Towards an Industrial Ecosystem for Power MEMS

by

Timothy Franklin Havel

Bachelor of the Arts in Chemistry, Reed College, Portland Oregon, 1975
Doctor of Philosophy in Biophysics, University of California at Berkeley, 1982

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Signature of Author: ____________________________________
MIT Sloan School of Management
May 11, 2007

Certified by: ____________________________________
Charles H. Fine, Thesis Supervisor
Chrysler Leaders for Manufacturing Professor
MIT Sloan School of Management

Certified by: ____________________________________
Jeffrey H. Lang, Thesis Reader
Professor of Electrical Engineering and Computer Science
MIT School of Engineering

Accepted by: ____________________________________
Stephen J. Sacca, Director
MIT Sloan Fellows Program in Innovation and Global Leadership

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Abstract

This thesis is concerned with the commercial applications of MEMS (Micro-Electro-Mechanical Systems) manufacturing processes to advanced energy technologies. This field of engineering has come to be known as Power MEMS. Four such technologies are singled-out for detailed consideration, based on the efforts that have gone into demonstrating the benefits which MEMS has to offer them. The first are micro engines or turbines which generate of order 10-100 Watts of power by driving an electric generator, as exemplified by the famous MIT microturbine. The second are micro fuel cells, electrochemical devices which air oxidize chemical fuels, particularly the direct methanol fuel cell which operates at modest temperatures and hence is suitable for use in portable electronics. The third are solid-state devices which convert heat into electricity via either the Seeback (thermocouple) or photovoltaic effects, or else via thermionic emission. Finally, we consider devices which scavenge vibrational or electromagnetic energy from their environment, and are an attractive means of powering remote autonomous sensors or medical implants such as pacemakers.

Following a survey of recent commercial activity in these technologies, we consider the markets they may serve, the economics of their MEMS-based production, and possible business models for their commercialization. Detailed case studies are presented of two recent startups, one of which is developing a heat-to-electricity conversion system based on the photovoltaic effect, and the other of which is studying a novel MEMS device which would use springs made out of carbon nanotubes to store energy. The conclusion is that the time is ripe for a power MEMS technology roadmap which can inspire energy technology companies to work together towards an industrial ecosystem like that now seen in the semiconductor industry. Specifically, we propose that by using MEMS as a unifying technology, it will become possible to easily buy, sell and trade knowledge, personnel, components and foundry services, facilitating experimentation with new products and business models and greatly accelerating the development of power MEMS itself. This may in turn lead to solutions to some of the pressing energy and environmental problems which society now faces.

Thesis Supervisor: Charles H. Fine
Chrysler Leaders for Manufacturing Professor

Acknowledgments

This thesis is the culmination of the two years I have spent in the MIT Sloan Fellows Program in Innovation and Global Leadership. Thus I would like to begin by thanking the Program's staff for making my time there as enjoyable as I expect it will be profitable. I would also like to thank my fellow Fellows from the 2006 and 2007 classes for all great events which they organized, for their friendship and support, and for tolerating my maniacal laugh. I would particularly like to thank the Chinese and Indian Fellows from 2006 for the wonderful events they arranged for us during our international trip, and Bob DiMatteo and Bernard Ho for agreeing to let me use their company as one of my case studies. This thesis has benefitted immeasurably from the comments made on it by my advisor Prof. Charley Fine at the Sloan and my reader Prof. Jeff Lang in the MIT School of Engineering. Thanks are further due to Prof. Don Lessard, who got me off in the right direction, and Prof. Jim Utterback, whose course on disruptive technology provided essential background for this work. I must also thank my supervisor Prof. David Cory in the MIT School of Engineering, the Cambridge-MIT Institute and the MIT Provost's Office for allowing me to continue to work part-time at MIT while also a student in the Program. This allowed me to bring my work as a principal research scientist in the MIT Dept. of Nuclear Science and Engineering, and as manager of the Cambridge-MIT Institute's Quantum Technologies Group, to a graceful conclusion. Finally I would like to thank my wife Debby and our birds for putting up with my many late nights out.

Biographical Note

Before joining the Sloan Fellows Program at the age of 52, I'd already had a long and checkered career doing diverse scientific research in widely dispersed locations in both Europe and the USA. It is long since past the point at which I myself can say what kind of a scientist I am, and even after my postdoctoral advisor Kurt Wüthrich from Switzerland won a Nobel Prize I continued to be told that I didn't belong wherever I wound up, as happened at the University of Michigan's Chemistry/Biophysics Dept., the Harvard Medical School's Dept. of Biological Chemistry and Molecular Pharmacology, and most recently the MIT Dept. of Nuclear Science and Engineering. Not to mention the dozens of other academic departments, including physics and mathematics as well as chemistry and biology, which all came to the same conclusion after interviewing me.

I finally decided I should've listened to the doctor who ended my half-hearted attempt to go to medical school over 30 years ago when he told me I should be an engineer. Live and learn. Being a bit old to start all over now, having become interested in alternative energy technology about the time I arrived in Boston in 1990, hanging around a lot of nuclear engineers starting in 2000, and finally watching my country spend a trillion dollars and thousands of lives putting the one of many tin-pot dictators on earth out of business who just happened to be sitting on a lot of oil, made me decide to go at it instead by studying micro/nanotechnology applied to energy under the guise of getting a Masters of Science in the Management of Technology at MIT. The rest is future.

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Chapter One: Energy, Technology, and Civilization

The best way to predict the future is to invent it.

Alan Curtis Kay, 1971

This work considers the possible long-term social and economic consequences of a particular application of micro-electro-mechanical systems (MEMS). This application is known as *power MEMS*, which broadly speaking is the use of MEMS technology for the purposes of producing electricity from other forms of energy, storing electricity by converting it into other forms, transmitting energy from one place to another, and reducing the amount of energy wasted in accomplishing these tasks. This initial chapter describes the author's motivation for the project, and attempts to place it in context of its times.

Standards of living and the intensity of energy use have been rising more or less in parallel since at least the dawn of civilization. Indeed some have equated the agricultural revolution with the harnessing of animal power, and the industrial revolution with the harnessing of fossil fuels. In light of its importance, it is worth considering a little more closely what we mean when we speak of "using energy." For, in contrast to common rhetoric, energy *per se* is not a rare commodity. Indeed, there are about 30 Watt-hours of energy in every cubic meter of air at atmospheric pressure, which you could extract if only there were a good vacuum nearby. Similarly, the energy contained in the form of heat in your body is about the same as that released on burning two liters of gasoline, which is also about 1% of the energy needed to put you into orbit (neglecting air resistance and the mass of your spaceship).[1] Alternatively, we can say that the speed of the atoms in a room-temperature gas is about 10% of the escape velocity of the earth, assuming those atoms have the same masses as those commonly found in your body.

The only physical difference between your frozen corpse flying skywards and your normal good health is that in the former case all the atoms happen to be moving with the same speed and in the same direction, while in the latter their motions are random so that they never get very far before they collide. Thus it is that the usefulness of energy is intimately tied to the information we have about its embodiment. Information (or more precisely, the lack thereof) about how energy is stored in a material is a form of *entropy*, and its study is the branch of science known as *thermodynamics.*

When we talk about "using" energy, all we are really doing is converting it from one form to another. To do this, we know something about how it is embodied within the physical system of interest. When you drive your car, for example,

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[1] To say nothing of the earth-shattering explosion that would result from converting your body's mass into energy according to Einstein's mass-energy relation.

you are converting (a small portion of) the energy contained in the chemical bonds of gasoline into heat and pressure, a (once again small) portion of which is converted into the motional energy of the car. Although thermodynamics places strict limits on how much of the heat released by burning gasoline can be converted into motional energy, far less actually goes into accelerating the payload, namely you. In fact about 99% of the energy is used to accelerate the mass of your car, which weighs well over 10 times what you do, or is lost to friction before it even reaches the wheels.[2] Clearly, we do not make efficient use of even what we do know about the energy we've got!

The foregoing discussion serves to show how deeply misconceptions about the physical nature of energy are embedded in the very language commonly used to describe it. Other examples may be found in such phrases as "generating" or "conserving" energy, both of which are oxymorons since the first law of thermodynamics states quite clearly that energy is *never* either created or destroyed, but is *always* conserved. What then do people really mean when they say such things? A little thought shows that "generating" energy really means finding and capturing it in some useful (i.e. nonrandom) form, and that energy is "used" once it has been lost again, generally in the form of heat. The term energy "conservation" simply means that we lose less energy as heat before getting useful work out of it than we otherwise would have.

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[2] "Reinventing the Wheels" by Amory B. Lovins & L. Hunter Lovins, *The Atlantic Monthly*, Jan. 1995.

The most widely useful form of energy is electricity, since this form is so readily converted into other forms (heat, light, motion), and can even be transmitted over long distances almost instantaneously and with only moderate loses. There is just one thing that cannot be done with electricity, which is to store it directly and compactly.[3] Of course electricity can be stored compactly by converting it into some other form, e.g. chemical bonds in the case of batteries, but devices for doing this are expensive (compared to the cost of the energy they store) and energy is inevitably lost in the process. Much of today's energy technology is devoted, in one way or another, to dealing with this basic problem, and accordingly it will receive considerable attention in the present work.

Let us now turn from the physics of energy to its economics. Mankind's first use of energy, other than its own muscular force, was fire. Fortunately, wood was fairly abundant in most places where people were inclined to live, so that a little muscular work was all that was needed to gather enough to cook a meal, fire a pot, or smelt iron. After a good meal cooked in said pot, a man was ready to use his iron axe to cut down more trees. A second early form of energy use came by domesticating animals, or enslaving humans, who were often used to grow the self-same food needed to sustain them - plus a little added value. In more recent times we learned to mine coal, drill for oil, and to split atoms of

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[3] Capacitors, of course, do store electrical energy directly and efficiently, but even ultracapacitors take up 25 times more space and weight than a comparable lithium ion battery. Other forms of low-density, large-scale energy storage include thermal phase transitions, flywheels, compressed air, pumped water and superconductors, but they are only economical when located in places where the large amounts of space required is almost free.

uranium. We have even learned how to make plutonium from the hot neutrons produced by nuclear fission, getting more fuel out than we put in (up to a point). In all cases we see a rather remarkable feature of energy as a commodity: it takes energy (in some useful form) to harvest energy (again in some useful form). So, in some sense, energy is its own precursor!

This odd situation leads not to a value chain, but to a value loop: part of the cost of each unit of useful energy harvested is due to the energy that went into harvesting it. This includes of course not only the energy consumed in operating the machines used to collect and transport it, but also the energy that went into collecting and processing the materials of which these machines are composed, the food that fed the machines' operators, and all the vast infrastructure of civilization needed to support them in the style to which they have become accustomed. Although I have never seen a serious, let alone convincing, analysis of the econo-physics of energy harvesting, it is clear that it can work only when one gets more useful energy out than one has to put in to get it. Considerably more, in fact, given all the other overheads involved.

Throughout most of history, this positive feedback loop has been operating in our favor, in that each new energy source we have exploited has provided us with the means to go after harder-to-get, but still profitable, energy sources. Positive feedback, however, works both ways. As long as new profitable energy sources can be found and exploited more rapidly than energy is being used to get at them, there will be a steadily accelerating shift towards a more energy intensive economy, but once that is no longer the case the shift back to a less energy intensive economy could begin to feed on itself. In its most benign form, this will happen gradually as the market forces people to find ways to do more with less - which as indicated above is certainly possible. There remains nevertheless the possibility of an abrupt and profound shift in the physical basis for our economy.

There are reasons to believe that such a shift is already starting to occur. For some time the rate at which new oil and gas reserves are being discovered, or technological developments have rendered them economically feasible to retrieve, has just barely kept up with the growth in demand - which in turn is destined to skyrocket if China and India continue to make rapid economic progress.[4] Although there is certainly plenty of coal available, the specter of global warming would also seem to be upon us, and its risks and potential costs will hopefully soon become apparent even to the president of the United States. A massive increase in coal use can only be contemplated in conjunction with gasification and carbon sequestration, the costs of which are not yet fully understood but which are certainly not negligible. Cellulosic ethanol is likewise under development, and in due course could probably largely replace gasoline for transportation, but biomass alone cannot power the entire economy of even

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[4] See e.g. "Winning the Oil Endgame" by Amory B. Lovins, E. Kyle Datta, *et al.*, The Rocky Mountain Institute, 2004.

the United States let alone more densely populated countries with less arable land. Other renewable energy sources such as wind, tidal and solar are likewise coming along quite nicely, but the question is "soon enough?"[5]

The only other non-renewable energy source that is seriously being considered as a near-term replacement for cheap oil is nuclear fission. Even though the technology is there to operate reactors safely and economically, the best part of a decade in the MIT Department of Nuclear Science and Engineering has failed to convince this author that this is a desirable course of action. The main reason for this lies in the dangers of nuclear proliferation, which no foreseeable technological advance can really overcome (even given the political will to use it). Any intense source of neutrons (including nuclear fusion) could be used to convert unenriched uranium into plutonium, which can then be extracted and used to make a bomb. It is not simple but, as long as you don't value people's lives or the environment, it is straightforward.[6]

Another serious problem with the nuclear option, at least in the United States, lies in the fact that the Nuclear Waste Policy Act Amendments of 1986 dictate that all nuclear waste must be disposed of at the Yucca Mountain repository in Nevada. It is the only repository under consideration anywhere on earth that

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[5] See "Making Technlogy Work" by J. M. Deutch & R. K. Lester, Cambridge Univ. Press, 2004, "Energy in the 21st Century" by J. R. Fanchi, World Scientific, 2005, or "Sustainable Energy: Choosing among the Options" by J. W. Tester, E. M. Drake, M. J. Driscoll, M. W. Golay & W. A. Peters, MIT Press, 2005.

[6] The purification of fissionable isotopes from natural uranium ores is much more difficult by comparison.

would be located above the water table and in porous tuff (solidified volcano ash) rather than crystalline rock, and after 20 years of trying the Department of Energy is still unable to argue convincingly that it will contain the actinide components of the waste for the millions of years that are necessary. Until the United States Congress repeals the Nuclear Waste Policy Act Amendments and permits the waste problem to be solved according to the science rather than the politics, it would be irresponsible to build more nuclear power plants.[7] Rightly or wrongly, this seems unlikely to happen any time soon, if ever.[8]

I conclude that, with the possible exception of coal gasification plus carbon sequestration, nonrenewable energy sources will hopefully play a rapidly diminishing role in the world's future energy mix. Instead we are going to have to learn to do more with less, and in addition to harvest renewable forms of energy more efficiently than we now do. The greatest single challenge we face in this regard stems from the intermittency of most renewable sources of energy. This in turn requires the conversion of energy from such sources into other forms of energy that can be transported and/or stored cheaply, safely and with low loses overall. It is here that new and in most cases underdeveloped or perhaps even unimagined energy technologies are likely to play a key role. The

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[7] This author favors drilling deep boreholes in the formation of crystalline rock nearest to each nuclear facility, so as to minimize the need to transport the waste for large distances.

[8] For further information, see "Understanding Radioactive Waste" by Raymond Leroy Murray & Kristin L. Manke, 5th edition published by Battelle Press, 2003, or "The Future of Nuclear Power," an interdisciplinary MIT study, http://web.mit.edu/nuclearpower, 2003.

market pull may not be there just yet, but it is coming, and fortune will favor the prepared!

The rest of this work will consider the applicability of micro/nanotechnology in general and MEMS in particular to these challenges. In closing these preliminary remarks, I would like to consider briefly what the coming energy transition may mean to the paradigm widely known as "distributed generation." This was in fact Edison's original vision of how to electrify the United States, but it did not survive the economies of scale associated with large thermal and hydroelectric power plants, combined with Steinmetz and Tesla's development of high-voltage alternating current power transmission.

Renewables, especially solar and wind, lend themselves naturally to distributed power generation, in that such facilities are relatively maintenance-free once properly installed so that there is no big advantage in terms of labor costs from putting many of them in the same place.[9] In addition, the relatively large amounts of land they require can most cheaply be obtained by co-locating them on land which primarily serves some other purpose - e.g. rooftops in the case of solar, or in farmers' fields in the case of wind. This also naturally eliminates the costs associated with long-distance power transmission, providing enough power can be stored locally to get through a rainy or windless week or two.

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[9] It turns out that most of the economies of scale associated with centralized power plants can be attributed to the fact that they enable the variable costs of labor to be replaced by the fixed costs of machines which can largely automate their operation.

This leads naturally to the widely-touted "hydrogen economy", in which all or at least most energy used by mankind is stored and/or transported in the form of hydrogen. Unfortunately, present technologies for storing and transporting hydrogen are neither extremely safe, cheap or maintenance-free, and a number of fairly significant technological advances must be made before the hydrogen economy is likely to become a reality. Moreover, there are a wide variety of other forms in which energy can be stored, and over moderate distances (say less than a thousand miles with no ocean in between), high-voltage power transmission is pretty hard to beat. At this point in time it is not clear that hydrogen is destined to play a key role in our comparatively inevitable transition to distributed energy generation from renewable resources.

Even given the present large-scale power grid, huge improvements in reliability and simplicity would be attained if electrical energy could be stored cheaply and efficiently. This is because electric power lines must be capable of handling their peak, rather than average, loads. If every home could store a day's worth of energy, a steady trickle of electricity would suffice for every household. Compressed air energy storage could easily provide this capability today, and would probably become economical if time-of-day pricing were introduced. Most of the market pull driving the development of advanced energy technologies today comes instead from the need for better remote or mobile power sources, which brings us at last to power MEMS.

We begin in Chapter 2 with an overview of the most important power MEMS applications, which are microgenerators driven by microengines, micro fuel cells, solid-state systems which convert heat to electricity directly, and energy scavengers which convert vibrations or radio-waves into electricity. In Chapter 3 we first assess the level of scientific and commercial activity in these same four areas of application of power MEMS, and then consider the markets at which products based on these technologies could be targeted. The economic issues involved in the production of MEMS-based products generally are then considered, followed by examples of business models with which one could actually generate returns from each of our four main applications. Chapter 3 closes with two case studies of nascent companies based on power MEMS.

Finally, in Chapter 4 we lay out our proposal for a Power-MEMS Roadmap, starting with the purpose of roadmapping, the main kinds of technology roadmaps, and the MEMS-wide roadmaps that currently exist. The justification, objectives and tasks needed to initiate the proposed Power-MEMS Roadmap are then presented, emphasizing that it is intended to be not merely a technology roadmap, but a *value-chain* roadmap. This is followed by a simplified model of innovation dynamics which helps explain why we expect that such a roadmapping exercise will contribute to the birth of an industrial ecosystem for power MEMS. In closing, we propose some technological challenges as a means of inspiring the future development of the power-MEMS industry.

Chapter Two: An Overview of Power-MEMS Applications

> *While MEMS has not yet lived up to the optimism of the 1990's, enhanced understanding of scale-dependent physics is helping us to make progress toward the buoyant expectations voiced during those times. We are moving from the early, relatively unenlightened days of "making macro solutions smaller" to doing things in a new way, through "microscale enabled solutions." ... MEMS is here to stay, and it will transform the future.*
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> From "MEMS from the Nanoscale Up" by A. C. Ratzel III,
> *Mech. Eng.* **129**, 24-29, Mar. 2007

This chapter will begin with a brief introduction to MEMS technologies, and then survey the most important kinds of power MEMS devices currently under development, namely microengines/turbines, micro fuel cells especially the direct methanol fuel cell, thermoelectric, thermionic and thermophotovoltaic devices, and finally vibrational and electromagnetic energy scavengers. It will conclude with a discussion of the impact that the commercialization of these devices is expected to have on solving the electrical energy storage problem.

1. MEMS = Micro-Electro-Mechanical Systems

MEMS is an offshoot of VLSI (Very Large Scale Integrated) circuit technology, which uses photolithography to simultaneously mass produce and connect together millions of microscopic electrical components on a silicon wafer. In the course of developing VLSI it was gradually realized that various kinds of sensors could also be made by the same processes and integrated on the same chip with the microelectronics needed to amplify and/or analyze the output signal. The first significant such product was a pressure sensor based on the piezoresistive properties of silicon, which was mass produced by National Semiconductor starting in 1974. Actuators, which are essentially sensors operated in reverse so that an electrical signal produces a desired effect, soon followed. Commercial sensors and actuators made by MEMS now include accelerometers, gyroscopes, ink jet printer nozzles, optical switches, and many others.

As in VLSI, the most important technique used in MEMS manufacture is optical photolithography. The wafer is coated with a thin layer of a photosensitive material called the "photoresist," and light (usually in the near ultraviolet) shone upon it through a photomask with a pattern of transparent regions on it. This projects the pattern onto the wafer and changes the chemical structure of the photoresist in the illuminated areas. In the case of a positive photoresist, the unilluminated photoresist is subsequently washed off by a suitable chemical bath, whereas with a negative photoresist the illuminated areas are removed. In either case the surface exposed after washing is often subjected to an etching process, which removes a controlled thickness of the underlying wafer and results in the desired three-dimensional contour. The etching process may be wet, in which the wafer surface is removed by strong aqueous acids or bases, or dry in which case ion bombardment or a plasma is used.

A variety of methods (spin casting, sputtering, chemical vapor deposition, etc.) are available to deposit thin films of diverse materials with desired physical properties (mechanical, electrical, thermal, optical, chemical, etc.) on the wafer, after which they may be covered with a photoresist which is patterned by photolithography, and then etched as above. By repeating this process many times, both geometrically and functionally complicated three-dimensional structures may be created. This is often called as surface micromachining, as opposed to bulk micromachining when the wafer itself is etched. Although not fundamentally different from VLSI, in MEMS one often goes all the way to sacrificial layers, which are totally removed at a later date leaving any additional layers previously supported by them standing free. The flexibility of such free-standing structures is one of the main sources of mechanical degrees-of-freedom in MEMS devices. Additional three-dimensional structure may be obtained by micromachining both sides of a wafer, or bonding multiple wafers together.

A great many variations on this basic scheme are widely used, and a number of rather different approaches are also regarded as "MEMS." For example, in the

LIGA technique synchrotron x-rays are used to create very deep but precise structures on a thick layer of positive photoresist, which are then filled in by electroplating and removal of the photoresist. The resulting pattern may be used as a template for micromolding other materials. A simpler approach to creating such deep, high-aspect ratio structures uses an epoxy widely known as SU-8 as a negative photoresist. Finally, deep reactive ion etching (DRIE) uses cycles of ion bombardment and passivation of the etched regions' sidewalls to achieve high-aspect ratios directly in silicon wafers.

Rather than attempting a more complete survey of all the variations here, we will simply introduce them as needed in what follows. A nontechnical introduction to MEMS by Franck Chollet and Hao Bing Liu is available on-line,[1] and complete accounts may be found in recent textbooks.[2]

2. The Main Kinds of Power-MEMS Devices

The term "power MEMS" was introduced by Alan Epstein and Steve Senturia from MIT, and was intended to cover any MEMS device which generated power or pumped heat.[3] A more general definition due to Dr. Richard Paur, a grant

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[1] F. Chollet and H.B. Liu, "A Not-So-Short Introduction to MEMS," version 2, August 2006, available from "http://memscyclopedia.org/IntroMEMS.html".

[2] See "Microsystem Design" by Stephen D. Senturia, Springer Verlag, 2000, "Modeling MEMS and NEMS" by John A. Pelesko & David H. Bernstein, CRC Press, 2002, or "Fundamentals of Microfabrication: The Science of Miniaturization" by Marc J. Madou, CRC Press, 2nd ed., 2002.

[3] A. H. Epstein, S. D. Senturia, *et al.*, "Power MEMS and Microengines," *Transducers '97, the 9th International Conference on Solid-State Sensors and Actuators*, Chicago IL, June 1997.

manager at the U.S. Army Research Office who funded much of the early work in the field, extends the term to any MEMS device with a high power or energy density.[4] We will stick to the former, function-based definition here, since it would otherwise be necessary to cover a wide variety of micromotors, microreactors and the like that are not directly relevant to the social problem of transitioning to a renewable energy economy, which is the ultimate motivation for this work. It should further be noted that while a variety of small power sources are available or under development, we will be limiting ourselves to those for which MEMS manufacturing processes like those introduced above have demonstrated value. A general review of all the technologies currently being considered for powering portable electronic devices has recently been published.[5]

2.1. Microengines and Microturbines

The progenitor of all power-MEMS devices is the MIT microturbine.[6] This project was conceived of by Prof. Alan Epstein in the MIT Dept. of Aeronautics and Astronomics in the mid-1990's, initiated with funds from MIT's Lincoln Laboratories, and then funded at about a million dollars a year for five years by Richard Paur at the U. S. Army Research Office (ARO). Additional funding for Lincoln Laboratories part in the project was obtained from the Defense Advanced

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[4] Richard Paur, personal communication, December 2006.

[5] "Personal Power Systems" by D. Dunn-Rankin, E. Martins Leal & D. C. Walther, *Prog. Energy & Combustion Sci.* **31**, 422-65, 2005.

[6] "Millimeter-Scale Micro-Electro-Mechanical Systems Gas Turbine Engines" by Alan H. Epstein, *J. Eng. Gas Turbines &* Power **126**, 205-26, 2004.

Research Agency (DARPA), and the project continued as part of a nation-wide Collaborative Technology Alliance in Power and Energy (CTAPE), funded again by the ARO under the direction of Dr. John Hopkins at the Army Research Laboratories, with Dr. Mukund Acharya at Honeywell as the Consortium Lead.

While the term “microturbines” has been widely misused for small gas turbines capable of a few tens of kilowatts, the MIT microturbine is truly micro in that it is little more than a centimeter across and capable of only a few tens of watts, with many features too small to discern by the naked eye. It is also extremely thin, since MEMS intrinsically makes planar structures, and it needs to spin far more rapidly than larger turbines because the power of a turbine scales with the square of its rotor’s peripheral speed. Since the stress also grows as the square of the peripheral speed, the rotor has to be able to take incredible stress, and since the combustion temperature is of order 1500°C the temperature gradients are also very high. Fortunately at small scales it becomes possible to manufacture single or fused crystal components that are essentially free of defects and hence able to withstand these extremes. Finally, the high surface-area-to-volume ratio (and hence low weight) of the rotor allows it to be supported almost without friction on a cushion of air siphoned off from the compressor stream. Initially it was thought that an electrostatic induction generator was most suitable for use with the microturbine, but the narrow gap between the rotor and the stator this required caused prohibitive frictional losses due to

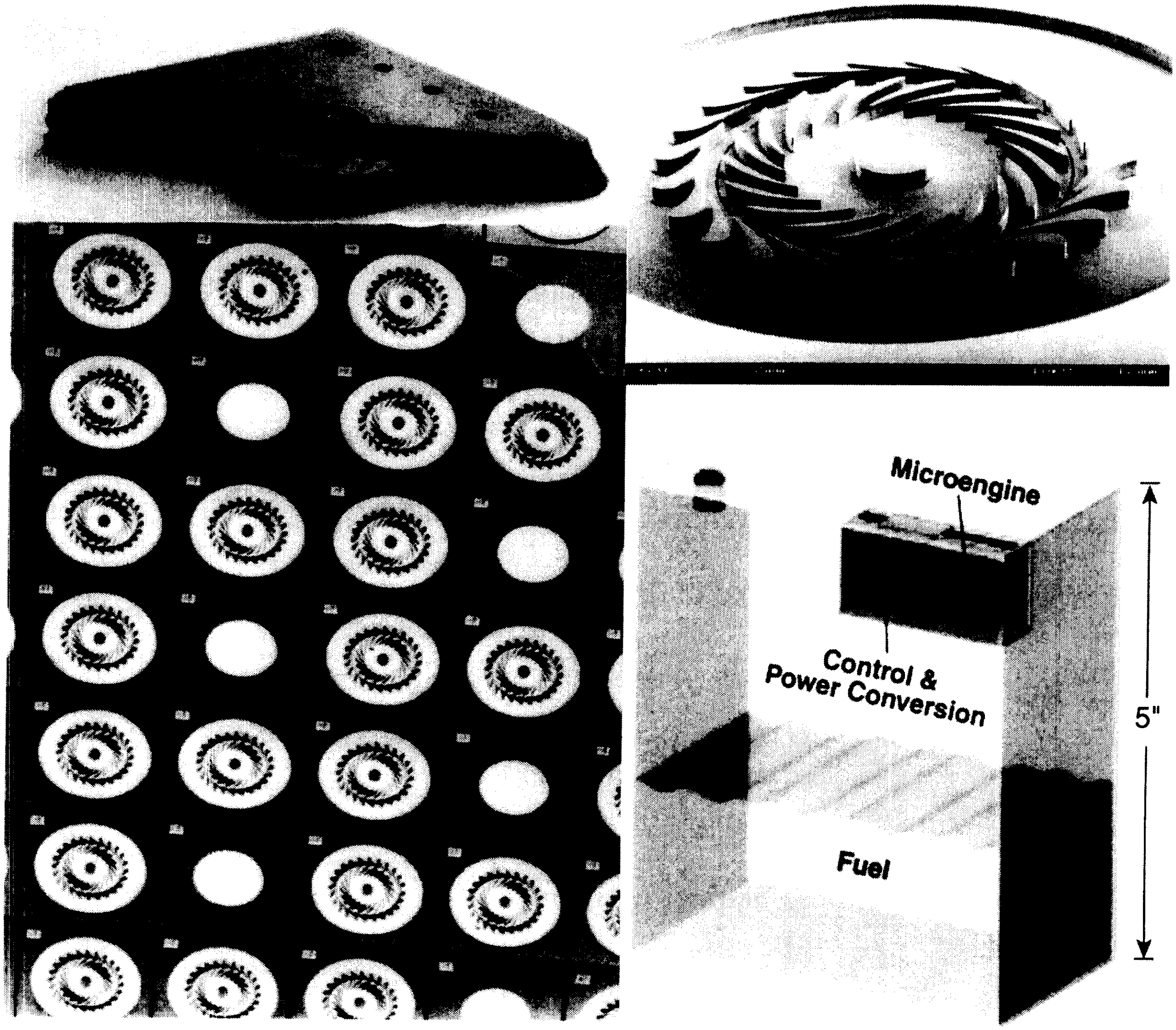

Figure 2.1. *Cutaway through an early prototype of the MIT microturbine (top left), a blow-up of a more recent version's compressor rotor (top right), a wafer of microturbines in the process of manufacture (bottom left) and a conceptual drawing of a complete portable power supply based on a microengine (bottom right). Reproduced with permission from Alan H. Epstein,* J. Eng. Gas Turbines & Power **126**, *205-226, 2004;* © 2004 American Society of Mechanical Engineers.

the viscosity of the air cushion, or jamming due to thermal expansion of the rotor itself. These problems were ultimately solved by switching to a completely different, electromagnetic generator designed in collaboration with the Georgia Institute of Technology, but capable of only about 10 Watts of power.

The initial reaction from the MEMS community, and indeed from some of the team's members themselves, to the idea of a dime-sized turbine driven by 1500°C gasses to spin at two million RPM was "It'll take ten miracles to get this thing to work." Today, the situation seems to be "OK, we've gotten ten miracles, but now we have to get them to all happen simultaneously." According to a recent interview with Prof. Epstein by the "The Future of Things" webzine,[7] this is currently expected to happen during the Summer of 2007. A company devoted to commercializing the technology as a portable means of power generation, suitable perhaps even for consumer electronics, may be expected to follow.

Within a few years of the MIT microturbine project's inception, several other research projects aimed at demonstrating MEMS-based microturbines as well as other kinds of microengines for power generation were initiated. Both Tokyo and Tohoku Universities in Japan launched microturbine projects, and Honda initiated another in collaboration with Stanford University. On the microengine side, Al Pisano, David Walther and their groups at the University of California

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[7] "Engine on a Chip: The Dream of a Personal Turbine" by Iddo Genuth, *The Future of Things*, Feb. 2007, see "http://www.tfot.info/content/view/114/58/".

Berkeley proposed MEMS-based rotary engines with rotor sizes ranging from 1.0 to 2.4 millimeters.[8] With funding from DARPA, a substantially larger (13 millimeter) prototype was built and demonstrated using wire EDM (electro-discharge machining) rather than MEMS, but the smaller MEMS versions have yet to be built - perhaps because funding was discontinued. In another DARPA-funded project (apparently separate from CTAPE), Honeywell Inc. and the University of Minnesota collaborated on a piston-based "Knock" microengine which used a novel "micro-homogeneous charge compression" ignition mechanism and a magnetic piston to generate electricity.[9] Eventually it was concluded that MEMS could not attain the component precision required, so the group turned to wire EDM, and the effort gradually petered out. At the time of writing the MIT microturbine project seems to be the only MEMS-based project of its kind still active.[10] An interesting review of these and several related projects is available in a conference proceedings,[11] and a very readable overview of the MIT microturbine project has just come out.[12]

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[8] "Design and Fabrication of a Silicon-Based MEMS Rotary Engine," by Kelvin Fu, A. J. Knobloch, F. C. Martinez, *et al.* in the *Proc. of the 2001 ASME Intnl. Congress and Exposition*, Nov. 2001.

[9] "Miniature Free-Piston Homogeneous Charge Compression Ignition Engine-Compressor Concept" by H. T. Aichlmayr, D. B. Kittelson, and M. R. Zachariah, *Chem. Eng. Sci.* **57**, 4161-86, 2002.

[10] A relatively low-power MEMS microengine, based on a very different principles, also remains under active development. This so-called "P^3 microengine" uses a convection-driven piezoelectric generator, see "Design, Fabrication and Testing of the P^3 Micro Heat Engine" by S. Whalen, M. Thompson, D. Bahr, C. Richards & R. Richards, *Sensors and Actuators A* **104**, 290-8, 2003.

[11] "A Review of Micro Propulsion Technology" by Norman Chigier and Tevfik Gemci, in the *41st Aerospace Sciences Meeting and Exhibit* (Amer. Inst. Aeronautics and Astronautics), Jan. 2003.

[12] "The Little Engine" by Michael Abrams, *Mech. Eng.* **129**, 30-3, Mar. 2007.

2.2. Micro Fuel Cells

A fuel cell is essentially a battery which stores its reducing agent in a compartment separate from its electrodes and electrolyte, so that it can be readily refueled rather than recharged; it usually uses atmospheric oxygen as its oxidant. The power density grows with the area of the fuel cell's electrodes while the energy density grows with the volume of the fuel tank, making it fairly straightforward to trade off between these performance criteria. From a technical point-of-view, the main advantages of fuel cells over microturbines and microengines are first, that fuel cells are not Carnot cycle limited and hence do not absolutely require high temperatures for high efficiency, and secondly that fuel cells do not require high-speed moving parts.[13] Unfortunately low-temperature fuel cells require expensive catalysts and the delicate control of temperatures, fluid flows and chemical concentrations within the narrow range needed for good performance. In addition, microengines and microturbines can be tailored fairly easily to burn a variety of fuels, whereas fuel cells can directly use only hydrogen, methanol or perhaps formic acid. Nonetheless, far more research has been devoted to micro fuel cells than to microengines and microturbines as a means of small-scale power generation.

Just as this section was being written, two extensive reviews of micro fuel cells emphasizing the role of MEMS and MEMS-like technologies appeared in a spe-

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[13] Although the resulting tribological challenges were overcome in the case of the MIT microturbine project.

Table 2.1. Operating Characteristics of the Main Kinds of Fuel Cells

Kind of Fuel Cell	Catalyst	Temperature	Potential Fuels
Solid Oxide (SOFC)	Nickel (-) & Perovskite (+)	800 - 1000°C	Almost anything
Molten Carbonate (MCFC)	Nickel	600 - 700°C	Almost anything
Phosphoric Acid (PAFC)	Platinum	180 - 200°C	Hydrogen
Alkaline (AFC)	Nickel, Platinum	65 - 220°C	Hydrogen, Hydrazine
Proton Exchange Membrane (PEMFC)	Platinum	60 - 80°C	Hydrogen, Methanol, Formic Acid

cial issue of the International Journal for Energy Research devoted to Micro and Nano Energy Systems,[14] which are a major source for what follows. There are essentially five different kinds of fuel cells, which are shown along with their operating characteristics in Table 2.1.

Due to the caustic chemicals and/or high temperatures utilized in other types of cells, most micro fuel cell research has been directed towards PEM fuel cells, particularly using methanol as the fuel without prior reformation to hydrogen (the so-called Direct Methanol Fuel Cell, or DMFC). Nevertheless, solid-oxide micro fuel cells are under development by a number of groups who are as undaunted by the challenge of containing the high temperatures these cells re-

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[14] "Recent Advances in Microdevices for Electrochemical Energy Conversion and Storage" by G. J. La Ó, H. Jin In, E. Crumlin, G. Barbastathis & Y. Shao-Horn, *Intnl. J. Energy Res.* **31**, 548-75, 2007; "Micro-Fuel Cell Power Sources" by J. D. Morse, *Intnl. J. Energy Res.* **31**, 576-602, 2007.

quire as the MIT microturbine group. There are roughly three levels at which MEMS technologies can play a role in fuel cells: (1) individual fuel cell components can be built using MEMS to make them smaller or more efficient, and then assembled using more conventional methods; (2) various combinations of related fuel cell components, and in particular a microreactor which produces hydrogen gas from more easily stored liquid fuels, can be integrated on a single chip; (3) a complete fuel cell, or even an entire fuel cell stack, can be integrated together with all the microfluidic channels, sensors and actuators needed to keep it functioning optimally.

At the first level, a MEMS methanol concentration sensor is widely used in DMFCs to feed methanol to the anode at just the rate at which it reacts so that none has a chance to diffuse across the proton-exchange membrane to the cathode unreacted. In addition, the power produced by fuel cells under a load is often limited by the rate at which reactants or conducting ions diffuse to and from the electrodes, and these rates may be enhanced by microstructuring the electrode assemblies using MEMS. Another approach to this same problem enhances the rate of gas diffusion to and from the catalyst with a layer of microporous silicon, which makes diffusion one-dimensional while maintaining intimate contact of the catalyst with a current collector (as seen in Figure 2.2 (a)).

In the most common instance of the second level of MEMS integration, microreactors are used to generate hydrogen from hydrogen-rich chemicals, rather than storing it as a gas at high pressures or cryogenic temperatures. This substantially simplifies the operation and reduces the amount of catalyst needed in a PEMFC over one that operates directly on methanol, although some of these reactions require temperatures so high that one might just as well use a micro SOFC. Table 2.2 gives a list of the most important chemical reactions that have been used to this end. With the exception of sodium borohydride hydrolysis (which is relatively costly), all these reactions involve elevated temperatures and, with the further exception of hydrocarbon partial oxidation, they also consume heat. In such cases the heat is supplied by burning a portion of the fuel or resulting hydrogen. The partial oxidation and steam reforming reactions also have the drawback of producing some carbon monoxide, which poisons the catalyst in PEM fuel cells unless thoroughly scrubbed, as does any unreacted ammonia from ammonia cracking.

An example of a MEMS-based microreactor capable of either hydrocarbon steam

Table 2.2. Common Chemical Reactions for Generating Hydogen

Common Reaction Name	Catalysts	Temperature	ΔH (kJ/mol)
Hydrocarbon Partial Oxidation	various	800-1200°C	-77 for CH_4
Hydrocarbon Steam Reforming	Rh, Ru, Pd	700-1000°C	+165 for CH_4
Ammonia Cracking	Cu, Ni, Ru	400-900°C	+46.4
Alcohol Steam Reforming	Cu, Zn, Pd	200-400°C	+49 for CH_3OH
Sodium Borohydride Hydrolysis	Ni, Co, Ru	10-100°C	-250 (approx.)

reforming or ammonia cracking is shown in Figure 2.2 (b). It consists of two parallel thin-walled U-shaped tubes embedded at their turns in a suspended silicon block, all contained within a vacuum-sealed insulating chamber. In one tube fuel is burned to supply the necessary heat, which is conducted via the silicon block to other tube which is packed with the catalyst, where the hydrogen is produced. The steady state temperature gradient along the tubes is of order 2000°C/mm. For steam reformation, a second microreactor is used to remove any residual carbon monoxide from the hydrogen stream.

The third category is perhaps the most interesting, because even though fuel cells manufactured using MEMS generally produce less power per unit electrode area than do cells made by conventional means, they can also be made nearly three orders of magnitude thinner than conventional cells. This means that one can produce a considerably greater amount of power from a given volume. Realizing this potential, however, requires a form of MEMS that can conveniently assemble three-dimensional structures such as fuel cells stacks with a minimum of wasted space. Even though wafers produced by conventional MEMS can be bonded together, unlike MEMS this is an inherently serial process, and in addition the interconnects between wafers are relatively difficult to arrange.

Table III in La Ó *et al.* (see footnote 14) presents a variety of three-dimensional fabrication methods developed for electrochemical capacitors, along with an extensive discussion of their merits for micro fuel cell construction. Another

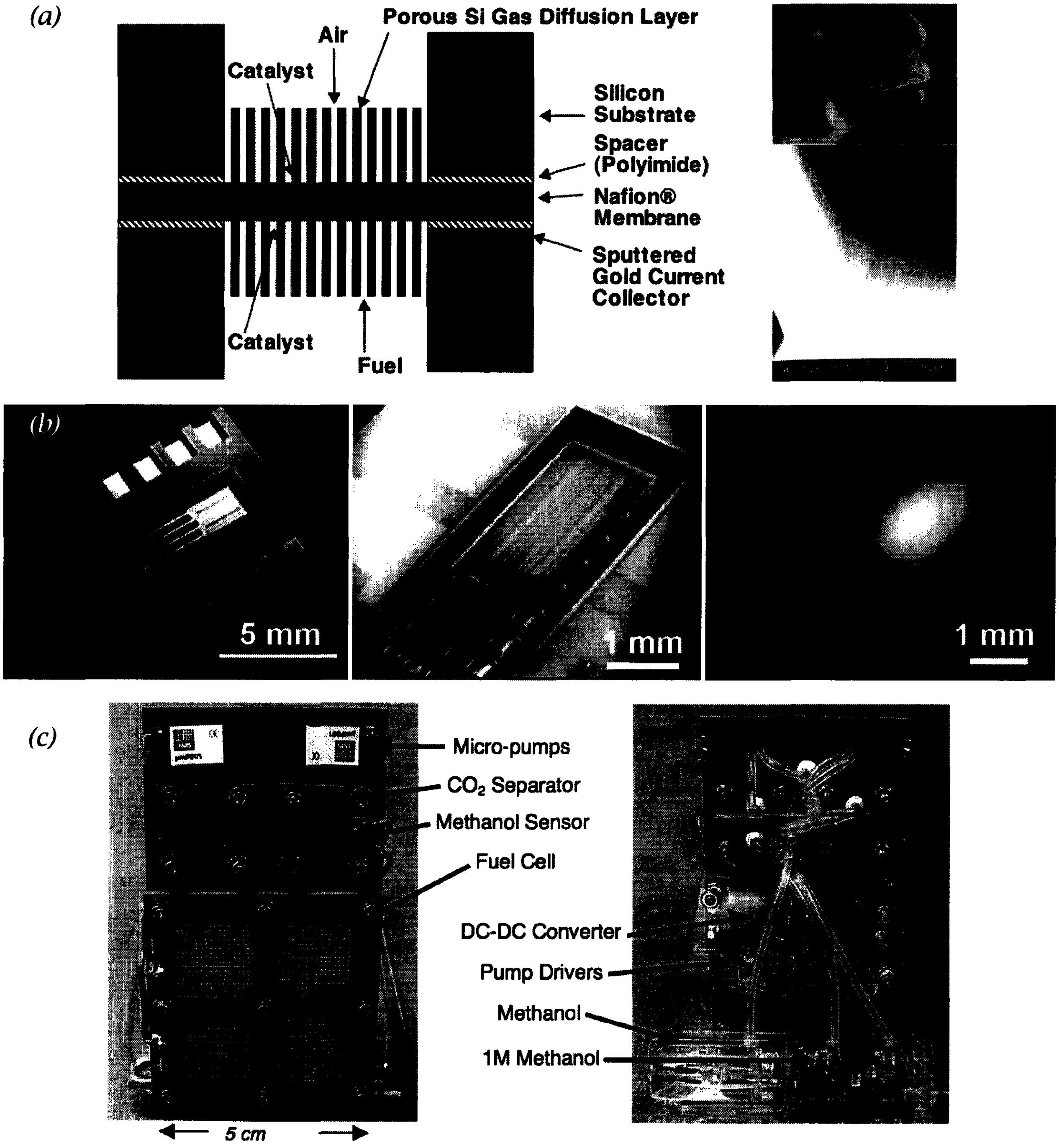

Figure 2.2. *Examples of the use of MEMS in micro fuel cells. (a) Microstructured PEMFC (Fig. 13 from J. D. Morse,* Intnl. J. Energy Res. **31**, *576-602;* © 2007 John Wiley & Sons, Ltd.*); (b) Microreactor for hydrogen production (Fig. 3 from K. F. Jensen,* MRS Bulletin **31**, *101-7;* © 2006 Materials Research Society*); (c) Ceramic MEMS DMFC (Fig. 11 from D. L. Wilcox* et al., MRS Symp. Proc. **687**, *B7.1.1-18;* © 2002 Materials Research Society*).*

method also developed for three-dimensional capacitors is however not mentioned in that table, probably because it lies a bit to one side of what most people regard as "MEMS." This method is known as Low-Temperature Cofired Ceramics (LTCC), and utilizes thin sheets of an organic binder impregnated with glass and metal particles. These sheets can be patterned with various materials on scales as small as 25 microns, and more importantly holes nearly that small can be drilled in them either mechanically or using lasers at rates of several hundred per second. These holes will form the fluid channels or, if filled with metal, interconnects between the layers. In the final step, up to 100 such layers are precisely positioned on top of one another, compressed and then fired at 850°C, leaving behind a ceramic block with the desired structures embedded in it. The main drawback of this approach is that no active electrical elements can survive such temperatures, but these can be added to the surface after firing if need be. Figure 2.2 (c) shows a DMFC produced by LTCC at Motorola Labs.[15]

2.3. Thermoelectrics, Thermionics and Thermophotovoltaics

Thermoelectrics are solid-state devices which produce electricity in the presence of a temperature gradient (the Seebeck effect), or heat flow when a current is driven through them (the Peltier effect). Thermionics convert heat to electricity by boiling electrons off a heated surface, exactly as in an old-fashioned vac-

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[15] "Add Ceramic MEMS to the Pallet of MicroSystems Technologies" by D. L. Wilcox Sr., J. W. Burdon, R. Changrani, Chia-Fu Chou, D. R. Koripella, M. Oliver, D. Sadler, P. von Allmen and F. Zenhausern, *MRS Symp. Proc.* **687**, B7.1.1-18, 2002.

uum tube. Thermophotovoltaics use a low-band-gap "solar" cell to convert the infrared light emitted by a hot object into electricity. Physically these three processes are quite different, but since they are functionally similar we treat them together here. None of them absolutely require MEMS for fabrication, but we shall see that in all cases there is a great deal to be gained by including micron-scale structures in them, which can be accomplished and adapted to mass production via MEMS.

The best materials for thermoelectrics have a low thermal conductivity but high electrical conductivity.[16] Alloys of (semi)metals from columns IV & V of the periodic table with those from column VI have these features and have been widely used in thermoelectrics, e.g. Bi/Te or Si/Ge. Their performance is typically summarized by a dimensionless figure of merit ZT, where T is the average of the hot and cold side temperatures in Kelvin. This figure of merit is usually less than one, in which case the efficiency of the power generation device can be at best about 20% of the Carnot limit. The efficiency rises to about 30% of the Carnot limit at $ZT = 2$ and to 50% for $ZT = 10$. Recently materials which enable a $ZT > 2$ have been formed by depositing thin films of thermoelectric materials with mismatched lattice structures, using much the same methods as are used to deposit thin films in MEMS. These materials are called superlattices.[17]

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[16] "Thermoelectric Materials, Phenomena, and Applications: A Bird's Eye View" by T. M. Tritt, M. A. Subramanian, *MRS Bull.* **31**, 188-94, 2006.

[17] "Aspects of Thin-Film Superlattice Thermoelectric Materials, Devices and Applications" by H. Böttner, Gang Chen & R. Venkatasubramanian, *MRS Bull.* **31**, 211-17, 2006.

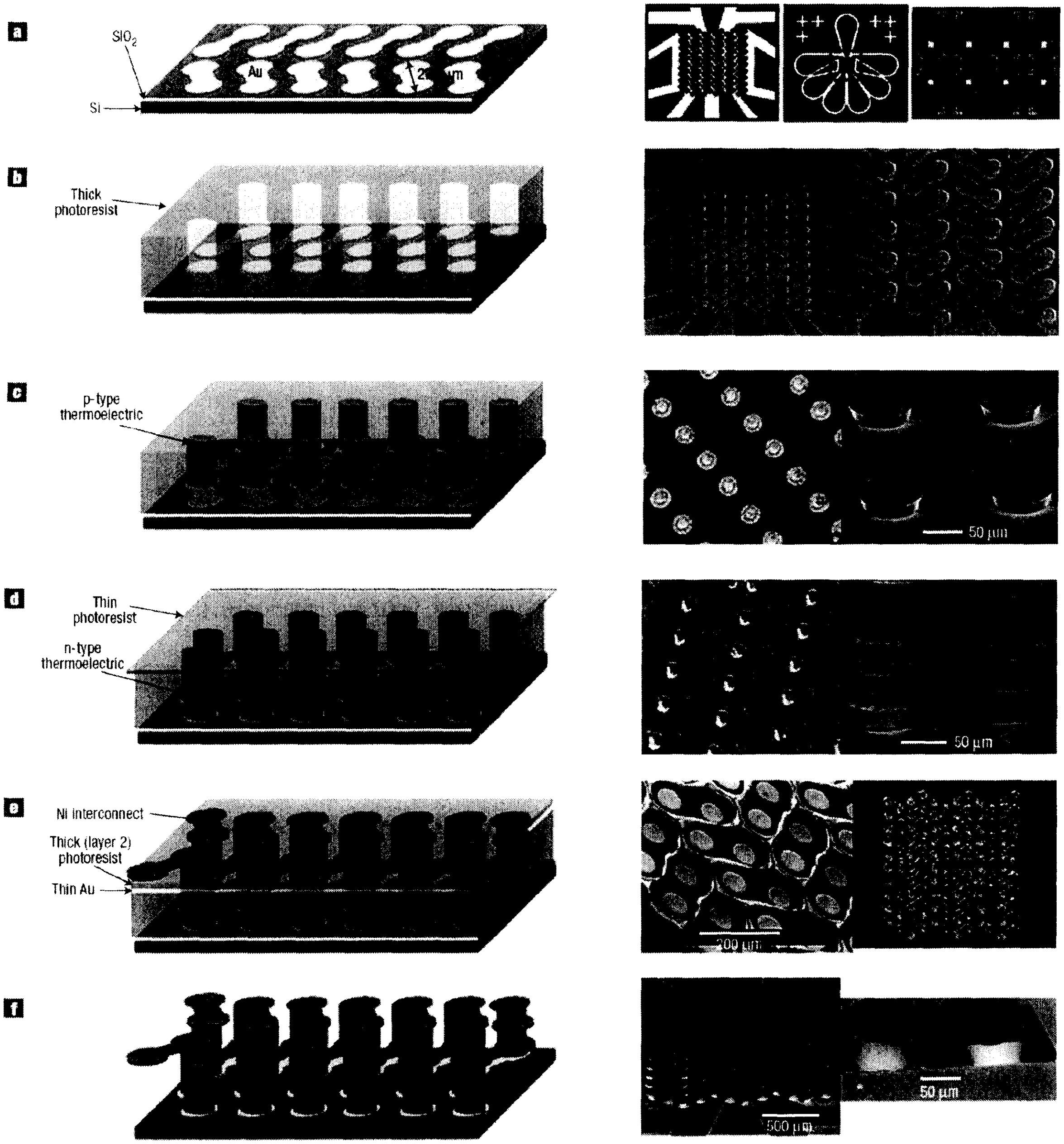

Figure 2.3. *Electrochemical MEMS fabrication steps for thermoelectric microdevice. Illustrations are shown on the left, and optical and SEM images on the right. Reproduced with permission from "Thermoelectric Microdevice Fabricated by a MEMS-like Electrochemical Process" by G. Jeffrey Snyder, J. R. Lim, Chen-Kuo Huang & J.-P. Fleurial,* Nature Materials 2, *528-31, 2003;* © 2003 Nature Publishing Group.

The efficiency of a thermoelectric device is not determined solely by the material, however, but also by how high the temperature of the hot side can be raised, by how effectively the other side can be cooled, by the electrical resistance of the thermopiles (blocks of thermoelectric material), and by the general requirement for good impedance matching. Because the voltage produced by any one thermopile is quite low, alternating blocks of n- and p-type thermopiles connected electrically in series but thermally in parallel are commonly used. With typical materials the individual thermopiles usually produce maximum power at a thickness of about 500 microns, which allows thermoelectric modules to be constructed by DRIE-style MEMS. An example of such a module is shown in Figure 2.3.

In practice, the susceptibility of semiconductor junctions to heat has limited thermoelectric generators to modest temperature gradients of at most a few hundred Kelvin. This is quite adequate for scavenging the waste heat produced by many industrial processes, and this becomes economical if the devices can be engineered to produce enough power per dollar invested, with efficiency *per se* playing only a secondary role.[18] One interesting example is a wristwatch thermoelectrically powered by body heat, which was developed by Seiko and is now a collector's item. In conjunction with a radio-isotope heat source thermoelectric systems also provide perhaps the most reliable and long-lived portable

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[18] "Recent Concepts in Thermoelectric Power Generation" by Gao Min & D. M. Rowe, *Proc. of the IEEE 21st Intnl. Conf. on Thermoelectrics*, 365-74, 2002.

power supply available, which was used for example to power the Apollo Program's lunar landers.

In cases in which expense remains an issue and the source of heat costs money but can achieve high temperatures, as for example with propane generated power for remote dwellings, thermionic[19] and thermophotovoltaic[20] systems become more attractive options. For small-scale power generation, MEMS finds a natural application in the form of microreactors to efficiently and safely generate the requisite temperatures of 500°C and above.[21]

Thermionic power convertors were first proposed in the early twentieth century, but it was not until the pioneering work of George N. Hatsopoulos while a graduate student at MIT in 1956 that the first practical devices were built.[22] The main problems to be overcome in making such devices are developing low "work function" electrodes which easily lose their electrons, and preventing "space-charge" effects in which the field from the electrons already in the gap

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[19] "Direct Energy Conversion: Fundamentals of Electric Power Production" by Reiner Decher, Oxford Univ. Press, 2006.

[20] "Microscale Radiation in Thermophotovoltaic Devices - A Review" by S. Basu, Y.-B. Chen & Z. M. Zhang, *Intnl. J. Energy Res.* **31**, 689-716, 2007.

[21] See e.g. "A Thermophotovoltaic Microgenerator for Portable Power Applications" by O. M. Nielsen, L. R. Arana, C. D. Baertsch, K. F. Jensen & M. A. Schmidt, *Proc. 12th Intnl. Conf. Solid State Sensors, Actuators and Microsystems*, pp. 714-7, IEEE, 2003, or "Microscale Combustion Research for Application to Micro Thermophotovoltaic Systems" by W. M. Yang, S. K. Chou, C. Shu, H. Xue, Z. W. Li, D. T. Li, J. F. Pan, *Energy Conversion & Management*, **44**, 2625-34, 2003.

[22] The company Hatsopoulos founded to commercialize his invention, Thermo Electron Corporation, expanded into environmental and other energy products with revenues of more than two billion dollars before it merged with Fisher Scientific in 2006. Although the company worked on thermionic power conversion for over twenty years, it made little or no money from it.

between the emitter and collector inhibits the emission of additional electrons. This latter problem may be alleviated in one or both of two ways: (1) by injecting positive ions, usually of alkali metals, into the gap which neutralize the charge, or (2) by placing the electrodes very close together so that emitted electrons are rapidly collected. In the extreme case of an interelectrode gap of order 10 nanometers, quantum mechanical tunneling may also lower the effective work function. At least one example of an integrated combustor and thermionic generator built using MEMS is available,[23] and nanostructures which allow nanometer inter-electrode gaps have recently been proposed.[24]

Thermophotovoltaic power generation, in contrast, converts the blackbody radiation emitted by a hot object into electricity using a photovoltaic cell. Such a photovoltaic cell should absorb radiation in the infrared, and semiconductors with band gaps down to almost a tenth of an electron volt are available. This corresponds to a wavelength of about 20 microns, which is squarely in the mid-infrared. The efficiency may be optimized first, by using specialized materials which selectively emit radiation at a frequency which matches the photocell's band gap, for example rare earth oxides, and second by using a filter which reflects other frequencies back onto the emitter where the energy may subse-

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[23] "Micro Combustion - Thermionic Power Generation: Feasibility, Design and Initial Results" by Chunbo Zhang, K. Najafi, L. P. Bernal & P. D. Washabaugh, *Proc. 12th Intnl. Conf. Solid State Sensors, Actuators and Microsystems*, pp. 40-4, IEEE, 2003.

[24] "Thermionic-Tunneling Multilayer Nanostructures for Power Generation" by Taofang Zeng, *Appl. Phys. Lett.* **88**, 153104, 2006.

quently be reemitted with the right frequency. Both the emitter and the filter may be made more selective by microstructuring them on a scale comparable to the desired wavelength to obtain "photonic bandgap materials," a task is well-suited for MEMS technologies.[25]

These measures to improve efficiency will nevertheless tend to decrease the power output. This in turn is limited by the so-called critical angle with the surface normal of the emitter, beyond which radiation is reflected at the surface back into the emitter. It turns out, however, that when a radiation emitting body is separated from an absorbing body by a distance less than the wavelength of the radiation, new mechanisms of energy transfer come into play which circumvent this limit and can increase the emitted power tenfold. Placing a photocell within microns of a hot emitter without destroying it is something of a trick, which MEMS promises to play a key role in making not only doable, but affordable. One of our case studies in Chapter 3 will be devoted to a company which aims to do precisely this.

2.4. Vibrational and Electromagnetic Energy Scavengers

Energy scavenging is also called energy harvesting, but as argued in Chapter 1 all forms of energy "generation" are better regarded as energy harvesting, so we prefer the term "scavenging" here. This differs from our use of the term "har-

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[25] "The Challenge of High-Performance Selective Emitters for Thermophotovoltaic Applications" by A. Licciulli, D. Diso, G. Torsello, S. Tundo, A. Maffezzoli, M. Lomascolo & M. Mazzer, *Semicond. Sci. Technol.* **18**, S174-83, 2003.

vesting" in that the energy is obtained as a by-product of some human activity that would otherwise just waste it. The production of electricity from waste heat using thermoelectrics, which was discussed in the previous subsection, is therefore an example of scavenging, as is the use of photovoltaic cells to extract energy from indoor light.

The reason that energy scavenging has recently received widespread interest lies in the fact that small MEMS-based sensors require very little power, while MEMS actuators may only need power for brief periods and so can be powered by MEMS-scale thin-film lithium ion batteries the charge of which is maintained by an energy scavenger. Self-organizing networks of such sensors and actuators communicating wirelessly are rapidly coming into widespread use to monitor the condition of infrastructure such as bridges, to turn off unneeded lights or maintain a constant temperature in buildings, and the like. The devices themselves are often referred to as "smart dust,"[26] and a discussion of various approaches to powering them was published a few years back.[27] Energy scavenging is also being studied as a means of powering medical implants.[28]

One thing our civilization's infrastructure is very good at is making noise. The threshold for hearing is about one pico-Watt applied to the ear drum, which is

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[26] "Sizing Up Smart Dust" by Pam Frost Gorder, *Comput. Sci. Eng.* **5**, 6-9, Nov.-Dec., 2003.

[27] "Power Sources for Wireless Sensor Networks" by S. Roundy, D. Steingart, L. Frechette, P. Wright & J. Rabaey, *Lec. Notes Comput. Sci.* **2920**, 1-17, 2004.

[28] "MEMS Inertial Power Generators for Biomedical Applications" by P. Miao, P. D. Mitchenson, A. S. Holms, E. M. Yeatman, T. C. Green & B. H. Stark, *Microsyst. Technol.* **12**, 1079-83, 2006.

used as the reference for the measurement of noise levels in decibels (ten times the logarithm of the ratio with that reference). The level of noise next to a freeway averages about 80 decibels, and the noise of a jet taking off can exceed 120 decibels - one Watt to your ear drum. Painful though that may be, it is hardly enough to power a small flashlight.

A comprehensive recent review of vibrational energy scavengers has recently been published.[29] These devices typically consist of a "proof mass" or weight attached to an elastic element such as a cantilever, the resonant vibrations of which in turn drive a generator of some sort. As with microengines, the generator itself is usually electromagnetic, electrostatic or piezoelectric in nature. The randomly varying current it produces may be rectified, filtered and used directly, though it would more commonly be used to charge a capacitor or thin-film battery to compensate for its intermittency. The power densities thus obtained are usually less than milli-Watt per cubic centimeter, which is nevertheless sufficient to power many MEMS devices. Although vibrational energy scavengers can certainly be made without MEMS, it is most economical to integrate a MEMS scavenger directly on the same chip as the device it powers.

Energy scavengers can attain somewhat higher power densities by utilizing the fact that the spectral density of noise is often greatest at very low frequencies,

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[29] "Energy Harvesting Vibration Sources for Microsystems Applications" by S. P. Beeby, M. J. Tudor and N. M. White, *Meas. Sci. Technol.* 17, R175-95, 2006.

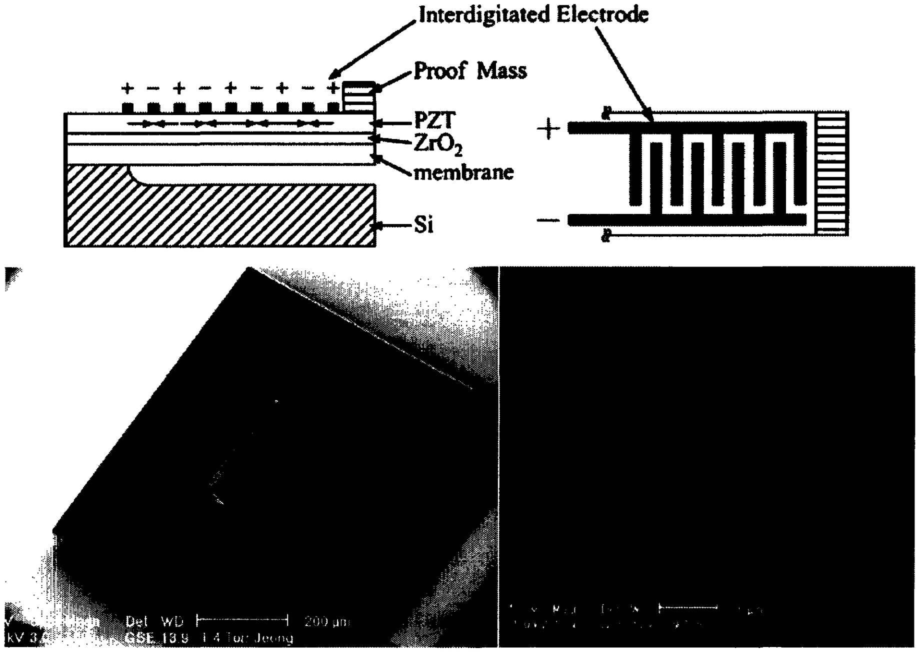

Figure 2.4 (a). *A vibrational energy scavenger based on a cantilever coated with the piezoelectric ceramic PZT, and with an SU-8 proof mass (sticking up from center of device in the lower left panel). Reproduced with permission from "MEMS Power Generator with Transverse Mode Thin Film PZT" by Y. B. Jeon, R. Sood, J.-h. Jeong & S.-G. Kim,* Sensors and Actuators A **122**, *16-22, 2005.* © 2005 Elsevier B.V. All Rights Reserved.

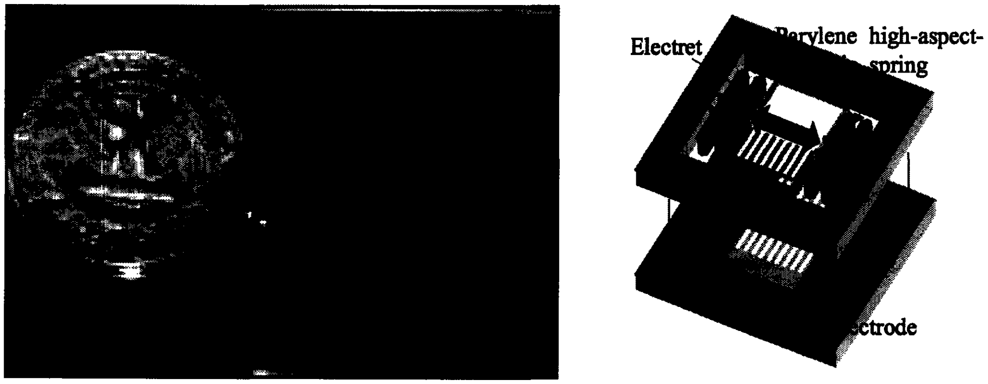

Figure 2.4 (b). *A vibrational energy scavenger using an electrostatic generator based on an "electret" material exhibiting a permanent electric dipole. Reproduced with permission from the powerMEMS 2006 paper, "Micro Seismic Electret Generator for Energy Harvesting" by T. Tsutsumino, Y. Suzuki, N. Kasagi, K. Kashiwagi & Y. Morizawa, available on-line from* http://www.thtlab.t.u-tokyo.ac.jp/Doc/for_web_pmems2006.pdf.

as in a self-winding wristwatch for example. Unfortunately, these are difficult to make via MEMS simply because the resonance frequency of a structure increases as its size decreases, all else being equal. Another design constraint stems from the fact that the output power is generally maximized when the output impedance matches the damping coefficient of the elastic element, whereas the range of frequencies that can be utilized increases with damping.

Figure 2.4 illustrates some recent MEMS-based vibrational energy scavengers, including a piezoelectric device developed by Prof. Sang-Gook Kim's group at MIT (a), and an electrostatic device utilizing a ferroelectric "electret" material which possesses a permanent electric dipole, which was developed by Prof. Nobuhide Kasagi's group at the University of Tokyo (b).

Another form of energy scavenging uses a rectifying antenna to extract energy from the radio-frequency electromagnetic radiation that permeates urban environments today.[30] Alternatively one may use a small radio transmitter of one's own, tuned to the device's resonance frequency, whenever power is needed. This is in fact how RFID chips work - although this is really energy transmission rather than scavenging. Because such devices have usually been built using conventional microelectronics processes without the use of MEMS *per* se, we will not discuss electromagnetic energy scavenging/harvesting in much detail

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[30] A particularly rich source of the latter are the high-voltage power lines which crisscross our countryside, although the electric utilities would rather you didn't know this!

here.[31] We note however that "RF-MEMS," the use of mechanical resonators, switches, variable capacitors and the like has become important in making efficient, high-quality, high-power single-chip transmitters and receivers for cell phones and many other devices, and these components should also be useful in building efficient broadband electromagnetic energy scavenging systems.[32]

3. Implications for Electricity Storage

The attentive reader may have noticed that none of the technologies introduced above are concerned with the storage of electricity *per se*. Energy scavenging just recovers some small amount of energy as electricity that would otherwise be dissipated, while microengine-driven generators and micro fuel cells convert chemical fuels into electricity, as do thermoelectric, thermionic and thermophotovoltaic devices when driven by a combustor. Indeed the chief impetus behind all these technologies is to produce relatively modest amounts of electricity in a portable fashion or in a remote location. In this capacity they threaten to largely displace rechargeable batteries, which are presently much more widely used for these purposes and are genuinely capable of storing electrical energy. What then is the connection to compact, cost-effective electricity storage?

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[31] See e.g. "Recycling Ambient Microwave Energy with Broad-Band Rectenna Array" by J. A. Hagerty, F. B. Helmbrecht, W. H. McCalpin, R. Zane & Z. B. Popovic, *IEEE Trans. Microwave Theory & Techniques* **52**, 1014-24, 2004; "RF Energy Harvesting with Multiple Antennas in the Same Space" by Minhong Mi, M. H. Mickle, C. Capelli & H. Swift, *IEEE Antennas & Propag. Mag.* **47**, 100-5, Oct. 2005.

[32] See e.g. "MEMS for Wireless Communications: 'from RF-MEMS Components to RF-MEMS-SiP'" by H. A. C. Tilmans, W. de Raedt & E. Beyne, *J. Micromach. Microeng.* **13**, S139-63, 2003.

The most obvious connection lies in the fact that nearly all of the devices we have considered can use hydrogen as a fuel, and electricity can be converted into hydrogen by the electrolysis of water with an optimized efficiency of about 80%. A fuel cell, also optimized for maximum efficiency, can convert the hydrogen back into electricity with about the same efficiency, so the net efficiency can be as much as 64%. Although cost considerations make it unlikely that one would ever operate such devices to maximize efficiency rather than throughput, this is already less than the 80% or so that could be achieved using batteries, flywheels, compressed air storage or even just pumping water uphill, let alone the 95% or more that can be achieved by ultra-capacitors or superconductors. More important, perhaps, is the fact that at this time we do not know of a more cost effective means of storing hydrogen in a portable device than can currently be achieved using lithium ion batteries to store the electricity directly - and much more efficiently. We conclude that, barring some fairly significant breakthroughs, none of the foregoing power-MEMS devices will be used with hydrogen for electricity storage purposes any time soon.[33]

The reasons we believe that power MEMS has a key role to play in solving the electricity storage problem actually have more to do with the history and sociology of technology than with the technology itself. The literature that we refer

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[33] This is not to imply that MEMS-like processes have not been widely applied to other kinds of energy storage devices. For example, TPL Inc. in Albuquerque NM (http://www.tplinc.com) has a patent held jointly with Northrup Grumman and CalTech on a supercapacitor built using bulk micromachining (#6,621,687), and CYMBET Corp. in Elk River MN (http://www.cymbet.com) sells thin-film lithium ion batteries produced by a plasma-enhanced CVD process.

to builds upon the concept of *disruptive technologies*, which include any technological development which qualitatively changes the dynamics of the marketplace, whether by creating new markets or enabling new value propositions. The most important authors behind the following discussion are Prof. Jim Utterback at the MIT Sloan School of Management and Prof. Clayton Christensen at the Harvard Business School.[34]

Almost by definition, a disruptive technology is one with an impact which most people do not see coming, with the result that it significantly changes the balance of power across one or more major lines of business. The best example from recent times is of course the internet, which spawned a plethora of new companies that came and went with dizzying speed. History, however, is replete with many other examples, including the telegraph, the railway system, the automobile, commercial aviation, the transistor and the integrated circuit it enabled, and even such seemingly staid businesses as the plate glass and ice making industries. In all cases the technological foundations for a radically new way of doing business were under development for a long time, during which they got relatively little attention because their "killer app" had not yet been discovered. In most cases this killer app was not the first application, nor was the first company to use the technology in a product necessarily the one that became dominant.

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[34] See "Mastering the Dynamics of Innovation" by James M. Utterback, HBS Press, 1996, and "The Innovator's Dilemma" by Clayton M. Christensen, HBS Press, 1997.

I believe that power MEMS will prove to be a rich source of such disruptive technologies, and that the cost-effective storage of electrical energy will be its ultimate killer app. I do not know, and do not care to predict, what form the dominant design will ultimately take, let alone the exact path by which it will evolve into that form. But I can say a bit more about why I believe it.

Chemistry and electrical engineering appear to be on a collision course. The former has always been nanoscopic, but still lacks any systematic means of designing large supramolecular structures with desired functional properties. Electrical engineering, in contrast, has been designing and building devices with specified functions all along, but has lacked the control needed to build nanoscopic systems. These two disjoint fields are now within an order of magnitude of operating on the same scale, but the cross-fertilization between them that will be needed to realize the best of both approaches has hardly even begun. Once it does, a merger of "top-down" and "bottom-up" approaches to nanotechnology will take place that will completely change both fields.

Of course the ability to design molecular structures with known functional properties would have a huge impact on every branch of engineering and the applied sciences, but this will not happen all at once. The exquisite balance of direct and entropic forces that dictates the structures of biological macromolecules, for example, may not ever be reduced to a predictive theory. It turns out however that the differences between the total energies of not very different molecular structures can be predicted quite well from first principles, at least if these energy differences exceed the energy of the interactions between the molecules and their environment.[35] Thus it is reasonable to expect that better ways of storing electrical energy will be one of the first things to come out of the on-coming top-down, bottom-up merger. In one of our case studies we will look at a specific example where this may already be within reach, in the form of a MEMS device which stores energy in the mechanical deformation of carbon nanotubes, much as a wristwatch stores energy in a steel main spring.

The first commercial applications of power MEMS, however, will probably be in the portable and/or remote power arenas, where it will simply displace traditional chemical batteries for many if not most purposes. While this may drive a few of the conglomerates that presently make most of the world's batteries out of the market, by and large it will be an example of a sustaining, rather than a disruptive, technological transition. The important point is that once it happens investment will begin to flow towards power MEMS in a big way. This in turn will create a critical mass of engineering talent and infrastructure, which will enable further research and development. At the same time the chemists will respond to this challenge from electrical engineering by finding new materials for better batteries, following the bottom up approach - and these will ultimately also find a use in power MEMS.

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[35] See e.g. "Toward Computational Materials Design: The Impact of Density Functional Theory on Materials Research" by J. Hafner, C. Wolverton & G. Ceder, *MRS Bull.* **31**, 659-68, Sep. 2006.

In order to gauge the impact which such an industrial ecosystem could have on how energy is used by the human race, let us make an analogy with the classic case of an industry that has been through many successive waves of disruptive innovations over the last half century: digital mass storage.[36] The first disk drive, the IBM RAMAC from 1956, stored about 250 bits per square inch, while today's disk drives are approaching a terabit per square inch, nearly four billion times the RAMAC. This remarkable pace of technological evolution is illustrated by the experience curve for the disk drive industry shown in Figure 2.5.

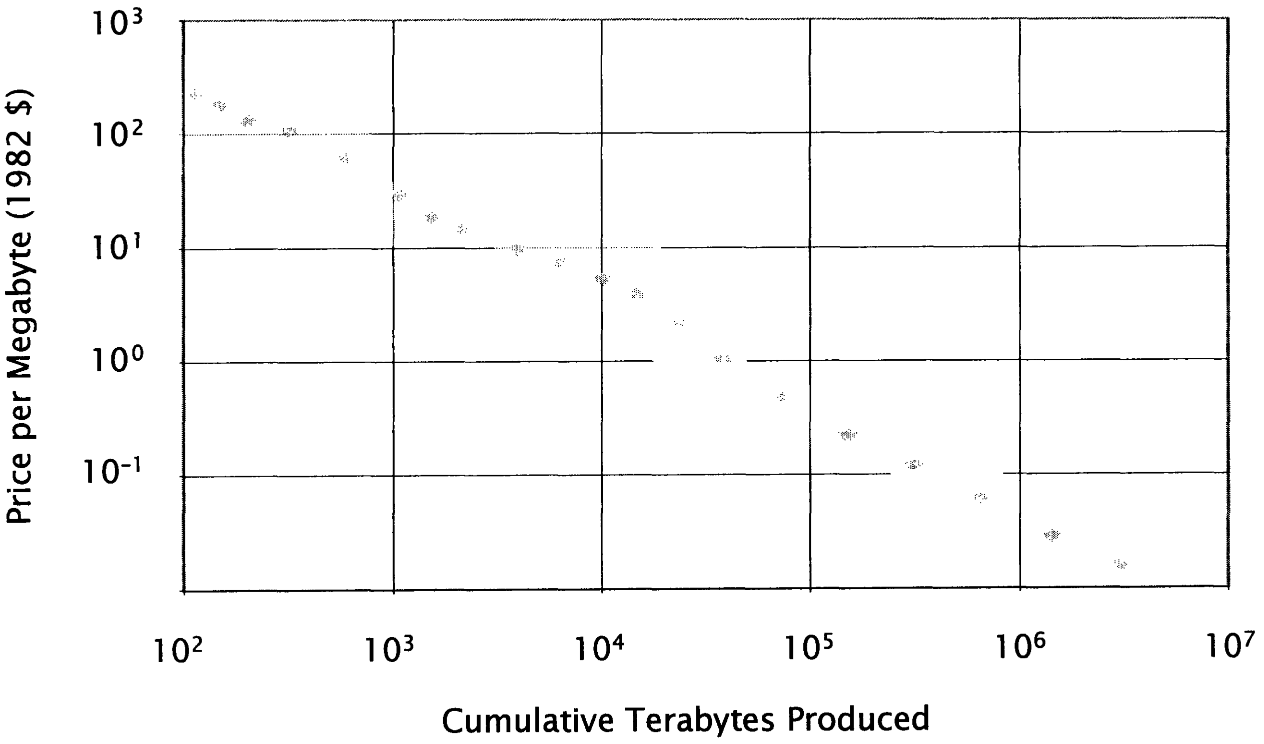

Figure 2.5. *Experience Curve for Disk Drive Industry, 1981 - 2000* (source: Fig. 1.3 of Christensen, footnote 34, through 1987 and a Salomon, Smith, Barney Brokerage Report thereafter, both of which obtained their data from Disk/Trend Report).

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[36] This is extensively discussed in Christensen, footnote 34.

At one terabit per square inch, the distance between adjacent bits is on the order of 25 nanometers. In order to gain some feeling for how far the degree of miniaturization attained in information technology might take us in the field of energy storage, let us suppose we can build a device of that size which stores energy by ionizing a hydrogen atom. This energy is 13.6 electron volts, or 2.18×10^{-18} Joule. If we now fill space with a cubic lattice of such energy storage devices, we obtain about 6.4×10^{19} devices per liter, for an energy density of 140 Joule per liter, or about 0.04 Watt-hours per liter. This is less than a thousandth of what can be obtained from chemical batteries, which is essentially why battery technology is still considered part of chemistry rather than electrical engineering. For now!

Chapter Three: Power MEMS Markets, Production and Business Models

> *... visionary scientists and engineers such as [Norbert] Wiener and [John] Diebold were essentially right fifty years ago when they foresaw the many potential applications of electronic computers ... Where some forecasts went badly wrong was in their estimation of the time scale. Wiener failed to take account of the long time lags in building up a capital goods supply industry and a component industry on a sufficient scale ... he underestimated the time scale needed to educate and train millions of people in the design, redesign, operation and maintenance of a huge variety of processes incorporating the new technology. Finally, he took insufficient account of the relative costs of the new technology which was still unattractive in purely economic terms for many potential applications.*

From *The Economics of Industrial Innovation* by Chris Freeman and Luc Soefe, p. 185, The MIT Press, Cambridge MA, 3rd edition, 1997

We begin this chapter with a survey of academic, inventive and commercial activity in the main technologies to which power MEMS is applicable, as identified in Chapter 2. We then move on to consider the markets for such advanced power supplies, the infrastructure, standards and cost structures associated with the production of MEMS-based devices generally, and consider some possible business models for the commercialization of power MEMS in each of these four main technologies. We close with two case studies, one of a company developing a MEMS-based thermophotovoltaic power supply, and the other devoted to a novel energy storage device based on MEMS and carbon nanotubes.

1. Scientific and Commercial Activity in Areas to which Power MEMS Is Applicable

At the time of writing there does not seem to be a single energy technology product on the market wherein MEMS plays a central role. There are however a couple of dozen startup companies out there dedicated to introducing such products within the next few years, and that number is growing rapidly. In addition, a number of well-established diversified companies are watching these startups, ready to partner with or acquire them as soon as their path to market becomes clear, or else supporting small in-house research teams which they hope will figure that out for them in due course. Furthermore, the power MEMS 2006 meeting held November 29 through December 1 at the University of

California Berkeley included an evening roundtable on commercialization, and the power MEMS 2007 meeting to be held November 28 through 29 in Freiburg, Germany will be back-to-back with the Fraunhofer Institute's Micro Energy Technology Symposium (aka "Power-to-Go") on November 27, which is directed mainly at industry participants.[1]

Let us begin by considering the rate at which relevant scientific papers have been published since 1990, which is plotted as a stacked bar graph in Figure 3.1. Here and in what follows, we have limited ourselves to the DMFC (plus one variant that uses a different liquid fuel, formic acid), since the numbers for all possible kinds of micro fuel cells would dwarf those of our other technologies. Clearly there has been an enormous upsurge of interest in all our technologies over this period, but even the DMFC is dwarfed in turn by the interest in lithium ion batteries, to which over 1000 papers a year have been devoted since 1999 (data not shown).

Turning now to patent activity (Figure 3.2), we see a similar trend, save that the DMFC does not come out nearly so far ahead of the other technologies, and is actually behind the conglomerate of thermoelectrics/photovoltaics (and thermionics). This is probably due to a much higher level of interest in the DMFC from academia, where not nearly so many patents would be issued. The abrupt decline in the number of patents starting in 2002 is due to the fact that

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[1] See http://www.powermems.org.

it becomes increasingly probable that a patent filed after this date will not yet have been issued by the USPTO.

Finally, a good-faith effort was made to identify all companies that currently offer products based on one of our four main classes of technologies, or are actively engaged in trying to bring such products to the market (Figure 3.3). Large diversified companies were included only if their press releases and patent fil-

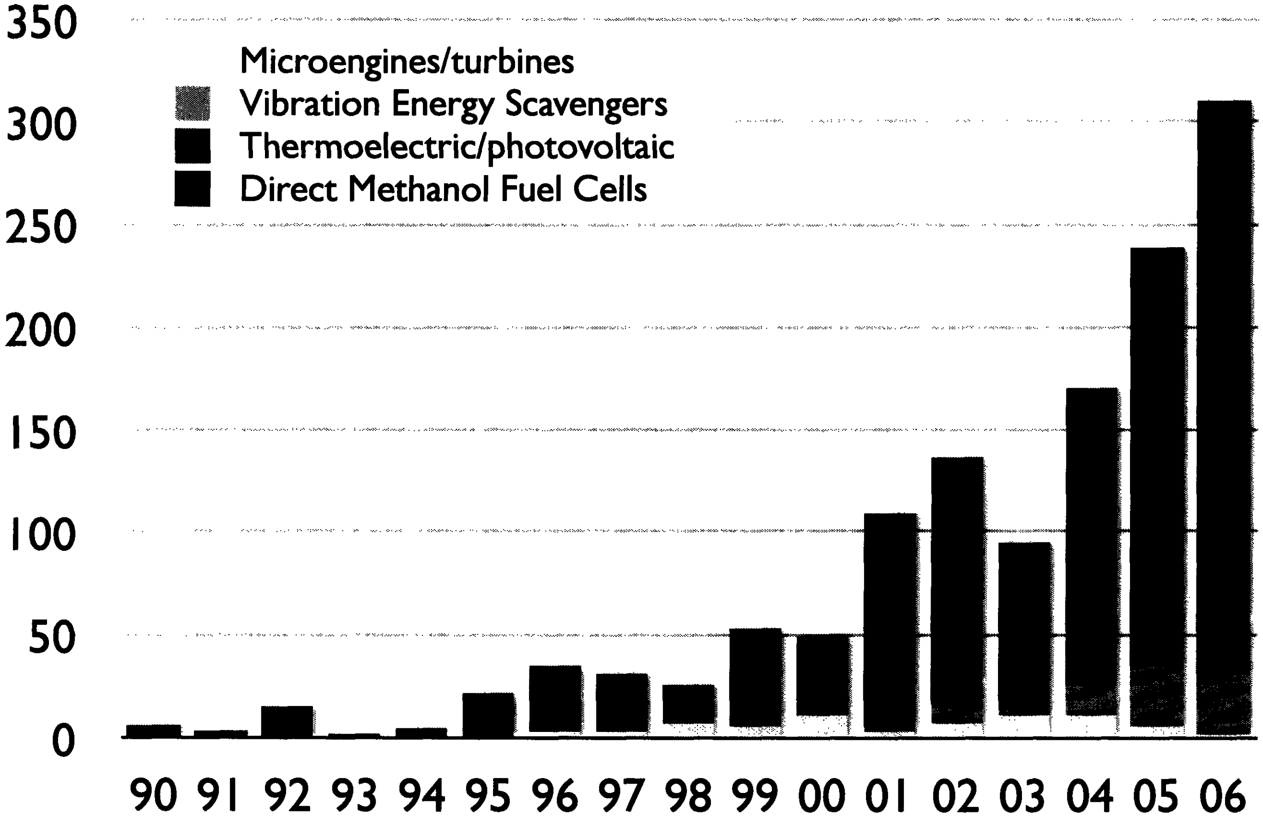

Figure 3.1. *Publications in the main classes of power MEMS technologies 1990 - 2006. Data were obtained via keyword searches of the Engineering Village INSPEC database on March 6, 2007, save for the microengines/turbines data where since these keywords were not specific enough, references were compiled from recent reviews and Ph.D. dissertations in the area. Note searches were* not *specific to MEMS-based technologies.*

ings indicated that they were engaged in such efforts. The main sources here were the Assignees of relevant patents, Dunn-Rankin *et al.'s* review (see footnote 4), the Thermoelectric News web site,[2] repeated internet searches, and word of mouth. No effort was made to restrict this list to those that are specifically focussed on MEMS, since this is difficult to do with certainty even for

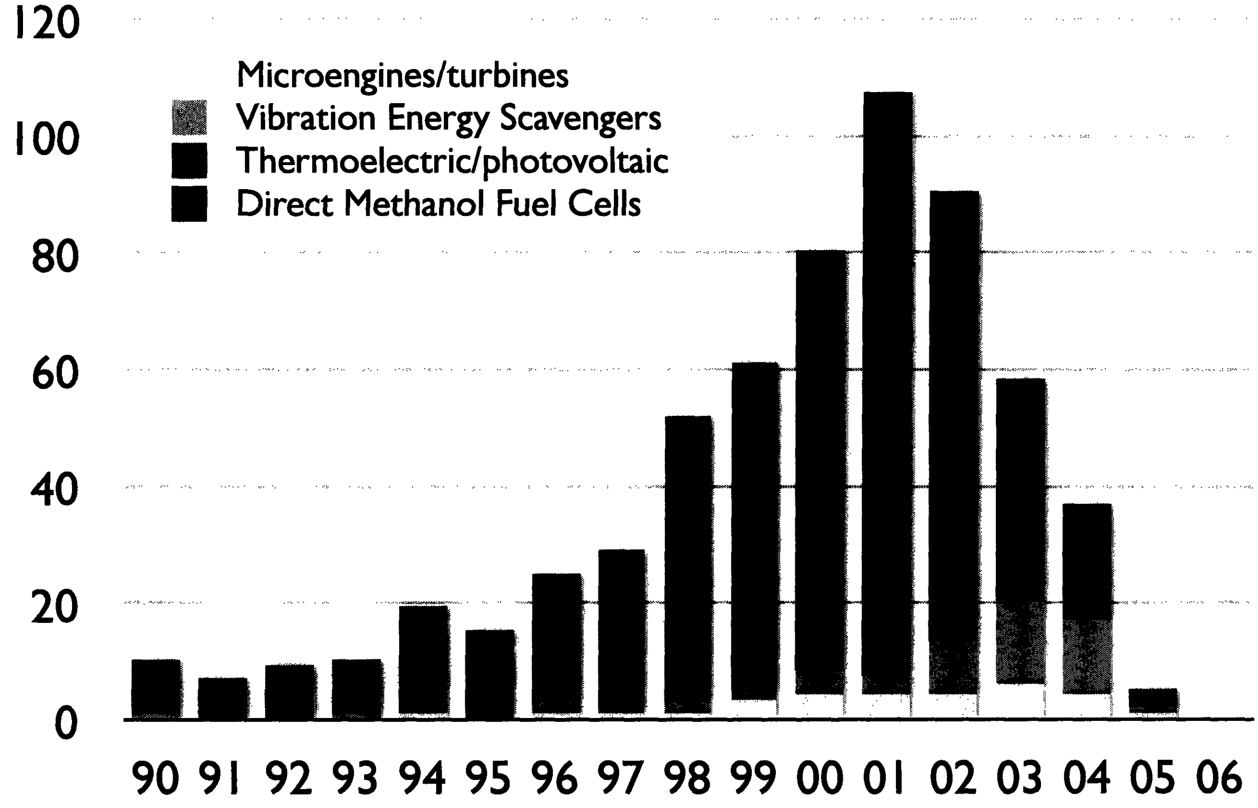

Figure 3.2. *Patents filed in the main classes of power MEMS technologies 1990 - 2006. Data were obtained via keyword searches of the US Patent & Trademark Office's web site in March 2007, save for the microengines/turbines data where since these keywords were not specific enough, patents were obtained from cross-references to the MIT microturbine patents plus a few others from Dunn-Rankin* et al. *(footnote 1). No pending patents included - that would have at least doubled the totals particular of the DMFC!*

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[2] http://www.zts.com, accessed in March 2007.

those products that are already out there. Nevertheless, when we list those companies explicitly in Appendix A, we will indicate those that are clearly known to be making essential use of MEMS. Thermoelectric companies include only those with an interest in power generation; those that appeared to be focussed solely on Peltier cooling were not included even when they used MEMS technologies.[3] Similarly, none of the many companies which make small, generally internal combustion, engines for hobbyists were included.

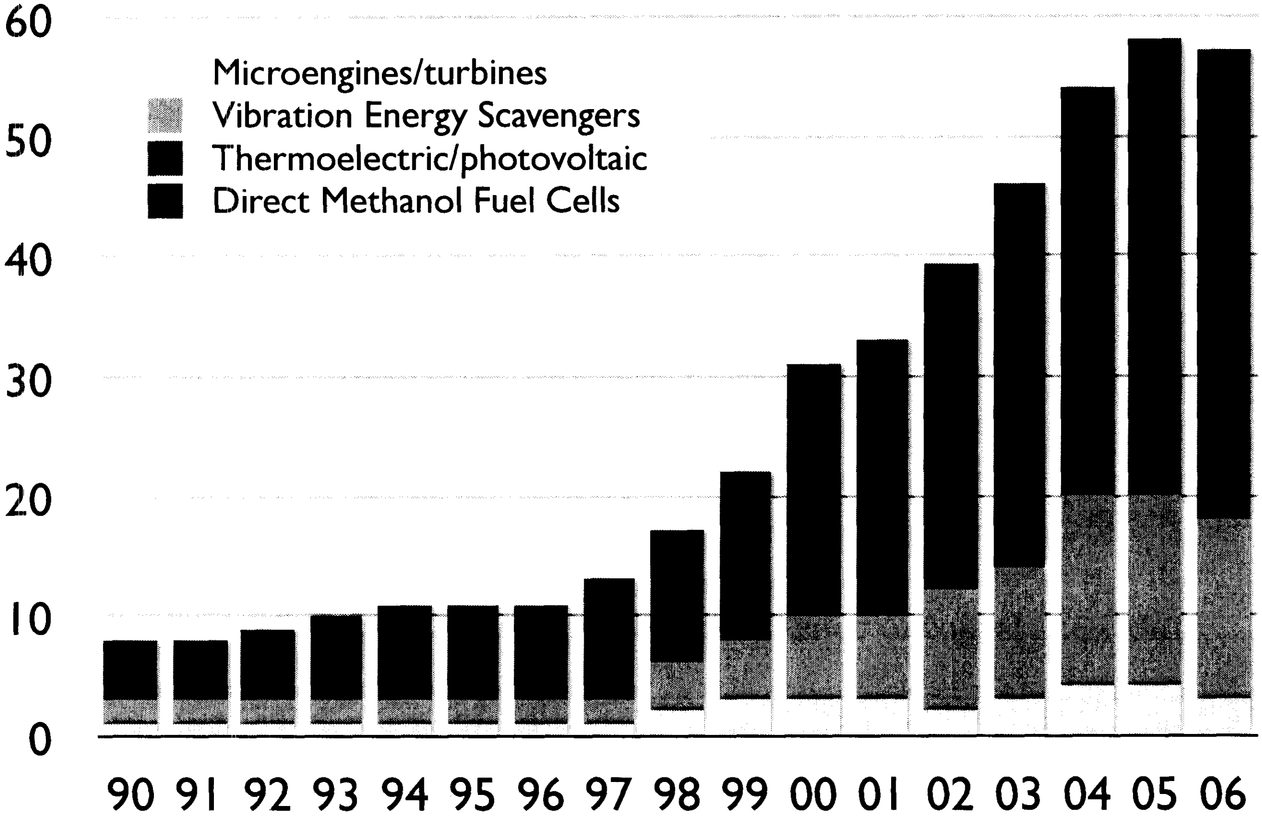

Figure 3.3. *Number of companies known to be working on technologies to which power MEMS is applicable 1990 - 2006 (see text for an indication of how these data were obtained). No attempt was made to restrict these data to companies using MEMS.*

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[3] See, for example, Nextreme (http://www.nextreme.com) and Nanocoolers (http://www.nanocoolers.com).

Taken together, these data indicate a substantial upswing in commercial activity devoted to small-scale electricity production even using such venerable technologies as small engines and thermoelectrics, to say nothing of more recent upstarts such as the DMFC. In many cases these activities are focussed on the new opportunities created by the advent of MEMS, the applications of which have also grown vastly since 1990. Let us now dig deeper into these issues.

2. Potential Power MEMS Markets

The market-pull behind most corporate interest in power MEMS today is the need to power small electronic devices, which can be either hand-held or laptop consumer electronics, or else autonomous sensors, actuators and vehicles. The reason is that nobody is very satisfied with existing battery technologies, even lithium ion batteries, which are well on their way to becoming the "dominant design" for this application. There remain, nonetheless, a number of po-

Table 3.1. Issues to consider in matching power supplies to markets

Performance	Economics	Convenience	Others
Volumetric energy density	Initial cost per unit performance	Degradation with number of uses	Undesirable by-products like heat
Gravimetric energy density	Cost of recharging	Degradation with time left unused	Environmental issues
Volumetric power density	Disposal costs, if any	Degradation with temperature etc.	Reliability under normal usage
Gravimetric power density	Safety under normal usage	Recharge time, form factor, etc.	Safety in fire, high impact etc.

tentially large, albeit perhaps less well-established, markets for better power supplies of all sorts, each with its own particular requirements and preferences. The features of power supplies which may be important to customers and investors are summarized in Table 3.1.

The performance of power supplies is typically compared using a Ragone plot,[4] in which power and energy density are plotted against one another on a logarithimc scale, as in Figure 3.4. In this Ragone plot, the diagonal lines are labeled by the time the power supply would last without recharging, and the various market requirements for performance are indicated by cross-hatched circles. The "Personal Power Target" range defined by Dunn-Rankin *et al.* (footnote 4) is indicated by the shaded parallelogram. The shaded regions correspond to each of the four main classes of power MEMS devices from Chapter 2, as indicated by the legend. It should be noted that the oval for vibrational energy scavengers should actually be moved much further to the right, since the amount of energy they deliver depends only on the amount of suitable energy in their environment and how long they last without wearing out. The thermoelectrics / photovoltaics (and thermionics) region includes that for vibration scavengers since in that realm they too are assumed to be operating as heat scavengers, rather than being fed heat from the combustion of a fuel as in the left-hand portion of the yellow region. The upside-down "L" shapes for micro fuel cell and micro-

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[4] "Personal power systems" by D. Dunn-Rankin, E. Martins Leal & D. C. Walthur, *Prog. Energy Combust. Sci.* **31**, 422-65, 2005.

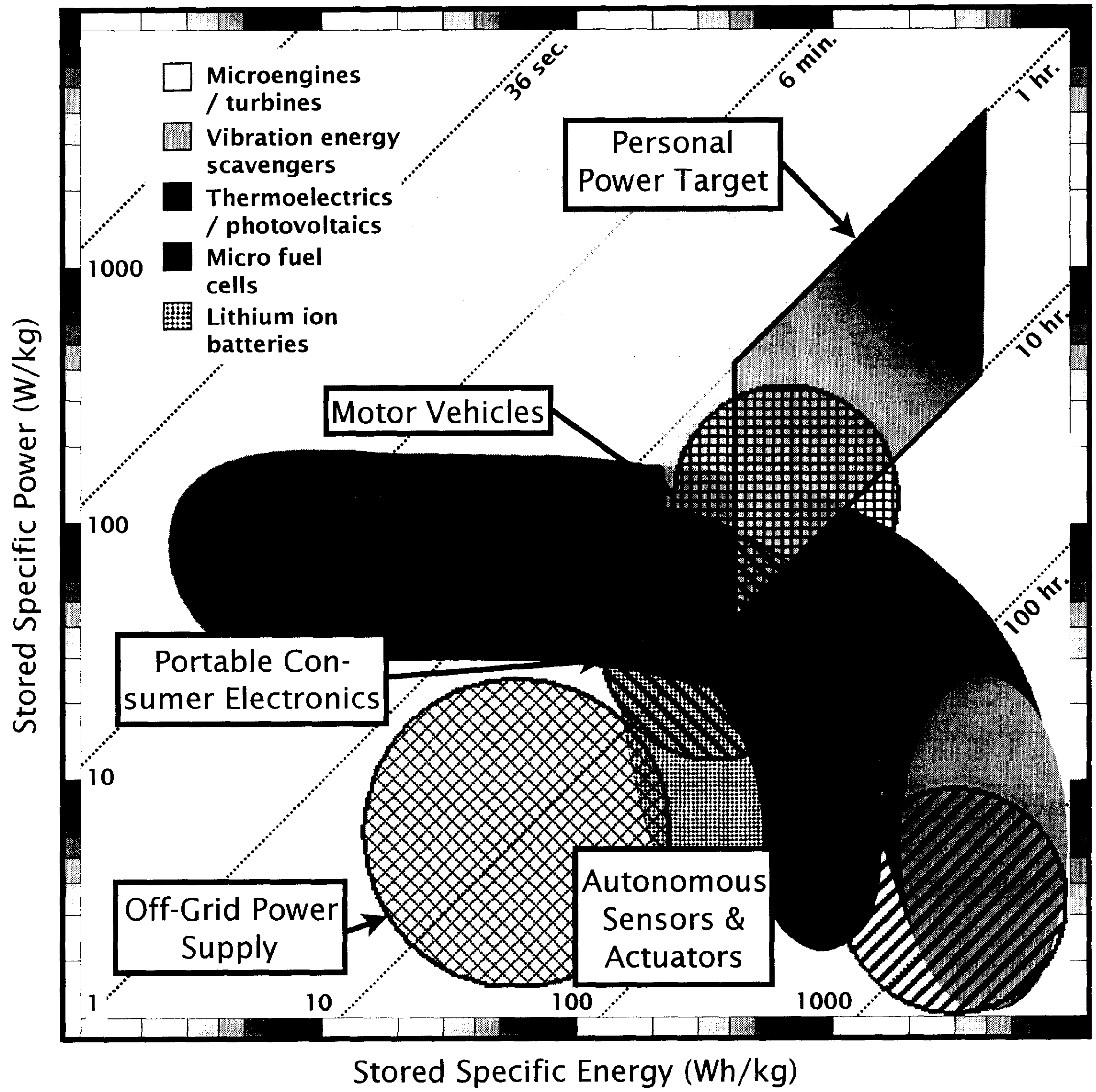

Figure 3.4. *Ragone plot of performance for power-MEMS technologies (colored regions), with cross-hatched circles covering selected markets (see text for Personal Power Target).*

engines / turbine regions stems from the fact that as one increases the amount of fuel in their tanks, the energy density approaches a constant value (determined by the fuel and their efficiency) while the power density goes steadily down. The upside-down "L" shape of the lithium ion battery region has to do with the fact that as one draws more power from such a battery, its efficiency drops so that its energy density likewise falls. This same effect also applies to micro fuel cells.

It is worth noting that none of the potentially MEMS-based technologies dealt with in this work save micro-turbines and perhaps advanced solid-state heat transducers overlap significantly with the Personal Power Target set by Dunn-Rankin *et al.* (footnote 4) in the Ragone plot of Figure 3.4. In particular, baring some fairly significant advances, micro fuel cells seem unlikely to make it, although they may achieve their more immediate and modest goal of powering cell phones and laptops for the better part of a day. Nonetheless, the investments made over the last ten years or so in various kinds of micro fuel cells, particularly direct methanol fuel cells (DMFC), have far exceeded those going into the other three classes of technologies combined. Adherents of micro fuel cells even have their own annual conference, Small Fuel Cells for Portable Applications, now in its ninth year (which they've managed to schedule to conflict with this year's main battery conference, Battery Power 2007). Similar concerns regarding this allocation of resources have been expressed by Donald Sadoway at MIT, although he would place all society's bets on lithium ion batteries.[5]

The Ragone plot above already goes a long ways towards segmenting the entire "electricity upon demand" market for us into reasonably well-defined submar-

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[5] "The Lithium Economy" by Kevin Bullis, MIT Technology Review, Nov. 22, 2005.

kets with respect to the performance criteria, which are relatively easy to quantify. This already shows that no single technology is clearly ahead of all the others even with respect to the gravimetric performance criteria. Ideally, we would like to further segment the market with respect to all possible combinations of the many different criteria shown in Table 3.1, in order to determine which market niches each technology should initially target. Since very few of the energy technologies under consideration have actually reached any markets

		Performance, Convenience and Other Criteria	
		Low on Average	High on Average
Economic Criteria	Low Cost	Present Cell Phone, PDA & Laptop Power Golf Carts Sail Boat Power Off-Grid Power Supplies Camping & Motor Homes	All-Day Cell Phone, PDA & Laptop Power Personal Transport (Segways, Wheelchairs, Powered Bicycles, etc.) Automobile Power Ultra-light or Unmanned Aircraft Personal Climate Control
	High Cost	X	Military Aerospace Remote Power Medical Implants

Figure 3.5. *Businessman's matrix segmenting the market for electric power on demand.*

in the form of products, it is much more difficult to say very much about the other classes of criteria, and we will content ourselves with a businessman's 2-by-2 matrix which lumps all the economic issues into a single parameter, lumps performance, convenience and all the other issues into another, and divides each into two classes, high and low, as seen in Figure 3.5. The upper right-hand region of this matrix probably includes most of the markets that would overlap with Dunn-Rankine *et al.'s* Personal Power Target in the Ragone plot.

3. MEMS Foundries, Standards & Cost Structures

The energy technology companies tallied the histogram of Figure 3.3 are listed explicitly in Appendix A, and are all either selling or developing products which do or could make good use of MEMS processes. It seems, however, that only a small fraction of them are actually doing so. A number of factors have probably contributed to this unfortunate state of affairs. The first is that a somewhat daunting knowledge base and physical plant are needed to design and manufacture devices based on MEMS. Yet there exists a substantial and growing family of design houses and MEMS foundries which can take over much of this task. Even though this fact does not completely eliminate the need for a basic understanding of how MEMS works, the availability of these services can greatly reduce the high costs of MEMS R&D and fabrication facilities in terms of time and money, by spreading these fixed costs over a large number of customers.

The MANCEF Roadmap, which is discussed in greater detail in Chapter 4, gives a list of 38 foundries (dated 2004) together with their URLs from all over the world. The Roadmap further noted that while most of the early foundries used old equipment previously designed for standard integrated circuits, specialized MEMS foundries were rapidly overtaking them. One of the best known is the

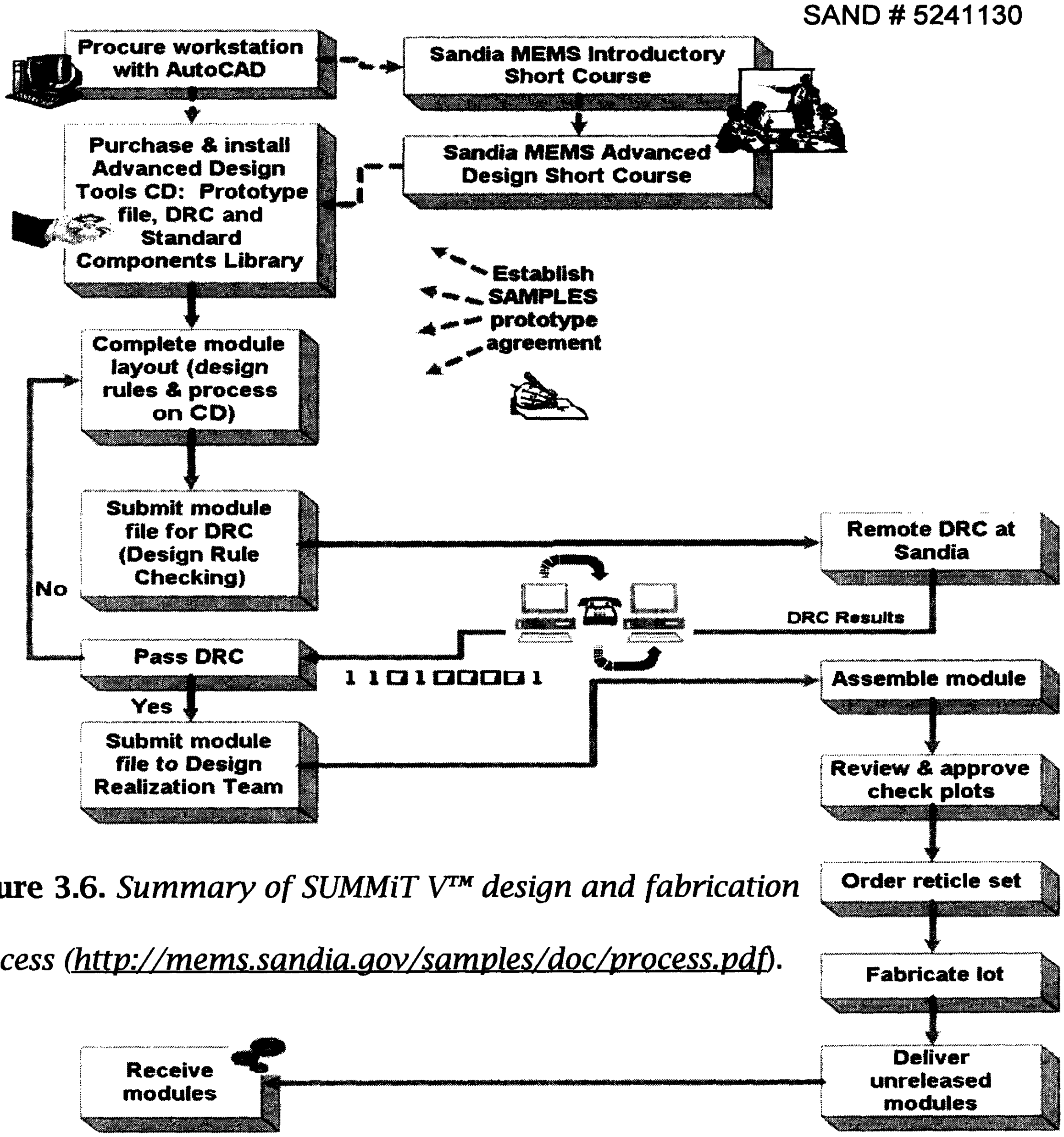

Figure 3.6. *Summary of SUMMiT V™ design and fabrication process (http://mems.sandia.gov/samples/doc/process.pdf).*

SUMMiT V™ foundry at Sandia National Laboratories, which offers visualization and design tools the output of which can be submitted directly to their web site for manufacture (cf. Figure 3.6). A less integrated but more versatile service is offered by the *MEMS Exchange*, a non-profit organization spun out of DARPA which both offers design services and serves as an intermediary between its

Table 3.2. Process Hierarchy of the MEMS Exchange as of April, 2007.

Process Class	Process Subclasses (total number of processes)
Wafer bonding	Anodic bonding, Fusion bonding, Glass frit bonding, Miscellaneous bonding (43)
Wafer cleaning	No subclasses (46)
Thin film deposition	Evaporation, Low-pressure CVD (aka Chemical Vapor Deposition), Plasma etch CVD, Surface oxidation, Spin casting, Sputtering, Low-stress SiN deposition, Miscellaneous deposition (307)
Doping	Diffusion, Ion implantation (18)
Wafter etching and resist stripping	Anisotropic etch, Deep RIE (Reactive Ion Etching), Isotropic etch, Stripping, Miscellaneous etch (182)
Lift off	No subclasses (7)
Lithography	Contact mask, Projection mask, Maskless, Miscellaneous (74)
Mask making	No subclasses (25)
Metrology	Electrical, Geometric, Miscellaneous (104)
Packaging	No subclasses (22)
Polishing	No subclasses (6)
Thermal	Annealing, Baking (32)
Unique capabilities	Hot embossing, Shape memory alloy deposition, LIGA, SiGe processes, Supercritical dry (17)

customers and a number of foundries which can mass produce the resulting product (see Table 3.2).[6] In April 2007, the MEMS Exchange claimed to give access to over 50 foundries in the USA alone.

The reasons why more startups are not making use of MEMS foundries include the expense, intellectual property concerns, and the high switching costs associated with changing designs or foundries. In addition many, or perhaps even most, of the power MEMS devices that have been built to date were developed in a university setting, where high yields and low production costs are generally not of great concern. Thus these designs often use processes or materials that are not widely available from foundries or other commercial facilities, so that licensing them for commercialization can be problematic even for large companies with in-house MEMS capabilities. Nevertheless, it seems that even the large Japanese and Korean electronics companies working on the DMFC are making little use of MEMS, although they certainly have the resources to do so. This is particularly striking in view of the fact that size is an issue for the DMFC.

The MANCEF Roadmap identifies an "MST basic toolset" consisting of the 37 processes most often found in MEMS manufacture (not all of which require an apparatus specific to that process). This roadmap moreover groups the sequences of processing steps required for most commercially available MEMS

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[6] See http://www.mems-exchange.org; Honeywell also offers integrated design and fabrication services, see http://www.memsservices.com.

devices into 10 "process streams," which consist of the basic toolset plus at most four additional stream dependent steps. This gives hope that standards can ultimately be developed that will facilitate the use of MEMS foundries, as it already has in the more mature integrated circuit industry. The MANCEF Roadmap predicts this will happen first for those processes which are largely compatible with existing integrated circuit foundries, although it does not give a timetable. A number of industry organizations are trying to improve the situation, including MANCEF's parent organization SEMI (Semiconductor Equipment and Manufacturing International), but at present each MEMS foundry offers a somewhat different set of services and a rather distinctive customer service interface. In other words, MEMS foundries have not yet become a commodity service.

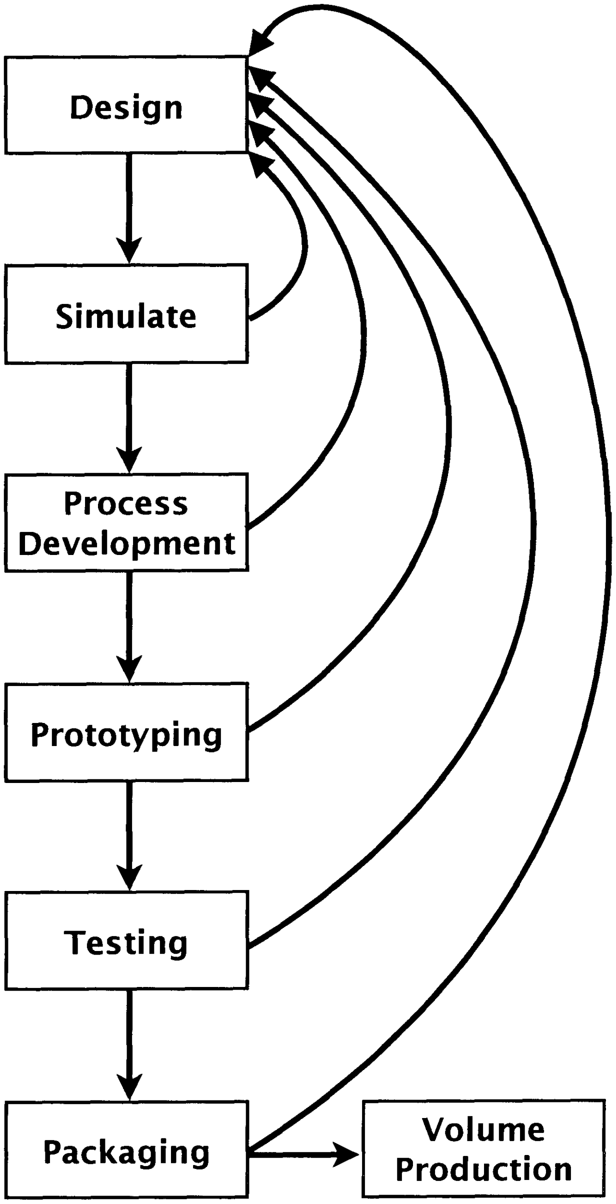

Figure 3.7. *Development process for a MEMS-based product.*

Those MEMS foundries which offer unique services, or are able to acquire such capabilities in response to customer demand, are therefore able to charge a significant but unpredictable premium. Moreover, the development of a novel MEMS-based product involves a considerable amount of trial-and error, as indicated in Figure 3.7, which makes the associated expense equally impossible to predict. We expect therefore that almost all startup companies trying to commercialize a MEMS-based product will be licensing their technology from a university, thereby pushing their R&D expenses into their cost-of-goods sold.

With this assumption, we can assign a fairly generic cost structure to the production of MEMS-based products, namely

$$\textit{Expected Unit Cost} = \left(N_M \times C_M + N_W \times (N_S \times C_S + C_C + N_D \times C_P)\right) \div (N_W \times N_D)$$

where N_M & C_M are the number of photolithography masks involved in the process and the cost per mask, N_S & C_S are the number of standard processing steps (e.g. those needing only the MST basic toolset identified in the MANCEF Roadmap), C_C & C_P are the costs of any custom steps needed and the cost of testing and packaging each die (device), and N_W & N_D are the number of wafers produced and the number of dies per wafer, respectively. Strictly speaking, the expected cost per unit (without packaging) should be divided by the probability the die is defective, which is often non-negligible. Clearly one would like to maximize the number of dies per wafer, although the increased cost of the equipment needed to produce larger wafers makes this option less attractive than it otherwise would be. In any case the only fixed costs involved are the masks, a set of which is generally produced during development anyway so that additional copies are needed only if parallel production lines will be used.

Although the values of all these parameters will vary greatly, in practice the fixed costs of MEMS foundries tend to be much less than those for state-of-the-art integrated circuit foundries, while the variable costs of MEMS-based devices are comparable to those for integrated circuits of comparable complexity.

4. Possible Business Models for Power MEMS

Having discussed the markets to which power MEMS is presently applicable, and having discussed the main issues involved in the production of MEMS-based devices generally, we are now ready to consider how a power-MEMS company might actually make money. Clearly this question has many possible answers, which are to a large extent conditional on the capabilities of the particular technology in question. For this reason we will break down this section into our four standard kinds of technologies to which power MEMS is applicable. Our focus will be on how a small startup, assumed to have cutting-edge expertise and intellectual property in power MEMS, could best acquire the generic complementary assets needed to capture the full value of its innovation.[7]

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[7] As first elucidated in "Profiting from Technological Innovation: Implications for Integration, Collaboration, Licensing and Public Policy" by David J. Teece, *Res. Policy* 15, 285-305, 1986.

4.1. Microengines and Microturbines

The value proposition enabled by these devices lies in their high specific power, together with the fact that their energy density will approach their efficiency times the energy density of the fuel they burn as the size of the fuel tank grows. Although the ultimate efficiency of these systems cannot yet be determined with confidence, 5% seems a safe lower bound, which with gasoline as the fuel implies an energy density about three times that of the best lithium ion batteries today. The first question is who would be willing to pay the most for these unique advantages?

I believe the most immediate high-premium market for such a power source would be the U.S. Army, specifically for personal climate control. A soldier today typically carries between 60 and 100 pounds of gear in the field, including several pounds of batteries. Particularly in hot climates, this can greatly limit their effectiveness and endurance. If those batteries could be replaced by a comparable weight in fuel plus a microengine or microturbine powered generator, the extra energy could be used to power a cooling system that helped to keep heat exhaustion at bay.[8] Although the noise some microengines produce would have to be muffled for this application, the MIT microturbine at least only produces noise at frequencies well above the audible range.

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[8] The best such system would be a solid-state thermoelectric device based on the Peltier effect, which could also lead to a pleasant confluence of MEMS-based technologies. Such devices are used, for example, to cool the seats in some luxury automobiles.

This choice of target market has the following advantages:

- Initial product development could be funded by an Army SBIR (Small Business Innovation Research) grant.
- There will be little or no marketing required, and only a small sales force.
- The customer can be expected to pay quickly and reliably upon delivery.
- The market is potentially quite large, so that it will not be saturated quickly.

One disadvantage will be the need for partnership with some other company which could incorporate the cooling system into a soldier's uniform, but the need for partnerships is likely no matter which market is targeted.

4.2. Direct Methanol Fuel Cells

Like microengines and microturbines, the energy density of these devices approaches their efficiency times the energy density of their fuel (methanol) as the size of their fuel tank grows, but they will deliver considerably less power per unit weight. Their greatest single advantage lies in the fact that their efficiency runs around 25%, so that even though methanol has half the energy of gasoline they still come out way ahead. As a result they also generate far less waste heat.

Right now most companies actively trying to commercialize the DMFC are aiming to provide all-day power to mobile consumer electronics such as laptops and cell phones. Indeed, just about every large Asian OEM in this industry, from

Hitachi to Toshiba (see Appendix A) has a major effort directed at the DMFC. The consequent widespread publicity has done so much to pave the path to user acceptance that it would probably be foolish to target any other market right now, despite the fierce competition it promises. It should also be noted that there remains a considerable amount of technological risk associated with the DMFC, which always seems just one more year away from a product launch.

Among the large diversified electronics firms now developing a DMFC, only Motorola seems to be making much use of MEMS (see Appendix A) even though, as noted in Chapter 2, MEMS promises a higher power density by using many thin cells in a fuel cell stack. For a startup seeking to take advantage of this fact, the key will be choosing the right strategic partner to provide the marketing and distribution resources needed to gain a first-mover advantage and so ensure that the full value of the company's innovation is captured by itself. Given the likelihood of encountering the "not invented here" syndrome at large consumer electronics firms, the most likely partner would be a firm which produces conventional batteries and can see the handwriting on the wall, when and if a good DMFC should come along. Procter and Gamble now owns Duracell, for example!

Another important point concerning business models for the DMFC is that, unlike microengines and microturbines, they are very fussy about their fuel. Not only must it be methanol, which is poisonous and not readily available in shops and stores, but in many cases it must have just the right amount of water in it with the right level of acidity. For these reasons the fuel will most likely be distributed in plugin canisters which work only with the manufacturer's own DMFC. This opens the possibility of a significant recurring revenue stream which could be used to compensate for the probable high cost of producing the DMFC itself. This is, of course, exactly how the ink-jet printer market works.

4.3. Thermoelectrics, Thermionics and Thermophotovoltaics

These versatile technologies can either generate electricity directly from the heat released on burning fuels, or scavenge waste heat and thereby make existing heat engines (like the MIT microturbine) more efficient. Given this versatility, it is a bit surprising that they have not been more widely utilized. Thermoelectrics, in particular, is a proven and fairly well-established technology which has recently been undergoing rapid improvements. In keeping with the results of a recent article on the commercialization of thermoelectrics,[9] we believe that using this technology to improve the efficiency of the automobile would be an excellent place to start, both because of its volume and because the amount of waste heat generated by today's automobiles is so incredibly large.

Since we are certainly not the first to have this idea, we must establish our competitive advantage by other means. A promising route to this end is provided by the ability of MEMS technologies to drastically cut the costs of ther-

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[9] "Commercialization of Thermoelectric Technology" by Francis R. Stabler, *MRS Symp. Proc.* **886**, F01-04.1-9, 2006.

moelectric modules, together with the fact that it seems no commercially available modules presently make any use of MEMS. Cost, of course, is of great concern in the automotive industry, since most of the cars sold are low-end commodity vehicles. Even though automobile manufacturers already use many MEMS-based components, they usually do not have in-house expertise and are happy to buy from the cheapest supplier. Finally they are under great regulatory pressure to improve the efficiency of their products, and even hybrids could profit from thermoelectric technology.

The MEMS advantage may not be sustainable for very long, but it should enable a new startup company to establish itself if it acts soon. The most important resource it will need is access to engineers in the automobile industry, which it could get by hiring away one or more sales people from an automotive components supplier which already has thermoelectric products out (such as the BSST LLC owned by Amerigon, Inc.; see Appendix A). Once it has established a revenue stream, the startup could turn towards commercializing efficient solid-state generators based on advanced thermionic or thermophotovoltaic systems for powering otherwise all-electric cars, which are beginning to appear on the market.[10] Unless the hydrogen economy actually comes to pass, these beautiful solid-state systems are likely to outperform and cost less than fuel cells which have to reform their fuels into hydrogen.

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[10] See e.g. http://www.teslamotors.com or http://www.apteramotors.com.

4.4. Vibrational and Electromagnetic Energy Scavengers

Vibrational and electromagnetic energy scavengers are characterized by very low power density but theoretically infinite energy density, limited only by the lifetime of the device. For this reason they are being widely considered as a means of powering wireless networks of autonomous sensors (see Chapter 2 and references therein). Although this MEMS application has great commercial promise, there are few products out yet and it may take some time before a large market for such sensor networks develops.

Right now, a more promising target market for a startup with expertise and intellectual property in energy scavenging would seem to be implantable medical devices such as pacemakers, drug delivery systems, and patient monitoring, to which MEMS is now also being applied.[11] Indeed several papers have been written on these applications,[12] and the U.K. Dept. of Trade and Industry has recently funded a consortium to develop such systems,[13] but no products have yet made it to the marketplace. So the field seems relatively open, and since

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[11] "A BioMEMS Review: MEMS Technology for Physiologically Integrated Devices" by A. C. Richards Grayson, R. S. Shawgo, A. M. Johnson, N. T. Flynn, Yawen Li, M. J. Cima & R. Langer, *Proc. IEEE* **90**, 6-21, 2004.

[12] "Development of an Electrostatic Generator for a Cardiac Pacemaker that Harnesses the Ventricular Wall Motion" by R. Tashiro, N. Kabei, K. Katayama, F. Tsuboi & K. Tsuchiya, *J. Artif. Organs* 5, 239-245, 2002; "MEMS Inertial Power Generators for Biomedical Applications" by P. Miao, P. D. Mitcheson, A. S. Holmes, E. M. Yeatman, T. C. Green & B. H. Stark, *Microsyst. Technol.* **12**, 1079-83, 2006.

[13] "Consortium Develops MEMS-Based Generator for Medical Implants" by staff writer, *The Semiconductor Reporter*, Dec. 18 2006; http://www.semireporter.com/public/15466print.cfm.

nobody wants to have to go in for surgery every time their battery runs down, the market is certainly there![14]

Even though some MEMS foundries have considerable experience helping their clients develop BioMEMS devices, a startup will still need to work through a company that can shepherd its product through the stringent approval process for implantable devices, and to provide the marketing and distribution resources that will be needed. Medtronic, for example, already makes a MEMS-based pacemaker, and recently invested in a startup spun out of the University of California Berkeley, EndoBionics Inc. (now Mercator MedSystems), developing a MEMS-based microsyringe catheter.[15] A smaller MIT spinoff, which may be more open to partnerships, is to be found in MicroChips Inc.,[16] which is developing wirelessly powered and controlled implantable drug delivery systems that might in some cases be better made fully autonomous using an integrated energy scavenging system. Regardless of the size of the company and the nature of its products, the key to favorable terms in such a partnership will be strong patent protection on an energy scavenger with distinctive advantages for the intended application.

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[14] One company, CardioMEMS Inc. (http://www.cardiomems.com), is close to commercializing implantable sensors which obtain their power from a dedicated microwave transmitter in the doctor's office; this is not really scavenging according to our definition.

[15] "Sticklers for Accuracy: Tiny Needles Provide Better Treatment for Restenosis, Diabetes and More" by B. Z. Powell, *Acumen J. of the Sciences*, May 20, 2003.

[16] See http://www.mchips.com.

5. Case Studies

In the following we present case studies of two power MEMS startup companies, one of which is funded by angel capital and private investors, the other of which is merely an idea for a company that has yet to even be officially created. These two companies were chosen because they illustrate the potential for disruptive innovations being created by power MEMS technologies, and because the principals thereof are personally known to the author; in the latter case they are in fact one and the same! So it behooves me to switch to first person at this point in the narrative.

5.1. MTPV Corporation

I first got to know Bob DiMatteo when I joined the Sloan Fellows Program at MIT in the Spring of 2005. At first all I knew about him was the he had come into the program from the Charles Stark Draper Laboratory, a non-profit R&D corporation spun out of MIT in 1973. It was only after he gave a lunchtime talk to the class on his work six months later that I learned about his work on a novel energy technology he called *micron-gap thermophotovolatics* (MTPV).

Bob tells me his interest in energy technology goes all the way back to the energy crisis of the late 1970's, when he read an article about a Ford Galaxy that someone had modified to get 100 miles-per-gallon. After graduating in government and social studies from Harvard, he worked briefly at Sikorsky Aircraft and the MITRE Corporation, then did eight years in a startup working on energy efficient homes and buildings in the Boston area. At that time he returned to school at MIT, where he obtained a dual masters in Electrical Engineering and Computer Science and in the Technology and Policy Program in 1996. His thesis was about micron-gap thermophotovoltaics and policies to promote the development of such energy efficient devices. After graduating he moved on to Draper Labs, where he continued to develop and demonstrate this technology over the next decade.[17] He obtained his MBA through the MIT Sloan Fellows Program in 2006, and has since been working as the CEO of MTPV Corporation, the company he founded to commercialize micron-gap thermophotovoltaic technology.

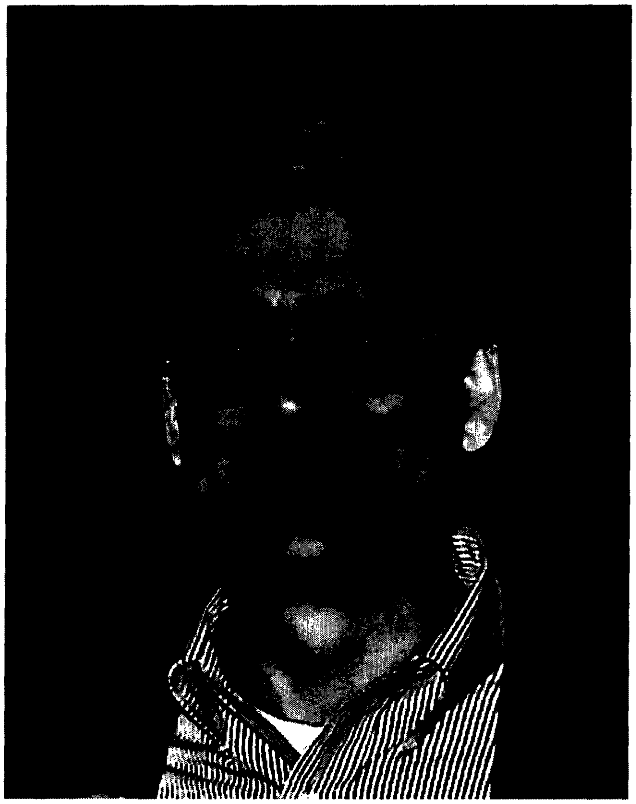

Figure 3.8. *Bob DiMatteo in the Sloan Fellows Program in 2005.*

As was described in Chapter 2 of this dissertation, TPV converts the infrared light emitted from a hot object into electricity using a low-bandgap PV (photo-

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[17] R. S. DiMatteo, P. Greiff, S. L. Finberg, K. A. Young-Waithe, H. K. Choy, M. M. Masaki & C. G. Fonstad, *Appl. Phys. Lett.* **79**, 1894-6, 2001.

voltaic) cell. The heat can be obtained from concentrated solar radiation, fossil fuel combustion or even nuclear reactions. In particular, TPV offers the tantalizing possibility of replacing the good old gasoline and diesel engines used in today's automobiles, and perhaps even tomorrow's advanced hybrid vehicles, with a solid-state device which silently converts these same fuels into electricity to power an otherwise electric car with 100 mile-per-gallon efficiency. Although TPV is simple in principle, a great deal of ingenuity is required to design a complete system with a fuel efficiency, a level of power and a cost comparable to existing power sources, be they large or small. In particular, the designer of a conventional TPV system is confronted with a Faustian bargain between relying on a large area of expensive PV cells to obtain sufficient power, or else operating at a very high temperature (1000-1500°C), which requires expensive insulation and cooling. Of the three companies founded in the late 1980's to commercialize TPV technologies, only the web site of JX Crystals Inc. indicates that they are ready to sell such systems at all.[18]

The use of a sub-wavelength gap between the infrared emitter and the PV cell greatly ameliorates this problem, by enabling a phenomenon known as "evanescent radiation transfer" to improve the power-per-unit-area at moderate

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[18] TPV Corporation of Waltham MA, whose founder Robert E. Nelson took a job at the Quantum Group in San Diego in the early 1990's and continued to patent TPV technologies at that company, which now sells only carbon monoxide sensors; EDTEK Inc., founded by William E. Horne from Boeing, which currently does contract engineering on solar energy systems; JX Crystals, founded by Lewis M. Fraas also from Boeing, which sells both ordinary and low-bandgap photovoltaic cells. See "A Brief History of Thermophotovoltaic Development" by R. E. Nelson, *Semicond. Sci. & Technol.* **18**, S141-3, 2003.

(500°C) temperatures by an order of magnitude or more (see Figure 3.9). The main challenge to realizing this advantage is to obtain excellent thermal isolation between the emitter and the PV cell despite their small separation, which requires a high vacuum. Although that is not itself a significant problem, it remains nontrivial to keep two surfaces a precise, sub-micron distance apart while heating one, cooling the other, and possibly enduring an occasional jolt from the outside. The solutions Bob has developed use MEMS technologies in an essential way.[19]

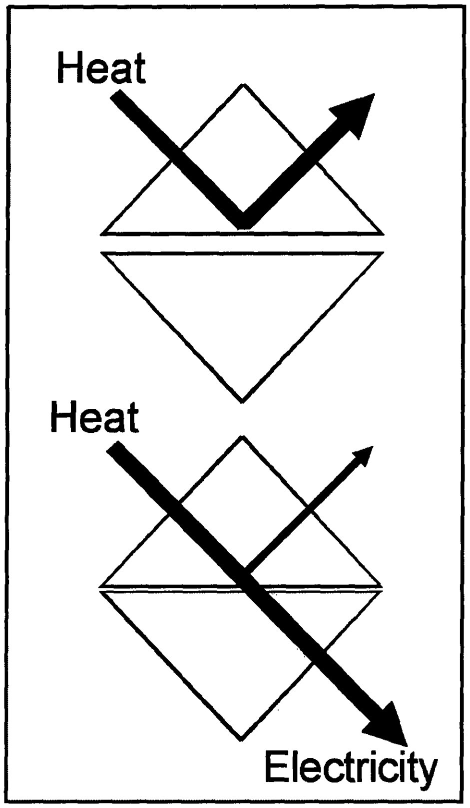

Figure 3.9. *Experiment illustrating phenomenon of evanescent radiation transfer when two prisms are brought into sub-wavelength proximity (drawing courtesy of MTPV Corporation).*

The process is essentially one of surface micromachining, whereby a sacrificial layer is used to create a hexagonal array of emitters supported on the surface of the PV cell by insulating (silicon oxide) "stand-offs," as seen in Figure 3.10. The sacrificial layer is removed by a solvent which enters through numerous "weep holes" created on their surfaces. The result is that the PV cell is almost entirely shielded from the

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[19] "Micron-gap ThermoPhotoVoltaics" by R. DiMatteo, P. Greiff, *et al.*, *Proc. 6th Conf. on Thermophotovoltaic Generation of Electricity* (A. Gopinath, T. J. Coutts & J. Luther, eds), **CP738**, 42-51, Amer. Inst. of Phys., 2004.

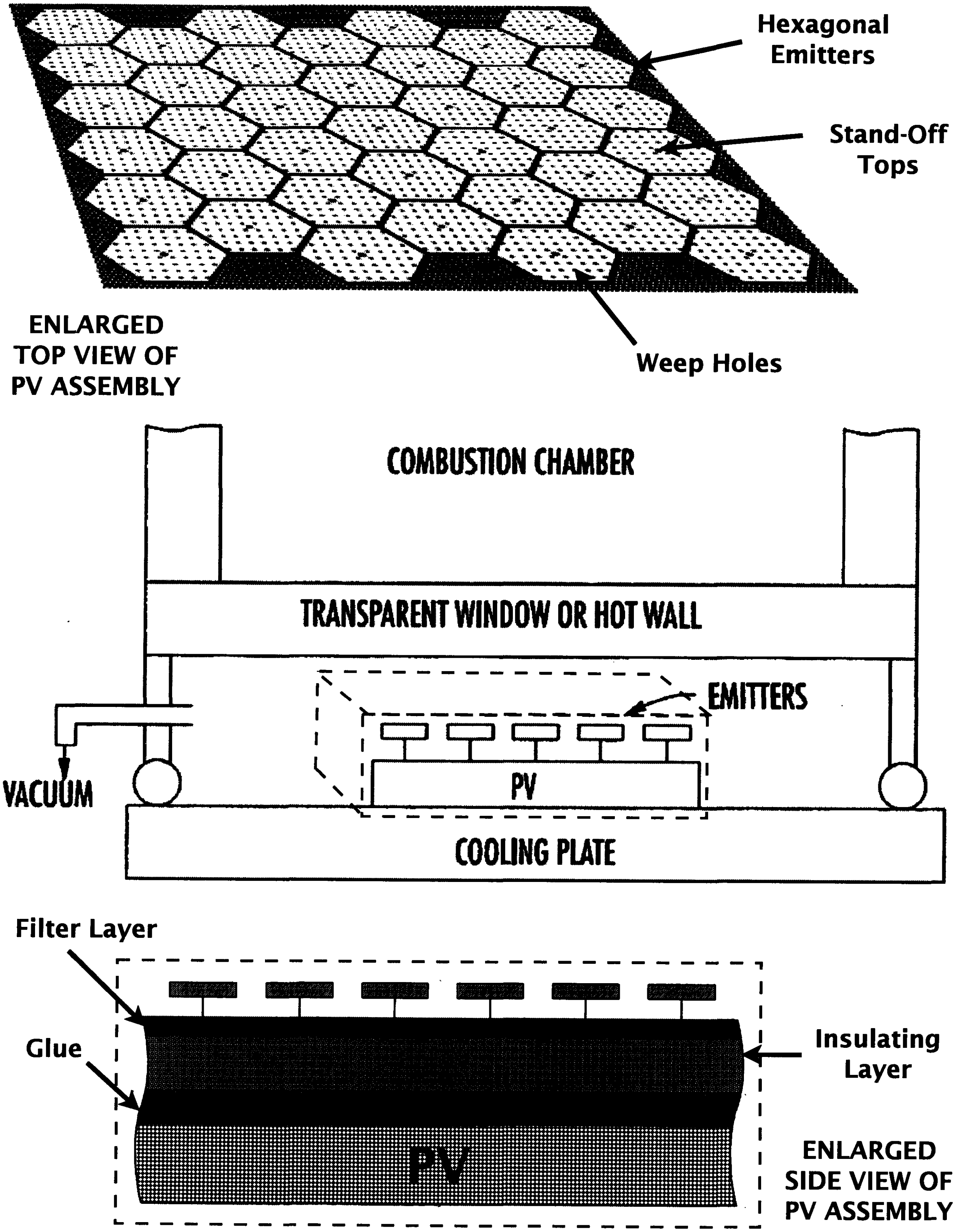

Figure 3.10. *Selected drawings of MTPV device adapted from DiMatteo patents (see text).*

hot surface by this array of secondary emitters, which are individually small enough, relative to the height of the stand-off, that their distance to the PV cell is little affected if they warp a bit under the imposed thermal gradient. They are also very light-weight and hence impervious to external shocks. Recent work has shown that the emitters can be made quite selective for the PV cell's band gap by making them out of thin silicon,[20] which is also of course amenable to MEMS. Finally it has been discovered that, contrary to initial expectations, the frequency selectivity can be improved via a thin metallic filter, and that the micron-gap need only be maintained between the emitters and the surface of this filter layer, rather than with the PV cell itself. This allows an insulating layer much thicker than a micron to be inserted between the filter and the PV cell, reducing the need to cool it.

At present MTPV Corporation has seven full-time employees, including another Sloan Fellow, Bernard Ho, who acts as sales manager. They have a demonstration device which they show to potential investors and customers, and are seeking strategic partners to help them sell into the areas of remote or portable power supplies, cogeneration, concentrating solar, and power for otherwise electric automobiles. If they succeed, it will bring a great deal of recognition to the field of power MEMS more generally, and may be just what is needed to jump start the whole industry. I wish them extremely well with their enterprise!

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[20] "Semiconductor Silicon as a Selective Emitter" by D. L. Chubb, D. S. Wolford, A. Meulenberg & R. S. DiMatteo, *Proc. 5th Conf. on TPV Generation of Electricity*, CP653 (Am. Inst. Phys.), 2003.

5.2. Elastic Energy Systems

MTPV Corporation's current activities may be described as trying to get the engine of an old-fashion crank-shaft automobile to turn over. The activities of those involved in our next case study are more like trying to design and build the automobile from scratch. My collaborator on this project, Prof. Carol Livermore in the Dept. of Mechanical Engineering, and myself have a concept, a few back-of-the-envelope calculations which are consistent with its commercial promise, and a small grant from the MIT Deshpande Center for Technological Innovation which currently pays a graduate student to perform simulations of our present ideas for functional embodiments. Assuming all goes well, we may be ready to actually start raising capital for the company in less than five years. Meanwhile, it must remain a laboratory project funded by grants and donations from far-seeing companies or organizations such as the Deshpande Center.[21]

The concept itself is simple enough. According to Hook's law, the energy stored in a mechanical spring grows as roughly one-half the product of the force applied to it and the displacement, i.e. the difference between its length and that when no force is applied. The maximum energy that can be stored in the spring before it bends or breaks therefore depends both on how stiff the spring is - how quickly does the force increase with the displacement - and on how great

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[21] We are presently hoping to receive additional funds from the Swiss watch industry, specifically the Association Suisse pour la Recherche Horlogère, which has been looking for a better main spring for generations, and from Schlumberger, an oil drilling consulting company in need of batteries that can tolerate the heat of a deep bore-hole.

of a displacement it can tolerate. Steel is quite stiff, of course, but can tolerate displacements of only about 1%, and hence the amount of energy that can be stored in a steel spring per unit weight is less than a thirtieth that of a lead-acid battery. Neoprene rubber, on the other hand, is less than a thousandth as stiff as steel, but can be stretched by 500% or more without breaking, and hence can achieve about the same energy density as steel springs can.

Carbon nanotubes differ from these macroscopic materials in that they are not only about five times stiffer than steel, but are also about fifteen times more flexible. It follows that they can store energy almost 100 times more densely than a lead-acid battery, which is about an order of magnitude denser than lithium ion batteries. The problem, of course, is that single carbon nanotubes, although enormous as molecules go, are still invisible to the naked eye and can individually store only insignificant amounts of energy. Methods of assembling many nanotubes into much larger structures such as ropes or yarns are available,[22] but the nanotubes in these assemblies are packed together in a largely random fashion, with the result that they generally are a great deal less flexible than are their constituent nanotubes. It is very likely that this problem can and will be overcome, and we hope our work on mechanical energy storage in carbon nanotubes will inspire further research along these lines.

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[22] "Mechanics of Carbon Nanotubes" by Dong Qian, G. J. Wagner, Wing Kam Liu, Min-Feng Yu & R. S. Ruoff, *Appl. Mech. Rev.* **55**, 495-533, 2003; "Fundamental Mechanical Properties of Carbon Nanotubes" by Min-Feng Yu, *J. Eng. Mater. Technol.* **126**, 271-8, 2004; "Progress on Mechanics of Carbon Nanotubes and Derived Materials" by J.-P. Salvetat, Sanjib Bhattacharyya & R. Byron Pipes, *J. Nanosci. Nanotechnol.* **6**, 1857-82, 2006.

Single carbon nanotubes, nevertheless, are large enough to make it possible to manipulate them inside MEMS devices, and it is also possible to make motors and generators small enough to use them as "supersprings" to store and recover electrical energy.[23] Besides potentially having a higher energy density than chemical batteries, such a device could also in principle have a much higher power density, a much shorter recharge time, a higher efficiency of storage and recovery, and a longer lifetime both on the shelf and in constant use. Of all the electrical energy storage devices presently under development, only supercapacitors offer most of these other benefits, but they still have quite a long way to go before they can match the energy storage density of batteries.[24] Coincidentally, the use of dense mats of carbon nanotubes for supercapacitor electrodes is one of the ways people are trying to increase supercapacitor energy density.[25]

The following are some of the technical challenges involved in trying to use MEMS to make carbon nanotube superspring batteries a commercially viable alternative to chemical batteries for the purposes of electrical energy storage:

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[23] "Experiments and Modeling of Carbon Nanotube-Based NEMS Devices" by C.-H. Ke, N. Pugno, B. Peng & H. D. Espinosa, *J. Mech. Phys. Solids* **53**, 1314-33, 2005.

[24] "Ultracapacitors Challenge the Battery" by J. M. Miller, *World and I*, 130-137, Jun. 2004; "The Supercap Communication Challenge" by staff writers, *Batteries and Energy Storage Technology*, 107-13, Winter 2005.

[25] "MIT Researchers Fired Up About Battery Alternative: Nanotube Structures Key to Work" by staff writers, *Science Daily*, Feb. 2006; "The Ultra Battery" by Kevin Bullis, *MIT Technol. Rev.*, article 16569, Mar. 2006; "MIT Research May Spell End for the Battery" by Hiawatha Bray, *Boston Globe*, Jun. 26, 2006.

- A supporting structure must be designed to balance the force exerted by the supersprings in their fully charged state, which can be no more than two or three times more massive than the superspring itself since the bigger it is, the more it will dilute the energy density of the superspring. Due to the remarkable strength of carbon nanotubes, this force will be greater than other materials can withstand unless it is distributed over the surface of the structure in such a way that atomic repulsion, which becomes arbitrarily large as atoms are brought closer together, can balance the forces exerted by the chemical bonds of the superspring. This explains, for example, why a glass sea float can be sunk in deep water and pulled up again uncrushed by the hundreds of pounds per square inch of pressure it has endured, although it can be broken by the tap of a hammer. Our ability to do this will be limited by the presence of random defects in the structure, but fortunately defect-free structures become easier to make as they get smaller, as illustrated for example by the rotor of the MIT microturbine.
- Although nanotechnology researchers have succeeded in making very small motors approaching even molecular dimensions, it is much more difficult to scale down electromagnetic or even electrostatic generators to the sub-millimeter scale. This is in large part because frictional and ohmic losses become prohibitive as the surface-to-volume ratio increases with decreasing size. About the only kinds of generators that work well at very small scales are piezoelectric generators, but even then daunting problems arise in wir-

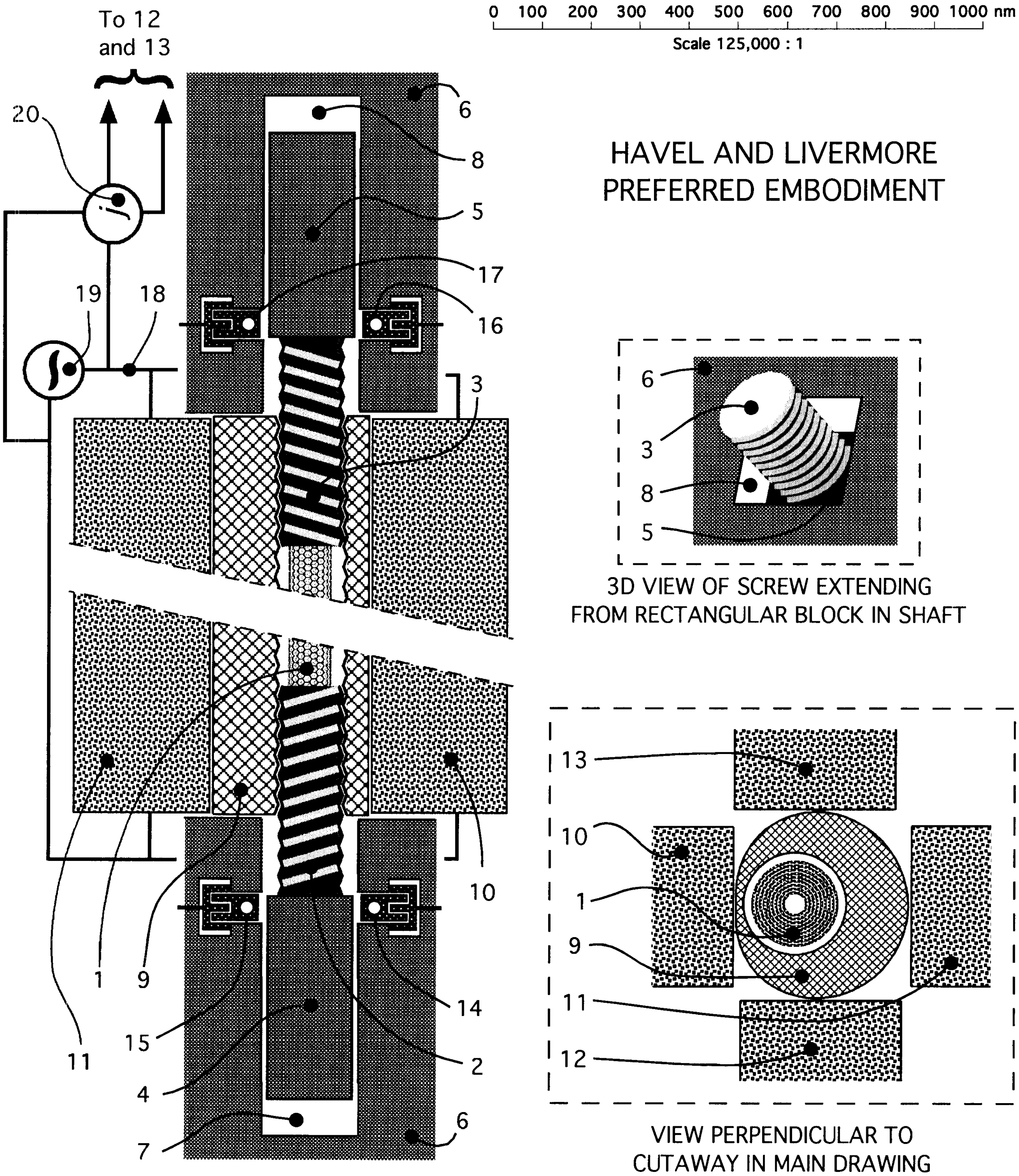

Figure 3.11. *Drawing of the preferred embodiment from pending U.S. patent application by Havel & Livermore: (1) Multi-walled carbon nanotube; (2 & 3) Oppositely threaded screws; (4 & 5) Rectangular blocks holding screws; (7 & 8) Shafts; (9) Mechanical cam; (10-13) Piezoelectric actuators; (14-17) Comb-drive driven wedges; (18-20) Electronics.*

ing micron-scale, high-power-density components together without serious energy losses due to unwanted capacitive couplings. This implies one should try to make the supersprings as large as possible, so that the associated hardware needed to deform them and recover the energy thereby stored in them as electricity can be built more easily. Unfortunately, the larger the superspring, the more difficult it becomes to assemble its constituent nanotubes in a highly ordered fashion, and as previously mentioned the randomness present in most carbon nanotube assemblies greatly decreases their flexibility and hence the amount of energy they can absorb. Hopefully a "sweet spot" in the size of the supersprings can be found that will make it possible to both make them highly ordered and large enough to be incorporated into an efficient electromechanical transducer – which once again must not be much more massive than the superspring itself. One possible embodiment, which is not expected to be commercially viable but could lead to an experimental proof of concept, is illustrated in Figure 3.11.

- Finally, methods for growing defect-free carbon nanotubes with well-defined chemical structures, positioning them precisely on the surfaces of silicon or other MEMS compatible materials, and fastening them firmly to these structures are really still in their infancy. In particular, in order to build the superspring it will almost certainly be necessary to embed the ends of single carbon nanotubes below the surface of crystalline silicon, and to form numerous covalent bonds between the silicon atoms and the carbon atoms of the nanotube so as to attach these two components together very strongly. Although the chemistry certainly allows this, the problem has not even been studied theoretically as far as my literature searches have been able to determine, let alone experimentally. This is somewhat surprising, given all the proposals out there for incorporating nanotubes into silicon-based semiconductor devices.

On the positive side, all of the above challenges lie squarely within the mainstream of nanotechnology today, and as a result enormous effort is already being devoted to research with the potential to overcome these challenges. In the next and final chapter of this dissertation we will consider the possibility of constructing a roadmap for future work on power MEMS more generally.

Chapter Four: Proposal for a Power-MEMS Roadmap

It has been argued that the rate and direction of advance in pure science must be considered as an autonomous factor in any theory ... of inventive activity ... [But] recall that the science of thermodynamics was, in large part, called forth by the development of steam engines, not vice versa ... [Similarly the great increase in] the proportion of articles relating to solid-state physics ... was, in considerable part, due to the invention of the transistor and the consequent spotlighting of the field.

Richard R. Nelson in *The Rate and Direction of Inventive Activity: Economic and Social Factors*, Princeton Univ. Press, 1962

The key point is that in modern competitive equilibrium theory [of economics], what can *be done is objectively and clearly defined ... In the Schumpeterian scheme, the limits of what can be done are never fixed and never clearly in view. Discovering what can be done is part of the problem for the individual actor ...*

Richard R. Nelson & Sidney G. Winter,

Am. Econ. Rev. **67**, p. 271, 1977

After describing the purposes and kinds of technology "roadmaps" which have been assembled in recent years, we review the trends and developments documented in this dissertation and argue that they point towards the conclusion that an industry-wide, exploratory power-MEMS roadmap could do much at this time to stimulate the genesis of power-MEMS industrial ecosystem. A set of goals are then proposed for such a roadmap, along with a set of tasks by which the roadmapping process could be set in motion. In order to help the Power-MEMS Roadmap participants better understand the long-term goal of this process, a conceptual framework is presented which attempts to pinpoint the feedback loop that has given rise to other major industrial ecosystems such as the semiconductor industry. Finally some technological challenges are considered, the solution of which could further advance the scope and long-term impact of power MEMS.

1. Roadmaps in General and MEMS Roadmaps in Particular

A roadmap is basically a tool to facilitate communication amongst a group of diverse individuals who share a common interest. In this sense it is similar to a blackboard or an audiovisual aid, but a roadmap is a bit more abstract in that it constitutes an attempt to paint a picture of what the future could be, if those concerned take appropriate actions in the present. Even if nobody can initially agree on what they should be doing together, participation in such an exercise can give rise to a process or forum whereby agreement is reached. In addition, the finished document can be used to help them communicate to other potentially interested parties, outside of the initial group, what the participants are doing and why.

A technology roadmap results when the common interest concerns a technology or an application of the technology. The best-known technology roadmap by far is the International Technology Roadmap for Semicondutors (ITRS).[1] This began as a national (US) technology roadmap in 1986, and by 1991 had forged a path designed to take the industry to a 1 gigabyte SRAM memory chip by 2003, a goal it actually achieved four years ahead of schedule. It is remarkable that such a fiercely competitive industry should have adopted such a high level of cooperation and communication regarding what the playing field should look like. The semiconductor industry has in effect decided that the basic research needed to keep it on the curve of Moore's law should be regarded as an innate part of the commonweal, with raw competition relegated to the individual firms' manufacturing and marketing capabilities.

The ITRS is the prime example of industry roadmapping for the purpose of achieving technological innovations which sustain existing markets and busi-

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[1] "Review of the Semiconductor Industry and Technology Roadmap" by Sameer Kumar and N. Krenner, *J. Sci. Edu. Technol.* 11, 229-36, 2002.

ness models. None of the firms involved in the ITRS expect to be put out of business by the technological advances they are helping to create. On the contrary they hope it will help keep the total market for their products expanding. Technology roadmapping can also be used within a firm, to help it decide how to allocate its R&D resources, but whether firm or industry wide, roadmapping to achieve sustaining innovations is known as target-driven roadmapping.

Such roadmaps tend to be prescriptive in nature, and if not updated constantly can have the dangerous effect of limiting the assimilation of new information or the exploration of alternatives, resulting in the premature lock-in of inferior technology or standards.[2] It is much more challenging to apply technology roadmapping to potentially disruptive technologies, since these are unpredictable by definition. As a result, such exploratory roadmaps tend to be largely descriptive in nature, and the exploratory roadmapping process is intended to inspire rather than define the future.[3] Significantly, the ITRS itself has included multiple scenarios in its "forecasts" since 2000.

Although it is really more than a single technology and certainly has far more than a single application, MEMS has been the subject of two major roadmaps, plus an assortment of more limited roadmaps and attempts at standardization.

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[2] For an excellent example, see "Clio and the Economics of QWERTY" by Paul A. David, *Am. Econ. Rev.* 75, 332-7, 1985.

[3] "Technology Roadmapping a Future for Integrated Photonics" by E. J. Bruce and C. H. Fine, preprint available on-line at http://www.hbs.edu/units/tom/seminars04-05/cfine.html.

Table 4.1. Main Working Groups for the Two Major MEMS Roadmaps

(an asterix indicates the group contributed to the 2004 MANCEF revisions)

The NEXUS Technology Roadmap for Microsystems	The MANCEF International Micro-Nano Roadmap
MEMS Packaging	Process and Equipment for MST*
Design, Modeling and Simulation	Equipment and Tooling for MNT*
Automotive	Simulation, Modeling and Design
Peripherals and Multimedia	IC Compatible Manufacturing
Telecommunications	Non-IC Compatible Manufacturing
Pharmaceutical and Analytical	Reliability, Testing and Metrology
Medical Devices	Packaging and Assembly*
Household Appliances	Integration
Aerospace and Geophysics	Status & Future of MEMS Foundries*
Lifestyle	Cost Models
	Standards, or the Lack Thereof
	Commercialization
	Market Forecasting
	Optical Microsystems
	BioMEMS
	RF MEMS*
	Nanotechnology*
	MEMS Patent Analysis*

Both of the major roadmaps have their origins in SEMI's (Semiconductor Equipment and Materials International) initial study of the MEMS standardization problem in the late 1990's.[4] The Europeans involved in that study, then organized as the European Microsystems Network, were funded by the European Commission to develop the NEXUS (Network of EXcellence in mUltifunctional microSystems) Roadmap. This was announced at the COMS (Commercialization of Micro Systems) meeting in 2000, and the first complete version was distributed at COMS 2003. It is a "technology/product-oriented" roadmap with the "User Supplier Clubs" and "Methodology Working Groups" listed in Table 4.1 responsible for its various sections.[5] A version of the NEXUS Technology Roadmap for Microsystems is distributed in the USA by the MEMS Industry Group.[6]

A second group based in the USA was spun off from SEMI as MANCEF (Micro And Nanotechnology Commercialization and Education Foundation), which produced its own International Microsystems Roadmap in 2002 and a more extended version renamed the International Micro-Nano Roadmap in 2004. It differs greatly from the NEXUS Roadmap in that it starts from the technology, moves on to the economics, and finally focuses on major areas of application. Even more importantly, while the NEXUS Roadmap seeks to extrapolate the fu-

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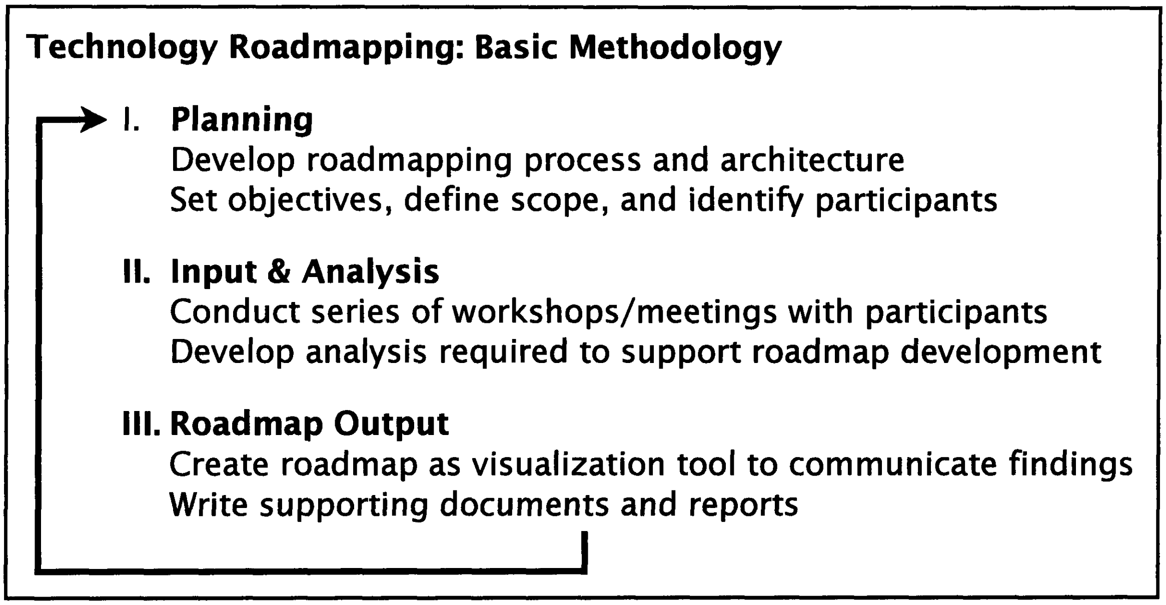
[4] "MEMS Standards and Roadmaps Summary" edited by Lubab Sheet, Sr. Director of Emerging Technologies at SEMI, Oct. 2006.

[5] See http://www.nexus-mems.com/userclubs.asp; the "Lifestyle" club is apparently no longer active.

[6] See http://www.memsindustrygroup.org.



Technology Roadmapping: Basic Methodology

I. **Planning**
Develop roadmapping process and architecture
Set objectives, define scope, and identify participants

II. **Input & Analysis**
Conduct series of workshops/meetings with participants
Develop analysis required to support roadmap development

III. **Roadmap Output**
Create roadmap as visualization tool to communicate findings
Write supporting documents and reports

Figure 4.1. *The three stages of roadmapping, as discussed in the main text. Adapted with permission from the reference in footnote 3.*

ture of MEMS within those industries wherein it plays a major role today, the MANCEF Roadmap is fundamentally an exploratory roadmap for those interested in what industries MEMS might disrupt tomorrow.[7] Moreover, the MANCEF Roadmap seeks to illuminate the entire value network associated with MEMS, rather than just its technologies and/or markets. This is particularly important if, as in the present case, one of the goals of the roadmap is to promote the development of a value network. It is our hope that the proposed Power-MEMS Roadmap will become an integral part of the broader MANCEF Roadmap.

Regardless of the nature of the technology, roadmapping is always a three-stage iterative process, which is summarized in Figure 4.1. In the planning stage one

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[7] "Roadmapping a Disruptive Technology: A Case Study of the Emerging Microsystems and Top-Down Nanosystems Industry" by S. T. Walsh, *Technol. Forecast. Social Change* 71, 161-85, 2004.

decides what the roadmap is intended to accomplish, how it can best achieve those goals, and sets up a framework for the ensuing discussions. As a rule it is initiated by a relatively small group of people, who must subsequently get a much larger group to put up the resources needed, consisting primarily of their time and expertise, but also of course the funds needed to cover remote communication and face-to-face meetings of all participants - which should occur at least once in each iteration. Initial discussions can however take place via E-mail or other electronic media, using for example the Delphi method to generate a preliminary list of issues to dig into at the face-to-face meetings.[8] A variety of analytic tools may also help achieve consensus regarding the issues to be dealt with and their resolution, including text and data mining,[9] selected case studies, negotiation and voting techniques,[10] statistical analysis of relevant technical or economic data collated from the literature or the participants,[11] and predictive modeling tools such as system dynamics.[12]

Finally the results must be assembled in some easily assimilated fashion and distributed for final approval. Often, especially in target-driven roadmaps, one creates a single chart or diagram which displays the main results in a visual

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[8] "The Delphi Method: Techniques and Applications" edited by H. A. Linstone and M. Turoff, Addison-Wesley, 1975; available on-line from http://www.is.njit.edu/pubs/delphibook.

[9] "The Elements of Statistical Learning" by T. Hastie, R. Tibshirani & J. Friedman, Springer, 2001.

[10] "Discrete Mathematical Models, with Applications to the Social, Biological and Environmental Problems" by F. S. Roberts, Prentice-Hall, 1976.

[11] "Technology Portfolio Planning and Management" by Oliver Yu, Springer, 2006.

[12] "Business Dynamics" by John Sterman, Irwin-McGraw-Hill, 2000.

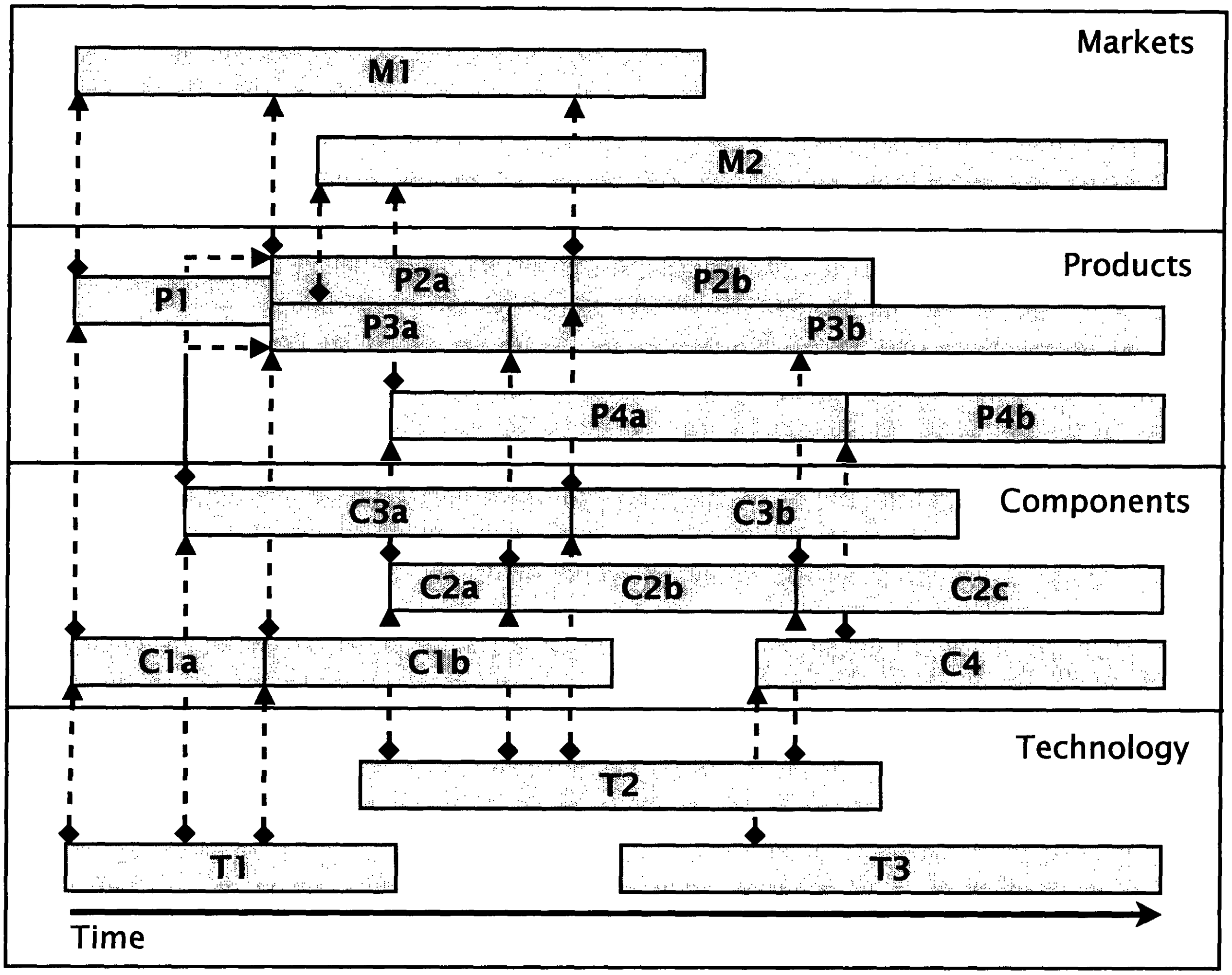

Figure 4.2. *Central graphic for a generic target-driven technology roadmap document.*

fashion, as illustrated in Figure 4.2, followed by a more detailed written document. Needless to say, such diagrams do not play such a big role in most exploratory roadmaps, though they may be used to display the results of scenario analysis, and the participants in an exploratory roadmap must often be rather creative in their choice of visual aids. The MANCEF Roadmap, for example, sometimes replaces "time" in a diagram like that in Figure 4.2 by a logarithmic measure of spatial scale, and often uses a topographic map with its features labeled by company, technology etc. to display the results of a cluster analysis.

2. Justification, Objectives and Tasks to Initiate the Power-MEMS Roadmap

In Chapter 1 of this work, we argued that society has an already poignant and rapidly growing need for an entirely new generation of energy technologies. In Chapter 2 we somewhat arbitrarily picked out four general kinds of advanced energy technologies that are currently under intense development. This selection was based both on the demonstrated applicability of MEMS and on the potential of these technologies to cause near-term disruptions in existing markets. The latter in turn is due simply to their use of chemical fuels or scavenging to enable energy densities well beyond even future generations of batteries. We then discussed each of these four broad classes of energy technologies and showed examples, taken largely from academic research, which illustrate the applicability of MEMS manufacturing processes to each. In Chapter 3 we used literature, patent and company database searches to show that innovative activity in these technologies has skyrocketed over the past decade, and then looked at the most important markets which they could immediately target. We next considered the economics of MEMS manufacturing with emphasis on how a small-to-medium size firm could get into the game, and gave some examples of applicable business models. Finally we presented two detailed case studies involving real people working to overcome the market and engineering risks associated with innovation in power-MEMS technologies.

This plot was meant to illustrate the theme of this dissertation, which is that MEMS has the potential to become a unifying foundation for not only the four broad classes of energy technologies that we chose to focus on, but for a completely new generation of energy technologies some of which we may glimpse only dimly today.[13] Such a unifying foundation is essential to the development of a vibrant industrial ecosystem in which a new generation of technologies, and their associated value chains, can be born and nurtured to maturity. The advent of MEMS is already transforming many industries, and the NEXUS and MANCEF Roadmaps are intended to help those industries realize the benefits which MEMS has to offer. Unfortunately, both of these roadmaps cost money, and no one is going to spend it unless they are already at least half-convinced, by some other means, that MEMS is going to be useful to them. It is a classic chicken-and-egg problem.

Thus it seems that the time is right for a meeting of the minds among representatives of energy technology companies with products that either do or could make good use of MEMS manufacturing processes, along with researchers from academic or government laboratories involved in the development of power MEMS, and government or industrial organizations interested in improving the availability and capabilities of advanced energy technologies. Of course this does not have to be structured as a roadmapping exercise; one could, for ex-

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[13] See, for example, "Thermal Integral Micro-Generation Systems for Solar and Conventional Use" by A. Kribus, *J. Solar Energy Eng.* **124**, 189-97, 2002.

ample, imagine creating an Energy X-Prize that could be won through the use of MEMS and raise awareness that way.[14] We have seen however that an exploratory roadmap is a proven means of establishing a formal process by which a diverse group of actors who do not necessarily know much about one another or their capabilities can begin to develop mutually beneficiary business relationships. This seems to be exactly what is called for at this point in time.

The four business sectors previously identified, i.e. microengines/turbines, micro fuel cells, solid-state devices for producing electricity from heat, and vibrational or electromagnetic energy scavengers, would seem to be a good place to start identifying the industrial participants. Certainly we hope that the foregoing chapters have made a convincing case that there now exists a real opportunity for these players to gain competitive advantage in the wider business world through the exchange of information and/or collaborating with MEMS foundries or research institutes on power-MEMS products. Most academic researchers now publishing in power MEMS are already known to one another through the power MEMS conference series, so getting them involved should be relatively straightforward. Representatives from non-profit organizations devoted to MEMS such as MANCEF and NEXUS should also be invited to participate, as should representatives from MEMS design houses and foundries. Fi-

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[14] See http://www.xprize.org; perhaps the power-MEMS roadmapping committee will decide to make this a priority, though we note that raising funds for the original Ansari X-Prize was an extremely demanding task in and of itself.

nally representatives from funding agencies, such as the NSF, DOE and DARPA in the USA, should be urged to participate, along with some of the venture capitalists and other financiers who are now vigorously pursuing investments in clean energy technology.[15] It would be appropriate to begin to contact possible participants this summer (2007), develop the issues to be discussed via a suitable electronic forum or blog, and then all meet and get started at the upcoming Power-to-Go / Power MEMS 2007 conferences which are being organized by Christopher Hebling at the Fraunhofer Institute in Freiburg, Germany over November 27-29, 2007.[16] This dissertation was written in large part to initiate a Power-MEMS Roadmap organized along these lines.

The scope of the roadmap should conform to its objectives, which may be summarized as promoting a wider understanding of what MEMS has to offer and how best to take advantage of it among managers and engineers in companies working on advanced energy technologies, making their needs and concerns better known to researchers, companies and other organizations within the MEMS community, and alerting funding agencies and financiers to the opportunities thereby created. It is important emphasize that we are seeking to develop a value-chain roadmap, rather than a mere technology roadmap. With this in mind, I propose the following roadmap objectives:

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[15] See "New CleanTech Report: 700 Investors Can't Be Wrong" by N. Parker, *Venture Capital J.*, pp. 54-5, Feb. 2006 or http://www.cleantech.com.

[16] See http://www.powermems.org.

1. To help key players in advanced energy technology companies to learn more about the services available from MEMS foundries and how to make the best possible use of them.
2. To promote a dialog between industry and academic participants, and in particular to showcase some potentially valuable university patents which may be available for licensing.
3. To assist recent university graduates in finding the best possible employment for their talents, and companies in finding the skills they need in order to take advantage of power MEMS.
4. To make policy makers, grant managers and venture capitalists more aware of the field of power MEMS and its capabilities, thereby encouraging further support for power MEMS R&D.
5. To take the first steps towards establishing a power MEMS components and services value network, and to begin the process of standardizing the interfaces between suppliers and producers.
6. To identify some outstanding technological challenges beyond the capabilities of any one firm to solve, which may subsequently be tackled within a university setting or via industrial consortia.

I will close this section with a brief discussion of intellectual property concerns, which might otherwise dampen participation. The main thing to realize here is that MEMS is a group of complementary enabling technologies with the important additional advantage of being well-suited to mass production. As long as the discussion is restricted to the generic capabilities of MEMS and features of advanced energy technologies which have already been published either as patents or in the engineering literature, and the fusion of these two fields is illustrated using only the many designs that have been developed in an academic setting, there should be little to fear. On the contrary, the potential for losing competitive advantage by staying out of the roadmapping process, in particular the knowledge and ready access to the resources that it will give its participants, should generally be of greater concern.

3. A Conceptual Framework for the Process of Creating a Power-MEMS Ecosystem

The attainment of the goals articulated above poses a useful and stimulating managerial problem. The dissemination of this dissertation amongst the stakeholders identified above may serve to kick it off, but the momentum needed to keep it going requires a deeper understanding on the part of its participants of the evolutionary process in which they are engaged. The management of technological knowledge and innovation is of course both a broad and a deep field, which is generally regarded as having begun with the work of Joseph Schumpeter over the first half of the last century.[17] It has really picked up over the

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[17] "Capitalism, Socialism, and Democracy" by Joseph A. Schumpeter, Harper & Brothers, 1942; 3rd edition, Harper & Row, 1950, reprinted in 1962, 1975.

last couple of decades as mainstream economists came to the belated conclusion that long-term economic progress depends more on technological advances than on capital investment *per se.*

I have been fortunate to have access to several of the main players in these developments during my sojourn at the MIT Sloan School of Management. It is of course not possible for me to do justice to all that I have learned from them here, but I think the following synopsis emphasizing the managerial and policy implications of this field of evolutionary economics will help to structure and enhance the roadmapping process for all its participants.[18] What follows extends our earlier discussion of disruptive technology (Section 2.4) to disruptive innovation more generally.

Following early work by Abernathy and Clark,[19] we begin by recognizing two principal dimensions in business innovation. The first is the novelty of the technology underlying the new product and its means of production, while the second is the novelty of the customer value proposition thereby created and the degree to which it opens new markets. Following subsequent work by Henderson and Clark,[20] we will further split the technology/production dimension into

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[18] See "The Evolutionary Theory of Economic Change" by R. R. Nelson & S. G. Winter, Harvard Univ. Press, 1982.

[19] "Innovation: Mapping the Winds of Creative Destruction" by W. J. Abernathy & K. B. Clark, *Research Policy* **14**, 3-22, 1985.

[20] "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms" by R. M. Henderson & K. B. Clark, *Admin. Sci. Q.* **35**, 9-30, 1990.

two distinct dimensions. The first is the degree to which the innovation affects the components, or core concepts, of a product, which we will somewhat arbitrarily identify with Abernathy and Clark's means of production. The second is the degree to which the innovation affects how the components are put together, which Henderson and Clark call the architecture or linkages of the product, and which corresponds more or less to the technology on which the product is based. Finally, in addition to the customer/market novelty of the product, we will also consider the impact the corresponding market's performance has on society, in particular society's ability or desire to develop new technologies. Examples of markets with huge impacts on the intensity and direction of research and development include pharmaceuticals, computers, and higher education; examples of markets with relatively small impacts include leisure, advertising, and clothing.[21]

While we agree with Afuah and Bahram's assertion that one should consider separately the effect of an innovation on each link in the value chain (or even value network),[22] we will simplify our analysis by looking only at the beginning and end of the value chain, namely technology development (knowledge creation) and product development (commercialization), regarding everything in between as "components" in much the same fashion as Henderson and Clark. Finally, in keeping with the tenants of system dynamics, we will seek to charac-

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[21] Although these markets have obvious economic significance.

[22] "The Hypercube of Innovation" by A. N. Afuah & N. Bahram, *Res. Policy* **24**, 51-76, 1995.

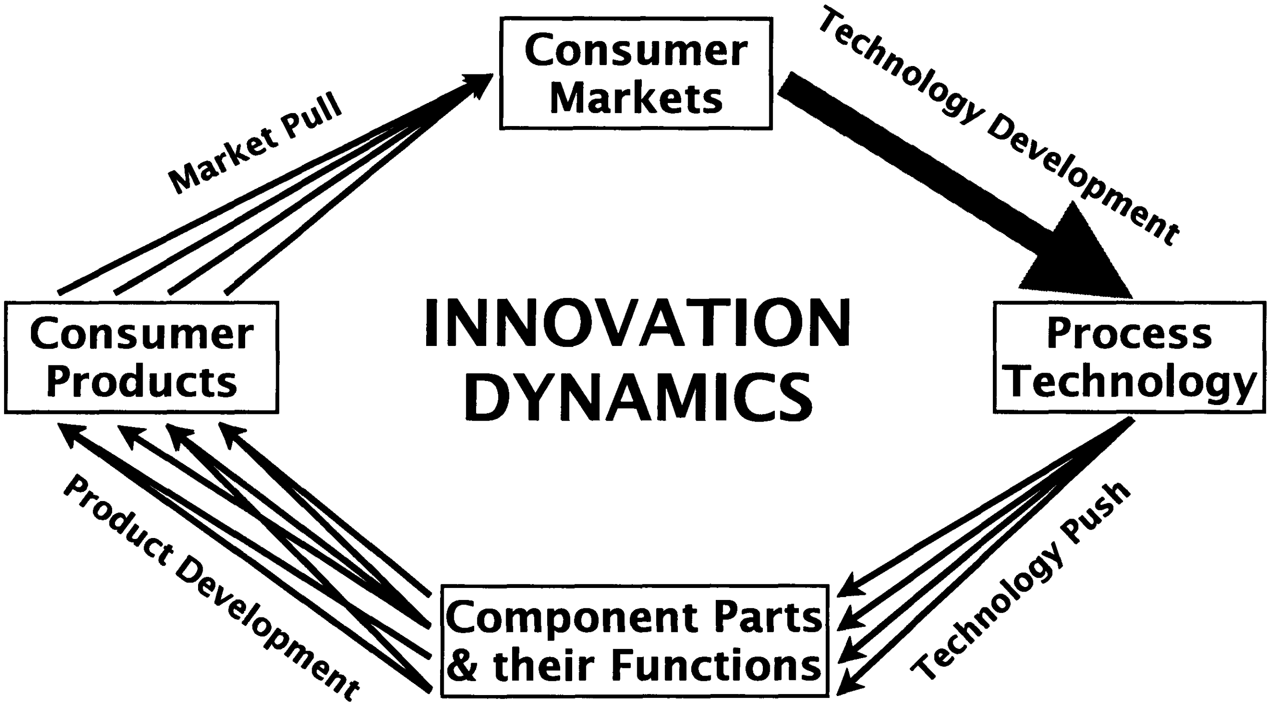

Figure 4.3. *The simplified model of innovation dynamics introduced in the main text.*

terize a critical positive feedback loop which is created by a final, non-economic and even rather intangible, link by which the markets dictate which technologies have demonstrable economic value and so get all that they need for further development. Taken together, these considerations lead to the simplified model of innovation dynamics illustrated in Figure 4.3.[23]

Let us further consider some important features of this model. First, by keeping just those products which are sold directly to end users in the Consumer Products category, we essentially restrict ourselves to products which are targeted

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[23] Note that the flows in this diagram count the numbers of new processes, components and products produced per unit time, not the number of times the process is used, nor the number of components produced, nor the number of units of a product sold. In short, we are concerned here with a value chain rather than a supply chain.

at one particular Consumer Market, as indicated by the converging arrows in Figure 4.3. Similarly, we will assume that Component Parts have been defined such that each is enabled at the time it is first produced by just one Process Technology (even though many more mature technologies may play a role in producing it), as indicated by the diverging arrows in Figure 4.3. The complexity of the dynamics thus arises in large part from the fact that the Component Parts can be put together in many different combinations each corresponding to a different Consumer Product, as indicated in Figure 4.3 by the non-parallel arrows connecting these two categories. Note that Figure 4.2 was also designed so as to be consistent with these observations and definitions.

The relations between Consumer Markets and Process Technology, on the other hand, are not merely complex, but also diffuse and not completely understood. This is indicated in Figure 4.3 by the use of a large grey arrow. Although almost anything that enhances the economy tends to increase the quantity and quality of Technology Development that can be done, there are (at least) three direct mechanisms by which the performance or creation of Consumer Markets can affect Technology Development.

1. The capital created by the Consumer Markets is used to support further Technology Development, whether directly by the companies involved, via joint ventures with or acquisitions of firms working in related areas, or contracts with and grants to universities and research institutes.

2. The publicity generated by the creation or dramatic expansion of a Consumer Market inspires technologists from all walks of life to work on related technologies, and financial or funding agencies to support them.
3. The products or components produced in response to the Market Pull sometimes serve as new tools which enable further Technology Development, in addition to their uses in Consumer Products.

Considerable empirical work would be needed to say very much more about these diffuse but important relations here.

It may now be seen that the four dimensions of innovation introduced above correspond to the four links shown in Figure 4.3. Instead of the 2-by-2 businessman's matrix used by Abernathy and Clark and again in a rather different way by Henderson and Clark to distinguish four kinds of innovation, we can classify innovations as high or low along each of these four dimensions and so obtain a 2-by-2-by-2-by-2 tensor which distinguishes <u>sixteen</u> kinds of innovation - perhaps more than is useful. More importantly, we have interpreted each of our dimensions as a characteristic of a flow in a dynamical system - a <u>co-flow</u> in system dynamics terminology. In this regard it should be noted that while there are significant delays, often many years in fact, involved in Technology Development, the delays involved in getting the Technology into new Components is generally much shorter, while time required for Product Development is shorter yet and the time to see a new Product accepted (or rejected) by the Market may be only a matter of days.[24] In system dynamics it is well known that diverse delays often lead to complex and non-intuitive behaviors.

Thus the qualitative conceptual model illustrated in Figure 4.3 can serve as the starting point for the development of certainly inexact but at least quantitative models of innovation dynamics. These presumably would generate the alternating waves of product and process innovation so often seen in practice, each separated by the emergence of a dominant design. Although probably not capable of making long-term predictions such a model would be quite useful in scenario analysis. In particular, in conjunction with the proposed Power-MEMS Roadmap this model could both generate scenarios to stimulate the discussion, and also by fitting the model to the roadmap's forecasts illuminate some of its consequences and thereby sharpen the hypotheses laid out therein.

4. The Challenges of Today Are the Promises of Tomorrow

The long-term goal of the Power-MEMS Roadmap, from my perspective at least, is to establish an industrial ecosystem which will lead to a whole new generation of energy technologies, and thereby perhaps even a practical and timely solution to some of the defects spelled out in Chapter 1 in our current energy

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[24] This is essentially the "clockspeed amplification" phenomenon discussed in the context of supply chains in *Clockspeed* by C. H. Fine, Perseus Publishing, 1998.

infrastructure. In this final section I wish to pose some technological challenges the solution of which would facilitate attaining this goal, at least eventually. Of course the first thing that needs to be done is to get a few good products out in which MEMS, and down the road a bit perhaps even NEMS (Nano Electro Mechanical Systems), play an essential role. I hope, and fully expect, that my thoughts in this area will evolve rapidly once the roadmapping process gets underway.

Most of the power-MEMS devices that have been built to date are not doing anything that absolutely could not be done without MEMS. It may still make sense to use MEMS, since the variable costs associated with MEMS manufacture are generally low enough to more than compensate for the high fixed costs of design and the equipment of a foundry, providing that the market for the product is large enough. Still, greater value will be obtained if a better device can be built using MEMS, and we fully expect that in due course products will come out that are fundamentally enabled by one or more of the technologies now viewed as part of MEMS.

In this regard it is worth noting that one thing MEMS does far better than any other manufacturing method is to make thousands of very small, identical devices in parallel. At present this unique capability is used mainly to decrease the cost of not-so-small devices, by making at most a few hundred at one time on a wafer which is then cut up into single devices to be packaged in a serial fashion for use. Not surprisingly, this latter "back-end" part of the process often costs more than the "front-end" manufacture of the device itself. A good example of this is likely to be the MIT microturbine (see Figure 2.1).

In cases where the underlying physics allows a smaller device to achieve higher levels of performance, it may instead be preferable to make thousands of such devices on a wafer and then package it in one piece, perhaps after bonding it to many other identical wafers, to obtain a three-dimensional array of millions of devices. Micro fuel cells seem to be in this category, as may the carbon nanotube based energy storage device proposed by Elastic Energy Systems (Section 3.4.2), since no single carbon nanotube can store a macroscopically significant amount of energy. A generic problem associated however with this approach is that it is very hard to collect the power produced by many small electric generators and feed it into an external load without prohibitive losses along the way due to stray capacitances or "parasitics."

I would like to propose a possible way around this problem, which would involve having each generator *deliberately* radiating its power from one or more antenna(e) integrated with them on the same chip, and packaging the wafer stack in a resonant cavity which collects the power being radiated from all the devices in parallel, without using any hardwire connections at all. It will be necessary to see to it that all the individual devices are radiating synchronously in order to avoid destructive interference, but this can be arranged by also controlling all the devices wirelessly at a difference frequency. All of this is physically possible,[25] and the rest is therefore only a matter of engineering research - which some of us try to make a living at.[26]

Another problem with making many things small lies in tribological challenges that have been encountered in micron-scale mechanical systems.[27] A great many solutions to these problems have been proposed, including exotic lubricants, diamond coatings and ultrasonic vibration, but the simplest thing which could be done is to avoid high-speed moving parts by designing passive speed regulation mechanisms into these devices. These could be either mechanical, electrical or even thermal in nature. Other problems that need to be solved in order to reach the nano scale include the difficulty of maintaining temperature gradients due to surface-to-volume effects, and the need to design mechanical systems which perform well even over substantial variations in the relative dimensions of their components.

Regardless of whether one uses the parallelism of MEMS to enable product or process enhancements, it will be necessary to climb an experience curve towards standardized designs for components with well-defined functions and

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[25] In the case of the carbon nanotube energy storage system, it will be necessary to use non-conducting nanotubes, or perhaps boron-nitride nanotubes which are nearly as strong and elastic but are always non-conducting.

[26] It is also worth noting that this scheme can be turned around for MEMS sensors, which can receive their power and transmit their information wirelessly, and which after suitable standards have been adopted would allow a fairly generic package to be developed for such sensors.

[27] "Tribology and MEMS" by J. A. Williams & H. R. Le, *J. Phys. D: Appl. Phys.* **39**, R201-14, 2006.

diverse applications.[28] This will allow complicated devices to be designed and assembled from modular components, rather than from scratch the way they generally are today - more like a work of art than of engineering. Note that these are component designs rather than actual physical components, which would be incompatible with putting everything on a single chip - although the ability to mix and match chip-level components may also be desirable. This parallels the ongoing debate within the MEMS community about when and which electronic components should go on the same chip as the mechanical components. The availability of such standard designs would greatly simplify the use of foundries, as well. Perhaps the main obstacle to the adoption of standard designs will be the patents that are routinely taken out on each new MEMS device, and it will take leadership and foresight on the part of the MEMS community to adopt open standards.[29] Power-MEMS components for which standardized designs are needed include various kinds of electrical generators, heat shields, mechanical power trains and resonators.

Even before any of the above challenges are solved, I believe there is real hope that MEMS can serve as the foundation for an industrial ecosystem that will lead to an experience curve as dramatic as that shown in Figure 2.5 for the disk

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[28] This experience curve, of course, will be greatly leveraged by the fact that the applications of MEMS technologies are far broader than those in the domain of power MEMS.

[29] Recall CBS' attempt to establish a color television monopoly through the imposition of standards; see "The General: David Sarnoff and the Rise of the Communications Industry" by K. M. Bilby, Harper & Row, 1986.

drive industry. In Christensen's analysis of that industry, he notes that time and time again a group of renegades has developed a smaller and relatively low performance disk drive, which found a niche market to support its development until its value, as measured in price-per-megabyte, exceeded that of larger disks and put most of the dominant disk drives firms out of business. Christensen is focused on the organizational features of firms that prevent them from responding to such threats before it is too late, and he never asks, let alone explains, why making disk drives smaller kept allowing them to be made better. It is my hope that in energy storage as well as information storage Fritz Schumacher's observation that "small is beautiful" will again prove true.[30]

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[30] "Small is Beautiful: Economics as If People Mattered" by E. F. Schumacher, 25th anniversary reprint from Hartley & Marks, 1999.

Appendix A: List of Companies with Technologies to which Power MEMS Could Be Applied

1. Microengines and Microturbines

The following companies are or have worked on microengines/turbines to produce portable electric power based on various non-MEMS technologies, where by "portable" we mean someone could carry it on their person while in use; larger-scale fuel-powered generators are unlikely to ever be made using MEMS.

Company Name (TICKER):	Sunpower Corporation, Athens OH (private)
History and Principals:	William Beale (1974); Lyn Bowman & Jarlath McEntee (1997).
Relevant Patent Numbers:	39 patents issued; only MEMS one is 5,941,079
Products Using MEMS:	Directly sells only engineering services
WWW URL for Activity:	http://www.sunpower.com
Additional Comments:	Specialist in Stirling cycle engines and coolers; not be be confused with Sunpower Inc., a much more recent manufacturer of solar panels based in Mountain View, CA (SPWR)

Company Name (TICKER):	Honeywell International, Morristown NJ (HON)

History and Principals:	Wei Yang, Ulrich Bonne, Burgess R. Johnson & Cleopatra Cabuz (circa 1996)
Relevant Patent Numbers:	6,276,313; 6,397,793; 6,460,493
Products Using MEMS:	Many, but none related to Microengine project
WWW URL for Activity:	http://www.menet.umn.edu/~haich/engine
Additional Comments:	Started as a DARPA contract to Honeywell, which was continued as a subcontract to the Dept. of Mechanical Engineering at the Univ. of Minnesota where it became the Ph.D. project of Hans T. Aichlmayr (2002) under the direction of Profs. David B. Kittelson and Michael R. Zachariah

Company Name (TICKER):	Aerodyne Research, Billerica MA (private)
History and Principals:	Kurt D. Annen, David B. Stickler, Paul L. Kebabian, Jaime Woodroffe (circa 1999)
Relevant Patent Numbers:	6,349,683; 6,479,964
Products Using MEMS:	Product apparently makes no use of MEMS
WWW URL for Activity:	http://www.aerodyne.com
Additional Comments:	Aerodyne web site claims "200-500 Watt prototype under construction" as of March 27, 2007

Company Name (TICKER):	Powerix Technologies, Ann Arbor MI (LLC)
History and Principals:	Rhett Mayor & Stephen W. Dryer (2001)
Relevant Patent Numbers:	Seem to be none
Products Using MEMS:	Product apparently makes no use of MEMS
WWW URL for Activity:	http://www.powerixtech.com

Additional Comments:	Micro Internal Combustion Swing Engine began as the Ph.D. project of Kevin Mijit (2000) in Mechanical Engineering at the Univ. of Michigan in Ann Arbor under Profs. Jun Ni and Werner Dahm, where Rhett Mayor was a Research Scientist

Company Name (TICKER):	AgilePower Systems, Bolton MA (private)
History and Principals:	Jon Wade (circa 2004)
Relevant Patent Numbers:	7,182,046 (Deformable combustion chamber-based internal combustion engine and generator)
Products Using MEMS:	Patent does not mention the use of MEMS
WWW URL for Activity:	None any longer
Additional Comments:	Little is known about this company save that its former president Jon Wade subsequently joined International Game Technology in Reno NV as Executive VP of Engineering

Company Name (TICKER):	Harris Corporation, Melbourne FL (HRS)
History and Principals:	C. W. Sinjin Smith, Charles M. Newton, Richard Gassman (2004)
Relevant Patent Numbers:	6,987,329 (Fuel flexible thermoelectric micro-generator with micro-turbine)
Products Using MEMS:	Patent claims generator could be used to power MEMS devices, but not that it itself uses MEMS
WWW URL for Activity:	None that I can find
Additional Comments:	Nothing on this has been published, according to an Engineering Village search on every author's name; it is not known if Harris Corporation will commercialize it

Company Name (TICKER):	Centro Ricerche FIAT / Società Consortile per Azioni, Orbassano ITALY (N/A)

History and Principals:	Piero Perlo, Gianfranco Innocenti, Gianluca Bollito, Bartolomeo Pairetti, Alessandro Zanella, Cosimo Carvignese (2003)
Relevant Patent Numbers:	6,932,030 (Microgenerator of electrical energy)
Products Using MEMS:	Patent does not mention the use of MEMS or micromachining
WWW URL for Activity:	None that I can find
Additional Comments:	Nothing on this has been published, according to an Engineering Village search on every author's name; it seems unlikely Fiat will commercialize it

2. Direct Methanol Fuel Cells

In contrast to the microengine/turbine arena, where only a handful of companies have yet ventured, starting in the late 1990's micro fuel cells, and the DMFC in particular, took off like a rocket. In the following, the numbers of "published-but-not-yet-issued" DMFC patents was determined from a USPTO search on Mar. 30, 2007 for all such patents with the indicated assignee name including "fuel cell" and "methanol" but not "reform$" ("$" is USPTO web site's wild card).

Company Name (TICKER):	Hitachi Ltd., Tokyo JAPAN (HIT)
History and Principals:	Hitachi had over a dozen patents on what subsequently came to be known as the DMFC before 1990, after which they slowed way down
Relevant Patent Numbers:	5,457,079; 5,788,821; 6,869,713; 7,105,244; 7,105,244; 7,108,939; 7,192,670

Products Using MEMS:	None of Hitachi's DMFC patents mention MEMS or micromachining
WWW URL for Activity:	http://www.hitachi.com
Additional Comments:	Hitachi Cable is working on the DMFC (Hitachi Cable Review 23, 37-39, August 2004), while a recent press release from Hitachi Maxwell touts a micro fuel cell using hydrogen generated from aluminum and water instead of the DMFC; there are 22 published-but-not-issued Hitachi patents

Company Name (TICKER):	Kabushiki Kaisha Toshiba, Tokyo JAPAN (TOSBF.PK)
History and Principals:	Toshiba's earliest DMFC patents date from 1993, but their work took off only in 2000
Relevant Patent Numbers:	5,364,711; 5,432,023; 6,416,898; 6,447,941; 6,565,763; 6,773,844; 6,878,473; 6,936,365; 7,189,472; 7,026,066; 7,147,950; 7,097,781; 7,097,784; 7,125,822; 7,153,604; 7,174,914
Products Using MEMS:	None of Toshiba's DMFC patents mention MEMS or micromachining
WWW URL for Activity:	http://www.toshiba.com
Additional Comments:	Rumored to be a passive device based only on capillary action and diffusion; lots of press releases but still no product yet; there are 65 (!) published-but-not-yet-issued Toshiba patents

Company Name (TICKER):	Sony Corporation, Tokyo JAPAN (SNE)
History and Principals:	Koichiro Hinokuma, Minehisa Imazato, Toshiaki Kanemitsu, Nobuaki Sato (2000)
Relevant Patent Numbers:	6,635,377; 6,726,963; 6,824,908; 6,824,912; 6,841,289; 6,869,721; 6,890,676; 7,037,619;
Products Using MEMS:	None of the above patents mention MEMS or micromachining

WWW URL for Activity: http://www.sony.com

Additional Comments: In 2001 Sony announced it had found a way to make better DMFC electrodes from fullerenes, but nothing has yet appeared; they have only two published-but-not-yet-issued DMFC patents

Company Name (TICKER): Matsushita Electric Industrial Co., Ltd., Osaka JAPAN (MC)

History and Principals: Hisaaki Gyoten, Hiroki Kusakabe, Eiichi Yasumoto, Osamu Sakai (2000); Toshihiko Ichinose, Masahiro Takada, Katsumi Kozu, So Kuranaka (2003); Hideyuki Ueda, Shinsuke Fukuda, Tetsuya Osaka, Toshiyuki Momma, Jong-Eun Park (2005)

Relevant Patent Numbers: 6,541,144; 7,129,674

Products Using MEMS: None of the above patents mention MEMS or micromachining, although one pending DMFC patent does (USPTO publication 20070054174)

WWW URL for Activity: http://panasonic.co.jp/mbi

Additional Comments: Matsushita Electric Industrial Co., Ltd. is better known as Panasonic; in addition to their DMFC they are also developing fuel cells for "home cogeneration"

Company Name (TICKER): Futjitsu Ltd., Tokyo JAPAN (FJTSF.PK)

History and Principals: Nawalage Florence Cooray, Fumio Takei, Masao Tomoi

Relevant Patent Numbers: 7,037,614

Products Using MEMS: None of the above patents mention MEMS or micromachining

WWW URL for Activity: http://www.fujitsu.com

Additional Comments: Seven published-but-not-yet-issued DMFC patents

Company Name (TICKER):	NEC Corporation, Tokyo JAPAN (NIPNY)
History and Principals:	Hidekazu Kimura, Suguru Watanabe, Tsutomu Yoshitake, Sadanori Kuroshima, Shin Nakamura, Yuichi Shimakawa, Takashi Manako, Hideto Imai, Yoshimi Kubo (2002); Kunihiko Shimizu, Toshihiko Nishiyama, Takashi Mizukoshi, Masayuki Sasaki (2004)
Relevant Patent Numbers:	7,115,337
Products Using MEMS:	No mention of either MEMS or micromachining
WWW URL for Activity:	http://www.nec.com
Additional Comments:	No news since their 2003 press release on a carbon nanotube electrode DMFC; two published-but-not-yet-issued patents to NEC Tokin Corp.

Company Name (TICKER):	Sanyo Electric Co., Ltd., Tokyo JAPAN (SANYF.PK)
History and Principals:	Shigeru Sakamoto, Hiroko Sanda, Hirosaku Nagano, Hidekazu Kuromatsu, Kiyoyuki Namura, Yasunori Yoshimoto, Hirokazu Izaki, Akira Hamada, Yugo Fukami
Relevant Patent Numbers:	7,011,905; 7,060,383
Products Using MEMS:	No mention of either MEMS or micromachining
WWW URL for Activity:	http://us.sanyo.com
Additional Comments:	The EETimes reported in 2005 that Sanyo was developing a DMFC for IBM's ThinkPad, which IBM has since sold off; 16 published-but-not-yet-issued patents

Company Name (TICKER):	Samsung Electronics Co., Ltd., Seoul KOREA (SMSN@LSE)
History and Principals:	Hyuk Chang, Chan Lim, Kyoung-hwan Choi (2000); Hae-kyoung Kim, Ju-hee Cho, Chan-ho Pak (2002)

Relevant Patent Numbers:	6,689,502; 6,743,541; 6,749,892; 6,774,150; 6,916,764; 6,955,712; 7,037,950; 7,132,385; 7,166,381; 7,169,500; 7,179,560
Products Using MEMS:	None of the above patents mention MEMS or micromachining
WWW URL for Activity:	http://www.samsung.com
Additional Comments:	Recent press releases say that Samsung is now working closely with MTI Micro Fuel Cells on their Mobion DMFC; there are 43 published-but-not-yet-issued Samsung DMFC patents

Company Name (TICKER):	LG Chem, Ltd., Seoul KOREA (LGCIF.PK)
History and Principals:	Jong-Kee Yeo, President & CTO
Relevant Patent Numbers:	None issued in the US at this time
Products Using MEMS:	None of the above patents mention MEMS or micromachining
WWW URL for Activity:	http://www.lgchem.com
Additional Comments:	The EETimes reported in 2005 that LG Chem claimed it would bring a DMFC to market within a year, which it has not; they do however have 5 published-but-not-yet-issued DMFC patents

Company Name (TICKER):	Motorola, Inc., Shaumberg IL (MOT)
History and Principals:	J. L. Davis (1997); C. R. Koripella, W. J. Ooms, D. L. Wilcox, J. W. Bostaph, A. M. Fisher, J. K. Neutzler, J. S. Pavio, D. S. Marshall (2000); B. D. Landreth, S. D. Pratt, S. Muthuswamy, R. J. Kelley, R. W. Pennisi, S. D. Pratt (2002)
Relevant Patent Numbers:	5,904,740; 6,387,559; 6,465,119; 6,497,975; 6,503,378; 6,660,423; 6,696,189; 6,696,195; 6,727,016; 6,670,403; 6,908,500; 6,936,361; 6,942,939; 6,986,957; 6,989,205

Products Using MEMS: Seven of the above patents mention MEMS or micromachining

WWW URL for Activity: http://www.motorola.com

Additional Comments: Recent prototypes have used "low-temperature cofired ceramics" as a form of "3D MEMS"; only one published-but-not-yet-issued DMFC patent

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Company Name (TICKER): MTI Micro Fuel Cells, Albany NY (MKTY)

History and Principals: W. P. Acker, M. S. Adler, G. Beckmann, J. A. Corey, S. Gottesfeld, G. C. McNamee, W. W. Dailey (2000); Xiaoming Ren, J. J. Becerra, E. J. Brown, M. S. DeFilippis (2001)

Relevant Patent Numbers: 6,460,733; 6,566,003; 6,589,679; 6,632,553; 6,645,655; 6,686,081; 6,699,021; 6,737,181; 6,761,988; 6,794,067; 6,794,071; 6,808,837; 6,821,658; 6,824,899; 6,824,900; 6,869,716; 6,890,674; 6,890,680; 6,908,701; 6,981,877; 6,991,865; 7,081,310; 7,125,620; 7,175,934; 7,179,501

Products Using MEMS: Only 4 of the 37 above patents mention MEMS or micromachining

WWW URL for Activity: http://www.mtimicrofuelcells.com

Additional Comments: Now shipping prototypes of their Mobion DMFC to selected customers (probably Samsung and Gillette - now Procter & Gamble); only one published-not-yet-issued DMFC patent

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Company Name (TICKER): Viaspace Inc., Pasadena CA (VSPC), operating through its majority-owned subsidiary Direct Methanol Fuel Cell Corp. (DMFCC)

History and Principals: Dr. Carl Kukkonen, CEO of both Viaspace and DMFCC (1998); no data available on scientific staff since all patents are from universities

Relevant Patent Numbers:	5,175,064; 5,599,638; 5,773,162; 5,795,496; 5,945,231; 5,992,008; 6,136,463; 6,146,781; 6,150,047; 6,221,523; 6,228,518; 6,248,460; 6,254,748; 6,265,093; 6,277,447; 6,291,093; 6,303,244; 6,306,285; 6,391,486; 6,399,235; 6,420,059; 6,440,594; 6,444,341; 6,444,343; 6,468,684; 6,485,851; 6,589,684; 6,680,139; 6,703,150; 6,740,434; 6,756,145; 7,125,621
Products Using MEMS:	None of the above patents mention MEMS or micromachining
WWW URL for Activity:	http://www.dmfcc.com
Additional Comments:	All the above patents obtained by exclusive license from the Calif. Inst. of Technology save one for the Univ. of Southern Calif., which have 16 published-but-not-yet-issued DMFC patents

Company Name (TICKER):	Neah Power Systems, Inc., Bothell WA (NPWS)
History and Principals:	L. J. Ohlsen, A. M. Cooke, J. C. Mallari, Chung M. Chan, G. L. Rice, C. E. Nelson (1999)
Relevant Patent Numbers:	6,641,948; 6,720,105; 6,808,840; 6,811,916; 6,852,443; 7,105,245; 7,118,822; 7,157,177
Products Using MEMS:	Four of the above patents mention micromachining
WWW URL for Activity:	http://www.neahpower.com
Additional Comments:	Competitive edge built on a "porous silicon" rather than a proton exchange membrane; reportedly heavily in debt and behind schedule; no published-but-not-yet-issued DMFC patents

Company Name (TICKER):	Polyfuel Inc., Mountain View CA (PYF@AIM)
History and Principals:	C. Lawrence, A. Salamini, B. MacGregor, D. Bliven, Shuguang Cao, Helen Xu, T. Jeanes, Kie Hyun Nam, Jian Ping Chen (1999); J. D. Balcom, CEO

Relevant Patent Numbers: 6,911,411; 7,005,206; 7,094,490

Products Using MEMS: None of the above patents mention MEMS or micromachining

WWW URL for Activity: http://www.polyfuel.com

Additional Comments: Spun out of SRI International in 1999; has 11 published-but-not-yet-issued DMFC patents

Company Name (TICKER): Medis El Ltd., ISREAL (MDTL) and its wholly-owned subsidiary More Energy, Ltd.

History and Principals: G. Finkelshtain, Y. Katzman (1992); Boris Filanovsky, Nikolai Fishelson, Zina Lurie (2000); Mark Estrin, Moti Meron, Eric Torgeman, Rami Hashimshony (2003); R. K. Lifton, CEO

Relevant Patent Numbers: 6,479,181; 6,554,877; 6,562,497; 6,730,350; 6,758,871; 6,773,470; 6,878,664; 7,004,207

Products Using MEMS: None of the above patents mention MEMS or micromachining

WWW URL for Activity: http://www.medistechnologies.com

Additional Comments: Claims to now sell a single-use "power-pack" for recharging batteries, which uses a mixture of sodium borohydride and methanol; 16 published-but-not-yet-issued patents

Company Name (TICKER): STMicroelectronics, Inc., Geneva Switzerland (STM)

History and Principals: S. Lo Priore, M. Palmieri, U. Mastromatteo, G. D'Arrigo, S. Coffa, R. Corrado Spinella (2001)

Relevant Patent Numbers: 6,969,664; 7,029,781

Products Using MEMS: Though neither of the above patents explicitly mention MEMS, STMicroelectronics is a major manufacturer of MEMS products generally

WWW URL for Activity: http://www.st.com

Additional Comments:	No company press releases indicating a forthcoming product; company has 4 published-but-not-yet-issued patents

Company Name (TICKER):	SFC Smart Fuel Cell AG, Brunnthal GERMANY (privately held).
History and Principals:	K. Colbow, M. Manmohan Kaila, Jiujun Zhang, J. Müller, G. Boehm (2000); Dr. Peter Podesser, CEO
Relevant Patent Numbers:	6,884,530
Products Using MEMS:	No explicit mention of MEMS or micromachining
WWW URL for Activity:	http://www.efoy.de (Energy FOr You)
Additional Comments:	Now selling DMFC's weighing "only" 7.5 kg; no published-but-not-yet-issued patents

Company Name (TICKER):	Antig Technology Co., Ltd., Taipei, TAIWAN (not traded on any exchange, perhaps government owed)
History and Principals:	No information available even on web site.
Relevant Patent Numbers:	No US patents yet issued
Products Using MEMS:	Product said to be made using "printed circuit board" process, which does not seem to be MEMS
WWW URL for Activity:	http://www.antig.com
Additional Comments:	Six published-but-not-yet-issued patents

Company Name (TICKER):	CMR Fuel Cell PLC, Cambridge UK (CMF@AIM)
History and Principals:	John Halfpenny, CEO since founding (2002)
Relevant Patent Numbers:	No US patents at all
Products Using MEMS:	Unknown
WWW URL for Activity:	http://www.cmrfuelcells.com

Additional Comments:	Uses proprietary "flow-through stack," but no products yet, or published-but-not-yet-issued US patents either

Company Name (TICKER):	Pure Energy Visions, Inc., Toronto CANADA (PEV)
History and Principals:	Wayne Hartford, CEO; Joseph Daniel-Ivad, CTO
Relevant Patent Numbers:	No US patents yet issued to this company
Products Using MEMS:	Unknown
WWW URL for Activity:	http://www.pureenergybattery.com
Additional Comments:	No published-but-not-yet issued patents

Company Name (TICKER):	INI Power Systems, Inc., Morrisville NC (private)
History and Principals:	Larry J. Markoski, Jeffrey S. Moore, Joseph W. Lyding
Relevant Patent Numbers:	6,713,206 (licensed from the Univ. of Illinois)
Products Using MEMS:	Unknown
WWW URL for Activity:	http://www.inipower.com
Additional Comments:	No published-but-not-yet issued patents

Company Name (TICKER):	Tekion Inc., Champaign IL (private)
History and Principals:	R. I. Masel, Yimin Zhu, Zakia Khan, M. Man, R. T. Larson, C. A. Rice, P. Waszczuk, A. Wieckwski (2002); Neil Huff, CEO
Relevant Patent Numbers:	7,108,773 (licensed from the Univ. of Illinois)
Products Using MEMS:	Unknown
WWW URL for Activity:	http://www.tekion.com

Additional Comments:	Uses formic acid rather than methanol, which simplifies the chemistry at the cost of a lower energy density; 4 published-but-not-yet-issued patents for this technology from the Univ. of Illinois

3. Thermoelectrics, Thermionics and Thermophotovoltaics

This, once again, is a very different field. It has been commercially active since the 1960's, and although some large diversified companies use thermoelectrics in their products, the companies that sell them as stand-alone products are mostly rather small. They are also by and large profitable!

Company Name (TICKER):	Global Thermoelectrics, Calgary CANADA (private)
History and Principals:	Peter Garrett, CEO & Director (2003)
Relevant Patent Numbers:	No patents save on solid oxide fuel cells, all of which were acquired by Fuel Cell Energy, Inc.
Products Using MEMS:	Unlikely
WWW URL for Activity:	http://www.globalte.com
Additional Comments:	Sells broad line of combustor/generator combinations from 15 to 550 MW for remote power use

Company Name (TICKER):	Tellurex Corporation, Traverse City MI (private)
History and Principals:	Charles J. Cauchy, President (1994)
Relevant Patent Numbers:	5,448,109; 6,103,967

Products Using MEMS: Unlikely

WWW URL for Activity: http://www.tellurex.com

Additional Comments: Sells small home-made TE modules and consumer products based on same

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Company Name (TICKER): Teledyne Energy Systems, Inc. of Hunt Valley, MD, a wholly-owned subsidiary of Teledyne Technologies, Inc. (TDY)

History and Principals: Dr. Robert Mehrabian, CEO (1999)

Relevant Patent Numbers: 6,410,842

Products Using MEMS: Unlikely

WWW URL for Activity: http://www.teledynees.com

Additional Comments: Has been selling thermoelectric generators since the SNAP3 space generator in 1961

Company Name (TICKER): Marlow Industries, Inc. of Dallas TX, a wholly-owned subsidiary of II-VI, Inc. (IIVI)

History and Principals: Raymond Marlow, CEO (1973)

Relevant Patent Numbers: 4,467,611; 6,169,245; 6,188,011; 6,207,888; 6,369,314; 6,399,871; 6,492,585; 6,660,925

Products Using MEMS: Unlikely

WWW URL for Activity: http://www.marlow.com

Additional Comments: Web site mentions power generation, but like most thermoelectric companies they focus much more or cooling and heating

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Company Name (TICKER): Hi-Z Technology, San Diego CA (private)

History and Principals: Norbert B. Elsner, John H. Norman (1990); Saeid Ghamaty (1994); Frederick A. Leavitt, John C. Bass (1996); Daniel T. Allen (1997); Nathan D. Hiller (2003)

Relevant Patent Numbers: 5,248,639; 5,550,387; 5,856,210; 6,019,098; 6,096,965; 6,053,163; 6,096,964; 6,519,947; 6,624,349; 6,828,579; 6,914,343; 7,038,234

Products Using MEMS: Unlikely

WWW URL for Activity: http://www.hi-z.com

Additional Comments: Sells small home-made TE power generation modules and consumer products based on same

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Company Name (TICKER): BSST, LLC, Irwindale CA, a wholly-owned subsidiary of Amerigon, Inc. (ARGN)

History and Principals: Lon E. Bell (2000)

Relevant Patent Numbers: 6,539,725; 6,598,405; 6,625,990; 6,637,210; 6,672,076; 6,812,395; 6,948,321; 6,959,555

Products Using MEMS: Unlikely

WWW URL for Activity: http://www.bsst.com

Additional Comments: Develops custom solutions for parent company and outside customers

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Company Name (TICKER): PowerMEMS, Cupertino, CA (private)

History and Principals: Carl R. Schulenburg, CEO (2004)

Relevant Patent Numbers: None issued or published as of March 2007

Products Using MEMS: No products at all yet

WWW URL for Activity: http://www.powermems.com

Additional Comments:	Plans to develop solar cell, thermoelectric and vibration energy scavenger combo to keep thin-film lithium ion battery charged for wireless sensor networks

Company Name (TICKER):	ENECO, Salt Lake City UT (believed privately held)
History and Principals:	Yan R. Kucherov, Peter L. Hagelstein (1999)
Relevant Patent Numbers:	6,396,191; 6,489,704; 6,779,347; 6,906,449; 7,109,408
Products Using MEMS:	No mention of MEMS or micromachining in their patents
WWW URL for Activity:	http://www.eneco.com
Additional Comments:	Developing a "Thermal Chip," or solid-state thermionic device, which they claim will have a much higher figure of merit than conventional thermoelectric materials; four published-but-not-yet-issued patents; Hagelstein is an associate professor in MIT's EECS department

Company Name (TICKER):	PowerChips PLC, Gibraltar (PWCHF.PK), a majority-owned subsidiary of Borealis Technical, Ltd., in turn owned by Borealis Explorations, Ltd. (BOREF.PK)
History and Principals:	J. S. Edelson, Isaiah Watas Cox, Rodney T. Cox, Avto Tavkhelidze (1996); Artemy Martinovsky Zaza Taliashvili, Rochel Geller, Leri Tsakadze (2001); Stuart Harbron (2003)
Relevant Patent Numbers:	5,874,039; 5,994,638; 6,064,137; 6,103,298; 6,214,651; 6,229,083; 6,281,514; 6,531,703; 6,495,843; 6,720,704; 6,876,123; 7,140,102; 7,166,786; 7,169,006
Products Using MEMS:	Four of the above patents mention micromachining, which appears to play a key role

WWW URL for Activity:	http://www.powerchips.gi
Additional Comments:	Developing a "Power Chip," which also appears to be a solid-state thermionic device projected to achieve 70-80% of the Carnot efficiency; no published-but-not-yet-issued patents

Company Name (TICKER):	MicroPelt, GmbH, Freiburg GERMANY, a spin-off of Infineon Technologie, AG (IFX)
History and Principals:	Harald Bottner, Axel Schubert, Bruno Acklin, Karl-Heinz Schlereth, Joachim Nurnus, Christa Kunzel (1999); Martin Jagle, Holger Kapels, Anton Mauder, Hans-Joachim Schulze, Helmut Strack, Jenoe Tihanyi (2002)
Relevant Patent Numbers:	6,815,244; 6,818,470; 7,084,502; 7,087,981
Products Using MEMS:	Products are based on structured thin-film thermoelectric on silicon made via MEMS
WWW URL for Activity:	http://www.micropelt.com
Additional Comments:	Now selling both Peltier cooling and Seeback power generation chips; the latter is intended mainly for energy scavenging at low temperature differences; patent 7,084,502 is joint with the Fraunhofer Institute in Freiburg

Company Name (TICKER):	JX Crystals, Inc., Issaquah WA (private)
History and Principals:	Lewis M. Fraas (1992); John E. Samaras (1993); Lucia G. Ferguson (1995); James E. Avery (1996)
Relevant Patent Numbers:	5,096,505; 5,091,018; 5,383,976; 5,401,329; 5,403,405; 5,439,532; 5,512,109; 5,551,992; 5,616,186; 5,865,906; 5,942,047; 6,057,507; 6,091,018; 6,177,628; 6,218,607; 6,232,545; 6,271,461; 6,303,853; 6,337,437; 6,353,175; 6,489,553; 6,538,193; 7,196,263
Products Using MEMS:	No mention of MEMS or micromachining on any of their patents

WWW URL for Activity:	http://www.jxcrystals.com
Additional Comments:	Sells both solar as well as TPV modules, which all the above patents pertain to; no pending-but-not-yet-issued patents

Company Name (TICKER):	MTPV Corporation, Cambridge MA (private)
History and Principals:	Robert DiMatteo, CEO (2003)
Relevant Patent Numbers:	6,084,173; 6,232,546
Products Using MEMS:	Preferred embodiment in patent 6,232,546 uses MEMS
WWW URL for Activity:	http://www.mtpvcorp.com
Additional Comments:	Patents cover micron-gap TPV technology, which they are working to commercialize; one pending-but-not-yet-issued patent

4. Vibrational and Electromagnetic Energy Scavengers

In addition to the following small companies, a number of large companies including Seiko Epscon Corporation, The Boeing Company, Rockwell Automation, General Electric, Schlumberger and Michelin have filed for patents on various kinds of vibration energy scavengers. They have not been included explicitly since they do not offer or intend to offer these as independent products, although they are included in the bar graph of Figure 3.5.

Company Name (TICKER):	Kinetron BV, Tilburg NL (believed privately held)

History and Principals: P. M. J. Knapen (1985); J. H. Wouterse (1987); P. A. F. Maria Goemans, B. J. Meyer (1992); M. V. Koningsberger (2002), Managing Director

Relevant Patent Numbers: 4,644,246; 4,908,808; 5,229,738; 5,923,619

Products Using MEMS: Not mentioned in any of their patents, although company web site states that "micro systems" are one of their key technologies

WWW URL for Activity: http://www.kinetron.nl

Additional Comments: Company sells a variety of motional and fluid-flow energy scavengers, micro generators, micro motors and micro magnets

Company Name (TICKER): PMG Perpetuum, Southhampton UK (private)

History and Principals: Roy Freeland (2004), CEO; Stephen Roberts (2005), Technical Manager

Relevant Patent Numbers: No US patents

Products Using MEMS: Present devices do not use MEMS, but company web site says they are developing one that is

WWW URL for Activity: http://www.perpetuum.co.uk/

Additional Comments: Currently sells three scavenger models designed for indoor use, automotive, and air transport resp., all based on electromagnetic induction; one published-but-not-yet-issued patent from inventors at Southampton Univ. (20070007827)

Company Name (TICKER): Ferro Solutions, Cambridge MA (private)

History and Principals: Jiankang Huang, R. C. O'Handley, D. Bono (2002)

Relevant Patent Numbers: 6,984,902

Products Using MEMS: MEMS probably plays only a minor role in their device since it uses an electromagnetic generator

WWW URL for Activity: http://www.ferrosi.com

Additional Comments: Company is supported by SBIR/STTR from ONR, and sells a ca. 75 cc scavenger which produces a few milliwatts under freeway conditions

Company Name (TICKER): LV Sensors, Inc., Emeryville CA (private)

History and Principals: S. Roundy, J. Bryzek, C. Ray, M. Malaga, D. L. Brown (2004)

Relevant Patent Numbers: Only one published-but-not-yet-issued patent

Products Using MEMS: Device believed to be based on MEMS

WWW URL for Activity: http://www.lvsensors.com

Additional Comments: Developing device to power automobile tire monitoring sensors

Company Name (TICKER): Mide Technology Corp., Medford MA (private)

History and Principals: Marthinus van Schoor, CEO & Founder (1990)

Relevant Patent Numbers: No patents on energy scavenging *per se*

Products Using MEMS: Scavenger probably does not use MEMS

WWW URL for Activity: http://www.mide.com

Additional Comments: Sells 40 cc piezoelectric scavenger yielding a few milliwatts at frequencies of order 100 Hz.

Company Name (TICKER): Microstrain, Inc., Williston VT (private)

History and Principals: C. P. Townsend (1993); M. J. Hamel (2000); Steven W. Arms (1987), President & CEO

Relevant Patent Numbers: 6,529,127; 7,081,693

Products Using MEMS: No mention of MEMS or micromachining in any of the embodiments claimed

WWW URL for Activity: http://www.microstrain.com

Additional Comments: They do not seem to sell their scavengers as independent products, but only as part of their broader line of sensors; 5 published-but-not-yet-issued patents on scavengers

Company Name (TICKER): Elecsci Corp., Rochester NY (private)

History and Principals: Michael D. Potter (2004), President; Lawrence C. Grumer (2004), CEO

Relevant Patent Numbers: 6,717,488; 6,750,590

Products Using MEMS: Web site says they are developing MEMS devices at the Rochester Inst. of Tech. and the Infotonics Technology Center in Canandaigua, NY

WWW URL for Activity: http://www.elecscicorp.com

Additional Comments: No products as yet; patents under assigned to Potter's previous company, Nth Tech Corp., and propose to use electrets based on his Embedded Electron technology

Company Name (TICKER): PowerMEMS, Cupertino, CA (private)

History and Principals: Carl R. Schulenburg, CEO (2004)

Relevant Patent Numbers: None issued or published as of March 2007

Products Using MEMS: No products at all yet

WWW URL for Activity: http://www.powermems.com

Additional Comments: Plans to develop solar cell, thermoelectric and vibration energy scavenger combo to keep thin-film lithium ion battery charged for wireless sensor networks

Company Name (TICKER): Polatis Inc., Cambridge UK (private), formed by merger with Continuum Photonics, Billerica MA which in turn subsumed Continuum Control Corp. at the same address

History and Principals:	Nesbitt W. Hagood, Kamyar Ghandi (1999); David Lewis (1998), CEO of Polatis
Relevant Patent Numbers:	6,231,779; 6,580,177; 6,655,035; 6,909,224; 6,995,496; 7,105,982
Products Using MEMS:	Company does not seem to sell any energy scavengers at this point in time
WWW URL for Activity:	http:///www.polatis.com
Additional Comments:	Long chain of energy scavenging patents that begins at MIT and end with a company that sells only optical switches

Company Name (TICKER):	Powercast LLC, Ligonier PA (private); formerly Firefly Power Technologies LLC
History and Principals:	J. G. Shearer, C. E. Greene, D. W. Harrist (2003)
Relevant Patent Numbers:	One published-but-not-yet-issued patent
Products Using MEMS:	Company does not seem to sell any energy scavengers at this point in time
WWW URL for Activity:	http://www.powercastco.com
Additional Comments:	Univ. of Pittsburgh spin-off devoted to powering mobile electronics wirelessly; pending patent is for RF energy harvesting, not vibration