*Kirk-Othmer Encyclopedia of Chemical Technology.*

# INSULATION, THERMAL

## 1. Insulation

A variety of cellular plastics exists for use as thermal insulation as basic materials and products, or as thermal insulation systems in combination with other materials (see Foamed plastics). Polystyrenes, polyisocyanurates (which include polyurethanes), and phenolics are most commonly available for general use, however, there is increasing use of other types including polyethylenes, polyimides, melamines, and poly(vinyl chlorides) for specific applications.

Originally polystyrenes and polyurethanes were developed for applications involving severe environmental conditions. In the 1990s, however, primary applications include use in refrigerators and freezers, where cellular plastics account for over 90% of total insulation; in the building envelope, ie, from foundation to roof, 70%; and in walls, sheathings, and basements, ca 40%. Other uses include pipelines, refrigerated transportation, chemical processing, road and runway beds, and cryogenic applications.

Foamed plastics (qv) were developed in Europe and the United States in the mid-to-late 1930s. In the mid-1940s, extruded foamed polystyrene (XEPS) was produced commercially, followed by polyurethanes and expanded (molded) polystyrene (EPS) which were manufactured from beads (1, 2). In response to the requirement for more fire-resistant cellular plastics, polyisocyanurate foams and modified urethanes containing additives were developed in the late 1960s; urea–formaldehyde, phenolic, and other foams were also used in Europe at this time.

The newer open-cell foams, based on polyimides (qv), polybenzimidazoles, polypyrones, polyureas, polyphenylquinoxalines, and phenolic resins (qv), produce less smoke, are more fire resistant and can be used at higher temperatures. These materials are more expensive and used only for special applications including aircraft and marine vessels. Rigid poly(vinyl chloride) (PVC) foams are available in small quantities mainly for use in composite panels and piping applications (see Flame retardants; Heat-resistant polymers).

Cellular plastics have been used extensively for low temperature applications (3–5); however, uses for cellular plastic insulations, particularly molded and extruded polystyrenes, polyisocyanurates, and phenolics, have expanded into the building arena (6–10) as a result of the energy crisis of the early 1970s, when the use of increased insulation for energy conservation became more economically attractive. All national codes and standards specify the need for levels of insulation in the building envelope (foundation to roof) dependent on the climatic region, and building applications in the 1990s account for over 80% of the total volume of cellular plastic materials used for insulation purposes (11) (see Building materials).

## 2. Function of Thermal Insulation

Three basic mechanisms of heat transmission occur in thermal insulation: radiation (electromagnetic waves) (12), conduction (atomic or molecular collisions), and convection (fluid motion). Radiation is the primary mode

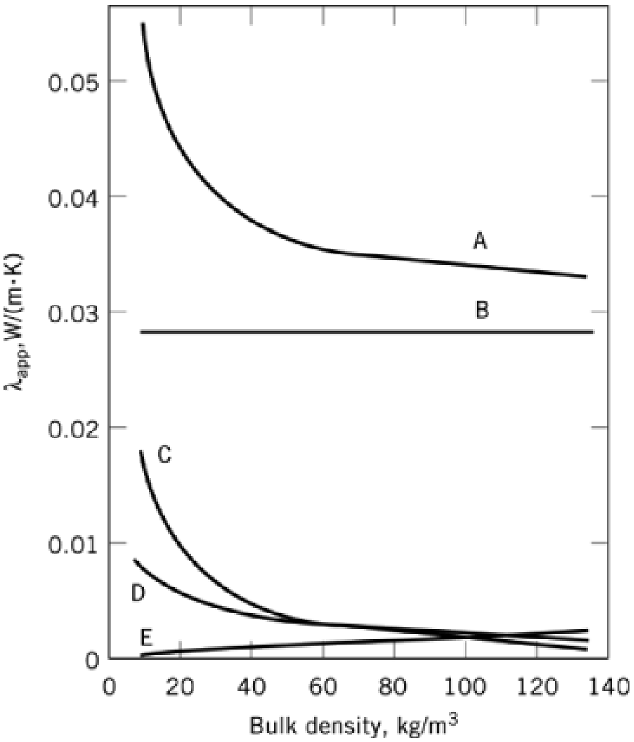

**Fig. 1.** Thermal conductivity components vs density for a typical thermal insulation material at 300 K: A, total conductivity; B, air conduction; C, radiation; D, convection; and E, conduction of solid polymer.

as shown in Figure 1. The function of thermal insulation is to minimize and control these modes. This is accomplished primarily by introducing low emittance–high reflectance barriers to attenuate radiation; incorporating a large number of small, low density, low thermal conductivity elements to minimize solid conduction and convection; and including high density, low thermal conductivity gas, or evacuation of encapsulated systems to minimize convection and gas conduction.

Although thermal performance is a principal property of thermal insulation (13–15), suitability for temperature and environmental conditions; compressive, flexure, shear, and tensile strengths; resistance to moisture absorption; dimensional stability; shock and vibration resistance; chemical, environmental, and erosion resistance; space limitations; fire resistance; health effects; availability and ease of application; and economics are also considerations.

## 3. Cellular Plastics as Insulation

A low $( \leq 0.4\text{W}/(\text{m·K}))$ thermal conductivity polymer, fabricated into a low density foam consisting of a multitude of tiny closed cells, provides good thermal performance. Cellular plastic thermal insulation can be used in the 4–350 K temperature range. Cellular plastic materials have been developed in various types, eg, open-cell, closed-cell (the most energy efficient), and closed-cell containing gases with a thermal conductivity approximately one-half that of air.

Organic foams have excellent thermal insulation characteristics including high strength-to-weight ratio, versatility, and cost effectiveness. They are also self-supporting and can support some load, depending on material and density. Organic foams are available in rigid, semirigid, flexible, and reinforced forms, can be fabricated as board and pipe stock by extrusion, expansion, and molding, and can be applied by spraying, foaming, or frothing. Pellets and beads are used as loose fill.

The drawbacks of cellular materials include limited temperature of applications, poor flammability characteristics without the addition of fire retardants, possible health hazards, uncertain dimensional stability, thermal aging and degradation, friability, and embrittlement due to the effects of uv light (3, 6, 15).

## 4. Materials

### *4.0.1. Polystyrene*

Polystyrene exists in two forms, namely extruded (XEPS) and expanded or molded (EPS). Extruded polystyrene is manufactured by passing a hot mixture of polystyrene, solvent, and pressurized gas, serving as a blowing agent, through an orifice. The gas expands resulting in a fine closed-cell ($>90\%$) structure. The EPS form is fabricated by heating performed polystyrene beads and a blowing agent, such as pentane, in a mold. The vapor pressure of the gas causes the beads to expand thus producing a predominantly closed-cell material.

Polystyrene foams are used in both residential and commercial/industrial buildings for insulating all parts of the building envelope (see Styrene plastics). Where it is used as exterior sheathing and backing of siding, polystyrene foam is often faced with a reflective foil and used in conjunction with an airspace to enhance the total thermal resistance of the system. The high resistance to water absorption of XEPS, as well as its improved mechanical strengths due to a higher density range of use, make it suitable for applications which include building perimeters, foundations, and upside-down roofs generally referred to as protected membrane roof (PMR) (see Roofing materials). The expanded beads alone are used as a loose fill insulation particularly for cavities in masonry constructions.

### *4.0.2. Polyisocyanurate Including Polyurethane*

Polyurethane foams are formed by the reaction of isocyanates and polyfunctional alcohols or polyols in the presence of a suitable blowing agent. Polyisocyanurates are manufactured from isocyanates, a catalyst, and similar blowing agents. A $>90\%$ closed-cell rigid foam is formed by choosing the appropriate isocyanate functionality, alcohol, and molecular weight (see Isocyanates, organic; Urethane polymers).

The foams are available in several forms. Slab stock is manufactured by mixing components and continuously feeding metered mixture onto a conveyor. For laminated material, mixture is fed between impermeable or low permeable facings such as aluminum foils or reinforced papers or plastics. The double-bond lamination process is used extensively with flexible laminates such as paper and reinforced polymer film. The materials can also be formed *in situ* by manual or automatic dispensing of the material components into a closed cavity, eg, appliance components and preformed building panels (16). Finally, a significant and increasing amount of foam is fabricated in the field by directly spraying onto any appropriate clean dry surface, especially roof decks (17).

These foams are used for board stock in commercial and industrial buildings as insulation for internal cavity and external walls, roof, floor, and foundations. Spray-applied foam, covered subsequently with one of a variety of protective coatings, is widely used for large roofing applications and has limited use as external walls. For residential buildings, the principal use is as external sheathing board.

### 4.0.3. Phenolic

The reaction product of a phenol and an aldehyde with a blowing agent in the presence of a catalyst is a phenolic foam. The manufacturing process for faced and unfaced materials is somewhat similar to that for urethane materials and results in a product having greater than 90% closed-cell content. Some open-cell or partially closed-cell materials are manufactured when a hydrocarbon blowing agent is used. Phenolic foams are used mainly for roofing insulation; application is limited as sheathing products for external wall insulation for building applications, and for shaped parts such as pipe and block insulation for industrial applications.

### 4.0.4. Polyethylene

This is essentially a closed-cell insulation manufactured at $448 \pm 2$ K by an extrusion process. A blowing agent and nucleating agent are employed to control the cell size, and primary use is in insulating pipelines for hot and chilled water lines, air conditioning, and processing systems.

### 4.0.5. Polyimide and Melamine

These are both low density, essentially open-cell foams used as pipe insulations, particularly those involved with fluids operating at temperatures up to 530 K. Because these foams operate at higher temperatures and have improved flammability characteristics compared to other foams, they are also used for some aircraft and marine applications.

### 4.0.6. Other

*4.0.6.1. Urea–Formaldehyde and Urea-Based.* In the 1970s and early 1980s, urea materials were in general use particularly for direct field retrofitting of cavity wall construction of wood frame and masonry. However, because of formaldehyde odor and excess shrinkage under specific conditions, this cellular plastic has limited use as an insulation.

## 5. Properties

Significant properties of insulation (Table 1) include thermal conductivity, fire resistance, and minimal production of toxic gases primarily during combustion. Other criteria include water-vapor permeability, resistance to water absorption, and dimensional stability over prolonged periods of submission to extreme environments.

### 5.1. Thermal Conductivity and Aging

Thermal performance is governed by gas conduction and radiation (18–20). In most cellular plastic insulations, radiation is reduced because normal densities of use are $4 - 50\ \mathrm{kg/m^3}$ and the average cell size is $<0.5\ \mathrm{mm}$. For open-cell and other materials containing air (at 24°C, $\gamma = 0.025\mathrm{W/(m{\cdot}K)}$) this results in total values of $\lambda$ at $0.029 - 0.0039\mathrm{W/(m{\cdot}K)}$.

However, for closed-cell extruded polystyrene, polyisocyanurate, and phenolic foams containing high molecular weight and other low thermal conductivity gaseous blowing agents (at 24°C, $\gamma = 0.025\mathrm{W/(m{\cdot}K)}$), the initial values of $\lambda$, as blown, are between 0.013 and $0.02\mathrm{W/(m{\cdot}K)}$. These values can be maintained only if the aging process cannot occur, ie, air cannot diffuse into the cells or the blowing agent cannot diffuse out or partially dissolve into the polymer matrix. To accomplish this, the materials must be contained with impermeable, thick membranes such as metal sheets or hole-free foils well adhered to the cellular polymer. Other more permeable facings, especially if not adhered to the foams faces, allow the aging process to take place.

**Table 1. Typical Properties of Cellular Plastic Materials Used as Thermal Insulation**

| Property | ASTM method | Polyisocyanurate | XEPS[a] | EPS[b] | Polyimide | Polyethylene | Phenolic |
|---|---|---|---|---|---|---|---|
| density, $kg/m^3$ | C591 | 30–40 | 30–48 | 12–30 | 8–12 | 21–32 | 45–60 |
| closed-cell content, % | | >90 | >90 | >90 | <10 | >90 | >90 |
| water-vapor permeability[c] | C355 | 2–3 | 0.4–0.15 | 1–4 | high | 0.02 | <1 |
| water absorption, vol % | C272 | 2–5 | 0.15 | 2–4 | | <1 | <2 |
| thermal expansion $\times 10^{-6}/^{\circ}C$ | E228 | 30–40 | 30–40 | 30–45 | 30–40 | 30–50 | 20–40 |
| heat capacity, J/(kg·K)[d] | C351 | 1500 | 1200–1300 | 1200–1300 | | | 2000 |
| thermal conductivity, W/(m·K) | C518 | $0.026^{e}$ $0.020^{f}$ | 0.028 | 0.038–0.033 | 0.043 | 0.035 | 0.018 |
| fire resistance | E136 | combustible | combustible | combustible | combustible | combustible | combustible |
| flame spread[c] | E84 | 25–50 | 5–15 | 10–25 | 12 | <25 | 20–25 |
| smoke development[a] | E84 | 155–50055–200 | 10–40 | 125 | 7 | <50 | 5–15 |
| toxicity | | toxic gases when burned | CO when burned | CO when burned | CO when burned | CO whenburned | CO when burned |
| dimensional stability, vol % | D2126 | 0–12 | <2 | <1 | | | <1 |
| upper temperature limit, °C | | 120 | 75 | 75 | 260 | 180 | 150 |

[a] Extruded.

[b] Molded.

[c] Arbitrary (qualitative) units given in ASTM test.

[d] To convert J to cal, divide by 4.184.

[e] Aged unfaced.

[f] Impermeable skins.

In general, unless carbon dioxide or another low molecular weight gas such as pentane is used as the blowing agent, the air components diffuse inward much faster than the outward diffusion of the blowing agents. The overall process is represented in Figure 2 which is based on measurements on thin and thick specimens. It occurs in two thickness-dependent stages, a primary $(<180-360\ \mathrm{d})$ and secondary $(\geq 10-20\ \mathrm{yr})$ phase, generally with a clear transition point. The process is complex and each stage occurs at a rate dependent on the polymer type, the structure of the foam, the temperature, the gas type, and its concentration and pressure. The permeation rate, *P,* requires knowledge of the diffusion coefficient, *D,* and the gas solubility, *S,* of the polymer (20).

Some practical results for different types and forms of cellular plastic that do exhibit aging are shown in Figure 3. It is necessary to use such aged values for true performance characteristics especially for specifications and energy use purposes. The more recently developed phenolic foams do not have the same aging characteristics as the extruded polystyrene and polyisocyanurates, probably due to higher density, smaller cell size, thicker cell walls, and lower gas permeability and solubility in the polymer. Similarly the somewhat improved performance of spray-applied urethane is due to a more uniform cell size and structure combined with

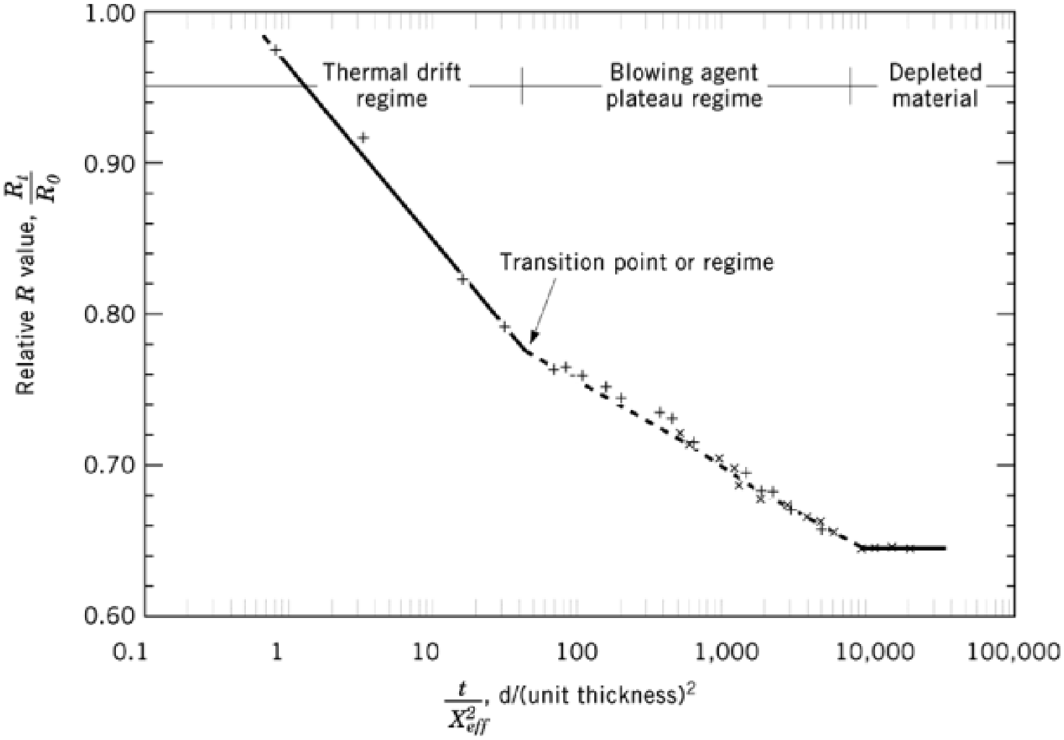

**Fig. 2.** Change in insulation value with time for insulation of various thicknesses. Slice thickness=2.5–6 mm; $R_t$ and $R_0$ are defined as thermal resistance at time *t* and zero, respectively.

the separately applied protective membrane on the outer surface (17). In addition, formation of intermediate higher density skin layers takes place during the application process which normally involves several separate passes of 10–12 mm thick sections to form the required thickness.

Many cellular plastic products are available with different types of protective faces, including composite metal and plastic foils, fiber-reinforced plastic skins, and other coatings. These reduce but do not eliminate the rate of aging. For optimum performance, such membranes must be totally adhered to the foam, and other imperfections such as wrinkles, cuts, holes, and unprotected edges should be avoided because they all contribute to accelerated aging.

### 5.2. Blowing Agents and Accelerated Aging Testing

Until the late 1980s, the fully halogenated chlorofluorocarbons (CFCs), primarily CFC11 and CFC12, were the predominant blowing agents used to produce closed-cell cellular plastic insulations. However, during the 1980s, there had been growing evidence that these gases were contributing both to a depletion of the ozone layer and to an increase in the so-called greenhouse warming effect (21). As a result, the Montreal Protocol, an international agreement whereby CFCs were to be phased out gradually, was developed in 1987 (22). It has been subsequently revised to ensure CFC elimination by the year 2000 at the latest. In addition, there was a nonbinding declaration of intent that the hydrochlorofluorocarbons (HCFCs), the most widely touted substitutes for CFCs, also be phased out no later than 2020 (see Fluorine compounds, organic–fluorinated aliphatic). Attention must also be paid to minimizing the release of either gas when outdated material is disposed of or recycled (see Recycling, plastics).

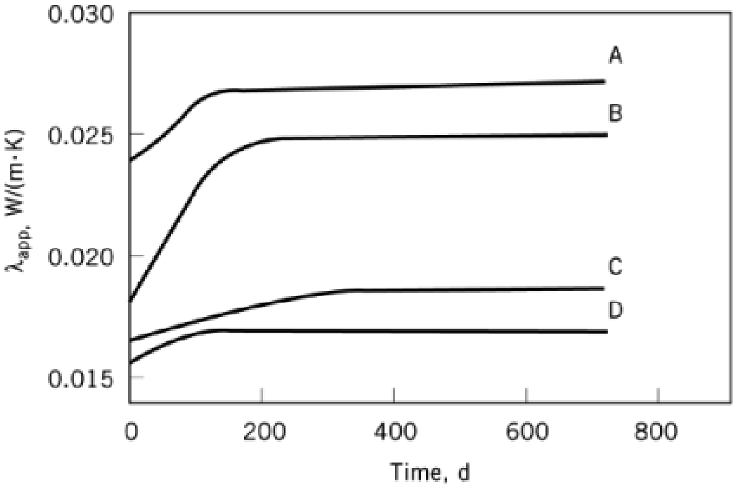

**Fig. 3.** Aging effect on thermal conductivity of cellular plastics: A, extruded polystyrene; B, unfaced polyurethane; C, unfaced phenolic; and D, polyurethane with thick steel skins.

Research and development programs have been initiated by the cellular plastics industry to develop viable substitute blowing agents. These must have similar or improved properties to their CFC counterparts at a reasonable cost. Emphasis was initially placed on HCFC 123 and HCFC 141b, both having much shorter lifetimes and considerably less effect (up to 50 times) on ozone layer depletion (22). However, various options, including gas mixtures, water, or $CO_2$ blown foams, continue to be studied ultimately to eliminate all CFCs and HCFCs.

The search for alternative blowing agents has necessitated a significant change in testing requirements to provide some assessment of aged value. Accepted accelerated testing procedures normally use $\geq 25 - \text{mm}$ thick specimens and time exposure periods of 180 days at 24°C or 90 days at 60°C to indicate some amount of aging. Measurements of thermal resistance are made after such conditioning to give curves such as those shown in Figure 3. However, there is both the need to obtain more realistic longer term ($\geq 20$ yr) values and to test much more rapidly, since the development of safe blowing agent substitutes cannot wait on determining realistic aged values. Diffusion coefficients are not a strong function of temperature nor are all gases changed equally, and elevated temperature exposure can damage foam structure.

An alternative method known as slicing and scaling has been developed (23, 24). In this, the rate of diffusion is determined on a thin specimen (6–10 mm thick) and a scaling factor $S$ used to relate the results to a thick specimen. For a material satisfying the requirements of a constant diffusion and constant initial pressure, $p$, the same ratio of time:thickness$^2$ provides the same values of $p$ and $\lambda$. Thus the thermal resistance of a specimen of thickness $l_1$ at time $t_1$ can be obtained by conditioning a specimen of thickness $l_2$ over a time $t_2$ given by

$$t_2 = t_1 \left[ \frac{(l_2)^2}{(l_1)^2} \right] \text{ ie, } t_2 = t_1 S$$

This technique reduces testing times significantly and provides reliable results for $\geq 20$ years material. The values plotted in Figure 2 (25) are an illustration of the viability of this technique as a means to provide realistic long-term thermal performance values (21).

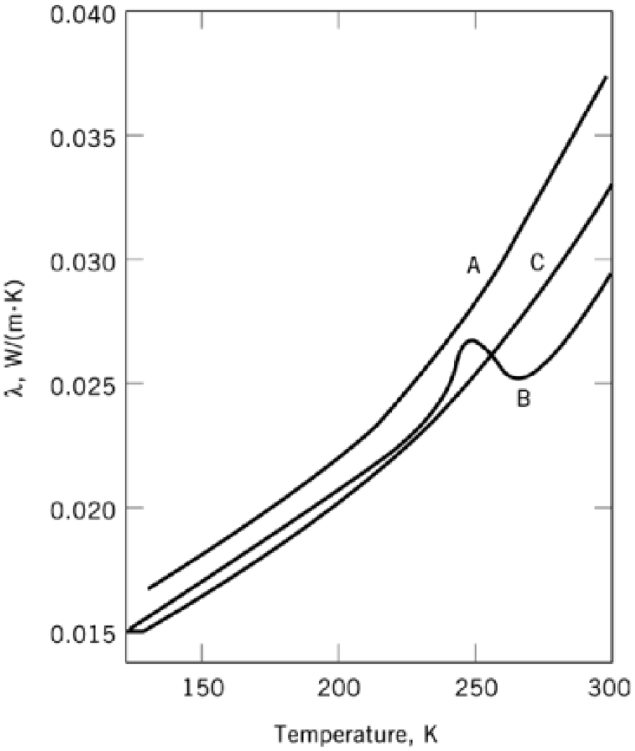

**Fig. 4.** Thermal conductivity of cellular plastics: A, extruded polystyrene, 32 kg/m$^3$; B, polyurethane, 32 kg/m$^3$; and C, PVC foam, 32 kg/m$^3$.

### 5.3. Thickness

The traditional definition of thermal conductivity as an intrinsic property of a material where conduction is the only mode of heat transmission is not applicable to low density materials. Although radiation between parallel surfaces is independent of distance, the measurement of $\lambda$ where radiation is significant requires the introduction of an additional variable, thickness. The thickness effect is observed in materials of low density at ambient temperatures and in materials of higher density at elevated temperatures. It depends on the radiation permeance of the materials, which in turn is influenced by the absorption coefficient and the density. For a cellular plastic material having a density on the order of 10 kg/m$^3$, the difference between a 25 and 100 mm thick specimen ranges from 12–15%. This reduces to less than 4% for a density of 48 kg/m$^3$. References (23–27) discuss the issue of thickness in more detail.

### 5.4. Mean Temperature

Thermal performance is highly dependent on mean temperature. Figure 4 illustrates the general effect for various typical cellular plastic materials. The inflection in the curve for polyisocyanurate is due to the change of phase of the particular blowing agent from liquid to gas. The position of this inflection depends on the blowing agent used.

The thermal conductivities of the most common insulation materials used in construction are shown in Table 2. Values at different mean temperature are necessary for accurate design purposes at representative temperatures encountered during winter or summer. For example, under winter conditions with an outside

**Table 2. Thermal Conductivities, W / (m·K)[a]**

| | | | | Polyisocyanurate (PI) | | |
|---|---|---|---|---|---|---|
| Condition | Mean temperature, °C | XEPS | EPS | Aged | Impermeable facing | Phenolic, faced |
| winter | 4 | 0.027 | 0.032 | 0.023 | 0.016 | 0.016 |
| ambient temperature | 24 | 0.029 | 0.036 | 0.025 | 0.018 | 0.017 |
| summer | 44 | 0.031 | 0.040 | 0.027 | 0.020 | 0.018 |

[a] Bulk densities of basic foam, $\mathrm{kg/m^3}$: EPS, 16; XEPS, 30; aged PI, 32; PI with impermeable facing, 32; and faced phenolic, 45.

temperature of -20 to -10°C, the mean temperature is 0–5°C. For summer, mean temperatures in excess of 40°C can be experienced.

### 5.5. Moisture

Absorbed and retained moisture, especially as ice, has a significant effect on the structural and thermal properties of insulation materials. Most closed-cell plastic foams have low permeance properties most notably where natural or bonded low permeance surface skins exist (29, 30). Design, building, and construction practices require adequate vapor retarders, skins, coatings, sealants, etc, in order to prevent the presence of moisture. However, moisture vapor cannot be completely excluded, thus the possibility of moisture absorption and retention is always present. The freezing of moisture and rupturing of cells result in permanent reduction of thermal and structural performance.

In standard tests for moisture absorption and water-vapor permeability, material is tested at isothermal temperature conditions. Where such testing has been done, results for extended conditioning periods indicate that it is possible for cellular plastics to absorb and retain large amounts of moisture. Thermal performance can be reduced 20–50% (31–33). However, a similar study (34), simulating roofing environments but under cyclic temperature and humidity conditions resembling those of specific climates, indicates that only small amounts of moisture are retained and thermal performance is reduced by 5% or less. New test methods utilizing specific gradient criteria of temperature and humidity are required to obtain realistic performance characteristics.

### 5.6. Mechanical Properties and Structural Performance

As a result of the manufacturing process, some cellular plastics have an elongated cell shape and thus exhibit anisotropy in mechanical, thermal, and expansion properties (35, 36). Efforts are underway to develop manufacturing techniques that reduce such anisotropy and its effects. In general, higher strengths occur for the parallel-to-rise direction than in the perpendicular-to-rise orientation. Properties of these materials show variability due to specimen form and position in the bulk material and to uncertainty in the axes with respect to direction of foam rise. Expanded and molded bead products exhibit little anisotropy.

Strength characteristics are important to consider when selecting materials for particular applications, especially those at low and cryogenic temperatures. Friability is significant in handling and in applications where vibration or movements are involved. Both the mechanical strength and friability depend strongly on density and are also affected by aging and moisture pickup. In general, a mechanical property $MP$ is related to density (37):

$$MP = K\ (\text{density})^{\alpha}$$

where K and $\alpha$ are constants depending on the type of foam, orientation, and temperature. Thus for a certain application an optimum density material can be selected with the desired combination of structural and thermal performance. Some typical mechanical properties are given in Table 3.

**Table 3. Mechanical Properties of Cellular Plastics, MPa**[a]

| | Polyisocyanurate | | | | XEPS $d = 32\ \mathrm{kg/m^3}$ | | EPS at 293 K | | Phenolic at 293 K |
|---|---|---|---|---|---|---|---|---|---|
| | $d = 32\ \mathrm{kg/m^3}$ | | $d = 96\ \mathrm{kg/m^3}$ | | | | | | |
| Strength | at 293 K | at 76 K | at 293 K | at 76 K | at 293 K | at 76 K | $d = 16\ \mathrm{kg/m^3}$ | $d = 32\ \mathrm{kg/m^3}$ | $d = 35 - 45\ \mathrm{kg/m^3}$ |
| ultimate tensile | | | | | | | | | |
| parallel | 0.35–0.4 | 0.4–0.5 | 1.1 | 1.6 | 0.25–0.3 | 0.20–0.25 | | | 0.18–0.25 |
| perpendicular | 0.25–0.35 | 0.3–0.4 | 1.1 | 1.7 | 0.20–0.25 | 0.15–0.18 | 0.11–0.14 | 0.16–0.19 | 0.13–0.16 |
| tensile modulus | | | | | | | | | |
| parallel | 10–15 | 20–30 | 30 | 70 | 25 | 30 | | | |
| perpendicular | 5–10 | 10–15 | 25 | 60 | 10 | 12 | 1.2–1.5 | 3.1–3.5 | 1.28 |
| maximum compressive | | | | | | | | | |
| parallel | 0.23–0.28 | 0.31–0.35 | 0.8 | 1.4 | 0.2–0.35 | 0.3–0.45 | | | 0.15–0.20 |
| perpendicular | 0.16–0.22 | 0.17–0.23 | 0.7 | 1.3 | 0.2–0.4 | 0.2–0.4 | 0.07–0.1 | 0.17–0.21 | 0.10–0.12 |
| compressive modulus | | | | | | | | | |
| parallel | 7–10 | 10–13 | 20 | 75 | 12 | 18 | | | |
| perpendicular | 5–6 | 5–6 | 18 | 60 | 10 | 15 | 1.0–1.4 | 3.0–3.5 | 5.7 |
| shear | | | | | | | | | |
| parallel | 0.16–0.21 | 0.16–0.24 | 0.8 | 1.4 | 0.2 | 0.18 | | | 0.10–0.12 |
| perpendicular | 0.15–0.2 | 0.12–0.22 | 0.75 | 1.3 | 0.2 | 0.18 | 0.12–0.15 | 0.23–0.25 | 0.09–0.10 |

[a] To convert MPa to psi, multiply by 145.

Polyurethane, PVC, and extruded polystyrene provide the bulk of the cellular plastics used for low and cryogenic temperature applications. In some cases, eg, the insulation of liquid hydrogen tanks on space systems, foams have been reinforced with continuous glass fibers throughout the matrix. This improves strength without affecting thermal performance significantly.

### 5.7. Flame Resistance

Traditionally, small-scale laboratory flammability tests have been used to initially characterize foams (38). However, these do not reflect the performance of such materials in bulk form. Fire characteristics of thermal insulations for building applications are generally reported in the form of qualitative or semiquantitative results from ASTM E84 or similar tunnel tests (39). Similar larger scale tests are used for aircraft and marine applications.

Although the tunnel test is widely accepted, conditions and orientations involved are not those normally found in installed insulations. New large-scale tests have been developed; the results can be taken to represent actual performance more closely. Such tests include the International Conference of Building Officials (ICBO) and ASTM E603 full-scale room tests, ASTM E108 roofing test, the UL roof deck construction test, the Factory Mutual Calorimeter Test, and both a large- and small-scale corner test.

Flame-spread and smoke-density values, and the less often reported fuel-contributed semiquantitive results of the ASTM E84 test and the limited oxygen index (LOI) laboratory test, are more often used to compare fire performance of cellular plastics. All building codes require that cellular plastics be protected by inner or outer sheathings or be housed in systems all with a specified minimum total fire resistance. Absolute incombustibility cannot be attained in practice and often is not required. The system approach to protecting the more combustible materials affords adequate safety in the buildings by allowing the occupant sufficient time to evacuate before combustion of the protected cellular plastic.

## 6. Health and Safety Factors

The long-term effects of CFCs and HCFCs leaking into the environment have been discussed. Combustion where all cellular plastics can evolve smoke containing carbon monoxide and in certain cases cyanide and other toxic gases from various constituents involved in their manufacture is also a consideration.

Urea–formaldehyde use has been greatly restricted because of free formaldehyde (qv) emissions which can cause eye irritation and in some cases serious illness. Some attempts at developing formaldehyde-free urea-based materials are ongoing.

## 7. Economic Aspects

In the mid-to-late 1980s, growth estimates of the use of polystyrene and polyurethane cellular plastic insulation materials and products were a healthy 10% per year and greater for phenolic (40, 41). The principal application where strongest growth was forecast for these types was for roofing, especially single-membrane systems (42).

From 1991 to 1992, consumption in North America of these forms of cellular plastic (11) rose 5–6% overall from approximately $600 \times 10^6$ to $631 \times 10^6$ kg. Of this EPS and XEPS each rose only by some 2.5%, and polyurethane by 4%, due solely to its use for appliances. Phenolic and other foams have also contributed but with small growth.

In Europe total consumption of plastic foam insulation for 1992 was $29 \times 10^6$ m$^3$ (>12 billion board ft) with little or no growth seen from 1991. All products were expected to grow by an average of 1% due primarily to the continued effects of the economic recession.

Costs of cellular plastic insulations are still higher than those of fibrous and other mass insulation types, but these can often be justified based on overall advantages of combined structural, thermal, and permeance properties. It is difficult to provide a single cost for each material type since there are many different forms of a material-based product available and differing forms of manufacture and application, often in combination with other materials. In the United States, EPS board costs on the order of \$0.12 to \$0.18; XEPS, \$0.25 to \$0.30; and PU, \$0.30 to \$0.35, per board foot (\$0.30/board ft $\approx$ \$127/m$^3$).

## 8. Uses

In addition to building applications, cellular plastics are used in low or cryogenic temperature applications, such as refrigerators and freezers; bulk transportation and storage of foods in refrigerated containers; process industries involving chilled and refrigerant fluids; liquefaction and storage of gases at cryogenic temperatures; pipelines for oil and gas, particularly in Arctic regions; under roads and airport runways in cold regions to resist frost heave; generation and transmission of electricity at low temperatures; marine applications; structures of aircraft and space vehicles and systems; structures and components of missiles and re-entry vehicles; medical and biological sciences, including preservation of blood, organs, and tissues; and electronic equipment where operation at a constant low temperature is essential to diminish electrical noise.

## BIBLIOGRAPHY

“Insulation, Thermal” in *ECT* 1st ed., Vol. 7, pp. 927–935, by C. B. Bradley, Johns-Manville Research Center; in *ECT* 2nd ed., Vol. 11, pp. 823–838, by R. H. Neisel and H. F. Remde, Johns-Manville Research & Engineering Center; in *ECT* 3rd ed., Vol. 13, pp. 591–605, by R. H. Neisel and J. D. Verschoor, Johns-Manville Sales Corp.

### Cited Publications

1. C. J. Benning, Plastic Foams, Vol. **1**, *The Physics and Chemistry of Product Performance and Process Technology*, John Wiley & Sons, Inc., New York, 1969.
2. A. H. Landrock, *Polyurethane Foams: Technology Properties and Applications*, Report 37, Plastic Technical Evaluation Center, Picatinny Arsenal, Dover, N.J., 1969.
3. *Thermal Insulation Systems—A Survey*, NASA Report SP-5027, NASA, Washington, D.C., 1967.
4. R. N. Miller, C. D. Bailey, R. T. Beal, and J. M. Freeman, *Advances in Cryogenic Engineering*, Vol. **8**, Plenum Press, New York, 1963, 417–424; *Ind. Eng. Chem.* **1**(4), 257 (Dec. 1962).
5. F. C. Wilson, *Refrig. Eng.* **65**(4), 57 (1957).
6. *An Assessment of Thermal Insulation Materials and Systems for Building Applications, DOE Report, BNL-50862 UC-95d*, U.S. Dept. of Energy, Washington, D.C., 1978; R. P. Tye and D. L. McElroy, eds., *ASTM STP 718, Thermal Insulation Performance*, American Society for Testing and Materials, Philadelphia, Pa., 1980, 9–26.
7. D. L. Johnston, *Roof Des.* **1**(1), 26 (June 1983).
8. D. L. Johnston, *Roofing Spec.* **11**, 26 (Dec. 1983).
9. C. A. Schutz, *J. Cell. Plast.* **4**(1), 37 (1968).
10. *Roofing/Siding/Insul.* **59**, 79 (Oct. 1982).
11. *Mod. Plast.* 83, 93 (Jan. 1993).
12. C. M. Pelanne, *Therm. Insul.* **1**, 48 (1977).
13. W. C. Turner and J. F. Malloy, *Thermal Insulation Handbook*, R. E. Krieger Publishing Co., Inc., Melbourne, Fla., 1981, 191–275.
14. R. M. E. Diamant, *Steam Heat. Eng.* **33**, 6 (1964).
15. W. R. Strzepek, in E. C. Guyer and D. L. Brownell, eds., *Handbook of Applied Thermal Design*, McGraw-Hill Book Co., New York, 1989, 3–30 to 3–41.
16. *Mod. Plast.*, 1, 8 (Mar. 1993).
17. R. P. Tye, in D. L. McElroy and J. F. Kimpflen, eds., *Insulation Materials Testing and Applications, ASTM STP 1030*, ASTM, Philadelphia, Pa., 1990, 141–155.
18. G. W. Ball, W. G. Healey, and T. B. Partington, *Eur. J. Cell. Plast.* **1**(1), 50 (Jan. 1978).
19. F. J. Norton, *J. Cell. Plast.* **18**, 300 (Sept./Oct. 1982).
20. D. W. Reitz, M. A. Schuetz, and L. R. Glicksman, *J. Cell. Plast.* **20**(2), 104 (1984).
21. F. Sherwood-Rowland, *Chlorofluorocarbons and Depletion of Stratospheric Ozone, Improved Thermal Insulation—Problems and Perspectives*, D. A. Brandreth, ed., Technomic Publishing Co., Inc., Lancaster, Pa., 1991, 5–25.
22. *Protocol on Substances that Deplete the Ozone Layer*, United Nation Environment Programme, Final Act, Montreal, Canada, Sept. 1987.
23. J. Isberg, *The Thermal Conductivity of Polyurethane Foams*, Chalmers University of Technology, Gothenburg, Sweden, 1988.
24. M. T. Bomberg, *J. Thermal Insulation* **13**, 149 (1990).
25. J. R. Booth and J. T. Grimes, *J. Thermal Insulation Build. Envelopes* **15**, 256 (Apr. 1993).
26. B. K. Larkin and S. W. Churchill, *J. AlChE* **5**(4), 467 (1959).
27. T. T. Jones, *Proceedings of the VIIth Thermal Conductivity Conference*, NBS Special Publication 302, National Bureau of Standards, U.S. Dept. of Commerce, Washington, D.C., 1967, 737–748.
28. B. Y. Lao and R. E. Skochodopole, *Proceedings of the 4th SPI International Cellular Plastics Conference, Montreal, Nov. 1976*, The Society of the Plastics Industry, New York, 1976, 175–182.
29. F. J. Dechow and K. A. Epstein, in R. P. Tye, ed., *ATM STP 660, Thermal Transmission Measurements of Insulation*, American Society for Testing and Materials, Philadelphia, Pa., 1978, 234–260.
30. G. Ovstaas, S. E. Smith, W. Strzepek, and G. Titley, in F. A. Govan, D. M. Greason, and J. D. McCallister, eds., *ASTM STP 789, Thermal Insulation Materials and Systems for Energy Conservation in the '80s*, American Society for Testing and Materials, Philadelphia, Pa., 1983, 435–454.
31. W. Tobiasson and J. Ricard, *Proceedings of the Fifth Conference on Roofing Technology*, sponsored by NBS and NRCA, Apr. 1979, National Roofing Contractors Association, Chicago, Ill., 1979, 4–16.
32. L. I. Knab, D. R. Jenkins, and R. G. Mathey, "The Effect of Moisture on the Thermal Conductance of Roofing Systems," *NBS Building Science Series 123*, National Bureau of Standards, U.S. Dept. of Commerce, Washington, D.C., Apr. 1980.

33. W. Tobiasson, A. Greatorex, and D. VanPelt, "Wetting of Styrene and Urethane Roof Insulations in the Laboratory and on a Protected Roof Membrane," F. J. Powell and S. L. Matthew, eds., in *Thermal Insulation Materials and Systems STP922*, ASTM, Philadelphia, Pa., 1987.
34. R. P. Tye and C. F. Baker, "Development of Experimental Data on Cellular Plastic Insulations Under Simulated Winter Exposure Conditions," in Ref. 33.
35. L. L. Sparks, in R. P. Tye and D. L. McElroy, eds., *ASTM STP 718, Thermal Insulation Performance*, American Society for Testing and Materials, Philadelphia, Pa., 1980, 431–452; *J. Therm. Insul.* **8**, 198 (Jan. 1985).
36. J. I. DeGisi and T. E. Neet, *J. Appl. Polym. Sci.* **20**, 2011 (1976).
37. R. K. Traeger, *J. Cell. Plast.* **3**(9), 405 (1967).
38. *ASTM Annual Book of Standards*, Vols. **08.01–08.02**, American Society for Testing and Materials, Philadelphia, Pa., 1984, Sect. 8.
39. *ASTM Annual Book of Standards*, Vol. **04.06**, American Society for Testing and Materials, Philadelphia, Pa. 1984, Sect. 4.
40. *Chem. Eng. News* **62**, 18 (June 25, 1984).
41. *Mod. Plast.* **60**, 72 (Sept. 1983).
42. *Plastic Foam Materials and Roofing Insulation, 1983–1989*, Peter Sherwood Associates, Inc., White Plains, N.Y., Apr. 1984; *Roofing/Siding/Insul.* **61**, 82 (Oct. 1984).

### General References

43. *U.S. Residential Insulation Industry*, U.S. Dept. of Commerce, Washington, D.C., Aug. 1977, Survey Report.
44. *U.S. Foamed Plastics Markets and Directory*, Technomic Publishing Co., Inc., Lancaster, Pa., 1984.
45. *J. Therm. Insul. (now J. Therm. Insul. Build. Env.)* Technomic Publishing Co., Inc., Lancaster, Pa., 1980–1993.

RONALD P. TYE
Consultant

## Related Articles

Urethane polymers; Isocyanates, organic; Building materials, survey