A Method to Incorporate Green Engineering in Materials Selection & Design

S.L. Kampe
Materials Science and Engineering Department
Virginia Tech
Blacksburg, Virginia 24061-0237

Introduction

The selection of a material-of-construction for any engineering component or system will have environmental implications. In some instances, the design objective and environmental stewardship are directly related and mutually compatible; a design that serves to minimize costs associated with the waste generated or energy consumed by an engineering system would be one such example. In many other instances, however, the primary design objective may have little apparent relationship to environmental issues; an example in this regard might be an objective which seeks to maximize the structural efficiency (e.g., strength, size, lifetime) of some component or system. In reality, both situations have direct environmental relevance since their objectives may further rely on (or assume) the manufacture of selected materials and their associated availability in a form suitable for the given application. Minimally, the availability of a material will involve the expenditure of energy to convert the material from its raw form (e.g., ore) into the specified (manufactured) form or shape.

Green engineering represents a design philosophy or approach where the implications of a particular design or material selection are considered on a total lifetime or "cradle-to-grave" basis. That is, while a certain material may offer advantages in terms of prior practice or in-service performance, it may additionally require substantial industrial and/or societal investment in terms of production, disposal, and public health. Thus, it is appropriate and ethical for engineers to consider such issues at the design stage of product development, since they are optimally positioned to make decisions in which environmentally-responsible options can be considered and potentially implemented.

This paper illustrates a method whereby the environmental load associated with the selection of a specific material can be routinely assessed as part of the overall decision-making process used in engineering design. The technique can be generically applied to any application or situation which utilizes traditional engineering constitutive equations which contain both extensive (design requirements) and intensive (scale-normalized material properties) variable groups. The specific example presented in this paper (i.e., the selection of a replacement material for asbestos insulation in habitable buildings) represents a case study where a diversity of goals within the purview of green engineering can be demonstrated. Specifically, the case study seeks to resolve a public health issue (asbestos replacement), achieve the minimization of in-service heat losses (energy conservation), and considers the energy expenditures associated with the availability of certain candidate replacement materials (upstream energy conservation). The incorporation of the latter component in material selection has been further summarized and demonstrated in a recent case study presented to illustrate how an engineer can routinely assess the implication of material selection on the lifetime energy consumption for materials utilized as structural components in transportation systems.[1] Both case studies represent subjects of projects recently assigned in a senior level course entitled "Materials Selection and Design," which is required of Materials Science and Engineering (MSE) majors and offered as a technical elective to students of other engineering disciplines at Virginia Tech. These case studies represent modest extensions of the generalized approach advanced by Ashby,[2,3] where selection charts are created to illustrate regions of material residency and performance trade-offs in two-dimensional relevant-property space.

Lifetime Energy Costs

The health detriments of asbestos insulation are well known and documented.[4] When considering a replacement material for applications associated with the insulation of hot water-based heating systems, a traditional engineering approach would likely focus on identifying materials which offer comparable or better performance (more insulating) at a comparable or lower initial cost. That is, trade-offs between initial and operational costs are typically explored.

A crude illustration of the engineering problem is shown in Fig. 1. Consider insulation of thickness Δr applied to the exterior surface of a pipe. An estimation of the per-area steady-state heat losses, Q (e.g., J/m^2), over a defined lifetime Δt can be easily computed:*

$$Q = -k \frac{\Delta T}{\Delta r} \cdot \Delta t \qquad \text{Eq. 1}$$

where k is the thermal conductivity of the insulating material and $\Delta T/\Delta r$ approximates the through-thickness thermal gradient. From a performance stand-point, materials with the lowest values of thermal conductivity would appear to represent the most viable candidates, independent of the extensive functional needs ($\Delta T/\Delta r$, Δt) of the design.

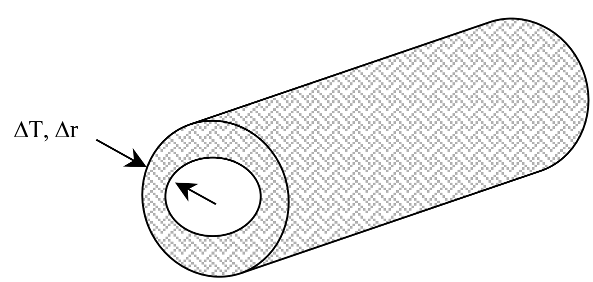

Figure 1. Insulation of a thickness Δr supporting a thermal temperature change of ΔT.

* The effect of increasing radius on heat transfer is not expected to influence the selection of the material for this application, and has thus been omitted from the analysis.

The initial per-area cost of the insulating material, C_A, can likewise be estimated:

$$C_A = \rho \cdot C_M \cdot \Delta r \qquad \text{Eq. 2}$$

where ρ is the characteristic material density, C_M is the per-mass cost of the material, and Δr is the utilized thickness of the insulation.

An analysis of the trade-off between two design objectives requires the incorporation of an exchange constant, C_E, capable of relating the two quantities described by their respective constitutive equations, as above. This is accomplished by incorporating an estimate of, or an otherwise documented, monetary value of energy. The cost of energy is generally known; it depends strongly on generating source, and sometimes on geographical and political issues. Incorporating the cost of energy (\$0.006/MJ)[5] derived from coal-burning power plants (such as that on the Virginia Tech campus) into Eq. 1 leads to a per-area lifetime cost of energy due to heat losses over the specified lifetime, C_L.

$$C_L = k \cdot \frac{\Delta T}{\Delta r} \cdot \Delta t \cdot C_E \qquad \text{Eq. 3}$$

The total lifetime cost, TLC, is thus the sum of the initial material cost plus the in-service lifetime cost due to energy losses:

$$TLC = \rho \cdot C_M \cdot \Delta r \quad + \quad k \cdot \frac{\Delta T}{\Delta r} \cdot \Delta t \cdot C_E \qquad \text{Eq. 4}$$

Trade-offs between the two components of lifetime cost can thus be visually examined using material selection charts in the manner of Ashby.[2] Trade-off lines, or lines showing combinations of material properties that offer identical cost for a given lifetime, can be constructed. Figure 2 illustrates such a material selection chart. In this example, a value for the total lifetime cost, TLC, is computed using values for asbestos (the basis of comparison) from representative material properties for porous asbestos insulation ($k \cong 0.2$ W/m·K, $\rho \cong 343$ kg/m^3, and $C_M \cong 1.44$ US\$/kg), and using expected or representative functional requirements (e.g., $\Delta T = 70$ K, $\Delta r = 5$ cm, and $\Delta t = 0.5$ years and 5 years). Lines (and related cost contours) showing the combination of material properties which lead to TLCs equal to that of asbestos are shown for the two defined lifetimes utilized. The spatial material property locations of a variety of example materials,[3,6] many of which could represent viable replacements to asbestos insulation, are also shown. Materials that reside at spatial locations below, or to the left of, the asbestos TLC lines represent options that would lead to lower lifetime costs.

In this example, the most obvious and effective materials to substitute for asbestos include a variety of polymeric foams (polyethylene, melamine, and polyurethane elastomeric foams), plus glass wool. For both long and short lifetimes, the polyethylene (PE) foam stands out with respect to minimization of lifetime costs, followed by glass wool, melamine foam, and polyurethane (PU) elastomeric foams. These materials are additionally flexible, facilitating installation, and are capable of surviving at the relatively low temperatures necessary in the present example.

Proceedings of the 2002 American Society for Engineering Education Annual Conference & Exposition

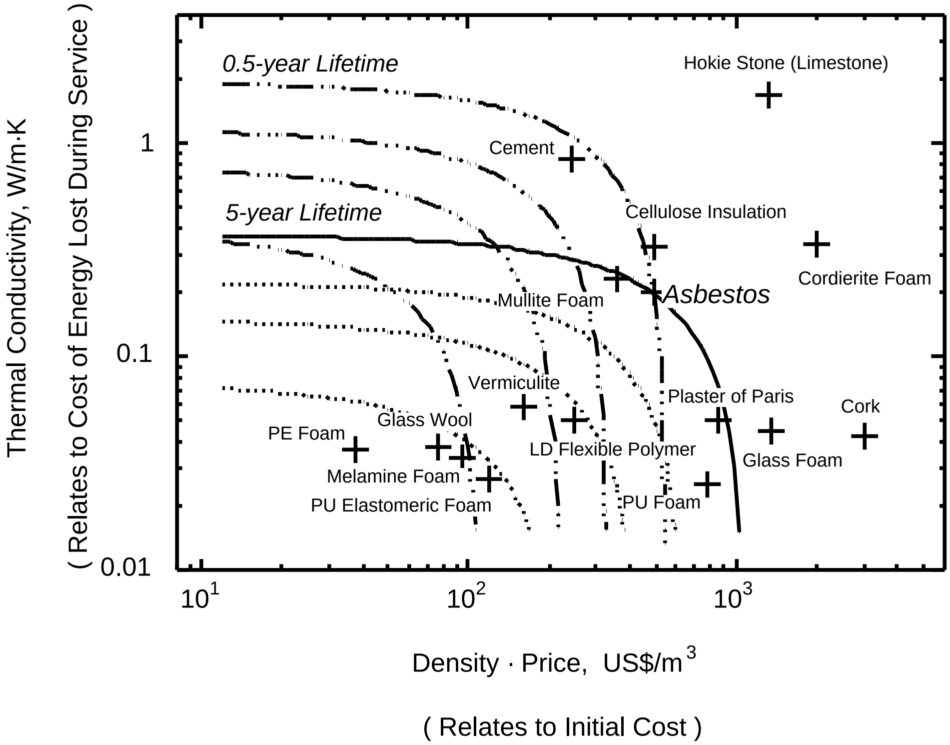

Figure 2. A selection chart illustrating thermal conductivity (the material property associated with in-service energy losses) as a function of the material properties associated with initial material cost. The bold curves represent combinations of properties that lead to lifetime costs that are equal to that of asbestos for each indicated lifetime and for an exchange constant (C_E) of 0.006 US$/MJ.[5] The contours represent lines of increasing improved value, with lifetime cost decreasing towards the lower left corner of the chart.

Lifetime Energy Expenditures

In traditional design environments, one might be content to conclude the design process with a cost analysis such as that summarized above. However, a materials scientist may recognize that polymer foams require a relatively high investment of energy to produce from raw material forms. Thus, from a green engineering perspective, these materials may not represent the most favorable option if one desires to consider the broader societal impact of these substitutions for asbestos in this application.

One can include an assessment of the environmental load implicated by the choice of material utilized in the design through a minor modification of the constituent relationship presented as Eq. 4. For this, one requires an additional material property that is, ideally, capable of quantifying the total energy expended in the production, manufacture, use, and disposal of the material. Such information is becoming increasingly available within various life cycle analysis (LCA) products,[7,8] and/or from various groups and organizations that are attempting to parameterize the environmental impact attributable to the use of specific materials.[9,10]

Examples of such indices include weighted assessments of the effects of certain materials on human health, damage to ecosystem quality caused by exotoxic emissions associated with manufacture, and damage to resources caused by extraction of minerals. Unfortunately, while detailed and of high generic value, many of these indices are not provided in a way that would facilitate selection to a level of specificity beyond broad material groups (e.g., metals versus ceramics versus organics).

An alternative means to assess initial environmental impact may be accomplished through the use of a material's energy content value. For most engineering materials, the energy content represents a per-mass accounting of the energy (e.g., Joules/kg) expended to convert a material from its raw form into a form ready for subsequent processing or manufacture (e.g., as ingot or billet).[3] Indeed, the energy content value for most engineering materials is often computed utilizing LCA techniques as applied to the production processes used to refine or create the material. It is noted that the energy content does not include the energy implications associated with disposal or recyclability.

In the example introduced above, the per-area lifetime energy expenditure, LEE, can be estimated through a modification of Eq. 4 to incorporate the energy expended to initially produce the candidate materials plus the energy expended due to in-service losses over the specified lifetime Δt:

$$LEE = \rho \cdot q \cdot \Delta r \quad + \quad k \cdot \frac{\Delta T}{\Delta r} \cdot \Delta t \qquad \text{Eq. 5}$$

where q is the energy content of the material (e.g., MJ/kg).

Figure 3 illustrates the resulting selection chart and the trade-off contours that relate initial energy expenditure to in-service energy losses. Comparison to Fig. 2 reveals that by these standards, several natural and/or mineral-based options become more competitive with the polymer foams identified by Fig. 2, and that polyethylene foam becomes less prominent relative to other candidates. Further, for short-term lifetimes, vermiculite emerges as the most energy-efficient alternative,* whereas polyurethane elastomeric foam appears to be the best choice for longer lifetimes.

Discussion

As with any material selection exercise, lifetime costs and energy consumption represent only partial criteria for successful material selection in design. In the present example, the ease of installation would certainly have to be considered, as would in-service temperature capability, long-term stability, and eventual disposal, to name but a few additional characteristics likely required.

* Ironically, certain ore bodies from which vermiculite has been commercially mined have been shown to contain asbestos as a contaminant at levels sufficient to pose potential health risks.[11]

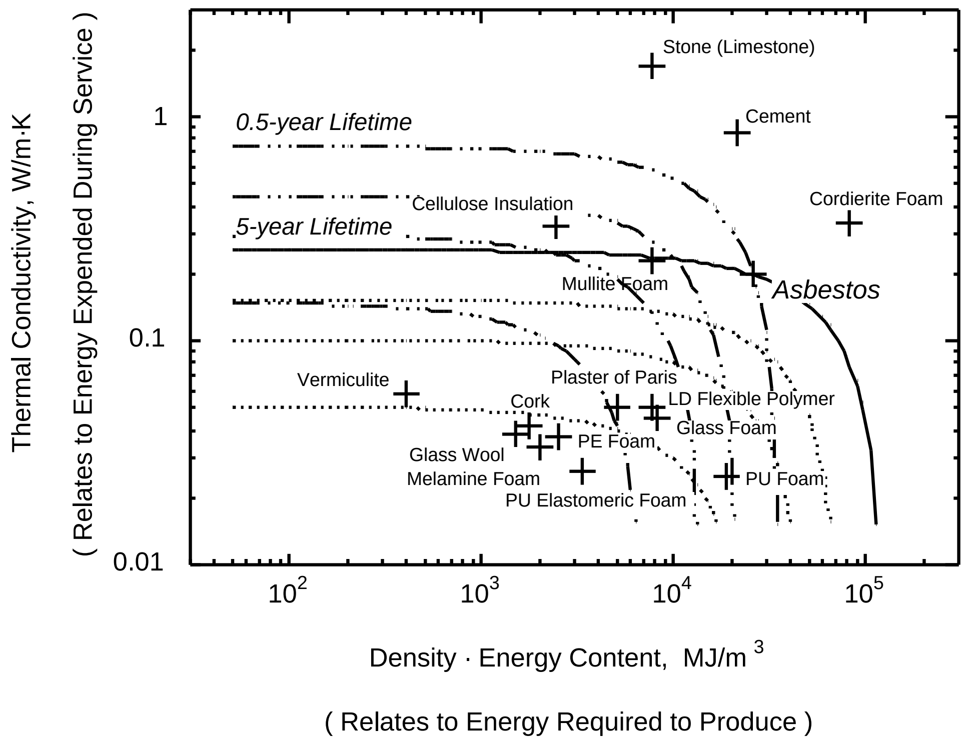

Figure 3. A selection chart illustrating thermal conductivity (quantifies the material-dependence of energy loss) as a function of the per-volume energy content (related to the energy required to initially produce a material). The indicated curves represent combinations of material properties where lifetime energy expenditures are equal to that of asbestos.

As noted, the energy content value of a material represents only a partial accounting of the lifetime energy investment in its behalf. The value does not take into account energy expenditures associated with the disposal, environmental damage, or energy recovery that could be realized by recycling. However, until such information becomes broadly available to the engineer, energy content values provide a meaningful means to partially assess the environmental load attributable to a design, and such assessments can be easily conducted on an ongoing and routine basis.

Acknowledgements

The development of the lifetime cost and energy consumption project summarized in this paper was generated at Virginia Tech for use in MSE 4055, Material Selection and Design, with funding assistance from the College of Engineering's Green-Engineering Initiative. The project is one of several that have been generated for the course under Green Engineering sponsorship since 1998. In particular, the author would like to acknowledge the Program's

role in obtaining the Cambridge Engineering Selector (CES) Software for student use; the availability of this resource has created numerous opportunities to explore green issues in material selection.

Bibliography

1. S.L. Kampe, "Incorporating Green Engineering in Material Selection & Design", *in Proc. of the 2001 Green Engineering Conference: Sustainable and Environmentally-Conscious Engineering*, Virginia Tech/U.S. EPA, Roanoke, VA, July 29-31, 2001, p. 7-1; also at http://www.grantadesign.com/userarea/papers.
2. M.F. Ashby, *Materials Selection in Mechanical Design*, Second Edition, Butterworth-Heinemann, Oxford, UK, 1999.
3. *Cambridge Engineering Selector*, Version 3.1 (CES3.1 application software), Granta Design, Inc., Cambridge, UK.
4. U.S. Environmental Protection Agency (2002, February 27), *Welcome to EPA's Asbestos Home Page*, Available: http//www.epa.gov/asbestos/index.html [2002, 14 March].
5. M.F. Ashby, Materials Selection: *Multiple Constraints and Compound Objectives*, Cambridge University Engineering Design Center Report CUED/C-EDC/TR-38, 1996, p. 1.13.
6. *CRC Handbook of Tables for Applied Engineering Science*, 2nd Ed., CRC Press, Boca Raton, FL, 1980, p. 117.
7. Battelle Memorial Institute (2002), *LCAdvantaage™ Software*, Available: http://www.battelle. org/ environment/lcm/LCAdv.stm [2002, 14 March].
8. Carnegie-Mellon University, eiolca.net, *Economic Input-Output Life Cycle Assessment*, Available: http:// www.eiolca.net [2002, March 14].
9. *The Eco-indicator 99 A Damage Oriented Method for Life Cycle Impact Assessment*; 2nd Edition, PRe' Consultants, B.V., Amsterdam, 2000.
10. U.G.K. Wegst and M.F. Ashby, "The Development and Use of a Methodology for the Environmentally-Conscious Selection of Materials" in the *Proceedings of The Third Biennial Conference on Integrated Design and Process Technology (IDPT)*, Vol. 5, 1998, Berlin, FRG, 88-93; also at http://www.grantadesign. com/userarea/papers.
11. U.S. Environmental Protection Agency (2002, February 27), *Asbestos Contamination in Vermiculite*, Available: http//www.epa.gov/opptintr/asbestos/verm.htm [2002, 14 March].

STEPHEN L. KAMPE is an Associate Professor of Materials Science and Engineering at Virginia Tech. In addition to Materials Selection and Design, Dr. Kampe teaches courses in Mechanical Behavior of Materials, Composite Materials, and introductory Materials Engineering for Aerospace and Ocean Engineering. He conducts research in the areas of advanced processing and synthesis of metals and metal matrix composites.