CHAPTER B7

THERMAL INSULATION OF PIPING

Kenneth R. Collier
Systems Engineer
Pittsburgh Corning Corporation
Pittsburgh, PA

Kathleen M. Posteraro
Systems Engineer
Pittsburgh Corning Corporation
Pittsburgh, PA

Thermal insulation serves many useful purposes in both industrial and commercial piping applications. In simplest terms, thermal insulation reduces heat flow from one surface to another. For hot, or above ambient, piping applications, thermal insulation reduces heat loss. On cold, or below ambient, piping applications, the insulation generally serves the purpose of minimizing heat gain.

In some cases the design purpose of the application may seem unrelated to heat loss or heat gain; however, the net result is that heat transfer is retarded. Two illustrations are insulation for personnel protection and insulation for condensation control.

For personnel protection there must be enough insulation to keep the surface temperature below a given design value—usually 140°F (60°C). For condensation control, there must be enough insulation to keep the surface temperature above the dew point. In both cases the insulation is used to control the surface temperature for a desired effect other than thermal conservation. The effect, however, is that in both cases insulation retards heat transfer enough to control the surface temperature at the given design criteria.

There is much more to correctly designing and specifying an insulation system than just selecting a particular insulation material to be used. This chapter will discuss some of the practical information necessary to initiate an effective insulation system design. The National Insulation Association (NIA) in its ''Wheels of Learning'' training program defines insulation as ''those materials or combination of materials which retard the flow of heat.'' As noted in the NIA definition of insulation, a combination of materials may be used. The emphasis on the word *system* when referring to the purpose of this chapter signifies the importance of considering *all* the materials, conditions, and parameters involved in insulation specification and design.

An insulation system is any combination of insulation materials used in conjunction with mastic, adhesives, sealants, coatings, membranes, barriers, and/or other accessory products to provide an efficient assembly for the reduction of heat flow. The engineering of insulation systems can frequently either determine or direct the ultimate performance of the process. Improperly engineered insulation systems are subject to damage and degradation. This degradation will compromise the performance characteristics of the insulation material and in many cases the entire process for which the insulation system was specified.

There are many different types of insulation materials available for commerical and industrial piping applications. Each material has its own set of properties and performance characteristics. And for each insulation material available, a correct application procedure and corresponding accessory materials, or "system," are available.

Before we get into the essence of this chapter, which addresses some of the design parameters, materials, and systems that are commonly incorporated into insulation system design, it is necessary to review some fundamentals of heat transfer.

FUNDAMENTALS OF HEAT TRANSFER

The following definitions, taken from ASTM C168-88a, *Standard Definitions of Terms Relating to Thermal Insulating Materials,* and the NIA "Wheels of Learning" training program, will be useful in reviewing the fundamentals of heat transfer.

Btu (*British thermal unit*): the amount of energy required to raise 1 lb of water 1°F (The equivalent metric designation is a *joule,* which is defined as the work done when the point of application of a force of 1 N is displaced a distance of 1 m in the direction of the force. 1 cal = 4.1868 J: furthermore, 1 Btu = 1055.06 J.)

Conduction: the transfer of energy (heat) within a body (material) or between two bodies in physical contact.

Convection: the transfer of heat by movement of parts of a liquid or gas within the liquid or gas because of differences in the density, temperature, etc., of the parts.

Radiation: the transfer of energy (heat) from a higher-temperature body, through space, to another lower temperature body without warming the space between.

Thermal conductivity k: the time rate of steady state heat flow through a unit area of a homogeneous material induced by a unit temperature gradient in a direction perpendicular to that unit area. Units are commonly Btu · in (h · ft^2 °F) [W/(m · K)].

Emittance E: the ratio of the radiant flux emitted by a specimen to that emitted by a black body at the same temperature and under the same conditions.

Radiance: the rate of radiant emission per unit solid angle and per unit projected area of a source in a stated angular direction from the surface (usually the normal).

Reflectance: the fraction of the incident radiation upon a surface that is reflected from the surface.

Heat flow or heat flow rate Q: the quantity of heat transferred to or from a system in unit time. Usually measured in Btu/h.

Thermal insulation: a material or assembly of materials used to provide resistance to heat flow.

Thermal insulation system: applied or installed thermal insulation complete with any accessories, vapor retarder, and facing required.

Heat is transferred by any one of, or combination of, conduction, convection, and/or radiation.

Conduction only occurs when there is physical contact. Heat is transferred through most metals very efficiently because metal is a good conductor. A good insulation material is a poor conductor. Convection, with respect to insulation systems, is the movement of air on or about the surface of an insulated body. And radiation is best described by referring to the warmth you feel when you stand in the sun or by a fire.

Heat transferred through insulation is primarily a function of the resistance of the insulation with respect to its thickness, the operating temperature of the surface being insulated, the surface characteristics of the outer membrane (see emittance above), and the ambient conditions involved.

Thermal conductivity, as defined above, is the rate of heat transfer in one direction (perpendicular to an area) per unit area, per unit temperature differential per unit thickness, per unit time. In the English system of units, typical dimensions are

$$|k| = \mathrm{Btu}/(\mathrm{h}\cdot{}^\circ\mathrm{F}\cdot\mathrm{ft}^2/\mathrm{ft}) = \mathrm{Btu}/(\mathrm{h}\cdot\mathrm{ft}\cdot{}^\circ\mathrm{F}) \qquad [\mathrm{W/cm}\cdot{}^\circ\mathrm{C}]$$

or $$|k| = \mathrm{Btu}/(\mathrm{h}\cdot{}^\circ\mathrm{F}\cdot\mathrm{ft}^2/\mathrm{in}) \qquad [\mathrm{W}/(\mathrm{m}^2\cdot\mathrm{K})]$$

or $$|k| = \mathrm{Btu}\cdot\mathrm{in}(\mathrm{h}\cdot\mathrm{ft}^2\cdot{}^\circ\mathrm{F}) \qquad [\mathrm{W}/(\mathrm{m}^2\cdot\mathrm{K})]$$

The units of measurement used have absolutely no effect on the fundamental equation of heat transfer. Heat transferred through flat surface geometry is most commonly represented by Eq. (B7.1):

$$Q = \frac{A(T_i - T_2)}{X/K + 1/f} \tag{B7.1}$$

where Q = total heat loss, Btu $(\mathrm{h}\cdot\mathrm{ft}^2)$ $(\mathrm{W/m}^2)$
A = area of heat flow, ft^2 (m^2)
T_i = inside operating temperature, °F (°C or K)
T_2 = outside ambient temperature, °F (°C or K)
X = insulation thickness, in (m)
k = thermal conductivity, Btu · in $(\mathrm{h}\cdot\mathrm{ft}^2\cdot{}^\circ\mathrm{F})$ $[\mathrm{W}/(\mathrm{m}\cdot\mathrm{K})]$
$1/f$ = surface resistance factor

Heat transferred through cylindrical, or pipe insulation, geometry is most commonly represented by Eq. (B7.2) and Fig. B7.1.

$$Q = \frac{2\pi KL(T_i - T_s)}{R_o \ln(R_o/R_i)} \tag{B7.2}$$

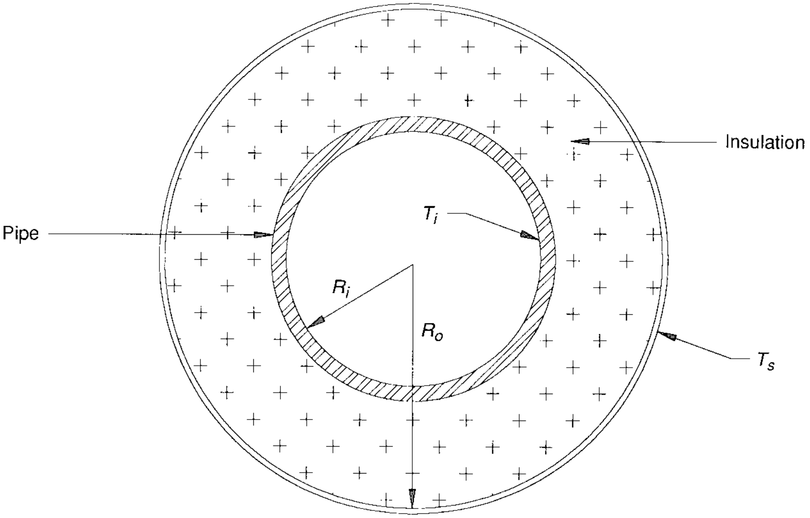

FIGURE B7.1 Cross-section of an insulated pipe.

where Q = total heat loss Btu/(h · ft^2)
k = thermal conductivity, Btu · in/(h · ft^2 °F) [W/(m · K)]
L = lineal ft (m)
T_i = inside operating temperature, °F (°C)
T_s = outside ambient temperature, °F (°C)
R_i = bare pipe radius, in (m)
R_o = radius to insulated surface, in (m)
ln = natural logarithm

Heat transferred through cylindrical, or pipe insulation, geometry with multiple layers of insulation is most commonly represented by Eq. (B7.3) and Fig. B7.2.

$$Q = \frac{T_i - T_s}{\left[R_s \ln(R_1/R_i)\right]/K_1 + \left[R_s \ln(R_2/R_1)\right]/K_2 + \left[R_s \ln(R_s/R_2)\right]/K_3 + 1/f} \tag{B7.3}$$

where Q = total heat loss, Btu/(h · ft^2) (W/m^2)
k = thermal conductivity, Btu · in/(h · ft^2 · °F) [W/(m · K)]
T_i = inside operating temperature, °F (°C)
T_s = outside ambient temperature, °F (°C)
R_i = bare pipe radius, in (m)
R_1 = radius of outer surface of first layer in (m)
R_2 = radius of outer surface of second layer, in (m)
R_s = outside radius of outermost layer, in (m)
ln = natural logarithm
$1/f$ = surface resistance factor

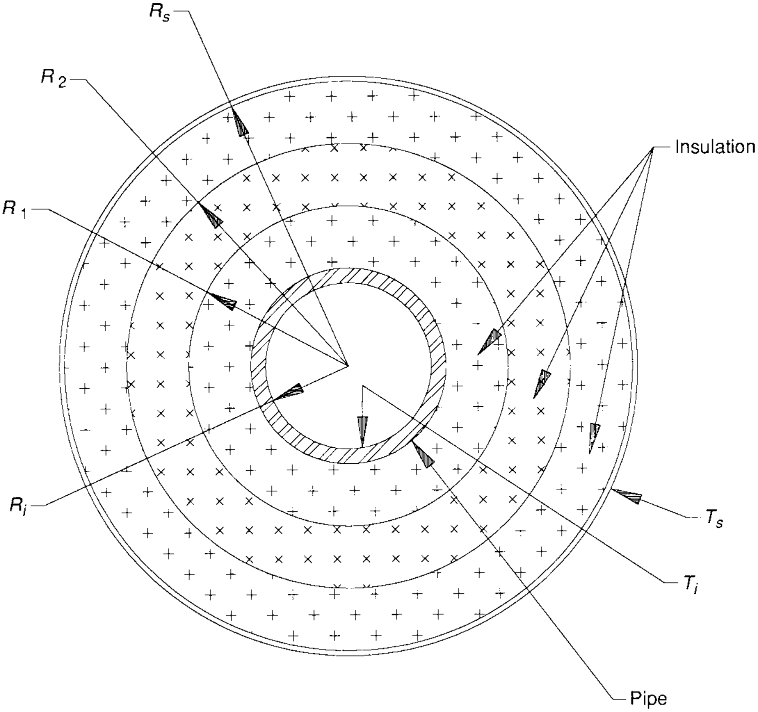

FIGURE B7.2 Cross-section of an insulated pipe with multiple layers.

Surface resistance is represented by the inverse of the air film (1/*f*) factor, as seen in Eqs. (B7.1) and (B7.3). When heat flows through a solid material and then out into another atmosphere (usually air), a resistance to heat flow created by the phase change at the interface between the two atmospheres is encountered at the surface separating the solid from the other atmosphere. Less heat will flow from the surface, therefore, than if no resistance were offered at this point.

In the case of good conductors of heat, surface resistance is the greater part of the total resistance of heat flow. In connection with efficient insulating materials, however, surface resistance is small compared with the resistance of the materials themselves.

Numerically, surface resistance is the reciprocal of the rate of heat transmission from surface to air. That is, if the rate of heat transmission from surface to air is 2.0 Btu/(ft$^2 \cdot$°F$\cdot$h) (W/m^2), the surface resistance is 0.5 (h$\cdot$ft^2)/Btu (m^2/W). A higher rate of heat transmission from the surface indicates a lower surface resistance, and vice versa.

Air velocity has a significant impact on surface resistance. Figure B7.3 shows values of surface resistance sufficiently accurate for use in insulation calculations, where the surface resistance is usually less than 25 percent and frequently less than 10 percent of the total resistance.

Thermal conductivity is a specific property of a homogeneous material. Its value is, like that of density, not dependent on the area, thickness, or shape of the material.

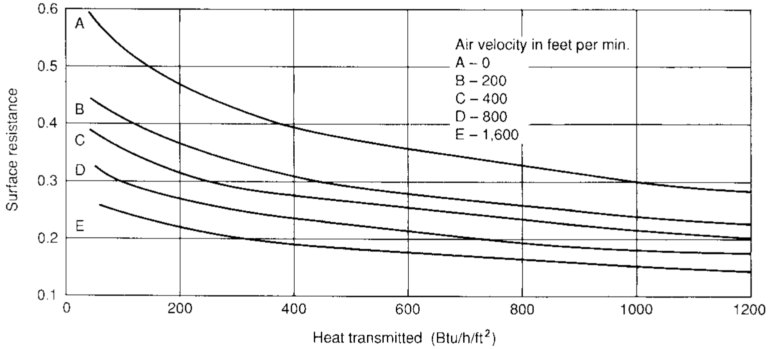

FIGURE B7.3 Surface resistance $1/f$ at various velocities.

It is a rate and is therefore unaffected by geometry. Heat transmission, however, is dependent upon the geometry of the body to be insulated and is predominantly governed by the length of the path (thickness).

Thermal conductivity is dependent upon temperature, but this is also true of other specific properties of a material, e.g., density. Standard test methods for determining thermal transmission properties of insulation materials are covered in

- ASTM Standard Test Method C177, *Steady-State Thermal Transmission (Properties by Means of the Guarded Hot Plate)*
- ASTM Standard Test Method C518, *Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter*

In Table B7.1, conservative thermal conductivity values are shown for several commonly used industrial and commercial insulation materials. The thermal conduc-

TABLE B7.1 Properties and Limitations of Insulation Materials

Insulation material	Compressive strength (psi)	Maximum temperature (°F)	Minimum temperature (°F)	Permeability (perm · in)	Conductivity [Btu · in/(h · ft² · °F)] at 50°F, 200°F	Spread/smoke density index
Calcium silicate	100	1000	250	NA	NA, 0.43	0/0
Cellular glass*	87	900	−450	0.005	0.28, 0.37	5/0
Elastomeric foam	NA	200	−40	0.03	0.29, NA	25/50
Fiberglass	2.5 at 10%†	850	42	75	0.29, 0.39	25/50
Mineral wool	10 at 10%†	1200	42	150		
Expanded perlite	70	1000	250	18	NA, 0.52	25/50
Phenolic foam	22 at 10%†	300	75	6–7	0.15, 0.25	25/50
Polystyrene foam	25	165	−65	1–5	0.23, NA	NA
Polyurethane and polyisocyanurate	30	250	−200	2–4	0.17, NA	25/50

* For flat surfaces capped per ASTM C240 (hot asphalt, 15# felt).

† While compressive strength technically measures the stress at which a material fails under load, deformation monitors a material's structural distortion *with or without* actual failure. So, with compressible insulations, failure is recorded as the point at which an insulation's deformation reaches a percentage of its thickness—usually between 5 and 25 percent—for various densities.

tivity values are shown as a function of the mean temperature between the inner and outer surfaces of the insulation. This method of expressing thermal conductivities permits their use in the calculation of heat transfer through materials whether used singly or in combination with other materials.

DESIGN PARAMETERS

By providing a medium for retarding heat transfer, thermal insulation serves many useful functions in industrial and commercial piping applications. In specifying an insulation system, it is important to consider the parameters of your process and application needs. These are the whys of insulation system design. Why, or for what purpose, is the pipe going to be insulated? The following are some common design criteria used in insulation system design for piping applications:

- Controlling heat loss on hot piping
- Providing personnel protection
- Providing personnel comfort in commercial buildings
- Reducing heat gain on cold piping
- Limiting or retarding surface condensation
- Providing process control
- Economic optimization or energy conservation
- Providing fire protection
- Providing freeze protection
- Providing noise control

In many applications these criteria will overlap, and designing for one condition will benefit by the attainment of another. One example of such overlapping criteria occurs with the control of heat loss. In designing for a maximum heat loss of a given value, an added benefit may be that the surface temperature is sufficient to provide personnel protection. Another example of overlapping criteria is condensation control. In humid environments, when insulation is sized according to condensation control parameters, the added benefit will often be an economically optimum design for the reduction of heat gain on the cold pipe.

Environmental, physical, and mechanical conditions play an important role in insulation system design. Indoor applications, for example, generally do not require the complexity of design that outdoor applications require.

Similarly, below ambient designs are often more complicated than above ambient designs. The physical abuse and mechanical conditions that an insulation system is subject to are also important to consider in the design process.

The following paragraphs offer a brief explanation of the purpose of considering each of the above items.

Controlling Heat Loss on Hot Piping

The objective behind controlling heat loss on hot piping can be very narrow or, very broad in scope with multifaceted purposes. As mentioned in the introduction to this chapter, insulation in any application serves one primary function: to reduce the heat flow from one surface to another.

Some of the areas that are listed above fall into the category of controlling heat loss on hot piping, i.e.,

- Providing personnel protection
- Providing personnel comfort in commercial buildings
- Providing process control
- Economic optimization or energy conservation
- Providing freeze protection

One of the most important things to understand about this particular subheading, ‘‘Controlling Heat Loss on Hot Piping,’’ is the word *control.* Insulation, by itself, does not have the ability to *maintain* or *hold* temperature within a system. Insulation can only provide a means for control. Insulation can *limit, retard, reduce, minimize,* or *slow down* the rate at which heat flows through or out of the system, but it cannot stop the process. Insulation is merely a resistor to heat flow; it is not a barrier to heat flow.

Insulation *systems,* however, can be designed to maintain a body or a mass at a given temperature. These systems require the use of additional energy input from any of a number of possible sources. Some of the more obvious sources of additional energy input are heat-tracing, pressure, and flow rate. Heat tracing, pressurized systems, and flow dependent systems will be discussed later in this chapter.

Personnel Protection. When providing for personnel protection, only enough insulation is applied to protect individuals from being burned by the heat of the pipe surface. Traditionally the upper temperature limit of the surface of the insulation, used as a guide-line for personnel protection, was 140°F (60°C). In recent years, however, a more conservative design temperature for personnel protection is 125°F (52°C).

The ASTM Standard Guide C1055, *Standard Guide for Heated System Surface Conditions That Produce Contact Burn Injuries,*[2] indicates that the normal metabolism threshold pain level occurs at approximately 111°F (44°C). At this point and up to 140°F (60°C), potential injury is still considered to be reversible. The maximum level of pain occurs at approximately 140°F (60°C), at which point injury from skin contact may have irreversible effects.

To date, there are no mandates or statutes that govern any upper temperature limit for personnel protection. However, many industries have accepted or adopted 125°F (52°C) as a common practice.

In some design applications where there is clearly no justification for insulation and insulation could actually be a detriment to the process, the fabricated guards are employed to provide personnel protection.

In other cases, where guards are impractical and insulation is more appropriate, the insulation is applied only to the piping that is within 7 ft (2.1 m) of the ground or platform in high risk areas. In a situation such as this where the insulation does not continue beyond the protected area, it is very important that the insulation system be properly flashed and sealed to prevent water ingress, as shown in Fig. B7.4.

In designing an insulation system for personnel protection, the outer surface conditions become very important. In general, on hot piping, less insulation is required with a painted metal or mastic finish than if a shiny metal finish is used.

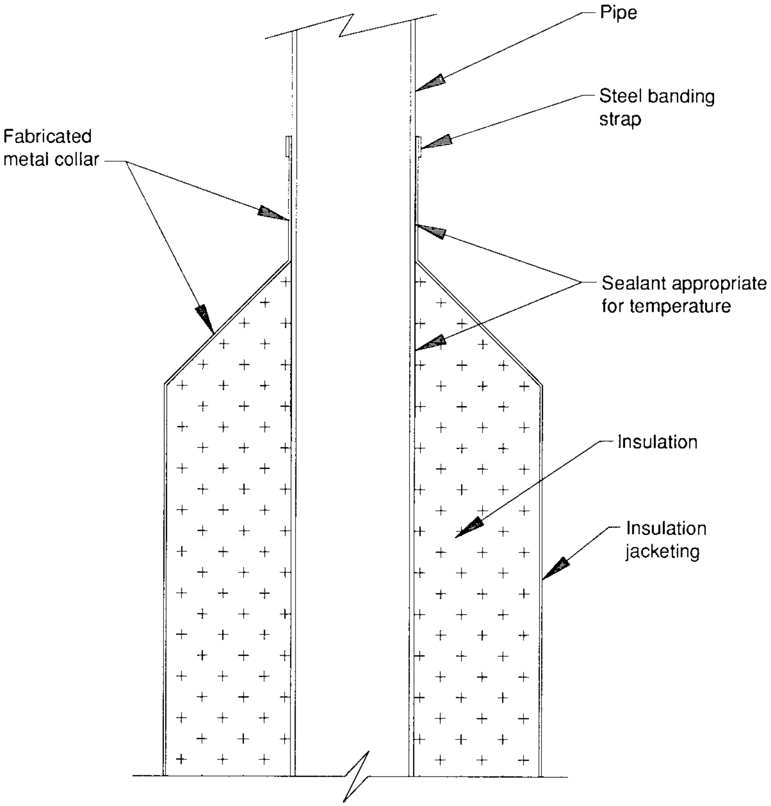

FIGURE B7.4 Flashing and sealing.

This is a direct function of the emissivity of the surface material. The emissivity of the surface material is a function of the material's reflectivity and absorptivity. The emittance of a surface material is determined on a scale where a reflective material, not emitting any infrared energy, is rated 0 and a nonreflective material, emitting all its infrared energy, is rated 1. Both limits are impractical to attain. Figure B7.5 simplifies the expression of emittance performance as it relates to personnel protection.[3]

In situations where solar loads are high, highly reflective metal jacketing materials reflect much of the radiant heat, thus causing surfaces which are too hot to touch. Dull, textured finishes such as fabric reinforced mastic will tend to absorb more of the radiant heat and thus have a higher emittance value, creating a surface condition which is cooler to the touch.

Wind conditions also make up an important design criterion in designing for personnel protection. In open areas in coastal regions, for example, there is usually a prevailing wind that can be considered in the insulation system design. In this situation, less insulation would be required than if the piping system were in an enclosed space sheltered from the wind.

This provides an additional source of heat loss—convection—which occurs at

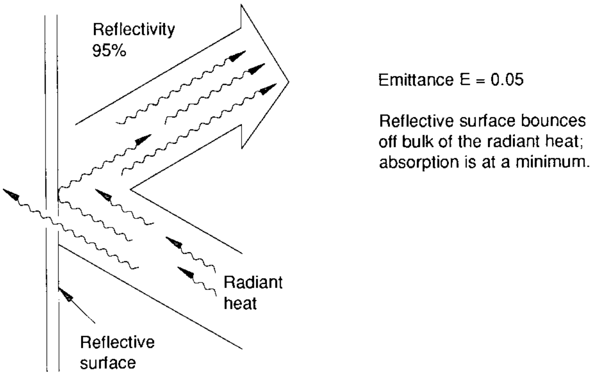

FIGURE B7.5 Emissivity illustration.

the surface in this case. This heat loss cools the surface of the insulation; however, it also decreases the effectiveness of the overall insulation system.

When designing for personnel protection on hot piping, these factors must be considered:

1. What are the worst case ambient temperature and wind conditions the system will be subjected to? Consider the ambient conditions which will create the hottest surface temperature for each application, such as summer weather with no wind and a metal jacketing material. Note that when designing for worst case weather conditions, in *most* applications it is best to use the average worst case conditions (i.e., average summer weather, average summer wind). If the absolute worst case condition is used as the design criterion, the system will usually have an uneconomical and even impractical insulation thickness.

2. What is the risk factor with respect to location of the piping to human contact? Consider the potential of human contact. If there is no opportunity for human contact, then insulation for personnel protection may not be necessary. Limited human presence may only require a sign or a fabricated guard. Frequent human presence will require insulation for personnel protection. And frequent human contact will require a thorough investigation into the most efficient insulation system for personnel protection.

Providing Personnel Comfort in Commercial Buildings. In addition to personnel protection and in a similar capacity, insulation has traditionally been used to provide personnel comfort in enclosed spaces. Heat loss from hot piping in commercial and institutional buildings is primarily an economic consideration. Of course, heat loss into the environment in enclosed spaces can significantly impact the comfort of the personnel occupying the space; however, this heat is usually offset by the climate control systems.

For example, in hot summer conditions when air conditioning is required, heat loss into enclosed spaces will significantly impact the loads on air compressors and associated climate control equipment. The personnel occupying the space may never actually feel the heat loss from the piping, but it will be evidenced in higher equipment maintenance costs and utility bills.

When designing for personnel comfort in commercial buildings, these factors must be considered:

1. What are the worst case ambient weather conditions that the building will be subjected to? Generally when designing mechanical HVAC systems for commercial buildings, the worst case ambient temperature is taken as an average for the seasons. The worst case in Saskatoon, Saskatchewan, will be an average of the temperatures from December through March. The worst case in Miami, Florida, will be an average of the temperatures from June through September.
2. What will be the effect on the HVAC systems that will have to offset the heat loss? The additional energy requirement placed on evaporators, compressors, and water chillers can be substantial. Properly designing and insulating the hot water and chilled water lines in commercial buildings will help minimize this problem.

Process Control. Process control is a very critical design parameter in many industrial environments. Providing a stable temperature flow throughout a process system is in many cases more important than any other design criterion. For example, in the transport of liquid sulfur through a piping system, it is imperative that the temperature of the sulfur never drop below its freezing point. In this scenario, the time and energy required to get the frozen sulfur into a molten and flowing state again are more expensive than the cost to replace the transport piping altogether. In another example, providing a uniform temperature heat transfer medium (i.e., steam, synthetic heat transfer fluids, etc.) to a chemical reaction vessel is essential to a proper chemical reaction. Not enough heat or too much heat can completely change or even nullify the chemical reaction. In both these examples, the cost of improper consideration of process control requirements is significant.

In a paper entitled ''Thermal Insulation Design Concepts,''[4] Charles W. Sisler, of Monsanto, Inc., states the following relating to process control:

> Thermal insulation has a primary function of keeping the process of its equipment and piping hot enough or cold enough to meet operating requirements. This function takes precedence over all others when the following conditions must be controlled:
>
> 1. Process in elevated temperature service:
>   - ***a.*** Excessive reflux condensation in distillation equipment.
>   - ***b.*** Crystallization of solids on equipment or piping walls.
>   - ***c.*** Yield loss or product deterioration from excessive heat input or pressure build-up to compensate for heat loss.

Process control is important in any piping system; however, it is not always the controlling design parameter. For example, a loss of process control in a hot water heating system in a commercial building will probably not cause the building to shut down until the process is stabilized. It may require that the climate control system operate longer and that the energy input be greater than it would normally be; however, it could conceivably operate under these conditions indefinitely.

As a controlling design parameter, the loss of process control would cause system shutdown, significant product loss, process or product failure, or a significant health and safety hazard.

When designing for process control with respect to heat loss on hot piping, these factors must be considered:

1. What is the worst case ambient temperature that the system will be subjected

to? For process control purposes, the worst case ambient temperature is the one which will most adversely affect the process. On hot piping applications, this will be the average winter weather conditions for the geographic location of the facility.

2. What are the temperature limitations of the process being controlled? Evaluate the insulation system based on the amount of temperature change that the process can tolerate. This will play an important role in how much insulation is required to control the process.

3. What are the consequences in terms of cost and safety of lost process control? If the system is allowed to extend outside the temperature limitations of the process, what will happen? A good example is steam. When allowed to cool, steam will begin to condense inside the pipe. If this is allowed to get out of control, it can cause serious process problems. Liquids do not convey as well as gases, the presence of liquids can cause corrosion problems, and it requires more energy to keep the liquid hot than it does to keep the gas hot.

Economic Optimization or Energy Conservation. One of the most common reasons people think of for placing insulation on hot piping is *economic optimization.* Actually, however, it is much less common today than in the mid-1970s to see insulation used for this purpose.

Prior to the ''energy crisis'' of the early 1970s, thermal insulation used on hot piping applications served two primary purposes: personnel protection and process control. These two design parameters are discussed above.

When the cost of energy began to increase in the early 1970s, large energy and oil consumers began to look for a means to control costs. One of the most cost effective ways to control energy costs is to provide an efficient insulation system. An efficient insulation system is a theoretically static system surrounding a body such that the energy requirement to control the heat loss from that body is reduced by a given or predetermined design value.

To better understand this concept, it is useful to first examine heat losses from

TABLE B7.2 Heat Losses from Bare Surfaces

Hot surface temp (°F)	Temperature diff (°F)	Loss [Btu/(ft^2 · h)]	Hot surface temp (°C)	Temperature diff (°C)	Loss (W/m^2)
100	30	50	38	17	157
200	130	295	93	72	930
300	230	654	149	128	2,061
400	330	1,145	204	183	3,609
500	430	1,806	260	239	5,693
600	530	2,666	316	295	8,404
700	630	3,765	371	350	11,869
800	730	5,126	427	406	16,160
900	830	6,799	482	461	21,434
1,000	930	8,885	538	517	28.010
1,100	1,030	11,400	593	572	35,939
1,200	1,130	14,394	649	628	45,378
1,300	1,230	17,896	704	683	56,418
1,400	1,330	21,758	760	739	68,594
1,500	1,430	25,983	816	795	81,913

Still-air conditions, air temperature 70°F (21.1°C), surface emittance = 0.95.

bare surfaces. The rates of heat loss from bare surfaces at temperature differences up to 1000°F (538°C) are shown in Table B7.2. These are average values for still-air conditions, and although there is some variation for different pipe sizes and for different absolute temperatures of surroundings, these variations are small as compared with those caused by comparatively low air velocities. Therefore, these average values are sufficiently accurate for engineering purposes.

Heat losses expressed only in British thermal units (Btu) are not usually so significant as when expressed in actual costs in dollars. In Fig. B7.6, the equivalent losses in dollars per square foot per year (8760 h) have been shown for various temperatures per 1,000,000 Btu (292,000 W · h). [And 1,000,000 Btu (292,000 W · h) is approximately equivalent to 1000 lb of steam at 350°F and 150 psig.]

The value of energy per 1,000,000 Btu either is known or may be computed readily for a given fuel of known cost and a given efficiency. Thus, this procedure renders Fig. B7.6 applicable to a wide range of fuels and conditions.

To approximate the most economically optimal insulation thickness, first the operating conditions and the environmental conditions must be defined. The op-

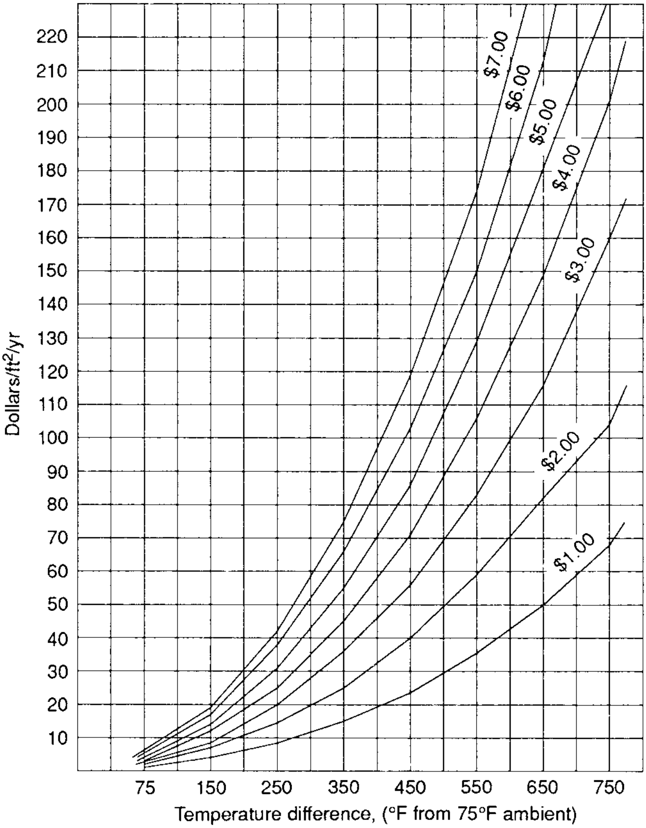

FIGURE B7.6 Equivalent loss in dollars per square foot at various fuel costs per 1,000,000 Btu.

erating conditions are the factors that make up the actual process (i.e., pipe size, contents, flow rate, operating temperature). The environmental conditions make up the atmosphere within which the insulated pipe will be operating (i.e., ambient temperatures, wind conditions, annual rainfall, humidity).

Example B7.1. Take as an example a 1-ft^2 surface area operating 7200 h/yr at 300°F (149°C) above the temperature of the surrounding air. Then the loss per year, at an energy value of \$3.50 per 1,000,000 Btu, is \$25.07 × 7200/8760= \$20.60. Suitable insulation savings upward of 90 percent of this loss may be applied at a cost considerably less than 1 year's savings, when compared to the cost of the energy consumption required with no insulation at all. This illustrates the desirability of insulating such surfaces as boiler drum heads, manways, flanges, and fittings which are frequently left uninsulated, even though adjacent piping is provided with effective insulation.

The magnitude of losses from bare heated surfaces as compared with the relatively small losses from such surfaces when properly insulated is illustrated in Fig. B7.7. In this illustration, heat losses per degree of temperature difference from bare surfaces are shown by the upper curve, and heat losses from insulated surfaces are shown by the lower curve. The area between the two curves represents the savings due to insulation.

When designing for economic optimization with respect to heat loss on hot piping, these factors must be considered:

1. What are the average ambient temperature conditions that the system will be subjected to? In the case of economic optimization, processes are usually evaluated on an annual basis, or on a life cycle basis if operated only during portions of the year. Taking an average ambient condition over the course of time during which the process will be in operation will enable the designer to determine the economically efficient insulation thickness.

2. What are the operating temperatures of the process? Each range of temperatures that will be involved in the process should be evaluated on its own criteria. If the process swings through a range of temperatures (cyclical systems), the thickness should be based on the worst case condition on a time weighted basis.

3. What is the life expectancy of the system being designed? Life expectancy is a very important variable in the evaluation of economic insulation thickness. A longer life expectancy will justify a more sophisticated insulation system than a quick turnaround project.

4. Will insulation thicknesses specified for economic optimization be a detriment or an asset to efficient process control? In some cases, the insulation thickness required for economic optimization may not be ideally suited to process control. For example, in some very humid regions, the economic insulation thickness for a chilled water line may not be sufficient to provide adequate condensation control. Another example is hot piping in a quick turnaround project. The economic insulation thickness required to insulate a heat transfer pipe at 650°F (343°C) for a 2-yr life expectancy will be less than what is required to keep the heat transfer fluid at a uniform and stable condition. In both examples, the process control condition would prevail over the economic thickness.

Providing Freeze Protection. The final subject, as defined above, with respect to controlling heat loss is insulation system design for the prevention of freezing. Freeze

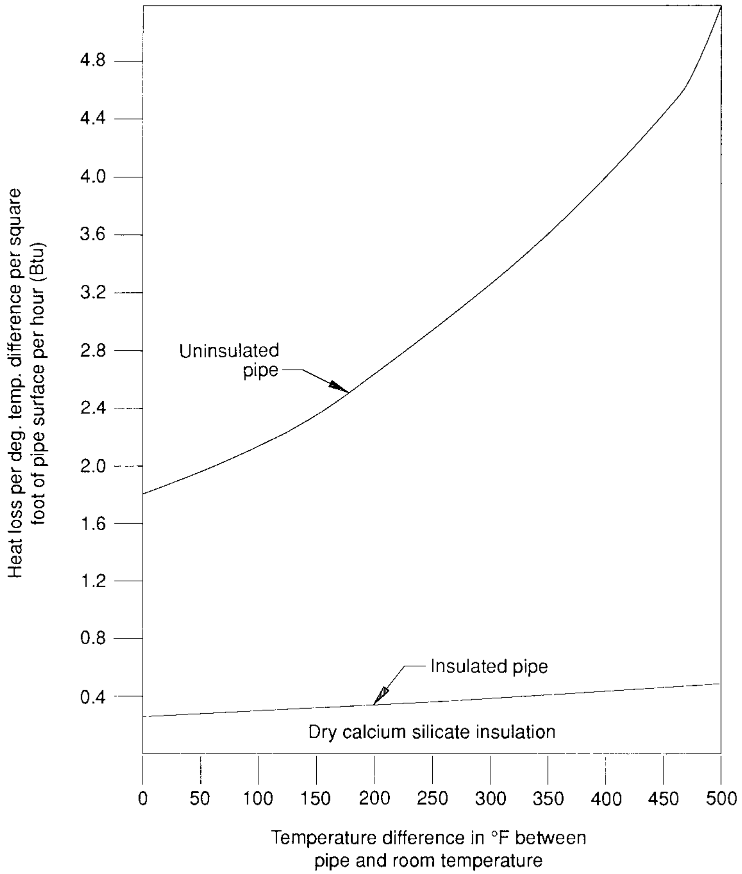

FIGURE B7.7 Heat-loss comparison.

protection can be provided by any of the following, but is usually a combination of three means:

1. Insulation thickness
2. Flow rate
3. Additional heat input

As mentioned earlier in this chapter, insulation alone cannot maintain a temperature. Regardless of the insulation thickness, if a fluid body is stagnant, there is no additional heat input, and the ambient temperature outside the pipe is below the freezing point of the fluid, then the fluid will eventually freeze. The thickness of the insulation can slow down the freezing process, but cannot stop it.

Fluid in motion takes much longer to freeze than stagnant fluid. Therefore, in the design of any freeze protection system, the flow rate must be factored in. If there is no flow during significant time intervals, consideration must be given to additional heat input.

Additional heat input is provided by means of various types of heat tracing. Typically there is steam, electric resistance tapes, and heat transfer fluids. Of these three, the most common application for piping purposes is electric resistance tapes. Additional heat input requirements are usually provided as a complimentary service of heat tracing manufacturers and by some, but not all, insulation manufacturers. Refer to Chap. B6 for heat tracing of piping.

When designing to provide for freeze protection, some of the factors that must be considered are as follows:

1. What is the worst case ambient temperature condition that the system will be subjected to? For freeze protection, the coldest temperature for the longest amount of time must be considered. For example, an underground water pipe that has to traverse a river on the underside of a bridge would have two ambient conditions: the ground temperature at the pipe depth and the winter weather conditions in the geographic location of the bridge.

If the bridge is in Houston, Texas, the worst case condition might be 30°F (−1°C) for 1 day with a 15 mph (24 kmph) wind. If the bridge is in Bemidji, Minnesota, the worst case condition might be −10°F (−23°C) with a 10 mph (16 kmph) wind for 20 days.

2. What is the lowest allowable operating temperature of the process? All liquids have different freezing temperatures. For example, water freezes at 32°F (0°C), but molten sulfur freezes at 120°F (49°C). Both would require freeze protection in Bemidji, but the water line may not require it in Houston.

3. What is the normal operating temperatue of the fluid? It is possible in many processes that the normal operating temperature of the fluid is higher than the freezing temperature. In a freeze protection evaluation, the time to reach a freezing temperature must be considered in addition to the time to freeze. In the case of the water line in Houston, the normal operating temperature of the water may be 55°F (13°C), and due to a possible drop in temperature, depending on the size of the pipe, it may not even reach 32°F (0°C) much less freeze before the temperature gets back up above 32°F (0°C).

4. What are the physical properties (i.e., density, specific heat) of the fluid? It is useful to know the physical properties of the fluid being protected if a detailed analysis is to be performed. For example, a high density fluid will take longer to reach its freezing point than a low density fluid.

5. What is the flow rate of the fluid? Fluid in motion (with enough pressure behind it) will not freeze. Therefore, in many applications if the liquid can be kept flowing, the use of insulation for the sole purpose of freeze protection can be eliminated. In most instances, however, it is when the flow is interrupted that the freeze protection is required.

6. What is the maximum downtime that the fluid might remain in a stagnant state? If the maximum downtime that the fluid is stagnant is less than the time required to freeze under the given design conditions, then insulation requirements can be reduced or eliminated.

Reducing Heat Gain on Cold Piping

In cold piping applications, the main objective of providing insulation is the reduction of heat gain. This process is most often evidenced in terms of providing process control and limiting or retarding surface condensation. The most important controlling factor in the effort to minimize heat gain on cold piping is the prevention of moisture migration into the insulation system, or water intake. This type of moisture migration will have a dramatic effect on system performance.

Process Control. As mentioned earlier in this chapter, in the explanation of process control as it relates to hot piping, process control is often the most important guiding criterion relating to insulation system design. In cold piping applications, this statement is even more paramount than in hot piping applications.

In most cold processes (with the exception of chilled water piping in climate control systems), the maximum allowable heat transfer for process control purposes is 30 to 40 Btu/(h · ft^2) (95 to 126 W/m^2). The consequences of exceeding this limit are so costly that a safety factor of 4 is frequently employed, resulting in a design limitation of 8 to 10 Btu/(h · ft^2) (25 to 31.5 W/m^2). By comparison, chilled water piping systems are usually designed around 40 to 50 Btu/(h · ft^2) (126 to 158 W/m^2), and hot water and steam systems are often designed around 100 Btu/(hr · ft^2) (316 W/m^2) or more.

In another example, liquefied gases must be kept below their boiling points. This is usually accomplished with a combination of pressure and insulation. If the temperature of the liquid gas is allowed to exceed the process control design parameters, the consequence is either a costly loss of gas through vaporization or a potentially hazardous buildup of pressure.

Cold piping systems are subject to degradation from the environment, more so than hot piping systems. This stems primarily from the direction of the vapor driving force in these applications. On hot systems, the water vapor driving force is away from the pipe, and although the ingress of water into the insulation can adversely affect the insulation performance, it is generally considered to be temporary. Conversely, on cold systems, the water vapor driving force is inward toward the pipe. The ingress of water, therefore, into the insulation system will gradually increase with time; it will slowly deteriorate and eventually destroy the system.

For these reasons, it is extremely important that the total insulation system design be very thoroughly thought out, to counteract the potential effects of the environment. The use of vapor barrier mastics and low permeability joint sealants is essential to adequate system performance. From a process control standpoint, these materials are just as important as the insulation itself to the performance of the process.

Limiting or Retarding Surface Condensation. Insulation systems can be designed to limit or retard surface condensation, but in most cases they cannot be designed to *prevent* condensation. In some very dry climates, insulation systems can be designed to prevent condensation most of the time; however, even in the driest desert, dew settles on the ground in the early morning hours. When dew settles on the surface of an insulation system, it is considered condensation.

In humid regions, it is not feasible to consider designing an insulation system to prevent condensation. In these areas the insulation thicknesses required of even the most efficient insulations available would be unrealistic from both a financial and a practical perspective.

Surface condensation can sometimes be a problem, primarily from a maintenance control perspective, but in the long term from an insulation efficiency standpoint as well. This is particularly a problem where absorptive insulation materials are present. Surface condensation can cause mold and mildew formation, which presents health and safety hazards. When metal jacketing is present, surface condensation can cause pitting and corrosion of the membrane. And when condensation is allowed to remain present for extended periods of time, it can cause membrane degradation, leading to moisture ingress into the insulation.

As with personnel protection, the outer membrane selected for limiting condensation plays an important part in providing good condensation control. The surface temperature of the insulation system is the controlling factor in how often condensation will form and how long it will be present.

When designing to limit or retard surface condensation, some of these factors should be considered:

1. What are the average summer ambient temperature and wind conditions (not worst case) that the system will be subjected to? For retarding surface condensation it is very important that the average summer conditions are used, not the worst case. This is because the worst case ambient weather conditions in the summer months, particularly in the coastal regions, are such that it is unrealistic to try to achieve condensation control. The insulation thicknesses required of even the most efficient insulations systems available are economically infeasible and impractical for worst case summer conditions.

2. What is the operating temperature of the process? The operating temperature of the process will have a significant effect on whether condensation control needs to be considered. For example, on a cryogenic pipeline the insulation required to provide process control will usually exceed the insulation thickness required to provide condensation control.

3. How important is condensation control in the overall performance of the process? In many outdoor conditions, condensation control is not a particularly important design criterion. Condensation does not present as much of a process problem as it does an aesthetic problem. In indoor or rooftop applications, condensation can be a problem as it represents building or structural degradation potential.

Providing Fire Protection

As a general rule, insulation materials are better suited for use as thermal insulation than as fire protection. However, the National Fire Protection Association (NFPA) and the American Petroleum Institute (API) acknowledge conditions under which some insulation materials may provide ''credit'' in the design and sizing of pressure relief valves. Accordingly, there are several test methods, some private and others public, which are used to determine the suitability of insulation materials for fire protection applications.

The Flammable and Combustible Liquids Code, NFPA 30,[5] states in section 2-2.5.7(a) that

> Insulation systems for which credit is taken shall meet the following performance criteria:
>
> **1.** Remain in place under fire exposure conditions.
> **2.** Withstand dislodgment when subjected to hose stream impingement during fire exposure. This requirement may be waived where use of solid hose streams is not contemplated or would not be practical.
> **3.** Maintain a maximum conductance value of 4.0 Btu/(h · ft^2 · °F) (W/m^2) when the outer insulation jacket or cover is at a temperature of 1660°F (904.4°C) and when the mean temperature of the insulation is 1000°F (537.8°C).

API Recommended Practice 521 requires the same basic performance criteria; however, it includes the following time limitation:

> Section 3.12.2.1 . . . This period of exposure may range from 20 minutes to one hour, depending on the adequacy of fire-fighting provisions, the accessibility of equipment, and the degree of skill and training of the fire-fighting group. . . .

In item 1 above, the requirement is that the insulation remain in place under the fire exposure conditions. This is usually accomplished by using a stainless steel jacketing material, of sufficient thickness (generally 0.015 in or greater) to withstand the flame intensity, with stainless steel banding and matching stainless steel clips.

Item 2 above is the hose stream dislodgment criterion. This criterion is not well defined in any text on this subject; however, API Recommended Practice 521,[6] section 3.12.2.2, states the following:

> The finished installation should ensure that the insulation will not be dislodged when subjected to the fire-water streams used for fire fighting, such as streams from hand lines or monitor nozzles, if installed.

Most insulations used in fire protection applications can withstand this criterion if jacketed and banded in place as described in the explanation of item 1 above.

Item 3 above requires a maximum conductance of 4.0 Btu/(h · ft^2 · °F) (W/m^2). Any insulation material suitable for use as fire protective insulation can meet this criterion.

Prior to specifying any insulation or accessory product material in a fire protection application, it is important to consult with the technical service department of the manufacturer and be advised of any special precautions that may be necessary.

Noise Control

Environmental acoustics is something that can be addressed in thermal insulation system design; however, serious noise problems should be treated as a separate and independent study. For the purpose of preliminary investigation, it is useful to know some basic concepts.

Sound absorption is both a process and a property of materials. Sound absorption is the process of dissipating sound energy as well as the property possessed by materials, objects, and structures, such as rooms, of absorbing sound energy. Sound attenuation is the reduction of the intensity of sound as it travels from the source to a receiving location.[2]

In thermal insulation design, sound attenuation is a natural by-product of the insulation application. Some insulation materials and accessory products provide greater sound attenuation due to their sound absorption characteristics than others. One of the best thermal insulation materials for sound attenuation is mineral wool. It is available in loose fill, rolls, blankets, boards, and preformed shapes. Therefore it can be applied in numerous different applications where sound absorption is a desired property of the insulation being applied.

The jacketing material used to cover the insulation can play an important role in sound attenuation. For example, a fabric reinforced mastic finish over insulation has better sound absorption properties than does a metal jacket. The environment in which the materials are being used will limit their ability to be considered for sound attenuation characteristics in some cases; however, with composite system design in the planning stage of the process, a combination of materials can often be arranged to provide both thermal and acoustical benefits.

DESIGN CONDITIONS

In addition to defining the purpose of the insulation system, it is important to define the conditions under which the insulation system will be used. Some of the conditions to be considered are

- Indoors or outdoors
- Conditioned space or nonconditioned
- Geographic location (coastal regions, northern climes, southern climes, rainy, dry, etc.)
- Long, straight runs or frequent bends
- Personnel traffic area or unaccessible
- Aboveground or below ground

Numerous conditions or combinations of conditions require consideration in insulation system design. The above list represents just a few of the more obvious ones. Most of these are self-explanatory; however, some require some attention to detail. Following is a brief explanation of each item.

Indoors or Outdoors

Indoor applications, in general, are much simpler to specify than outdoor applications. The main reason for this difference is that indoor applications are not subjected to rain, snow, and solar loads. Indoor applications are subjected to vapor pressure differential problems, as are outdoor; however, this problem is not complicated by the other environmental difficulties, as the outdoor applications are. The reason that rain, snow, and solar loads are such a problem with insulation systems is moisture migration. The single most detrimental element in any insulation system is the migration of moisture into the insulation system. Water in insulation destroys the insulating value. Approximately 4 percent moisture by volume in an insulation material will increase the thermal conductivity by as much as 70 percent.[7]

Thermal insulations must be dry to function according to design. Water in the insulation causes part of or all the air spaces and gas spaces in the insulation to be filled with water. Its conductivity then approaches that of water instead of that of air or gas. The thermal conductivity of water at 70°F (21°C) is 4.1 $\text{Btu} \cdot \text{in}/(\text{h} \cdot \text{ft}^2 \cdot {}^\circ\text{F})$ (0.59 W/mK, compared to 0.17 $\text{Btu} \cdot \text{in}/(\text{h} \cdot \text{ft}^2 \cdot {}^\circ\text{F})$ (0.0245 W/mK) for air. The heat transmission, therefore, is about 24 times greater for water saturated insulation than for dry insulation.[1]

In addition to this significant drop in thermal performance of the insulation, water in insulation when in contact with metal piping can significantly increase the chance of, and even contribute to, severe corrosion problems. Water and snow, therefore, should be avoided; every precaution should be taken to prevent moisture entry into the system. This is another reason why solar loads present problems in outdoor insulation systems.

As mentioned in the section addressing personnel protection, solar loads on the surface of the insulation can significantly increase its surface temperature, therefore increasing the risk of injury to personnel.

In addition to increasing surface temperature, solar loads on the surface of the insulation cause expansion and contraction of metal jacketing and premature aging of mastic finishes. The expansion and contraction of metal can cause joints to open up or ''fish-mouth,'' creating paths for water to enter. They can also cause a gradual loosening up of the bands, leading to a movement of the jacket or loss in high-wind conditions. Premature aging of mastic finishes can lead to cracks or pits in the finish, which also creates a path for water migration into the insulation system.

When designing for indoor or outdoor applications, consideration must be given to the environmental conditions that the system will be subjected to.

Conditioned Space or Nonconditioned Space

This application differs slightly from that of indoor and outdoor in that either space would be considered indoor; however, nonconditioned space is not climate controlled. This has the advantage of not having to worry about liquid water or solar loads; however, the vapor pressure driving force is still present. This driving force can have a significant detrimental effect on chilled water and other low-temperature piping insulation systems. Water vapor tends to migrate in the direction of the coldest surface. Therefore, any below ambient piping application will have a positive water vapor pressure in the direction from the outside of the insulation to the surface of the pipe. Example B7.1 illustrates how this might occur on a chilled water pipe in the unconditioned space of a commercial building in a relatively temperate climate.

Example B7.1. *Chilled Water Pipe Insulation Water Intake.* In this illustration, a calculation is done to show how a typical chilled water pipe insulated with 2 in (51 mm) of polyurethane insulation might become saturated with water simply due to the water vapor driving force generated by the ambient conditions around the pipe and the operating conditions of the pipe.

Calculation for Amount of Condensation per Linear Foot of Piping per Year:

	Nominal	Actual
Outside diameter (OD) of pipe:	NPS 2 (DN 50)	2.375 in (60 mm)
Service temperature:	41°F (5°C)	
Ambient air temperature:	70°F (21.1°C)	
Ambient air relative humidity:	70%	
Insulation thickness:	2-in (51-mm) nominal polyurethane	
OD of polyurethane insulation:	6.63 in (168.4 mm)	
Outside finish:	All service vapor retarding (ASJ; formerly vapor barrier jacket): permeance = 0.6 perm	
Permeability of polyurethane:	4.321 perm · in (10.96 perm · cm)	

Water vapor flow:

$$G = \frac{\Delta P}{R_{\text{vapor}}} \tag{B7.4}$$

where

G = water vapor flow

ΔP = water vapor pressure difference, inches of mercury (inHg) (mmHg)

R_{vapor} = resistance to vapor diffusion for any given material, 1 inch/perm (1 cm/perm) or μ

$$= \frac{\text{thickness}}{\text{permeability}} = \frac{\text{in} \cdot \text{ft}^2 \cdot \text{h} \cdot \text{inHg}}{\text{gr} \cdot \text{in}} = \frac{\text{mm} \cdot \text{cm}^2 \cdot \text{h} \cdot \text{mmHg}}{\text{gr} \cdot \text{mm}}$$

$$= \frac{1}{\text{permeance}} = \frac{\text{ft}^2 \cdot \text{h} \cdot \text{inHg}}{\text{gr}} = \frac{\text{cm}^2 \cdot \text{h} \cdot \text{mmHg}}{\text{gr}}$$

Calculation for Pressure Drop across Insulation System:

P_r in ambient air = real partial pressure of water vapor in air

$$= R_H \times P_s \tag{B7.5}$$

P_s = partial pressure of water vapor in saturated air

R_H = relative humidity = 0.07

At 70°F (21° C)

$$P_s = 0.73964 \text{ inHg}^{\dagger} \quad (18.79 \text{ mmHg})$$

$$\begin{aligned} P_r &= 0.7 \text{ (relative humidity of 70\%)} \times 0.73964 \text{ inHg} \quad (18.79 \text{ mmHg}) \\ &= 0.517748 \text{ inHg} \quad (13.15 \text{ mmHg}) \end{aligned}$$

So with a real pressure at 70 percent relative humidity of 0.517748 inHg (13.15 mmHg), the dew point temperature t_s is found to be

$$t_s = 59.8°\text{F} \quad (15.3°\text{C})$$

At 41°F (5°C),

$$P_s = 0.25765 \text{ inHg} \quad (6.544 \text{ mmHg})$$

Therefore,

$$\begin{aligned} \Delta P = P_r - P_s &= 0.517748 \text{ inHg} - 0.25765 \text{ inHg} \\ &= 0.26010 \text{ inHg} \quad (6.61 \text{ mmHg}) \end{aligned} \tag{B7.6}$$

---

†See Ref. 8.

From here, the actual thickness of insulation on the insulated pipe must be converted to an equivalent thickness of insulation in flat-plane geometry, in order to be used further in the calculation.

Equivalent Thickness of Insulation:

$$\begin{aligned}\text{Equiv. thickness} &= \frac{\text{OD}}{2}\ln\frac{\text{OD insulation}}{\text{OD pipe}}\\ &= \frac{6.63\text{ in}}{2}\ln\frac{6.63\text{ in}}{2.375\text{ in}} = \frac{168.4\text{ mm}}{2}\ln\frac{168.4\text{ mm}}{60.33\text{ mm}} \qquad \text{(B7.7)}\\ &= 3.403\text{ in} = 86.4\text{ mm}\end{aligned}$$

Total Resistance against Water Vapor Diffusion. Determining the total resistance against water vapor diffusion is simply a matter of adding the total resistances from materials in the path of the vapor flow. This is calculated as follows for the vapor retarder:

$$R_{\text{vapor}} = \frac{1}{0.6\text{ perm}} = 1.667\,\frac{1}{\text{perm}} \qquad \text{(either units)}$$

and for thermal insulation:

$$R_{\text{vapor}} = \frac{3.403}{4.321} = 0.788\text{ in}/(\text{perm}\cdot\text{in}) = 0.788\text{ cm}/(\text{perm}\cdot\text{cm})$$

Therefore, the total resistance

$$\begin{aligned}R_{\text{vapor}} &= R_{\text{vapor}}\text{ (vapor retarder)} + R_{\text{vapor}}\text{ (thermal insulation)}\\ &= 1.667\,\frac{1}{\text{perm}} + 0.788\,\frac{1}{\text{perm}} \qquad \text{(B7.8)}\\ &= 2.455\,\frac{1}{\text{perm}}\end{aligned}$$

Now, given ΔP and R_{vapor}, we solve for G (water vapor flow) as follows, using Eqs. (B7.4), (B7.6), and (B7.8):

$$G = \frac{0.26010\text{ inHg}}{2.455\text{ perm}} = 0.1059\text{ inHg}\cdot\text{perm} = 2.7\text{ mmHg}\cdot\text{perm}$$

And

$$\begin{aligned}1\text{ perm} = 1\,\frac{\text{gr}}{\text{ft}^2\cdot\text{h}\cdot\text{inHg}} &= \frac{\text{ngr}}{\text{Pa}\cdot\text{s}\cdot\text{m}^2}\\ = 0.1059\,\frac{\text{gr}}{\text{ft}^2\cdot\text{h}} &= 2.7\,\frac{\text{ngr}}{\text{m}^2\cdot\text{s}}\end{aligned}$$

At this point the total vapor flow has been calculated and determined to be

$$0.1059\,\frac{\text{gr}}{\text{ft}^2\cdot\text{h}} = 2.7\,\frac{\text{ngr}}{\text{m}^2\cdot\text{s}}$$

The next step is to calculate the outside surface area in order to express the results in terms of square feet per lineal foot of insulation.

Calculation for the Outside Surface of Insulation Expressed in Square Feet per Lineal Foot:

$$6.63 \text{ in} \times \pi \times 12 \text{ in/ft} = 249.945 \text{ in}^2/\text{lin ft}$$

$$168.4 \text{ mm} \times \pi \times 1000 \text{ mm/m} = 592{,}044 \text{ mm}^2/\text{m}$$

or

$$\frac{249.945}{144} = 1.735 \text{ ft}^2/\text{lin ft} = \frac{592{,}044 \text{ mm}^2}{1{,}000{,}000} = 0.6 \text{ m}^2/\text{m}$$

And finally the calculation for the migration of water vapor that condenses in the system per year and per lineal foot of piping reveals the following:

$$\begin{aligned} \text{Total water migration} &= \text{water vapor flow } G \times \text{surface area per lineal foot} \times \\ &\quad \text{hours/day} \times \text{days/year} \\ &= 0.1059 \text{ gr/(ft}^2 \cdot \text{h)} \times 1.736 \text{ ft}^2/\text{ft} \times 24 \text{ h/d} \times 365 \text{ d/yr} \\ &\quad [2.7 \text{ ngr/(m}^2 \cdot \text{s)} \times 0.6 \text{ m}^2/\text{m} \times 86{,}400 \text{ s/d} \times 365 \text{ d/yr}] \\ &= 1610.46 \frac{\text{ngr}}{\text{yr} \cdot \text{lin ft}} \quad \left(5.1 \times 10^7 \frac{\text{ngr}}{\text{yr} \cdot \text{lin m}}\right) \end{aligned} \qquad \text{(B7.9)}$$

since

$$1 \text{ gr} = 1 \text{ lb}/7000 \qquad (64.8 \text{ mg})$$

and

$$1 \text{ lb} = 16 \text{ oz}$$

Therefore,

$$\frac{1610.46 \times 16}{7000} = 3.681 \frac{\text{gr} \cdot \text{lb} \cdot \text{oz}}{\text{yr} \cdot \text{lin ft} \cdot \text{gr} \cdot \text{lb}}$$

Or the total amount of water that can pass through the existing water vapor retarder and the thermal insulation system in this illustration equals:

$$3.681 \frac{\text{oz}}{\text{yr} \cdot \text{lin ft}} \qquad \left(104{,}354 \frac{\text{mg}}{\text{yr} \cdot \text{lin m}}\right)$$

As represented above in this example, a large amount of moisture can be accumulated in an insulation medium over a relatively short time if the insulation system is not designed to prevent the ingress of water vapor. Even with the best application procedures, incorrect materials selection for the environment or service requirements can have very dramatic results in terms of performance losses and maintenance costs.

Geographic Location

The geographic location of the system being insulated is very important to factor into the design process. The National Weather Service has information available for climates all over the world. Seasonal averages, worst case conditions, annual rainfall, average and worst case humidities, and any other climatic data needed should be fully evaluated during the specification process.

Long, Straight Runs or Frequent Bends

The layout of the piping with respect to bends and straight runs needs to be considered for the purpose of expansion and contraction control. Depending on the temperature range of the process piping being insulated, expansion and contraction joints in the insulation system may need to be employed.

The differential expansion between the metal substrate of the pipe and the insulation can have critical significance depending on the length of the pipe run. Table B7.3 lists different metals and their expansion and contraction in inches per 100 ft through various temperature ranges. It is clear that on long runs of piping, provision must be made for differential expansion between the insulation and the pipe. This is accomplished through the use of control joints or expansion joints. Many different types of control joints are used in insulation specifications. One system for controlling contraction on cold piping is illustrated in Fig. B7.8. It is advisable to consult the insulation manufacturer for more specific recommendations which are application-dependent.

TABLE B7.3 Thermal Expansion and Contraction Properties

Operating temperature (°F)	in/100 ft						
	Steel	Stainless steel	Copper	Cellular glass	Polyurethane insulation	Calcium silicate	Mineral wool
−200	−1.62	−2.51	−2.44	−1.0	−16.20	*	†
−100	−1.12	−1.76	−1.70	−0.75	−10.20	*	†
0	−0.50	−0.77	−0.73	−0.35	−4.20	*	†
200	0.99	1.46	1.51	0.68	7.80	*	NIA
400	2.70	3.80	3.89	1.82	*	NIA	NIA
600	4.60	6.24	6.40	3.07	*	Shrinks‡	Shrinks§
800	6.70	8.80	*	4.42	*	Shrinks	Shrinks
1000	8.89	11.48	*	†	*	Shrinks	Shrinks

* Material not recommended for use in this temperature range.

† Material requires special precautions for use in this temperature range. Consult manufacturer for recommendations.

‡ Calcium silicate experiences a maximum of 2 percent shrinkage at 1200°F and less than that at lower temperatures. Calcium silicate manufacturers recommend that their materials be double-layered for operating temperatures greater than 500°F due to shrinkage cracks that form.

§ ASTM C547, *Standard Specification for Mineral Fiber Preformed Pipe Insulation,* indicates linear shrinkage as below 2 percent in accordance with the recommended temperature limits. Vitrification and compaction of binder materials may occur at elevated temperatures.

NIA: no information available.

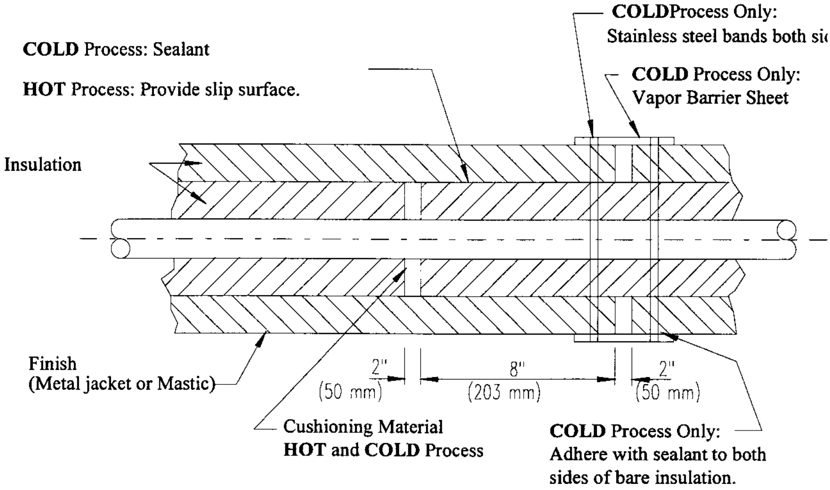

FIGURE B7.8 Cross-section of a contraction control joint.

Personnel Traffic Area

High traffic areas require insulation that can take abuse. Although it is standard practice to install "Do Not Walk on Pipe" signs anywhere this might occur, the real-world situation is that people walk on insulated pipes. It is important, therefore, to consider the use of high compressive strength insulations and/or heavy duty jacketing or membrane covering in these areas.

Aboveground or Below Ground

Aboveground insulation applications can be complicated and require thorough design evaluation and analysis for proper specification. Below ground applications are very complicated, and mistakes can be extremely costly. It is absolutely essential that every possible condition be considered and a thorough analysis of all variables be done.

The two most common means for accommodating underground piping applications that require thermal insulation are precast trenches and direct burial.

Precast Trenches. Precast trench systems provide a tunnel underground for the piping to be channeled through. In this type of application, the insulation system is generally designed exactly as it would be for an aboveground application. No special precautions are taken for expansion and contraction of the pipe because it is allowed to move freely within the trench, as any aboveground piping system would. The most important factor to keep in mind when designing an underground precast trench system is the groundwater.

Groundwater infiltration into the trench, depending on its magnitude can cause the piping system to become completely surrounded by water for extended periods. This can cause irreparable damage to protective membranes, it can cause the insulation to become saturated and literally fall off the pipe, and it can lead to serious corrosion problems. Consideration should be given to the use of impermeable-type insulation materials with sealants, adhesives, and covering materials appropriate for the service temperature of the piping being insulated.

Direct Burial. In direct-burial thermal insulation applications, most commonly, four types of systems are employed.

1. Preinsulated. Preinsulated piping systems for underground direct-burial applications generally consist of either plastic or steel piping which is covered with a foamed-in-place polyurethane insulation and then a high-impact-resistant formed plastic covering.

This type of application would look in cross section very much like the cross section shown in Fig. B7.1. These types of systems are most commonly employed in hot water and chilled water piping services. They are not recommended for use on steam lines owing to the temperature limitations of the insulation. They can be used on condensate return lines; however, caution must be exercised to avoid overheating. Some condensate return lines are used to evacuate steam which might be released from the primary steam supply line if there is a pressure relief requirement. If this occurs one time on a preinsulated piping system, it can permanently affect the performance of the insulation and its protective coverings.

2. Preinsulated Conduit with Annulus Airspace. Preinsulated conduit with annulus airspace (conduit systems) has for many years been the primary system used for steam lines by the U.S. government. Thorough analysis of underground direct-buried piping systems during the late 1950s and the 1960s revealed that almost no insulation system performed well. The reason was that groundwater infiltration into the insulation materials was able to get close enough to the piping to vaporize, and the underground steaming caused everything to deteriorate. This led to the development of a system that provided an airspace which theoretically allowed any moisture that might enter the system to vent out of the system, enabling the insulation to dry out after saturation. Figure B7.9 shows a cross section of a conduit system.

In actual application, it has been found that the annulus airspace is relatively ineffective in providing good moisture venting. However, these systems are still employed in many areas where high-temperature piping must be run underground and groundwater penetration is a concern.

3. Field-Installed. Field-installed insulation systems are one of the most cost-effective ways to insulate high-temperature lines which must be run underground. The most common material used for field installation is cellular glass, which can be used for operating temperatures up to 900°F (482°C). Cellular glass has a closed cell glass structure which resists penetration from any groundwater present. It is usually covered with an asphaltic membrane and sealed with sealants appropriate for the temperature range of the service piping.

With any of the above three direct-burial piping systems, it is very important to consider the location of all pipe anchors, in-line guides, and expansion loops. A thorough pipe stress analysis must be performed to avoid uncontrolled pipe movement, which will destroy any underground thermal insulation system. It is also extremely important to provide good drainage for the piping to try to minimize the potential of groundwater infiltration. Figure B7.10 illustrates this type of drainage recommendation. It is best to consult individual manufacturers for their recommendations with respect to application and design.

4. Pour-in Loose Fill. The most common type of pour-in loose-fill insulation for underground applications is calcium carbonate powder. This type of loose-fill insulation is poured directly into the trench after the pipe is in position. The pipe is propped up off the ground with wooden blocks to allow the calcium carbonate

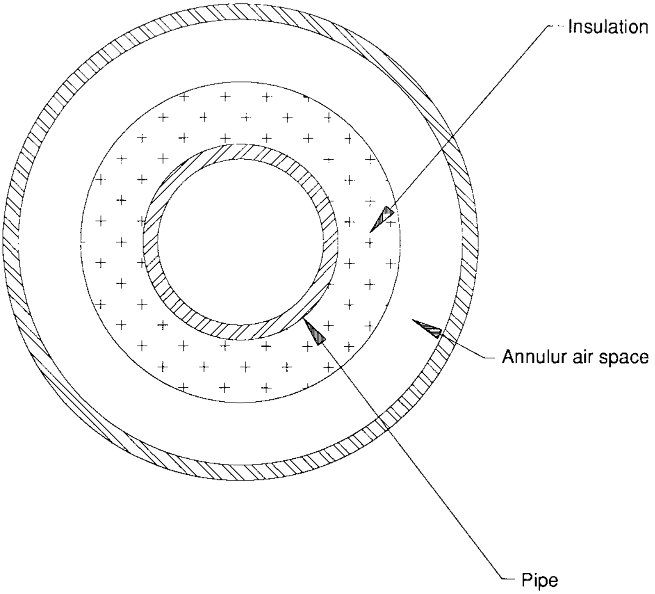

FIGURE B7.9 Cross-section of a conduit system.

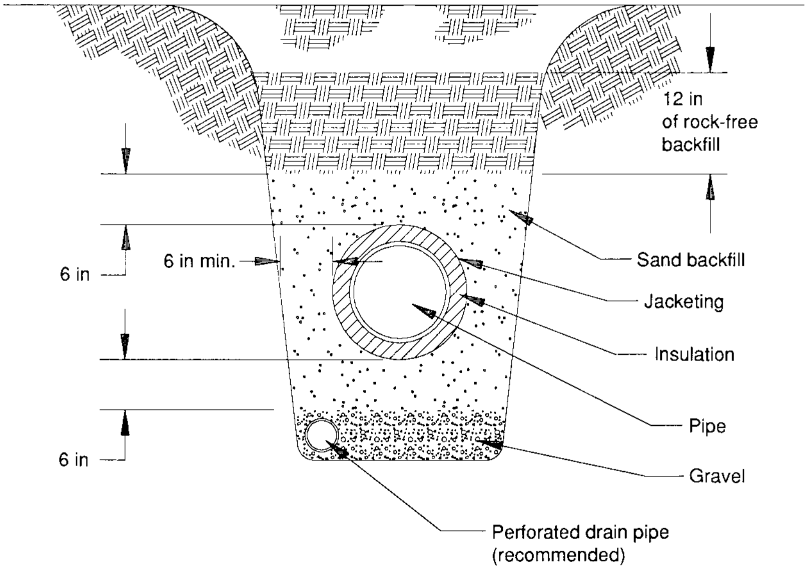

FIGURE B7.10 Backfill detail.

powder to fill in underneath. The powder is then tamped into place with a mechanical tamper. The plastic bags that the powder comes in are placed on top of the calcium carbonate prior to backfilling, to help prevent the migration of water into the insulation.

Having the above design parameter information available will allow the specifying engineer to make an educated decision about the thickness for the insulation system used. There are a number of useful sources for information on calculating insulation thickness requirements for various applications. A few of the more common sources for this type of information are:

- *ASHRAE Fundamentals Handbook*[8]
- *Annual Book of ASTM Standards,* volume 4.06, *Thermal Insulation; Environmental Acoustics*[2]
- *Thermal Insulation Handbook*[9]

Some examples of heat flow calculations are as follows: Example. B7.2 shows how heat gain would be calculated on a typical chilled water pipe in an enclosed space (representing commercial or institutional type of construction).

Example B7.2 Typical Chilled Water Pipe Calculation

Pipe size:	NPS 2 (DN 50) 2.375 = in (60 mm) actual OD
Operating temperature:	42°F (5.5°C)
Ambient temperature:	95°F (35°C)
Insulation thickness:	2 in (51 mm) nominal 2.11 in (54 mm) actual
Insulation type:	Cellular glass
Length of pipe:	120 lineal ft (36.5 m)

From Eq. (B7.2),

$$Q = \frac{2\pi K L (T_i - T_s)}{R_o \ln (R_o/R_i)}$$

where $K = 0.277\ \text{Btu} \cdot \text{in}\ (\text{h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}) = 0.0225\ \text{Btu}/(\text{h} \cdot \text{ft} \cdot {}^\circ\text{F})$ (at 50°F mean temp.) $[0.039\ \text{W}/(\text{m}^2 \cdot \text{K}) = 0.0038\ \text{W}/(\text{m} \cdot \text{K})]$

$T_i = 42^\circ\text{F}\ (5.5^\circ\text{C})$

$T_s = 95^\circ\text{F}\ (35^\circ\text{C})$

$R_i = 2.375\ \text{in}/2\ (60\ \text{mm}/2)$

$R_o = (6.62\ \text{in}/2)\ (168\ \text{mm}/2)$

$$Q = \frac{2\pi[0.0255\ \text{Btu}/(\text{h} \cdot \text{ft} \cdot {}^\circ\text{F})](120\ \text{ft})(42^\circ\text{F} - 95^\circ\text{F})}{6.62 \ln [(6.62/2)\ \text{in}/(2.375/2)\ \text{in}]}$$

$$= \frac{6.2832(0.0255\ \text{Btu/h})(120)(-53)}{6.62 \ln (3.31/1.1875)}$$

$$= \frac{-1019.0\ \text{Btu/h}}{6.786} = -150.2\ \text{Btu/h}$$

Next, to determine the relative heat transfer with respect to area, the following calculation is used:

$$\text{Circumference} = \pi d = 3.14159(6.62\text{ in}) = 20.80\text{ in}$$

$$\begin{aligned}\text{Area} &= \text{circumference} \times \text{length} = (20.80\text{ in})(120\text{ ft} \times 12\text{ in/ft})\\ &= 29{,}952\text{ in}^2 = 208\text{ ft}^2\end{aligned}$$

So

$$-150.2\text{ Btu/h}/208\text{ ft}^2 = -0.72\text{ Btu/(h} \cdot \text{ft}^2)$$

In this calculation, the minus sign in the final result indicates that the heat flow is in the direction of the pipe rather than away from the pipe. Therefore, there is a 0.72 Btu/(h · ft^2) heat gain in this illustration. And 0.72 Btu/(h · ft^2) is much greater than what would typically be employed for an application of this type, because chilled water piping cannot usually create a serious process upset condition. The thickness selected, therefore, is greater than is necessary, and further exploration of thickness requirements is needed.

The minimum thickness for cellular glass on a 2-in nominal pipe size pipe is 1 in (specified by cellular glass insulation manufacturers as a limiting factor for handling and durability). The calculation performed again using 1 in of cellular glass instead of 2 in reveals the following:

$$R_i = 2.375\text{ in}/2 \qquad R_o = 4.50\text{ in}/2$$

$$\begin{aligned}Q &= \frac{2\pi[0.0255\text{ Btu/(h} \cdot \text{ft} \cdot {}^\circ\text{F)}](120\text{ ft})(42^\circ\text{F} - 95^\circ\text{F})}{4.5\ln[(4.50\text{ in}/2)/(2.375\text{ in}/2)]}\\ &= \frac{6.2832(0.0255\text{ Btu/h})(120)(-53)}{4.5\ln(2.25/1.1875)}\\ &= \frac{-1019.0\text{ Btu/h}}{2.875} = -354.4\text{ Btu/h}\end{aligned}$$

Next, to determine the relative heat transfer with respect to area, the following calculation is used:

$$\text{Circumference} = \pi d = 3.14159(4.50\text{ in}) = 14.14\text{ in}$$

$$\begin{aligned}\text{Area} &= \text{circumference} \times \text{length} = (14.14\text{ in})(120\text{ ft} \times 12\text{ in/ft})\\ &= 20{,}362\text{ in}^2 = 141.4\text{ ft}^2\end{aligned}$$

So

$$\frac{-354.4\text{ Btu/h}}{141.4\text{ ft}^2} = -2.51\text{ Btu/(h} \cdot \text{ft}^2)$$

A heat gain on chilled water piping of 2.51 Btu/(h · ft^2) is still conservative with respect to process control [it is typically 8 to 10 Btu/(h · ft^2) (25 to 31.5 W/m^2)]. The minimum thickness for this application therefore equals 1 in of cellular glass insulation.

Example B7.3 is a calculation of heat loss on a typical steam piping application.

Example B7.3 Typical Steam Pipe Calculation

Pipe size:	NPS 6 (DN 150) 6.625 in (168 mm) actual OD
Operating temperature:	400°F (204°C)
Ambient temperature:	75°F (24°C)
Insulation thickness:	2 in (51 mm) nominal 2.11 in (54 mm) actual
Insulation type:	Calcium silicate
Length of pipe:	75 lineal ft (22.8 m)

Using Eq. (B7.2) gives

$$Q = \frac{2\pi K L (T_i - T_s)}{R_o \ln (R_o / R_i)}$$

where $K = 0.501$ Btu · in (h · /ft^2 · °F) [0.072 W/(m · K)] (at 165°F mean temp.)
$T_i = 400$°F (204°C)
$T_s = 75$°F (24°C)
$R_i = 6.625$ in/2 (168 mm/2)
$R_o = 10.75$ in/2 (273 mm/2)

$$Q = \frac{2\pi [0.501 \text{ Btu}/(\text{h} \cdot \text{ft} \cdot {}^\circ\text{F})](75 \text{ ft})\ (400^\circ\text{F} - 75^\circ\text{F})}{10.75 \ln [(10.75/2)/(6.625/2)]}$$

$$= \frac{76{,}729.5 \text{ Btu}/(\text{h} \cdot \text{ft})}{5.2 \text{ ft}} = 14{,}755.6 \text{ Btu/h}$$

Therefore,

$$\frac{14{,}755.6 \text{ Btu/h}}{75 \text{ ft}} = 196.7 \text{ Btu}/(\text{h} \cdot \text{ft})$$

$$\text{Circumference} = \pi d = 3.14159(10.75 \text{ in}) = 33.77 \text{ in}$$

Therefore, the total surface area per lineal foot of insulation equals

$$\text{Circumference} \times 12 \text{ in/ft} = 405.27 \text{ in}^2/\text{lin ft}$$

and

$$\frac{405.27 \text{ in}^2}{144 \text{ in}^2/\text{ft}} = 33.72 \text{ ft}^2/\text{ft}$$

$$\text{Heat loss} = \frac{196.7 \text{ Btu}/(\text{h} \cdot \text{ft})}{2.81 \text{ ft}^2/\text{ft}}$$

$$= 70 \text{ Btu}/(\text{h} \cdot \text{ft}^2)$$

For most hot processes, both from a process control perspective and accounting for personnel protection, a desirable heat-loss range is between 100 and 150 Btu/(h · ft^2). Since 70 Btu/ (h · ft^2) is well below this rough guideline, it becomes necessary to perform the calculation again. Solving for the same parameters with 1.5 of calcium silicate instead of 2 in reveals the following:

$$Q = \frac{2\pi[0.501\ \text{Btu}/(\text{h}\cdot\text{ft}\cdot{}^\circ\text{F})](75\ \text{ft})(400^\circ\text{F} - 75^\circ\text{F})}{9.62\ln[(9.62/2)/(6.625/2)]}$$

$$= \frac{76{,}729\ \text{Btu}/(\text{h}\cdot\text{ft})}{3.58\ \text{ft}} = 21{,}432.7\ \text{Btu/h}$$

Therefore,

$$\frac{21{,}432.7\ \text{Btu/h}}{75\ \text{ft}} = 285.7\ \text{Btu}/(\text{h}\cdot\text{ft})$$

We solve for the surface area per lineal foot of insulation:

$$\text{Circumference} = \pi d = 3.14159(9.62\ \text{in}) = 30.22\ \text{in}$$

$$\frac{\text{Area}}{\text{Linear ft}} = \text{circumference} \times 12\ \text{in/ft} = 362.66\ \text{in}^2/\text{lin ft} = 2.51\ \text{ft}^2/\text{ft}$$

Therefore, the heat loss per square foot of surface area with the minimum amount of calcium silicate insulation is [285.7 Btu/(h · ft)] / (2.51 ft^2/ft)=113.8 Btu/(h · ft^2).

SERVICE CONSIDERATIONS

One other area that needs to be considered when properly designing an insulation system is the service that the piping is providing. Service is very important in designing insulation systems because of the different physical properties of the contents of the pipe. The following are some, but not all, generalized service types that are common to industrial and commercial construction:

- Hot water and chilled water
- Steam and condensate return
- Heat-transfer fluids
- Hot oils
- Liquefied gas (cryogenic service)
- Sanitary and sewerage water

Hot Water and Chilled Water. Hot water and chilled water lines are generally employed in commercial and institutional facilities as a means of providing climate control. The heated or cooled water is transported through a pipe loop system from the mechanical facilities room of the building or buildings and is used as a heat-transfer medium to provide either heating or cooling.

Geographic location is a very important consideration for this type of service. Insulation systems for chilled water piping in the state of Florida are very susceptible to problems with moisture infiltration. Insulation system design in this environment is of critical importance. The correct application of closed-cell impermeable insulation materials and highly flexible joint sealants with a vapor retarding membrane is necessary to the success of the entire mechanical system operation. Incorrect application and specification in an environment like this can cost thousands of dollars in mechanical system maintenance and repair, water damage from soggy, dripping insulation, and high utility costs from overworking the mechanical systems. In very dry, or arid, regions of the world, critical attention to the materials is not as paramount. Water vapor is not as great a threat.

Steam and Condensate Return. Steam and condensate return lines will operate without insulation. Therefore, the chance of a process failure or process upset condition due to a poorly insulated steam line is rather small. However, the savings that can be achieved by properly insulating steam lines are substantial. This is graphically illustrated in Fig. B7.8 in a heat loss comparison of an uninsulated surface and an insulated surface.

Before the energy crisis of the mid-1970s, most steam lines that were insulated were done so without consideration of energy costs. The main purpose was to protect personnel from the extreme temperatures of the surface of a bare steam line. These personnel protection insulation thicknesses, many of which are still in use today, are not adequate for providing optimum energy conservation. One technique used somewhat commonly today to increase energy conservation is often referred to as *retrofitting* the existing insulation system. A retrofit procedure involves the use of composite insulation systems and/or materials. To retrofit in this sense of the word is to take the existing insulation system that may have been underdesigned at the time and add an extra layer of insulation.

There are several benefits that can be obtained by retrofitting insulation in this fashion. First, the additional insulation will reduce energy consumption; therefore, operating costs will go down. Second, the increased insulation thickness will provide better personnel protection due to a significantly lowered surface temperature. And third, but most importantly, by creating a retrofit system, there is an opportunity to take advantage of the optimum performance benefits of more than one material. An illustration of this ability to optimize efficiencies is given below.

Figure B7.11 shows the crossover point between thermal conductivity and mean operating temperature of two common industrial thermal insulation materials: cellu-

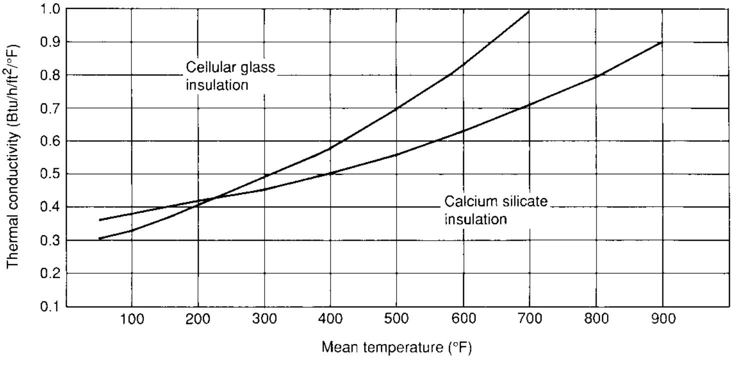

FIGURE B7.11 *K*-value crossover.

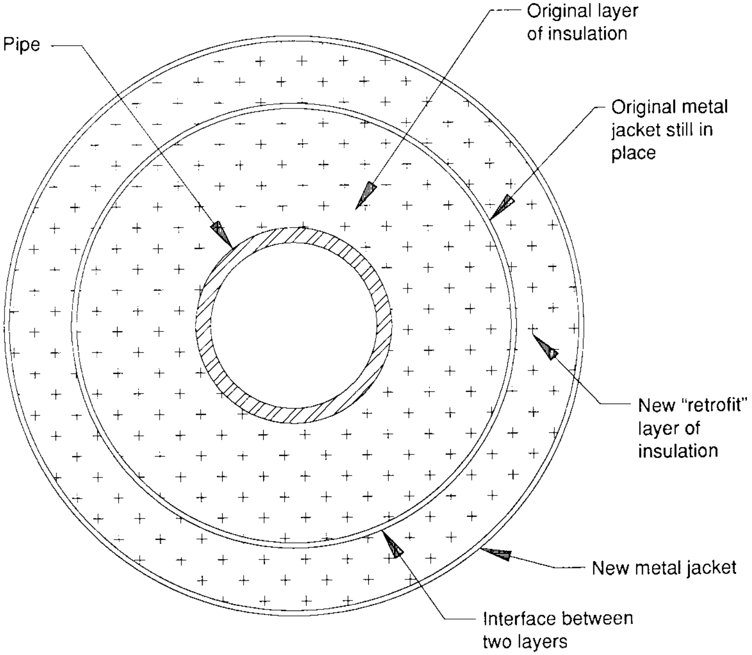

FIGURE B7.12 Cross-section of a retrofit system.

lar glass and calcium silicate. Figure B7.12 shows a cross-sectional view of what a typical retrofitted insulation system might look like and where the interface temperature will occur.

In this illustration, the crossover point of the two curves shows the ideal temperature at which each material's thermal performance characteristics can be maximized. The two curves cross over at a mean temperature of about 225°F (107°C). This shows that the cellular glass insulation has better thermal performance for mean operating temperatures at or below 225°F (107°C) and that the calcium silicate has better thermal performance for mean operating temperatures above 225°F (107°C). To maximize the performance of both materials, they can be used together in a composite retrofit system.

To use these two materials together and maximize their performance, the optimum interface temperature must be determined. The interface temperature is the point at which the two layers of insulation meet. Given that the crossover point between the two materials is at 225°F (107°C), the interface temperature can be determined by the calculation shown in Example B7.4.

Example B7.4 Desired Interface Temperature Calculation

Mean temperature = average temperature across insulation layer

In this example,

$$\text{Mean temperature} = \frac{\text{interface temperature} + \text{ambient temperature}}{2}$$

where mean temperature = 225°F (107°C)
ambient temperature = 70°F (21°C)

Therefore,

$$225^\circ\text{F} = \frac{\text{interface temperature} + 70^\circ\text{F}}{2}$$

$$2(225^\circ\text{F}) = \text{interface temperature} + 70^\circ\text{F}$$

$$2(225^\circ\text{F}) - 70^\circ\text{F} = \text{interface temperature}$$

$$\text{Desired interface temperature} = 380^\circ\text{F} \quad (193^\circ\text{C})$$

Determining the appropriate thickness for the new retrofitted layer of insulation, in this case cellular glass, is an iterative process. Knowing that the interface temperature should be approximately 380°F (193°C) provides a target point to work toward. The following example shows the calculation process by which the correct thickness can be determined.

Example B7.5 Retrofit Layer Thickness Calculation. In this example the following theoretical conditions will be employed:

Pipe size:	NPS 8 (DN 200), 8.625 in (219 mm) actual OD
Operating temperature:	600°F (315.5°C)
Ambient temperature:	70°F (21°C)
Calcium silicate thickness:	2 in (51 mm) nominal, 2.02 in (51.3 mm) actual

Equation (B7.5) will be used to find the actual interface temperature with the initial assumed insulation thickness of 2 in for the first iteration.

$$t_1 = t_i - Q\frac{R_s \ln (R_1/R_i)}{k_1} \tag{B7.10}$$

where Q = heat loss, Btu/(h · ft^2)
t_i = temperature of inner surface = 600°F (315.5°C)
t_1 = temperature of interface between layers, °F (°C)
t_s = temperature of ambient air = 70°F (21°C)
R_i = inner radius of first layer = 4.3125 in
R_1 = outer radius of first layer and inner radius of second layer = 6.375 in
R_s = outer radius of second layer = 8.50 in
k_1 = thermal conductivity of first layer
= 0.52 Btu · in (h · ft^2 · °F) [0.075 W/(m · K)]
ln = natural logarithm
$1/f$ = surface resistance factor = 0.53 (approximated from Fig. B7.3)

In solving for interface temperature t_2, the heat loss Q of the total retrofitted system must first be calculated. Using Eq. (B7.3), the heat loss for the first trial, assuming the initial iteration for the second layer with a nominal insulation thickness of 2 in, is as follows:

$$Q = \frac{t_i - t_s}{\dfrac{R_s \ln (R_1/R_i)}{k_1} + \dfrac{R_s \ln (R_s/R_1)}{k_2} + \dfrac{1}{f}} \tag{B7.11}$$

where k_2 = thermal conductivity of second layer
= 0.42 Btu · in/(h · ft^2 · °F) [0.061 W/(m · K)]

Thus

$$Q = \frac{600°\text{F} - 70°\text{F}}{\dfrac{8.50 \ln (6.375\ \text{in}/4.3125\ \text{in})}{0.52\ \text{Btu} \cdot \text{in}/(\text{h} \cdot \text{ft}^2 \cdot °\text{F})} + \dfrac{8.50 \ln (8.50\ \text{in}/6.375\ \text{in})}{0.42\ \text{Btu} \cdot \text{in}/(\text{h} \cdot \text{ft}^2 \cdot °\text{F})} + 0.53}$$

$$= \frac{530°\text{F}}{12.74\ \text{Btu}/(\text{h} \cdot \text{ft}^2 \cdot °\text{F})} = 41.60\ \text{Btu}/(\text{h} \cdot \text{ft}^2)$$

Therefore,

$$t_2 = 600°\text{F} - 41.60 \frac{(8.50\ \text{in}) \ln (6.375\ \text{in}/4.3125\ \text{in})}{0.52\ \text{Btu} \cdot \text{in}/(\text{h} \cdot \text{ft}^2 \cdot °\text{F})}$$

$$= 334.20°\text{F} \quad (168°\text{C})$$

Since this is lower than the desired interface temperature of 380°F (193°C), the iteration process can end at this step. To truly maximize the efficiency of the cellular glass and the calcium silicate, the next step would be to perform a second or third calculation with increasing thicknesses until an interface temperature at, or around, 380°F (193°C) is obtained. For this trial, however, the thickness of cellular glass used, 2 in, was sufficient to obtain a heat loss of 41.60 Btu/(h · ft^2) (131 W/m^2) which is well below what would normally be considered acceptable by today's standards for heat loss. If the interface temperature had come out greater than what was tried on the first iteration, the next step would have been to try again with a smaller thickness.

With an interface temperature of 334.2°F (168°C), the mean temperature can be recalculated to determine how close to the thermal conductivity crossover point the 2-in thickness provided. As shown above,

$$\text{Mean temperature} = \frac{\text{interface temperature} + \text{ambient temperature}}{2}$$

where interface temperature = 334.2°F (167.8°C) and ambient temperature = 70°F (21.1°C).

Therefore,

$$\text{Mean temperature} = \frac{334.2°\text{F} + 70°\text{F}}{2}$$

$$= 202.1°\text{F} \quad (94.5°\text{C})$$

This shows that the mean temperature across the outer layer of insulation is 202.1°F (94.5°C) which is only slightly below the crossover point.

Many old steam lines are insulated with a minimal amount of calcium silicate insulation. As mentioned earlier in this chapter, this was done during times when there was not a heightened sense of insulation awareness. For these types of applications, this retrofitting option is a very efficient way to revitalize old insulation systems.

Heat-Transfer Fluids. Heat-transfer fluids are liquids that are used as a means of providing process control. These liquids are generally thermally stable fluids. They can be heated or cooled to a given design temperature and transported to its desired process control point while maintaining temperature stability. Insulation system design for heat-transfer fluids must take into account the temperature range that the fluid will be operating at and whether it is a constant temperature or a cyclical temperature.

Many catalyst reaction reactor vessels operate at temperatures that swing from as low as −60°F (−51°C) to as high as 450°F (232°C). This type of cyclical service presents a complicated insulation system design dilemma. Generally, insulation systems are designed to withstand the rigid environmental and process temperature conditions at either hot or cold operating conditions. When the operating conditions are both hot and cold, a thorough study of all possible combinations of ambient conditions and operating variabilities must be conducted.

In cold process applications, the insulation materials specified are usually either plastic foam insulation or cellular glass insulation. In hot process applications, the insulation materials specified are usually mineral fiber insulation, calcium silicate insulation, or cellular glass insulation.

In applications where process temperatures swing from below ambient to hot process over the course of an operating cycle, the insulation system needs to be designed to account for both ends of the cycle. These applications are typically insulated with double or multiple layers of insulation material. It is important to insulate with the proper thickness. The critical aspect of this calculation is that the thickness must be calculated to achieve a thermal gradient in the hot condition that will not cause damage to the joint sealant in the outer layer that is necessary for the cold end of the process. Careful consideration of the appropriate sealants, adhesives, and accessory materials for the process must be given. It is advisable to consult with insulation manufacturer's technical support groups for recommendations for these types of processes.

Another important consideration in specifying insulation systems for heat-transfer fluids is fire safety. Many of the common heat-transfer fluids, whether organic or inorganic, can present a very serious fire hazard if they are absorbed into a permeable insulation material. It has been shown that some of these fluids, although thermally very stable at their peak operating temperatures, become much less so when absorbed into insulation materials. Spontaneous heating is the problem. Another term for the condition is auto-ignition. Monsanto Industrial Chemicals Company manufactures a product called Therminol which is a very useful and highly effective heat-transfer fluid. In the Therminol technical data sheet a description of the problem is offered:[10]

> Organic heat transfer fluids such as Therminol exhibit a slow oxidation reaction with air in the presence of insulating materials when system temperatures are above 500°F (260°C). Porous insulation material such as calcium silicate offers a large reaction surface in the face of poor heat dissipation conditions, and this, along with possible catalysis from the insulation material can cause a temperature build-up. This temperature build-up can result in ignition of the fluid when the saturated insulation is exposed to air (i.e., should the insulation be opened for repair, etc.).

> This phenomenon is not fully understood, but appears not to occur with cellular glass, possibly because of its closed cell structure. Cellular glass should be used in all areas where leakage is a possibility and the system temperature is greater than 400°F (240°C).

There are numerous other reference which relate similar, if not identical, information about this problem and the precautions that need to be taken in the design and application process. The Bibliography for this chapter contains a number of references on this subject. As in the case of cyclical service, it is important to contact the manufacturer before writing the insulation system specification for high-temperature heat-transfer fluid applications. The manufacturers of the heat-transfer fluid should also be consulted for their own precautions and recommendations.

Hot Oils. Hot oil piping and equipment applications require the same attention to detail as do heat-transfer fluids with respect to insulation system design. For hot oils, even though they frequently do not operate at the temperature extremes of heat-transfer fluids, the auto-ignition can be just as serious. Fires have occurred in oils at temperatures as low as 176 to 302°F (80 to 150°C), in coal tar distillates at temperatures as low as 212 to 482°F (100 to 250°C), and in mineral oils at temperatures as low as 392 to 572°F (200 to 300°C).[11]

Liquefied Gas (Cryogenic Service). Cryogenic temperatures range from −40°F (−40°C) down to absolute zero (−459°F, or −273°C). In this temperature range, the primary concern is the prevention of water vapor migration toward the pipe surface. Water vapor that is allowed to enter the insulation system will rapidly destroy the thermal performance of the insulation.

Cryogenic piping is usually insulated in multiple layers. The best vapor barrier joint sealants available remain flexible only down to a temperature of about −80°F (−62°C); therefore the inner layer of insulation is usually left unsealed. The outer layer or layers are completely sealed with vapor barrier joint sealants, and the final layer of insulation is usually covered with a vapor barrier mastic or membrane.

Plastic foam insulation must be covered with a complete vapor barrier envelope. Cellular glass insulation is sometimes just vapor-sealed over the joints and then covered with a weather barrier.

At extreme cryogenic temperatures, there is also the possibility of condensation of oxygen. This can occur anywhere below −290°F (−179°C). The National Fire Protection Association states[12]

> Liquid oxygen is the most concentrated common source of oxygen. Contamination of liquid oxygen with most organic substances often renders the mixture subject to violent explosion.
>
> An inadvertent oxygen enriched atmosphere can be created within insulation on piping and equipment containing materials at temperatures below the condensation temperature of oxygen (e.g., liquid hydrogen or nitrogen), if the oxygen in the atmospheric air is condensed within the insulation.

Therefore, there is a risk of liquid oxygen explosion with organic insulation materials and accessory products. Organic foam insulations, if used in the potential presence of condensing oxygen, require that the foam must be protected by a gas-impermeable membrane.[13]

Sanitary and Sewerage Water. Water lines and sewerage lines are generally insulated only as a means to prevent freezing. All the considerations appropriate for freeze protection requirements discussed earlier in this chapter should prevail.

MATERIALS

There are many different types of insulation materials available for both commercial and industrial piping applications. There are in fact too many to discuss in detail here. For the purposes of this chapter, a few of the more common commercial and industrial piping insulation types, or classifications, will be described. The following list, sorted alphabetically, comprises the material classifications most common to the industrial and commercial piping industry:

- Calcium silicate insulation
- Cellular glass insulation
- Elastomeric foam insulation
- Fiberglass and mineral wool insulations
- Perlite insulation
- Phenolic foam insulation
- Polystyrene foam insulation
- Polyurethane and polyisocyanurate foam insulations

Table B7.1 illustrates some of the properties of insulation materials that are commonly referred to in the insulation material selection process. Table B7.4 through Table B7.16 provide thickness guidelines for the materials referenced in

TABLE B7.4 Calcium Silicate Insulation Thickness Table
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 5.0 mph
Hot pipe worst-case ambient temperature of 90.0°F for a surface temperature of 140.0°F or less

Temperature (°F)	Nominal pipe size (NPS)													
	0.5	1.0	1.5	2.0	3.0	4.0	6.0	8.0	10.0	12.0	16.0	18.0	24.0	Flat
	Calcium silicate thickness (in)													
200.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
300.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
400.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
500.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0
600.0	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5
700.0	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.5	2.5	2.5	3.0	3.0	3.0	3.5
800.0	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0
900.0	2.0	2.0	2.0	2.5	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.5	5.0
1000.0	2.0	2.5	2.5	3.0	3.0	3.5	3.5	4.0	4.0	4.5	4.5	5.0	5.0	6.0

Maximum heat flow = 115.1 Btu/(h · ft^2) (highest heat flow of any in the table).

TABLE B7.4M Calcium Silicate Insulation Thickness Table
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 8 km/h
Hot pipe worst-case ambient temperature of 32°C for a surface temperature of 60.0°C or less

Temperature (°C)	Diameter nominal (DN)													
	(15)	(25)	(40)	(50)	(80)	(100)	(150)	(200)	(250)	(300)	(400)	(450)	(600)	Flat
	Calcium silicate thickness (mm)													
75	25	25	25	25	25	25	25	38	38	38	38	38	38	38
100	25	25	25	25	25	25	25	38	38	38	38	38	38	38
150	25	25	25	25	25	25	25	38	38	38	38	38	38	38
200	25	25	25	38	38	38	38	38	38	38	38	38	38	38
250	25	25	25	25	38	38	38	38	38	38	51	51	51	51
300	25	38	38	38	38	38	51	51	51	51	64	64	64	64
350	38	38	38	38	51	51	51	64	64	64	64	76	76	76
400	38	38	51	51	64	64	64	64	76	76	76	89	89	102
450	51	51	51	64	64	76	76	76	89	89	102	102	102	114
500	51	51	51	64	76	76	89	89	102	102	114	114	114	127
550	64	64	64	76	89	89	102	102	114	114	127	127	127	152

Maximum heat flow = 378.1 W/m^2 (highest heat flow of any in the table).

Table B7.1. Tables B7.17 through Table B7.22 provide thermal conductivity data for each of these materials. It is important to remember that the properties of the material alone should not control the specification process. It is the combined properties of the insulation material and the corresponding accessory products that make up the total system that should control.

TABLE B7.5 Calcium Silicate Insulation Thickness Table
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 5.0 mph
Hot pipe worst-case ambient temperature of 80.0°F for a surface temperature of 140.0°F or less

Temperature (°F)	Nominal pipe size (NPS)													
	0.5	1.0	1.5	2.0	3.0	4.0	6.0	8.0	10.0	12.0	16.0	18.0	24.0	Flat
	Calcium silicate thickness (in)													
200.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
300.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
400.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
500.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2.0
600.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.5
700.0	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.5	2.5	2.5	3.0
800.0	1.5	1.5	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5	3.0	3.0	3.0	3.5
900.0	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0
1000.0	2.0	2.0	2.0	2.5	2.5	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	5.0

Maximum heat flow = 138 Btu/(h · ft^2) (highest heat flow of any in the table).

TABLE B7.5M Calcium Silicate Insulation Thickness Table
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 8 km/h
Hot pipe worst-case ambient temperature of 27°C for a surface temperature of 60.0°C or less

Temperature (°C)	Diameter nominal (DN)													
	(15)	(25)	(40)	(50)	(80)	(100)	(150)	(200)	(250)	(300)	(400)	(450)	(600)	Flat
	Calcium silicate thickness (mm)													
75	25	25	25	25	25	25	25	38	38	38	38	38	38	38
100	25	25	25	25	25	25	25	38	38	38	38	38	38	38
150	25	25	25	25	25	25	25	38	38	38	38	38	38	38
200	25	25	25	25	25	25	25	38	38	38	38	38	38	38
250	25	25	25	25	25	25	38	38	38	38	38	38	38	38
300	25	25	25	38	38	38	38	38	38	38	51	51	51	51
350	25	38	38	38	38	38	51	51	51	51	64	64	64	64
400	38	38	38	38	51	51	51	64	64	64	64	76	76	76
450	38	38	51	51	51	64	64	64	76	76	76	76	89	89
500	38	51	51	51	64	64	76	76	76	89	89	89	102	114
550	51	51	51	64	76	76	89	89	89	102	102	102	114	127

Maximum heat flow = 474 W/m^2 (highest heat flow of any in the table).

Calcium Silicate Insulation. Calcium silicate is a very rigid, high-density material used exclusively for applications above 250°F (121°C). This insulation material has been a standard for high temperature applications for many years. Compressive strengths are very good, and it is noncombustible. It is suitable for temperatures from 250°F (121°C) up to 1000°F (538°C). Calcium silicate is manufactured from a

TABLE B7.6 Cellular Glass Insulation Thickness Table (Hot)
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 5.0 mph
Hot pipe worst-case ambient temperature of 90°F for a surface temperature of 140.0°F or less

Temperature (°F)	Nominal pipe size (NPS)													
	0.5	1.0	1.5	2.0	3.0	4.0	6.0	8.0	10.0	12.0	16.0	18.0	24.0	Flat
	Super_k™ FOAMGLAS® insulation,* inches													
200.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
300.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
400.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
500.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0
600.0	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5	2.5	3.0
700.0	1.5	2.0	2.0	2.0	2.5	2.5	2.5	2.5	3.0	3.0	3.5	3.5	3.5	4.0
800.0	2.0	2.0	2.5	2.5	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.5	5.0
900.0	2.5	2.5	3.0	3.0	3.5	3.5	4.0	4.5	4.5	5.0	5.0	5.0	5.5	6.5

Maximum heat flow = 116.7 Btu/(h·ft^2) (highest heat flow of any in the table).
*Super_k™ FOAMGLAS® insulation is a registered trademark of Pittsburgh Corning Corporation.

TABLE B7.6M Cellular Glass Insulation Thickness Table (Hot)
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 8 km/h
Hot pipe worst-case ambient temperature of 32°C for a surface temperature of 60.0°C or less

Temperature (°C)	Diameter nominal (DN)													
	(15)	(25)	(40)	(50)	(80)	(100)	(150)	(200)	(250)	(300)	(400)	(450)	(600)	Flat
	Super_k™ FOAMGLAS® insulation,* mm													
75	25	25	25	25	25	25	25	38	38	38	38	38	38	38
100	25	25	25	25	25	25	25	38	38	38	38	38	38	38
150	25	25	25	25	25	25	25	38	38	38	38	38	38	38
200	25	25	25	25	25	25	25	38	38	38	38	38	38	38
250	25	25	25	25	38	38	38	38	38	38	51	51	51	51
300	38	38	38	38	38	51	51	51	51	51	64	64	64	64
350	38	38	51	51	51	51	64	64	64	64	76	76	76	89
400	51	51	64	64	64	64	76	76	89	89	89	102	102	114
450	51	64	76	76	76	76	89	102	102	102	114	114	127	140
500	76	76	89	89	89	102	102	114	127	127	140	140	140	178

Maximum heat flow = 356 W/m^2 (highest heat flow of any in the table).
*Super_k™ FOAMGLAS® insulation is a registered trademark of Pittsburgh Corning Corporation.

slurry that is poured into molds to make various pipe-covering shapes. It is generally available in half sections, quad-sections, and flat blocks. Calcium silicate is applied to the piping with metal bands and generally covered with a metal jacket.

Cellular Glass Insulation. Cellular glass insulation is a high-strength, versatile insulation used in temperature services that range from −450°F (−268°C) up to

TABLE B7.7 Cellular Glass Insulation Thickness Table (Hot)
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 5.0 mph
Hot pipe worst-case ambient temperature of 80°F for a surface temperature of 140.0°F or less

Temperature (°F)	Nominal pipe size (NPS)													
	0.5	1.0	1.5	2.0	3.0	4.0	6.0	8.0	10.0	12.0	16.0	18.0	24.0	Flat
	Super_k™ FOAMGLAS® insulation,* inches													
200.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
300.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
400.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
500.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2.0
600.0	1.0	1.0	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.5	2.5	2.5
700.0	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.5	2.5	2.5	3.0	3.0	3.0	3.0
800.0	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0
900.0	2.0	2.0	2.5	2.5	3.0	3.0	3.5	3.5	4.0	4.0	4.5	4.5	4.5	5.0

Maximum heat flow = 143.4 Btu/(h · ft^2) (highest heat flow of any in the table).
*Super_k™ FOAMGLAS® insulation is a registered trademark of Pittsburgh Corning Corporation.

TABLE B7.7M Cellular Glass Insulation Thickness Table (Hot)
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 8 km/h
Hot pipe worst-case ambient temperature of 27°C for a surface temperature of 60.0°C or less

Temperature (°C)	Diameter nominal (DN)													
	(15)	(25)	(40)	(50)	(80)	(100)	(150)	(200)	(250)	(300)	(400)	(450)	(600)	Flat
	Super_k™ FOAMGLAS® insulation,* mm													
75	25	25	25	25	25	25	25	38	38	38	38	38	38	38
100	25	25	25	25	25	25	25	38	38	38	38	38	38	38
150	25	25	25	25	25	25	25	38	38	38	38	38	38	38
200	25	25	25	25	25	25	25	38	38	38	38	38	38	38
250	25	25	25	25	25	25	38	38	38	38	38	38	38	38
300	25	25	38	38	38	38	38	38	38	51	51	51	51	51
350	38	38	38	38	51	51	51	51	51	64	64	64	64	76
400	38	38	51	51	51	64	64	64	64	76	76	76	89	89
450	51	51	64	64	64	76	76	76	89	89	102	102	102	114
500	51	64	76	76	76	89	89	102	102	102	114	114	127	140

Maximum heat flow = 436 W/m^2 (highest heat flow of any in the table).
*Super_k™ FOAMGLAS® insulation is a registered trademark of Pittsburgh Corning Corporation.

900°F (538°C). Cellular glass insulation is all closed-cell glass with no organic binders or fillers. The closed-cell glass structure renders it impervious to liquid water and the driving force of water vapor pressure. It is manufactured in flat blocks which are then fabricated into any shape specified. Fabrication techniques are governed by ASTM Standard Recommended Practice for Inner and Outer Diameters of Rigid Thermal Insulation for Nominal Sizes of Pipe and Tubing. Cellular glass is

TABLE B7.8 Fiberglass Insulation Thickness Table (Hot)
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 5.0 mph
Hot pipe worst-case ambient temperature of 90°F for a surface temperature of 140.0°F or less

Temperature (°F)	Nominal pipe size (NPS)													
	0.5	1.0	1.5	2.0	3.0	4.0	6.0	8.0	10.0	12.0	16.0	18.0	24.0	Flat
	Fiberglass thickness (in)													
200.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
300.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
400.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
500.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
600.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0
700.0	1.0	1.0	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.5	2.5	2.5
800.0	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.5	2.5	2.5	2.5	3.0	3.0	3.0
850.0	1.5	1.5	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5	3.0	3.0	3.0	3.5

Maximum heat flow = 121.9 $Btu/(h \cdot ft^2)$ (highest heat flow of any in the table).

TABLE B7.8M Fiberglass Insulation Thickness Table (Hot)

Recommended thickness table

Surface emittance = 0.4 Average wind velocity = 8 km/h

Hot pipe worst-case ambient temperature of 32°C for a surface temperature of 60.0°C or less

Temperature (°C)	Diameter nominal (DN)													
	(15)	(25)	(40)	(50)	(80)	(100)	(150)	(200)	(250)	(300)	(400)	(450)	(600)	Flat
	Fiberglass thickness (mm)													
75	25	25	25	25	25	25	25	38	38	38	38	38	38	38
100	25	25	25	25	25	25	25	38	38	38	38	38	38	38
150	25	25	25	25	25	25	25	38	38	38	38	38	38	38
200	25	25	25	25	25	25	25	38	38	38	38	38	38	38
250	25	25	25	25	25	25	38	38	38	38	38	38	38	38
300	25	25	25	38	38	38	38	38	38	38	51	51	51	51
350	38	38	38	38	38	51	51	51	51	51	64	64	64	64
400	38	38	51	51	51	51	64	64	64	64	76	76	76	90
450	38	51	64	64	64	64	76	76	76	89	89	89	89	102

Maximum heat flow = 348.2 W/m^2 (highest heat flow of any in the table).

applied to cold piping in single or double layers and usually is used with a joint sealant and then covered with either a fabric-reinforced mastic or a metal jacket. On hot piping applications, cellular glass is applied to the pipe in single or double layers with metal bands. No sealants are used on hot applications. It is then covered with metal jacket.

TABLE B7.9 Fiberglass Insulation Thickness Table (Hot)

Recommended thickness table

Surface emittance = 0.4 Average wind velocity = 5.0 mph

Hot pipe worst-case ambient temperature of 80°F for a surface temperature of 140.0°F or less

Temperature (°F)	Nominal pipe size (NPS)													
	0.5	1.0	1.5	2.0	3.0	4.0	6.0	8.0	10.0	12.0	16.0	18.0	24.0	Flat
	Fiberglass thickness (in)													
200.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
300.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
400.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
500.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
600.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2.0	2.0
700.0	1.0	1.0	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.5	2.5
800.0	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.5	2.5	2.5	2.5	3.0	3.0	3.0
850.0	1.5	1.5	2.0	2.0	2.0	2.0	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.5

Maximum heat flow = 146 Btu/(h · ft^2) (highest heat flow of any in the table).

TABLE B7.9M Fiberglass Insulation Thickness Table (Hot)
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 8 km/h
Hot pipe worst-case ambient temperature of 27°C for a surface temperature of 60.0°C or less

Temperature (°C)	Diameter nominal (DN)													
	(15)	(25)	(40)	(50)	(80)	(100)	(150)	(200)	(250)	(300)	(400)	(450)	(600)	Flat
	Fiberglass thickness (mm)													
75	25	25	25	25	25	25	25	38	38	38	38	38	38	38
100	25	25	25	25	25	25	25	38	38	38	38	38	38	38
150	25	25	25	25	25	25	25	38	38	38	38	38	38	38
200	25	25	25	25	25	25	25	38	38	38	38	38	38	38
250	25	25	25	25	25	25	25	38	38	38	38	38	38	38
300	25	25	25	25	25	25	38	38	38	38	38	38	38	38
350	25	25	38	38	38	38	38	38	38	51	51	51	51	51
400	38	38	38	38	38	51	51	51	51	51	64	64	64	76
450	38	38	51	51	51	51	64	64	64	64	76	76	76	89

Maximum heat flow = 428.5 W/m^2 (highest heat flow of any in the table).

Elastomeric Foam Insulation. Elastomeric foams are used almost exclusively in commercial, institutional, and residential facilities. It is used primarily on hot water and chilled water lines, or for water and sewer lines for freeze protection. Elastomerics are extruded into pipe dimensions and generally available in ½-in (13-mm), ¾-in (19-mm), and 1-in (25-mm) thicknesses. It is available in sheet form for equipment. These foams are usually taped, wired, or glued in place.

TABLE B7.10 Perlite Insulation Thickness Table (Hot)
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 5.0 mph
Hot pipe worst-case ambient temperature of 90°F for a surface temperature of 140.0°F or less

Temperature (°F)	Nominal pipe size (NPS)													
	0.5	1.0	1.5	2.0	3.0	4.0	6.0	8.0	10.0	12.0	16.0	18.0	24.0	Flat
	Perlite thickness (in)													
200.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
300.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
400.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2.0
500.0	1.0	1.0	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.5	2.5	2.5
600.0	1.5	1.5	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5	3.0	3.0	3.0	3.5
700.0	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0
800.0	2.0	2.0	2.0	2.5	3.0	3.0	3.5	3.5	3.5	4.0	4.5	4.5	4.5	5.0
900.0	2.5	2.5	2.5	3.0	3.5	3.5	4.0	4.0	4.5	4.5	5.0	5.0	5.0	6.0
1000.0	2.5	3.0	3.0	3.5	4.0	4.0	4.5	4.5	5.0	5.5	5.5	5.5	6.0	7.0

Maximum heat flow = 122.3 Btu/(h·ft^2) (highest heat flow of any in the table).

TABLE B7.10M Perlite Insulation Thickness Table (Hot)
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 8 km/h
Hot pipe worst-case ambient temperature of 32°C for a surface temperature of 60.0°C or less

Temperature (°C)	Diameter nominal (DN)													
	(15)	(25)	(40)	(50)	(80)	(100)	(150)	(200)	(250)	(300)	(400)	(450)	(600)	Flat
	Perlite thickness (mm)													
75	25	25	25	25	25	25	25	38	38	38	38	38	38	38
100	25	25	25	25	25	25	25	38	38	38	38	38	38	38
150	25	25	25	25	25	25	25	38	38	38	38	38	38	38
200	25	25	25	25	25	25	38	38	38	38	38	38	38	51
250	25	25	38	38	38	38	51	51	51	51	51	51	51	64
300	38	38	38	38	51	51	51	64	64	64	64	64	76	76
350	38	51	51	51	64	64	64	64	76	76	89	89	89	102
400	51	51	51	64	64	76	76	76	89	89	102	102	102	114
450	51	64	64	64	76	76	89	89	102	102	114	114	114	140
500	64	64	64	76	89	89	102	114	114	127	127	127	140	165
550	64	76	76	89	102	102	114	127	127	140	152	152	165	191

Maximum heat flow = 366 W/m^2 (highest heat flow of any in the table).

Fiberglass and Mineral Wool Insulations. Fiberglass and mineral wool are actually two separate and distinct types of insulation; however, many of their applications and physical properties are similar. These products are generally used in hot applications, but with some restrictions they can be used in cold applications as well. Fiberglass is often used from chilled water piping temperatures up to a maximum

TABLE B7.11 Perlite Insulation Thickness Table (Hot)
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 5.0 mph
Hot pipe worst-case ambient temperature of 80°F for a surface temperature of 140.0°F or less

Temperature (°F)	Nominal pipe size (NPS)													
	0.5	1.0	1.5	2.0	3.0	4.0	6.0	8.0	10.0	12.0	16.0	18.0	24.0	Flat
	Perlite thickness (in)													
200.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
300.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
400.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	2.0
500.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0
600.0	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5
700.0	1.5	1.5	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5	3.0	3.0	3.0	3.5
800.0	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0
900.0	2.0	2.0	2.0	2.5	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.5	5.0
1000.0	2.0	2.5	2.5	3.0	3.0	3.5	3.5	4.0	4.0	4.5	4.5	5.0	5.0	6.0

Maximum heat flow = 146 Btu/(h · ft^2) (highest heat flow of any in the table).

TABLE B7.11M Perlite Insulation Thickness Table (Hot)
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 8 km/h
Hot pipe worst-case ambient temperature of 27°C for a surface temperature of 60.0°C or less

Temperature (°C)	Diameter nominal (DN)													
	(15)	(25)	(40)	(50)	(80)	(100)	(150)	(200)	(250)	(300)	(400)	(450)	(600)	Flat
	Perlite thickness (mm)													
75	25	25	25	25	25	25	25	38	38	38	38	38	38	38
100	25	25	25	25	25	25	25	38	38	38	38	38	38	38
150	25	25	25	25	25	25	25	38	38	38	38	38	38	38
200	25	25	25	25	25	25	25	38	38	38	38	38	38	38
250	25	25	25	25	38	38	38	38	38	38	51	51	51	51
300	25	25	38	38	38	38	51	51	51	51	64	64	64	64
350	38	38	38	38	51	51	51	64	64	64	64	76	76	76
400	38	38	51	51	51	64	64	64	76	76	76	89	89	102
450	51	51	51	64	64	76	76	76	89	89	102	102	102	114
500	51	51	51	64	76	76	89	89	102	102	114	114	114	127
550	64	64	64	76	89	89	102	102	114	114	127	127	127	152

Maximum heat flow = 479 W/m^2 (highest heat flow of any in the table).

TABLE B7.12 Mineral Wool Insulation Thickness Table (Hot)
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 5.0 mph
Hot pipe worst-case ambient temperature of 90°F for a surface temperature of 140.0°F or less

Temperature (°F)	Nominal pipe size (NPS)													
	0.5	1.0	1.5	2.0	3.0	4.0	6.0	8.0	10.0	12.0	16.0	18.0	24.0	Flat
	Mineral wool thickness (in)													
200.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
300.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
400.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
500.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2.0	2.0
600.0	1.0	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.5	2.5	2.5
700.0	1.5	1.5	2.0	2.0	2.0	2.0	2.5	2.5	2.5	2.5	3.0	3.0	3.0	3.5
800.0	1.5	2.0	2.0	2.0	2.5	2.5	3.0	3.0	3.0	3.5	3.5	3.5	4.0	4.5
900.0	2.0	2.5	2.5	2.5	3.0	3.0	3.5	3.5	4.0	4.0	4.5	4.5	4.5	5.5
1000.0	2.5	2.5	3.0	3.0	3.5	4.0	4.0	4.5	4.5	5.0	5.0	5.5	5.5	6.5
1100.0	2.5	3.0	3.5	4.0	4.0	4.5	4.5	5.0	5.0	6.0	6.0	6.5	6.5	8.0
1200.0	3.0	3.5	4.0	4.5	4.5	5.0	5.0	5.5	6.0	7.0	7.0	7.5	7.5	9.5

Maximum heat flow = 119.5 Btu/(h · ft^2) (highest heat flow of any in the table).

TABLE B7.12M Mineral Wool Insulation Thickness Table (Hot)
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 8 km/h
Hot pipe worst-case ambient temperature of 32°C for a surface temperature of 60.0°C or less

Temperature (°C)	Diameter nominal (DN)													
	(15)	(25)	(40)	(50)	(80)	(100)	(150)	(200)	(250)	(300)	(400)	(450)	(600)	Flat
	Mineral wool thickness (mm)													
75	25	25	25	25	25	25	25	38	38	38	38	38	38	38
100	25	25	25	25	25	25	25	38	38	38	38	38	38	38
150	25	25	25	25	25	25	25	38	38	38	38	38	38	38
200	25	25	25	25	25	25	25	38	38	38	38	38	38	38
250	25	25	25	25	25	25	38	38	38	38	38	38	38	51
300	25	25	38	38	38	38	51	51	51	51	51	51	51	64
350	38	38	38	38	51	51	51	64	64	64	64	64	76	76
400	38	38	51	51	64	64	64	64	76	76	89	89	89	102
450	51	51	51	64	64	76	76	89	89	89	102	102	102	114
500	51	64	64	76	76	89	89	102	102	114	114	114	127	140
550	64	76	76	89	89	102	114	114	127	127	140	140	140	178
600	64	76	89	102	102	114	127	140	140	152	165	165	165	203
650	76	89	102	114	127	127	140	152	165	178	178	191	191	241

Maximum heat flow = 371.3 W/m^2 (highest heat flow of any in the table).

TABLE B7.13 Mineral Wool Insulation Thickness Table (Hot)
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 5.0 mph
Hot pipe worst-case ambient temperature of 80.0°F for a surface temperature of 140.0°F or less

Temperature (°F)	Nominal pipe size (NPS)													
	0.5	1.0	1.5	2.0	3.0	4.0	6.0	8.0	10.0	12.0	16.0	18.0	24.0	Flat
	Mineral wool thickness (in)													
200.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
300.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
400.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
500.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	2.0	2.0
600.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0
700.0	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.0	2.5	2.5	2.5	3.0
800.0	1.5	1.5	2.0	2.0	2.0	2.0	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.5
900.0	2.0	2.0	2.0	2.0	2.5	2.5	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.5
1000.0	2.0	2.5	2.5	2.5	3.0	3.0	3.5	3.5	4.0	4.0	4.5	4.5	4.5	5.5
1100.0	2.5	2.5	2.5	3.0	3.5	3.5	4.0	4.5	4.5	5.0	5.0	5.5	5.5	6.5
1200.0	2.5	3.0	3.0	3.5	4.0	4.5	5.0	5.0	5.5	5.5	6.0	6.0	6.5	8.0

Maximum heat flow = 142 Btu/(h·ft^2) (highest heat flow of any in the table).

TABLE B7.13M Mineral Wool Insulation Thickness Table (Hot)
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 8 km/h
Hot pipe worst-case ambient temperature of 27°C for a surface temperature of 60.0°C or less

Temperature (°C)	Diameter nominal (DN)													
	(15)	(25)	(40)	(50)	(80)	(100)	(150)	(200)	(250)	(300)	(400)	(450)	(600)	Flat
	Mineral wool thickness (mm)													
75	25	25	25	25	25	25	25	38	38	38	38	38	38	38
100	25	25	25	25	25	25	25	38	38	38	38	38	38	38
150	25	25	25	25	25	25	25	38	38	38	38	38	38	38
200	25	25	25	25	25	25	25	38	38	38	38	38	38	38
250	25	25	25	25	25	25	25	38	38	38	38	38	38	38
300	25	25	25	25	38	38	38	38	38	38	51	51	51	51
350	25	25	38	38	38	38	51	51	51	51	51	64	64	64
400	38	38	38	38	51	51	51	64	64	64	64	76	76	76
450	38	51	51	51	64	64	64	64	76	76	89	89	89	102
500	51	51	51	64	64	76	76	76	89	89	102	102	102	114
550	51	64	64	76	76	89	89	102	102	102	114	114	127	140
600	64	64	76	76	89	102	102	114	127	127	140	140	140	165
650	64	76	76	89	102	114	127	127	140	140	152	152	165	203

Maximum heat flow = 469 W/m^2 (highest heat flow of any in the table).

of 850°F (454°C). Mineral wool has a peak temperature limit of 1200°F (649°C). Fiberglass is made from glass fibers bonded together with resin binders. Mineral wool is made from rock slag fibers and bonded together with resin or clay binders. These materials are generally applied with metal bands or wire or tape and are covered with a metal or nonmetallic flexible jacket. On indoor applications they are frequently covered with an all-service jacket.

Perlite Insulation. Perlite insulation is generally used in the same types of applications as calcium silicate. It is somewhat lighter in density and lower in compressive strength than calcium silicate; however, it usually is treated with a water inhibitor

TABLE B7.14 Polyurethane and Polyisocyanurate Insulation Thickness Table (Hot)
Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 5.0 mph
Hot pipe worst-case ambient temperature of 90.0°F for a surface temperature of 140.0°F or less

Temperature (°F)	Nominal pipe size (NPS)													
	0.5	1.0	1.5	2.0	3.0	4.0	6.0	8.0	10.0	12.0	16.0	18.0	24.0	Flat
	Polyurethane and polyisocyanurate thickness (in)													
200.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
250.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
300.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5

Maximum heat flow = 42.9 Btu/(h · ft^2) (highest heat flow of any in the table).

TABLE B7.14M Polyurethane and Polyisocyanurate Insulation Thickness Table (Hot)

Recommended thickness table
Surface emittance = 0.4 Average wind velocity = 8 km/h
Hot pipe worst-case ambient temperature of 32°C for a surface temperature of 60.0°C or less

Temperature (°C)	Diameter nominal (DN)													
	(15)	(25)	(40)	(50)	(80)	(100)	(150)	(200)	(250)	(300)	(400)	(450)	(600)	Flat
	Polyurethane and polyisocyanurate thickness (mm)													
75	25	25	25	25	25	25	25	38	38	38	38	38	38	38
100	25	25	25	25	25	25	25	38	38	38	38	38	38	38
150	25	25	25	25	25	25	25	38	38	38	38	38	38	38

Maximum heat flow = 136 W/m^2 (highest heat flow of any in the table).

TABLE B7.15 Cellular Glass Insulation Thickness Table (Cold)

Recommended lower pipe temperature limits for given insulation thickness (°F)
Insulation material: Super_k™ FOAMGLAS® insulation
Ambient temperature = 90.0°F Heat flow limit = −10.0 ± 0.1 Btu/(h·ft^2)
Wind velocity = 5.0 mph Emittance = 0.9

NPS	Insulation thickness (in) Super_k™ FOAMGLAS® insulation*																
	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0
0.05	23	−32	−95	−139	−245	−396											
0.75	35	−13	−68	−105	−191												
1.00	25	−17	−73	−145	−234	−363											
1.50	33	−2	−26	−79	−141	−221	−331										
2.00	35	0	−44	−95	−157	−237	−364										
2.50	37	20	−17	−59	−110	−173	−265	−381									
3.00	40	9	−26	−67	−117	−187	−268	−378									
4.00	41	13	−19	−57	−107	−162	−230	−346									
5.00	43	17	−12	−51	−92	−141	−217	−296	−403								
6.00	46	21	−10	−43	−81	−138	−194	−263	−353								
8.00		20	−6	−45	−80	−122	−170	−229	−302	−398							
10.00		19	−6	−35	−68	−105	−149	−199	−261	−339	−439						
12.00		20	−4	−32	−63	−98	−139	−186	−242	−311	−399						
14.00		26	2	−23	−53	−86	−124	−167	−218	−280	−357						
16.00		27	3	−21	−50	−82	−118	−159	−207	−264	−335	−424					
18.00		27	4	−20	−48	−79	−113	−153	−198	−252	−318	−400					
20.00		28	5	−19	−46	−76	−109	−147	−191	−242	−304	−381					
24.00		28	6	−17	−43	−72	−104	−140	−180	−228	−284	−353	−437				
28.00		29	7	−15	−41	−69	−100	−134	−173	−217	−270	−333	−411				
30.00		29	8	−15	−40	−68	−98	−132	−170	−213	−264	−325	−400				
36.00		29	8	−13	−38	−65	−94	−126	−163	−204	−251	−307	−375				
42.00		30	9	−12	−37	−63	−91	−122	−157	−197	−242	−295	−358	−434			
48.00		30	9	−12	−35	−61	−89	−120	−153	−191	−235	−285	−345	−417			
60.00		30	10	−11	−34	−59	−86	−115	−148	−184	−225	−272	−327	−393			
72.00		31	10	−10	−33	−57	−84	−113	−144	−179	−218	−263	−316	−378			
96.00		31	11	−9	−32	−56	−81	−109	−139	−173	−210	−253	−301	−358	−425		
120.00		31	11	−9	−31	−54	−80	−107	−137	−169	−205	−246	−293	−347	−410		
168.00		31	12	−8	−30	−53	−78	−105	−133	−165	−200	−239	−283	−334	−393		
Flat		32	13	−7	−28	−50	−73	−99	−125	−154	−186	−221	−260	−303	−353	−410	

* Super_k™ FOAMGLAS® insulation is a registered trademark of Pittsburgh Corning Corporation.

TABLE B7.15M Cellular Glass Insulation Thickness Table (Cold)

Recommended lower pipe temperature limits for given insulation thickness (°C)
Insulation material: Super_k™ FOAMGLAS® insulation
Ambient temperature = 32°C Heat flow limit = −31.5 W/m^2
Wind velocity = 8 km/h Emittance = 0.9

	Insulation thickness (in) Super_k™ FOAMGLAS® insulation*																
NPS	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0
0.05	−4	−35	−70	−95	−154	−238											
0.75	1	−25	−55	−76	−124												
1.00	−3	−27	−58	−98	−148	−219											
1.50	0	−19	−32	−62	−96	−140	−202										
2.00	1	−18	−42	−70	−105	−149	−220										
2.50	2	−6	−27	−50	−79	−114	−165	−229									
3.00	4	−12	−32	−55	−83	−121	−166	−227									
4.00	5	−10	−28	−49	−77	−108	−145	−210									
5.00	6	−7	−24	−46	−69	−96	−138	−182	−241								
6.00	7	−5	−23	−42	−63	−94	−125	−164	−214								
8.00		−6	−21	−42	−62	−85	−112	−145	−186	−239							
10.00		−7	−21	−37	−55	−76	−100	−128	−163	−206	−262						
12.00		−6	−20	−35	−53	−72	−95	−121	−152	−190	−239						
14.00		−2	−16	−30	−47	−65	−86	−110	−139	−173	−216						
16.00		−2	−15	−29	−45	−63	−83	−106	−132	−164	−204	−253					
18.00		−2	−15	−28	−44	−61	−80	−102	−128	−158	−194	−240					
20.00		−2	−14	−27	−43	−60	−78	−99	−124	−152	−187	−229					
24.00		−1	−13	−26	−41	−57	−75	−95	−118	−144	−175	−214	−260				
28.00		−1	−13	−25	−40	−56	−73	−92	−114	−138	−168	−203	−246				
30.00		−1	−13	−24	−40	−55	−72	−91	−112	−136	−164	−198	−240				
36.00		0	−12	−24	−39	−54	−70	−88	−108	−131	−157	−188	−226				
42.00		0	−12	−23	−38	−52	−68	−86	−105	−127	−152	−181	−217	−259			
48.00		0	−12	−23	−37	−51	−67	−84	−103	−124	−148	−176	−209	−249			
60.00		0	−11	−23	−36	−50	−65	−82	−100	−120	−143	−169	−199	−236			
72.00		0	−11	−22	−36	−49	−64	−80	−98	−117	−139	−164	−193	−227			
96.00		0	−11	−22	−35	−48	−63	−78	−95	−114	−134	−158	−185	−217	−254		
120.00		0	−11	−22	−35	−48	−62	−77	−93	−112	−132	−154	−180	−210	−245		
168.00		0	−11	−22	−34	−47	−61	−76	−92	−109	−129	−150	−175	−203	−236		
Flat		0	−10	−21	−33	−45	−58	−72	−87	−103	−121	−140	−162	−186	−214	−246	

* Super_k™ FOAMGLAS® insulation is a registered trademark of Pittsburgh Corning Corporation.

which tends to keep it drier than calcium silicate. Perlite insulation is also made in molds to fit the range of pipe-covering shapes required by industry. It is usually applied with metal bands and covered with a metal jacket.

Phenolic Foam Insulation. Phenolic foam is a very low thermal conductivity organic foam insulation used primarily for plastic piping in freeze protection applications. Phenolic foam insulation is made in a catalyst reaction bun and is cut in a fabrication process to the sizes needed for the applications. It is generally applied with tape or wire and covered with all-service jacket or metal jacket depending on the ambient conditions and the geography.

Polystyrene Insulation. Polystyrene is a very inexpensive, efficient thermal insulation used almost exclusively in residential and food processing applications. It comes in expanded boards and extruded buns. The extruded buns are sometimes used to fabricate pipe covering for chilled water lines or water and sewer lines. In residential applications it is used in the wall panels. In food processing it is used in the walls

TABLE B7.16 Polyurethane or Polyisocyanurate Insulation Thickness Table (Cold)
Recommended lower pipe temperature limits for given insulation thickness (°F)
Insulation material: urethane
Ambient temperature = 90.0°F Heat flow limit = −10.0 ± 0.1 Btu/(h · ft^2)
Wind velocity = 5.0 mph Emittance = 0.9

	Insulation thickness (in)																
NPS	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0
0.05	−18	−94	−171	−359													
0.75	0	−69	−138	−289	−425												
1.00	−15	−74	−144	−230	−345												
1.50	−2	−55	−152	−226	−328	−443											
2.00	0	−52	−109	−170	−245	−349											
2.50	3	−74	−128	−189	−265	−384											
3.00	8	−38	−85	−137	−197	−283	−386										
4.00	9	−32	−76	−124	−185	−251	−339										
5.00	13	−25	−67	−118	−167	−225	−322	−416									
6.00	17	−20	−65	−108	−154	−222	−291	−381									
8.00		−21	−59	−109	−153	−202	−261	−338	−421								
10.00		−23	−60	−98	−138	−183	−234	−299	−379	−448							
12.00		−21	−57	−93	−132	−174	−222	−281	−354	−428							
14.00		−12	−46	−82	−119	−159	−204	−257	−323	−399							
16.00		−11	−45	−79	−116	−154	−197	−247	−308	−382	−445						
18.00		−10	−44	−78	−113	−150	−192	−239	−297	−367	−433						
20.00		−10	−42	−76	−111	−147	−187	−233	−288	−355	−422						
24.00		−9	−41	−73	−107	−142	−180	−223	−274	−336	−404						
28.00		−8	−40	−72	−104	−139	−176	−217	−264	−323	−389	−444					
30.00		−8	−39	−71	−103	−137	−174	−214	−260	−317	−382	−439					
36.00		−7	−38	−69	−101	−134	−169	−207	−251	−304	−366	−425					
42.00		−7	−37	−68	−99	−131	−166	−203	−245	−295	−354	−414					
48.00		−6	−36	−67	−98	−129	−163	−199	−240	−288	−345	−405					
60.00		−6	−36	−65	−96	−127	−159	−194	−233	−279	−332	391	−440				
72.00		−5	−35	−65	−94	−125	−157	−191	−229	−272	324	−381	−432				
96.00		−5	−34	−63	−93	−123	−154	−187	−223	−264	−313	−368	−420				
120.00		−5	−34	−63	−92	−121	−152	−184	−220	−260	−306	−360	−412				
168.00		−4	−33	−62	−91	−120	−150	−181	−216	−254	−299	−350	−402	−444			
Flat		−4	−32	−60	−88	−116	−144	−174	−206	−241	−281	−327	−377	−421			

and on the roofs. It has a low permeability rating and is easy to work with. It is applied with bands, tape, wire, or glue depending on the application.

Polyurethane and Polyisocyanurate Foam Insulations. Polyurethane and polyisocyanurate foams are two chemically different insulation materials; however, their cell structure and physical properties are so similar that they are usually lumped into a common category. This is probably not fair to polyisocyanurate foam insulation because it generally tends to be of higher quality. Both insulations have very good thermal properties. They are used from about −200°F (−129°C) up to 300°F (149°C) both indoors and outdoors. On cold applications they require multiple layers due to the contraction characteristics. These insulations are manufactured in batch bun processing and then sold to fabricators who cut them into various shapes and sizes depending on the applications. These insulation materials are usually applied with tape or wire and covered with either a fabric-reinforced mastic or a metal jacket.

TABLE B7.16M Polyurethane or Polyisocyanurate Insulation Thickness Table (Cold)

Recommended lower pipe temperature limits for given insulation thickness (°C)
Insulation material: urethane insulation
Ambient temperature = 32°C Heat flow limit = 2.93 W/m^2
Wind velocity = 8 km/h Emittance = 0.9

	Insulation thickness (in)																
NPS	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0
0.05	−28	−70	−113	−217													
0.75	−17	−56	−94	−178	−254												
1.00	−26	−59	−98	−145	−209												
1.50	−19	−48	−102	−143	−200	−264											
2.00	−17	−46	−78	−112	−154	−211											
2.50	−15	−59	−88	−122	−165	−231											
3.00	−12	−39	−65	−94	−127	−175	−232										
4.00	−12	−35	−60	−87	−120	−157	−206										
5.00	−10	−32	−55	−83	−110	−143	−196	−248									
6.00	−8	−29	−54	−77	−103	−141	−179	−229									
8.00		−29	−50	−78	−102	−130	−163	−205	−251								
10.00		−30	−51	−72	−94	−119	−148	−184	−228	−266							
12.00		−29	−49	−69	−91	−114	−141	−173	−214	−255							
14.00		−24	−43	−63	−84	−106	−131	−160	−197	−239							
16.00		−24	−42	−62	−82	−103	−127	−155	−189	−230	−265						
18.00		−23	−42	−61	−80	−101	−124	−150	−182	−222	−258						
20.00		−23	−41	−60	−79	−99	−122	−147	−177	−215	−252						
24.00		−22	−40	−58	−77	−97	−118	−142	−170	−204	−242						
28.00		−22	−40	−57	−76	−95	−115	−138	−164	−197	−233	−264					
30.00		−22	−39	−57	−75	−94	−114	−136	−162	−194	−230	−261					
36.00		−21	−39	−56	−74	−92	−111	−133	−157	−186	−221	−254					
42.00		−21	−38	−55	−73	−90	−110	−130	−154	−181	−214	−247					
48.00		−21	−38	−55	−72	−89	−108	−128	−151	−178	−209	−242					
60.00		−21	−37	−54	−71	−88	−106	−126	−147	−172	−202	−235	−262				
72.00		−21	−37	−53	−70	−87	−105	−124	−145	−169	−197	−229	−257				
120.00		−20	−36	−52	−68	−85	−102	−120	−140	−162	−188	−218	−246				
168.00		−20	−36	−52	−68	−84	−101	−118	−137	−159	−184	−212	−241	−264			
Flat		−20	−35	−51	−66	−82	−98	−114	−132	−152	−174	−199	−227	−252			

TABLE B7.17 Calcium Silicate Insulation *k* Value Table
Thermal conductivity as a function of temperature for calcium silicate (calsil)

English units		Non-SI metric units		SI units	
At uniform temperature (°F)	Thermal conductivity [Btu · in/(h · ft^2 · °F)]	At uniform temperature (°C)	Thermal conductivity [kcal/(h · m^2 · °C)]	At uniform temperature (K)	Thermal conductivity [W/(m · K)]
0.0	0.373	−17.8	0.0462	255.4	0.0537
50.0	0.388	10.0	0.0481	283.1	0.0559
100.0	0.403	37.8	0.0499	310.9	0.0580
150.0	0.418	65.6	0.0518	338.7	0.0602
200.0	0.433	93.3	0.0537	366.5	0.0624
250.0	0.449	121.1	0.0557	394.3	0.0647
300.0	0.466	148.9	0.0577	422.0	0.0671
350.0	0.483	176.7	0.0599	449.8	0.0696
400.0	0.501	204.4	0.0622	477.6	0.0722
450.0	0.521	232.2	0.0646	505.4	0.0750
500.0	0.541	260.0	0.0671	533.2	0.0780
550.0	0.563	287.8	0.0698	560.9	0.0812
600.0	0.587	315.6	0.0728	588.7	0.0846
650.0	0.612	343.3	0.0759	616.5	0.0882
700.0	0.639	371.1	0.0793	644.3	0.0921
750.0	0.668	398.9	0.0829	672.0	0.0963
800.0	0.700	426.7	0.0868	699.8	0.1008
850.0	0.733	454.4	0.0909	727.6	0.1057
900.0	0.769	482.2	0.0954	755.4	0.1109
950.0	0.808	510.0	0.1002	783.2	0.1165
1000.0	0.849	537.8	0.1053	810.9	0.1224

The values of the thermal conductivity of the insulation shown above were determined by evaluating a polynomial at the insulation temperature. This polynomial, giving the thermal conductivity in Btu · in/(h · ft^2 · °F) as a function of temperature in °F, is $K(T) = 0.3728 + 2.98\text{E-}4(T) - 2.3\text{E-}8(T^2) + 2.02\text{E-}10(T^3)$.

This curve is based on an insulation density of 16.0 lb/ft^3 and may be subject to decreasing reliability outside the temperature range from 250.0 to 1000.0°F.

TABLE B7.18 Super_k™ FOAMGLAS® Insulation K Value Table
Thermal conductivity as a function of temperature for Super_k™ FOAMGLAS® insulation*

English units		Non-SI metric units		SI units	
At uniform temperature (°F)	Thermal conductivity [Btu · in/(h · ft^2 · °F)]	At uniform temperature (°C)	Thermal conductivity [kcal/(h · m^2 · °C)]	At uniform temperature (K)	Thermal conductivity [W/(m · K)]
−300.0	0.109	−184.4	0.0135	88.7	0.0156
−250.0	0.126	−156.7	0.0156	116.5	0.0181
−200.0	0.146	−128.9	0.0181	144.3	0.0210
−150.0	0.168	−101.1	0.0208	172.0	0.0242
−100.0	0.193	−73.3	0.0239	199.8	0.0278
−50.0	0.219	−45.6	0.0272	227.6	0.0316
0.0	0.247	−17.8	0.0307	255.4	0.0356
50.0	0.277	10.0	0.0344	283.1	0.0399
100.0	0.309	37.8	0.0383	310.9	0.0455
150.0	0.342	65.6	0.0425	338.7	0.0494
200.0	0.378	93.3	0.0469	366.5	0.0545
250.0	0.416	121.1	0.0516	394.3	0.0600
300.0	0.457	148.9	0.0566	422.0	0.0658
350.0	0.500	176.7	0.0621	449.8	0.0721
400.0	0.548	204.4	0.0679	477.6	0.0789
450.0	0.599	232.2	0.0742	505.4	0.0863
500.0	0.654	260.0	0.0811	533.2	0.0943
550.0	0.715	287.8	0.0887	560.9	0.1031
600.0	0.782	315.6	0.0969	588.7	0.1127
650.0	0.855	343.3	0.1060	616.5	0.1232
700.0	0.935	371.1	0.1159	644.3	0.1347
750.0	1.023	398.9	0.1268	672.0	0.1474
800.0	1.119	426.7	0.1388	699.8	0.1613
850.0	1.225	454.4	0.1520	727.6	0.1766
900.0	1.342	482.2	0.1664	755.4	0.1934

* Super_k™ FOAMGLAS® insulation is a registered trademark of Pittsburgh Corning Corporation.

The values of the thermal conductivity of the insulation shown above were determined by evaluating a polynomial at the insulation temperature. This polynomial, giving the thermal conductivity in Btu · in/(h · ft^2 · °F) as a function of temperature in °F, is $K(T) = 0.2472 + 5.811\text{E-}4(T) + 3.4561\text{E-}7(T^2) + 3.2\text{E-}13(T^3) + 5.3092\text{E-}13(T^4) - 9.64\text{E-}17(T^5)$.

This curve is based on an insulation density of 7.5 lb/ft^3 and may be subject to decreasing reliability outside the temperature range from −250.0 to 800.0°F.

TABLE B7.19 Fiberglas Insulation *K* Value Table
Thermal conductivity as a function of temperature for fiberglass

English units		Non-SI metric units		SI units	
At uniform temperature (°F)	Thermal conductivity [Btu · in/(h · ft² · °F)]	At uniform temperature (°C)	Thermal conductivity [kcal/(h · m² · °C)]	At uniform temperature (K)	Thermal conductivity [W/(m · K)]
0.0	0.195	−17.8	0.0241	255.4	0.0280
50.0	0.216	10.0	0.0268	283.1	0.0311
100.0	0.237	37.8	0.0294	310.9	0.0342
150.0	0.258	65.6	0.0320	338.7	0.0372
200.0	0.280	93.3	0.0347	366.5	0.0403
250.0	0.301	121.1	0.0373	394.3	0.0433
300.0	0.322	148.9	0.0399	422.0	0.0464
350.0	0.343	176.7	0.0426	449.8	0.0495
400.0	0.364	204.4	0.0452	477.6	0.0525
450.0	0.386	232.2	0.0478	505.4	0.0556
500.0	0.407	260.0	0.0505	533.2	0.0587
550.0	0.428	287.8	0.0531	560.9	0.0617
600.0	0.449	315.6	0.0557	588.7	0.0648
650.0	0.471	343.3	0.0584	616.5	0.0678
700.0	0.492	371.1	0.0610	644.3	0.0709
750.0	0.513	398.9	0.0636	672.0	0.0740
800.0	0.534	426.7	0.0663	699.8	0.0770
850.0	0.556	454.4	0.0689	727.6	0.0801

The values of the thermal conductivity of the insulation shown above were determined by evaluating a polynomial at the insulation temperature. This polynomial, giving the thermal conductivity in Btu · in/(h · ft² · °F) as a function of temperature in °F, is $K(T) = 0.195 + 4.25\text{E-}4(T) + 0.0000(T^2)$.

This curve is based on an insulation density of 5.63 lb/ft³ and may be subject to decreasing reliability outside the temperature range from 42.0 to 800.0°F.

TABLE B7.20 Mineral Wool Insulation *K* Value Table
Thermal conductivity as a function of temperature for mineral wool

English units		Non-SI metric units		SI units	
At uniform temperature (°F)	Thermal conductivity [Btu · in/(h · ft^2 · °F)]	At uniform temperature (°C)	Thermal conductivity [kcal/(h · m^2 · °C)]	At uniform temperature (K)	Thermal conductivity [W/(m · K)]
0.0	0.228	−17.8	0.0283	255.4	0.0329
50.0	0.248	10.0	0.0307	283.1	0.0357
100.0	0.271	37.8	0.0336	310.9	0.0391
150.0	0.297	65.6	0.0368	338.7	0.0428
200.0	0.326	93.3	0.0405	366.5	0.0470
250.0	0.358	121.1	0.0444	394.3	0.0516
300.0	0.393	148.9	0.0488	422.0	0.0567
350.0	0.432	176.7	0.0535	449.8	0.0622
400.0	0.473	204.4	0.0586	477.6	0.0681
450.0	0.517	232.2	0.0641	505.4	0.0745
500.0	0.564	260.0	0.0699	533.2	0.0813
550.0	0.614	287.8	0.0761	560.9	0.0885
600.0	0.667	315.6	0.0827	588.7	0.0961
650.0	0.723	343.3	0.0897	616.5	0.1042
700.0	0.782	371.1	0.0970	644.3	0.1127
750.0	0.844	398.9	0.1047	672.0	0.1217
800.0	0.909	426.7	0.1128	699.8	0.1311
850.0	0.978	454.4	0.1212	727.6	0.1409
900.0	1.049	482.2	0.1300	755.4	0.1511
950.0	1.123	510.0	0.1392	783.2	0.1618
1000.0	1.200	537.8	0.1488	810.9	0.1729
1050.0	1.280	565.6	0.1587	838.7	0.1845
1100.0	1.363	593.3	0.1690	866.5	0.1965
1150.0	1.499	621.1	0.1797	894.3	0.2089
1200.0	1.538	648.9	0.1908	922.2	0.2217

The values of the thermal conductivity of the insulation shown above were determined by evaluating a polynomial at the insulation temperature. This polynomial, giving the thermal conductivity in Btu · in/(h · ft^2 · °F) as a function of temperature in °F, is $K(T) = 0.228 + 3.72\text{E-}4(T) + 6.0\text{E-}7(T^2)$.

This curve is based on an insulation density of 11.7 lb/ft^3 and may be subject to decreasing reliability outside the temperature range from 42.0 to 1100.0°F.

TABLE B7.21 Perlite Insulation *K* Value Table
Thermal conductivity as a function of temperature for perlite

English units		Non-SI metric units		SI units	
At uniform temperature (°F)	Thermal conductivity [Btu · in/(h · ft^2 · °F)]	At uniform temperature (°C)	Thermal conductivity [kcal/(h · m^2 · °C)]	At uniform temperature (K)	Thermal conductivity [W/(m · K)]
0.0	0.403	−17.8	0.0500	255.4	0.0581
50.0	0.434	10.0	0.0538	283.1	0.0626
100.0	0.464	37.8	0.0575	310.9	0.0668
150.0	0.492	65.6	0.0610	338.7	0.0709
200.0	0.519	93.3	0.0644	366.5	0.0748
250.0	0.546	121.1	0.0677	394.3	0.0787
300.0	0.572	148.9	0.0709	422.0	0.0824
350.0	0.598	176.7	0.0741	449.8	0.0862
400.0	0.624	204.4	0.0774	477.6	0.0899
450.0	0.650	232.2	0.0806	505.4	0.0937
500.0	0.677	260.0	0.0840	533.2	0.0976
550.0	0.705	287.8	0.8740	560.9	0.1016
600.0	0.734	315.6	0.0910	588.7	0.1058
650.0	0.764	343.3	0.0948	616.5	0.1101
700.0	0.796	371.1	0.0987	644.3	0.1148
750.0	0.830	398.9	0.1029	672.0	0.1196
800.0	0.866	426.7	0.1074	699.8	0.1248
850.0	0.905	454.4	0.1122	727.6	0.1304
900.0	0.946	482.2	0.1173	755.4	0.1363
950.0	0.990	510.0	0.1228	783.2	0.1427
1000.0	1.038	537.8	0.1287	810.9	0.1496

The values of the thermal conductivity of the insulation shown above were determined by evaluating a polynomial at the insulation temperature. This polynomial, giving the thermal conductivity in Btu · in/(h · ft^2 · °F) as a function of temperature in °F, is $K(T) = 0.4030 + 6.38\text{E-}4(T) - 3.56\text{E-}7(T^2) + 3.53\text{E-}10(T^3)$.

This curve is based on an insulation density of 12.0 lb/ft^3 and may be subject to decreasing reliability outside the temperature range from 250.0 to 1000.0°F.

TABLE B7.22 Polyurethane or Polyisocyanurate Foam Insulation *K* Value Table
Thermal conductivity as a function of temperature for urethane

English units		Non-SI metric units		SI units	
At uniform temperature (°F)	Thermal conductivity [$\mathrm{Btu \cdot in/(h \cdot ft^2 \cdot {}^\circ F)}$]	At uniform temperature (°C)	Thermal conductivity [$\mathrm{kcal/(h \cdot m^2 \cdot {}^\circ C)}$]	At uniform temperature (K)	Thermal conductivity [$\mathrm{W/(m \cdot K)}$]
−100.0	0.179	−73.3	0.0222	199.8	0.0258
−50.0	0.179	−45.6	0.0223	227.6	0.0259
0.0	0.174	−17.8	0.0215	255.4	0.0250
50.0	0.166	10.0	0.0206	283.1	0.0239
100.0	0.165	37.8	0.0204	310.9	0.0238
150.0	0.180	65.6	0.0223	338.7	0.0260
200.0	0.225	93.3	0.0279	366.5	0.0324
250.0	0.316	121.1	0.0391	394.3	0.0455
300.0	0.470	148.9	0.0583	422.0	0.0677
350.0	0.710	176.7	0.0880	449.8	0.1023

The values of the thermal conductivity of the insulation shown above were determined by evaluating a polynomial at the insulation temperature. This polynomial, giving the thermal conductivity in $\mathrm{Btu \cdot in/(h \cdot ft^2 \cdot {}^\circ F)}$ as a function of temperature in °F, is $K(T) = 0.1735 - 1.549\text{E-}4(T) - 3.389\text{E-}7(T^2) + 8.377\text{E-}9(T^3) + 1.819\text{E-}11(T^4)$.

This curve is based on an insulation density of 2.0 $\mathrm{lb/ft^3}$ and may be subject to decreasing reliability outside the temperature range from −50.0 to 250.0°F.

ACCESSORY MATERIALS

The accessory materials referenced in the above paragraphs and throughout the chapter are a necessary part of the insulation system. There are many manufacturers and suppliers of these materials, and the quality can vary dramatically from one to another. The following are a few of the more common accessory materials used in industrial and commercial insulation system specifications. See also Table B7.23.

Acrylic Latex Mastic

Acrylic latex mastic is a heavy-bodied weather barrier coating used primarily to cover rigid insulations such as cellular glass and polyurethane. It is generally applied in two coats with a reinforcing mesh fabric for impact and tear resistance. This material does not provide vapor protection.

Aluminum Banding

Aluminum bands are used as securement for many types of insulation materials. The most common sizes specified are 0.5 in × 0.020 in (13 mm × 0.5 mm) aluminum bands with matching seals for piping vessels, or equipment with ODs of 48 in (1219 mm) or less. For larger ODs, use 0.75 in × 0.020 in) (19 mm × 0.5 mm) aluminum bands. These bands are secured in place with metal band clips or seals of common dimensions. Aluminum bands should not be used in applications where the insulation is being installed for fire protection applications.

TABLE B7.23 ASTM Specification Reference

Material	ASTM Specification
Calcium silicate	C533-95
Cellular glass	C552-91
Elastomeric foam	C534-94
Fiberglass and mineral wool	C553-92, C547-95, C612-93
Expanded perlite	C610-95
Phenolic foam	C1126-96
Polystyrene foam	C578-95
Polyurethane modified polyisocyanurate foam	C591-94
Aluminum jacketing and banding	C921-96
Stainless steel jacketing and banding	C921-96
FRP	C921-96
ASJ	C921-96
Asphalt cutback mastic	C647-95
Acrylic latex mastic	C647-95
Hypalon mastic	C647-95
6 × 6 mesh fabric	NA
10 × 10 glass scrim	D1668-86

Aluminum Jacketing

Aluminum jacketing comes in many different sizes and finishes. In piping applications, either smooth or slightly embossed jacketing of 0.016 in (0.4-mm) thickness is most common. When specifying aluminum jacketing for use with permeable and hygroscopic insulation materials, it is important to specify the jacketing with a factory-applied moisture barrier liner.

ASJ

ASJ jacketing stands for all-service jacket. This material is a Kraft paper/foil/scrim laminate material used exclusively on indoor commercial applications. ASJ jacketing is usually factory-applied and serves the primary function of providing protection to the outer insulation surface. These are classified as vapor retarders.

Asphalt Cutback Mastic

Asphalt cutback mastics are heavy-bodied asphalts that are cut with mineral spirits so they can be applied by spraying or with a trowel. When applied, the mineral spirits dissipate, and leave behind a hard asphaltic vapor barrier finish. It is generally applied in multiple coats used in conjunction with reinforcing fabric. Metal jackets are used to cover this finish on aboveground, outdoor applications for ultraviolet protection to the mastic.

FRP Jacketing

FRP stands for *fiber resin plastic* or *fiber-reinforced plastic.* Either definition is acceptable. The material is a hard plastic membrane reinforced with glass fibers. FRP jacketing can be used in many of the same applications where aluminum is used. FRP jacketing is often the material of choice in chemical resistance areas. The jacketing comes in sheet or rolled form, and the laps are sealed with a resin sealant recommended by the manufacturer.

Hypalon Mastics

Hypalon is a trade name for a highly flexible and durable vapor barrier mastic material. There are numerous products on the market that use this material in their compositions to form what are referred to as *elastomeric membranes.* These elastomeric membranes are referred to as *hypalons.* Hypalons are usually reinforced with a 10 × 10 or a 10 × 20 fiberglass fabric to provide stability and tear resistance. Hypalon mastics should not be used in conjunction with cellular glass.

Stainless Steel Banding

Stainless steel bands are used to support or secure insulation materials to piping, tanks, or vessels. Typical sizes specified are 0.5 in × 0.015 in (13 mm × 0.38 mm) stainless steel bands with matching clips or seals for caustic service or where the insulation is being used for fire protection applications.

Stainless Steel Jacketing

Stainless steel jacketing is used to cover insulation materials of all types for various applications. Due to the cost, stainless steel is generally used where it is required for its chemical or fire resistance. Stainless steel usually has a smooth finish and is 0.010 in (0.25 mm) thick. On some large diameter applications 0.015 in (0.38 mm) thick may be specified.

Stainless Steel Tie Wire

Wire may be used to secure fittings or insulation sections. Check with the insulation manufacturer for recommendations on its usage. Soft annealed wire is best suited for field conditions, so as not to work-harden in the field. Wire is typically utilized in 18 and 16 gage thicknesses.

Fiberglass-Reinforced Tape

Tape is typically 1-in (25 mm) wide, high-tensile-strength, fiber-reinforced, strapping tape. Tape is appropriate for providing temporary insulation securement for piping with insulation ODs 18 in (457 mm) or smaller as long as it is covered with metal jacket afterward. Tape is not acceptable as a primary means of securement if the insulation system is being designed to provide fire protection.

Mesh Fabric

A 6 × 6 mesh refers to the number of strands of primary fiber in 1 in^2 of fabric (2.4 meshes/cm^2). A 6 × 6 mesh will have six primary strands going in one direction and six primary strands perpendicular. In a polyester mesh fabric, the primary strands are woven together by a method designed to create a fabric that does not fray or pucker. This fabric is typically specified to accompany applications of heavy-bodied mastics such as acrylic latex and asphalt cutback.

Glass Scrim

Glass scrims come in many different configurations. The most common scrims used in industrial and commercial piping applications are the 10 × 10 (3.9 meshes/cm^2) or the 10 × 20. As with the mesh fabric, the numerical designation refers to the number of primary strands in 1 in^2 of fabric. Glass scrims are best suited to light-bodied mastics, paints, and elastomeric membranes.

REFERENCES

1. National Insulation Contractors Association, Insulation Craft Training Program, *''Theory of Heat Transfer and Moisture Effects on Insulation.''*
2. American Society for Testing and Materials, *Annual Book of Standards,* Vol. 4.06, *Thermal Insulation; Environmental Accoustics.*
3. Charles M. Pelanne, *''Heat Flow Principles,''* Johns Manville Refractory Products Research and Development Division, August 1976.
4. Charles W. Sisler, *''Thermal Insulation Design Concepts,''* Monsanto, Inc.
5. NFPA 30, *The Flammable and Combustible Liquids Code,* 1990 ed. National Fire Protection Association, Quincy, MA,
6. API Recommended Practice 521-82, *Guide for Pressure Relieving and Depressurizing Systems.*
7. Ludwig Adams, *''Thermal Conductivity of Wet Insulations,'' ASHRAE Journal,* October 1974.
8. *ASHRAE Fundamentals Handbook,* Table 2, ''Thermodynamic Properties of Water in Saturation,'' American Society of Heating, Refrigerating, and Air Conditioning Engineers, 1997.
9. William C. Turner and John F. Malloy, *Thermal Insulation Handbook,* Robert E. Krieger/McGraw-Hill, New York, 1981.
10. *Therminol Heat Transfer Fluid,* Data Sheet Monsanto MIC-4-081, Industrial Chemicals Co., pp. 1–24.
11. P.C. Bowes, ''Fires in Oil Soaked Lagging,'' Building Research Establishment Current Paper, CP 35/74, February 1974, pp. 1–11.
12. Fire Hazards in Oxygen Enriched Atmosphere, NFPA 53M, National Fire Protection Association, Quincy, MA, 1990.
13. ''Precautions for the Proper Usage of Polyurethanes, Polyisocyanurates and Related Materials,'' *Technical Bulletin,* The Upjohn Chemical Division, Vol. 107, May 1980, p. 44.

BIBLIOGRAPHY

‘‘Accident Prevention in High Temperature Heat Transfer Fluid Systems,’’ A.R. Albrecht and W.F. Seifert, Reference paper presented at Loss Prevention Symposium, 76th Annual Meeting, American Institute of Chemical Engineers, Atlanta, GA, February, 15–18, 1970 (Dow Chemical Company, revised and updated May 1987), pp. 11–33.

American Society for Testing and Materials, *Annual Book of Standards,* vol. 4.06, *Thermal Insulation; Environmental Acoustics.*

ASHRAE Fundamentals Handbook, American Society of Heating and Refrigerating Engineering, 1989.

‘‘Criteria for Installing Insulation Systems in Petrochemical Plants,’’ W.C. Turner, *Chemical Engineering Progress,* vol. 70, no. 8, August 1974, pp. 3–7.

Fire Hazards in Oxygen Enriched Atmosphere, National Fire Protection Association, Quincy, MA, ANSI/NFPA 53M, December 7, 1985 pp. 10, 17.

‘‘Fires in Oil Soaked Lagging,’’ P.C. Bowes, Building Research Establishment Current Paper, CP 35/74, February 1974, pp. 1–11.

‘‘Heat Flow Principles,’’ Charles M. Pelanne, Johns Manville Refractory Products Research and Development Division, August 1976.

‘‘Heating with Mobiltherm Heat-Transfer Oils’’ Mobil Oil Corporation, *Mobil Technical Bulletin,* TBL6887101, September 3, 1988, pp. 1–15.

‘‘Method for Fire Hazard Assessment of Fluid-Soaked Thermal Insulation,’’ Robert R. Buch and Daniel H. Filsinger, *Plant/Operations Progress*, vol. 4, July 1985, pp. 176–180.

National Insulation Contractors Association, Insulation Craft Training Program, ‘‘Theory of Heat Transfer and Moisture Effects on Insulation.’’

‘‘Precautions for the Proper Usage of Polyurethanes, Polyisocyanurates and Related Materials,’’ *Technical Bulletin,* Upjohn Chemical Division, vol. 107, May 1980, p. 44.

‘‘Thermal Conductivity of Wet Insulations,’’ *Ludwig Ada Journal*, October 1974.

‘‘Thermal Insulation Design Concepts,’’ Charles W. Sisl Inc.

Thermal Insulation Handbook, William C. Turner and John F. Malloy, Robert E. Krieger Publishing Company, 1981, McGraw-Hill Book Company.

Therminol Heat Transfer Fluid, Data Sheet MIC-4-081, Monsanto Industrial Chemicals Company, pp. 1–24.