MATERIALS INNOVATIONS IN CONTEXT

W. David Kingery
Department of Materials Science and Engineering
University of Arizona
Tucson, AZ 86721

ABSTRACT

A consideration of the role of materials in innovative technology shows that materials, microstructures and properties are rarely of much interest standing alone. They gain significance as components in devices that are parts of systems having value for society. Some of the many-layered contexts affecting materials innovations in nascent and infant industries are discussed.

DISCUSSION

In thinking about technological innovation in advanced materials, it is helpful to keep in mind the widely used Materials Science and Engineering paradigm relating processing to structure, properties and performance (Fig. 1). Structures and properties that characterize

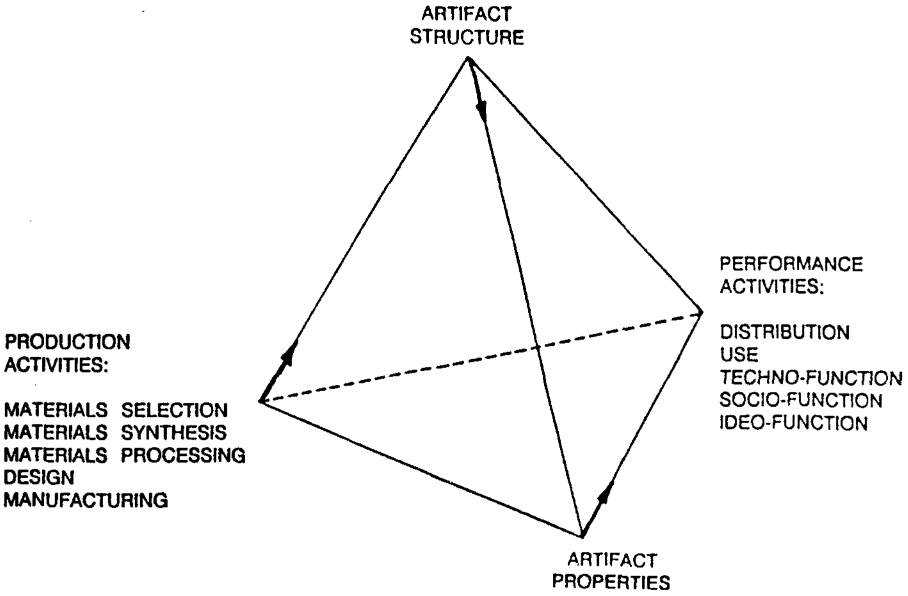

Fig. 1. Artifact attributes - structure and properties - are different in kind from the production activities which give rise to structure and properties and the performance activities which make use of structure and properties.[1]

a product are inanimate attributes that can be precisely measured and compared. In contrast, materials synthesis, preparation, processing and manufacturing are socio-technological activities that involve not only artifacts but also human behavior, human perceptions and social organization. Likewise, product or process performance involves not only the process or product itself, but human behavior, human perceptions and social organization as well as fiscal, legal and political considerations. These in turn are embedded in a larger cultural and social context. Separating the artifact from its context gives rise to reductionist research papers in the classic form we have come to expect. It must always be kept in mind that these reports reorganize beyond recognition the rather inefficient starts and stops and stumbling progress of the actual research process. They also usually mask the larger significance, if any, of the research result.

In discussing advanced materials innovations we often discuss technological changes in which new discoveries and inventions are the starting point. As we investigate deterministic origin stories, we find it increasingly difficult to have much confidence in separating out any particular discovery of invention as an intrinsic starting point. As one example, the discovery of high temperature oxide superconductivity by Bednorz and Müller in 1986 was initially greeted with no great enthusiasm. Other oxide superconductors were well known. The increase in T_c from 23°K to 36°K had no particular technical advantage and no next step seemed obvious. It was Professor Kitazawa's confirmation of the result and description of the structure of the superconducting phase to an attentive audience of materials scientists that unleashed a self-catalyzing burst of research and a continuing stream of developments. Economists define inventions as the conception and reduction to practice of a new idea sufficiently different that it would not have been obvious to a practitioner skilled in the art. Innovation is the introduction of a new or improved process into the market and requires entrepreneurship.

Commercial innovations require acceptance in the market place of customers or design engineers or factory workers to become a *fait accompli.* In much the same way, research or technological accomplishments only become a *research innovation* or a *technological innovation* when they are accepted as such in the market place of a research or engineering community. This can only occur when a novel accomplishment is put into the public domain by means of a published patent disclosure, conference presentation, distributed preprint, news conference or article describing the accomplishment. We are all overwhelmed by the deluge of publications, but they are essential for the research innovation process. A very small fraction of research achievements come to be accepted by a community of practitioners, diffused throughout the community and serve as *paradigms,* model achievements (in the sense of Thomas Kuhn[2]) which are widely recognized, adopted and used within a technical community. A research innovation is recognized by its success in the market place.

As discussed by Kuhn and by M. Polanyi[3] the essential element for market acceptance of a novel research or technological innovation is the anticipation of future promise as is exemplified by high temperature oxide superconductors. Recognition of future promise tends to be muted in most scientific publications; researchers have found that speedy recognition is more often achieved with a story in the *Wall Street Journal* or the *New York Times* than in *The Journal of Materials Research.* Name recognition of the researcher within the technical community can also accelerate or impede the transition from research accomplishment to a recognized research innovation. A part of the skepticism about diamond synthesis in the Derjaguin laboratory can be attributed to that group's affiliation with the earlier discredited claim for a new form of water, polywater, which was found to be nonexistent. A third factor is related to the level of frustration that lack of success has engendered in a research community. Metallic superconductors seemed to have reached an asymptotic critical temperature limit of 23.2°K. Finally, there are cultural factors affecting the various communities concerned. Some communities have a strong "only if invented here" approach to novelty; others are eager to embrace and expand on the work of others. Research innovations and technological innovations occur within a cultural and social context in which human behavior, human perceptions and social organization are as important as physico-chemical processes and product attributes. Recognition and acceptance of an innovation in the technological marketplace by the involved community is not absolute, but involves perceptions and judgments about which informed observers may differ.

Thomas Hughes[4] has pointed out that successful inventors and innovators have identified and focused their attention on critical problems which he has called, in analogy with a military front, reverse salients of technological systems. Sperry's invention of the gyro-compass as a basic component of navigational systems for use on steel ships resulted from Sperry's perception that compass technology was a reverse salient in the change from wooden sailing ships to steel steamships. It is widely agreed that Edison's development of a lighting system required an effective integration of all system components: generating plant and distribution lines as well as an effective incandescent light bulb. Basalla[5] has pointed out that innovation always consists of a replacement or substitution of a new material, device or process having some analogical relationship to a predecessor. This is true even of those inventions that we think of as revolutionary new ways of doing things. It explains why revolutionary inventions have occurred so often as multiple events and have so frequently been predicted in science fiction. It's not so much imagining what to do but rather how to do it within an effective integrated system of technology.

For advanced materials we may wonder if these historical insights are good analogies because material innovations are driven not so much by reverse salients in an existing materials technology, but rather by reverse salients in the development of systems *incorporating* new materials. However, in large measure the differences between opportunity and need lie in the eye of the beholder. Silicon nitride was perceived by the British Admiralty in the 1950s as a reverse salient, a critical necessity to achieve the vision of a future high temperature light weight gas turbine. The need for this existed in what we may see as a cultural imperative for improved gas turbines for advanced weapon systems. This was clearly perceived in Britain but generally overlooked in other military cultures. Two decades later in the U.S., DARPA, an agency created for the special purpose of identifying and developing opportunities related to weapons systems, perceived an opportunity for a ceramic automotive gas turbine as worth pursuing. A few years later with the oil shock of the 1970's there came into being a widely perceived *need* for more efficient engines and gas turbines which was combined in Japan with the perceived opportunity (and need in their island economy) for the economic advantage of being on the forefront of cutting new technologies; this led to MITI sponsorship of silicon nitride research. Sometime later, Isuzu and Kyocera as well as Nissan and NGK Spark Plug Co. saw an opportunity to develop marginally improved automobile engine performance as a way of improving processing capabilities. They perceived this opportunity as providing long term advantages, starting with small and almost insignificant markets; a necessary way of learning by doing. The anticipation of a significant profitable market for silicon nitride structural ceramics remains an anticipation after fifty years and several hundred million dollars of investment in research and development programs. (But automotive parts including supercharger turbines are now a break-even business of more than one hundred million dollars per year).

The measure of strength of an opportunity for nascent innovation in advanced materials lies not in the materials themselves but rather from the fact that these materials may be the critical component, the reverse salient, in an existing or imagined device or system having a much larger value than the potential cost of the advanced material. While it seems extremely unlikely that the discounted future value of silicon nitride as a commercial innovation will ever approach the hundreds of millions of dollars and forty years of research and development already invested, that is not necessarily true of higher temperature low weight gas turbine engines. Even so, engine manufacturers have not been betting their own money on this proposition. It is rather the potential users of this technology, military establishments or power generation systems focussing on an even more expensive system than the engine itself, for whom the potential benefits may possibly match the cost.

In contrast to silicon nitride, there has been extensive industrial investment aimed at developing manufacturing processes for new synthetic materials such as diamonds and oxide superconductors. This represents the judgment, perhaps the fear, that commercial innovation of these materials will have a significant impact on computer systems (for the likes of AT&T, IBM and Hitachi), military instrumentation (for DARPA) and now in Japan for long term programs for power generation and perhaps even magnetic levitation systems. In a sense we have come a full circle in that opportunities are also seen as perceived needs of system designers and system users who have a sufficient stake in the outcome to justify the discounted costs of present research in advanced materials. *Push-pull models of the innovation process are inextricably intertwined.*

If we accept that advanced materials are of value because they are incorporated into larger, more valuable devices or systems, we expect that the current existence of such a device or system, or the precision with which it can be designed and the necessary performance factors predicted, or the extent to which it is merely a blurred vision of the future should affect the rate of advanced material technological innovation. In 1896, Walther Nernst discovered electrolytic conduction in solids and invented the concept of a light bulb operating in air, without the necessity of a vacuum enclosure, using a refractory zirconia-yttria glower as the electrically conducting incandescent element. The device was clearly envisioned, a satisfactory glower was the critical achievement necessary and the glower fit into an existing system of power generation and distribution with no system changes required. The technology to achieve this — forming the glowers, providing circuitry for preheating the incandescent element and adding a necessary ballast resistance — were rapidly developed along with the processing of the advanced ceramic material suitable for manufacturing the Nernst glower. This new light bulb was a successful commercial innovation achieved in less then two years. (But it also had a short life, soon being replaced by superior tungsten filament bulbs). High dielectric constant barium titanate was able to substitute directly for other materials as a capacitor dielectric; soon after its discovery it was introduced as a successful advanced material innovation. More recently, the rediscovery of solid ionic conductors such as stabilized zirconia and beta alumina has created new opportunities for developing energy storage systems, solid electrolyte batteries and fuel cells. None of these devices would directly substitute for part of an existing system. Not only advanced materials and new devices are required, but also substantially modified systems would have to replace or substitute for complex existing systems. This is obviously a task requiring a much greater activation energy and longer time constant than merely replacing a component.

Evaluation of the potential rate of commercial innovation for an advanced material must begin by considering required modifications to the system in which it is implanted or the creation of a new system, the complications of new device development, and only then working back to material attributes such as structure, properties and processes of material synthesis. This conjecture requires that the use technologies of the system, device, and material plus legal, fiscal, political and cultural perceptions as well as social organizations associated with all these components of a system are essential constituents for any analysis of advanced materials technology innovation. Advanced materials technologies are essentially *enabling* technologies.

As we have seen with silicon nitride, a consequence of the requirement for transforming a discovered opportunity into a novel component giving rise to a changed device which is part of a new product in a modified system is that the time required from discovery to significant commercial innovation may be very long. From the 1911 discovery of low temperature superconductivity in metals some five decades passed before commercial innovation was achieved. It has been suggested[6] that the half life for materials innovation is becoming shorter, but we have doubts about that as a general proposition. It depends on the nature of the system and the advanced material. For a direct replacement of one material by another without changing the product or device very much, change can be rapid. When whole new systems need to be developed, we see no short rapid path to commercial innovation.

A consequence of the importance of user systems would seem to be that the rate of progress toward innovation is proportional to the strength of the feedback loops between system users and designers, device users, designers and manufacturers, and materials users, designers and manufactures. Materials developed for internal use achieve commercial success much more rapidly than those searching for markets.[7] In electronic ceramics the maintenance of close interactions with users and rapid feedback was a principle characteristic of the growth of Kyocera as a leading electronic ceramics manufacturer.[8] More recently the close relationship of Nissan with NGK Spark Plug Co. and Isuzu with Kyocera in developing ceramic components for automobiles seems to have been an essential constituent of their successful innovations.

The degree of change required in downstream components, devices, products and systems for an advanced material innovation to occur is a function of both the advanced material and the system. The long time constants imposed by system changes resulting from advanced materials innovation place the value of such innovations in the realm of system developers and system users, i.e., defense departments, MITI and large corporations with a long time frame. The requirement for effective user technology, design technology and manufacturing technology feedback would seem to favor corporate cultures with close relationships between users and manufacturers. In the U.S. these relationships exist in the field of military procurement in spite of nominal arms length negotiation. As a result, the rate of advanced materials innovation in military systems has been very high. Otherwise, the American culture of purchasing agents playing off one supplier against another, low cost bid procurement procedures and price-determined procurement would seem to mitigate against the close feedback loops required for effective innovation. The vertical structure and closer relationships of large manufacturers with customers and with client suppliers in the Japanese corporate structure would seem to be a much more fertile environment for advanced materials innovation in the commercial market.

In his discussions of the progress of science, Michael Polanyi (1958) has pointed to the importance of tacit knowledge. We know that there is a large element of tacit knowledge involved in the development of new or modified methods of synthesizing, processing, manufacturing and using advanced materials. This means that there must be a large amount of learning by doing and implies the need for close interaction and strong feedback between users of products with material-enhanced performance, workers and engineers actually making things and the scientist-engineers designing them. The transfer of tacit knowledge must go in both directions along a chain of interactions — in materials manufacturing from the process designers to the production engineers and also from production engineers to process designers. This was certainly the case in 1900-1902 at the Nernst Lamp factory in Pittsburgh where chemists and engineers were active participants at the factory engaged in the invention and production of the Nernst glower as a unified activity. Increasingly, as a result of scientific management, of Taylorism, and the development of mass production, there has grown to be a chasm between management, engineers and workers in the U.S. A corporate culture has developed in which management directs the team effort and often considers workers as cogs in the manufacturing process. This culture of strong specific direction makes the acceptance that tacit knowledge flows in both directions difficult and hampers successful innovation.

Effective internal communication within a manufacturing corporate culture between designers, engineers and manufacturing workers seems essential to the commercial innovation of processes involving tacit knowledge and requiring learning-by-doing. This also implies that there be a reasonably long time frame and steadiness of purpose in which learning by doing can be accomplished. In the U.S. corporate culture, the communication requirement seems to be best achieved in the environment of small capital venture organizations in which bureaucratic rigidities and chasms between management and handson workers have not had a chance to develop. However, in order to achieve the long time frame necessary it is essential that these organizations have a large wealthy corporate or governmental sponsor. The cultural environment of vertically integrated groups within Japanese corporate culture, and perhaps the absence of an historical imperative toward Taylor's "scientific management", seems to be more conducive to advanced material processing development.

Nascent and infant technologies are properly seen as being nucleated or germinated by discovery or invention. Increasingly, with extensive government support of science, we find the number of discoveries growing at an exponential rate independent of any conscious aim at innovation. Nonetheless, many potential opportunities for nascent technological innovation are created. We conjecture that these discoveries lie fallow until there is a perception or recognition of their being needed for the improvement or development of a technological system. Silicon nitride was first patented in 1895. It was first proposed as a refractory bond in 1905. It was not until the 1950's that the first tentative commercial innovation occurred. In contrast, the discovery of oxide high T_c superconductors in 1987 was immediately perceived as being a source of potentially critical components for systems seen as cultural imperatives.

SUMMARY

A key concept necessary to understand the rate of innovation of advanced materials technology is that these materials are valued as they are incorporated in more valuable devices and systems. Advanced materials innovations depend on the nature and extent of innovations required for modifying these devices and systems. The rate of innovation depends on the availability of inventions and discoveries, the effective use of feedback loops between systems users and designers, product users and designers, component users and designers and materials users and designers. In order for rates of process innovation to be high, the transfer of tacit knowledge by effective personal interactions in these feedback loops is essential.

The key elements seem to be (1) the number of inventions and discoveries available for exploitation, (2) the degree of change required in components, devices, products and systems to take advantage of a nascent advanced material technology, (3) the effectiveness of the feedback loops and information exchange between user technology, design technology and manufacturing technology and (4) the effective transfer of tacit technological knowledge between design engineers and production workers in the required process of learning by doing.

REFERENCES

[1]W.D. Kingery, "Ceramic Materials Science in Society", *Annu. Rev. Mater. Sci, 19,* 1-20 (1989).

[2]T.S. Kuhn, *The Structure of Scientific Revolutions,* Univ. of Chicago Press, 1970.

[3]M. Polani, *Personal Knowledge,* Univ. of Chicago Press, 1958.

[4]T.P. Hughes, *American Genesis,* Viking Penguin Press, New York, 1989.

[5]G. Basalla, *The Evolution of Technology,* Cambridge Univ. Press, 1988.

[6]L.L. Hench, "From Concept to Commerce: The Challenge of Technology Transfer in Materials", *MRS Bulletin,* August, 49-53 (1980).

[7]J. Economy, "A Spectrum of Advanced Materials Innovations", *The Chemist, 9,* 15-20 (1980).

[8]K.B. Clark and E. Rothman, "Management and Innovation: The Evolution of Ceramic Packaging for Integrated Circuits"; pp. 335-350 in W.D. Kingery, ed. *High Technology Ceramics: Past, Present and Future,* Amer. Ceramic Soc., Westerville, Ohio, 1986.