cost of the insulation must be compared to the average annual cost of lost energy, or the cost of the energy lost each year must be expressed in present dollars and compared with the total cost of the insulation investment. The former method, annualizing the insulation cost and comparing this with the average annual cost of lost energy, is easier to compute.

Insulation reduces the size and capital costs of the heating and cooling equipment required for an installation because it lowers energy demand. This capital cost may be annualized by considering the plant depreciation period, cost of money, annual energy output for the plant, and operational expenses.

Figure 6 shows curves of total annual costs of operation, insulation costs, and lost energy costs. Point A on the total cost curve corresponds to the economic insulation thickness, which, in this example, is in the double-layer range. Viewing the calculated economic thickness as a minimum thickness provides a hedge against unforeseen fuel price increases and conserves energy.

ECONOMIC THICKNESS: BUILDING ENVELOPES

In buildings such as residences and warehouses, the internal energy gains are insignificant compared with the heat losses and gains through the envelope. For these buildings, the heating and cooling requirements are roughly proportional to the difference between the indoor and outdoor temperature. For commercial, industrial, and institutional buildings, internal heat loads can be significant, and the heating and cooling requirements are not as directly related to the indoor/outdoor temperature difference. In both types of buildings, solar heat can be an important factor and should be evaluated.

Dominant Heat Loss and Gain Through Envelope

Thermal insulation is generally installed in building envelope components (e.g., ceilings, walls, and floors) to reduce space heating and cooling costs on a long-term basis. Additional benefits may include increased occupant comfort, reduced heating and cooling system capacity, and elimination of condensation on wall surfaces in cold climates. When possible these benefits should be considered. The economically optimal insulation thickness (best measured in terms of thermal resistance) in an envelope component minimizes total life-cycle space heating and cooling costs attributable to it. Total life-cycle costs are the sum of present-value heating and cooling costs over the useful lifetime of the insulation plus the installed cost of the insulation and the installed cost of the heating and cooling equipment.

If the R-value of the insulation used is continuously variable (e.g., loose-fill insulation in attics), uniformly small increments of insulation can be used to determine appropriate optimal thicknesses; or calculus can be used to determine an exact optimum. If the insulation materials used are available only in discrete levels of thermal resistance (R-12, R-18, R-27), the increment used in determining optimal thickness should be based on differences between those levels (R-12 over R-0, R-18 over R-12, R-27 over R-18). Where discrete increments of resistance are used, determining the resistance level for which incremental savings equal incremental costs may not be feasible. In such cases, the selection should be left to the judgment of the analyst based on the level of conservation desired. In addition, an increase in insulation may make it possible to reduce the size of the heating and cooling equipment, which becomes a discrete reduction in equipment cost.

If a building envelope component requires structural modifications to accommodate increased insulation thickness, this cost must be included in the installed cost of the additional insulation. Generally, such modifications should only be considered when they are less costly than the use of more efficient (i.e., lower thermal conductivity) but more expensive insulation materials than those ordinarily used.

Typically, the incremental energy savings and insulation costs differ for each building envelope component; therefore, the optimal insulation level differs for each component in the same building. Less efficient heating plants and higher costs of heating energy necessitate higher optimal insulation levels in each building envelope component. Conversely, more efficient heating equipment reduces the optimal insulation level. The effects of climate, cooling energy costs, and cooling equipment efficiency on optimal insulation levels are less clear and differ widely, depending on overall building design and operational profile.

Dominant Internal Heat Loads

In buildings with dominant internal loads, the energy requirements vary so widely that no generalizations can be made regarding insulation. This contrasts with envelope-dominated structures, in which more insulation reduces energy consumption (Hart 1981).

In internal-load-dominated buildings with both annual heating and cooling loads, higher thermal resistance increases cooling energy consumption while reducing heating energy consumption. Therefore, the calculation of economically optimum resistance becomes quite complex and involves multiple measure or hourly methods described in Chapter 31. Spielvogel (1974), Burch and Hunt (1978), and Rudoy (1975) give more details.

Figure 7 shows the results of these calculations for a building in Columbus, Ohio, with 8.2 Btu/h·ft^2 of internal heat gains that operates 24 h per day (Spielvogel 1974). This solution is not the only one possible, but illustrates problems faced by the designer. In this case, thermal resistance increases, the U-factor decreases, annual heating energy decreases, and annual cooling energy increases. The energy optimum exists at Point Y in Figure 7, where the total heating and cooling energy is at a minimum. Because the cost of cooling energy differs from the cost of heating energy, the economic optimum will not be the same as the energy optimum.

These results occur in some localities where there are far more hours per year with outdoor temperatures between 50 and 75°F than between 75 and 100°F. At temperatures between 75 and 100°F, low U-factors result in less energy consumption for cooling. However, for temperatures between 50 and 75°F, low

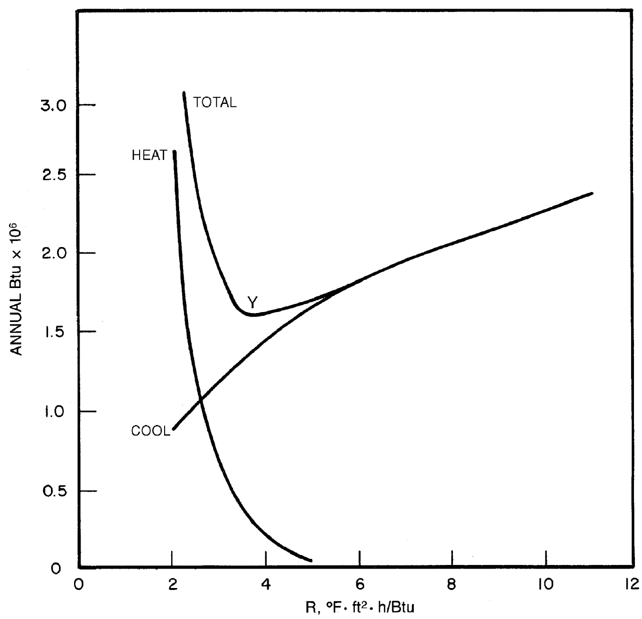

Fig. 7 Example of Optimal Thermal Resistance for Building with Internal Heat Gains
(Adapted from Spielvogel 1974)

U-factors inhibit the flow of internal heat from the building, thereby creating higher cooling loads and higher energy requirements than those in buildings with higher U-factors. What might be saved at outdoor temperatures over 75°F can be more than spent in additional cooling energy at temperatures below 75°F. Economizer cycles could offset these excess internal gains with ventilation air, however.

Where the hours of use or the quantity of internal heat gains vary from room to room, the optimum thermal resistance also varies. For example, in a cold climate, a hotel kitchen requires little or no insulation, because the internal heat is sufficient to heat the space almost all year. In a meeting room adjacent to the kitchen, substantially more insulation is justified. Thus, the economic thermal resistance of any envelope element, such as a roof, will not be the same throughout the entire building.

This type of analysis must include the level and duration of internal gains and the nature of the energy consumption of the heating and cooling systems. Most buildings need evaluation of walls, roofs, and floors on a room-by-room basis. Computer programs make these more complex analyses possible. Due to the wide diversity of building types, internal gains, system types, and operating conditions, no simple rules can establish U-factors for minimum energy consumption.

Effectiveness of Added Insulation

The effectiveness of added insulation varies with many factors, including climate, original insulation level, preparation costs, and predicted life, based on payback calculations. Building codes generally balance life-cycle costs between construction, financing, and energy expenditures. Figure 8 shows typical relationships between life-cycle costs and energy consumption. Individual points on the curve represent different combinations of ceiling, wall, and floor insulation in R-values and glazing types (single, double, or triple). Because life-cycle costs vary not only with construction and energy costs but also with climatic factors, the profiles of this curve vary according to locality. In Figure 8, the optimal condition for this example is attained with R-30 attic insulation, R-19 wall insulation, R-11 floor insulation, and double glazing. However, the effectiveness of added insulation can be determined only by analyzing actual conditions.

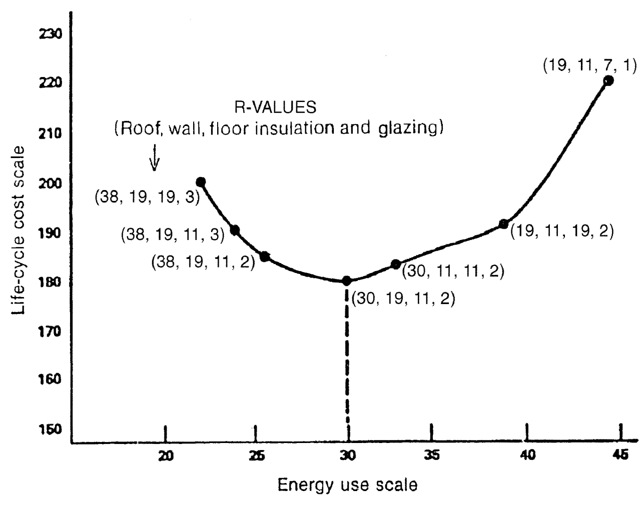

Fig. 8 Typical Relationship of Life-Cycle Cost to Energy Use

MOISTURE IN BUILDINGS

MOISTURE PROBLEMS IN BUILDINGS

Moisture control is necessary to avoid moisture-related problems with building energy performance, building maintenance and durability, and human comfort and health. Moisture degradation is the largest factor limiting the useful life of a building and can be visible or invisible. Invisible degradation includes degradation of the thermal resistance of building materials and decrease in the strength and stiffness of some materials. Visible moisture degradation may be in the form of (1) mold and mildew, (2) the decay of wood-based materials, (3) spalling of masonry and concrete caused by freeze-thaw cycles, (4) hydration of plastic materials, (5) corrosion of metals, (6) damage due to expansion of materials (e.g., buckling of wood floors), and (7) a decline in visual appearance (e.g., buckling of wood siding or efflorescence of masonry materials, which is the formation of a salt crust from the leaching of free alkalies). In addition, high moisture levels can lead to odors and mold spores in indoor air, which can seriously affect occupant health and comfort. Short summaries of such moisture conditions and related performance and health issues follow.

Mold, Mildew, Dust Mites, and Human Health

Mold and mildew in buildings are offensive, and the spores can cause respiratory problems and other allergic reactions in humans. Mold and mildew will grow on most surfaces if the relative humidity at the surface is above a critical value and the surface temperature is conducive to growth. The longer the relative humidity remains above the critical value, the more likely is visible mold growth; and the higher the humidity or temperature, the shorter is the time needed for germination. The surface relative humidity is a complex function of material moisture content, material properties, and local temperature and humidity conditions. In addition, mold growth depends on the type of surface. Fully recognizing the complexity of the issue, the International Energy Agency Annex 14 (1990) nevertheless established a surface humidity criterion for design purposes: The monthly average surface relative humidity should remain below 80%. Others have proposed more stringent criteria, the most stringent requiring that surface relative humidity remain below 70% *at all times*. Although there still is no agreement on which criterion is most appropriate, mold and mildew can usually be avoided by limiting surface moisture conditions over 80% to short time periods. These criteria should only be relaxed for nonporous surfaces that are regularly cleaned. Hukka and Viitanen (1999) developed a mathematical model for the prediction of a mold growth index. This model was successfully implemented and linked to a hygrothermal model by Karagiozis and Salonvaara (1998). Most molds grow at temperatures above approximately 40°F. Moisture accumulation below 40°F may not cause mold and mildew if the material is allowed to dry below the critical moisture content before the temperature rises above 40°F.

Dust mites can trigger allergies and asthma (Burge et al. 1994). Dust mites thrive at high relative humidities (over 70%) at room temperature, but will not survive sustained relative humidities below 50% (Burge et al. 1994). These relative humidities relate to local conditions in typical places that mites tend to inhabit such as mattresses, carpets, soft furniture, etc.

Paint Failure and Other Appearance Problems

Moisture trapped behind paint films may cause failure of the paint. Water or condensation may also cause streaking or staining. Excessive swings in the moisture content of wood-based panels or boards may cause buckling or warping. Excessive moisture in masonry and concrete may cause efflorescence, a white powdery area or lines, or, when combined with low temperatures, may cause freeze-thaw damage and spalling (chipping).