through to biological, and medical science (encompassing microbiology and enzymology) on the other. The materials scientist and chemical engineer confronted with the task of evolving new systems for catalytic conversion needs to be a polymathic individual capable of roaming freely, and with discrimination, through this vast field of endeavor.

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Materials for the Next Millenium

Consumption Trends
Technico-Economics
European Performance
Materials Development

By Ernest D. Hondros* and Edward Bullock *

1. Introduction – The Materials Spectrum

The materials that make up the things which surround our daily lives and which are taken so much for granted are the product of a highly sophisticated and interactive chain of processes. The mineral-based materials in particular, extracted from the earth as raw ores are converted into alloys, composites and fine ceramics by techniques which call on the utmost ingenuity of man. The complexity of the basic, interactive, scientific disciplines involved in the production of modern, advanced materials is illustrated in Figure 1. The whole spectrum from the minerals in the earth to the formed material component, which has been finely tuned to closely specified properties to meet the requirements of a particular application, is shown.

The intricacy and breadth of such an interdependent chain of processes has evolved over many centuries to meet the immediate needs of society. Progress in materials utilization has largely determined the advance and ascendancy of soci-

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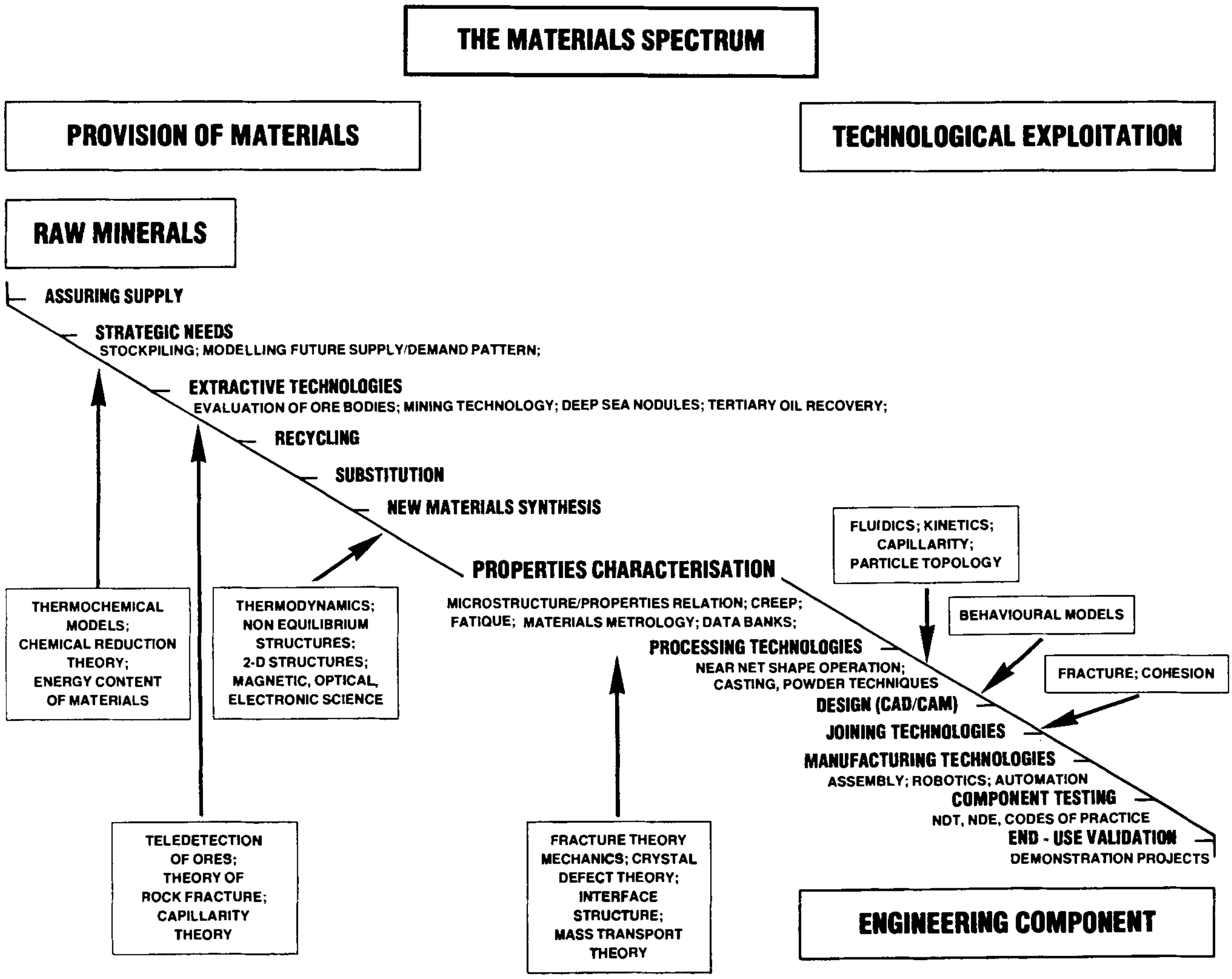

Fig. 1. The materials spectrum.

eties and has always been an issue of high priority. This situation still pertains today and will continue into the future.

As the complexity of materials processes has increased, so too has the volume of use, from the first, relatively insignificant fabrication of artifacts in the Stone Age, through the increasing demands of the Bronze and Iron Ages and accelerating during the last century to the prodigious levels of today. Concurrent with this massive expansion in volume has come a wide diversification in material types as conventional materials are developed to their physical limit and new materials are sought. Thus today in the industrially developed countries, the consumption of iron and steel, and of lead and copper have reached the top of the "S" curve of growth rate with time, while relatively new materials such as plastics, aluminum and composites are growing rapidly, and highly innovative materials, typically engineering ceramics and intermetallics are in the initial stage of slow development prior to mass exploitation.

The trend towards diversity will continue as current high growth rate materials reach their limits and saturate (including perhaps aluminum by the end of the century) to be replaced by new materials. Furthermore, as the demands for materials performance become more exacting, materials will become increasingly tailored to specific performance needs so that the trend will be for the use of combinations of highly specialized materials, each developed for a specific function within the operating system.

2. Materials Consumption Trends – The Global Responsibility

The staggering increase in utilization of the physical resources of the world, quantified in Figure 2 for the US, has led to wide concern that with such continuous growth in materials consumption, there is a danger of global exhaustion.

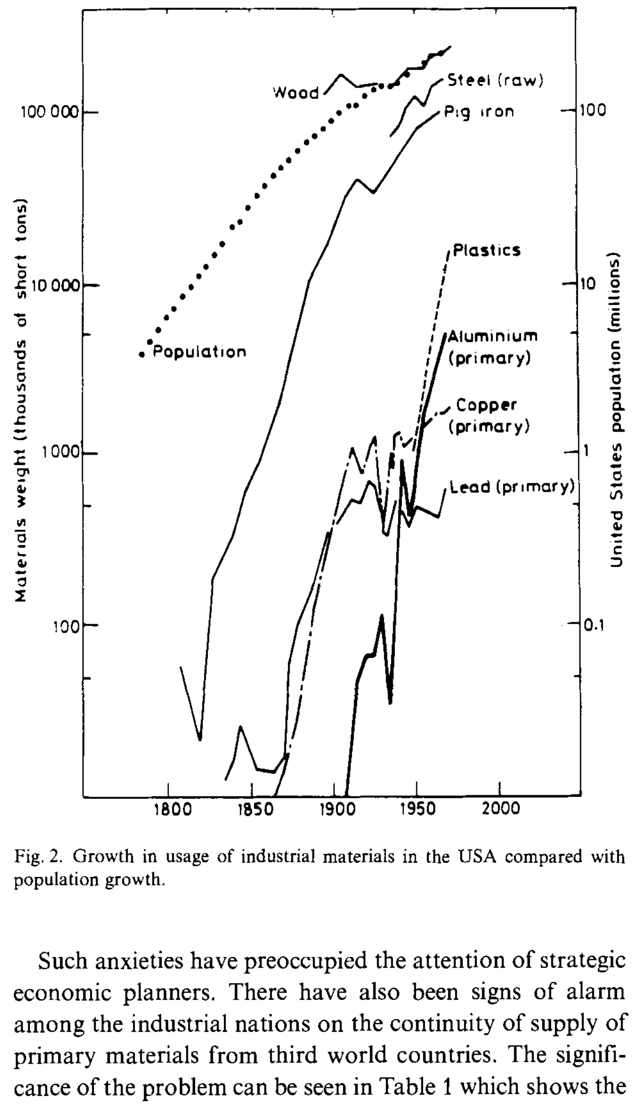

Fig. 2. Growth in usage of industrial materials in the USA compared with population growth.

Such anxieties have preoccupied the attention of strategic economic planners. There have also been signs of alarm among the industrial nations on the continuity of supply of primary materials from third world countries. The significance of the problem can be seen in Table 1 which shows the

Table 1. Import dependence of raw materials by trading areas.

	EEC	(% of consumption) USA	Japan	COMECON
Aluminum	61	85	100	28
Copper	90	14	94	4
Chromium	100	91	98	2
Cobalt	100	98	100	68
Iron Ore	79	36	99	5
Lead	76	13	78	3
Nickel	100	70	100	13
Manganese	100	98	98	3
Tin	87	83	98	
Titanium	100			
Tungsten	99	52		
Zinc	91	57	74	9

amount of some principal metals imported in the form of ores and concentrates as a percentage of consumption. Among the major trading blocs, the dependence on external supplies of raw materials is most critical for Japan. The position of America is somewhat better than for example, the European Community, but nevertheless there has been considerable concern in regard to the more vulnerable strategic metals such as chromium, cobalt, tungsten and manganese, and especially fears that politico-economic movements in the Third World could produce serious restrictions to supply.

The problems of whether the growth in demand in goods and services can continue, and what constitutes the physical limit, have been the source of much agitated public debate in the past years. This was expressed perhaps in its most sensational form in the deliberations of the "Club of Rome" which led to many popular books, presenting the alarmist vision of declining natural resources.

This matter is central to any forecast of the shape of the next millenium in terms of the materials infrastructure. For this reason many analytical methodologies have been applied to the problem of forecasting the demand for raw materials throughout the world in the next century. Indeed, many of the forecast scenarios have appeared alarming.

The analysis we refer to is that of *Malenbaum*[2] who presented the outlook for demand in terms of two component elements – *the intensity of use* and *the total output of final goods and services*. He found that the intensity of use of most materials has been declining in recent years, with the exception of aluminum. The forces giving rise to a declining pattern of intensity of usage, especially in the richer waste producing countries, originate partly from technological developments, from substitutions among the raw materials and from shifts in the types of final product that consumers expect. This development, the decline in the intensity of usage, symbolizes a conscious slackening of Man's consuming appetite for raw materials.

Typical results of this type of analysis are shown in Figure 3 for three elements, chromium, tungsten and cobalt in which the intensity of usage per unit of (GDP) is plotted versus time. This indicates at least saturation in intensity of usage and even in some cases a significant reduction. The broad outcome of this analysis is that by the turn of the century the world will be consuming a volume of raw materials two to three times greater than in the previous quarter of a century. In most cases the ratios are closer to a factor of two. Compared with forecasts of equivalent ratios of five to ten made according to other models, this is an optimistic forecast.

In contrast to earlier anxieties, this represents a hopeful vision of Man and society working in close symbiosis with nature and leading to the reduction in the rates of materials consumption. It represents a conscious trend to limit the consumer appetite of Man. Since analyses of this type were made, there has been time to check on their validity and they appear to be closer to the true pattern of events. This model then is a salutary change from the Doomsday Doctrine, which suggests Man's helplessness in the face of resource exhaustion or of the deterioration of the environment. Given a certain measure of global political stability, this level of demand in raw materials can be met through existing reserves for some hundreds of years.

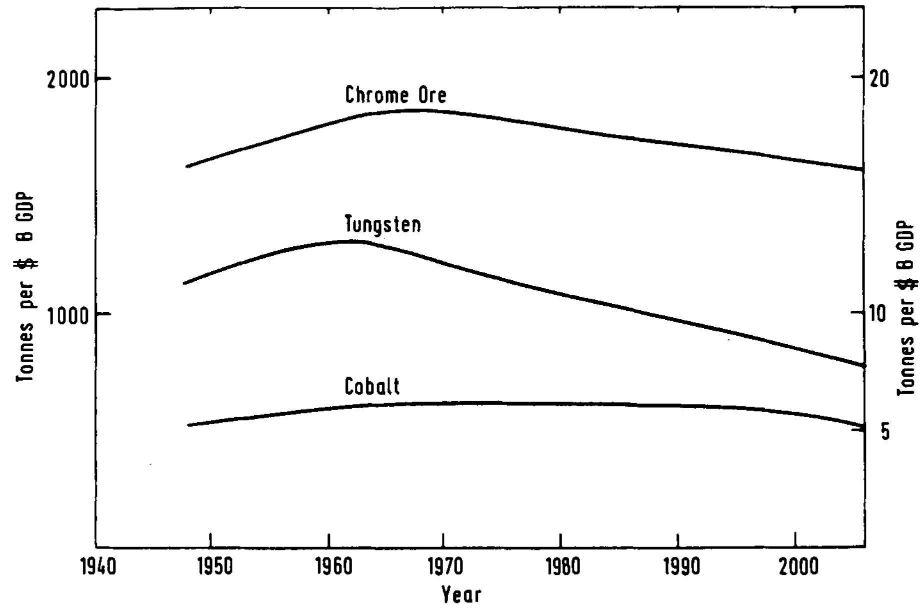

Fig. 3. Changes in intensity of use per unit GDP with time, for chromium, tungsten and cobalt.

Incidently, one conclusion from the above is that the setting of materials science and technology research objectives in terms of the substitution for scarce or unavailable materials is not a tenable assumption.

3. Materials and Future Technologies

It is now widely recognized that materials play an underpinning rôle to the major industries; they provide a substantial framework for the mechanical, chemical, building, process engineering and transport sectors. Hence, the existing euphoria about materials is partly a recognition of the fact that materials represent the rate determining step in the emergence of future technologies and for the competitivity of many existing technologies.

This is illustrated in a dramatic form in the outcome of a survey carried out by the Japanese[3a] to determine the measures that will be necessary to cope with the future requirements in industry, energy, natural resources and the environment. The question was posed as part of a systematic study of the necessary conditions for satisfying human expectations for a stable and prosperous future society. Many distinguished men and women of learning were involved in this "Delphic" type of forecasting methodology, an approach which can be considered as a process of iteration towards a consensus in games of clairvoyance. The outcome of this study, presented in Table 2, is a summary of the principal science and technology innovations for which future realization is expected. The vast amount of information collated and displayed in a chronological manner shows clearly that materials developments per se are some of the high priority items; however, the important observation is that in a large number of items in the forecast it is the materials *factor* which is implied as the rate determining step. In other words, to realize the major technological developments indicated in the table there will be a concurrent need to develop materials with specific functions.

Table 2. Technology Development Forecast (Japan).

2006	Forecasting earthquakes within one month.
2005	Super conductors with critical temperature of liquified nitrogen (77 K).
2004	Means of converting cancerous cells into normal cells.
2003	Steel production from nuclear energy.
2002	Submersible cargo ships: Aircraft and automobiles using hydrogen fuel.
2001	Drugs for arteriosclerosis.
2000	Large scale environmental purification technologies.
1999	Chemical agents for treating clotted cancer growths.
1998	Direct aluminum refining technology (direct reduction). Earthquake prediction through sea-bed crust activity.
1997	Deep sea extraction of metallic nodules. Large scale commercial nuclear fuel reprocessing plant.
1996	Engineering laboratory in space. Three dimensional memory devices.
1995	Deep sea (several hundred metres) drilling technologies. Disposal of high level radioactive wastes by solidification techniques.
1994	Super LSI – 10^9 devices per chip.
1993	Super computer (high speed devices): High efficiency thermoelectric conversion.
1992	Advanced robots for complex working environments.
1991	Long range meteorological forecasting.
1990	Large area amorphous silicon solar cell.
1989	Satellite prospecting (minerals, fishing, agricultural).

It is remarkable that in most of the categories involved in this forecast, technologies are cited which clearly depend on materials developments – thus materials related technologies are destined to be crucial in those innovations that will compose the fabric of the industries and societies of the next millenium. It seems clear that, whether in connection with the equipment for deep sea mining or for realizing thermonuclear fusion or for replacing diseased human organs or developing large area solar conversion cells, the critical step in the realization of all these innovations will be the advent of the materials precursor.

From such a broad recognition of the rate determining rôle of materials technologies, most of the industrialized countries have recently launched programs with central government support in order to stimulate growth in materials innovations. As early as 1980 the USA in its National Materials and Minerals Policy Act highlighted the critical importance of minerals and materials to the national economy, defence and standard of living and urged the government to intervene in areas where there is a potential for high "pay-off" technology. At the same time, Japan has galvanized its institutions into action and has mobilized behind advanced materials, including fine ceramics, polymers, amorphous metals and composite materials. The same note is being struck in many places and at different levels of action – in fact with a strangely repetitive beat. In the UK the *Collyear* report recommended a program of the order of a hundred million pounds over five years in new materials, equally financed by industry and government. In Germany, the German Federal Ministry for Research and Industry (BMFT) has implemented a large materials research program, to continue over about ten years, with links between the universities and the public sector in order to procure close collaboration. In France the Materials Mission has been published which is aimed at the establishment of a mobilization program to double government investment. Similarly there have been materials proposals in the Netherlands, in Belgium, more recently in Italy and currently in Spain and Portugal. In the European Community programs, materials is the pivot of the new Institute of Advanced Materials, shaped from the materials R & D activities of two establishments (Petten and Ispra) of the Joint Research Centre. Finally, materials R & D will feature strongly in collaborative cost-shared programs and in the next phase of the BRITE program, materials innovations will be closely linked with the technological end-use, particularly in the manufacturing and processing industries.

4. A Sectorial Approach

The types of materials that should be developed in the coming years in Europe are those linked to the industries in which Europe has an economic and trading ascendancy. The materials must be closely interlinked with the manufacturing industries. Hence, it might be instructive to take a glimpse at the world competitive market position of the European Community. Figure 4 shows graphically the European position. We see that the European Community has a high market share (30–40%) in a number of very high output industrial sectors, such as the chemistry sector, electrical engineering, motor manufacturing, mechanical engineering

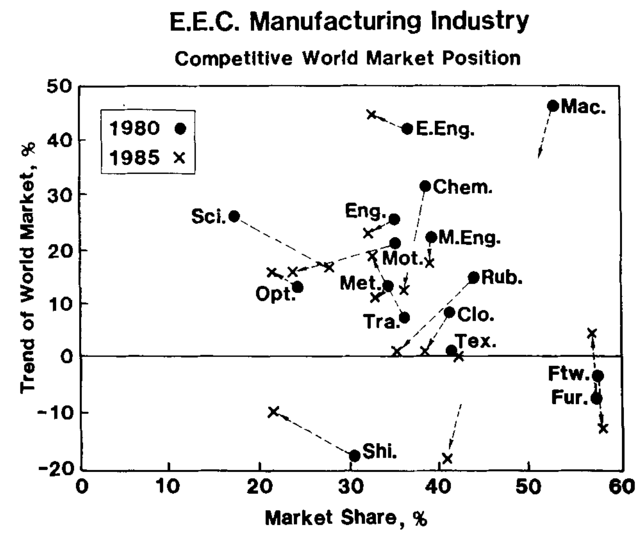

Fig. 4. EEC manufacturing industries competitive world market position.

as well as in clothing and textiles. The next point to note is the ominous drift towards a lower market share in high volume industries, in all cases except the chemical sector, mechanical engineering and textiles. The only sector which is showing a highly significant growth is that of scientific instruments, hardly a volume market. We note for example the large decline in the motor manufacturing industry, in shipping as well as in the rubber industries.

This can be compared with the Japanese position in the world market place (Fig. 5). Consistent with a total Japanese economy which is lower in volume than that of the European Community, many industrial sectors in Japan have a lower world market share. However, the targeted increases in the important sectors, notably electrical engineering, general engineering and metallurgical products are clear.

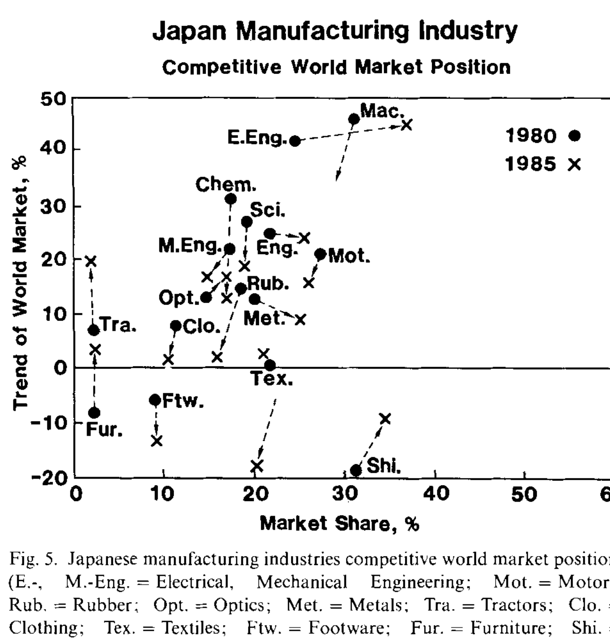

Fig. 5. Japanese manufacturing industries competitive world market position. (E.-, M.-Eng. = Electrical, Mechanical Engineering; Mot. = Motors; Rub. = Rubber; Opt. = Optics; Met. = Metals; Tra. = Tractors; Clo. = Clothing; Tex. = Textiles; Ftw. = Footware; Fur. = Furniture; Shi. = Shipping; Mac. = Machines; Chem. = Chemicals; Sci. = Science).

The broad findings of this enquiry are that in the major sectors, although the EC and the USA hold the largest part of the world market, the EC's rate of growth is low and Japan is catching up very quickly. In all of the industrial sectors, it was noted that either the USA or Japan has the most important R & D expenditure.

Looking at it in this competitive way, which we must, the overall position is that Europe has to work harder and invest in more R & D in order to retain its market position in nearly all of the industrial sectors. This gives us a wide field of choice. The materials innovations in Europe in the coming years have to underpin a wide variety of industries, in particular those related to electrical and mechanical engineering.

5. Technico-Economic Aspects

In the western world, outside the defence sector, the future materials scene will be determined not only by the innovation and the competence of the materials scientists, but also by market forces – by the technico-economic aspects. This latter field is complex and usually neglected by the scientists. However, in a forward look such as this, it must be emphasized that the future does not depend only on the genius of the scientist and inventor.

As an example, consider the introduction of new ceramic materials into the engines of the future. We are all aware of the euphoria about advanced ceramics, and more recently, this earlier hyper-enthusiasm has been toned down to more realistic levels. Figure 6 shows an example from a worldwide

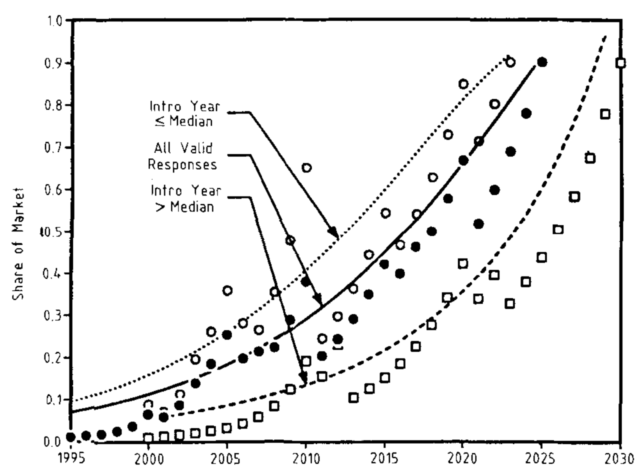

Fig. 6. Usage of ceramics in heat engines – forward look.

"Delphic" survey[3b] on the introduction of ceramics into heat engines. This was a wide, very subtle survey and the results can be treated with respect. They show the market penetration curves for ceramic engine components such as light-duty engine valves and heavy duty engine piston caps. These show reasonably good penetration prospects. The ceramics are considered to make improvements in performance through reduced fuel consumption, increased power density, reduced inertia for light duty engines and improved durability and heat insulation for heavy-duty engines.

The above scenario is highly speculative: it means that the model *could* apply, not that it is bound to apply. The realization of the above depends critically on market factors. Cost is the primary barrier; there will be a price premium for the first few years and this should inhibit manufacturers from introducing new ceramics. Are the technical advantages worth the extra cost? This is what the manufacturer has to decide – to take the risk that the public is sufficiently appreciative of the benefits.

This question throws up the whole complex subject of the strategic commitment to manufacturing among industrial firms. Enlightened industrialists are aware that in their companies, a "higher charge against the present is necessary to ensure a long term future", to quote the words of *Malpas*,[4] ex-director of B.P. research. These considerations will be essential in the introduction of advanced materials into the technologies of the next millenium. This is illustrated in the model for funds flow, (Fig. 7)[4] for a typical advanced mate-

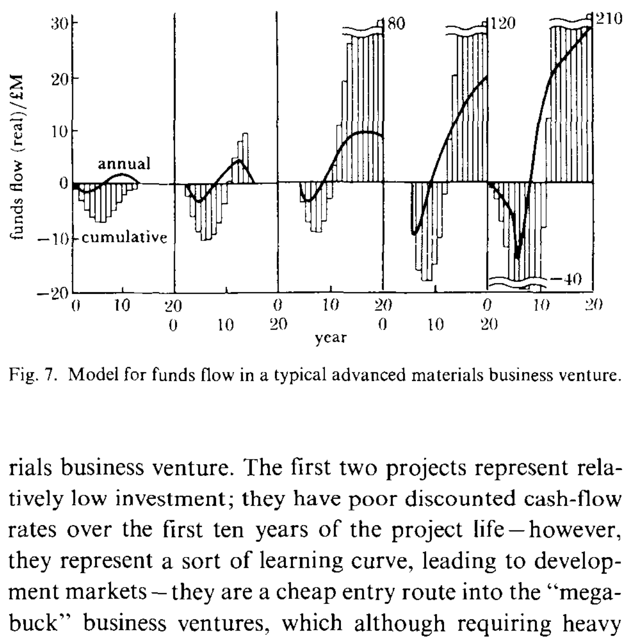

Fig. 7. Model for funds flow in a typical advanced materials business venture.

rials business venture. The first two projects represent relatively low investment; they have poor discounted cash-flow rates over the first ten years of the project life – however, they represent a sort of learning curve, leading to development markets – they are a cheap entry route into the "megabuck" business ventures, which although requiring heavy capital funding, indicate more attractive return rates. The projects 3 to 5 will be embarked upon only with the experience and "comfort factor" based on the earlier, loss making projects.

These are the vital considerations for a business with a positive strategy of long term investment, which applies in particular to high risk ventures on advanced materials.

6. The Conceptual Trends

For the materials innovations of today and the future, if there exists one grand design or overriding idea it is the following: all materials innovations are in the direction of incorporating a greater knowledge content per unit weight of material. This important concept is shown in Figure 8, which

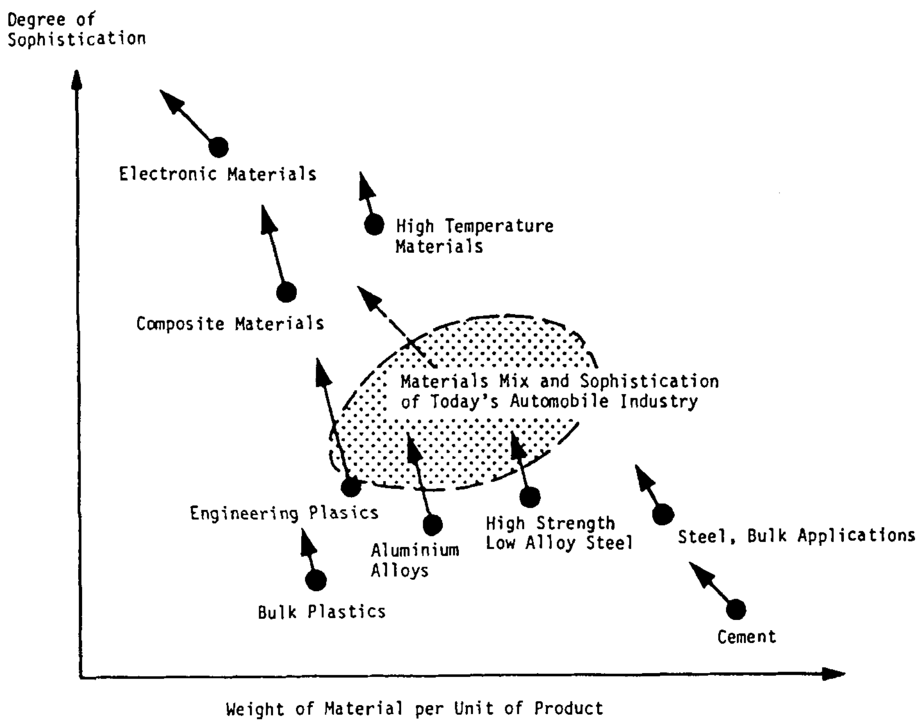

Fig. 8. Heuristic model correlating quantity of material in a given product and "information" attached to the material and its use.

is a heuristic model indicating the time dependent movement between the quantity of material in a product and information content of the material. This is derived from the work of *Altenpohl*.[5] On the diagram, each point indicates the trend for the future. In short this means that the materials innovations are increasingly incorporating a higher level of intellectual sophistication. This is consistent with the notion of the development of goods and manufactured products which have a high added value. The trend holds, whether it is for highly exotic materials for electronics applications or for bulk materials such as cement, where we see the vector moving towards improved macro-defect free cements.

Again, if we can discern a grand conception in the *means* for innovating materials for the future, it is in the ambition to design materials architectures with specific properties from basic building blocks. We are still a long way off from this, yet there are strong indicators and promising overtures in the production of two dimensional modulated structures at an atomic level which have highly specific and unique electronic properties. This grand design is the approach to the subject in terms of matter in extremely small assemblages, either two dimensional or three dimensional, these assemblages procuring properties that are completely different from those of the macroscopic forms. For example, a new type of strengthening has been suggested for an artificially produced material consisting of alternate layers of pure metals where the thickness of the layer is below a hundred nanometers. If the layers are so thin, it may not be possible for a Frank-Read source to operate in either layer, in which case the mode of plastic deformation will be by single dislocation movement.

For the development of materials for the next millenium, there are a number of conceptual trends, which can be considered as a collection of the accumulated thinking and experience among materials scientists. Here, specific themes which may exert a significant influence on materials development over the next two decades are highlighted.

7. Highlighted Themes of Future Significance

7.1. High Knowledge Content Structural Materials

In this category, the materials enable the engineering concept to be realized: the materials supply a supportive rôle. They find their value in that they permit the engineering structure to fulfil its functions and in this sense they are used to contain, to connect, to control or to display an engineering device. Here we are concerned with designing complex engineering structures to operate over a longer and more reliable lifespan, that is, we try to avoid over-design. We are concerned essentially with the benefit that is available through the incremental improvement of existing materials.

Material advances here are aimed to procure economic benefit through, for example, improved performance in the development of hexagonal boron nitride for hard coating applications or improved durability in an attempt to reduce the rates of corrosion, wear and fatigue. For example, in a recent survey[5b] it was found that in the USA some 4% of the gross national product is lost through the fracture of materials and structures.

7.2. Materials with Specific Functions

Here we are concerned with materials which in themselves constitute part of a potentially useful scientific phenomenon. They are now increasingly being referred to as 'functional' materials and their applications are typically in electronics, and optical and magnetic products. Thus, whereas in 1959 the number of transistors on a semiconductor chip was one, the increase over the last two decades has been of such enormous magnitude that in the near future we expect to have a hundred million tiny transistors on a single chip. In addition to this planar silicon technology, there are opportunities in newer, faster materials such as those provided by compounds of group III elements in the periodic table (gallium, aluminum, indium) with group V elements (antimony, arsenic, phosphorus) which offer new potential properties for opto-electronic and microwave applications. In the field of fiber optics, the traditional electric current in copper for transmitting messages is being replaced by laser light moving in a tiny glass fiber. The power of this new technology is such that each fiber can transmit the equivalent of a complete Encyclopedia Brittanica in one minute. The research opportunities here are obvious: improved fiber and better light carriers.

This is of course a very extensive and rapidly moving technological field with a large industrial infrastructure. The future will see new materials for such micro-electronics applications involving rapidly evolving techniques of fabrication, as in wafer production, epitaxial growth, sputter deposition, oxidation and diffusion of impurities, ion implantation and surface analysis techniques.

7.3. Improved Conventional Volume Materials

In spite of the slackening in the rate of consumption of traditional metals and steel in particular, these materials as well as common cement will be required in greater volumes in the future, both for advanced applications and in the more common aspects of Man's daily life such as in building materials. In particular, hydraulic cements are energy-cheap and today we see efforts being directed towards improving the strength of cement through a close study of porosity, rheology and the nature of the particle packing.

Newly innovated cements are already available, such as those known as macro-defect free cements which owe their improved strength to the removal of macroscopic voids, giving rise to cements with a bending strength of up to 70 MPa compared with the normal low strength of Portland cement of 5 MPa. In fact, a research team at ICI[6] has shown that by using combinations of high alumina cement and a copolymer of vinyl acetate and vinyl alcohol, strengths of up to 150 MPa may be achieved.

7.4. Property Design by Microstructure and Microchemistry Control

The marked influence that very small changes in chemistry or microstructure can have on bulk properties has long been recognized and exploited, as in the traditional addition of carbon to iron to make steels with highly tunable properties. In the last decade the importance of highly localized micro-environments, both chemical and structural, has been increasingly appreciated especially in the leverage effect they have on bulk mechanical properties. Examples abound; segregation to grain boundaries in metals, low melting grain boundary phases in structural ceramics, local defect populations especially in surfaces creating sites for fracture initiation, all factors controlling materials degradation and failure. Fortunately the phenomena are not exclusively deleterious and numerous opportunities to tailor the micro-environment for benefit are currently exploited; the addition of rare earth elements at trace levels to enhance the stability of corrosion protective scales on metals, the development of mechanically alloyed microstructures to enhance alloy strength, and the influence of boron in reducing brittleness in intermetallic alloys are examples.

The engineering of the micro-environment of materials has only recently begun, but is firmly founded on the basic principles that properties are in general determined by interfacial atomic interactions and that in a complex material, integrity is dependent on weakest link failure. Future exploitation of these ideas opens a promising field for materials advances, and already interesting innovative materials are emerging. Just one such example is given by the recent development of nano-crystalline structures. This novel idea of *Gleiter*[7] and his coworkers is to construct a material from nano-crystalline assemblages. This is tantamount to the production of a new state of matter, intermediate between a

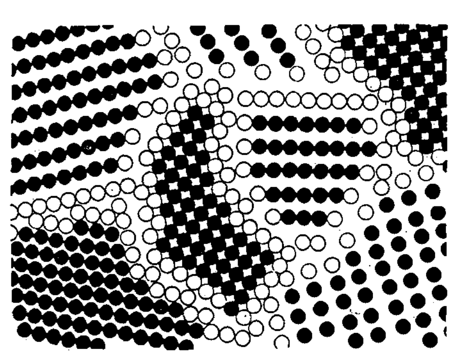

Fig. 9. Microstructural model of nanocrystalline materials.

polycrystal and a glass. The structure of the nano-crystalline metal made by evaporation on to a cold substrate followed by compaction of the fine powder is shown in figure 9. The crystal grains are so small that almost half the atoms in the metal occupy intergranular sites. As a result of the presence of a large proportion of matter in grain boundary sites, diffusion creep can operate even at low temperatures where the mass transport occurs along the grain boundary regions.

7.5. Synthesis of Non-Equilibrium Structures

The introduction of means that prevent lower free energy or ground state structures and compositions from being formed in alloys provides new opportunities for materials synthesis and property processing. More generally, the study of non-equilibrium phenomena is throwing up ideas of fundamental importance for the formation of metallurgical microstructures. The mixing of chemical species to produce alloys and ceramics has up to now been constrained by equilibrium thermodynamics – the rigid, inescapable laws of classical theory. In effect, metallurgists and solid state scientists have had to put up with a sort of tyranny of the constitutional phase diagram. By varying the processing conditions, in particular by imposing cooling rates exceeding $10^6\,^{\circ}C\,s^{-1}$, important constitutional changes can be introduced so that the retained metallurgical phases have compositions outside their equilibrium limits.[8] The resulting non-equilibrium phases may be crystalline or glassy. Such glassy materials often have unusual combinations of chemical and physical properties including strength, hardness, electric response, catalytic ability and corrosion resistance.

Already such materials have been aimed at applications, especially where combinations of extreme hardness and high corrosion resistance are required, as in cutting devices. Since these materials combine magnetic softness with mechanical hardness, they are useful for tape-recording heads. In particular ferromagnetic glasses are very easily magnetized, because magnetic domain walls move through them with ease and they therefore make excellent electric power transformers, with markedly reduced core losses. Figure 10 compares the energy losses in transformers of various sizes made by various companies. The decreases achieved by using metallic glass are quite dramatic. This is an area with enormous economic potential – it has been calculated that the introduction of metallic glass cores in the 40 million power distribution transformers in the USA could make a potential saving of a thousand million dollars per year.

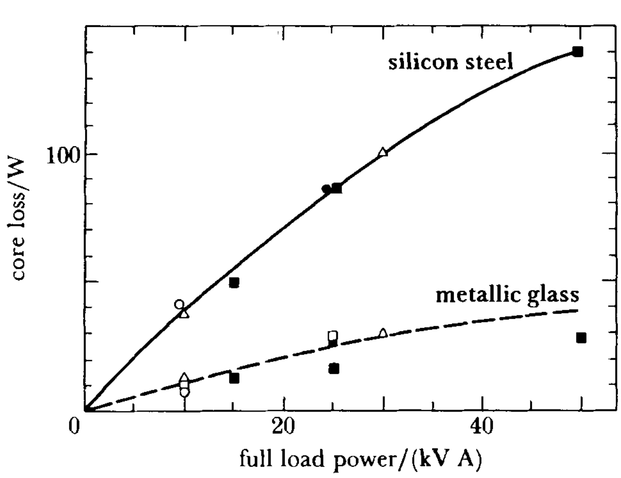

Fig. 10. Energy loss comparison in commercial transformers; with silicon steel and metallic glass cores. o McGraw-Edison △ Osaka ◻ Westinghouse ■ Allied Signal ● General Electric.

7.6. "Two-Dimensional" Phenomena

Surfaces and interfaces have long been regarded as critical regions with a fundamental importance for many solid state phenomena of technological application. Catalysis, corrosion and adhesion are some examples of surface controlled phenomena. In the past decade we have seen many advances in methods for modifying surfaces in order to control such properties. Future trends in the surface sciences of relevance to materials technologies will be the exploration of physical and chemical phenomena on and just below and just above the surface, that is, in zones with an extremely small third dimension.

Thus the introduction of ion implantation techniques, with cascade ion mixing and continuous or pulsed laser heating introduces possibilities for obtaining new types of surface phases. Alloy compositions can be produced with extended solid solubilities and with these one may manipulate basic engineering properties. A wide range of properties can be modified by these treatments. An important example of this is an improvement in wear resistance in a titanium/aluminum/vanadium alloy used for artificial hipjoints. The incorporation of nitrogen can increase the lifetime of this joint by a factor of 400.

A completely different class of "2-D" phenomena is emerging for atomically layered structures which are grown on specially prepared surfaces. By using well controlled vapor deposition and other techniques for thin film deposition, a totally new area of *artificially structured materials* is being opened up which holds great promise for the discovery of new basic phenomena. Thus for modulated metallic alloys, unusual elastic, magnetic and superconductor properties have been observed. The field of greatest interest is in optoelectronic devices made from layered structures, the chemical composition being modulated from layer to layer.

7.7. Computerized Materials Information Systems

An important future trend in the materials science is the development of computerized information systems of increasing complexity. In typical first and second generation database services they are generally specialized on a single subject, making them important for use by experts in that subject field. Already the total number of publicly available

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databases of European origin is somewhat over 800. These are mostly bibliographic databases and in the non-scientific fields.

In the case of materials information systems for engineering the complex nature and high costs have hitherto hindered the construction and exploitation of factual databases of the second and third generation type aimed at the professional engineer. The future will see the development of factual data banks as an everyday tool for the materials engineer who will have access to a comprehensive, reliable and up to date data base on engineering materials.

Related to this is the trend in future materials processing now referred to as "intelligent processing" in which sensors embedded in the material while it is being formed, or non-intrusive sensors such as ultrasonic beams, will feed back information at the microstructural level during dynamic forming. Based on the physical model for the process, the computer in turn should make the adjustments or changes necessary to ensure a defect free final shape.

7.8. Micro Non-Destructive Evaluation

The value of the non-destructive evaluation of defect structures in metals, for component acceptance, for integrity evaluation of structures, welds, components in operation etc., is long established and considerable attention is being devoted to extend these techniques to the monitoring of large scale plant. The major challenge for the future will be to adapt this technology to new materials such as engineering ceramics which have intrinsically much higher defect sensitivity and have inherently high flaw population densities, arising from processing constraints. Here, critical flaw sizes are of the order of tens of micrometers. While workers in the ceramics processing technologies struggle to achieve higher reliability using finer powders, better particle size distributions and ultra-clean conditions, inevitably a proportion of a production product will contain defects of significant size, discontinuities, porosity or surface cracking, which may be detected only if the appropriate technique can be developed.

A number of possibilities are under investigation, developed from the acoustic and thermal non-destructive testing (NDT) principles of metal testing methodologies. For example, acoustic microscopy shows promise in surface crack detection and the resolution obtained using the scanning acoustic microscopy (SAM) and scanning electron acoustic microscopy (SEAM) is of the necessary order. At the current stage of development, the correct interpretation of even simple images requires a high degree of expertise and offers a major challenge to the developers of computer image identification.

8. Conclusions

The main points of this study are as follows:

- materials will increasingly grow in importance as a basic enabling technology—determining the development and innovation of other important future technologies in a variety of industrial sectors—transport, communication, etc.
- at a global level, there should be no fear of a collapse in supply of conventional materials, especially metals due to over-consumption.
- there are efforts and planning at a European level to stimulate materials R&D, to fill technology gaps and to strengthen the declining industrial sectors; here R&D cooperative networks are recognized as important.
- for making new materials into market products, innovation is necessary but not sufficient: technico-economic considerations (e.g. investment decisions) are paramount.
- a number of conceptual trends in future materials R&D can be discerned, based on the development of materials with higher "intellectual density."

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