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T. A. READ MEMORIAL LECTURE

ENTHUSIASMS AND REALITIES IN ADVANCED MATERIALS

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Tom Read arrived at Columbia University on the same day that I did in 1948. He was a new Professor in the School of Mines and I was a new graduate student. He was more than just a new professor. He was exceptional for that time. His father, T. T. Read, had been famous as an archeological metallurgist and Professor at Columbia during the period when the School of Mines was the premier school of its kind in the country. A measure of its eminence is that Irving Langmuir chose to study there rather than in a standard chemistry department. The younger Tom Read had studied physics at Columbia under Prof. Shirley Quimby; one of the few solid-state physics professors of the time (pre-transistor). After graduation he worked at the Frankford Arsenal and at the Westinghouse Research Laboratories where he and Frederick Seitz wrote their definitive review of the mechanisms of the plastic deformation of solids.

When he came back to Columbia as a professor, Tom Read's physics background made him almost unique among metallurgy professors. And, he had the zeal of a crusader. He was determined to teach fundamental knowledge rather than recipes. His techniques were often novel.

For example, one semester we were to learn about ferromagnetism. But he

had trouble finding a good American text, so he announced that we would study both ferromagnetism and German using the famous book by Becker and Doring called Ferromagnetismus. A result is that I have never forgotten the essentials of ferromagnetism. This became important for me many years later when my laboratory at Allied Chemical pioneered the revolution in soft magnetic materials brought about by metallic glasses.

Although I studied surface effects on the plasticity of crystals some of my fellow students at Columbia studied martensitic transformations in Au-Cd and In-Tl alloys. These are now known as shape-memory alloys. Tom Read's seminal work on the crystallographic theory of martensitic transformations derived from the experimental studies that were going on.

I was pleased recently when I opened a copy of Khatchaturyan's treatise on the theory of phase transformations to find that the first item on the reference list is the classic paper by Wechsler, Lieberman, and Read on the theory of habit plane determination.

Tom Read had a major effect on the style of teaching in materials departments in this country. Although physical chemists had brought their knowledge and style to materials science previously, no one had really emphasized physical principles in depth before Tom did it at Columbia and at the University of Illinois. Others have followed, and I expect that the trend will continue because the materials technology profession will need it increasingly.

Now I shall make some general comments about the past, present, and future of materials technology. I shall emphasize technology quite deliberately

because I agree with de Solla Price, and Vannevar Bush, and Irving Langmuir, and Ruston Roy, and others that civilization advances through technological invention first; followed later by science. The reason for this is fundamental. Invention is based on knowledge that is not yet organized, while science consists of knowledge that is already organized. Thus, invention is predominantly synthetic while science is analytic in character. It is certainly true that science aids the development of technology, but the prime movers are the technological advances.

Synthesis is much more difficult to execute than analysis because its result is not qualitatively known *a priori*. In the case of analysis the result is known qualitatively *a priori*, although not quantitatively.

Another difficulty that is associated with synthetic advances is that they must be accomplished economically. In other words, a disinterested and untutored public must place a competitive value on them. Otherwise they do not constitute an advance. I have learned this the hard way in bringing new products to the marketplace. Proving to a potential user that a product offers increased utility to him/her at constant direct cost is not a trivial task.

A result of economic constraints is that although thousands of new substances are synthesized each year, only a few of them are used by some one on a day-to-day basis. The process by which a substance becomes a material is lengthy. For demanding applications, it typically takes 15 years. Two examples to which I have had direct experiential exposure are: directionally-solidified components for jet-engines; and metallic glasses for power-transformer cores.

Both took about 15 years.

The realities of economic constraints combined with technical requirements are the enemies of enthusiasms about the prospects for interesting substances to become materials.

Looking in the other direction, if it were not for enthusiasm, no new substance would be able to hurdle both the economic and technical barriers. Therefore, enthusiasm sobered by reality is to be appreciated and honored. But, if enthusiasm gets out of control, large amounts of effort are dissipated on things that are touted by enthusiasts but which soon pass from interest. Ten examples are:

1. The ancient dream of chemical transmutation.
2. Sapphire turbine blades.
3. Bridges built of iron-whiskers.
4. Ductile ceramics.
5. Thermoelectric power plants.
6. Molybdenum turbine blades.
7. Corfam shoes.
8. "All-black" aircraft turbines.
9. Metallic hydrogen explosives.
10. Silicon nitride automobile engines.

On the other side of the ledger, there have been marvelous advances in engineering materials in the past few decades. A few of these, but by no means all, are:

1. Multi-layered semiconductors.
2. Ultra-strong fibers: graphite, aramids, and polyethylene.
3. Liquid crystals.

4. Low-loss optical fibers.
5. Crystals for non-linear optics.
6. Shape-memory alloys.
7. Metallic glass soft magnets.
8. Neodymium-boron-iron permanent magnets.
9. Monocrystalline turbine blades.
10. Ceramic cutting tools.

These advances as well as many others show that the field of materials has impressive vigor and is growing in exciting new directions. However, the growth is not uniform so it is important to study and interpret the trends.

As I pointed out earlier, it is important to appreciate the difference between a substance and an engineering material. Sometimes newly discovered substances become developed into materials, but this is rare because a large number of constraints must be satisfied before it can occur. The constraint that most often blocks commercialization is manufacturing cost, but there are many others including safety features. The degree to which the profile of the physical properties of the new material matches the profiles required by specific applications is also critical. These profiles were quite simple many years ago, but they continually become more complex.

Historically, the property profiles of materials were determined by the primary producers (1). This started at the mines and their associated smelters; at the clay-pits and their associated potteries; at the forests and their lumber-mills; and so on. Whatever they produced is what the user had to work with. As methods for fabrication advanced, the variety of shapes that could be manufactured increased, and their property profiles became increasingly determined by the methods used by the fabricators to make semi-finished mill

products. Later, the emphasis shifted to finished products that were differentiated by the material they were constructed from. That is, there were discrete metal components, ceramic components, plastic components, and so on.

The culmination of this period is represented by the advent of components made of polymeric structural materials. The market for these objects developed rapidly; not because raw polymers are inexpensive or possess outstanding properties, but because polymers can be formed into complex shapes inexpensively. This is quite different from the earlier case of the growth of the steel industry. The success of steel was based on inexpensive raw materials combined with outstanding engineering properties.

In the most recent several decades a process of integration has been occurring (2). This has been shifting commercial opportunities to industries that use materials, and from those that produce them. It has also been increasing the demand for extensive profiles of properties, as contrasted with the relatively narrow profiles that were needed when materials formed clearly differentiated components of machines.

One consequence of the trend toward integration is that the functions of materials have become much more important than their origins; or the cost of their raw materials. In looking to the future, this trend will continue because it is here that materials technology will make the greatest advances, and it is here that the greatest fractional utility is added as defined by the demands of society.

For example, a pound of aluminum as ingot is worth roughly a dollar a pound. After conversion to a semi-finished structural shape it is worth perhaps

five dollars per pound; but after conversion to a microconductor on a silicon chip it is worth roughly 500,000,000 dollars per pound! Most of the value comes, of course, from the processing that integrates the aluminum into a system.

Another way to make this same point is to consider the elasticity of demand for materials (3). For commodity materials, price elasticity is high so large changes in consumption cause only small changes in price. But for materials that have been integrated into systems, price elasticity is relatively low, so small changes in consumption lead to substantial changes in price. Since low elasticity helps to maintain gross margins, business operations in this arena will tend to prosper more than those dealing with commodities.

Still another indicator is relative price changes. By this I mean price changes relative to an average change of zero for the economy as a whole. Some relative changes are increases, and some are decreases, while the sum of all relative changes is zero. For many years (at least 25), the relative real prices of commodity materials have been decreasing. At the same time, the relative prices of materials in sophisticated integrated systems have been increasing. Thus materials in their commodity forms have been getting relatively less important commercially, while the opposite is true for their integrated forms.

What I have said so far has been a preamble to saying that opportunities in the materials area lie principally in materials systems, and much less in components made from differentiated individual materials. I'll try to clarify this through some examples.

The phrase "material system" implies an operational function. Therefore, in

considering where opportunity lies, it is important to ask, "what functional areas are likely to grow most in the foreseeable future?" I think that the technologies that are likely to show major growth are:

1. Photonics
2. Robotics
2. Prosthetics
3. Astronautics
4. Nanoelectronics

I shall describe selected examples of materials systems associated with these.

These examples are intended to be illustrative, not comprehensive or optimal.

1. Photonics

Electronics has been based on the large ratio of charge to mass for electrons which allows them to be manipulated efficiently. The particles of photonics, namely photons, have neither charge nor mass. Their lack of mass allows them to be manipulated at very high frequencies which is useful in communication systems. Their lack of charge allows them to be concentrated into very small volumes which is useful for fabricating materials.

There are two principal branches of photonics. One is optical communications (including data processing) in which advanced materials are needed to: generate, transmit, detect, analyze, focus, and display light. The other principal branch is materials processing in which advanced materials are needed to make powerful lasers together with systems for manipulating

and controlling them.

In this field, outstanding advances have been made in the purification of materials so they can transmit light over long distances. In a few years this capability was improved by a factor of ten thousand compared with the best of previous glasses (Figure 1). The performance of pure glasses in terms of transparency is truly spectacular (Figure 2). There is not enough space here to describe the many other new materials that are involved with photonics, but I do want to describe a device that illustrates how various functional materials integrate to perform a higher level function.

Figure 3 shows a battery-operated laser that emits a highly collimated beam of green light. It does this by means of the following chain of events: a battery provides electric current to drive a small array of GaAs lasers which emit light that excites an yttrium aluminum garnet rod that contains fluorescent neodymium ions. This rod lases emitting a beam of infra-red light. The infra-red beam then passes through a crystal of lithium niobate which converts it into a beam of green light. Thus the device consists of an integrated series of materials each of which performs a specific function.

2. Robotics

Although the inputs to robots are critically important, so are the outputs. For actuating the outputs nothing as versatile as biological muscle has been found thus far, but one actuator design that is close is shown in Figure 4. For its "muscles" it uses a "shape-memory" alloy. This is a metal that remembers its shape prior to a phase-transformation that is induced by

temperature. In the case of this robot hand, there are actuating wires that are short above a certain temperature and long below the same temperature. These actuating wires are heated by electric currents to make the fingers bend and the wrist rotate. The result is a robotic system that is much more compact, and lighter, than those actuated by hydraulic cylinders or stepping motors.

3. Prosthetics

There is a powerful demand for improved prosthetic materials systems. It is generated by accidents, disease, violence, and by aging of the population. Perhaps the most commonly known system in this class is contact lenses. Dental prostheses are also well known.

Most non-biological materials irritate living tissues. Some mildly, some severely enough to induce carcinomas. One of the most benign and therefore potentially most useful is pure carbon. This has been known for millenia by people with tatoos. A hard form of it, known as "glassy-carbon", has been used for many years in artificial heart valve systems. But a disadvantage of glassy carbon is that it is quite brittle; also, it is extremely stiff which often makes it mechanically incompatible with biological tissues; including bone.

In recent years, considerable work has been done on the development of composites consisting of carbon fibers embedded in carbon matrices, called carbon-carbon composites. They are mainly intended for high temperature applications such as engines and rocket nose-cones, but they have considerable potential for prosthetics. For certain levels of porosity they can

be both compliant and tough (non-brittle). These properties combined with their high level of bio-compatibility make them highly desirable.

4. Astronautics

This topic includes both the exploration and the exploitation of space. Both will require new power supplies; probably of the nuclear fusion variety. Implosions driven by ion-beams appear to have the best chance for success in realizing the necessary controlled fusion reactions. For building effective ion-acceleration systems, materials that can be quickly and easily magnetized are needed. Among many other materials, of course.

The speed with which a material can be magnetized depends on the mobility of the magnetic domain-walls within it. As these move they change the magnetization. A dramatic improvement in domain-wall mobility occurred in recent years with the advent of metallic glasses. These are made by cooling selected alloys very rapidly from the liquid state so they retain the glassy structure of the liquid. Because of the ease with which they can be magnetized and demagnetized (Figure 5), metallic glasses have made it possible to build very efficient transformers that are being used in the distribution system for electric power.

In addition, these new materials have made it possible to design the huge magnetic switches that are one of the keys to the ion-accelerators needed for controlled thermonuclear reactors which in turn are needed for advances in astronautics. Switches that weigh a few tons and can switch terawatt-sized pulses of electric power have been built from metallic glasses. The nano-

second pulses consist of as much as one million amperes at 2.5 million volts.

5. Nanoelectronics

We are all familiar with the profound effects that micro- electronic devices have had on our lives in the two decades. These devices have structural elements in them as small as one micrometer.

A new generation of even smaller devices is now being developed. They will be as small as one nanometer, or one billionth of a meter, which is the size of many individual molecules and much smaller than many biological molecules.

One example is the use of a nano-engineered structure to increase the mobility of electrons in a semiconductor system. Figure 6 shows a structure that is layered at the nanometer level (10nm. layers) while Figure 7 is a schematic diagram of such a layered structure. This schematic diagram indicates that electrons, put into the material by the Al donors in the layers of GaAlAs, can lower their energies by moving into the pure GaAs layers. Once they are in these pure layers, the electrons can move around without being scattered by Al-ions. Therefore their mobilities are much higher than in monolithic GaAlAs where they are subject to Al-ion scattering. The increase can be as much as a factor of one thousand.

In closing let me emphasize once more that the trend in advanced materials is toward integration. Materials and their functions are being combined to form materials systems. These systems are fabricated by being built up "organically". This is occurring both at large scales where composites are integrated into

airframe structures, and at small scales where semiconductors, metals, and insulators are integrated into nanoelectronic systems. It is a trend that has important implications. Not just for business activities, but also for educational issues. It seems apparent that if practice becomes integrated education must follow.

Acknowledgment

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FIGURES

1. Dramatic reduction in the absorption of light in glass in recent history.
2. Comparison of the transmission of light through glasses.
3. Battery-operated laser system in which light that is generated by semiconductor diodes is used to pump a YAG:Nd laser whose red output is converted to green light by a lithium niobate crystal (courtesy Amoco Corporation).
4. Robotic hand actuated by shape-memory wires (courtesy Hitachi, Ltd.).
5. Comparison of domain-wall mobilities in glasses versus previous crystalline materials.
6. Portion of one hundred layer specimen in which 13 nm. layers of InP alternate with 10 nm. layers of GaInAs alloy. Magnification is 600,000X. Tsang et al., APL 50, 540 (1987).
7. Schematic drawing of layered material with accompanying sketch of energy level diagram for electrons in this structure.

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Figure 1.

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