الجامعة التكنولوجية
قسم هندسة المواد
Department of Materials Engineering

Selection of Engineering Materials

Lec-2

Attribute limits and material indices

By

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INTRODUCTION AND SYNOPSIS

Material properties limit performance. We need a way of surveying them to get a feel for the values that design-limiting properties can have. One property can be displayed as a ranked list or bar chart, but it is seldom that the performance of a component depends on just one property. More often it is a combination of properties that matter: the need for stiffness at low weight, for thermal conduction coupled with corrosion resistance, or for strength combined with toughness, for example. This suggests the idea of plotting one property against another, mapping out the fields in property space occupied by each material class and the subfields occupied by individual materials.

The resulting charts are helpful in many ways. They condense a large body of information into a compact but accessible form; they reveal correlations between material properties that aid in checking and estimating data; and, as examined in later chapters, they become tools for materials selection, for exploring the effect of processing on properties, for demonstrating how shape can enhance structural efficiency, and for suggesting directions for further material development.

The ideas behind materials selection charts are described briefly in Section 4.2. Section 4.3 introduces the charts themselves. It's not necessary to read it all, but it is helpful to persist far enough to be able to read and interpret the charts fluently, and to understand the meaning of the design guide lines that appear in them. If, later, you use a particular chart, you should read the background to it, given here, to be sure of interpreting it correctly.

As explained in the Preface, the charts can be copied and distributed for teaching purposes without infringing the copyright.[1]

EXPLORING MATERIAL PROPERTIES

Each property of an engineering material has a characteristic range of values. The span can be large: many properties have values that range over five or more decades. One way of displaying this is as a bar chart like that of Figure 4.1 for Young's modulus. Each bar describes one material; its length shows the range of modulus exhibited by that material in its various forms. The materials are segregated by class. Each class shows a characteristic range: Metals and ceramics have high moduli; polymers have low; hybrids have a wide range, from low to high. The total range is large—it spans a factor of about 10^6—so logarithmic scales are used to display it.

More information is displayed by an alternative plot, illustrated in the schematic of Figure 4.2. Here, one property (the modulus, E, in this case) is plotted against another (the density, ρ). The range of the axes is chosen to include all materials, from the lightest, flimsiest foams to the stiffest, heaviest metals, and it is large, again requiring log scales. It is found that data for a given family of materials (polymers, for example) cluster together; the *subrange* associated with one material family is, in all cases, much smaller than the *full* range of that property. Data for one family can be enclosed in a property envelope—envelopes are shown on this schematic. A real $E - \rho$ chart is shown in Figure 4.3. The family envelopes appear as in the schematic. Within each envelope lie white bubbles enclosing classes and subclasses.

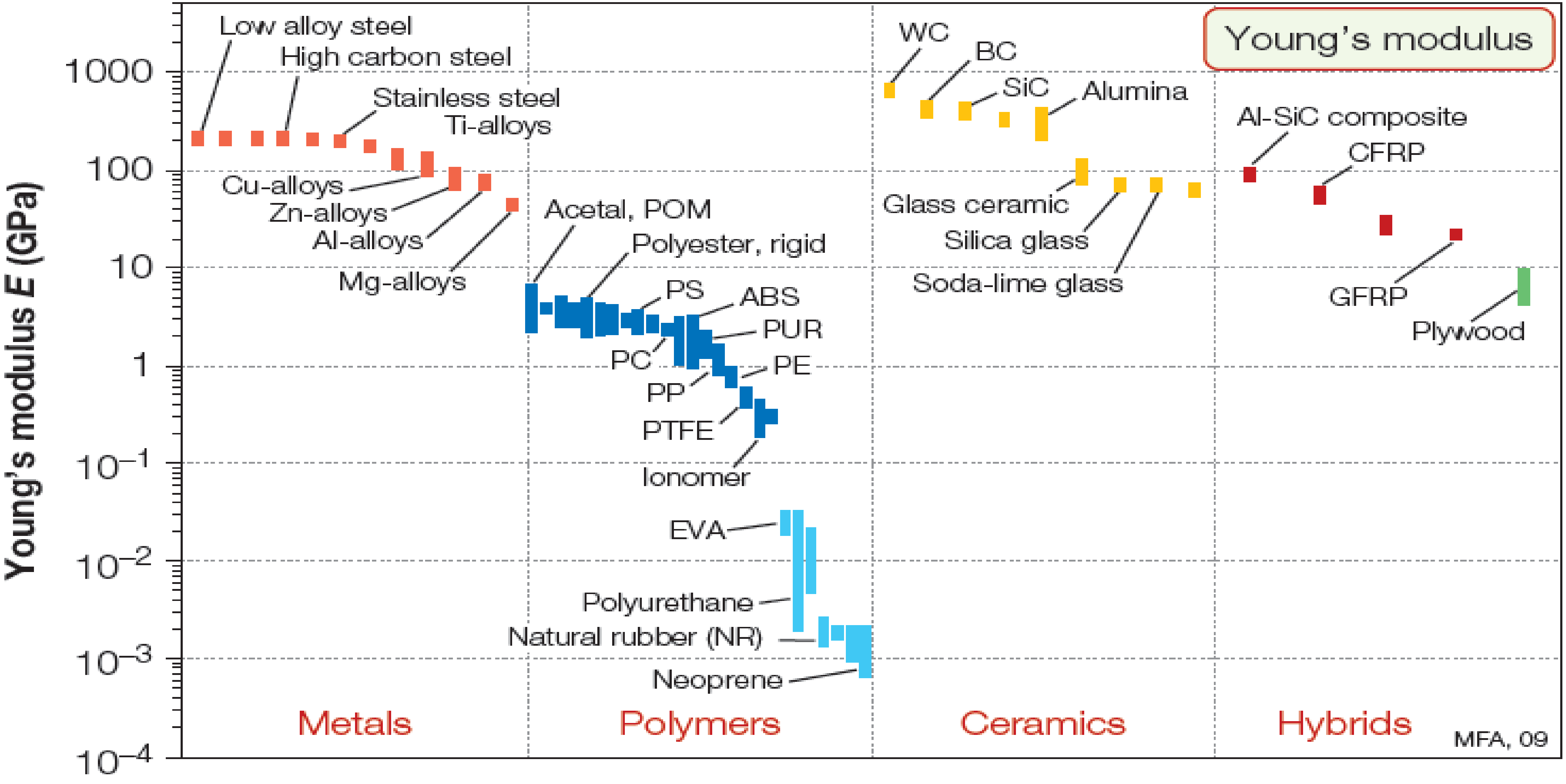


FIGURE 4.1

A bar chart showing modulus for families of solids. Each bar shows the range of modulus offered by a material, some of which are labeled.

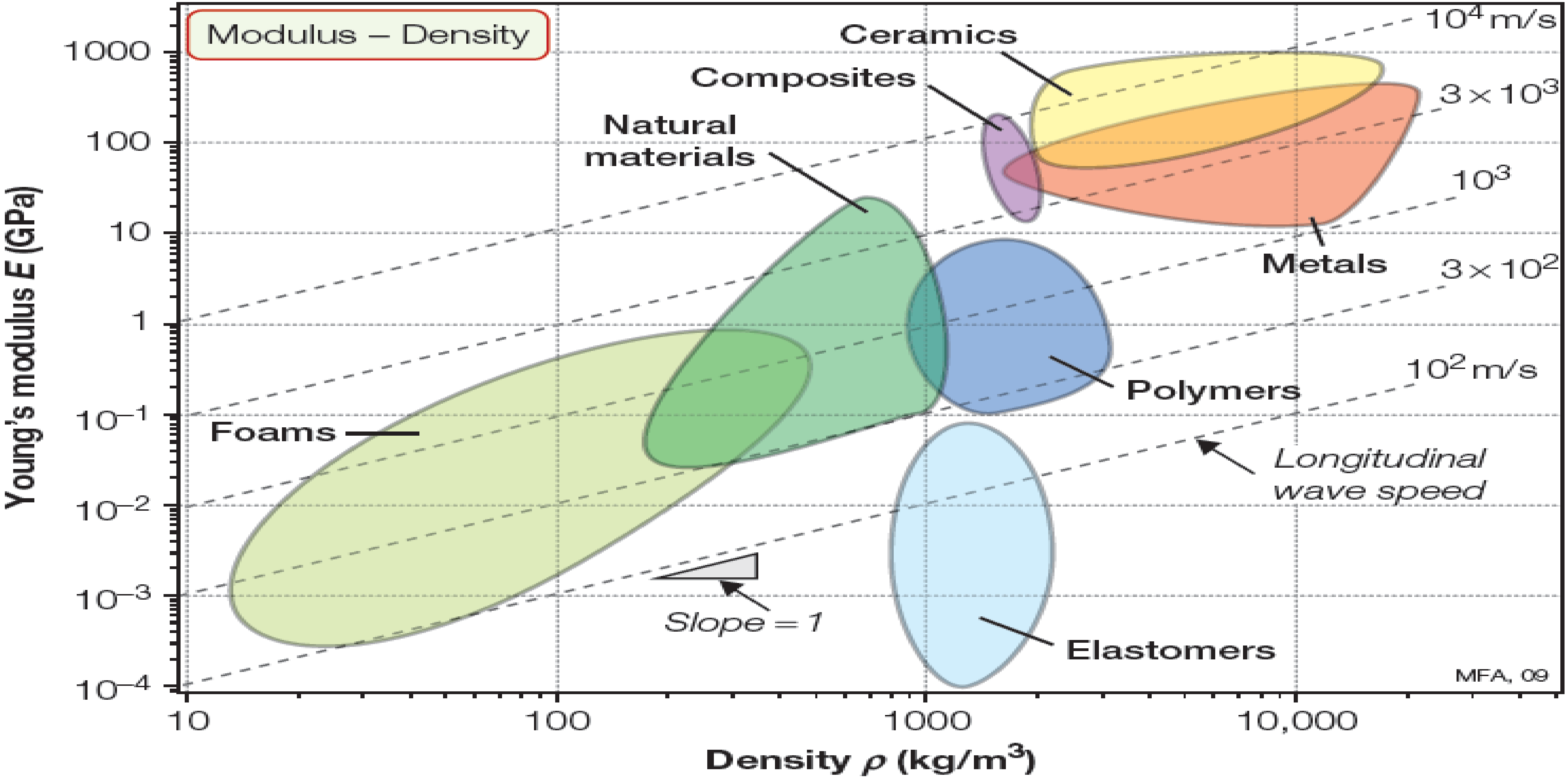


FIGURE 4.2

The idea of a material property chart: Young's modulus E is plotted against the density ρ on log scales. Each material class occupies a characteristic field. The contours show the longitudinal elastic wave speed $\nu = (E/\rho)^{1/2}$.

Attribute limits

Constraints set property limits. Objectives define material indices, for which we seek extreme values. When the objective in not coupled to a constraint, the material index is a simple material property. When, instead, they are coupled, the index becomes a group of properties like those cited above. Both are explained below. We start with two simple examples of the first—uncoupled objectives.

Heat sinks for hot microchips

A microchip may only consume milliwatts, but the power is dissipated in a tiny volume. The power is low but the *power-density* is high. As chips shrink and clock-speeds grow, heating becomes a problem. The Pentium chip of today's PCs already reaches 85°C, requiring forced cooling. Multiple-chip modules (MCMs) pack as many as 130 chips on to a single substrate. Heating is kept under control by attaching the chip to a heat sink (Figure 2.1-4), taking pains to ensure good thermal contact between the chip and the sink. The heat sink now becomes a critical component, limiting further development of the electronics. How can its performance be maximized?

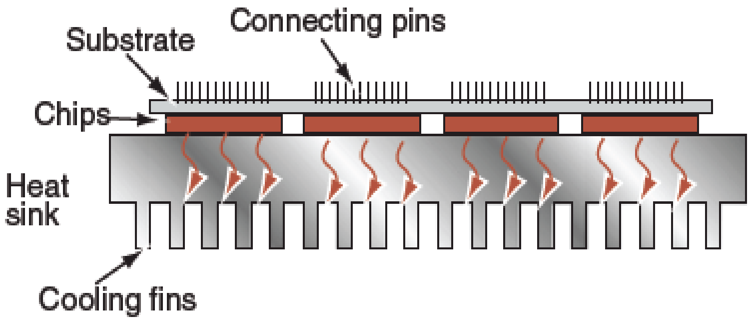


Figure 2.1-4 A heat sink for power micro-electronics. The material must insulate electrically, but conduct heat as well as possible.

To prevent electrical coupling and stray capacitance between chip and heat sink, the heat sink must be a good electrical insulator, meaning a resistivity, $\rho_e > 10^{19}$ μΩ.cm. But to drain heat away from the chip as fast as possible, it must also have the highest possible thermal conductivity, λ. The translation step is summarized in Table 2.1-2, where we assume that all dimensions are constrained by other aspects of the design.

To explain: resistivity is treated as a *constraint*, a go/no go criterion. Materials that fail to qualify as "good insulator", or have a resistivity greater than the value listed in the table, are screened out. The thermal conductivity is treated as an *objective*: of the materials that meet the constraint, we seek those with the largest values of λ and rank them by this—it becomes the material index for the design. If we assume that all dimensions are fixed by the design, there remains only one *free variable* in seeking to maximize heat-flow: the choice of material. The procedure, then, is to *screen* on resistivity, then *rank* on conductivity.

The steps can be implemented using the λ—ρ_e chart, reproduced as Figure 2.1-5. Draw a vertical line at $\rho_e =$ 1019 μΩ.cm, then pick off the materials that lie above this line, and have the highest λ. The result: aluminum nitride, AlN, or alumina, Al_2O_3. The final step is to seek supporting information for these two materials. A web-search on "aluminum nitride" leads immediately to detailed data-sheets with the information we seek.

Table 2.1-2 Function, constraints, objective, and free variables for the heat sink

Function	Heat sink
Constraints	• Material must be "good insulator", or $\rho_e > 10^{19}$ μΩ.cm • All dimensions are specified
Objective	Maximize thermal conductivity, λ
Free variables	Choice of material

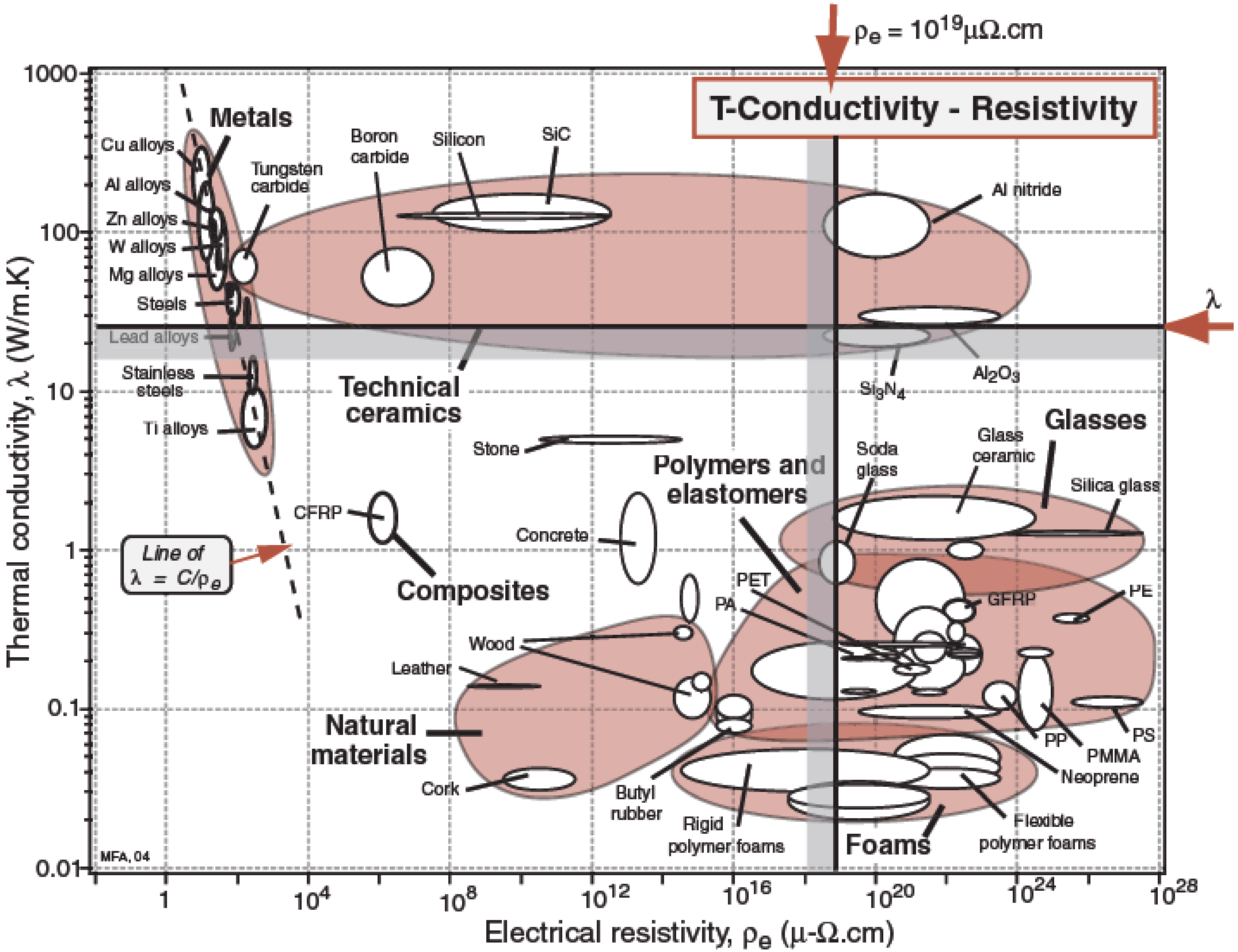


Figure 2.1-5 The λ— ρ_e chart of Figure 4.10 with the attribute limit $\rho_e > 10^{19}$ $\mu\Omega$.cm and the index λ plotted on it. The selection is refined by raising the position of the λ selection line.

Material Indices

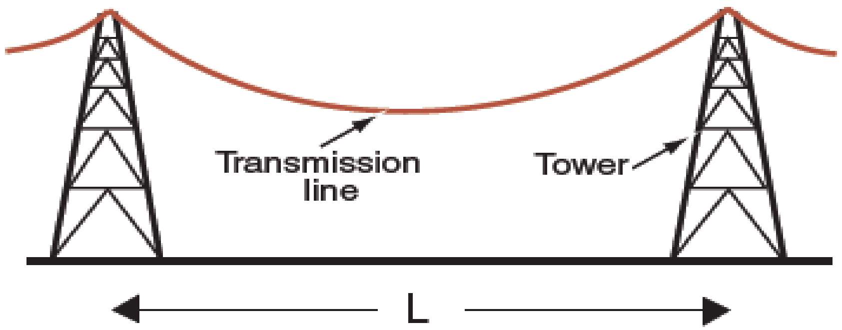
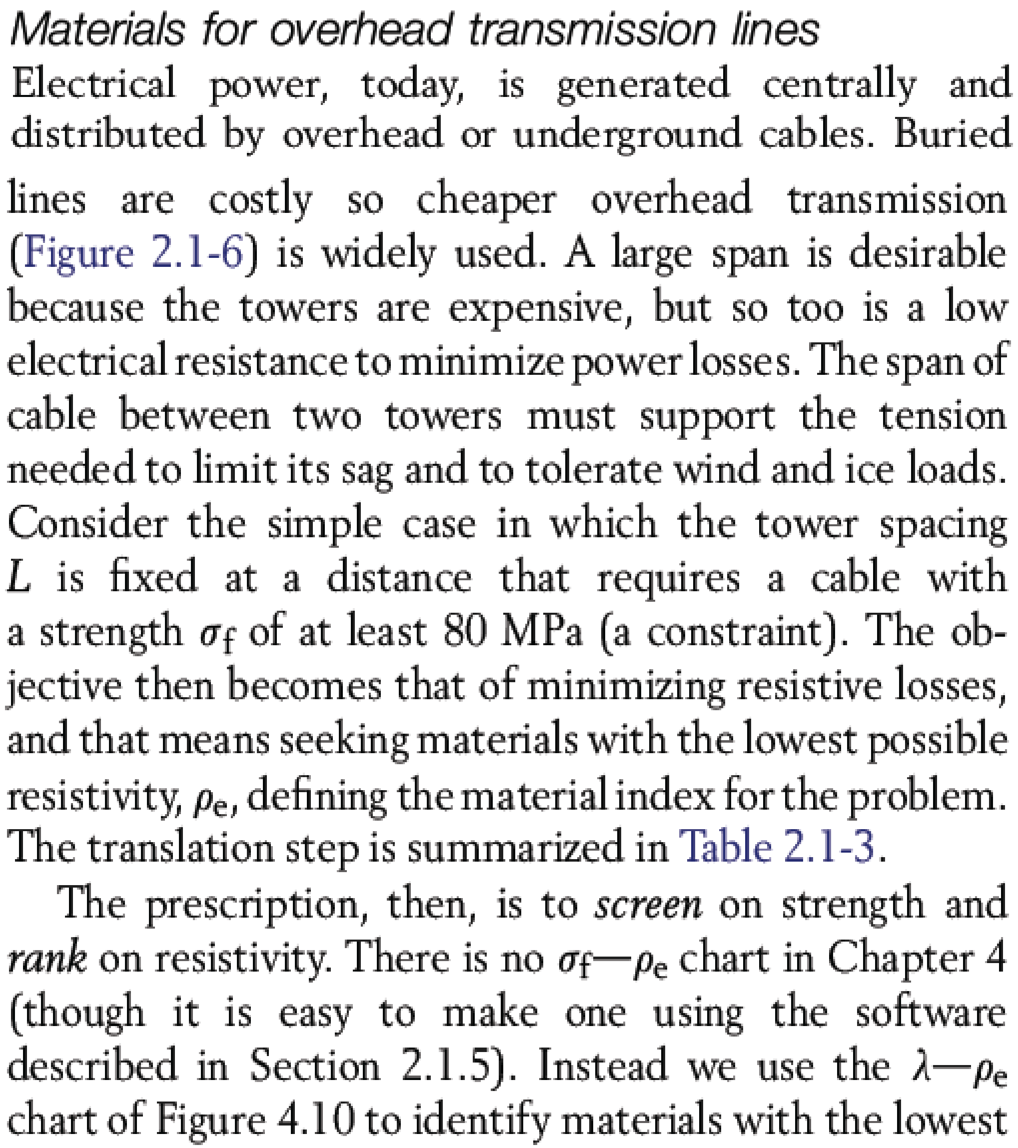
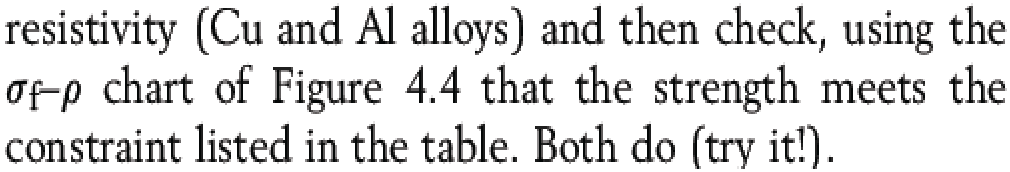


Figure 2.1-6 A transmission line. The cable must be strong enough to carry its supporting tension, together with wind and ice loads. But it must also conduct electricity as well as possible.

Materials for overhead transmission lines

Electrical power, today, is generated centrally and distributed by overhead or underground cables. Buried lines are costly so cheaper overhead transmission (Figure 2.1-6) is widely used. A large span is desirable because the towers are expensive, but so too is a low electrical resistance to minimize power losses. The span of cable between two towers must support the tension needed to limit its sag and to tolerate wind and ice loads. Consider the simple case in which the tower spacing L is fixed at a distance that requires a cable with a strength σ_f of at least 80 MPa (a constraint). The objective then becomes that of minimizing resistive losses, and that means seeking materials with the lowest possible resistivity, ρ_e, defining the material index for the problem. The translation step is summarized in Table 2.1-3.

The prescription, then, is to *screen* on strength and *rank* on resistivity. There is no σ_f—ρ_e chart in Chapter 4 (though it is easy to make one using the software described in Section 2.1.5). Instead we use the λ—ρ_e chart of Figure 4.10 to identify materials with the lowest resistivity (Cu and Al alloys) and then check, using the σ_f–ρ chart of Figure 4.4 that the strength meets the constraint listed in the table. Both do (try it!).

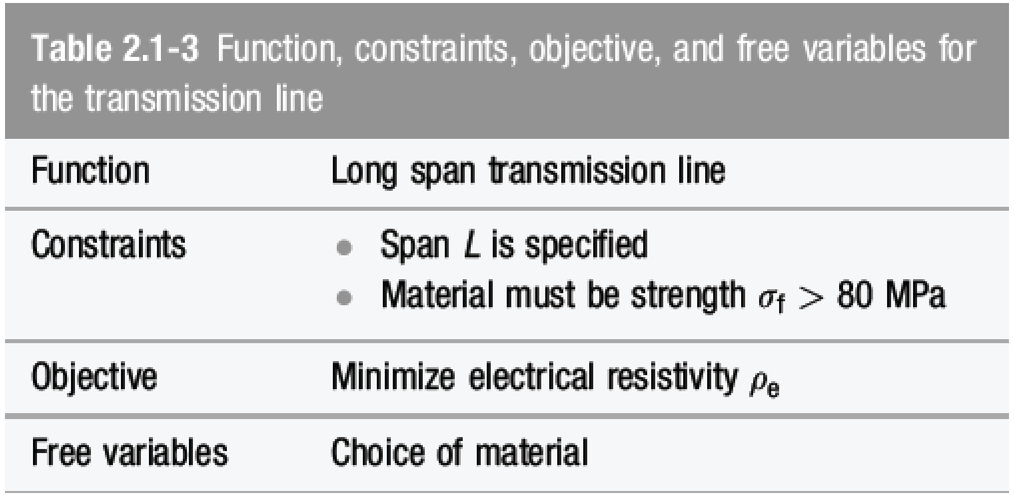


Table 2.1-3 Function, constraints, objective, and free variables for the transmission line

Function	Long span transmission line
Constraints	• Span L is specified • Material must be strength $\sigma_f > 80$ MPa
Objective	Minimize electrical resistivity ρ_e
Free variables	Choice of material

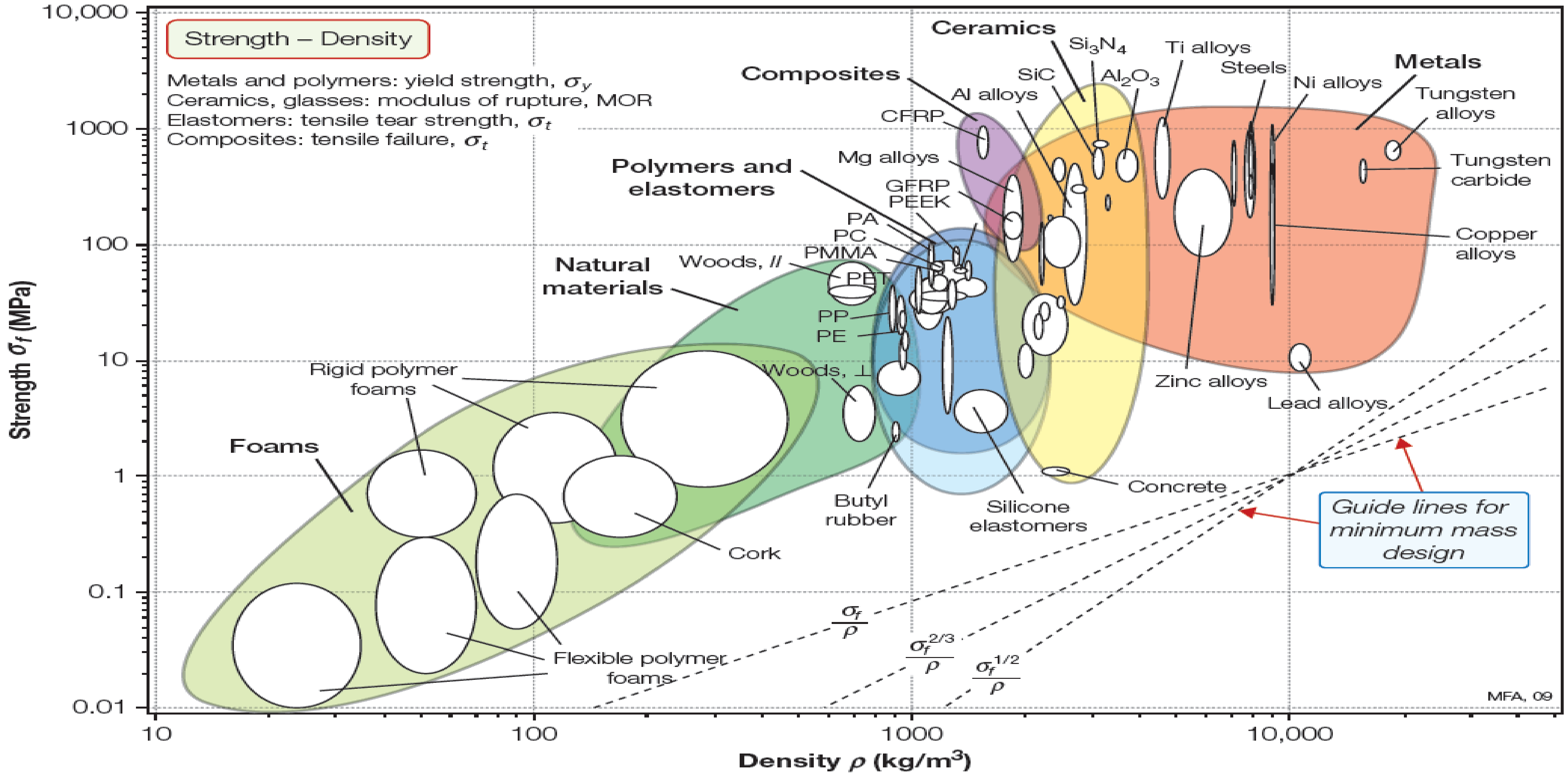


FIGURE 4.4

Strength σ_f plotted against density ρ (yield strength for metals and polymers, compressive strength for ceramics, tear strength for elastomers, and tensile strength for composites). The guide lines of constants σ_f/ρ, $\sigma_f^{2/3}/\rho$, and $\sigma_f^{1/2}/\rho$ are used in minimum weight, yield-limited, design.