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Policies, Plans, and Research and Development Investment in Advanced Materials in the Major Countries [and Discussion]

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Policies, plans, and research and development investment in advanced materials in the major countries

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Technological change is accelerating and broadening. New materials are among the most dramatic areas of such change, and are increasingly being incorporated into existing and new industrial activity. Japan and the United States of America are leading the European economies in many areas of creation and use of new materials. Europe's talent base in new materials is smaller and weaker than those of the U.S.A. and Japan. Strengthening that talent base through improvements in education and training, and in industry and university collaboration in particular, is Europe's most pressing challenge in this area.

Introduction

Ten years ago, there was no such thing as a personal computer. Today, the personal computer market is worth some $\$14 \times 10^9$. The standard minicomputer for the past several years has been the VAX 700 series from Digital Equipment Corporation, a machine that sells for around \$250000. Last year a number of small personal computer companies introduced microcomputers with computing power about equal to the VAX 700, but at a cost of around \$30000.

The semiconductor market, traditionally regarded as a so-called 'high-tech' market, now behaves more like the market for wheat than one for other 'high-tech' products. In economic terms, the semiconductor is a commodity. Laser beams now read grocery items to speed checkout at the supermarket, and help management keep tighter inventory. Everywhere we look, new technologies are altering the way that we perform traditional tasks and are opening up new opportunities for feats unimaginable only a few years ago.

At the same time, the structure of the world economy is shifting. Export-led growth in nations such as Taiwan, South Korea and Brazil, as well as Japan before them, have altered the world trade situation dramatically, reducing the share of the world trade market of the European economies and, to a lesser extent, that of the U.S.A. For example, in 1960 the European Community produced 28.3% of the steel consumed worldwide. By 1985, their market share had fallen to just 16.7%. In that same period, the U.S.A.'s share fell from 26.0 to 11.2%. After rising from 6.4% in 1960 to 15.5% in 1980, Japan's world market share in steel fell to 14.7% by 1985. The rest of the world increased its share from 39.3% in 1960 to 57.4% in 1985. In the past 25 years, in other words, the Organization for Economic Corporation and Development (OECD) world market share in steel fell from nearly two thirds to less than half.

In short, we now find ourselves in a period of rapid and comprehensive change, both in technological and in competitive terms. In a sense, it is fortuitous that the two are occurring simultaneously because new technological breakthroughs are at every turn providing opportunities for advanced economies to change and adapt in the face of increased competition. This also means that comparative advantage is shifting in three directions simultaneously: toward those advanced countries able to capture benefits from new technology; toward developing countries enjoying low labour and resource costs; and away from advanced countries with high labour and resource costs and an inability to benefit from technological progress. The experience of recent years has shown that five technologies, or groups of technologies in particular, have been most important in this regard: computers, telecommunications, robotics, biotechnology and advanced materials. Of these, computers have been the most visible, biotechnology and robotics the slowest to be integrated into existing industrial activity, and new materials perhaps the least appreciated and most underrated in importance. For that reason, of these new 'core' technologies, it is perhaps most useful to discuss new materials at some length.

The importance of new materials to a wide range of industries

Traditional categories of new materials include functional and engineering ceramics, composites (usually made of a matrix in polymer or metals reinforced by fibre in glass, graphite or kevlar, etc.) and polymers. Because exotic techniques (rapid solidification, powder metallurgy, isothermal forging) now permit the production of sophisticated alloys and metals that can compete successfully with non-metallic materials, 'new materials' also includes improved metals.

As a group, new materials have gone largely unrecognized as a major component of the current technological revolution. And yet, looking at the roles they are already playing in a wide variety of industries, there is no denying their importance. This is due in part to the evolutionary nature of technological progress in new materials (in contrast to, say, computers, where change continues to be revolutionary) and in part to its at once pervasive and incremental incorporation into both existing and new products and processes. A few examples of where new materials are now being used will help illustrate.

(*a*) Medium or large capacity airliners, as gain in mass gives decisive cost advantage. Airframe and critical components of aircraft are increasingly made of polymers and composites (see table 1).

Table 1. Mass composition of some aircraft (%)

(Source: *Matér. Tech., Paris* **10** and **11** (1985).)

	light alloy	steel	titanium	composite
Airbus A310	76.5	13.5	4.5	5.5
Boeing 767	81	14	2	3
Mirage 2000†	81.5‡	6.5	5.5	6.5

† Landing gears and flight controls excluded.
‡ Aluminium and miscellaneous.

(*b*) Satellites, where carbon–resin composites are well established and the introduction of metallic matrix composites are under study.

(*c*) Helicopters, where composites are already used extensively (e.g. the rotors).

(*d*) Spacecraft, where the structures of small-size, short-range missiles are already largely non-metallic (more than 80% for antitank missiles). This is not yet so for spacecraft, but changes are being introduced: although now entirely metallic, the structure of the Ariane rocket will gradually go over to composites, starting with Ariane 4.

(*e*) Automobiles, where the shift from metal to polymers is fairly advanced. It has been predicted that by 1990 plastics will account for 30% (by mass) of the average North American car. Already there are several 'plastic' cars being produced. This does not mean, however, that special steel will have no role to play in the future. The mass share of highly resistant steel in cars has doubled in the past five years.

(*f*) Telecommunications systems is an area that is also marked by the erosion of conventional metals markets. Optical glass fibre (fused silica) is gradually being substituted for copper in cables. The outstanding properties of optical fibres may even give cable communication systems a strong competitive edge over satellite communication systems.

(*g*) Semiconductors, make up a wide field of applications of advanced ceramics. Whereas silicon is the most largely used element in the making of integrated circuits (95.2% of the total), great hopes are put in various gallium arsenide or phosphide compounds. The U.S. Department of Defense is already spending about $\$150 \times 10^6$ in research on these new, exotic semiconductors.

(*h*) Lastly, lasers, where rare-earth metals are increasingly critical in providing the lasers needed for medical care and in the submicrometre wavelength range for exotic applications, such as the U.S. Strategic Defense Initiative (SDI).

This list of materials-linked sectors and materials-based technologies shows the amazing potential for dissemination of new materials throughout numerous manufacturing sectors. Materials research is no longer the indirect consequence of other policy concerns and the natural vagaries of the market; it has now become an important driving force for technological change and economic growth in its own right.

Investment in new and improved materials

The materials policies of OECD countries reflect the twofold impact of the big technological programmes (space, nuclear energy, electronics, etc.) and the changes required in conventional materials due to trends in energy and raw materials markets. They also reveal obstacles to investment at both firm and national levels.

Among the major obstacles to investment in new materials, one can mention the following.

(i) *High risk and uncertainty surrounding the markets for new products*

Uncertainties involve both technical and market factors; for example, the Association of Japanese manufacturers of fine ceramics estimates the world consumption of ceramic parts for engines to be between $\$0.5 \times 10^9$ and $\$3.8 \times 10^9$ from 1983 to 2000. This large imprecision reflects our present lack of knowledge about technological trends (for example, the future of ceramics for use in automobile engines will depend upon the success obtained in reducing brittleness, in lowering manufacturing costs, in setting up reliable tests to identify defects and in improving metal–ceramic interfaces). In certain cases, the lower extremity of the forecast includes the possibility that there would be no market at all for the product (for example, the applications of silicon nitride in automobile engines: Battelle Columbus predicts a market of between \$0 and $\$10^7$ in 1990).

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(ii) *Long time scale of new-materials investment before any financial return is generated, in sharp contrast with investment in other sectors*

Engineering evaluations are often incomplete. Not much is known, for example, about susceptibility of composites to damage, propagation of flaws and reparation. New materials must therefore undergo long periods of testing before being introduced on the market. Research on metal matrix composites, for example, started 20 years ago, yet it took over 10 years for the first metal matrix composite to find a market: the boron aluminium compound used at the end of the 1970s in the American space shuttle. Moreover, many materials, such as composites and ceramics, are expensive to manufacture and tool.

(iii) *Lack of awareness among many firms of the possibilities that new materials offer*

Lack of awareness is due to: (*a*) insufficient linkage between enterprises and sources of knowledge; (*b*) old materials traditions (use of new materials usually requires modifications in product design, production machinery and quality control and maintenance systems); (*c*) complexity of research involving multidisciplinary teams or lack of innovative management. In this context, acceleration and continuity of technical progress and stimulation of use of new materials and related processes require greater awareness and investment by both governments and industry.

Strategic considerations

In addition to the tremendous commercial significance of new materials, there are also major strategic considerations, such as security of supply, particularly with regard to military products. Countries may also wish to encourage substitution of new materials for conventional ones to avoid constraints imposed by raw materials imports on the balance of payments or for defence purposes. The U.S. Congress has stated that the 'availability of materials is essential for national security, for economic well-being and for industrial production' (National Materials and Minerals Policy act of 1980). In the Netherlands, the following justifications for a national materials policy are put forward:

> 'security of supply in basic raw materials, and in the case of scarce raw materials the need to find substitutes; vulnerability with respect to foreign suppliers of materials essential to domestic industry; R & D in substitute materials in order to reduce dependence on foreign suppliers; increased value added in industrial production, implying improvements in the quality and competitiveness of domestic products.'

Policies and programmes

Most OECD countries have significant challenges facing them in the formulation and execution of their policies in advanced materials. For this reason, the OECD recently initiated a major project on advanced materials technologies, industries, and policies. Much of this paper reflects some preliminary findings of that project.

Japan probably enjoys the largest and deepest capacity for adaptation and exploitation of advanced materials, having recognized their economic potential years ago. It has created a remarkably large talent pool of materials scientists and engineers and has invested considerable sums, from both public and private sector, to create capabilities to diffuse and incorporate new materials into a wide range of products and processes.

The U.S. government has not mobilized behind advanced materials in the same way the Japanese government has, but it does have a range of public and private efforts and previous capabilities that have permitted it to enter the age of advanced materials with a small head start relative to Europe. In particular, the aerospace, microelectronics, and telecommunications industries in the U.S.A. are well developed and have long histories of experience in new materials. In recent years, the Departments of Defense and Energy have also invested significant sums in materials R&D, as table 2 illustrates. There may be differences in emphasis in each of the agencies listed, but they share an emphasis on fields where a substantial innovatory impetus is expected, i.e. ceramics, high-temperature alloys, sintered metallic materials, amorphous metals, special polymers, semipermeable materials, composites and catalysts. These investments are now, of course, growing well beyond the figures shown because of the SDI, the so-called 'Orient Express' and several smaller efforts recently introduced.

TABLE 2. FUNDING OF MATERIALS R & D BY U.S. DEPARTMENTS AND PUBLIC INSTITUTIONS IN 1983 (MILLIONS OF DOLLARS)

(Source: General Accounting Office report GAO/RCED 85.63, 9 September, 1985.)

amount	DOE[1]	DOD	NSF[2]	NASA	BOM	NBS
R & D funding	368	296	100	75	32	12

1. 1982, 2. 1984

In Europe, attention to new materials is growing much more slowly than in Japan and the U.S.A. at both the industrial and governmental levels, and begins from a point far behind its two chief trading partners. In fact, there is some concern that Europe will be caught unprepared in this area much like it was in the case of microelectronics. When the 64K RAM chip hit the market in around 1981, there was not a single competitive manufacturer of memory chips in Europe. Since then, with the encouragement of European governments, European companies have fought a losing battle, to get into the computer race. Even now, as AT&T has been using 1 megabit RAMS in its high-speed switching terminals for several years, Siemans and Philips are struggling to produce a 1 megabit chip, with technical assistance from Toshiba and financial assistance from the German and Dutch governments. By the time they 'catch up' with their assumed target, they may very well find traditional silicon chips replaced by gallium arsenide chips, organic chips or even optical memory chips.

Poor availability of data, multiplicity of funding sources for R & D and differences in definition considerably limit the scope for international comparisons. Furthermore, the concept of material is usually not identified in statistical nomenclatures. This means that quantitative analysis is mainly based on very imprecise estimates. As a result, table 3 is far from satisfactory, all the more so as the figures have been converted into U.S. dollars, thereby introducing another factor of instability (the exchange rate). To a certain extent, the economic significance of these data may also be questionable. For example, the $\$12.7 \times 10^6$ indicated for the programme on basic technologies for future industries in Japan is ridiculously low compared with analogous U.S.A. investment. According to some sources, materials R & D coordinated by MITI in fact

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TABLE 3. ESTIMATED GOVERNMENT FUNDING

(Source: OECD Secretariat and various national documents.)

	year	annual support to major projects/$\$10^6$	long-term programme
U.S.A.[1]	1983	1000	
Japan	1984 +28 % per year	12.75 81–85	1981–1991, 10 years, $\$186 \times 10^6$
Germany	1985	27.7 federal	10 years, $\$386 \times 10^6$
France	1983	21	1983–1986, 3 years, $\$115 \times 10^6$ Mission proposal
U.K.	1985	66	5 years, $\$160 \times 10^6$ Collyear proposal
Sweden	1983/84	8.5	
EEC	—	—	BRITE[2] last contract 4 years, $\$130 \times 10^6$

1. Total government support.
2. Under the BRITE programme half of precompetitive projects selected from bids submitted by multinational groups of academics and industrialists are financed by the EEC budget. Partly devoted to new materials, BRITE is targeting the broader area of machining and factory automation. At European level, one can also mention the advanced industrial turbine project under the EUREKA framework.

exceeds $\$270 \times 10^6$, suggesting that materials funding is one of the main elements in MITI initiatives towards industry. The need for expanding investments in materials R & D has been recognized in many countries but variously implemented. In Japan, an important programme was launched by MITI as early as 1981. This programme is based on three main lines of action, two of which are concerned primarily with new materials: (*a*) new materials (ceramics, polymers, composites) and (*b*) new types of semiconductor. The R & D activities under this programme extend over periods of eight to ten years, so that it represents a coordinated and long-term effort.

In the U.K., the chief recommendation of the Collyear report published last year is the establishment of a $\$160 \times 10^6$, five years R & D programme in new materials, equally financed by industry and government. In France also, the materials Mission, which was commissioned to study new materials and make proposals in the field, suggested the establishment of a mobilization programme to double government investment. Finally, the German Federal Ministry for Research and Industry (BMFT) has implemented a large materials research programme as a follow-up to earlier programmes concerned with raw materials. Planned to last about ten years, this programme aims at linking the basic research potential of the universities and public sector research centres with industrial R & D capacity in the framework of jointly designed and executed research projects. This should facilitate a better transfer of knowledge concerning new materials for industrial innovation purposes.

Consequently, governments are pursuing three general types of strategies in this broad and fragmented field.

(i) The *global strategy* attempts to cover the maximum of fields. Such a strategy is consistent with a powerful industrial structure, enormous R & D capacity and efficient coordination of efforts. Although in a formal sense the U.S.A. lacks a coherent national materials policy, it would obviously fall into this category. U.S.A. policy focuses both on security of supply in raw materials, and on the importance of technological innovation and R & D in materials as key contributors to economic growth.

(ii) In countries adopting the *strategy of priority lines of action*, governments attempt to define those fields in which the national efforts should be concentrated. For example, Japan is mounting a broad-based effort to compete in four important areas: fine ceramics, carbon fibres, engineering plastics and amorphous metals, considering them as the most promising market segments, as suggested by following MITI forecast shown in table 4. In the U.K., the Collyear report looked at four classes of materials: composites, engineering ceramics, rapid solidification technology and electronics materials. It also considered enabling technologies: assurance of product performance, surface and joining technology and near net shaping methods of manufacture. These priorities have been selected on the basis of urgency and development potential.

TABLE 4. NEW AGAINST OLD: PRODUCTION STATISTICS

(Source: IBI; MITI for 1983 conventional material figures.)

	1983 actual/10^9 yen	1990 forecast/10^9 yen	annual growth forecast 1983–1990 (%)
new materials			
fine ceramics	396	1500	21.0
high polymers (engineering plastics)	430 (259)	1000 (650)	13.0 (14.0)
new metals (amorphous metals)[1]	170 (3)	550 (35)	18.0 (42)
composite materials (carbon fibres)	25 (15)	150 (38)	29.0 (14.0)
total (A)	**1021**	**3200**	**18.0**
conventional materials			
steel	16073	19000	2.0
non-ferrous metals	6935	8500	3.0
ceramics	8627	10500	3.0
chemicals	19227	24000	3.0
textiles	8062	9500	2.0
pulp and paper	7061	8200	2.0
total (B)	**65985**	**79700**	**3.0**
A/B	1.5%	4.0%	

1. Based on total price of components.

(iii) Thirdly, countries adopting the *strategy of market niches* are those in which the size of the country and the constraints of its economic structure and resources force the choice of limited market segments and priorities, taking into account in particular the potential of the available knowledge and talent base. The important aim here is to ensure that the national R & D system follows international trends while maintaining its technological advance and special 'know-how' in specific branches of industry. The Swedish government, for example, devotes 41% of its total support to the new materials to powder metallurgy and melting technologies, 28% to polymers and 12% to ceramic, reflecting its industry's technical comparative advantage in metallurgy, chemistry and automobiles. In recognition of its natural resource base, Australia is turning its attention towards research on zirconia, rare earths and aluminium.

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Ceramics

Ceramics are a major area where these strategies are being applied because of their supportive role in the growth of many high technology industries (such as electronics, computers, telecommunications, robotics, aerospace), their utility in solving energy and resource problems and their capacity to bring about productivity improvements in processes. In this area, Japan, which is far and away the market leader, captured about 50% of the $4.15 \times 10^9 world market (Kenney & Bowen 1983) in 1980, shared between electroceramic for electronics (70–80% of the total) and structural ceramics, most of which are in cutting tools, wear parts and catalyst carriers for automobiles. Despite U.S. scientific and technological leadership, commercialization of U.S. ceramic products seems to lag. In Europe, ceramics as a whole have for a long period been neglected by government and industry, the gap with U.S.A. and Japan being large and now widening.

One of the most disturbing aspects of this neglect in Europe is the small talent base in ceramics. As table 5 shows, Europe, with an economy more than two and a half times the size of Japan's, has roughly one quarter the number of research scientists and engineers in the various fields relevant to advanced ceramics. This means not only that firms dependent on advanced ceramics technology who operate in Europe are as a group ill-prepared to compete with their counterparts in the U.S.A. and Japan, but more important, that their chances of catching up with and overtaking their competitors in certain areas are very small.

Table 5. Research personnel for new materials (advanced ceramics)

(Source: Advanced Ceramics. Technology Situation Report by MKM Consultants International.)

country	scientists and engineers	technicians
Japan	2000	2000
U.S.A.	1000	1000–2000
Europe	500	not estimated
Canada	50–100	not estimated

In line with the important advanced ceramics market potential identified by most experts (aggregated market for advanced ceramics in Japan and the U.S.A. could reach $7.7 \times 10^9–$10.4 \times 10^9 in 1990 and $16.2 \times 10^9–$24.3 \times 10^9 in 2000. Source: MITI and U.S. Department of Commerce), governments are carefully planning public sector ceramics research according to these overall strategies, resource availability and the competitiveness of their firms. Major projects in structural ceramics in the U.S.A. focus on advanced gas turbine engines for aircraft and automobiles and diesel engines for tanks. Most of the government funds are invested by the U.S. Department of Energy (DoE) and the U.S. Department of Defense (DoD), and R & D is being performed in both private and government laboratories. In Japan, the advanced ceramics industry is now well established (see table 6) and has started to manufacture some ceramic components for diesel engines.

This success is a product of both private initiative and government effort. Five laboratories within MITI perform research on ceramic structural materials and related areas, and five laboratories of the Science and Technology Agency (STA) conduct basic research in this field. Apart from direct investment through the ten-year project on industrial base technology

Table 6. Advanced ceramics

(Source: MKM Consultants International.)

	industry R & D/$\$10^6$	government spending/$\$10^6$
U.S.A.	100	\$100
Japan	100–250	\$50

development, MITI, via its Fine Ceramic Office is sponsoring the creation of an industrial R & D association to help industry cooperate in long-term R & D efforts.

In Europe, structural ceramics is an important part of the recently launched German advanced materials project. Large German companies are expressing growing interest in participating in the long-term potential associated with advanced ceramics, especially in its vehicular applications. Other leading countries are: Sweden, which is, after Germany, the most active European government in this field; the U.K., which holds a good position at the research stage (e.g. sialon patents) and is developing projects through clubs or consortia of companies; and France, the last to enter the race.

Policy issues

Given their vast sphere of activity, materials policies involve multiple and reciprocal interactions between science and technology systems and industrial circles. The nature of these interactions and their complexity do not permit us to the formulate a single efficient and consistent policy. Important issues for the design of the policies are the following.

(i) *University–industry relations*

These appear even more essential to new materials than to other fields. It would seem that they can be fruitful only with enterprises that have their own R & D laboratories and that may therefore be capable of assessing the possibilities and the scientific limitations of technological manufacturing operations. Such laboratories will obtain significant benefits from links with universities. The most important long-term benefit of this collaboration is that industry can help the universities define basic research agendas to solve fundamental technical problems, and in the process, help the universities train and educate materials scientists and engineers with the sorts of background and skills industry most urgently requires.

(ii) *Adjustment of financing methods to long-term research*

In most countries the research funds are allocated on an annual basis. This method of financing is inappropriate for long-term research of the type necessary in the various fields of new materials. It thus appears desirable to draw up contractual, coordinated and long-term R & D programmes.

(iii) *The cost of installations and equipment*

Laboratory equipment is perhaps the most important factor limiting the progress of materials R & D. Sophisticated instruments make it possible to go much further, not only in calculation and measurement, but in the analysis of the characteristics of elements and their microscopic structures as well. However, such equipment is often beyond the financial means of research teams. A good example is the synchrotron light source, which, even in the high budget environment of the U.S.A., is increasingly viewed as affordable only on a national or at least regional basis. To keep investment costs within bounds, different forms of cooperation may be envisaged, including the shared use of installations and instruments.

(iv) *Critical mass*

This concept appears at several levels. First, many laboratories have neither sufficient size nor the material resources necessary to undertake effective R & D in new materials. Second, the national R & D potential is often limited. Third, the restricted size of potential markets has implications for technological development and hence for R & D. This is particularly true for small countries, but also applies to large countries where certain high-technology fields do not have a broad enough R & D base to support a sustained research effort capable of leading to the creation of new industries.

(v) *Materials centres*

Institutional arrangements may be useful to promote cooperation among disciplines and laboratories. In the U.S.A. the NSF-funded materials research laboratories at universities operate on an interdisciplinary and multi-investigator basis. They are undertaking unique research, risky and highly innovative, and different from that which can be accomplished by individual researchers in universities. In France the Materials Mission proposes that materials centres should be set up by laboratories concerned with different disciplines, their task being to organize 'on-the-spot' specific training at doctoral level, to form research teams for materials projects and to jointly manage the major items of equipment required for the research.

(vi) *Education and training*

The development of new types of materials is increasingly based on the combined application of knowledge originating from traditionally separated scientific fields (solid-state physics, chemistry, mathematics). It therefore appears to be necessary to reconsider the education and training programmes for materials science researchers and engineers to meet this requirement for multidisciplinary backgrounds. The concept of so-called engineering research centres in France and the U.S.A. is an important innovation in this area.

(vii) *Performance and use standards*

The accurate technical description of materials requires a set of standards documents so that performance under laboratory conditions can be compared. Trends towards increasing specialization in materials production obviously call for great standardization efforts at the international level. In this regard, positive steps have already been taken: the Versailles advanced materials and standards project (VAMAS) led by the U.S.A. and the U.K. provides a framework to support the generation of codes of practice for advanced materials on an international basis and to promote exchange of information on these codes. Technical working parties responsible for the definition and conduct of programmes on specific topics are being established. The main objective of the project is to facilitate cooperation and the adoption of agreed standards.

In summary, the strongest case for resolute government action is in education and training. This is of course true for all areas of science and technology, but perhaps even more so for

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advanced materials. The interdisciplinary nature of advanced materials R & D, and the huge range of industries which apply advanced materials to their product and process problems, make this task particularly challenging, but potentially highly profitable as well.

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Discussion

R. Bullough (*AERE, Oxfordshire, U.K.*) I wonder if there is any significance in the apparent anticorrelation between numbers of research proposals and numbers of standards for the topic of corrosion; the former was a maximum and the latter a minimum. Without standards is it perhaps easier to define an acceptable research proposal or is there a more subtle explanation?

J. M. Marcum. I think there is a more subtle explanation. In the early stages of research on a topic like corrosion resistance, which is changing rapidly as a result of progress in new materials, it is normal to see a large number of new research proposals and to have standard setting efforts lag behind new technical developments. It is important that standards be developed as early as possible during this process to avoid impeding the economic returns from new scientific developments. In my view, however, standards in and of themselves do not affect the number of research projects proposed.

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