluminum | D-2240 |
| Rockwell "R" | 110–120 | 120 | | D-785 |
| | | *Thermodynamics* | | |
| Coefficient of thermal linear expansion per °F, in.$^2$/°F | $2.8 \times 10^{-5}$ | $3.4 \times 10^{-5}$ | | D-696 |
| Thermal conductivity, cal/cm$^2$/s/°C | $3.4 \times 10^{-4}$ | | Average specific heat of 0–100°C | |
| Specific heat, cal/g/°C | 0.20–0.28 | | Ratio of thermal capacity to that of water at 15°C | |
| Maximum operating temperature, °F | 140 | 180 | Pressure rating is directly related to temperature | |
| Heat deflection temperature, 264 psi, °F | 165 | 217 | Thermal vibration and softening occurs | D-648 |
| Decomposition point, °F | 400+ | 400+ | Scorching by carbonization and dehydrochloration | |
| | | *Electrical* | | |
| Dielectric strength, V/mil | 1,400 | 1,170 | Electric insulator and nonmagnetic | D-147 |
| Dielectric constant, 60 Hz, 30°F | 3.70 | 3.25; 1,000 Hz | | D-150 |
| Power factor 60 Hz, 30°F, % | 1.255 | 0.007; 1,000 Hz | | D-150 |
| Specific volume resistivity, 73°F, ohm/cm | $3.5 \times 10^{15}$ | $3.4 \times 10^{15}$ | | D-257 |
| | | **Other material data** | | |
| Specific gravity, g/cm$^3$ | 1.38 | 1.55 | Relative density | D-792 |
| Water absorption, % | +0.05 | +0.03, 73°F<br>+0.55, 180°F | Weight gain in 24 h | D-570 |
| Poisson's ratio, 73°F | 0.38 | 0.37 | | |
| Cell designation | 12454-B | 23447-A | | D-1784 |

**Table B.1 (continued)**

| Nominal pipe size (IPS)[d] (in.) | Schedule 40 PVC | Schedule 80 PVC | | | Schedule 80 CPVC | SDR pressure-rated pipe[c] PVC plain and belled end | | |
|---|---|---|---|---|---|---|---|---|
| | Plain & belled[e] | Plain end | Threaded[f] | Roll grooved | Plain end[g] | SDR 26 | SDR 21 | SDR 13.5 |
| 1/4 | NA[h] | 1130 | NA | NA | NA | NA | NA | NA |
| 1/2 | 600 | 850 | 420 | NA | 850 | NA | NA | 315 |
| 3/4 | 480 | 690 | 340 | NA | 690 | NA | 200 | |
| 1 | 450 | 630 | 320 | NA | 630 | NA | 200 | |
| 1 1/4 | 370 | 520 | 260 | NA | 520 | 160 | 200 | |
| 1 1/2 | 330 | 470 | 240 | NA | 470 | 160 | 200 | |
| 2 | 280 | 400 | 200 | 400 | 400 | 160 | 200 | |
| 2 1/2 | 300 | 420 | 210 | 420 | 420 | 160 | 200 | |
| 3 | 260 | 370 | 190 | 370 | 370 | 160 | 200 | |
| 4 | 220 | 320 | 160 | 320 | 320 | 160 | 200 | |
| 5 | 190 | 290 | NR[i] | 290 | 290 | 160 | 200 | |
| 6 | 180 | 280 | NR | 280 | 280 | 160 | 200 | |
| 8 | 160 | 250 | NR | 250 | 250 | 160 | 200 | |
| 10 | 140 | 230 | NR | 230 | 230 | 160 | 200 | |
| 12 | 130 | 230 | NR | 230 | NA | 160 | 200 | |

[a]PVC = polyvinylchloride.
[b]ASTM = American Society for Testing and Materials.
[c]Standard dimensional ratio pipe (SDR) will carry the same pressure rating (PR) for all diameters according to the SDR number.
[d]IPS = International Pipe Standard.
[e]Threading Schedule 40 with SDR/PR pipe is not recommended.
[f]Threading Schedule 80 pipe above 4 in. is not recommended.
[g]CPVC threaded connections should be avoided when possible at elevated temperatures and pressures.
[h]NA = not available.
[i]NR = not recommended.
*Source*: Adapted from Elston Company data.

***NOTES***:

The operating pressures listed above are based on the hydrostatic design of the product using water as a test medium at 73°F. Compounding nomenclature for Eslon PVC is PVC 1120 with a cell class of 12454-B. For Eslon CPVC pipe it is CPVC 4120 with a cell class of 23447-A.

For schedule-rated products and SDR/PR pipe, the following equation was used to determine operating pressures for outside diameter controlled pipe:

$$P = \frac{2ST}{D - T},$$

where

$P$ = pressure (psi)
$D$ = average outside diameter
$T$ = minimum wall thickness
$S$ = hydrostatic design stress (HDS);
for both Eslon CPVC and Eslon PVC, Type 1, Grade 1, HDS = 2.000 psi.

The following temperature corrections must be used to derate all PVC and CPVC pipe, valves, and fittings when operating temperatures are expected to exceed 73°F.

The working pressure of PVC and CPVC pipe is directly affected by temperature changes. When the operating temperature of the pipe increases, the pipe loses its stiffness and tensile strength decreases. A drop in pressure capacity results. The drop can be calculated using this chart. Multiply the pipe's maximum working pressure by the temperature correction factor for a known temperature.

**Table B.1 (continued)**

*Example*: For 2-in., Schedule 80 PVC pipe, the maximum working pressure is 400 psi. If the operating temperature is known to be 110°F, the correction factor can be found on the chart to be 0.50. The adjusted pressure would then be 400 × 0.50 = 200 psi.

**Temperature correction factors**

| | Operating temperature (°F) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pipe type | 70 | 80 | 90 | 100 | 110 | 115 | 120 | 125 | 130 | 140 | 150 | 160 | 170 | 180 | 200 |
| PVC 1120 | 1.00 | 0.88 | 0.75 | 0.62 | 0.50 | 0.45 | 0.40 | 0.35 | 0.30 | 0.22 | NR[a] | NR | NR | NR | NR |
| CPVC 4120 | 1.00 | 1.00 | 0.91 | 0.82 | 0.77 | 0.74 | 0.65 | 0.66 | 0.62 | 0.50 | 0.47 | 0.40 | 0.32 | 0.25 | 0.20 |

[a]NR = Not recommended.

**Table B.2. Technical data on high-density polyethylene (HDPE)**

Hostalen® GM 5010 T2: high-molecular-weight HDPE resin pipe compound in pellet form, black (American Hoeshst® Corp.)

| Typical properties | GM 5010 T2[a] | ASTM[b] |
|---|---|---|
| Density | 0.955 g/cm | D 792 |
| Melting point | 257°F | DSC |
| (RSV) | 3.0 dL/g | D 1601 |
| Melt index | | |
| 12.16 | 0.14 g/10 min | D 1238 (E) |
| 121.6 | 11.0 g/10 min | D 1238 (F) |
| ESCR | >192 F20 h | D 1693 (C) |
| Tensile yield strength | >3200 psi | D 638 |
| Elongation at break | 800% | D 638 ( Spec 1) |
| Tension modulus of elasticity | 113.000 psi | D 638 |
| Flexural modulus | 136.000 psi | D 790 |
| Vicat softening temperature | 255°F | D 1525 |
| Brittleness temperature | −180°F | D 746 |
| Heat distortion temperature | 172°F | D 648 |
| Thermal expansion | $1 \times 10^{-4}$ in.$^2$/°F | D 696 |
| Rockwell hardness | 49 (L scale) | D 785 |
| Shore hardness | 63 (D scale) | D 2240 |
| Hydrostatic design stress basis | 1600 psi | D 2837 100.000 h 73°F (23°C) |
| Classification: type class/category/grade | III C/5/P34 | D 1248 |
| Cell classification | 345434 C | D 3350 |
| PPI[c] recommended designation | PE 3408 | |
| NSF[d] approved for potable water | | |

[a]The data listed were determined on press-molded test specimens and may, therefore, deviate from specimens taken from pipes.

[b]ASTM = American Society for Testing and Materials.

[c]PPI = Plastics Pipe Institute.

[d]NSF = National Science Foundation.

*Source*: Adapted from data from American Hoechst Corp., Plastics Division.

**Table B.3. Technical data on insulation properties**

| Nominal diameter (mm) | Description |
|---|---|
| | *Pipes and pipe fittings* |
| | *Straight pipe—steel* |
| ≤100 | Seamless or longitudinally welded steel pipes to SIS141232 or SIS141330. |
| 125–700 | Spiral-welded or longitudinally welded steel pipe to SIS141312. |
| | *Bends—steel* |
| 20–150 | Cold-bent seamless steel pipes to SIS141330-05. |
| 125–150 | To special order, welded with seamless bends to SIS141330-5. |
| 200–700 | Welded (EWS bend) of steel to SIS141330. |

***Inspection***

Inner pipes are inspected radiographically on a 10% sample basis. 100% weld inspection is available to order.

Welded pipe elements are hydraulically tested with water at 2.1-MPa gauge pressure.

Brazed copper pipe elements are tested at 1.3-MPa gauge pressure.

***Outer jackets***

The outer jackets of high-density polyethylene (HDPE) are manufactured specially for district heating mains duty and provide adequate protection against the internal and external stresses encountered during manufacture, installation, and service. The material is a high-molecular-weight HDPE. Some of the characteristic features of this material are as follows:

- very high resistance to stress corrosion cracking;
- stabilized against thermal, chemical, oxidizing biological, and other decomposition processes;
- high water strength and impact strength—also at low temperatures; and
- easy to weld, complying with requirements of DIN 19537, Sect. 2.

Jacket pipes are manufactured in accordance with DIN 8075, Sect. 1.

***Insulation***

Thermal insulation consists of foamed polyurethane (PF) with an average density of about 80 kg/m$^3$ and a minimum density of 60 kg/m$^3$.

PF has excellent mechanical and thermal insulating qualities. About 95% of this foam consists of closed, gas-filled cells. This material can withstand temperatures up to 150°C for short periods and 130°C continuously.

Two thicknesses of insulation are used: the thinner insulation is referred to as Series 1 and the thicker insulation as Series 2.

Mechanical properties of insulation with an average density of 80 kg/m$^3$ are as follows:

| | |
|---|---|
| Compressive strength | 700 kPa |
| Tensile strength | 685 kPa |
| Bending strength | 300 kPa |
| Shear modulus | 14 800 kPa |
| Modulus of elasticity | 8.6 kPa |
| Strain | 8% |
| Dimension change after heating to 120°C, % | +0.8% |
| Weight loss after heating to 120°C | 1.9% |

**Table B.4. Material property data sheet**

(Stepanfoam® C-605)

*Uses*

Aircraft control sections, potting electronic units, structural panels. Designed for large cross-section pours.

*Physical properties*

Stepanfoam C-605 has a small, uniform-cell structure and a slightly viscous pour point. The following data are from machine-mixed samples.

| Property | Stepanfoam C-605 |
|---|---|
| Shear strength | 100 psi |
| Stress at 2% strain | 100 psi |
| Compressive strength | 120 psi |
| Tensile strength | 165 psi |
| Modulus of rigidity | 1600 psi |
| Modulus of elasticity | 4200 psi |
| Density | 5 $lb/ft^3$ |
| K-factor | 0.27 $(Btu/h) \cdot ft^2 \cdot (°F/in.)$ |
| Water-sorption, 10-ft head, 24 h | 1.5% |
| Dielectric constant, 9.375 KMC | 1.1 |
| Loss tangent, 9.375 KMC | $0.02 \times 10^{-3}$ |
| Maximum operating temperature | 250°F |

*Source*: Adapted from *Technical Information Bulletin, Stepanfoam® C-605*, Stepan Chemical Company, Northfield, Ill.

## Appendix C

## PARAMETRIC EVALUATION OF THE EFFECT OF MATERIAL PROPERTY VARIATION ON THE MAXIMUM STRESSES AT THE INNER SURFACE OF THE POSTCHLORINATED POLYVINYLCHLORIDE PIPE

## APPENDIX C

## PARAMETRIC EVALUATION OF THE EFFECT OF MATERIAL PROPERTY VARIATION ON THE MAXIMUM STRESSES AT THE INNER SURFACE OF POSTCHLORINATED POLYVINYLCHLORIDE PIPE

### C.1 STATEMENT OF PROBLEM

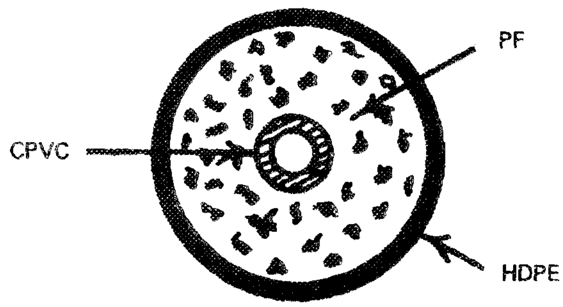
Imposition of the requirements contained in the *ASME Code for Pressure Piping* (ANSI/ASME B31.3-1984) for the variation of allowable design stress levels as a function of temperature results in the postchlorinated polyvinylchloride (CPVC) having only a marginal strength level (1.5 MPa) at the upper temperature level of interest in this study [200°F (93.3°C)]. If more temperature-resistant forms of the materials used in the pipe-in-pipe concept can be identified, or if it can be demonstrated that the design stress reductions with temperature contained in the Code are overly conservative, the structural feasibility of using the concept at higher temperatures and pressure can be demonstrated.

### C.2 APPROACH

A parametric study was conducted to evaluate the effect of the variation of material properties on the maximum stresses that occur at the inner surface of the CPVC pipe (e.g., the limiting condition). In the study, the two pipe geometries presented in Fig. C.1, Models 1 and 4; the two internal pressure levels, 0.69 MPa and 1.55 MPa; and the two thermal loading cases, 73°F (23°C) and 200°F (93.3°C), investigated were also used. Seven specific conditions were investigated analytically for each pipe geometry and are identified as Case Nos. 1–7 in Table C.1. Table C.2 relates the case numbers in Table C.1 to the specific parameter investigated.

### C.3 MATERIAL PROPERTIES

Material properties used for the CPVC are presented in Table C.3. The properties were obtained from representatives of B. F. Goodrich Chemical Company, Cleveland, Ohio, in a meeting held at Oak Ridge National Laboratory on August 28, 1986. Mechanical properties for the urethane foam (PF) and high-density polyethylene (HDPE) at room temperature [73°F (23°C)] were assumed to be the same as presented in Table C.4. At 200°F (93.3°C), the mechanical properties of the PF and HDPE were assumed to vary in the same manner as those of the CPVC presented in Table C.3. A summary of the mechanical properties for CPVC, PF, and HDPE is presented in Table C.5. Thermal properties for the materials were assumed also to be the same as those in Table C.4.




| Model number | Pipe geometries (mm) | | | | | |
|---|---|---|---|---|---|---|
| | CPVC[a] | | PF[b] | | HDPE[c] | |
| | $d_i$ | $d_o$ | $d_i'$ | $d_o'$ | $d_i''$ | $d_o''$ |
| 1 | 20.93 | 26.67 | 26.67 | 77.93 | 77.93 | 88.90 |
| 4 | 154.05 | 168.28 | 168.28 | 254.51 | 254.51 | 273.05 |

[a]CPVC = postchlorinated polyvinylchloride.
[b]PF = urethane foam.
[c]HDPE = high-density polyethylene.

**Fig. C.1. Pipe geometries investigated.**

**Table C.1. Specific conditions investigated analytically in parametric study**

| Material | Material property retention at temperature (%)[a] | | | | | | |
|---|---|---|---|---|---|---|---|
| | Case number | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Postchlorinated polyvinylchloride | 100 | 75 | 50 | 75 | 25 | 50 | 50 |
| Urethane foam | 100 | 75 | 50 | 50 | 50 | 75 | 25 |
| High-density polyethylene | 100 | 75 | 50 | 50 | 50 | 50 | 50 |

[a]Percentage of ultimate strength at temperature level of interest.

**Table C.2. Case studies related to each parameter investigated**

| Parameter | Case numbers |
|---|---|
| Material property retention | 1, 2, 3 |
| Postchlorinated polyvinylchloride | 3, 4, 5 |
| Urethane foam | 3, 6, 7 |

**Table C.3. Postchlorinated polyvinylchloride (CPVC) material properties**

Hi-Temp Geon CPVC 3007, extrusion compound (pipe)

| Property | Typical values (compression molded) | ASTM[a] number |
|---|---|---|
| | *Characteristics* | |
| Specific gravity | 1.55 | D-792 |
| Hardness, Rockwell "R," method A | 120 | D-785 |
| | *Physical properties* | |
| Izod impact strength, 1/4-in. bar | | D-256 |
| 73°F | 3.0 ft-lb/in. notch | |
| 32°F | 1.8 ft-lb/in. notch | |
| 0°F | 1.0 ft-lb/in. notch | |
| -40°F | 0.6 ft-lb/in. notch | |
| Tensile properties, strength | | D-638 |
| 32°F | 9,900 psi | |
| 73°F | 8,400 psi | |
| 140°F | 5,800 psi | |
| 180°F | 4,100 psi | |
| 200°F | 3,400 psi | |
| 230°F | 2,400 psi | |
| Modulus of elasticity in tension | | D-638 |
| 32°F | 498,000 psi | |
| 73°F | 423,000 psi | |
| 140°F | 323,000 psi | |
| 180°F | 269,000 psi | |
| 200°F | 227,000 psi | |
| 230°F | 188,000 psi | |
| Heat deflection temperature, 264 psi, annealed samples | 221°F | D-648 |
| Flammability | | |
| 0.125-in. sheet | Nonburning | D-635 |
| 0.010-in. sheet | Nonburning | D-568 |
| Flexural strength, 73°F | 15,600 psi | D-790 |
| Flexural modulus, 73°F | 426,000 psi | D-790 |
| Thermal conductivity | 0.95 (Btu/h)·ft²·(°F/in.) | C-177 |
| Coefficient of thermal expansion | $3.8 \times 10^{-5}$ in.²/°F | D-696 |
| Dielectric strength | 1,300 V/mil | D-149 |
| Dielectric constant | | D-150 |
| $10^3$ cps | 3.4 | |
| $10^6$ cps | 3.3 | |
| Power factor | | D-150 |
| 60 cps | 0.019 | |
| 1000 cps | 0.015 | |
| Water absorption, 73°C, 24-h gain | 0.05% | D-570 |
| | *Chemical resistance* | |
| (1) 93.5% $H_2SO_4$, 14 d, 55°C, flexural strength change | +0.02% | D-543 |
| weight change | −0.01% | |
| (2) ASTM oil #3, 30 d, 23°C, weight change | +0.04% | D-543 |
| (3) 93.5% $H_2SO_4$, 28 d, 210°F, weight change | -1.72% | D-543 |

Table C.3 (continued)

| Property | Typical values (compression molded) | ASTM[a] number |
|---|---|---|
| | *Miscellaneous data* | |
| PPI[b] hydrostatic design stress ratings | | |
| 73°F | 2,000 psi | |
| 180°F | 500 psi | |
| NSF[c] listing for potable water (specific colors) | 73°F and 180°F | |
| Cell designation | 23557-A | D-1784-69 |
| Application: Pipe and custom extrusion | | |
| (1) Industrial pipe for chemical processing | | |
| (2) Water supply pipe: this compound is used to make pipe designed to meet the requirements of ASTM D-2846 for transporting hot water under 100 psi at 180°F | | |
| (3) Profile extrusion | | |

[a]ASTM = American Society for Testing and Materials.
[b]PPI = Plastics Pipe Institute.
[c]NSF = National Science Foundation.
*Source:* Adapted from data from B. F. Goodrich Chemical Company, division of B. F. Goodrich Company, 3135 Euclid Avenue, Cleveland, Ohio.

## C.4 ANALYTICAL INVESTIGATION

A two-dimensional, finite-element (FE) analysis was conducted for the pipe-in-pipe system. For each of the cases defined in Table C.1, elastic analyses of an infinitely long pipe (plane strain) were performed using the two geometries presented in Fig. C.1. Also, for each of the cases, two internal pressures (0.69 and 1.55 MPa) and two thermal loadings [73°F and 200°F (23°C and 93.3°C)] were considered. The thermal loadings represent a steady state analysis using ADINAT[1] where the inside surface of the CPVC was given a prescribed constant temperature [73°F or 200°F (23°C or 93.3°C)], while a convective boundary condition simulating heat transfer to the surrounding soil was employed at the outside surface of the composite pipe. The steady state temperature distributions from ADINAT[1] were then input to ADINA,[1] and a stress analysis was performed for each of the two models.

## C.5 RESULTS

The results of the study are summarized in Table C.6 for each of the case numbers in Table C.1. SIGMAX is the largest of $|\sigma_{max}|$, $|\sigma_{min}|$, and $|\sigma_{normal}|$, while TAUMAX is the largest of $|(\sigma_{max} - \sigma_{min})/2|$, $|(\sigma_{max} - \sigma_{normal})/2|$, and $|(\sigma_{min} - \sigma_{normal})/2|$. Assuming a design stress limit for the CPVC of 50% of its ultimate strength value at the temperature level of interest, stress levels in the CPVC for the seven cases investigated remain below the design stress limits, except as noted.

**Table C.4. Material properties**

| Property | Postchlorinated polyvinylchloride | Urethane foam | High-density polyethylene |
|---|---|---|---|
| Compressive strength, MPa | | | |
| Ultimate, 23°C | 75.3[a] | 0.83[b] | 19.4[c] |
| Design, 23°C | 18.9[d] | 0.44[e] | 10.2[e] |
| Design, 93.3°C | 2.1[d] | 0.31[f] | 1.1[g] |
| Tensile strength, MPa | | | |
| Ultimate, 23°C | 55.0[a] | 1.14[b] | 23.4[h] |
| Design, 23°C | 13.8[i] | 0.60[e] | 12.3[e] |
| Design, 93.3°C | 1.5[g] | 0.42[f] | 1.3[g] |
| Modulus of elasticity, MPa | | | |
| 23°C | 2895[i] | 29.0[b] | 827[h] |
| 93.3°C | 315[g] | 20.3[f] | 90[g] |
| Thermal expansion coefficient, $mm^2/°C$ | $63 \times 10^{-6}$ (*i*) | $72 \times 10^{-6}$ (*i*) | $180 \times 10^{-6}$ (*c*) |
| Conductivity, $cal \cdot cm/s \cdot cm^2 \cdot °C$ | $0.35 \times 10^{-3}$ (*a*) | $1.12 \times 10^{-3}$ (*b*) | $1.2 \times 10^{-3}$ (*c*) |
| Specific heat, cal/°C/gm | 0.24[a] | 0.42[c] | 0.55[c] |
| Density, $gm/cm^3$ | 1.55[a] | 0.08[a] | 0.96[c] |
| Poisson's ratio | 0.27[a] | 0.31[j] | 0.35[k] |

[a]*Source:* Data sheet from Michael Barnes.

[b]*Source: Technical Information Bulletin,* Stepanfoam C-605, Stepan Chemical Company, Northfield, Ill.

[c]*Source: Modern Plastics Encyclopedia,* McGraw, New York, 1985–86.

[d]Assumes compressive properties vary same with temperature as design properties in tension presented in *ASME Code for Pressure Piping,* ANSI/ASME B31.3-1984.

[e]Scaled according to ratio of design stress to ultimate stress given in *ASME Code for Pressure Piping,* ANSI/ASME B31.3-1984.

[f]Foam properties vary linearly with temperature between −73°C and 260°C. Values were scaled accordingly. *Source: Structural Design with Plastics,* B. S. Benjamin, Polymer Science and Engineering Series, Society of Plastics Engineers, Inc., Van Nostrand Reinhold, 1969, p. 95.

[g]Assumes property loss varies linearly with temperature as presented in *ASME Code for Pressure Piping,* ANSI/ASME B31.3-1984.

[h]Stress-strain curve high-density polyethylene thermoplastic.

[i]*Source: ASME Code for Pressure Piping,* ANSI/ASME B31.3-1984.

[j]Rough estimate.

[k]*Source: Structural Plastics Design Manual,* FHWA-TS-79-203.

The effect of varying the properties of the materials (i.e., the percentage of ultimate strength at which the materials can operate for extended periods of time) is presented in Table C.7. Conditions where the maximum stress at the inner surface of the CPVC pipe exceeds the corresponding design stress limits (50% of ultimate strength value) are noted in the table. Results indicate that, in general, as the property retention decreases, the SIGMAX stress increases slightly and TAUMAX decreases. In Model No. 1, for the condition where the internal pressure is the same but the temperature changes, there is a significant increase in SIGMAX and TAUMAX for a pressure of 0.69 MPa; but for an internal pressure of 1.55 MPa, there is a slight decrease in SIGMAX with an increase in temperature. In Model No. 4, however, for the condition where the internal pressure

**Table C.5. Material mechanical properties used in parametric study**

| Material | Tensile strength (MPa) | | Compressive strength (MPa) | | Modulus of elasticity (MPa) | |
|---|---|---|---|---|---|---|
| | 23°C | 93°C | 23°C | 93.3°C | 23°C | 93.3°C |
| Postchlorinated polyvinylchloride | 57.9 | 23.4 | 79.3 | 32.0 | 2920 | 1565 |
| Urethane foam | 1.14 | 0.46[a] | 0.83 | 0.34[a] | 29 | 15.6[a] |
| High-density polyethylene | 23.4 | 9.46[a] | 19.4 | 7.87[a] | 827 | 443[a] |

[a]Properties assumed to vary with temperature in same manner as postchlorinated polyvinylchloride properties.

remains the same but the temperature changes, SIGMAX remains essentially unchanged and TAUMAX increases slightly as the temperature increases.

The effect of varying the CPVC properties while retaining the properties of the PF and HDPE is summarized in Table C.8. Results presented in this table indicate that the effect of reducing the properties of the CPVC (notably the modulus of elasticity) is to reduce the maximum tensile and shear stresses that occur in the CPVC. Also, as the CPVC properties decrease, the number of instances in which the maximum stress at the CPVC inner surface exceeds the design limits increases. Conditions where this occurs are noted in the table.

Table C.9 summarizes the effect of varying the PF properties while retaining those of the CPVC and HDPE. The results indicate that, in general, as the properties of the PF decrease, SIGMAX increases for all loading parmeters considered.* For the range of loading parameters considered, TAUMAX is relatively unaffected by the change in PF properties.

## C.6 SUMMARY

A parametric study was conducted to provide information on the effect of material properties of the pipe-in-pipe system on the stresses that occur at the inner surface of the CPVC pipe. For the temperature and pressure loading parameters considered in our limited study, the magnitude of internal pressure is more significant with respect to the maximum stresses that occur at the inner surface of the CPVC pipe. Also, for the same pressure and temperature loading conditions, the maximum stresses that occur at the inner surface of the CPVC pipe increase significantly as the pipe-in-pipe system size increases. As the mechanical properties of the CPVC increase, the number of instances in which the stresses exceed the CPVC design stress limit (50% of ultimate strength value) is reduced. Also, as the properties of the PF are increased, the maximum stresses that occur at the inner surface of the CPVC pipe are reduced. These results tend to indicate that the

*The one exception is for Model No. 1 with loading parameters of 0.69 MPa and 200°F (93.3°C). In this case, SIGMAX decreases with a reduction in PF properties.

**Table C.6. Summary of results for Case Numbers 1–6 in Table C.1**

| Loading parameters | | CPVC[a] maximum stress (MPa) | | | | CPVC design stress limit (MPa)[b] | | |
|---|---|---|---|---|---|---|---|---|
| | | Model No. 1 | | Model No. 4 | | | | |
| Pressure (MPa) | Temperature (°C) | SIGMAX | TAUMAX | SIGMAX | TAUMAX | Tension | Compression | Shear |
| *Case No. 1 (100% properties)* | | | | | | | | |
| 0.69 | 23 | 2.55 | 2.08 | 6.74 | 4.60 | 28.9 | 39.7 | 34.3 |
| 1.55 | 23 | 5.82 | 4.03 | 15.20 | 9.17 | 28.9 | 39.7 | 34.3 |
| 0.69 | 93.3 | 6.18 | 4.33 | 6.72 | 6.04 | 11.7 | 16.0 | 13.9 |
| 1.55 | 93.3 | 5.75 | 5.61 | 15.18[b] | 9.22 | 11.7 | 16.0 | 13.9 |
| *Case No. 2 (75% properties)* | | | | | | | | |
| 0.69 | 23 | 2.57 | 1.96 | 6.75 | 4.37 | 21.7 | 29.7 | 25.7 |
| 1.55 | 23 | 5.83 | 3.90 | 15.21 | 8.94 | 21.7 | 29.7 | 25.7 |
| 0.69 | 93.3 | 4.49 | 3.54 | 6.74 | 5.12 | 8.8 | 12.0 | 10.4 |
| 1.55 | 93.3 | 5.78 | 4.78 | 15.20[c] | 9.24 | 8.8 | 12.0 | 10.4 |
| *Case No. 3 (50% properties)* | | | | | | | | |
| 0.69 | 23 | 2.58 | 1.82 | 6.76 | 4.13 | 14.5 | 19.8 | 17.2 |
| 1.55 | 23 | 5.85 | 3.77 | 15.22[c] | 8.71 | 14.5 | 19.8 | 17.2 |
| 0.69 | 93.3 | 2.81 | 2.68 | 6.75[c] | 4.34 | 5.9 | 8.0 | 6.9 |
| 1.55 | 93.3 | 5.81 | 3.96 | 15.21[c] | 8.91[c] | 5.9 | 8.0 | 6.9 |
| *Case No. 4 (75% CPVC, 50% PF*[d] and HDPE[e] properties) | | | | | | | | |
| 0.69 | 23 | 2.61 | 1.89 | 7.04 | 4.33 | 21.7 | 29.7 | 25.7 |
| 1.55 | 23 | 5.91 | 3.86 | 15.83 | 9.06 | 21.7 | 29.7 | 25.7 |
| 0.69 | 93.3 | 4.44 | 3.50 | 7.02 | 5.22 | 8.8 | 12.0 | 10.4 |
| 1.55 | 93.3 | 5.86 | 4.79 | 15.81[c] | 9.36 | 8.8 | 12.0 | 10.4 |
| *Case No. 5 (25% CPVC, 50% PF and HDPE properties)* | | | | | | | | |
| 0.69 | 23 | 2.53 | 1.75 | 6.06 | 3.70 | 7.2 | 9.9 | 8.6 |
| 1.55 | 23 | 5.66 | 3.63 | 13.64[c] | 7.84 | 7.2 | 9.9 | 8.6 |
| 0.69 | 93.3 | 2.49 | 1.84 | 6.06[c] | 3.81[c] | 2.9 | 4.0 | 3.5 |
| 1.55 | 93.3 | 5.65[c] | 3.71[c] | 13.63[c] | 7.95[c] | 2.9 | 4.0 | 3.5 |
| *Case No. 6 (75% PF, 50% CPVC and HDPE properties)* | | | | | | | | |
| 0.69 | 23 | 2.54 | 1.85 | 6.58 | 4.09 | 14.5 | 19.8 | 17.2 |
| 1.55 | 23 | 5.76 | 3.78 | 14.81[c] | 8.55 | 14.5 | 19.8 | 17.2 |
| 0.69 | 93.3 | 2.85 | 2.68 | 6.57[c] | 4.30 | 5.9 | 8.0 | 6.9 |
| 1.55 | 93.3 | 5.73 | 3.96 | 14.80[c] | 8.76 | 5.9 | 8.0 | 6.9 |
| *Case No. 7 (25% PF, 50% CPVC and HDPE properties)* | | | | | | | | |
| 0.69 | 23 | 2.63 | 1.78 | 7.03 | 4.17 | 14.5 | 19.8 | 17.2 |
| 1.55 | 23 | 5.95 | 3.75 | 15.82[c] | 8.90 | 14.5 | 19.8 | 17.2 |
| 0.69 | 93.3 | 2.76 | 2.68 | 7.02[c] | 4.37 | 5.9 | 8.0 | 6.9 |
| 1.55 | 93.3 | 5.92[c] | 3.98 | 15.81[c] | 9.10[c] | 5.9 | 8.0 | 6.9 |

[a]CPVC = postchlorinated polyvinylchloride.
[b]Design stress limits are assumed to be 50% of CPVC ultimate strength values utilized at temperature level of interest.
[c]CPVC design stress limit exceeded.
[d]PF = urethane foam.
[e]HDPE = high-density polyethylene.

**Table C.7. Effect of material property retention on maximum stresses at inner surface of postchlorinated polyvinylchloride (CPVC) pipe**

| Loading parameters | | CPVC maximum stress (MPa) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Load case | | | | | |
| | | No. 1 | | No. 2 | | No. 3 | |
| Pressure (MPa) | Temperature (°C) | Property retention | | | | | |
| | | 100% | | 75% | | 50% | |
| | | SIGMAX | TAUMAX | SIGMAX | TAUMAX | SIGMAX | TAUMAX |
| | | *Model No. 1* | | | | | |
| 0.69 | 23 | 2.55 | 2.08 | 2.57 | 1.96 | 2.58 | 1.82 |
| 1.55 | 23 | 5.82 | 4.03 | 5.83 | 3.90 | 5.85 | 3.77 |
| 0.69 | 93.3 | 6.18 | 4.33 | 4.49 | 3.54 | 2.81 | 2.68 |
| 1.55 | 93.3 | 5.75 | 5.61 | 5.78 | 4.78 | 5.81 | 3.96 |
| | | *Model No. 4* | | | | | |
| 0.69 | 23 | 6.74 | 4.60 | 6.75 | 4.37 | 6.76 | 4.13 |
| 1.55 | 23 | 15.20 | 9.17 | 15.21 | 8.94 | 15.22[a] | 8.71 |
| 0.69 | 93.3 | 6.72 | 6.04 | 6.74 | 5.12 | 6.75[a] | 4.34 |
| 1.55 | 93.3 | 15.18[a] | 9.22 | 15.20[a] | 9.24 | 15.21[a] | 8.91[a] |

[a]CPVC design stress limit exceeded.

**Table C.8. Effect of postchlorinated polyvinylchloride (CPVC) property retention on maximum stress at inner surface of CPVC pipe[a]**

| Loading parameters | | CPVC maximum stress (MPa) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Load case | | | | | |
| | | No. 4 | | No. 3 | | No. 5 | |
| Pressure (MPa) | Temperature (°C) | Property retention | | | | | |
| | | 75% | | 50% | | 25% | |
| | | SIGMAX | TAUMAX | SIGMAX | TAUMAX | SIGMAX | TAUMAX |
| | | *Model No. 1* | | | | | |
| 0.69 | 23 | 2.61 | 1.89 | 2.58 | 1.82 | 2.53 | 1.75 |
| 1.55 | 23 | 5.91 | 3.86 | 5.85 | 3.77 | 5.66 | 3.63 |
| 0.69 | 93.3 | 4.44 | 3.50 | 2.81 | 2.68 | 2.49 | 1.84 |
| 1.55 | 93.3 | 5.86 | 4.79 | 5.81 | 3.96 | 5.65[b] | 3.71[b] |
| | | *Model No. 4* | | | | | |
| 0.69 | 23 | 7.04 | 4.33 | 6.76 | 4.13 | 6.06 | 3.70 |
| 1.55 | 23 | 15.83 | 9.06 | 15.22[b] | 8.71 | 13.64[b] | 7.84 |
| 0.69 | 93.3 | 7.02 | 5.22 | 6.75[b] | 4.34 | 6.06[b] | 3.81[b] |
| 1.55 | 93.3 | 15.81[b] | 9.36 | 15.21[b] | 8.91[b] | 13.63[b] | 7.95[b] |

[a]Urethane foam and high-density polyethylene are assumed to retain 50% of their ultimate strength values at temperature level of interest.

[b]CPVC design stress limit exceeded.

**Table C.9. Effect of urethane foam property retention on maximum stresses at inner surface of CPVC pipe[a]**

| Loading parameters | | CPVC maximum stress (MPa) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Load case | | | | | |
| | | No. 6 | | No. 3 | | No. 7 | |
| Pressure (MPa) | Temperature (°C) | Property retention | | | | | |
| | | 75% | | 50% | | 25% | |
| | | SIGMAX | TAUMAX | SIGMAX | TAUMAX | SIGMAX | TAUMAX |
| | | | | *Model No. 1* | | | |
| 0.69 | 23 | 2.54 | 1.85 | 2.58 | 1.82 | 2.63 | 1.78 |
| 1.55 | 23 | 5.76 | 3.78 | 5.85 | 3.77 | 5.95 | 3.75 |
| 0.69 | 93.3 | 2.85 | 2.68 | 2.81 | 2.68 | 2.76 | 2.68 |
| 1.55 | 93.3 | 5.73 | 3.96 | 5.81 | 3.96 | 5.92[b] | 3.98 |
| | | | | *Model No. 4* | | | |
| 0.69 | 23 | 6.58 | 4.09 | 6.76 | 4.13 | 7.03 | 4.17 |
| 1.55 | 23 | 14.81[b] | 8.55 | 15.22[b] | 8.71 | 15.82[b] | 8.90 |
| 0.69 | 93.3 | 6.57[b] | 4.30 | 6.75[b] | 4.34 | 7.02[b] | 4.37 |
| 1.55 | 93.3 | 14.80[b] | 8.76[b] | 15.21[b] | 8.91[b] | 15.81[b] | 9.10[b] |

[a]CPVC and high-density polyethylene are assumed to retain 50% of their ultimate strength values at temperature level of interest.

[b]CPVC design stress limit exceeded.

capabilities of the pipe-in-pipe system can be increased by increasing the properties of either the CPVC or PF materials, or both.

## C.7 REFERENCE

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