International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

The Future of Materials

Ayres, R.U.

IIASA Working Paper

WP-87-023

February 1987

WORKING PAPER

THE FUTURE OF MATERIALS

R.U.Ayres

February 1987
WP-87-023

IIASA
International Institute
for Applied Systems Analysis

THE FUTURE OF MATERIALS

Robert U. Ayres

February 1987
WP-87-23

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
A-2361 Laxenburg, Austria

FOREWORD

This paper was originally written as a background piece for the Commission on Technology and Employment (US National Academy of Sciences/National Research Council). It will presumably appear in due course in a publication of the NAS/NRC. However, it is also relevant to IIASA's Technology-Economy-Society Program, particularly the Dynamics of Technology (DOT) activity. For this reason it seems appropriate for limited circulation as an IIASA working paper.

Vitali Kaftanov
Deputy Director

THE FUTURE OF MATERIALS

Organization of the Paper

Diversity is the most noteworthy characteristics of materials. It seems sensible, therefore, to begin with a taxonomy, the following is taken from the Table of Contents of a standard Handbook.

Ferrous Alloys

Light Metals

Aluminum-Base Alloys

Nickel-Base Alloys

Other Metals

Glasses and glass ceramics

Aluminum and other refractories

Composite

Polymers

Electronic Materials

Nuclear Materials

Biomedical Materials

Graphitic Materials

Even a cursory summary of all these technologies in a short paper is bound to be unbalanced and, in many ways, unsatisfactory. One can scarcely hope to do more than pick out a few salient trends. A selection principle is urgently needed, however.

It is probably useful to start with the observation that the present economic importance of the material categories is virtually inverse to their present day interest from a research

---

[1]C.T. Lynch (ed). Handbook of Materials Science CRC Press, 1975. The major construction materials and materials from natural sources have been omitted.

perspective. Natural materials like wood, paper, rubber, leather, cotton, wool, stone and clay are still enormously important in the world economy, but they are declining in importance (Larson, Ross & Williams, 1986). The same is true with the "old" metals, copper (bronze, brass), lead, zinc (pewter), tin, silver, gold, and iron as well as concrete and plate glass. To be sure, any of these may enjoy a revival, either because of a new method of processing (e.g. plywood or fiberboard) or a new use (e.g. the superconducting properties of certain tin alloys). But given the necessary brevity of this paper and the enormous scope of its coverage, it seems justified to start by eliminating this group from further consideration.

On further reflection, it also seems clear enough that steel and its close relatives, too, have largely had their day in the sun. The steel industry burst into prominence after 1860, after a long accumulation of incremental improvements in furnace design and metallurgy finally culminated in the great inventions of Bessemer, Kelley, Mushet, Siemens, Martin and Thomas. The metallurgy of steel and ferro-alloys progressed rapidly for the next half-century or so. However, since World War II, the potential of iron-based alloys technology has been largely exhausted[2] and research emphasis in metallurgy has shifted to the ultra light metals, on the one hand, and the nickel or cobalt based "superalloys" on the other. Both of these developments have been driven by aerospace requirements (for air-frames and jet engines, respectively). In any case, iron-based steel) alloy

---

[2]Applications of high strength low alloy (HSLA) steels are still continuing to increase, however, especially in the auto industry. Major <u>process</u> innovations, notably The Basic Oxygen Furnace (BOF) and continuous casters, also appeared after WW II.

technology--whether moribund or not--will not be considered further in this paper.

To conclude this introduction, some further remarks on diversity of attributes seem appropriate. It is tempting, at times, to try to measure technological progress in materials in terms of simple measures like "strength". Yet, even a moments' thought suggests that there are many other properties of importance. Each application calls for a different combination of properties. This is especially well illustrated in the case of synthetic fibers. By and large polymer-based materials do not compete with metals. They do compete, in general with wood, paper, natural rubber, and natural fibers.

The first "synthetic" fibers in the 1893-85 era were cellulosed-based (viscose rayon and cellulose acetate). The rayon industry boomed in the 1920's and 1930's. Later, completely man-made polymers were introduced, beginning with nylon (1939). See Table 1 below. An effort to discern some meaningful trend was made by Gordon & Munson in 1982. They convened a panel of experts, who identified four parameters as being "important" and weighted them as follows:

Parameters	Panel Weight
- Tensile strength (gms/denier)	.2581
- Elastic recovery (percent recovery from percent stretch)	.2903
- Modulus (gms/denier)	.2903
- Moisture regain (percent)	.1613
	1.0000

A comparison of the major man-made fibers is given in Table 1 and Figure 1. It is obvious that the index constructed from the

Table 1

MAN-MADE FIBERS DATA

FIBER NAME	YR OF INTRO	TENSILE STRENGTH	ELASTIC RECOVERY	MODULUS	MOISTURE REGAIN	SOA
VISRAYON	1892	2.4	74	11.1	13	
ACERAYON	1894	1.5	65	5.5	6.5	
NYLON	1935	5.7	100	24	3.8	
ORLON	1949	5	84	24	.9	
DACRON	1951	5	95	25	1.38	
VICARA	1953	1.25	99.5	3.5	10	
ACRILAN	1953	3	75	30	1.7	
DYNEL	1953	3	87	9.7	.4	
ARNEL	1955	1.4	84	5.2	3.2	
ZEFRAN	1959	3.5	92	11	2.5	
DARVAN	1959	2	75	7	3	
KODEL	1959	3	87	11	.4	
VYCRON	1962	8	60	.16	.6	
ARNEL 60	1962	2.3	70	10	4	
ZEFKROME	1964	4.2	84	11.3	2.5	
ENCRON	1968	5	70	5.3	4	
SEF	1972	2.6	99	3	2.5	
TRIACETATE	1980	1.3	70	5.2	3.2	

TENSILE STRENGTH-- Tensile Strength (gms/denier)

ELASTIC RECOVERY-- Elastic Recovery (percent recovery from percent stretch)

MODULUS-- (gms/denier)

MOISTURE REGAIN-- Moisture Regain (percent)

SOURCE: Textile World Man-Made Fiber Chart, several years.

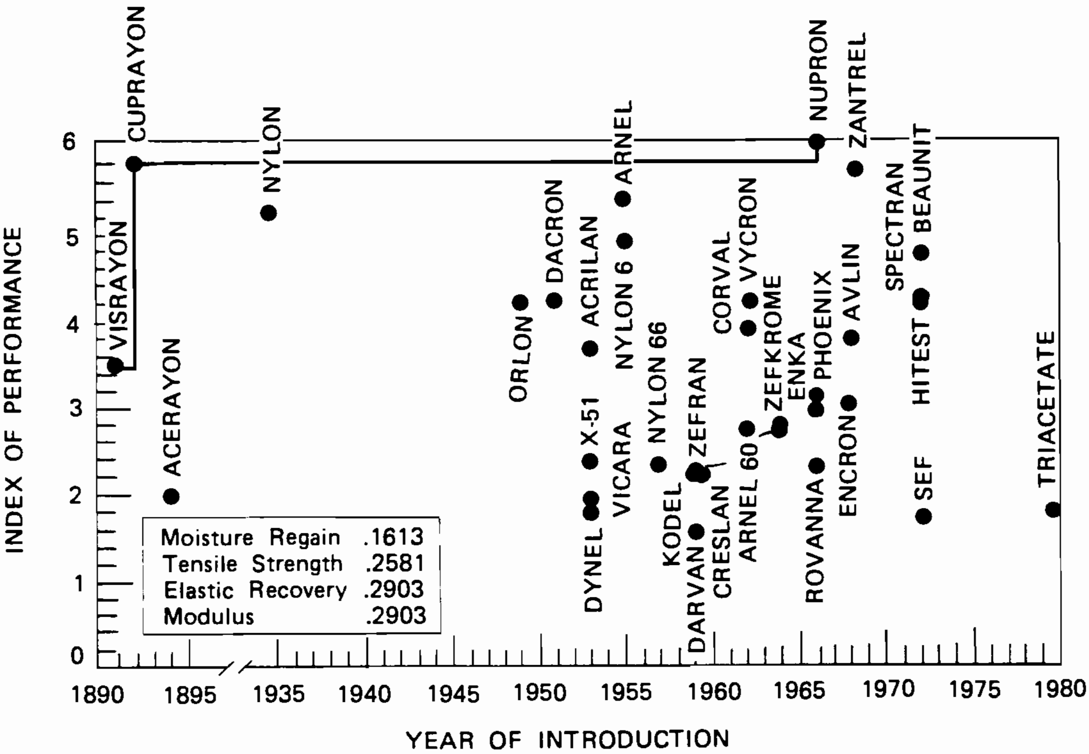


Fig. 1: Man-Made Fibers Performance Index when Values are Nondimensionalized by Scaling Between 0 and 1

Source: Gordon & Munson '82

above parameters, weighted as indicated <u>a priori</u> by the panel, does not explain the success of newer fibers. In fact, an early form of rayon (cuprayon) is superior than all the more recent fibers but one, in terms of the index introduced in 1892. Clearly, a number of other (perhaps less quantifiable) factors such as "feel" are important. Moreover, the optimum "mix" of factors evidently varies significantly from one fiber use to another. The salient feature of recent developments in this field is diversity itself.

Much the same point can be made about other categories of materials. While alloy steels have not been getting significantly stronger or harder, in recent decades the number of specialized steel alloys with different combinations of properties continues to grow. The same trend is even more pronounced for other metal alloys, refractories and ceramics, and for polymers and composites.

Having said this, the remainder of the paper will focus only on three of the possible topics.

High Temperature Materials

Electronic Materials

High Strength Composites

<u>High Temperature Materials</u>

A requirement common to many material uses is a combination of toughness (i.e. ductility) and strength at high temperatures with minimum weight. Early uses for such materials were mainly for high speed drilling and cutting tools (hence: "high speed" steels). Jet engines and gas turbines currently exemplify this requirement. The essential point is that increased fuel economy and higher thrust-to-weight ratio as achieved by operating at higher temperature and pressures. A 150°F increase in inlet temperatures yields a 20% increase in thrust [Clark and Flemmings, 1986]. (For comparison, thrust-to-weight ratio for large jet engines has somewhat more than doubled in the last 30 years [Steinberg, 1986]. Airframes and reentry vehicles (RV's) also require a combination of high strength and low weight at high temperatures.

Two radically different cases can immediately be distinguished, depending on whether exposure to air is also essential or not. Thus carbon fiber, one of the strongest and lightest of all materials, cannot be used in engines, for instance, because of its combustibility. On the other hand, non-metallic refractories such as oxides, carbides or nitrides are quite strong and not affected by the presence of oxygen, but they tend to be brittle, i.e. they lack ductility. Thus, two major lines of development can be discerned. The first is metallurgical. The problem is to find metallic alloys with better combinations of strength and ductility for applications in oxidizing environments, especially for turbine engines.

Here again, a panel of experts convened by Gordon and Munson (1982) identified three relevant parameters and weighted them.

Parameter	Weight Factor
rupture strength	.333
creep strength	.333
ductility	.333

Data for a number of high temperature alloys introduced since WW II are shown in Table 2. In this case (since the application is relatively unchanged), the single composite index Figure 2 does seem to have some explanatory power. However, even here there

Table 2

HIGH-TEMPERATURE MATERIALS:
NONDIMENSIONALIZED PARAMETERS AND PERFORMANCE INDEX

	YEAR	RUPUT	CREEP	DUCTL	SOA
NIMONIC	1941	0	0	.812	.271
S-816	1943	.348	.476	.246	.357
NIMONIC 80A	1944	.022	.11	.391	.174
NIMONIC 90	1945	.04	.11	.971	.374
L-605	1947	.203	.079	.551	.278
M 252	1949	.384	.215	.087	.229
RENE 41	1950	.312	.319	.478	.37
UDIMET	1955	.384	.424	.275	.361
GMR 235	1955	.565	.476	0	.347
ALLOY 713C	1955	.71	.581	.246	.512
UDIMET 700	1957	.529	.267	.42	.405
NIMONIC 105	1958	.268	.168	.493	.31
NIMONIC 115	1959	.529	.288	.29	.369
IN-100	1960	.855	.843	.043	.58
B-1900	1962	.855	.895	.058	.603
ALLOY 713LC	1964	.674	.581	.275	.51
MM 509	1964	.493	.476	.333	.434
MM 246	1965	.964	1	.072	.679
HA-188	1966	.167	.079	1	.415
MM200(DS)	1966	1	1	.072	.691
UNITEMP	1970	.746	.895	.174	.605

K(1)= .333333333
K(2)= .333333333
K(3)= .333333333

SOURCE: Gordon/Munson, 1982

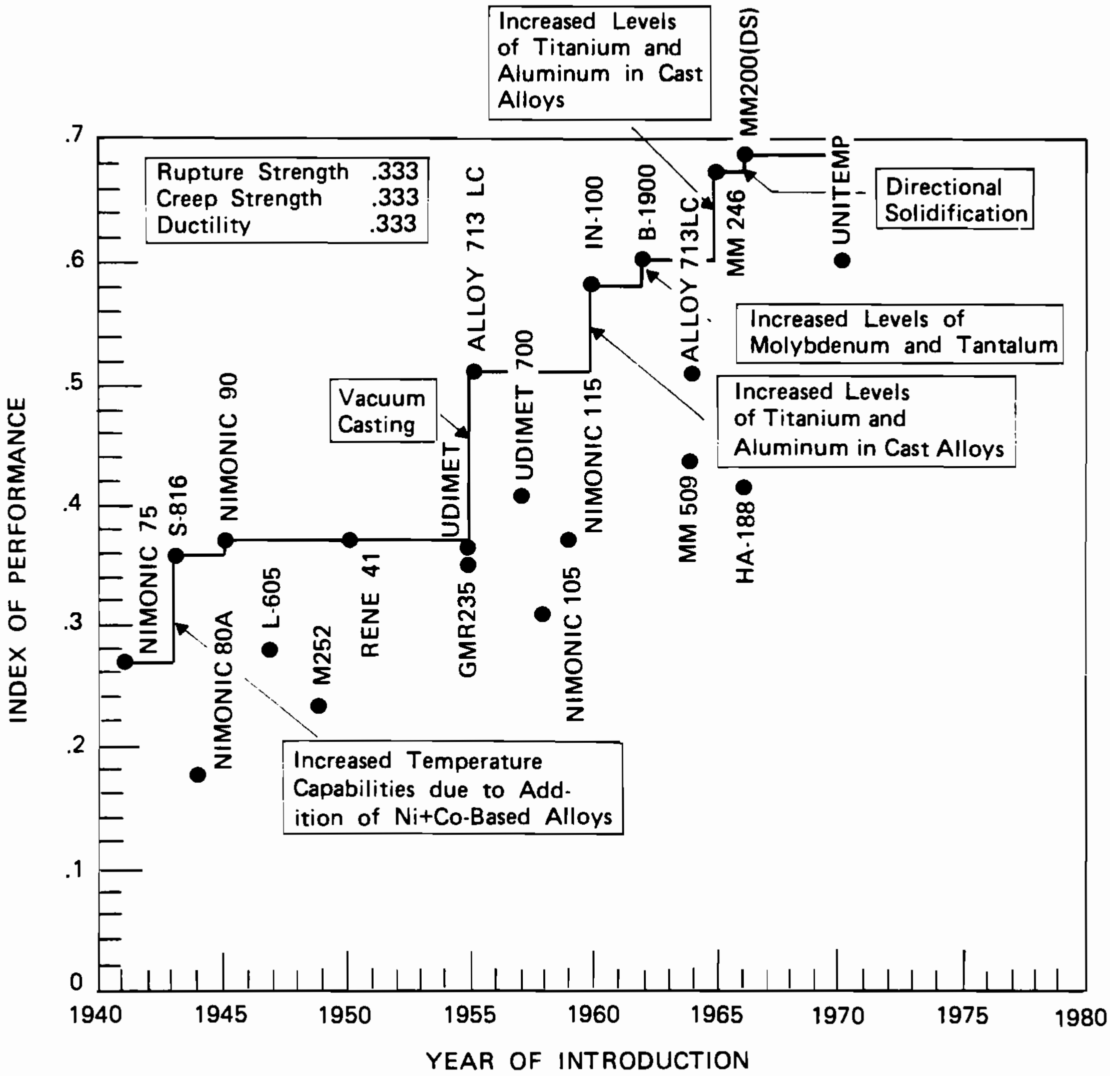


Fig. 2: High-Temperature Materials Performance Index

Source: Gordon & Munson '82

were two different applications, viz turbine blades and vanes. For blades, nickel-based alloys were preferred because of higher strength and stress resistance, while for vanes, cobalt-based alloys were preferred (because of reduced environmental degradation. The only three cobalt-based alloys in the study were S-816, MM 509 and HA-188. The latter show almost no upward trend in the composite index. Up to the mid-1960's, there was a clear and rapid upward trend in the index of performance for nickel-based alloys, on the other hand. Since then, improvements have been achieved mainly by the use of directional crystallization techniques in the investment casting process. Incremental improvements in high temperature metallurgy have permitted gas turbine operating temperatures to increase at the rate of 10-12°P about (6-7°C) per year since the 1960's [Clark & Fleming, 1986].

The alternative line of research in high temperature materials is focussing on advanced ceramics, such as silicon carbide, silicon nitride and lithium aluminum silicate. Concern over possible shortages of cobalt, chromium and other so-called "strategic" metals played a major role in accelerating the research effort in this field. Based on their known properties, ceramic matrix composites seem to offer a potential of raising turbine inlet temperatures from about 1850°F (1985) to as high as 2700°F [Clark & Flemings, 1986]. This would increase turbine fuel efficiency, if realized.

As of 1986, major applications of structural ceramics are for cutting tools and mechanical seals. However, ceramic automobile turbochargers are now being produced by Nissan in Japan and ceramic glow plugs and precombustion chambers for Diesel engines are being made by Isuzu [Robinson, 1986]. Ford and Garret Corporation are about to test a 100 hp. gas turbine engine with a metal housing and ceramic parts in contact with the hot gases (Ibid). Unfortunately, the U.S. auto companies have done little, so far, to develop ceramic piston engines or suitable low-cost production technologies. There is disturbing evidence that they may be leaving this field to the Japanese Yet losing this race (if it is one) could have unfavorable long-term economic consequences for the U.S. automobile industry.

The problems of utilizing advanced ceramics such as silicon nitride, for engines or other purposes where they compete with metals are not so much their well-known brittleness (i.e. lack of ductility) as their tendency to fail unpredictably. This, in turn, is because the distribution of microscopic defects -- which concentrate and propagate stress -- cannot be predicted *a priori*, due to scatter in the experimental data, as shown in Figure 3. A theoretical possibility is "proof test", namely to test all ceramic parts up to a certain level of performance and throw away those that fail. This greatly decreases the odds of random failure among the survivors as shown in Figure 4. However under present conditions, yields are likely to be as low as 10%, which is far too low. Until yields of 70% or better can be achieved in practice, the economics are unfavorable.

Part of the problem of unpredictability may have its origin in the traditional techniques of compaction and hot pressing (sintering). The quality of the product is dependent on the size distribution and uniformity of the starting material. New processing techniques such as "sol-gel" processing may offer hope. A "sol" is a colloidal suspension of particles in sizes from 1 to 100 nanometers. As the "sol" loses liquid, it gradually becomes a "gel". Although the concept is old, this

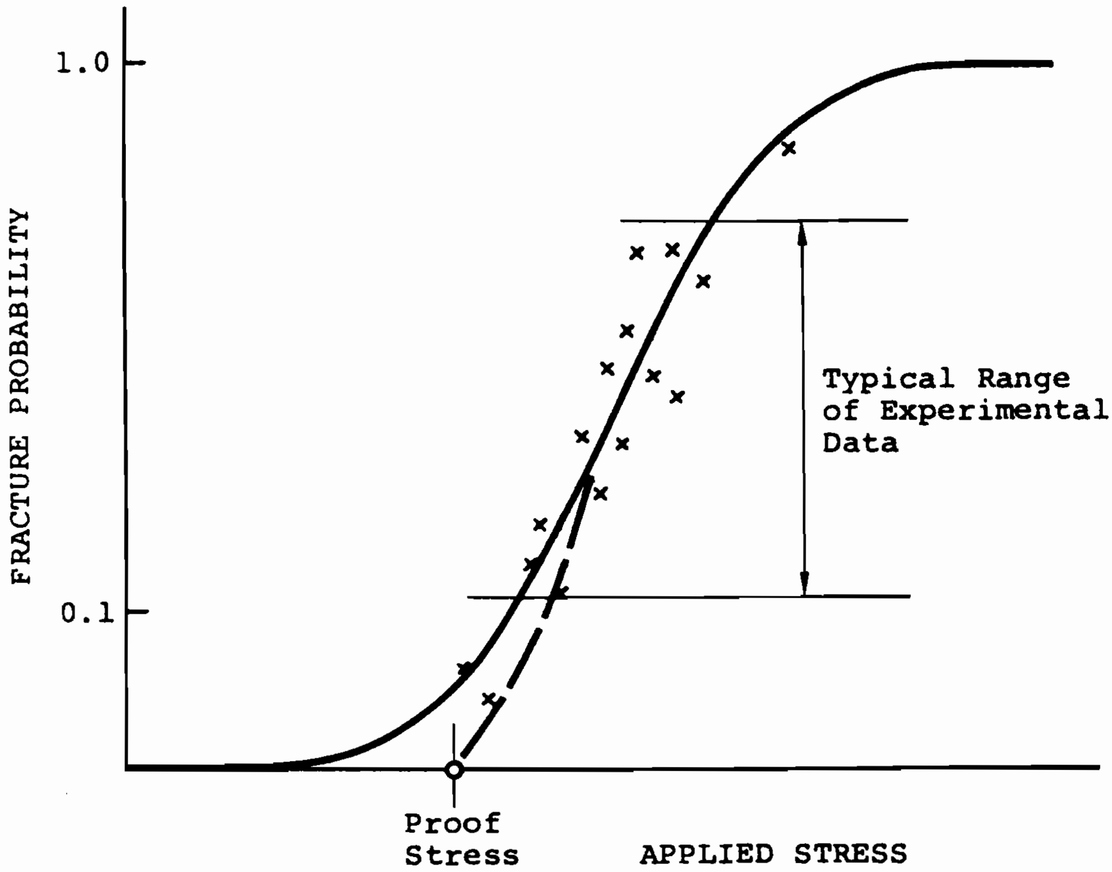


FIG. 3 TYPICAL STRENGTH VARIABILITY CURVE FOR A CERAMIC

Source: NRC 75

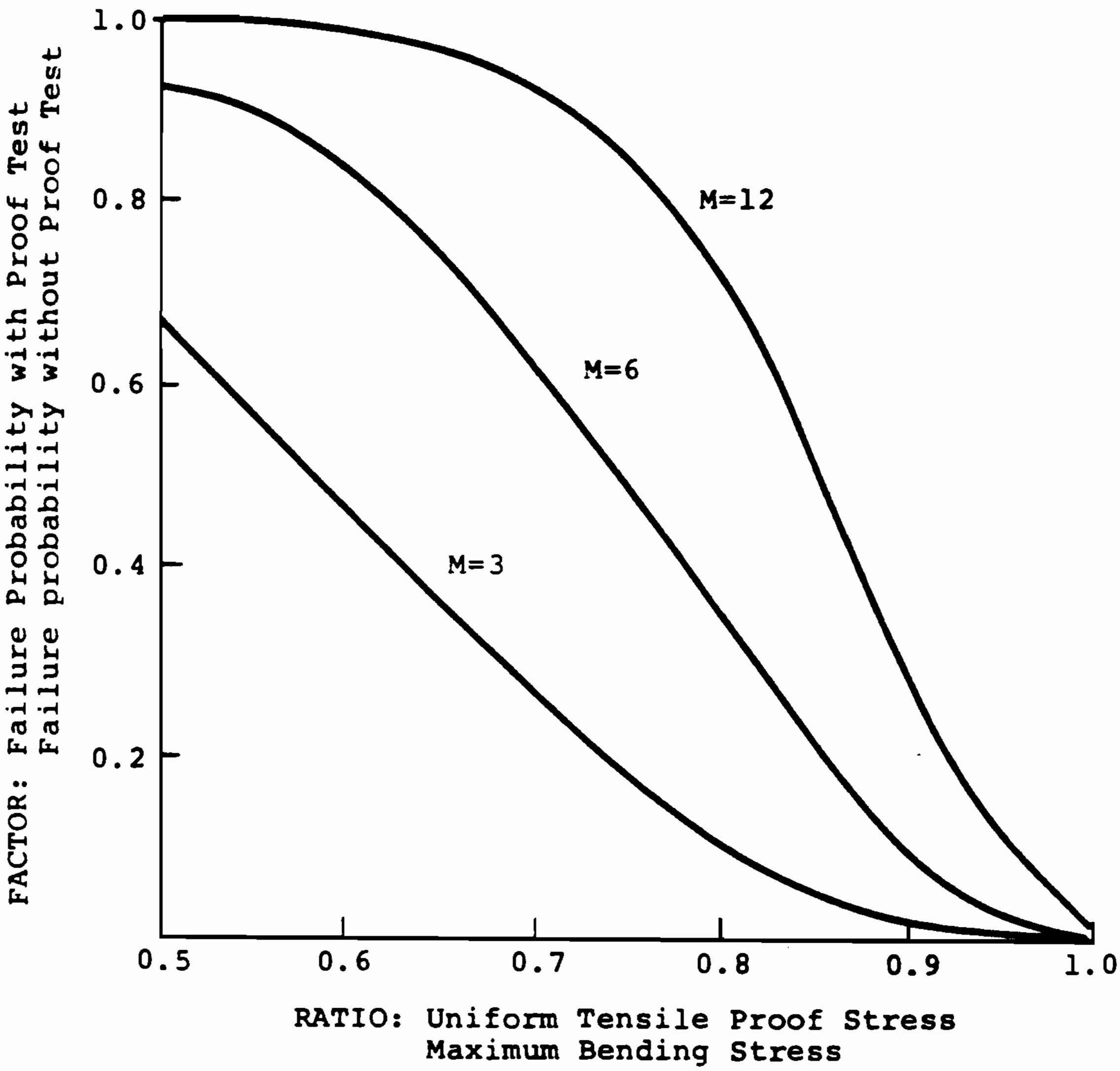


FIG. 4 EFFECT OF A UNIFORM TENSILE PROOF TEST ON FAILURE PROBABILITY OF A BAR IN BENDING

Source: NRC 75

technique has only been widely practiced for about 3 years, and its popularity is growing rapidly (ibid). However, this growing interest in chemical-based techniques can be interpreted as evidence that the older physics based techniques are reaching a dead end. At present, it appears safe to predict that advanced ceramics will rapidly grow in economic importance, but that they will not become serious competitors with metals (e.g. in auto, diesel or jet engines), for at least another decade, and probably longer. This means that major technical improvements in engine performance -- hence fuel economy -- especially in large-scale applications cannot be expected for at least 15 or 20 years.

Strong Light Materials

For most practical purposes "strength" is a combination of two characteristics, namely resistance to stretching and resistance to bending. The first is commonly measured in terms of the amount of pulling or tensile stress required to cause the sample to break (in p.s.i. or pounds per square inch of cross section). The second is measured in terms of the tensile stress required in principle to stretch the sample to twice its original length, also measured in p.s.i. This number is called "Youngs' modulus". For purposes of comparison, typical values of breaking strength and stiffness for standard engineering materials are as follows:

	Tensile Strength (X10³) psi	Stiffness (Modulus) (X10³) psi
Wood (spruce, along grain)	15	2000
Bone	20	4000
Glass (window or bottle)	5-25	10000
Aluminum	10	10500
Carbon steel (mild)	60	30000

In principle, it seems obvious that these numbers must bear some relation to the attractive forces between atoms of the material. But if only interatomic forces were involved, materials should be 10 to 50 times stronger than they actually are. Very careful experiments in the 1940's and 1950's showed that flawless microscopic crystals or whiskers or very thin fibers of glass approached theoretical breaking strength much more closely than macro materials (Gordon '68).

In the 1950's, theory (supported by newly available empirical data from x-ray microscopy and other new research tools) began to catch up, and the essential mechanisms of defect propagation, in brittle materials and "crack-stopping" behavior in ductile metals and natural composites (such as wood and bone) were finally understood (ibid). "Composites" are composed of two or more components; viz, very strong small fibers (oriented or not) embedded in a much weaker matrix. A factor of 5 or so difference in strength between the two components is essential. This insight opened the door to synthetic composites, of which the first commercially important one was fiberglass reinforced plastic (FRP). FRP is still by far the most important composite, commercially but by the beginning of the 1970's a large family of new high performance composites had been developed, largely by the aerospace industry.

The key to a practical composite material is the strong component, which can be a glass fiber, a mineral crystal such as sapphire (Al_2O_3), a boron (B) or graphite (C) fiber, a metallic crystal ("whisker") or even a complex structure consisting of a silicon carbide coated boron fiber or a core of thin (e.g. tungsten) wire on which a coating of boron (B) or a boron-carbon compound (B_4C) have been vapor-deposited.

For almost all commercial applications, the matrix or binder is an epoxy or phenolic resin that can be easily molded. However, if the composite material must also be heat resistant and non-inflammable, only mineral materials or metals can be used. In such cases, manufacturing techniques may be similar to those used in ceramic manufacturing (powder compaction, followed by isostatic compression and sintering). As noted above, recent trends in advanced structural ceramic applications research suggest that physical techniques may be supplanted by chemical methods, such as the "sol-gel" method (Robinson '86).

Another approach to the creation of metallic composites is to arrange matters so that a two phase system of metallic crystals with the requisite difference in strength. Such a system can be created by powder-forming techniques (metal matrix composites) or by dissolving one metal in another and allowing it to crystallize within the melt under controlled conditions. The result is called a eutectic alloy or an `intermetallic" alloy. A number of combinations have been identified that have the requisite characteristics, e.g. Lynch (1975). The most promising example at present, is nickel aluminide (Ni_3Al), with small amounts of boron added to increase cohesion and small amounts of hafnium to increase yield strength [Claasen & Girifalco, 1986].

The list of possible metal-matrix composites and eutectics may get much longer in time, but it is difficult to say whether significant improvements in absolute performance are likely. In any case, the primary objective of R&D over the next few years is to improve predictability and formability. One major problem is the fact that most of the interesting composites are patented and the relevant processes are proprietary. This limits the R&D effort that can be focussed on any one material.

Well over a decade after their initial introduction into the aerospace industry (for specialized uses in military aircraft and spacecraft), ultra-strong graphite-based composites finally appeared in a few selected commercial products like tennis rackets, ski's and golf clubs in the late 1970's. They are gradually increasing market share as prices come down and designers learn how to utilize the new materials to best advantage. However, there are many other potential "civil" applications where strength, light weight and corrosion resistance will make a difference. Bicycle frames, motorcycles and small light aircraft would probably be the next obvious applications followed by substantial use in commercial aircraft.

In principle, composites can replace aluminum for most of the structural parts of any aircraft, including the exterior "skin" and significant part of the engine. Even small savings in weight in aircraft (or spacecraft) have a significant payoff in terms of fuel economy or, equivalently, increased payload. Undoubtedly, these materials will ultimately have a significant impact on the economics of air transportation. Commercialization has been slow, up to now, because of the long product "life cycle" in the aircraft industry, the specialized knowledge involved, and the fact that most of it is proprietary to the aerospace industry. All of these factors result in rather high costs. However, many of the basic patents have already expired and the key "process" patents will be expiring over the next few years. This will open up the field to more intense competition -- especially by the Japanese. It can be expected that the ratio of "composites" to metals in newly designed subsonic aircraft will rise rapidly through the 1990's. For example, all the control surfaces on the Boeing 757 and 767 aircraft will be made of graphite-epoxy composites, yielding a saving of 845 lb in weight and a 2% saving in fuel [Clark & Fleming, 1986].

Beyond aircraft applications, there will eventually also be important applications in automobiles. Until 1980 or so, only fiberglass (FRP) has found a significant use (in the Chevy Corvette body). But an increasing number of bumpers, and body panels and some complete metal automobile bodies are being replaced by unreinforced thermoplastic polymers (as in the case of the Pontiac Fiero), so the first major opportunity for lightweight composites may be to replace steel in the chassis and frame. The overall proportion of plastics in the weight of an average auto (now 9%) can be expected to grow significantly. In fact, as many as 1.6 million auto bodies may be made of plastic annually by 1990 [Compton & Gjostein, 1986]. A second-generation supersonic aircraft such as the "Orient Express", recently proposed by the Reagan Administration, would probably consist of 50% polymer-matrix composites, plus 10% metal-matrix composites, 15% aluminum-lithium alloy and 25% other metals such as steel, aluminum and titanium [Steinberg, 1986]. Meanwhile, as noted above, ceramics may replace much of the metal in the conventional engine, and high-strength low-alloy steel will continue to replace mild steel in chassis and frame. The benefits of weight reduction in automobiles (and trucks) are not as great as in the case of aircraft[3], but are nevertheless significant. However, it is clear that a great deal remains to be learned about large scale manufacturing with composite materials before they can replace metals in mass produced products. Up until now, the U.S. auto industry has not invested much effort in this field. In view of the long lead times in the industry, Polymer-matrix composites (except FRP) cannot be expected to begin to replace steel in major automobile structural parts until well beyond the year 2000, and probably after 2010.

Electronic Materials

This category of materials includes "ordinary" conductors, semiconductors, superconductors, photoconductors, photoelectrics, photovoltaics, photomagnetics, ferromagnetics, diamagnetics, paramagnetics, magnetostrictives, piezoelectrics, laser materials and a host of others. Even a brief summary of the physical phenomena involved would be far too long for a paper such as this, and a list of the major types of electronic transducers[4] will have to suffice for purposes of illustration (Appendix).

---

[3]Which explains why aluminum has not replaced steel in the automobile industry.

[4]Transducers are devices, mostly used for measurement, which respond to an electrical, magnetic, optical or mechanical input and generate an output in some other form (i.e. electrical, magnetic, etc.).

Since the development of the transistor in 1947 -- as a substitute for the electron tube or "vacuum tube" -- research in the field of semiconductors has grown spectacularly. The rapid growth of basic knowledge about the materials has been driven by burgeoning demand for electronic devices, from telephone switchboards to radio, television, radar, sonar and computers. The latter application has proved the most important, especially after the successive development of integrated circuits (c. 1960 followed by the "microprocessor" (c. 1970), and then LSI, VLSI and now ULSI. Table 3 summarizes these dramatic changes.

One of the key technological driving forces, whose impact seems to have been consistently underestimated, is the relationship between operating speed, power consumption, cost and scale. The original motivation for the invention of the transistor was to cut down on the electric power consumption of telephone switching systems. Miniaturization and large scale required the solution of many difficult technological problems such as controlling even smaller line width's (Figure 5). However, as these technical problems were solved, it proved to be a powerful cost-cutting strategy for manufacturers sharply declining semi-conductor circuitry costs, in turn, generated steady increases in demand, including wholly new applications.

The growth of demand for more "computer power" seems to be continuing unabated, as costs continue to fall. In fact, major new <u>categories</u> of computer and communications applications, such as voice processing, vision processing and "artificial intelligence", are just beginning to emerge (Table 4). As a consequence, huge resources are now being poured into large-scale projects such as Japan's "5th generation" computer project;

Table 3

Development of Semiconductors

	Vacuum tube	Transistor	IC		LSI	VLSI
			SSI	MSI		
Period of diffusion	to 1945	1955-	1965-		1975-	1985-
Integration (elements per unit or per chip)	1 unit	1 unit	2-100	100-1.000	1.000-100.000	100.000-1.000.000
Functions per unit or per chip	1~2	1	100		10.000	100.000
Reliability per function	0.05	1	30		1.000	10.000
Price per function (per chip or per unit)	¥300	¥10	¥1		¥0.05	less than ¥0.05

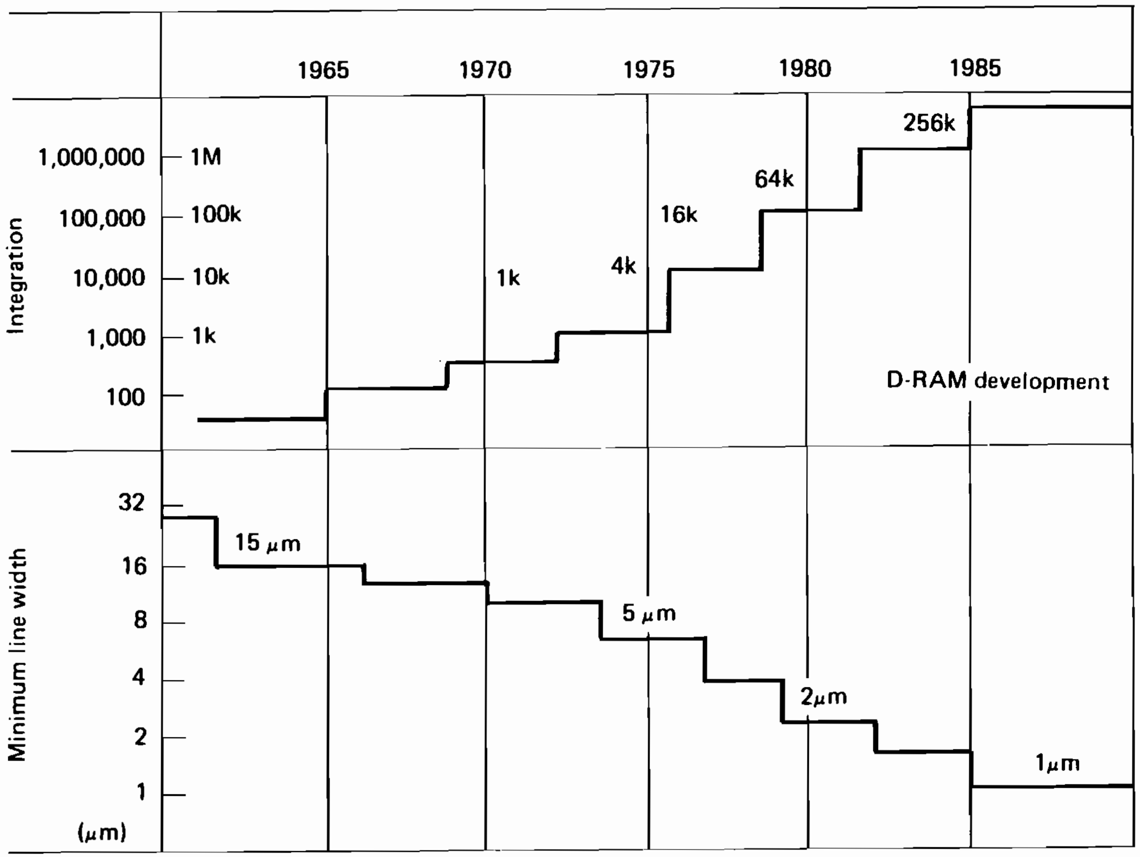
Source: NIRA lecture material etc

Table 4

Breakthroughs Expected in Electronics

Field	Technological need	Current technology	New technology	Performance comparison
Communications	Large volume transmission	Microwaves	Milliwaves	10 times
Information processing	High-speed processing	Silicon LSI	GaAs	5-6 times
			Josephson-junction device	At least 10 times
	High-density memory	Horizontal magnetic recording	Perpendicular magnetic recording	At least 10 times
	Larger-scale integration devices	Planar integration	Three-dimensional circuit devices	—
Instrumentation and control	Improved sensitivity	—	Josephson-junction device	(10^{-6}-10^{-7}G)
	Improved resolution	—	Ultra-sonics (microscope)	(1 μm or less)

Source: Hitachi Research Institute, *In Search of Future Technology in Electronics*.



Source: Electronic Industries Association of Japan

Fig. 5: Changes in Scale of Integration and Minimum Line Width

Europe's grab-bag EUREKA program; the Philips-Siemens "megabit" chip project, the US Defense Departments' VHSLIC program (to develop very high speed chips), AT&T's optical transistor and "ballistic chip" projects, and IBM's "biochip" project[5]. It is literally impossible to forecast with any confidence the "winners" and "losers" in this intense competition. A few conclusions can be drawn, however:

1. Switching speeds and micro-miniaturization can still be increased by orders of magnitude, in principle, exploiting optical technologies now becoming ever more important (Table 5).
2. Manufacturing techniques are becoming more and more critical. The need for microscopic tolerances, and ultra-low levels of impurity contamination require increasingly sophisticated (and expensive) and totally automated, robotics facilities.
3. Design complexity is becoming the limiting factor. Sophisticated CAD is already essential for "chip" design and the next generation of 4 to 16 megabit chips[6] will certainly require an enhanced (by artificial intelligence) form of CAD to the functions performed by human designers at present. This, in turn, will emphasize the role of the very few research institutions capable of assembling a "critical mass" of front-rank A.I. researchers, applied mathematicians and

---

[5]This project, now at a very early stage, is really an attempt to synthesize organic macromolecules capable of performing circuit functions. It does not involve semiconductors.

[6]A 16 megabit chip was announced in early 1987 by NTT (Nippon Telephone & Telegraph Co.)

Table 5

Breakthroughs Expected in Optics

Field	Technological need	Current technology	New technology	Performance comparison
Communications	Large volume transmission	Milliwaves (10^{11} Hz)	Laser light (10^{14} Hz)	1,000 times
	Long-distance transmission (relaying distance)	Electro-magnetic waves (1 km)	Laser light (10–100 km)	10–100 times
	Transmission cost reduction (cable weight)	Coaxial cable (130 kg/m)	Optical fiber cable (70g/m)	About $\frac{1}{2000}$
Information processing	High-speed processing	Josephson-junction device (6-7 picoseconds)	Laser light (10 picoseconds)	0.6 times
	Intra-CPU transmission (data volume/second)	Sequential processing	Parallel processing	Several dozen times
	Spatial image information-processing	Unidimensional development needed	Parallel processing of two-dimensional image possible	Advantageous for image information processing
	High-density recording	Perpendicular magnetic recording (10M bits/cm^2)	Magneto-optic recording (20M bits/cm^2 minimum)	At least 2 times
Instrumentation and control	High-reliablity: Electromagnetic interference Crosstalk Short circuits	 Present Present Present	 Absent Absent Absent	Light is advantageous

Source: NIRA, Author

logicians, electronic engineers and software specialists.

For the above reasons, the semiconductor, telecommunications and computer industries are now inextricably linked and marching together. R & D projects are becoming enormous in scope and expense, bringing governments increasingly into the picture. "New starts", small firms and small countries are now essentially out of the game. Even large established companies cannot be sure of survival. The U.S. semiconductor industry, consisting mostly of medium-sized firms (by modern standards) will have increasing difficulty in staying in the race.

One of the major apparent opportunities for research in the field of electronic materials has been superconductors.[*] The advent of a practical commercial helium liquefier in the early 1950's resulted in an explosion of exploratory research in this field. Only a few superconductors were known up to that time, but by 1970 several hundred superconducting compounds and alloys had been identified. Moreover, by that time superconducting magnets were being sold commercially (by Westinghouse). Such magnets have now become fairly standard laboratory research tools, and are embodied in at least one large particle accelerator (Argonne National Laboratory).

On the other hand, the cost of liquid helium has not fallen significantly since 1960 and is not likely to. Many, once active projects -- such as the development of a superconducting computer (IBM) -- have been dropped. As of 1975 the highest known

---

[*]These are materials that lose all electrical resistivity at a temperature below some "critical" level to and so long as the magnetic field strength (including the field induced by the superconductive current itself) is below a critical level.

critical temperature ($Al_{0.8}Ge_{0.2}Nb_3$) was only 20.7°K, which was still below the boiling point of liquid hydrogen (22.7°K).

The first sign of a major breakthrough was the discovery in 1986 of a new class of barium-copper-lanthanum oxide superconductors which achieved superconductivity at 35°K. In January 1987 partial superconductivity in a similar coumpound was reported at 52°K, under very high pressure. Only a few weeks later another metallic oxide compound was reported to be superconductive at 98°K. More discoveries are to be expected. Dozens of laboratories around the world are now said to be searching for new compounds capable of superconductivity at even higher temperatures, and many physicists are now optimistic about the possibility of achieving superconductivity at room temperature (Sullivan, 1987).

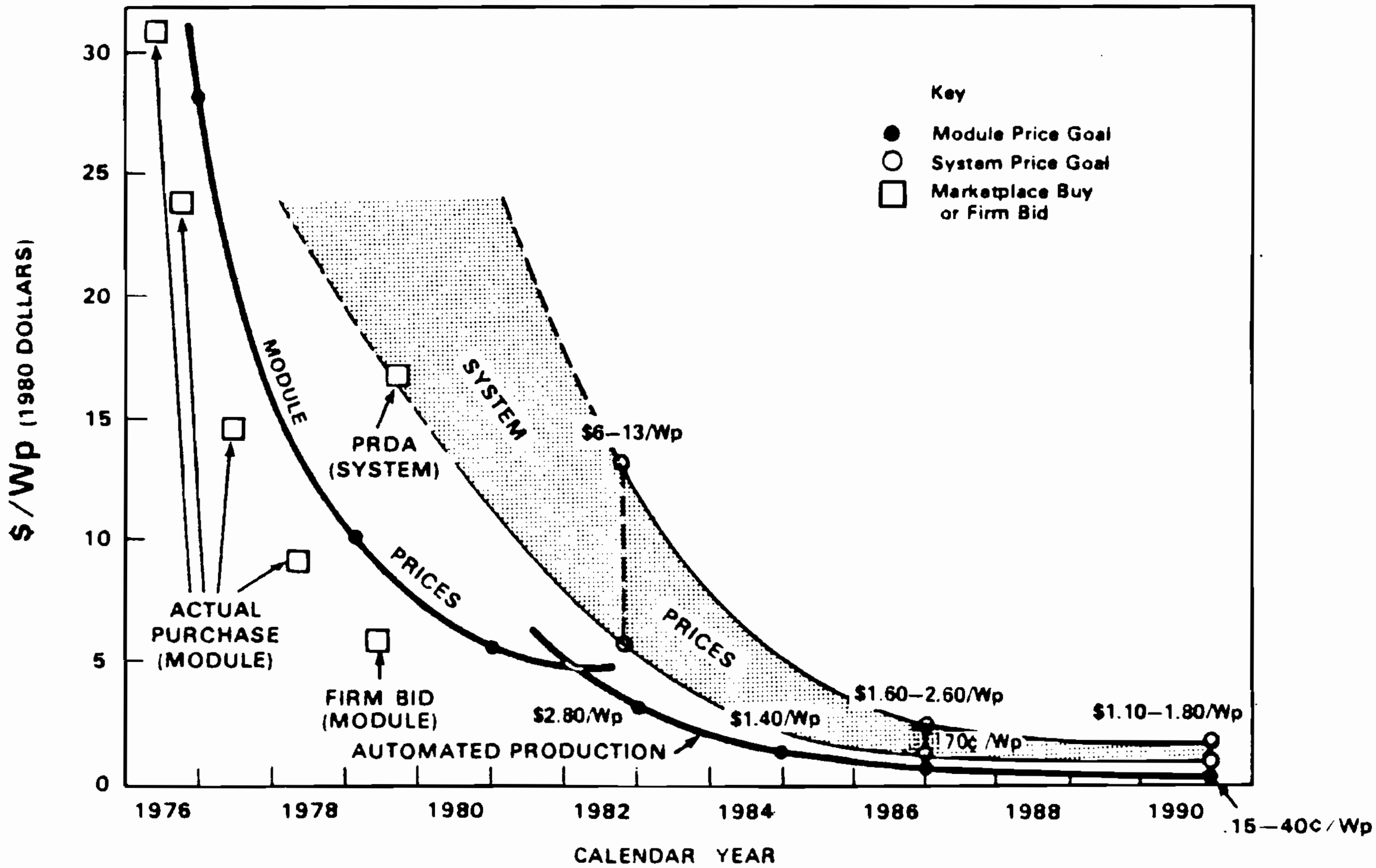
However the 77°K barrier, which has now been exceeded, was the truly signficant one. Below that temperature only liquid helium is a feasible coolant (except in space), whereas above that point liquid nitrogen (77°K) can be used. Liquid nitrogen is available in industrial quantities as a by-product ofthe production of liquid oxygen used by the steel industry and for rocket propulsion. It costs only 10% as much as liquid helium and is far less volatile. Thus, it is now realistic to think in terms of large-scale applications of superconductivity, e.g. power generation and transmission and magnetic levitation of high speed trains.

Photovoltaic materials are another category of potential importance as solar cells. Major candidates include silicon crystalline or amorphous), gallium arsenide, copper indium diselenide, and cadmium telluride. Silicon is by far the most widely used, at present, with achievable solar conversion efficiency of 18% for the crystalline form. Amorphous silicon has achievable conversion efficiency of at least 11%, but it can be manufactured at much lower cost. Laboratory cells have already achieved 21% conversion efficiency, however, and 30% is now regarded as likely by the end of this decade. Some experts think that ultimately an 80% conversion rate is conceivable. Apart from progress in the fundamental science, there has been very rapid progress on the technological side. A number of new techniques for coating thin films of semiconductive materials onto a glass (or other) substrate have been developed, e.g. by Mobil-Tyco, Westinghouse and Honeywell. Spectacular progress has also been made in reducing film thinkness by a factor of 100, as compared with early cells (Zweibel, 1987).

NASA, DOD, and Bell Laboratories supported much of the early R & D work in this field to obtain long-lived solar cells for application in satellites. The first solar cells, used mainly by NASA, cost $ 1000 per watt. An array of solar cells in 1975 cost about $75 per watt of peak capacity, as compared to $.5 per watt for a large nuclear power plant in 1975 $. The "energy crisis" of 1973-74 precipitated the creation of the Department of Energy (DOE) in the 1970's, and resulted in an accelerated program of R & D in this area, focussed mainly on bringing down the cost of manufacturing. The DOE program was cut back sharply by the Reagan administration (from $150 million in F.Y. 1980 to $43 million in F.Y. 1987), but not before major progress had been made, as shown in Figure 6 [Maycock, 1982]. As of 1982, it was confidently expected that costs would reach levels low enough to justify earth-based photovoltaic power generation by the late

FIGURE 6

PHOTOVOLTAIC MODULE AND SYSTEM PRICE GOALS



Source: Maycock, 1982

1980's or 1990. A 300 kW system installed by the City of Austin, Texas (1986) cost $9 per peak watt, roughly twice the level of coal, oil or nuclear electricity (New York Times, February 13, 1987). As of 1987, it is estimated that a photovoltaic array system will cost between $2.50 and $3.00 per watt peak capacity to install by 1990 (Kiss 1987). The "industry" (mostly US and Japanese) is already significant and growing rapidly, with sales in the range of $100 million. Major U.S. producers include ARCO, Chronar and Solarex. Chronar has production facilities for producing about 1,000,000 square feet of thin-film coated glass per year.

Thus, it seems a very good bet that even without significant federal government support silicon-based photovoltaic systems will become a commercially significant in the 1990's, reaching the billion dollar level by 1992-95 and growing even more rapidly thereafter. The first important commercial customers might be small tropical or semi-tropical Islands such as Bermuda, the Bahamas and the Antilles, many of which are now forced to generate electricity by diesel engines using expensive imported oil fuel. Many individual hotels, ranches, mines and processing plants located in remote arid places, especially in the tropics, will also be early customers. Gradually, as the scale is increased, photovoltaic facilities can begin to produce electric power even in direct competition with nuclear and coal-based generation.

Another important category of materials that is worth discussing briefly is ferromagnetic materials (White, 1985). In a way, this is surprising, since the phenomenon of ferromagnetism has been known for such a long time. However, as in the case of "strong materials", the relationship between magnetic fields on the micro (interatomic) scale and the macro-scale was not adequately understood until the 1940's when Néel, Kittel and others developed the basic physical concepts that have dominated subsequent R & D in magnetism. The progress in basic physics of ferromagnetism was rapidly translated into increased practical interest, especially because of the growing importance of magnetic materials.

Ferrites, a new class of magnetic oxide materials -- mainly Fe_2O_3 -- were first used for data recording in the 1930's[7]. Ferrites also rapidly found in application in transformers, radar, communication equipments and (in the late 1950's) in computer memories. Discrete ferrite "cores" have now been superceded by high-speed semiconductors; but ferrite-based magnetic tapes and disks remain the major form of read-in/ read-out medium to long term data storage system. (It is not yet clear to what extent optical storage devices will ultimately replace magnetic devices, however). The world market for magnetic particles is now $235 million, and for finished media (tapes and disks), it is $8 billion (Ibid).

New non-iron-based ferromagnetic alloys for permanent magnets also began to be discovered in the 1930's, beginning with the Al-Ni-Co family. This was mainly research by trial and error. In the 1950's Philips Laboratories produced permanently magnetized ferrites based on iron oxides combined with strontium or barium, aligned in powder form, then compacted and sintered.

---

[7]Data recording requires "soft" magnetic materials, i.e. materials that can easily be magnetized and demagnetized at high frequency without large "eddy current" losses. The latter requirement cannot be met by metals, but oxides fill the bill because of the very high electrical resistivity.

The rare-earth-cobalt ($SmCo_5$) based permanent magnets (REPM's) were discovered in 1967 and first commercialized by 1970. A second generation series based on $Sm_2 Co_{17}$ was introduced around 1981, and an important boron-based compound $Fe_{14} Nd_2 B$ appeared in 1983 (Ibid).

For permanent magnets there are two important parameters, viz. energy product (the amount of stored magnetic energy*) and coercivity, the resistance to reversal or demagnetization by an external field H_c. Progress since 1900 in these two areas is shown in Figures 7 and 8, respectively. It is interesting to note that the theoretical maximum value of energy product for iron would be 107 MGO_e, (if all the micro-domains could be completely aligned), and for other alloys it may well be much higher (Ibid). Thus, there is still room for progress.

Applications of permanent magnets are widespread in many types of devices, but perhaps the most important single application is in electric motors. The world market for permanent magnetic materials is currently around $1 billion (Ibid). Recent improvements in magnet performance can be expected to be reflected in improved electric motor performance. In fact, a whole new class of compact motor designs now appears practical (White, Ibid). This, in turn, will result in at least some significant new applications. For instance, compact high-power electric motors can replace hydraulic motors in robots, resulting in a substantial increase in speed of operation (Kanade 83).

One final example worth mentioning is a class of organic liquids whose viscosity is strongly dependent on the imposed

---

*Magnetic energy is measured in megagaun-Oersteds or MGOe

Fig. 7

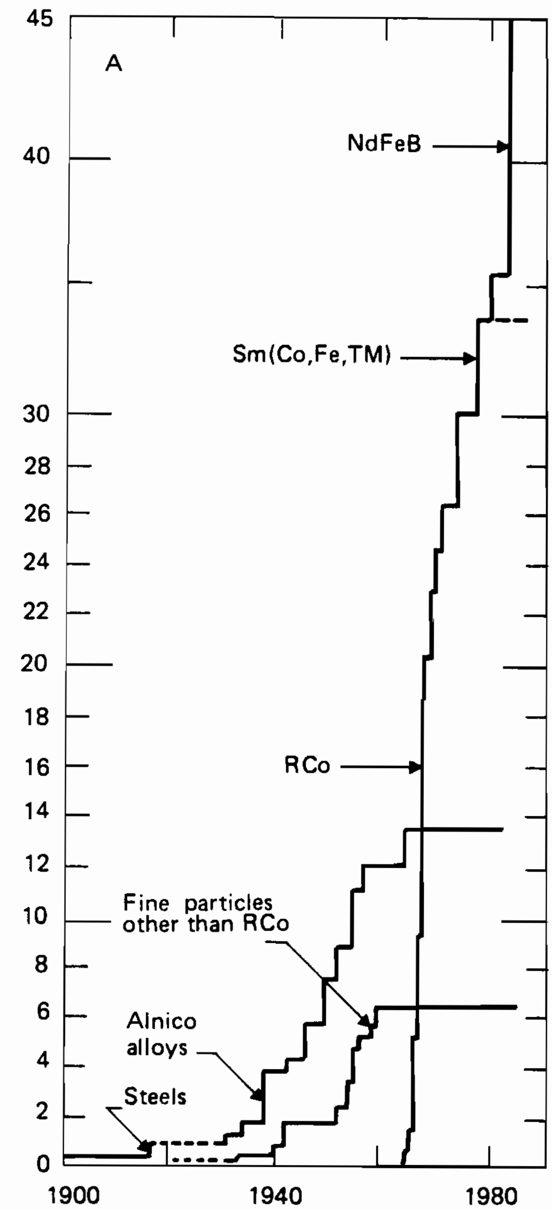
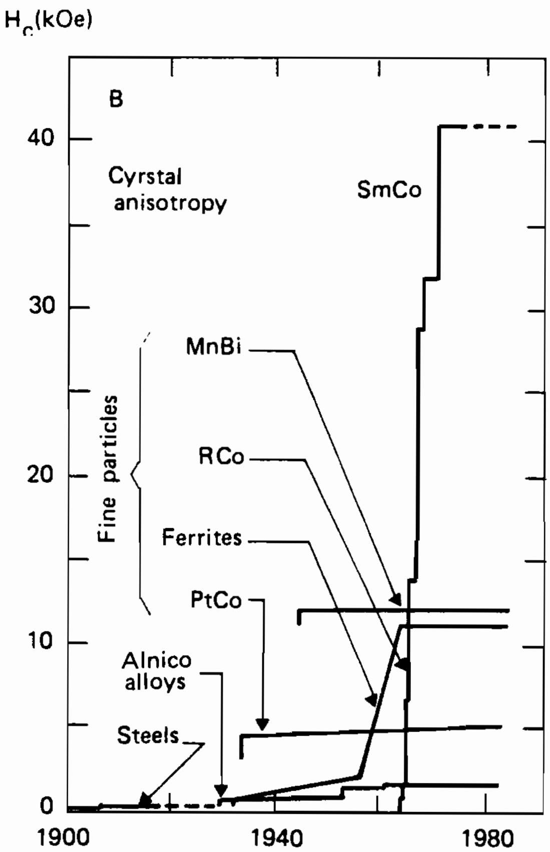


Fig. 8



Figs. 7 & 8: Changes in energy product (A) and coercivity (B) of various permanent magnet materials, 1900 to 1980.

electric field. When a transverse field (voltage) is imposed, such a liquid becomes extremely viscous -- almost glassy; yet when the field is removed it flows freely. This class of materials may become the basis of electrically-controlled clutches, brakes, or robotic grippers, thus eliminating much of the mechanical complexity that now plagues such devices. However, much research remains to be done, primarily in the optimization of the molecular synthesis and the scale-up of manufacturing technology.

Conclusion

Materials are the underpinnings of technology -- not only figuratively but literally. Some of the most important of all "breakthroughs" were associated with materials. The ability to make hard, impervious ceramic pots for the storage of liquids and seeds was one of the first requisites of urban civilization, around 8000 BC. The "bronze" age and the "iron age" were major technological milestones. The discoveries of paper and glass were only a little less significant. Iron tools and weapons are an enormous improvement over bronze tools, but require much more advanced methods of smelting and working. Steel is as much an improvement over older forms of iron as iron was over bronze. The historian Elting Morrison called it "almost the greatest invention", with some justice.

However, in some sense the "age of materials", is now past and the "age of information" is upon us. To be sure, most traditional uses of basic materials will continue for many decades, with gradual but cumulative reductions in the sheer mass of materials required for most purposes. Material of all kinds are becoming more sophisticated and "information intensive", in the sense that they offer more service to the end-user.

But greatly overshadowing this rather glacial trend is the enormously rapid increase in the uses of materials specifically for purposes of energy conversion (e.g. magnets, photovoltaics) and processing or storing information. The semi-conductors and ferrites constitute the two obvious examples of the latter, but it can be argued that the dominant trend of the future is toward the development of materials that are "information intensive" in this narrower sense. A rough tabulation of the materials of greatest research interest today is given in Table 6 below.

Table 6

Breakthroughs Expected in Materials

Technological need		Breaktrough technology	Materials
Communications	Large-volume transmission	Milliwaves, laser beams	Compound semi-conductors (InP, GaAlAs, etc.)
	Long-distance transmission	Low-loss optical fiber	Non-silicic material
Information processing	High-speed operations	Compound Semiconductors ICs	Compound semi-conductors (GaAs, InP, etc.)
		Josephson-junction device	Superconductive materials (alloys, compounds)
	High-density recording	Perpendicular magnetic recording	Perpendicular magnetized film
		Magneto-optic recording	Magneto-optic recording materials
		Molecular memory	High polymers, biological sub-stances (protein)
Instrumentation and control	Improvement in sensing performance	Josephson-junction device	Superconductive materials (alloys compounds, etc.)
		Biosensor	Biological sub-stances (micro-organisms, enzymes, etc.)
	Improved re-sistance to environmental conditions	Devices more resistant to environmental conditions	Compound Semi-conductors (GaAs, InP, etc.)

Table 6 (continued)

Technological need		Breaktrough technology	Materials
Energy Conversion	Solar energy, especially in remote areas	Photovoltaics	Silicon (crystalline or amorphous) Ga-As, Cd-Te, Cu-In-Se
	More efficient generators, transmission lines	Super-conductivity	Cu-Ba-La-O Other methane oxygen compounds
Transportation	Magnetic levitation	Ferromagnets	Sm-Co Nd-Fe-B
		Super-conductors	Cu-Ba-La-O Other metallic oxygen compounds

REFERENCES

[Claasen&Girifalco 86] Claasen, R.S. & Girifalco, L.A.. Materials for Energy Utilization, *Scientific American* 255(4), 1986. :85-92.

[Clark&Flemings 86] Clark, J.P. & Flemings, M.C.. Advanced Materials and the Economy, *Scientific American* 255(4), 1986. :43-49.

[Compton&Gjostein 86] Compton, W.D. & Gjostein, N.A.. Materials for Ground Transportation, *Scientific American* 225(4), 1986. :75-82.

[Gordon 68] Gordon, James E.. *The New Science Of Strong Materials*, Penguin Books Ltd., Harmondsworth, Mddx, U.K., 1968.

[Gordon&Munson 82] Gordon, T.J. & Munson, T.R.. Research into Technology Output Measures, *The Futures Group*, 1982.

[Kiss 87] Kiss, Zoltan. New York Times, February 13 1987. [NOTE: Interview]

[Larsonetal 86] Larson, Eric D., Marc, H. & Williams, Robert H.. Beyond the Era of Materials, *Scientific American 254*(6), June 1986. :24-31.

[Lynch 75] Lynch, Charles T.. *Handbook Of Materials Science*, CRC Press, Cleveland, Ohio, 1975.

[Maycock 82] Maycock, P.D.. *Overview-Cost Goals In The Lsa Project*, 1982. [NOTE: Unpublished]

[NIRA 85] NIRA. *Comprehensive Study Of Microelectronics 1985*, , National Institute for Research Advancement, Tokyo, Japan, 1985.

[NRC 75] NRC. *Structural Ceramics*, , National Materials Advisory Board, National Research Council, Washington, D.C., 1975.

[NRC 86] NRC. *Advanced Processing Of Electronic Materials In The United States And Japan*, , National Materials Advisory Board, National Research Council, Washington, D.C., 1986.

[Robinson 86] Robinson, Arthur L.. A Chemical Route to Advanced Ceramics, *Science* 233(4579), 4 July 1986. :25-27.

[Steinberg 86] Steinberg, M.A.. Materials for Aerospace, *Scientific American* **255**(4), 1986. :59-64.

[Sullivan 87] Sullivan, Walter. New York Times, February 17 1987.

[White 85] White, R.M.. Opportunities in Magnetic Materials, *Sience* **229**(4708), 5 July 1985. :11-16.

[Zweibel 87] Zweibel, Kenneth. New York Times, February 13 1987. [NOTE: Interview]

APPENDIX

INSTRUMENT TRANSDUCERS

Table A. Classification of Transducers

Name or class	*Nature and principle*	*Basic measurement*
	EXTERNALLY POWERED TRANSDUCERS (PASSIVE)	
VARIABLE RESISTANCE		
1. Variable resistor	Slider or contact varies resistance in potentiometer or bridge circuit	Displacement, linear or angular
2. Resistance thermometer	Wire or thermistor, with large temperature-coefficient of resistivity	Temperature
3. Resistance strain gage	Resistance of a wire grid; foil or semiconductor changed by stress	Displacement, strain
4. Hot-wire meter	Heated wire or film (constant temperature or constant current) in fluid stream	Temperature (fluid velocity inferred)
5. Radiation bolometer	Radiation focused on resistance-thermometer sensor	Temperature (total radiation inferred)
6. Thermistor radiometer	Radiation focused on thermistor bolometer	Temperature (total radiation inferred)
7. Thickness gage	Resistance between contacts depends on thickness and resistivity of separating material	Dimension
8. Photoconductive cell	Radiation on photoresistive element	Radiation
9. Photoemissive or photomultiplier tube	Radiation causes electron emission and current (amplification available)	Radiation (illumination)
10. Ionization gage	Glow-discharge tube in high-frequency field; asymmetry generates voltage	Displacement
11. Resistance hygrometer	Resistivity of conductive strip changed by moisture	Partial pressure (humidity)
VARIABLE CAPACITANCE		
12. Adjustable capacitor	Capacitance varied by changing distance between plates or area of plates	Displacement
13. Capacitance bridge pickup	Modification of No. 12 using a-c bridge; high sensitivity	Displacement
14. Dielectric gage	Capacitance varied by changing position or thickness of dielectric	Displacement, dimension
15. Dielectric thermometer	Variation of capacitance with temperature of dielectric	Temperature
16. Condenser microphone	Capacitance between diaphragm and fixed electrode varied by sound pressure	Displacement
VARIABLE INDUCTANCE		
17. Air-gap gage	Self-inductance or mutal inductance changed by varying the magnetic path	Displacement, thickness
18. Differential transformer	Transformer with differential secondaries and movable magnetic core	Displacement
19. Reluctance pickup	Reluctance of magnetic circuit varied by positioning or core material	Displacement
20. Eddy-current gage	Inductance of a-c coil varied by position of eddy-current plate	Displacement
21. Magnetostriction gage	Magnetic properties varied by pressure and stress	Force
22. Hall-effect transducer	Magnetic field interacts with current through semiconductor to produce voltage at right angle	Field strength
23. Inductance bridge pick up	Modification of No. 17 using inductance bridge	Displacement
	SELF-GENERATING TRANSDUCERS	
24. Moving magnet-and-coil generator	Relative movement of coil and magnet varies output voltage	Displacement velocity, linear or angular
25. Thermocouple and thermopile	Pairs of dissimilar metals or semiconductors generate voltage if terminals not at same temperature	Temperature
26. Piezoelectric pickup	Quartz or other crystal mounted in compression, bending, or twisting	Force
27. Photovoltaic cell	Layer-built semiconductor cell or transistor generates voltage from radiation	Radiation, light
28. Radiation counter (special class)	Gas counters collect charge released by ionizing radiation	Radiation, radioactive or nuclear

Table B. Examples of Transducer Applications

Table B lists some typical applications of instrument transducers and common types of transducers used for each measurement. Since the properties of materials play a large part in all measurement techniques, tables that give such properties will suggest other applications of transducers. Another major field of transducer use not listed here is in energy measurements.

Quantity to be measured	*Transducers* — *Common examples*	*Transducers* — *See Table A numbers*
Acceleration, angular	Unbonded strain gage; force balance	3, 12, 19, 26
Acceleration, linear	Seismic potentiometer; piezoelectric accelerometer	3, 12, 19, 26
Altitude	Capsule or bellows altimeter	1, 18
Angle	Variable reluctance pickup	18, 19
Blast pressure	Piezoelectric pickup	3, 12, 26
Count, events	Stroboscope; electronic-pulse counter	8, 27
Count, particles	Photoconductive cell; photovoltaic element	
Current, stream	Rotating-current meter; impact-tube meter	24
Density, gas	Hot-wire meter	4
Dewpoint	Photovoltaic cell	11, 27
Dielectric constant	Dielectric gage	14
Dimension, linear	Differential transformer; slide-wire resistor	1, 3, 7
Dimension, micrometer	Capacitance gage; unbonded strain gage	3, 12, 13, 14
Displacement, angular	Slide-wire potentiometer; inductance gage; eddy-current gage; electrolytic	1, 3, 17, 19, 20
Displacement, linear	Differential transformer; slide-wire resistor; reluctance pickup	1, 3, 12, 17, 18, 19, 20
Distance	Slide-wire resistor	1, 3, 12, 17, 20
Duration, time	Tuning fork	
Emissivity	Thermopile radiometer	5, 6, 25
Field strength, magnetic	Hall-effect pickup	22

Quantity to be measured	*Transducers* — *Common examples*	*Transducers* — *See Table A numbers*
Film thickness	Dielectric gage	7, 12, 14, 17
Flow, gas or vapor	Differential head meter (orifice, nozzle, pitot); hot-wire or thermocouple anemometer	3, 4, 18, 19, 25
Flow, liquid	Differential head meter (orifice, venturi); turbine flowmeter	1, 3, 18
Flow, open-channel	Rotating-current meter	24
Force	Reluctance pickup; carbon pile; strain gage; magnetostrictive gage	3, 12, 17, 18, 19, 21, 23, 26
Frequency	Moving-coil generator; stroboscope	17, 19, 24
Gamma rays	Geiger counter	28
Hardness	Indenter (displacement)	3, 12, 17, 18
Head		(See pressure)
Heat flow	Thermopile sandwich	25
Humidity, air	Resistance hygrometer; thermocouple physchrometer	2, 11, 27
Infrared	Thermistor bolometer; thermopile photoconductive cell	5, 6, 8, 25
Ionization		10
Jerk		3, 12, 26
Level, liquid	Dielectric gage; capacitance gage	12, 14
Light intensity	Photovoltaic cell	5, 8, 25, 27
Load, force or weight	Bonded strain gage (strut); inductor (elastic element); proving ring (displacement)	1, 3, 12, 13, 17, 18, 19, 21, 26

Table B. Examples of Transducer Applications (continued)

Quantity to be measured	*Transducers* — *Common examples*	*See Table A numbers*
Moisture, in solids	Resistance gage; dielectric gage; nuclear magnetic resonance	1, 14
Noise	Condenser microphone; piezoelectric crystal	16, 26
Nuclear radiation	Geiger counter	28
Particle counting	Ionization gage	10, 28
Position, angular	Resistance gage; differential transformer	1, 12, 18, 19
Pressure, absolute		
Position, linear	Contact potentiometer	1, 12, 18, 19
	Bourdon-tube potentiometer	1, 3, 18, 19
Pressure, differential	Bellows gage	1, 12, 18, 19
Pressure, dynamic	Piezoelectric pickup; strain gage	3, 12, 16, 19, 26
Pressure, gage	Reluctance gage; strain-gage pickup; capacitor (elastic element)	1, 3, 12, 18
Pressure, impact	Pitot and bellows with differential transformer	12, 18, 19
Radiation, light (optical)	Optical-target thermopile; photo-resistive gage	8, 9, 27
Radiation, nuclear	Geiger counter	10, 28
Radiation, total	Photomultiplier tube; bolometer	5, 6, 8, 25
Reflectivity	Radiometer	5, 6, 25
Rotational speed	Reluctance pickup	19, 24
Rugosity	Moving-coil tracer	19, 24
Shock	Ceramic crystal	

Quantity to be measured	*Transducers* — *Common examples*	*See Table A numbers*
Sound pressure	Piezoelectric; condenser microphone	16, 26
Speed, rotational	Moving-coil tachometer; pulse counter; stroboscopic counter	19, 24
Strain	Wire or foil strain gage	3
Temperature	Thermocouple; wire resistance; thermistor	2, 5, 6, 8, 15, 25
Thickness, metal	Eddy-current gage, capacitance pick-up; contact gage (resistance); ultra-sonic probe, isotope gage	1, 3, 12, 13, 14, 17
Time	Synchronous motor; tuning fork	
Torque	Strain gage	3, 12, 18, 26
Turbulence, fluid	Hot-wire pickup	4
Vacuum, high	Ionization gage	10
Vacuum, low	Corrugated diaphragm	
Velocity, linear	Moving-coil generator	
Vibration acceleration	Piezoelectric crystal; strain gage (force)	3, 12, 18, 26
Vibration displacement	Reluctance gage; seismic vibrometer	18, 19
Vibration frequency	Calibrated oscilloscope; stroboscopic counter	
Vibration velocity	Magnet and coil	24
Viscosity	Drag-cup torque meter; falling-ball displacement gage	3, 18
Voltage	Moving-coil meter or galvanometer	19, 20, 24
Weight	Strain gage; force balance	3, 12, 17, 18, 26

REFERENCE

Minnar, E. J., Ed., *ISA Transducer Compendium*, Plenum Press, New York, 1963.

From Bolz, R. E. and Tuve, G. L., Eds., *Handbook of Tables for Applied Engineering Science*, 2nd ed., CRC Press, Cleveland, 1973, 975.