Looking Beyond the Last 50 Years: The Future of Materials Science and Engineering

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Author's Note: *On this special occasion of TMS's 50th Anniversary, I have been given the onerous task of commenting on the future of materials as we head into the 21st century. Predicting future innovations and discoveries in the materials world is virtually impossible; however, one can observe trends and societal needs, which will motivate engineers and scientists to respond, innovate, give birth to products, and enhance the quality of life on this planet.*

RETROSPECTIVE VIEW

As Pearl S. Buck said so eloquently: "One faces the future with one's past;" it will be interesting to go back and view the future in view of the past.[1] What was the world like in 1957 when TMS was formed (as a member society of The American Institute of Mining, Metallurgical, and Petroleum Engineers) to enable materials scientists and engineers to advance their profession on an international scale? The figures for 1957 and 2003 presented in Table I clearly show growth both in world population and U.S. federal spending and debt.[2,3] In a little less than 50 years, the world population has more than doubled, and the U.S. gross domestic product (GDP) increased by 24-fold.

As one looks back and reflects on the last 50 years, what is most astounding is the number of discoveries and events that occurred which have significantly altered our lives:[4] Sputnik's launch into outer space (1957); lasers (1958); silicon single crystals grown for semiconductors (1960); man landing on the moon (1969); soft contact lenses (1972); computed tomography scan (1972) and magnetic resonance imaging (1981) diagnostics; personal computers introduced (1981) and World Wide Web available to the masses (1991); not to mention the end of the Cold War in 1989 (see the sidebar for a detailed list of major discoveries since 1957). Could we have predicted these discoveries and events back in 1957? I do not think so. However, some things that have been constant over time are human innovation and creativity, the engineer's ability to address societal needs, and the entrepreneurial spirit of engineering. I believe that going forward, one thing we can bet on is the human ability to innovate and address societal needs.

During the last seven decades, the mainstream materials science and engineering (MSE) community has worked in principally two R&D areas: the industrial sector and defense-related industries. After World War II, there was a major drive by corporations to invest in basic science and engineering. Corporations employed many scientists and engineers in their research centers and laboratories (e.g., Dupont, IBM, General Motors, Ford, U.S. Steel Corporation, General Electric, Bethlehem Steel, Alcoa, etc.); it was a time of many discoveries and advances in the field of materials. Just to cite one example, some of the most important discoveries made on steels occurred at U.S. Steel Corporation's Edgar C. Bain Laboratory for Fundamental Research in Monroeville, Pennsylvania; this facility alone employed several hundred scientists and engineers dedicated to advancing the knowledge base. Unfortunately, in the recent past (since 1990) we have seen these industrial centers and labs shrink if not disappear; for those remaining, the focus has shifted toward more "D" than "R."

Since 2000, thanks to the use of the Internet, knowledge has become "communalized;" we have witnessed and experienced "Flattening of the World"[6] as well as read the book! The connectivity provided by the Internet has generated new markets for products and services and has made available labor that is often both educated and inexpensive. This has had a profound impact on the distribution of wealth in both developed and developing parts of the world.[7] Globalization is driven by market economies, and corporations are offshoring for services in both information technology and R&D,

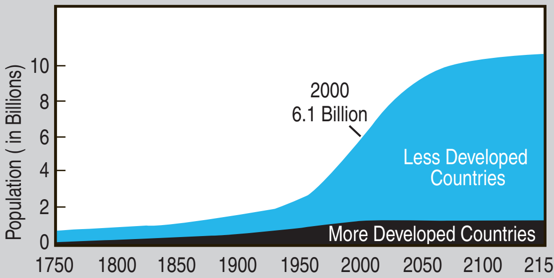


Figure 1. World population growth, 1750–2150.[14]

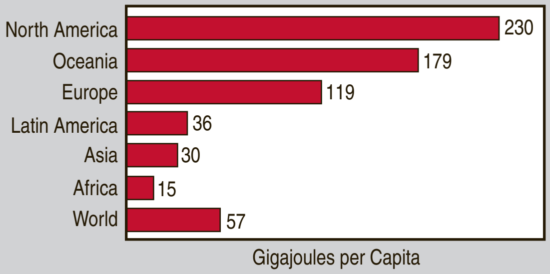


Figure 2. Energy consumption per capita, world regions, 1999 (2002).[15]

and this trend will increase. As pointed out by T.J. Sturgeon,[8] the end of the cold war and abandonment of autarkic "import substituting" development policies in countries like Russia, India, and China have increased the size of the global workforce from 1.5 billion to 2.9 billion—the "great doubling" of the global workforce. The heydays of corporate research centers based in the western hemisphere are behind us, and in the future we will see a continual redistribution of wealth. To quote G. Tryggvason et al.,[7] "skill is rapidly becoming a commodity that can be brought from low-cost providers anywhere. It does not matter what you know how to do, someone else knows it too and is willing to do it for less."

As to the defense-related industries, much growth occurred in this sector after World War II. With the advent of the Korean and Vietnam wars, NASA, Star Wars, and most recently with homeland security, the military industrial complex has grown and important discoveries have been made. It is interesting to note that in January 1961, as President Dwight David Eisenhower was leaving office, he cautioned the nation about the growth of the military industrial complex:[9]

> "We annually spend on military security more than the net income of all United States corporations. . . . In the councils of government, we must guard against the acquisition of unwarranted influence, whether sought or unsought, by the military industrial complex. The potential for the disastrous rise of misplaced power exists and will persist."

With impending and burgeoning societal issues affecting the human condition on our planet, the MSE community has a responsibility and an opportunity to truly make a difference by addressing the needs of the world of tomorrow—needs in energy, transportation, housing, food, recycling, and health.

PROSPECTIVE VIEW

As reviewed previously, many societal advancements over the last 50 years are due to MSE advancements. We have witnessed the re-shaping of our lives through revolutions that have taken place in medicine, telecommunications, and transportation industries. Yet a close examination of the MSE research agenda in the United States over the last 4–5 decades indicates that many of the resources for MSE R&D have been defense-centric rather than focused on societal needs. The driving force for R&D in the United States has been primarily provided by the Department of Defense (Army, Navy, Air Force, Defense Advanced Research Projects Agency [DARPA], etc.). Defense is a critical societal need; however, it is not the only need and a balance is needed to ensure that basic human needs are being addressed.

Table I. World Population and U.S. Statistics Comparing 1957 with 2003

	1957 (billion)	2003 (billion)	X-fold Increase
World Population	2.88	6.31	2.19
U.S. Population	0.172	0.290	1.68
U.S. Federal Spending	76.58	2,158	28.18
U.S. Federal Debt	272.3	6,783	24.91
U.S. GDP*	461	10,961	23.77

*GDP = gross domestic product

MAJOR DISCOVERIES SINCE 1957[4]

Fortran language commercially available (John Backus at IBM–1957)
The former Soviet Union launches Sputnik on the plains of Kazakhstan (1957)
First artificial hip replacement by John Charnley (1958)
Charles Townes and Arthur Schawlow introduce the concept of a laser (1958)
Float glass developed by Alastair Pilkington (1959)
Amorphous metal processed by Paul Duwez (1959)
Large single crystals of silicon grown for semiconductors (1960)
Leonard Kleinrock discovers queuing networks and packet-switching technology, enabling the Advanced Research Projects Agency Network, transmission control protocol/Internet protocol, and the Internet (1962)
Acrylic paints commercially available (1964)
Carbon fiber developed by Leslie Phillips (1964)
W.L. Gore develops Gore-Tex by stretching polytetrafluoroethylene (1969)
Apollo 11 lunar landing by Neil Armstrong (July 20, 1969)
Soft contact lenses introduced to market (1971)
Computed tomography scan introduced for medical diagnostics (1972)
Altair 8800, the world's first minicomputer kit, available for $397 (1975). (Programming was done by adjusting toggle switches, had 256 bytes of memory, and output was in the form of patterns of flashing lights.[5])
Electrically conducting organic polymers are discovered (1977)
Rare earth metals refined (1980s)
Magnetic resonance imaging introduced for medical diagnostics (1981)
IBM introduces the personal computer (1981)
Apple introduces Macintosh (1984)
Shift of data storage and retrieval from magnetic to optical; CD-ROM introduced (1984)
Synthetic skin developed (1986)
Cold War ends, Berlin Wall comes down (1989)
Nanotechnology (1990s)
World Wide Web available to general public (1991)

Today, the United States spends close to $450 billion per year on defense[10] (not including additional appropriations of more than $100 billion for war efforts); the rest of the world spends approximately an additional $450 billion per year. Thus, we the inhabitants of this world spend a little less than $2.5 billion per day to "defend" ourselves (from each other), and we do so in the following context:

- The World Bank estimates that close to 20% of the world population is living in absolute poverty (about 1.2 billion people out of 6.5 billion today); absolute poverty is defined as having less than $1 a day to live on.[11]
- Eighteen percent of the world's population lacks access to safe drinking water and nearly 40% has no access to sanitation. Moreover, it is projected that by 2030 about half of the world's population will live in water-stressed areas.[12]
- We entered the 20th century with 1.6 billion people and exited it with 6.1 billion, almost a four-fold growth in 100 years. The world

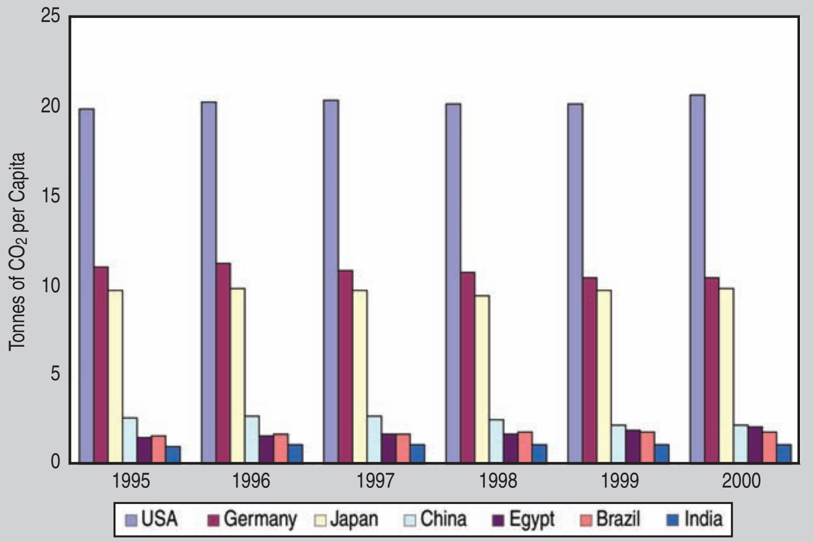


Figure 3. The CO_2 emissions for different countries over the period 1995–2000.[19]

- population is projected to be 9.3 billion by 2050, but more critically, there is a large disparity between the developed and the less developed countries.[13] Population is growing at much higher rates in the less developed countries in comparison to the average population growth rate of the world, which is 1.4%. United Arab Emirate's growth rate is 7.7%, Afghanistan's is 4.92%, Saudi Arabia's is 3.5%, and Africa's, 2.4%.[14] Specifically, of the 80 million people currently added to the world each year, 95% live in the less developed regions (see Figure 1).
- Projections are that global energy use will grow by 1.7% annually until 2025, which is a faster rate than the world population growth rate. Moreover, average energy use per person is still more than nine times greater in developed regions than in less developed regions. However, this will shift significantly with the ever-growing consumption needs of China and India. North Americans consume far more energy than any other region of the globe. In 1999, per-capita energy use among North Americans was nearly twice that of Europeans, nearly eight times that of Asians, and 15 times that of Africans[15] (see Figure 2).

Materials and society are interlinked, and it is only rational that we should see a close relation between the MSE research agenda and societal issues that affect the human condition on this globe. This, however, is not the case. There are disconnects between where we channel our resources (where we spend our money) and what we deem to be critical and important issues. I am not advocating that we adopt Gross National Happiness (GNH) as a new economic index rather than gross national product (GNP), as they do in Bhutan,[16] though it is a novel and meritorious idea. Rather, I am pointing out that there are burgeoning needs that society faces with respect to energy resources, transportation, housing, food distribution/packaging for the masses, recycling, and health care/health care delivery. These serious societal needs are an opportunity for the MSE community to influence public policy and to make a difference by how we direct our efforts for shaping the world of tomorrow.

ENERGY RESOURCES AND ENERGY STORAGE MATERIALS

Thomas Malthus observed back in the 1700s that population was growing faster than agricultural production in England. Population was growing geometrically and the food supply was increasing arithmetically. We have come a long way in agricultural innovations to feed more people than we could have ever imagined. However, with the burgeoning earth population (see Figure 1), the real question is not how many people the earth can support but how many people the earth can support with what quality of life?[17] Sustainable development is the key.

Sustainable development is the level of human activity that can meet the needs of the present without compromising the ability of future generations to meet their own needs. To quote David Bower, "We do not inherit the earth from our fathers. We borrow it from our children."[18] Present world CO_2 emissions are quite alarming (see Figure 3).[19] The picture with ozone-depleting chlorofluorocarbon (CFC) consumption is also quite serious (see Figure 4).[20] The United States and European Union have addressed the ozone depletion issue with government policies and strict enforcement; China and Brazil have yet to rise to the occa-

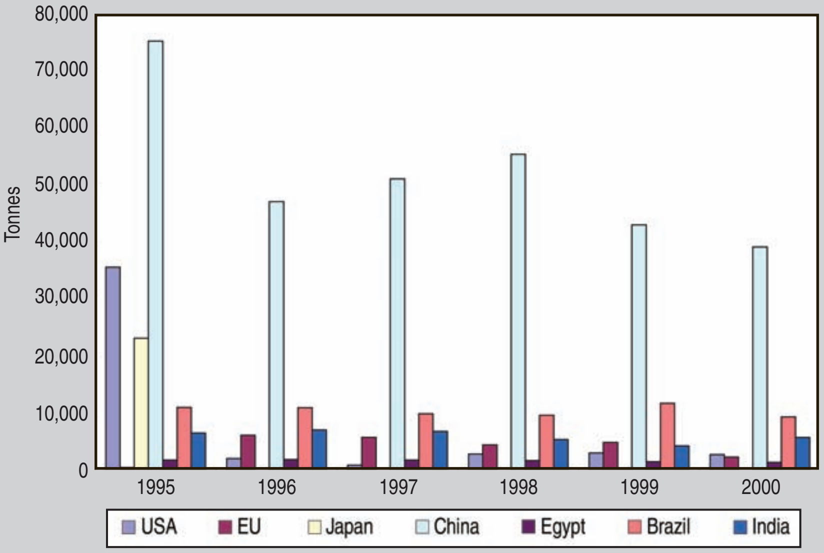


Figure 4. Consumption of CFCs for different countries over the period 1995–2000.[20]

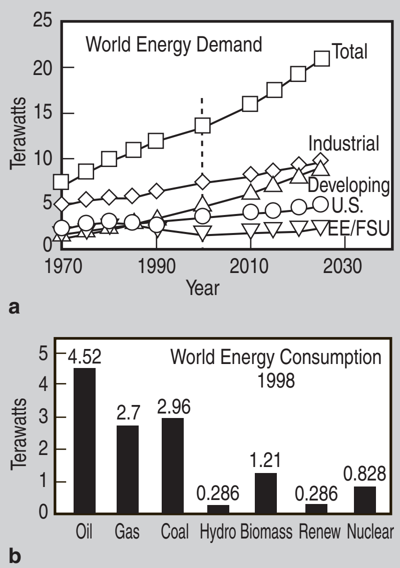


Figure 5. (a) World energy usage over time (1970–2030), and (b) 1998 world consumption showing the sources of fuel used.[22]

sion. On October 30, 2006, Nicholas Stern, speaking at the London School of Economics, reviewed the U.K.-commissioned report on how to prevent dangerous climate change. Stern's review estimates "that if we don't act, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year, now and forever; if a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more."[21] In contrast, the cost of reducing greenhouse gas emissions to avoid the worst impacts of climate change is estimated to be around 1% of the global GDP each year. The Stern report leads to a simple conclusion: the benefits of strong and early action far outweigh the economic costs of not acting.[21]

The outlook is optimistic, especially when we see initiatives to reduce greenhouse gas emissions in the United States as well as certain European nations (e.g., Finland). In the United States, a tenth of venture capital is invested in clean energy. *The Economist* estimates that the total investment going into clean energy in 2006 is $63 billion (versus $49 billion in 2005, and $30 billion in 2004).[22] Nanosolar Inc., based in California, hopes to significantly cut the cost of producing solar panels. Nanosolar uses new non-silicon semiconductor materials with the absorber being two orders of magnitude thinner than that of silicon wafer cells.[23] Tekes, the National Technology Agency of Finland, has announced targets for increases in total consumption of renewable energy of 40% by the year 2025.[24]

The global demand for energy is growing at alarming rates, and the demand from developing countries will further exacerbate the situation (Figure 5). The current energy utilization worldwide is about 14 terawatts, and by the end of the 21st century, it may reach 50 terawatts.[25] There has to be a shift to renewable energy sources from fossil fuels, which today supply about 80% of the world's energy. Earth-based renewable sources of energy (i.e., hydroelectricity, wind, geothermal, biomass, etc.) will not be sufficient to meet the energy consumption needs of the world. Solar power will certainly be an important resource. We will see future material developments in nanostructured materials, advanced photovoltaic materials such as nanocrystalline silicon thin films and novel chalcogenides, advanced catalysts with more accessible surface area, nanostructured catalyst supports, and membranes. Light-emitting diodes with enhanced quantum efficiency for lighting devices will also play an important role.

The hydrogen economy has the potential to enable us to provide for our future energy needs from renewable energy sources. However, we need to be able to develop efficient catalytic electrolytic processes to convert water to hydrogen using sunlight. Hydrogen storage is another serious issue, and advanced materials will be developed to safely store hydrogen and also to have the ability to release the hydrogen when needed. Nanostructured materials and novel hydrides will play an important role in these endeavors. Lastly, we will see many advances in fuel cells, which utilize hydrogen to convert chemical energy to electrical energy and have the advantage of generating power quietly and without harmful emissions; the challenge will be for fuel cells to have high sustainable energy densities. We will see major developments in solid-oxide fuel cells, molten carbonate fuel cells, polymer electrolyte membrane fuel cells, and phosphoric acid fuel cells.[26]

TRANSPORTATION

Global consumption will increase significantly in the next few decades, especially when some of the developing countries are experiencing annual growth rates of around 8% for several years in succession. Figure 6 shows the anticipated increase in motor vehicles, and as expected the growth is dramatic for the developing countries.[27] In 1995, bicycles were the predominant mode of transportation on the streets of Beijing; today cars have replaced the bicycles. The contrast is astounding. Transportation is a basic human need, and we need to develop future materials and modes of transportation to meet the demands of our society in a sustainable way.

We should applaud the efforts made by some car manufacturer such as Toyota and its *Prius* model, as well as Ford and GM with developments in hybrids and electric cars. However, hybrids alone will not solve the problem. With 600 million cars and light trucks in the world, each having an average life span of 10–12 years, it could take more than a decade for hybrids to achieve significant penetration and to make a difference. In the future, diesel engines will replace many of the existing gasoline-powered internal combustion engines. Diesel engines have tremendous torque, they are efficient, and enjoy much better fuel efficiencies than gasoline-powered engines. Case in point is Audi's TDI engines; the 2006 Le Mans race was won by an Audi *R10*

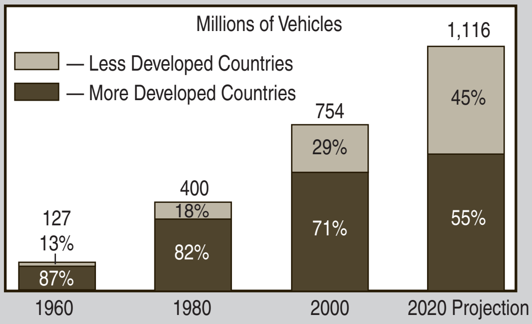


Figure 6. The usage of motor vehicles, 1960–2020.[25]

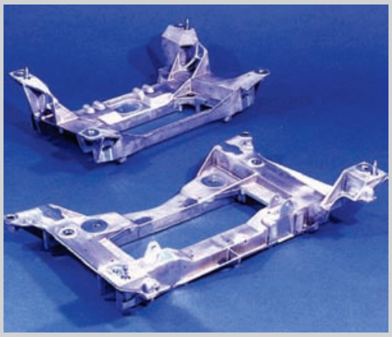


Figure 7. A lightweight aluminum chassis made by novel die casting processing methods with controlled solidification.[26]

TDI diesel engine!

Public transportation will need to be the dominant means of transporting the masses. This certainly has been effective in Japan, France, and many other European countries. Developments will occur in high-speed trains and the infrastructural needs to accommodate these lines will be challenging. Lightweight structural materials, specifically alloy development and processing, will be the focus of future materials (i.e., foamed structures, magnesium-based components, and advanced aluminum alloys that can be selectively stiffened). Figure 7 shows the high-volume production of an advanced aluminum chassis with a controlled solidification structure and excellent mechanical properties; it is lightweight and cost-effective.[28]

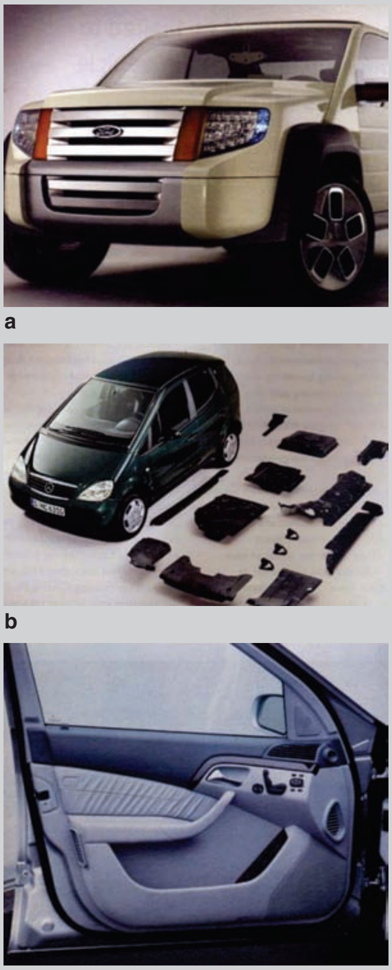
Future materials will certainly include innovative material uses such as recyclable composites and bio-composites. The hybrid-electric *Model U* developed by Ford makes extensive use of recyclable composites (see Figure 8a). Corn-based materials are used in the interior roof fabric and floor matting, while soy and corn-derived resins replace carbon black in the tires. The synthetic polyester used to cover seats and door panels can also be recycled back to polyester.[29] Underbody components previously manufactured from glass-fiber-reinforced composites are now being replaced by bio-composites such as flax and polypropylene, as shown in Figure 8b for the Mercedes Class A autos. Duralin fibers (made by Ceres in the Netherlands) are produced when flax straw is steamed, dried, and cured.[30] The modern door inner trim panels shown in Figure 8c are molded using mats of 60% natural fiber in a Baypreg® polyurethane resin.[31] Strong and lightweight materials, sustainability, and material recyclability will be some of the major factors influencing the development of future materials for our transportation needs, including, of course, the future material developments discussed previously for energy usage.

SUSTAINABLE CONSTRUCTION MATERIALS (HOUSING)

Housing has always been a fundamental human need. With increasing world population as well as increasing global poverty, the MSE community has an opportunity to make a major impact by developing novel construction materials that are sustainable, green, and energy efficient, as well as construction materials that are affordable for the masses.

In the future we will see more energy-efficient homes that use intelligent materials and intelligent designs. As an example, the Institute of Solar Energy Systems in Freiburg, Germany discovered a means to integrate the temperature-equalizing effect of thick walls within a millimeter thin layer of plaster.[32] The material contains micro-encapsulated paraffin. When summer temperatures inside the building rise above 24°C, the encapsulated paraffin in the wall begins to melt. This draws off the heat in the room, preventing the indoor temperature from rising. At night when the temperature falls, the paraffin solidifies and releases the stored heat (see Figure 9). The impact on energy savings, reduction of pollutants, etc. is significant. The premise is that much more needs to be done in this whole arena of intelligent materials that are green and energy efficient—a fertile area for MSE discoveries and innovations.

The Riyadh International Stadium in

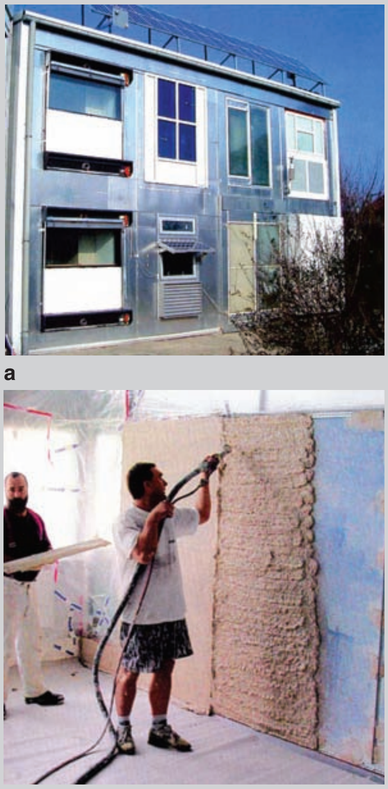


a

b

c

Figure 8. Green composite materials for automotive applications;[29] (a) recyclable composites used in the Ford *Model U* hybrid-electric car, (b) underbody components made from flax/polypropylene material, (c) inner trim panels molded using 60% natural fiber in a Baypreg® polyurethane resin.



a

b

Figure 9. Novel material development at Fraunhofer Solar Building Innovation Center; (a) test facility for evaluating heat storage media, (b) application of plaster containing microencapsulated paraffin.[32]

Figure 10. Recycled materials showing the diversity of collected metals and materials classified as steel, copper, Al/Mg/Cu/Zn, plastics, etc.[44]

Saudi Arabia is an example of the use of innovative materials and novel construction methods. The Teflon-coated fiberglass membrane roof of the stadium is about 300 meters across and can hold 60,000 spectators. Pinnacles of green buildings are the Toyota headquarters in Torrance, California and Genzyme's headquarters in Cambridge, Massachusetts; the latter has set a new standard in environmentally responsible architecture. Phenix Bio-composites Inc. of Mankato, Minnesota has developed a bio-based composite material with the appearance of traditional burled woods produced from agricultural fiber from North Dakota and South Dakota that is bonded with a proprietary formaldehyde-free binder.

Future developments will be realized through innovative design and collaboration with architects and builders. As an example, a resource that my own institute—Metal Processing Institute—has used extensively is Material Connexion, which is the leading depository of information about new and innovative materials for architects and designers.[33] The MSE community has an opportunity to partner with leading architects to address both issues—energy-efficient and sustainable construction materials—as well as providing shelter needs for the world's poor. The work of Billie Faircloth, a professor at University of Texas in Austin[34] and architects Kennedy & Violich of Boston are notable and laudable.[35]

World poverty is not receding; it is, by all measures, advancing. Today, nearly three billion people, almost half the world population, live on less than two dollars per day.[36] Globalization is wonderful in that it thrives on market economies and promotes democracy. However, the latter does not necessarily mean that wealth will be distributed evenly. Planet Finance was established in 1998 by Jacques Attali to help the poorest fulfill their potential through microfinance; it is a noble endeavor and one that is working.[37] Muhammad Yunus of Bangladesh and the Grameen Bank were jointly awarded the 2006 Nobel Peace Prize.[38] Yunus, an economist, founded the bank, which is one of the pioneers of micro-credit lending schemes for the poor, especially women, in Bangladesh. In an effort to reduce or eliminate poverty, the world will need to address the housing needs for the inhabitants of developing regions, and we need to make use of indigenous raw materials of those regions. There are many local issues in the less developed countries, and the solutions need to be local ones. Shelter needs for the world population require novel material solutions as well as novel housing designs.

PACKAGING MATERIALS/ RECYCLING

With increasing world population concomitant with urbanization of the masses, packaging materials will play an important role. Distribution of food, water, medicine, and certainly consumer products will require novel packaging materials that can be recycled without harming the environment. Between 1960 and 2000, the municipal solid waste generated in the United States increased from 80 million tonnes to 210 million tonnes. On average, each American produced 2 kg of garbage each day in 2000 (up from 1.2 kg in 1960). This waste is either burned (emitting pollutants) or deposited in landfills introducing toxic substances to groundwater and the soil.[39] If we look at the toxic materials that are found in municipal solid waste (see Table II), there is need for concern.

Future world needs will require materials that are recyclable or biodegradable. Novel natural plastics that are biodegradable will be used for packaging applications; these materials are made by fermentation of plant sugars and oils using microbial biofactories. A good example is a material made by Metabolix of Cambridge, Massachusetts, which is a semi-crystalline thermoplastic polymer. These natural plastics range in properties from stiff thermoplastics suitable for molded goods to highly elastic grades to grades suitable for adhesives and coatings. When exposed to microbial organisms the natural plastic breaks down enzymatically and decomposes.[41] In terms of future opportunities, the MSE community can play an important role in developing such novel materials for packaging applications and ultimately

Table II. Common Toxic Materials in Municipal Solid Waste[40]

Substance	Sources	Health Effects
Cadmium	Batteries, inks, paints	Carcinogen, ecotoxin, reproductive effects
Lead	Batteries, varnishes, sealants, hair dryers	Neurotoxin, reproductive effects
Mercury	Batteries, paints, fluorescent lamps	Ecotoxin, neurotoxin, reproductive effects
Methyl Chloride	Paint, paint strippers, adhesives, pesticides	Carcinogen
Methyl Ethyl Ketone	Paint thinner, adhesives, cleaners, waxes	Neurotoxin, reproductive effects
Perchloroethylene	Rug cleaners, spot removers, fabrics	Carcinogen, ecotoxin, reproductive effects
Phenol	Art supplies, adhesives	Ecotoxin, developmental effects
Toluene	Paint, nail polish, art supplies, adhesives	Ecotoxin, mutagen, reproductive effects
Vinyl Chloride	Plastics, apparel	Carcinogen, mutagen, reproductive effects

reduce waste and protect the environment.

It is astounding that one third of the world's copper is found in landfills.[42] Recycling of metals will be a critical technology in the world of tomorrow; it is certainly an important technology today, however the need for recycling will escalate enormously as the world's appetite for consumption increases (see Figure 10).[43] Recycling 1 kg of aluminum saves up to 6 kg of bauxite, 4 kg of chemical products, and 14 kWh of electricity.[44] Sorting of metals rapidly and sorting them by their specific composition will allow us to recycle effectively and efficiently. Moreover, with increasing sources of scrap (e.g., beverage cans) and with enabling technologies that allow rapid recycling as well as rapid melt cognition (e.g., laser-induced breakdown spectroscopy technology[45]), the concept of aluminum mini-mills will be a reality.

There is no doubt that material recyclability and use of biodegradable packaging materials will play an increasingly important role on the MSE agenda. Enabling technologies for the recycling of metal components will change the paradigm for production of metals—both ferrous and nonferrous.

BIOMATERIALS AND HEALTH

Life expectancy over the years has increased significantly. During the last five decades alone, life expectancy has risen by 15% (from 69 to 80 years) in North America, and we see similar trends across the globe except for Sub-Saharan Africa[46] (Figure 11). More importantly, not only are we living longer but our quality of life has dramatically improved thanks to the many advances in medicine, biology, and MSE.

We have seen tremendous advances in biomaterials; A. Courey defines biomaterial to be "a structural material, derived from synthetic or natural sources, that interacts with tissue for medical therapeutic or diagnostic purposes."[47] The market potential for structural tissue engineering is $90–100 billion, and for the biomaterials industry R&D growth spending is about 24% a year.[47] Recent advances and developments include: cornea tissue regeneration, artificial skin (e.g., Epicel manufactured by Genzyme Corporation of Cambridge, Massachusetts), caticel implantation in the perosteal flap, etc. Devices such as artificial heart valves (e.g., mitral valve), coronary stents, and particularly drug eluting stents have seen significant utilization for the benefit of society[47,48] (see Figure 12). These developments are critically dependent on the advances that have been made and continue to be made in MSE.

Implantable medical devices have seen a huge growth during the last decade (see Table III).[49] Hip joints, artificial knees, spinal cord fusion devices, and many other parts are now being replaced on almost routine basis. Thus, in the last two decades alone we have witnessed medical advances that have profoundly improved quality of life; the unfortunate part is that many parts of the globe cannot afford these advances nor do they have access to such medical services.

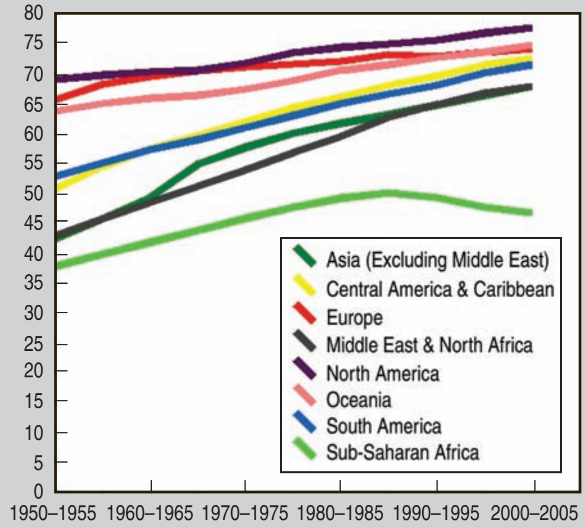


Figure 11. Life expectancy over the last five decades.[46]

Table III. Demand for Implantable Medical Devices (for U.S.)

Implantable Devices	1997	2002	2007
Cardiac Implants	3,620	7,080	13,740
Orthopedic Implants	4,460	6,410	8,730
Other Implants	640	1,120	1,880
Total	8,720	14,610	24,350

In the future we will see major developments in the area of surface modification of biomaterials to better control blood and tissue compatibility; biomaterials can be modified by plasma treatment or by chemical grafting.[50] Through surface modification, we will be able to manipulate material attributes such as resistance to infection, resistance to clot formation, lubricity, and wear resistance. A good example is how heparin (an anticoagulant) is covalently coupled to a multi-layered base coat of a biomaterial surface.[50] Implants and devices that are also vehicles for drug delivery will be another area for future developments. Examples of such devices are steroid-releasing pacing electrodes and drug-eluting stents.[50] Tissue engineering coupled with innovative materials for the manufacture of "smart" heart valves is another area for growth and opportunity for future developments. The whole field of biomaterials for regenerative medicine is a fertile area for the MSE community; S.I. Stupp[51] recently reviewed these opportunities and cited many examples for the use of biomaterials for regenerative medicine. One example is how we might use biomaterials to regenerate insulin-producing cells of the pancreas from stem cells. Technologies that will be critical for the development of regenerative medicine will be supramolecular chemistry and self-assembly of atoms to create the necessary bio-active architecture. In brief, biomaterials of the future will not solely serve mechanical functions, rather they will be regulators of biological activity.

In the future we will see major advances in bio-organic-inorganic composites; at present, bio-erodable polyanhydrides are being synthesized as vehicles to release large as well as small molecules. In the future we will see this field blossoming to carry out "local chemotherapy."[52] Langer has pioneered the field of drug release systems; he and his colleagues developed controlled release

Figure 12. Innovative materials for medical applications: clockwise from top right corner: knee implant; hip joint; Medtronic's Sofamor Danek INFUSE® bone graft and cage lumber fusion device; and coronary stent.[47]

of large molecules (e.g., polypeptide) by using micro-spheres made of hydrophobic polymers.[52] The approach of synthesis and application of bio-erodable polymers for implantable tissue scaffolds will be used to create liver tissue, blood vessels, nerves, and heart muscle.[53] R.M. Bergman of Medtronic Inc. sees that in the future "InfoTech plus biotech will transform health care."[50] Fusion of information technology, biotechnology, nanotechnology, and neural networks will allow us to not only prevent but also cure disease.

The difficult issues we will face in the future are not technological ones, but rather ethical ones. Imagine what will be the consequence of being able to know the prognosis for disease and especially a life-threatening disease in a newborn. In less than a decade when the Genome project is completed, we will be able to have such information. How will insurance companies assess risk and how will society cope with these issues? The future is bright for medical advances as a result of the developments in MSE; what we have seen in the recent past is only the beginning. The difficult questions will be societal ones: will health care only benefit those that can afford it? How do we cope with inequalities across the globe? Lastly, we will need to address the ethical issues that will arise by knowing a-priori a person's propensity for disease and poor health. My hope is that future advances will enable us to cure diseases and mitigate the difficult ethical issues!

CONCLUSION

The world of tomorrow—projecting 50 years ahead—will be a much different world than when TMS was formed in 1957. It is virtually impossible to predict future discoveries and inventions; what we can predict, however, are societal needs, which beckon the MSE community to respond. In reviewing the last 50 years in view of the next five decades, we have reminded ourselves of the Cold War era, as well as the post-Cold War era, and the immense resources that have been and are being channeled globally toward defense needs, which are certainly important and critical. However, in my opinion, we are out of balance with respect to global and societal needs facing the world of tomorrow. The latter is even more compelling if we identify the United States as a superpower, or view the total GDP of the G7 countries!

The global MSE community has a responsibility to address significant problems that our society needs and will be facing in the future. These pertain to basic human needs such as energy, transportation, housing, packaging and distribution of food, recycling, health, etc.—all matters that affect quality of life on this planet. I am suggesting that the MSE community has a responsibility to be an advocate for these issues and to have representation at world forums to make the case and to ensure that resources are being channeled toward these endeavors. It is one thing to be the recipient of funds and to do work as directed by an agency; it is another to influence policy and to ensure that resources become available for critical global needs. The work of the Academy of Finland and the Finnish National Technology Agency in producing the *FinnSight 2015*[54] report is a good benchmark; the report (released October 2006) identifies the establishment of internationally competitive centers of excellence in areas that address global societal issues such as environment and energy, well-being and health, materials, etc. The MSE community has an incredible opportunity to respond to such issues. These are the "right" issues and if we act, they will have tremendous dividends in ways that we cannot envision.

Lastly, we are living in a society that is market driven (another definition of globalization), and thus we are not immune to the realities of capital markets. Material developments take far too long and in the eyes of capital markets the return on the investment is difficult to justify. Future MSE developments will need to do so in an accelerated fashion to attract investments of capital and resources. The time needed to move from concept to implementation will need to be shortened. For the adoption of a new material class, 20 years are needed including the time required for the establishment of design practices. The latter is not acceptable to investors and it is an impediment to the MSE community. Recent advances by the DARPA Advanced Insertion of Materials project, as well as the recommendations of the National Research Council panel that studied accelerating technology transition,[55] are noteworthy and suggest that a culture change should occur that fosters innovation, rapid development, and accelerated technology transition. As Antoine de Saint-Exupery said: "When it comes to the future, our task is not to foresee it, but rather to enable it to happen."

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