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Educating Materials Engineers*

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This contribution reviews the requirements for a successful professional career and the scope of materials engineering as a specific area of professional competence. Basic concepts associated with communication and performance in the engineering workplace are summarised. The selection of core courses for materials engineers is discussed and the role of case histories in developing engineering insight is emphasized. The extent to which technological forecasting and risk assessment can be usefully included in the course curricula is also assessed and some of the dilemmas associated with the undergraduate teaching of professional ethics are noted.

Keywords: Materials; knowledge acquisition; career; case histories; catastrophic failure.

INTRODUCTION

A PROFESSIONAL career requires a lot more than professional competence in some chosen field of specialization, and one recipe for success is shown in Fig. 1. This shows a 'Greek temple' built on a strong foundation of 'personality' and supported by pillars of ability that correspond both to the competence expected from a sound education in a recognized profession, and also many additional qualities such as communication skills, cultural awareness, creativity and the ability for leadership.

SOME BASIC CONCEPTS

Alan Mackay (private communication) has suggested a useful and general way of thinking about how knowledge is acquired (Fig. 2). Most of us distinguish between the 'real' world, in which we live and work, and another, 'conceptual' world consisting of what goes on inside our heads (not just the brain, but rather the mind). Observations made in our real world are generalized 'in the head' by *induction.* These generalizations are then rationalized into acceptable theories which are used to make 'real world' predictions by *deduction*. These predictions can then be checked against further observations, and the cycle repeated to further develop our understanding of the material world.

In addition to this simple model for the generation of knowledge, it is useful to have 'dictionary' definitions that will help disentangle our understanding of engineering from the parallel concepts of science or technology:

- *Engineering* is the profession that applies scientific principles to the design, construction, operation and maintenance of engines, instruments, machines and other man-made artefacts for transportation, communication, medicine or any other human endeavour.
- *Science* is the systematic study of the nature and behaviour of the material universe, based on observations, experiments and measurements that result in the formulation of general laws to describe this universe.
- *Technology* is the route by which raw materials are transformed into final, man-made products by the application of scientific principles and engineering skills.

PROFESSIONAL SKILLS

In addition to these philosophical considerations we should also note the more specific requirements

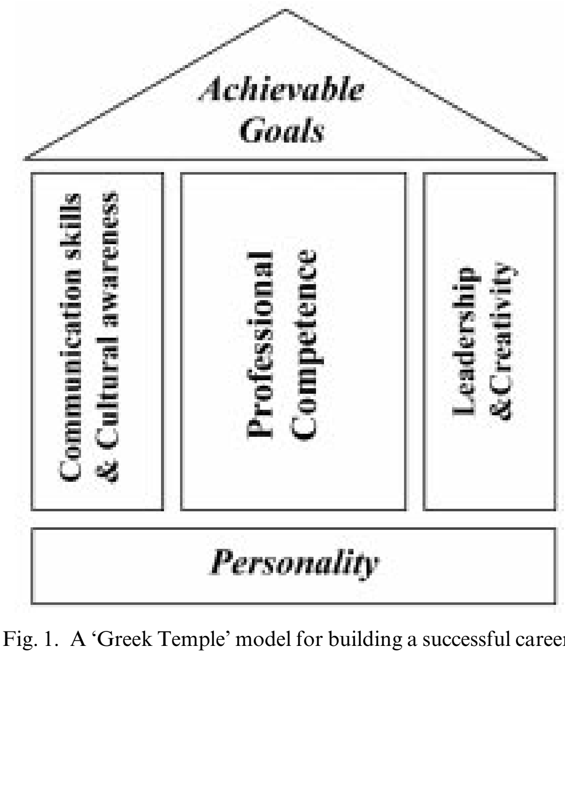

Fig. 1. A 'Greek Temple' model for building a successful career.

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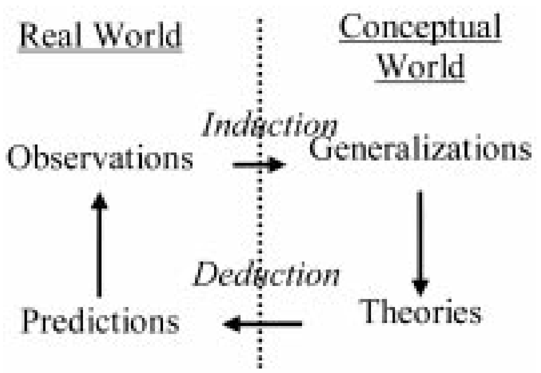

Fig. 2. Alan Mackay's model for scientific progress by inductive and deductive reasoning.

of a discerning employer wishing to recruit professional staff: a graduate engineer is expected to be able to analyse a problem that falls within his area of competence, and then synthesize a technically and financially satisfactory solution. He is expected to do this quantitatively, as far as possible, and he is expected to be able to report his work cogently and coherently, both verbally and in writing. The twin skills of numeracy and literacy have to be translated into powers of communication that include cultural awareness and enable him to deal, not only with the management to whom he reports, but also with the workforce for whom he is responsible, the suppliers with whom he must deal, and the customers whose good will must be assured. These requirements are summarised in Fig. 3.

MATERIALS COURSE CONTENT

Of course, materials educators have always recognized the need for a programme that includes breadth of scope and depth of perspective; none more so than Prof. M.F. Ashby, who, together with his colleagues, has produced some quite revolutionary teaching texts [1, 2], together with an analysis of materials selection procedures and an evaluation of materials performance data [3] (Fig. 4). These have contributed to making Ashby one of the most cited materials engineers of our time.

In addition to providing teachers with some remarkably effective tools for rationalizing the wealth of materials data that bombard any student engineer, Ashby has also reminded us of the rapidly accelerating rate at which materials expertise is changing, and has helped to provided generations of students with some sense of historical perspective (Fig. 5). However, we still have no answer to the demands now made on us to incorporate courses for the materials engineer on quantum-mechanical and electro-optical properties, the implications of nanotechnology, or the ever-expanding interface between soft-tissue engineering, that is, biomaterials, and materials science.

If we confine ourselves to a classical schema for courses on materials, then *mi casa es su casa,* 'my house is your house' (Fig. 6) provides a useful conceptual framework for describing the range of topics covered by both applied courses in materials engineering (the rectangle) and pre-requisite, core courses in materials science (the triangle). The course content summarised in Fig. 6 ignores any division into either materials specialities (metals and alloys, polymers and plastics, ceramics and glasses, semiconductors and dielectrics, or composites), or into engineering specialities (aerospace, civil, marine, nuclear or other engineering applications of materials)

The Materials Engineering 'living area' in Fig. 6 rests on secure foundations of materials '*processing & performance*', and shares a common materials '*structure & properties*' interface with the protective 'roof-space' of Materials Science. The 'rooms' of the living area serve to house the engineering specialities which are associated with materials *shaping*, *joining* and *finishing*, on the one hand, and materials *selection*, *testing* and *quality control*, on the other hand, our 'attic' houses a strongly science-oriented expertise in materials *characterization*, and is capped by a 'weather-proof roofing' of physical theory.

Of course, any number of variants on this materials course content is possible, depending on the strengths of the teaching staff and the national job market for materials engineers, but, in our globalized world, the basic logistics of providing materials engineering students with marketable professional skills is unlikely to allow

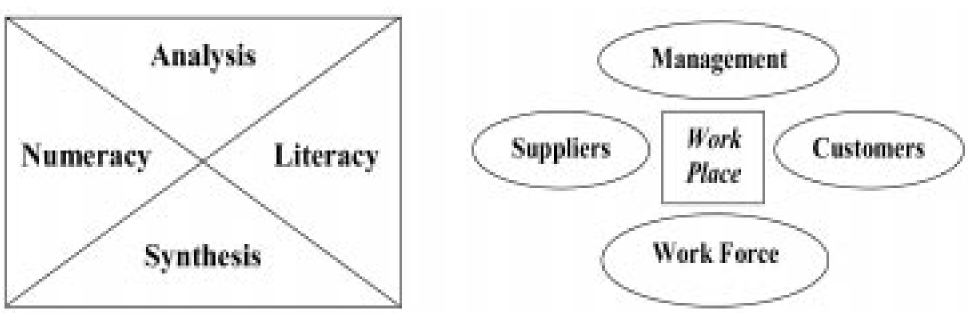

Fig. 3. The basic requirements for professional competence (on the left) and the work place forum (on the right) include communication skills and cultural awareness.

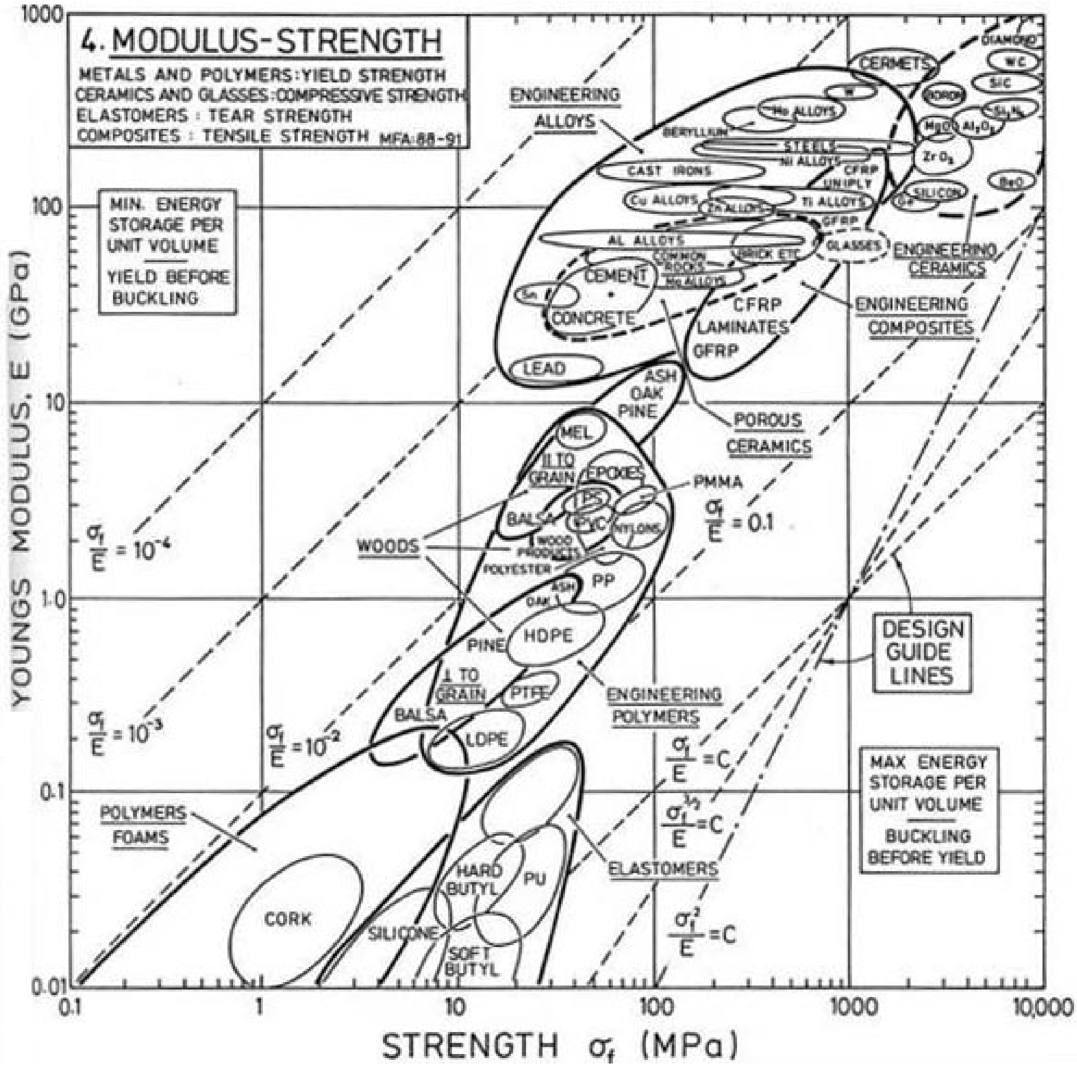

Fig. 4. An Ashby data summary [3] showing the relation between strength and elastic modulus for different classes of engineering materials.

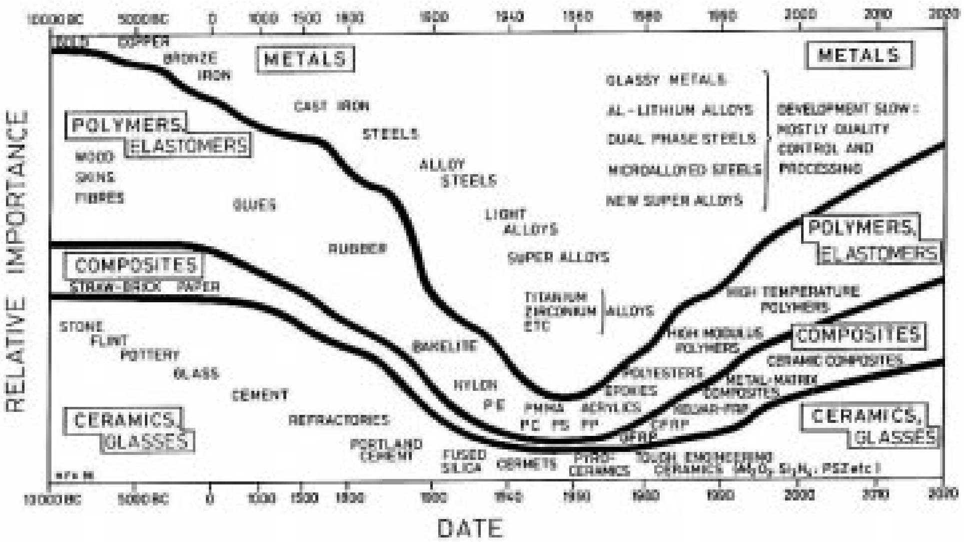

Fig. 5. Ashby's time-line [3] for the development of structural materials from the dawn of agriculture to the present day and beyond (but note the absence of functional materials for modern electronic and electro-optic applications).

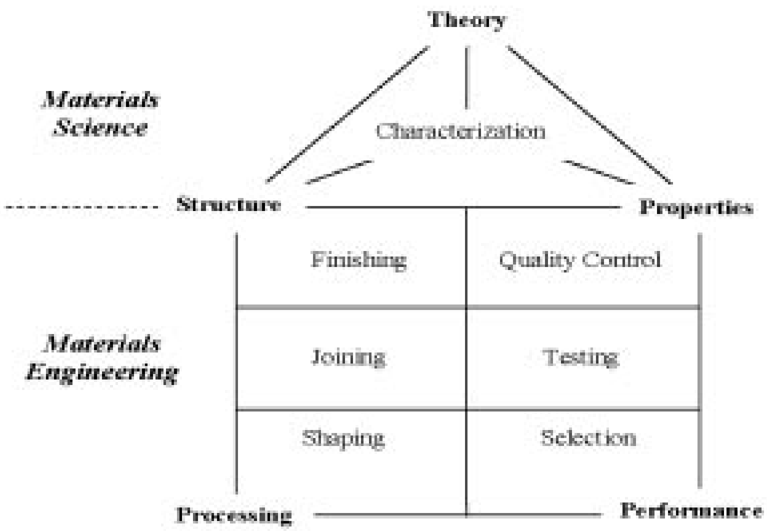

Fig. 6. The scope of the materials science and engineering professions.

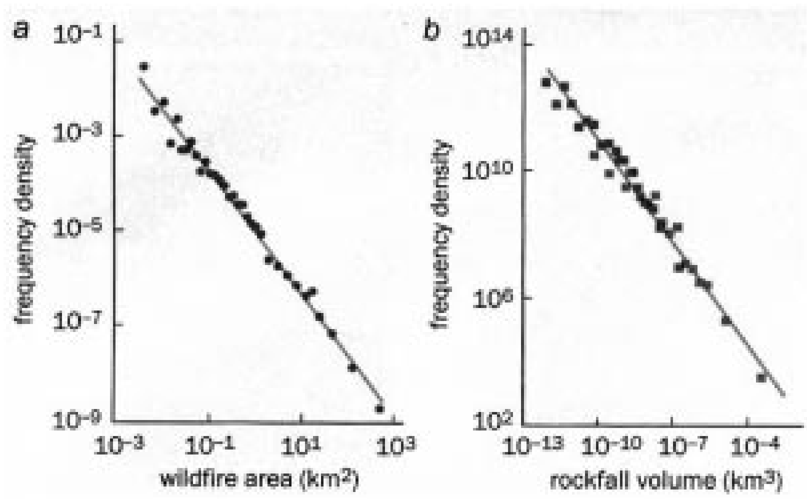

Fig. 7. Power laws describe the severity/frequency relation for both natural and engineering disasters [4].

us much freedom to change the general form of this schema. There is one area of contention that does deserve some in-depth appraisal. What about the pre-requisite, core courses that should provide the scientific principles on which our 'house' is constructed? We recognize the essential nature of some core courses:

- Applied Mathematics
- Condensed Matter Physics
- Chemical Thermodynamics
- Elasticity & Plasticity
- Transport Processes (heat and mass transfer, and fluid mechanics)

But today's curricula allows less and less time for the student to gain insight into the professional implications involved in materials selection, joining technologies and the rest.

What about the extraordinary spectrum of new tools for the characterization of materials structure and properties? Characterization occupies an increasing volume in the 'roof-space' of our house (Fig. 6), driven most recently by the rapid growth of nanotechnology. What about soft-tissue science? This speciality is in increasing demand, as the interface between materials engineering and the health sciences continues to develop.

And what should we teach our students about the statistics of failure? At least they ought to be aware that the severity of the damage caused by engineering disasters—the failure of dams and the incidence of civil airplane crashes—usually obeys the same probability power laws as natural disasters—forest fires and rock slides (Fig. 7).

How aware are our students of the gulf that separates the death toll from the economic cost of a disaster? The table below compares these two measures for three events of truly catastrophic proportions (data taken from published newspaper reports).

A partial answer to these questions lies in the provision of well-chosen and well-structured elective courses. It is certainly important to put aside sufficient time for the analysis and discussion of

Table 1. Recent data on catastrophic events

Year	Event	Deaths	Economic cost $billion	Ratio Dollars/death
1992	Hurricane Andrew	~50	~30	~6,000,000
1995	Kobe earthquake	~6,400	~132	~200,000
2004	Indian Ocean tsunamis	~250,000	~14	~600

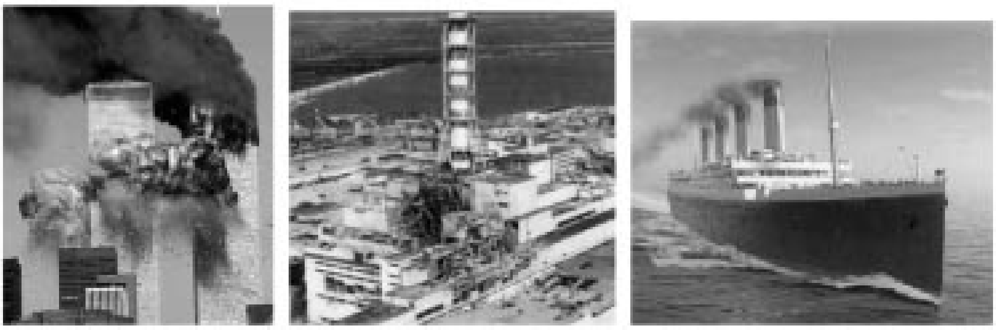

Fig. 8. Engineering catastrophes: the World Trade Center, September 11, 2001; the Chernobyl Reactor, April 26, 1986; the sinking of the Titanic, April 15, 1912.

case-histories in product development, failure analysis and materials selection. All these additional courses require a great deal of preparation, they need to be updated each year, and in many cases they are probably best given by adjunct staff who have had some practical experience.

At the moment we are experimenting with an elective course on 'Engineering Disasters, Human Error and Materials Failure'. This experimental course covers a wide range of case-histories in the fields of aerospace, nuclear, civil and marine engineering. The *smorgasbord* of topics includes the 2001 collapse of the World Trade Center that followed the terrorist attack, the 1986 destruction of the Chernobyl nuclear reactor, and the 1912 sinking of the *Titanic* (Fig. 8, from Internet archival images).

How can we avoid this type of course becoming a 'soft option' for lazy minds? We have to make sure that students research their own examples of engineering disasters, and then report their results in class seminars and in-depth essays (honing their communication skills in the process).

GLOBALIZATION AND STANDARDIZATION

We all want the best for our graduates, which in itself should be sufficient motivation for ensuring that our admissions policy, our course content and our evaluation procedures are all in accord with international standards. But if that motivation is insufficient, then we are surely aware of the growing need for the international recognition of engineering qualifications granted by any university.

Adapting the teaching methods of other universities and copying their course content or their educational practice might not sound like a very exciting route to follow, but it is still a lot better than blind adherence to any 'traditional' programme on engineering education that has long ceased to be of relevance in the market place for professional skills. It follows that we should at least consider the benefits and obstacles attached to a sensible use of Distance Learning, Internet Textbooks and the Virtual Laboratory. We should also look closely at financial and practical options for integrating Study Abroad or Student Exchange into our programmes, and examine the feasibility of industrial and research internships, both at home and abroad. This is also the place to consider the need to develop cultural awareness and provide adequate time in our overcrowded curricula to develop language skills.

In the workplace, materials engineers will come in contact with engineers from many other disciplines, as well as with lawyers, economists and businessmen. Our graduates have to accept that professionals in these other disciplines not only lack any understanding of the complex behaviour of engineering materials, but also have no need for a knowledge of the basics of metal fatigue or pitting corrosion.

TECHNOLOGICAL FORECASTING

Forecasting the future is a risky and error-prone business. On the other hand, it is also necessary, since engineers will always have to predict performance scenarios. There is no point in over-designing components to last beyond the required life of an engineering system, but every reason to guarantee that they will not fail before the system is taken out of service. The problem is compounded when a new and untested technology is involved, for which no previous experience of long-term application or extreme conditions of use is available. At the simplest structural level, materials engineers have to predict creep life, corrosion resistance and toughness for prototype engineering assemblies which have yet to be used in practice, and which, in addition, may incorporate newly developed and incompletely tested materials.

The cell-phone revolution has been with us less than 10 years and has dramatically changed the way we communicate. Personal computers and the lap-top have been around rather longer. Genetically modified foods are struggling for acceptance, and are now on the supermarket shelves (whether we like it or not). None of these technologies have been developed by materials scientists or engineers who had been trained to do so, and none of our students today can hope to know what new technologies they will be developing, using or implementing in ten years time. It will be another quarter of a century before today's students reach the peak of their professional careers. The education that they receive today has to provide a complete grounding in basic science and engineering principles if these students are to adapt successfully as engineering graduates in an unknown technological future.

PROFESSIONAL ETHICS

Should we instruct our students in codes of professional ethics? The media frequently present the 'whistle-blower' as a role model for society, but professional engineers also have contractual (and ethical) obligations to their employers which cannot be breeched with impunity. The infringement of patents is a legal issue, as is the release of sensitive material to a third party, if it is protected by commercial confidentiality, non-disclosure agreements or the state security laws. These issues bring us back to Fig. 1. Intellectual property is often stolen and patent rights are routinely infringed. Although proven cases of science fraud exist, many accusations of scientific fraud have been found to be false.

There is every chance that the careers of our future graduates will place them in situations for which they are required to make an ethical judgement. Can we prepare them for this? The engineer's awareness of social responsibilities has to be integrated with the skills that make for professional success. A success that depends not only on the engineer's professional competence, but also on the social skills that enable him to function both at work and in the community. Science and technology cannot provide much help in establishing ethical guidelines for an engineer who finds his duty to his employer in direct conflict with his social conscience. Neither do they help when the engineer must balance his belief in the need to inform the public of a technological hazard against his duty to his employer and the dangers of generating unjustified panic.

NEW COURSES

So what might be missing from the standard course content of a degree in materials science or engineering? A tentative short-list of new, elective courses might read as follows:

- Biomaterials science & soft-tissue engineering
- Professional ethics and social responsibility
- The social impact of technological change
- Engineering disasters & human error

None of these courses are 'required' for professional competence or scientific excellence, but all are able to provide a social dimension to the future work of the materials engineer. Taken together they should enable the materials engineering graduate to integrate successfully into our rapidly changing, multicultural world.

END LINE

A *New Yorker* cartoon some years ago showed an excerpt from a graduation speech delivered by a suitably gowned academic: *'. . .and as you go out into the world, I predict that you will gradually and imperceptibly forget all you ever learned at this university.'* I know that this assessment is untrue—but it is surely our job to make sure of that.

Acknowledgements—The author has been involved in the development of materials engineering programmes for nearly forty years, during which time he has seriously and knowingly imitated the work of his predecessors and his peers. He has been fortunate enough to have had access to the academic staff of universities in Europe (mainly France, Germany and England) and the United States (across the continent), most of whom have been happy to share their thinking on curriculum development. Materials Science originated as a discipline after the Second World War, on the Atlantic Seaboard of the United States. Our profession started as a response to the wealth of demands on materials created by nuclear energy and the electronics industries, and later supplemented by the communications and data processing revolutions. Without these clearly defined educational needs it is doubtful whether this author would have been motivated to stay the course.

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David Brandon, on receiving his doctorate, joined the staff of the Department of Metallurgy at Cambridge where he was in charge of a program of the U.K. Atomic Energy Authority for the development of field ion microscopy. In 1963 he moved to Geneva, Switzerland, where he worked for the Battelle Memorial Institute. In 1966 he joined the Technion, and in 1967 he was appointed to the Arturo Gruenebaum Chair. He was a Senior SRC Fellow at the University of Cambridge, England, and a Visiting Senior Scientist at the Ecole Nationale Superieure des Mines, Paris. He was a Visiting Fellow of Wolfson College at the University of Oxford and a Visiting Scholar at Lehigh University, USA. He is a Fellow of the Institute of Physics (UK) of the Institute of Metals (UK), and of ASM International, as well as being a member of the American Ceramic Society. He has held numerous administrative posts at the Technion, including Head of the Department of Materials Engineering, Chairman of the Technion Senate-Students Joint Committee, Director of the Israel Institute of Metals and Director of the Materials Research Center. He was Coordinator for International Student Exchange at the Technion, and is currently head of the Technion Center for Pre-Academic Education, and a member of the Board of Directors of Acta Metallurgica Inc. (USA) and Cerel, Advanced Ceramic Technologies Ltd (Israel).