The following words should be regarded as inviolable engineering design terminology(some have well defined etymology in the *OED*):

Design Need: The primary motivation for a design investigation (usually expressed in the form of a *problem statement* – *e.g*., *"There are too many automobile accidents during holiday periods"* or *"My arthritic aunt is unable to open her milk carton"*);

- *Design goal*: The primary functional objective of a design (usually expressed in terms of outcomes without reference to embodiment – *e.g*., *"a means for delivering a payload along a water channel"* rather than *"a boat"*);

- *Design objectives*, or *design requirements*: Desired features or characteristics of a specific design (*e.g*., *"safe"*, *"reliable or robust"*, *"cheap"*);

- *Constraint*: Mandatory design requirement (*e.g*., *"the device must weigh less than 5 kg"*, or *"It must be inflammable"*);

- *Restriction:* Flexible design requirement (*e.g*., *"The lecture theatre should accommodate 200 students"*, or *"The cockpit should accommodate 98% human population size"*);

Criterion (or *criteria* – plural): The scale on which the "fitness for purpose" of the design is measured (*e.g*., for *cheap* the *criterion* is $, or whatever monetary unit is in use, for reliable or robust the criterion is mean time to failure or mean time to repair, for comfortable the criterion is the subjective judgement of a group of end users of the product).

THE ROLE of the materials engineer in the design and manufacture of today's highly sophisticated products is varied, complex, exciting, and always changing. Because it is not always the metallurgical or materials engineer who specifies the material.

Today, the selection of the material and its processing, product design, cost, availability, recycleability, and performance in final product form have become inseparable. As a result, more and more companies are forming integrated product development (IPD) teams to ensure that all needed input is obtained concurrently

Design engineers need not only develop competence in their field but they must also cultivate a strong sense of responsibility and professional work ethic.

There are roles to be played by codes and standards, ever-present economics, safety, and considerations of product liability. The survival of a mechanical component is often related through stress and strength. Matters of uncertainty are ever-present in engineering design and are typically addressed by the design factor and factor of safety, either in the form of a deterministic (absolute) or statistical sense. The latter, statistical approach, deals with a design's *reliability* and requires good statistical data.

In mechanical design, other considerations include dimensions and tolerances, units, and calculations.

Design Considerations

Sometimes the strength required of an element in a system is an important factor in the determination of the geometry and the dimensions of the element. In such a situation we say that strength is an important *design consideration*.

1 Functionality **2** Strength/stress **3** Distortion/deflection/stiffness

4 Wear **5** Corrosion **6** Safety **7** Reliability

8 Manufacturability **9** Utility **10** Cost **11** Friction
12 Weight **13** Life

Standards and Codes

A *standard* is a set of specifications for parts, materials, or processes intended to achieve uniformity, efficiency, and a specified quality. One of the important purposes of a standard is to limit the multitude of variations that can arise from the arbitrary creation of a part, material, or process.

A *code* is a set of specifications for the analysis, design, manufacture, and construction of something. The purpose of a code is to achieve a specified degree of safety, efficiency, and performance or quality. It is important to observe that safety codes *do not* imply *absolute safety.* In fact, absolute safety is impossible to obtain. Sometimes the unexpected event really does happen. Designing a building to withstand a 120 mi/h wind does not mean that the designers think a 140 mi/h wind is impossible; it simply means that they think it is highly improbable.

Some of the organizations and societies listed below have established specifications for standards and safety or design codes.

American Society of Mechanical Engineers (ASME)
American Society of Testing and Materials (ASTM)
American Welding Society (AWS)
ASM International
British Standards Institution (BSI)
International Standards Organization (ISO)

Economics

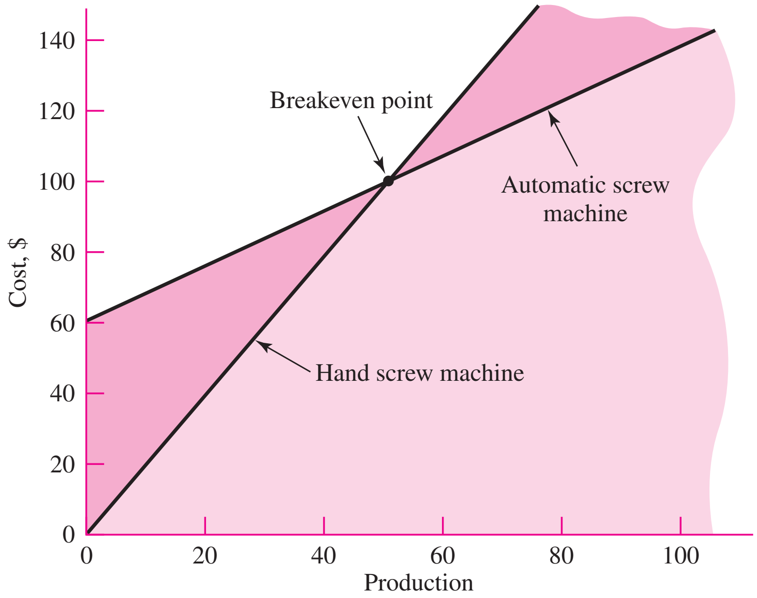
The consideration of cost plays such an important role in the design decision process that we could easily spend as much time in studying the cost factor as in the study of the entire subject of design.

Figure 1–3

A breakeven point.

Breakeven Points

Sometimes it happens that, when two or more design approaches are compared for cost, the choice between the two depends on a set of conditions such as the quantity of production, the speed of the assembly lines, or some other condition. There then occurs a point corresponding to equal cost, which is called the breakeven point.



Safety and Product Liability

- The best approaches to the prevention of product liability are good engineering in analysis and design, quality control, and comprehensive testing procedures. Advertising managers often make glowing promises in the warranties and sales literature for a product. These statements should be reviewed carefully by the engineering staff to eliminate excessive promises and to insert adequate warnings and instructions for use

Uncertainty

Uncertainties in machinery design abound. Examples of uncertainties concerning stress and strength include

- Composition of material and the effect of variation on properties.
- Variations in properties from place to place within a bar of stock.
- Effect of processing locally, or nearby, on properties.
- Effect of nearby assemblies such as weldments and shrink fits on stress conditions.
- Effect of thermomechanical treatment on properties.
- Intensity and distribution of loading.
- Validity of mathematical models used to represent reality.
- Intensity of stress concentrations.
- Influence of time on strength and geometry.

- Effect of corrosion.
- Effect of wear.
- Uncertainty as to the length of any list of uncertainties.

Engineers must accommodate uncertainty. Uncertainty always accompanies change. Material properties, load variability, fabrication fidelity, and validity of mathematical models are among concerns to designers.
There are mathematical methods to address uncertainties. The primary techniques are the deterministic and stochastic methods. The deterministic method establishes a *design factor* based on the absolute uncertainties of a loss-of-function parameter and a maximum allowable parameter. Here the parameter can be load, stress, deflection, etc.
Thus, the design factor n_d is defined as

$$n_d = \text{loss-of-functionparameter} \, / \, \text{maximum allowable parameter} \qquad \text{Equ. (1.1)}$$

Stochastic methods are based on the statistical nature of the design parameters and focus on the probability of survival of the design's function (that is, on reliability) EXPLAINED LATER.

Design Factor and Factor of Safety

A general approach to the allowable load versus loss-of-function load problem is the deterministic design factor method, and sometimes called the classical method of design. The fundamental equation is Eq. (1–1) where n_d is called the *design factor*. All loss-of-function modes must be analyzed, and the mode leading to the smallest design factor governs. After the design is completed, the *actual* design factor may change as a result of changes such as rounding up to a standard size for a cross section or using off-the-shelf components with higher ratings instead of employing what is calculated by using the design factor. The factor is then referred to as the *factor of safety, n*. The factor of safety has the same definition as the design factor, but it generally differs numerically.

Since stress may not vary linearly with load , using load as the loss-of- function parameter may not be acceptable. It is more common then to express the design factor in terms of a stress and a relevant strength

EXAMPLE 1–1 Consider that the maximum load on a structure is known with an uncertainty of ±20 percent, and the load causing failure is known within ±15 percent. If the load causing failure is *nominally* 2000 lbf, determine the design factor and the maximum allowable load that will offset the absolute uncertainties.

Solution To account for its uncertainty, the loss-of-function load must increase to $1/0.85$, whereas the maximum allowable load must decrease to $1/1.2$. Thus to offset the absolute uncertainties the design factor, from Eq. (1–1), should be

Answer

$$n_d = \frac{1/0.85}{1/1.2} = 1.4$$

nd should be the largest value to be in the safe side for this the Numerator should be as biggest as it could be while the denominator should be as smallest as it could be. For that we take 1/(1-0.15) for num. while 1/(1+0.2) for denom.

From Eq. (1–2), the maximum allowable load is found to be

Answer

$$\text{Maximum allowable load} = \frac{2000}{1.4} = 1400 \text{ lbf}$$

EXAMPLE 1–2 A rod with a cross-sectional area of A and loaded in tension with an axial force of $P =$ 2000 lbf undergoes a stress of $\sigma = P/A$. Using a material strength of 24 kpsi and a *design factor* of 3.0, determine the minimum diameter of a solid circular rod. Using Table A–17, select a preferred fractional diameter and determine the rod's *factor of safety*.

Solution Since $A = \pi d^2/4$, $\sigma = P/A$, and from Eq. (1–3), $\sigma = S/n_d$, then

$$\sigma = \frac{P}{A} = \frac{P}{\pi d^2/4} = \frac{S}{n_d}$$

Solving for d yields

Answer

$$d = \left(\frac{4Pn_d}{\pi S}\right)^{1/2} = \left(\frac{4(2000)3}{\pi(24\,000)}\right)^{1/2} = 0.564 \text{ in}$$

From Table A–17, the next higher preferred size is $\frac{5}{8}$ in $= 0.625$ in. Thus, when n_d is replaced with n in the equation developed above, the factor of safety n is

Answer

$$n = \frac{\pi S d^2}{4P} = \frac{\pi(24\,000)0.625^2}{4(2000)} = 3.68$$

Thus rounding the diameter has increased the actual design factor.

Reliability

The reliability method of design is one in which we obtain the distribution of stresses and the distribution of strengths and then relate these two in order to achieve an acceptable success rate. **The statistical measure of the probability that a mechanical element will not fail in use is called the *reliability*** of that element. The reliability R can be expressed by

$$R = 1 - p_f$$

where p_f is the *probability of failure,* given by the number of instances of failures per total number of possible instances. The value of R falls in the range $0 < R < 1$. A reliability of $R = 0.90$ means that there is a 90 percent chance that the part will perform its proper function without failure. The failure of 6 parts out of every 1000 manufactured might be considered an acceptable failure rate for a certain class of products. This represents a reliability of $R=1-(6/1000)=0.994$ or 99.4 percent.

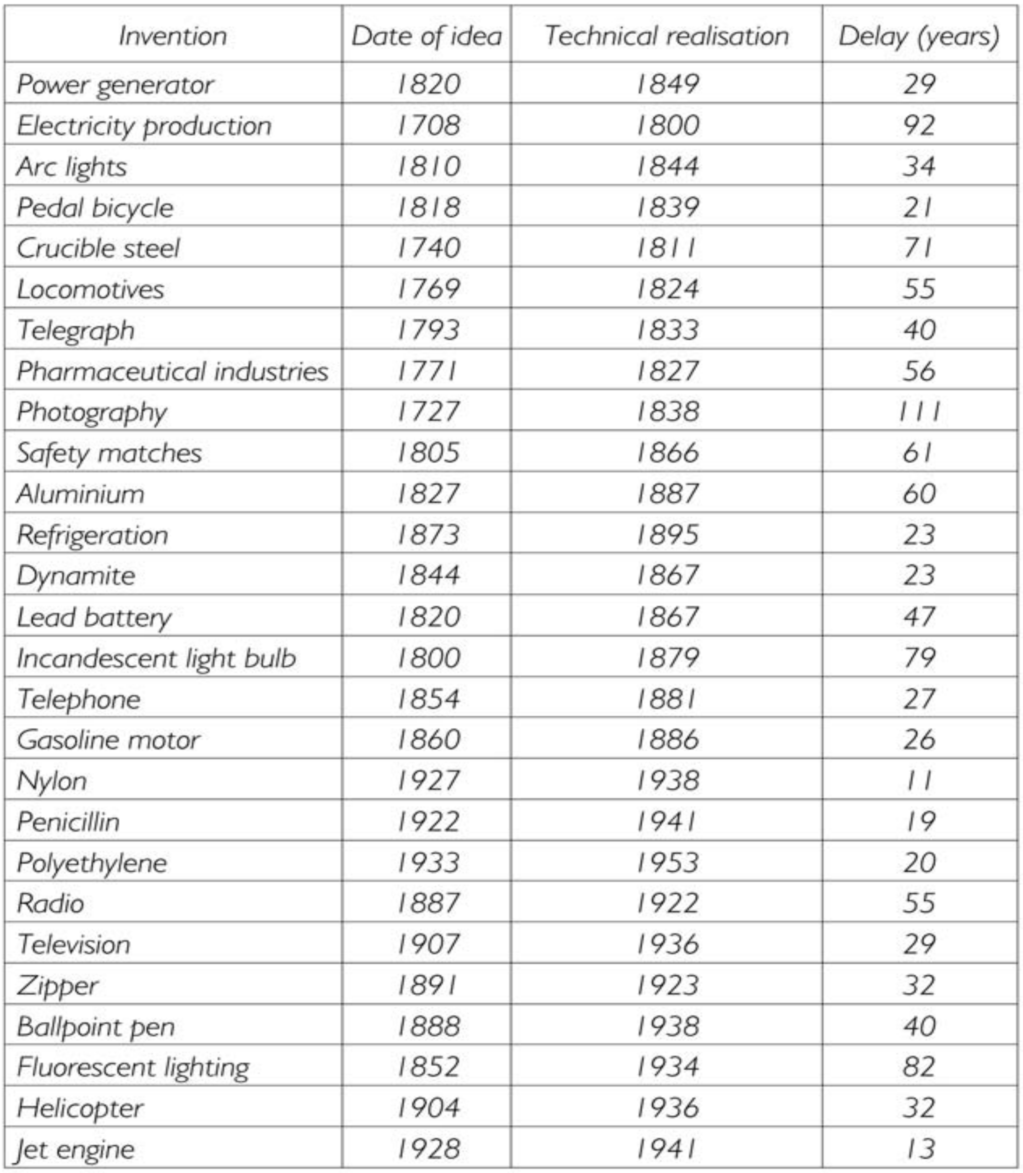
In the *reliability method of design*, the designer's task is to make a judicious selection of materials, processes, and geometry (size) so as to achieve a specific reliability goal. Thus, if the objective reliability is to be 99.4 percent, as above, what combination of materials, processing, and dimensions is needed to meet this goal? If a mechanical system fails when any one component fails, the system is said to be a *series system*. If the reliability of component i is R_i in a series system of n components, then the reliability of the system is given by

$$R = \sum_{i=1}^{n} R_i$$

For example, consider a shaft with two bearings having reliabilities of 95 percent and 98 percent. The overall reliability of the shaft system is then $R = R_1 R_2 = 0.95\,(0.98) = 0.93$. Your product is your story, your story is your product.

Materials are the ingredients designers use to imagine, create, and modify an idea so that when it is made it becomes more than an object or a product, part of a bigger system of storytelling and experiences.

Table 2.1 Inventions and their technical realisation (Source: Mensch[2.7])



Invention	Date of idea	Technical realisation	Delay (years)
Power generator	1820	1849	29
Electricity production	1708	1800	92
Arc lights	1810	1844	34
Pedal bicycle	1818	1839	21
Crucible steel	1740	1811	71
Locomotives	1769	1824	55
Telegraph	1793	1833	40
Pharmaceutical industries	1771	1827	56
Photography	1727	1838	111
Safety matches	1805	1866	61
Aluminium	1827	1887	60
Refrigeration	1873	1895	23
Dynamite	1844	1867	23
Lead battery	1820	1867	47
Incandescent light bulb	1800	1879	79
Telephone	1854	1881	27
Gasoline motor	1860	1886	26
Nylon	1927	1938	11
Penicillin	1922	1941	19
Polyethylene	1933	1953	20
Radio	1887	1922	55
Television	1907	1936	29
Zipper	1891	1923	32
Ballpoint pen	1888	1938	40
Fluorescent lighting	1852	1934	82
Helicopter	1904	1936	32
Jet engine	1928	1941	13

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3.1 INTRODUCTION AND SYNOPSIS

Materials, one might say, are the food of design. This chapter presents the menu: the materials shopping list. A successful product—one that performs well, is good value for money, and gives pleasure to the user—uses the best materials for the job, and fully exploits their potential and characteristics. It brings out their flavor, so to speak.

The families of materials—metals, polymers, ceramics, and so forth—are introduced in Section 3.2. What do we need to know about them if we are to design with them? That is the subject of Section 3.3, in which distinctions are drawn between various types of materials information. But it is not, in the end, a *material* that we seek; it is a certain *profile of properties*—the one that best meets the needs of the design. Properties are the currency of the materials world. They are the bargaining chips—the way you trade off one material against another. The properties important in thermo-mechanical design are defined briefly in Section 3.4. It makes boring reading. The reader who is confident in the definitions and units of moduli, strengths, damping capacities, thermal and electrical conductivities, and the like, may wish to skip this, using it for reference, when needed, for the precise meaning and units of the data in the property charts that come later. Don't, however, skip Section 3.2. It sets up the classification structure that is used throughout the book. The chapter ends, in the usual way, with a summary.

3.2 THE FAMILIES OF ENGINEERING MATERIALS

It is conventional to classify the materials of engineering into the six broad families shown in Figure 3.1: metals, polymers, elastomers, ceramics, glasses, and hybrids. The members of a family have certain features in

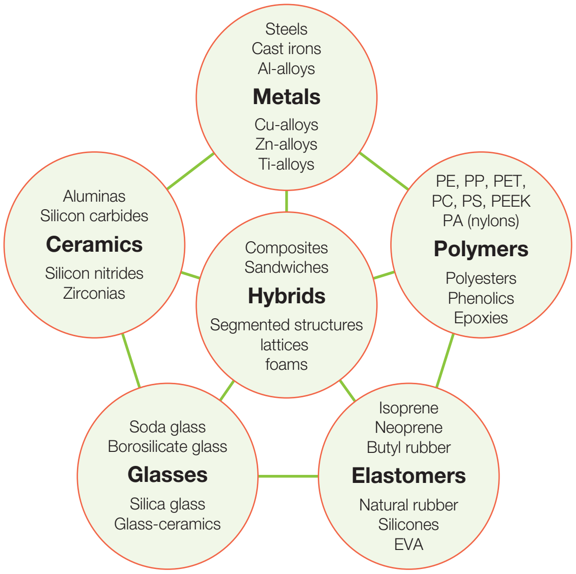

FIGURE 3.1

The menu of engineering materials. The basic families of metals, ceramics, glasses, polymers, and elastomers can be combined in various geometries to create hybrids.

common: similar properties, similar processing routes, and, often, similar applications.

Metals are stiff. They have relatively high elastic moduli. Most, when pure, are soft and easily deformed. They can be made strong by alloying and by mechanical and heat treatment, but they remain ductile, allowing them to be formed by deformation processes. Certain high-strength alloys (spring steel, for instance) have ductilities as low as 1%, but even this is enough to ensure that the material yields before it fractures and that fracture, when it occurs, is of a tough, ductile type. Partly because of their ductility, metals are prey to fatigue and of all the classes of material, they are the least resistant to corrosion.

Ceramics, too, have high moduli, but unlike metal, they are brittle. Their "strength" in tension means the brittle fracture strength; in compression it is the brittle crushing strength, which is about 15 times greater. And because ceramics have no ductility, they have a low tolerance for stress concentrations (like holes or cracks) or for high-contact stresses (at clamping points, for instance). Ductile materials accommodate stress concentrations by deforming in a way that redistributes the load more evenly, and because of this, they can be used under static loads within a small margin of their yield strength. Ceramics cannot. Brittle materials always have a wide scatter in strength, and the strength itself depends on the volume of material under load and the time over which it is applied. So ceramics are not as easy to design with as metals. Despite this, they have attractive features. They are stiff, hard, and abrasion-resistant (hence their use for bearings and cutting tools); they retain their strength to high temperatures; and they resist corrosion well.

Glasses are noncrystalline ("amorphous") solids. The most common are the soda-lime and borosilicate glasses familiar as bottles and ovenware, but there are many more. Metals, too, can be made noncrystalline by cooling them sufficiently quickly. The lack of crystal structure suppresses plasticity, so, like ceramics, glasses are hard, brittle, and vulnerable to stress concentrations.

Polymers are at the other end of the spectrum. They have moduli that are low, roughly 50 times lower than those of metals, but they can be strong—nearly as strong as metals. A consequence of this is that elastic deflections can be large. They creep, even at room temperature, meaning that a polymer component under load may, with time, acquire a permanent set. And their properties depend on temperature so that a polymer that is tough and flexible at 20°C may be brittle at the 4°C of a household refrigerator, yet may creep rapidly at the 100°C of boiling water. Few have useful strength above 200°C. Some polymers are mainly crystalline, some are amorphous (noncrystalline), some are a mix of crystalline and amorphous—transparency goes with the amorphous structure. If these aspects are allowed for in the design, the advantages of polymers can be exploited. And there are many. When combinations of properties, such as strength per unit weight, are important, polymers can compete with metals. They are easy to shape. Complicated parts performing several functions can be molded from a polymer in a single operation. The large elastic deflections allow the design of polymer components that snap together, making assembly fast and cheap. And by accurately sizing the mold and precoloring the polymer, no finishing operations are needed. Polymers resist corrosion (paints, for instance, are polymers) and have low coefficients of friction. Good design exploits these properties.

Elastomers are long-chain polymers above their glass-transition temperature, T_g. The covalent bonds that link the units of the polymer chain remain intact, but the weaker Van der Waals and hydrogen bonds that, below T_g, bind the chains to each other, have melted. This gives elastomers unique properties: Young's moduli as low as 10^{-3} GPa (10^5 times less than that typical of metals) increase with temperature (all other solids show a decrease), and have enormous elastic extension. Their properties differ so much from those of other solids that special tests have evolved to characterize them. This creates a problem: If we wish to select materials by prescribing a desired attribute profile, as we do later in this book, then a prerequisite is a set of attributes common to all materials.

To overcome this, we use a common set of properties in the early stages of design, estimating approximate values for anomalies like elastomers. Specialized attributes, representative of one family only, are stored separately; they are for use in the later stages.

Hybrids are combinations of two or more materials in a predetermined configuration and scale. They combine the attractive properties of the other families of materials while avoiding some of their drawbacks. The family of hybrids includes fiber and particulate composites, sandwich structures, lattice structures, foams, cables, and laminates; almost all the materials of nature—wood, bone, skin, and leaf—are hybrids. Fiber-reinforced composites are, of course, the most familiar. Most of those at present available to the engineer have a polymer matrix reinforced by fibers of glass, carbon, or Kevlar (an aramid). They are light, stiff, and strong, and they can be tough. They, and other hybrids using a polymer as one component, cannot be used above 250°C because the polymer softens, but at room temperature their performance can be outstanding. Hybrid components are expensive, and they are relatively difficult to form and join. So, despite their attractive properties, the designer will use them only when the added performance justifies the added cost. Today's growing emphasis on high performance and fuel efficiency provides increasing drivers for their use.

3.3 MATERIALS INFORMATION FOR DESIGN

If you're going to design something, what sort of materials information do you need? Figure 3.2 draws relevant distinctions. On the left a material is tested and the data are captured. But these raw data—unqualified numbers—are, for our purposes, useless. To make data useful requires statistical analysis. What is the mean value of the property when measured on a large batch of samples? What is the standard deviation? Given these, it is possible to calculate allowables: values of properties that, with a given certainty (say, one part in 10^6) can be guaranteed. Material texts generally present test data; by contrast, data in most engineering handbooks are allowables.