**The Potential for
Microtechnology Applications
in Energy Systems**

**Results of an
Experts Workshop**

February 1995

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MASTER

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Summary

In conjunction with the U.S. Department of Energy (DOE) Office of Building Technologies (OBT), scientists and engineers at the Pacific Northwest Laboratory (PNL) have proposed that a research and development program be initiated in the area of energy systems miniaturization. This program, which would begin in FY 1997 or FY 1998, would focus on the development of microscale technologies for heating, ventilating, and cooling of manufactured housing.

The future development of microtechnologies may be relevant to other energy applications. To define this potential, and to further discuss the research needs associated with energy-related microtechnologies, PNL conducted an external workshop on this subject on May 25 and 26, 1994. The workshop involved energy experts and microtechnology experts from universities, national laboratories, and industry. Potential application areas were identified and prioritized, and some of the research requirements for these applications were defined. In addition, the workshop provided expert advice on the potential importance of a microtechnology/energy research program. This report documents the results of that workshop as well as PNL's interpretation of the implications of those results for a potential DOE research and development program in energy systems miniaturization for building energy applications.

The workshop results have some strong implications for the proposed OBT initiative in energy systems miniaturization. A review of the results has led to the following recommendations:

- *The technical focus of the proposed program should be on miniaturizing distributed heating and cooling systems and on sensor development.* Sensors offer the potential for a near-term impact with direct relevance to industry; distributed energy systems offer the potential for radical changes in buildings energy use.
- *Programmatic activities should focus on developing a vision for the initiative, teaming relationships, and linkages with related research efforts.* Programmatic activities should include a solid evaluation of the value of distributed energy systems and sensors. In addition, there is a need to continue to develop linkages to potential microtechnology team members and with other programs in microtechnology.
- *Microtechnology offers important energy applications outside the buildings sector.* Workshop results identified a number of potential applications of microtechnology to other energy sectors. This suggests that other organizations within DOE should be made aware of the status and potential for microtechnology with the objective of developing collaborative research.

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1.0 Introduction

Microscale technologies, or microelectromechanical systems (MEMS), are currently under development in the United States and abroad. Examples include microsensors, microactuators (including micromotors), and microscale heat exchangers. Typically, microscale devices have features ranging in size from a few microns to several millimeters, with fabrication methods adapted from those developed for the semiconductor industry.

Microtechnologies are already being commercialized; initial markets include the biomedical and transportation industries. Applications are being developed in other industries as well.

Researchers at the Pacific Northwest Laboratory (PNL)^(a) hypothesize that a significant number of energy applications are possible. These applications range from environmental sensors that support enhanced control of building (or room) temperature and ventilation to microscale heat pumps and microscale heat engines that could collectively provide for kilowatt quantities of energy conversion. If efficient versions of these devices are developed, they could significantly advance the commercialization of distributed energy conversion systems, thereby reducing the energy losses associated with energy distribution.

Based upon the potential for energy savings, the U.S. Department of Energy (DOE) Office of Building Technologies (OBT) has proposed a new initiative in energy systems miniaturization. The program would focus on the development of microtechnologies for the manufactured housing sector and would begin in either FY 1997 or FY 1998, ramping up to \$5 million per year investment by FY 2001.

1.1 Introduction to Microtechnology

Microtechnologies are currently being developed as a natural extension of fabrication techniques initially developed for the semiconductor industry. Specific adaptations of existing photolithographic techniques have included such additions as "sacrificial layers," which, when removed, provide one or more degrees of movement (freedom) to a structural element.

Sensor applications have been the quickest to reach the market. These include microscale accelerometers (for control of automobile air bags) and microscale pressure and temperature sensors. A number of microscale chemical gas sensors are also under development.

Microelectromechanical components that have already been demonstrated include linear and rotary microscale motors having dimensions on the order of 100 microns (one-tenth of a millimeter) and employing electrostatic, piezoelectric, and electromagnetic actuation methods. Development and assembly of such actuators into first-generation components (pumps, valves, gears) that perform typical, engineered unit operations are also taking place at a number of research institutions. There is

(a) PNL is a multiprogram national laboratory operated for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830 by Battelle Memorial Institute.

an expectation that individual microscale components can be assembled, perhaps as an integral portion of the fabrication sequence, into microscale systems that perform the same types of general functions (e.g., chemical conversion and energy conversion) as those typically provided by macroscale systems.

1.2 Energy Applications of Microtechnology

Near-term applications of microtechnology will most likely involve microscale sensors. Examples include microscale temperature sensors to control HVAC system operation, CO₂ microsensors to regulate ventilation, and microscale photosensors for lighting systems. Applications for microscale pressure, temperature, and flow sensors exist in macroscale heating and cooling equipment.

PNL's consideration of the potential for microscale energy conversion systems (i.e., microscale heat pumps and heat engines) suggests that such devices would radically change how energy is used in many important applications. For example, successful development of a cost-competitive microtechnology-based sheet heat pump (containing an array of microscale heat pumps) could have a profound impact on energy use in buildings. For such applications, sheet heat pumps can be distributed throughout a building, eliminating the need for central heating and cooling equipment and the associated ducting system.

Distributed heating and cooling using microscale energy conversion devices will also facilitate efficient local control of temperature. In many cases, ducting system losses and losses associated with cycling the central heating and cooling equipment can consume up to 50% of the output of the heating and cooling equipment. Distributed heating and cooling using microscale energy conversion devices could avoid many of these losses.

PNL researchers envision the ultimate development of thermally active materials with embedded microscale sensors, controls, and energy conversion systems that enable the material to provide ventilation, to act as either an enhanced conductor or an insulator, to provide heating and cooling, and to store thermal energy. Longer-term development opportunities include the microscale heat engine, a device that could be used in natural gas-fired heating systems to provide for energy cascading, including cogeneration of electricity, and thermal energy for hot water heating and space heating.

1.3 Workshop Objective

As part of the planning for the proposed OBT initiative, PNL hosted a workshop in May 1994 on potential energy applications of microtechnology. Key participants included energy and microtechnology experts from around the United States, who initially brainstormed new energy applications of microtechnologies and then discussed the research and development requirements associated with these applications. The objective of the workshop was to enlist the experts' assistance in defining a possible energy systems miniaturization research agenda for DOE.

1.4 Report Scope

The workshop approach is specifically described in Section 2.0. The outcome of the workshop is documented in Section 3.0. Observations and conclusions from the PNL researchers on the implications for the proposed DOE program are then presented in Section 4.0. Workshop participants are listed in Appendix A. Appendix B contains a copy of the workshop agenda. Potential energy applications of microtechnologies are described in Appendix C.

2.0 Workshop Description

Organizers at PNL identified two goals for the workshop: 1) to identify and describe attractive energy applications of microtechnologies; and 2) to define high-priority research needed to take advantage of the applications. In support of the two goals, the following workshop objectives were identified:

- Provide an opportunity for exchange of information and ideas among microtechnology and energy systems experts.
- Document different experts' views on the potential for microtechnology development and applications in energy systems.
- Identify new energy applications in energy systems for microtechnology.
- Identify research needed and, to the extent possible, prioritize the research agenda.

Workshop participants included 25 U.S. experts in energy systems and microtechnologies. A list of participants is provided in Appendix A.

The two-day workshop was held in Richland, Washington, on May 25 and 26, 1994. The agenda (Appendix B) involved the following activities:

- introducing participants
- presenting workshop goals and objectives
- exchanging technical information
- brainstorming potential applications
- identifying and discussing benefits, challenges, and needed research
- preparing write-ups on potential applications
- reviewing work, discussing follow-on activities, and adjourning.

As the workshop began, the microtechnology experts presented their work; the energy systems participants then asked questions. Once this was completed, the participants were divided into three teams (Appendix B) and given time to brainstorm, discuss, and describe potential applications. In all of their deliberations, the groups were required to record their work on flip charts and portable computers. At the end of the workshop, each group reported on its ideas, and an open discussion followed.

While the groups worked in parallel, members were free to check the ideas and work of other groups. Each group was asked to identify energy applications of microtechnology. For each idea, the group was asked to discuss and record its findings on the following topics:

- description - What is this application?
- benefits - Why is it good?
- challenges - What is keeping it from reality?
- research needs - What kind of research is needed?

In the cases where they could do so, the groups were asked to also gauge the *probability of success* of the application and indicate the approximate *funding level* that might be required for the research.

Based on suggestions from workshop participants, another activity was added. This effort focused on identifying application characteristics that would allow microtechnology to be successfully applied to the application.

3.0 Workshop Results

The workshop results, as developed by the participants, are delineated in this section. Potential energy applications of microtechnology identified by the participants are summarized in Section 3.1. In Section 3.2, recommendations on technical research issues are presented. Section 3.3 discusses recommendations on programmatic issues.

3.1 Potential Energy Applications of Microtechnology

The three working groups identified 18 potential energy applications of microtechnology. These applications are listed in Table 3.1. Appendix C provides a detailed description of each application.

Groups 1 and 2 developed descriptions of several potential applications (Applications 1 through 10). Group 3 developed a general process for evaluating and developing microtechnology for energy applications and suggested that the procedure be applied to seven potential applications. The evaluation process is described in Item 11, and the seven potential applications are those numbered 11.1 through 11.7.

Although building energy applications of microtechnology predominated (Applications 1, 2, 3, 9, 10, 11.1, 11.2, 11.3, 11.4, and 11.5), other potential applications had wider implications. Applications 3, 4, 9 and 11.7 could be relevant to many industrial processes. Applications 5, 6, and 8 would result in components that could become important in many areas including energy, transportation, and medicine. Application 7 could be of great interest to the electronics industry.

In addition to identifying potential applications, workshop participants also identified key characteristics that could be used to screen candidate microtechnology applications. The group identified five relevant characteristics. These include the following:

1. Microtechnology can be attractive where distributed needs are being met by centralized processes. Microtechnology offers the possibility of using a highly distributed technology.
2. Applications where weight, volume, or area are very important are natural applications for microtechnology. Microscale components provide inherent advantages when weight, volume, or area are significant design constraints.
3. Microtechnology is attractive when it allows the user to do things that cannot be done in any other way. Two examples are microscale chemical processing and implanted microsensors.
4. Microtechnology will be more attractive for high-value applications where cost is relatively unimportant.
5. Microtechnology can be more attractive where the use of a large number of similar components allowing economy of production becomes important.

Table 3.1. Potential Energy Applications of Microtechnology

Number	Application
1	Distributed Energy Conversion Systems in Buildings
2	Sensors and Actuators for Distributed Systems
3	Control of Boiler/Burner Combustion Processes
4	Power Distribution and Management
5	Regenerative Heat Exchangers
6	Piezoelectric Micropump
7	Microscale Cooling Technologies for Electronic Devices
8	Bimorph Energy Generator
9	Distributed Sensor Validation System
10	Integrated Occupancy-Sensor and Plenum Airflow Controller for HVAC ("Smart" Plenum)
11	Miniaturization Technologies Applied to Distributed Processes
11.1	Distributed Heating and Cooling
11.2	Building Air Quality
11.3	Hot Water Heater Power (Household Cogeneration)
11.4	Lighting
11.5	Windows
11.6	Transportation Comfort Control Distributed HVAC
11.7	Microscale Chemical and Biological Processes

3.2 Recommendations on Technical Research Issues

In reviewing their work, the participants developed several suggestions. Such suggestions are valuable because they will enhance the quality of any future DOE program in microtechnology. The recommendations on technical issues are listed here using the wording developed by the workshop participants. These suggestions were the basis for the conclusions presented in Section 4.0. The order in which the suggestions are listed does not imply or reflect any type of prioritization.

- Know the customer. Focus on the market needs and know what the market wants. We need to focus on the customer and really seek to understand the fundamental functions and requirements for the device(s).

- Get theoreticians together to examine our understanding of microscale thermodynamics, heat transfer, and fluid dynamics. This should follow from the 1991 work of the National Science Foundation.
- There appears to be value to distributed processes for thermal systems; however, some hard numbers are needed to validate the benefits of the concept.
- There is a large role for sensors in microtechnology applications in energy systems.
- We must have a strong justification for a DOE energy systems miniaturization program, and the justification should be based on projected energy savings.
- Costs will ultimately decide the commercial success of the research. However, we realize that there will be value from spin-offs, even if the program is not completely successful.
- A program must focus primarily on determining the fundamental feasibility of key components.
- Focus on "systems" because complete systems have the greatest potential for economic success.
- Focus on proof-of-principle tests to be followed by larger-scale demonstrations.
- Set and track standards and performance goals.

3.3 Recommendations on Programmatic Issues

Workshop participants also had suggestions on programmatic issues; those listed below essentially reflect the wording and expressions that emerged from the workshop deliberations. The participants also offered a number of suggestions for future collaboration.

- Keep this original workshop team informed and appropriately involved.
- Any new DOE program must complement other MEMS activities and programs. Know who is doing what and do not conflict with them; e.g., the Japanese, Honeywell, the Department of Defense Advanced Research Projects Agency (ARPA), and others.
- Work in partnership with others to develop a new technology; e.g., micropumps.
- Resist the temptation to spend money on a microscale fabrication facility. Use the facilities that already exist.
- Be sure to form an industry advisory board.
- DOE needs to provide the vision for the program.

- Promote the exchange of technical information through journal publications. For example, insert material in the *Journal of Micromechanics*.
- Work through ARPA to facilitate communications.
- Use technical sessions of existing conferences (e.g., American Society of Mechanical Engineers, World Congress of Chemical Engineering 1996) to promote microtechnology development.
- Develop some mechanism for identifying basic research needs.
- Conduct another experts workshop to focus on other energy-related sectors (e.g., environmental cleanup) not covered in this first workshop.
- Communicate with other government agencies. For example, investigate the potential for interactions with the U.S. Environmental Protection Agency.
- Avoid duplication of efforts through high-quality communications activities. For example, using electronic bulletin boards, coordinate with the National Science Foundation (NSF), air force and army programs, medical research programs, the Electric Power Research Institute, and others.

4.0 Conclusions

Based on the written responses from participants, the workshop appears to have successfully achieved its goals. The results of the workshop suggest a number of conclusions related to the technical and programmatic issues. We have evaluated these results and have identified key implications for the proposed DOE Office of Building Technologies energy systems miniaturization initiative.

4.1 Technical Conclusions

Potential applications of complete miniature or microscale systems include distributed energy conversion systems (HVAC) for buildings, electric power distribution and management, chemical and biological processing plants, and the combustion processes. Distributed systems is definitely a promising application area for microtechnology. Other applications involve individual components such as sensors, heat exchangers, generators, and pumps. Sensor applications are particularly important because effective control of many systems is limited by the lack of process control information.

Key technical conclusions are summarized in the list that follows. Although the workshop participants were not in unanimous agreement on every suggested idea, the conclusions represent our understanding of the general areas of agreement resulting from the workshop.

- *Many important applications of microtechnologies exist outside buildings.* The experts identified numerous potential energy applications for miniaturized energy systems. Some of these applications, such as microdevices for power electronics and miniaturized chemical processes, may not have a strong relevance to building energy application but may be of interest to other organizations within DOE.
- Distributed heating and cooling is a key application, but *there is significant challenge in developing efficient and cost-effective components.* Two of the three groups identified the development of distributed energy systems as having a high priority. Further, development of distributed energy systems was included in the list of technical recommendations. Developing efficient and cost-effective systems will be challenging but not impossible.
- *Sensor development is a second key application area.* All three working groups identified sensors as being a key application of microtechnology to building energy applications. In some cases, microsensors will provide information not currently available. However, in most buildings energy applications, macroscale sensor technology exists and the key issues are related to reducing cost.
- *A microtechnology research program should focus on developing miniaturized energy systems appropriate for distributed applications rather than assuming a priori that microtechnology will be the preferred approach.* The benefits of distributed energy systems do not depend exclusively on microtechnology. In some applications, miniature energy systems may be a better choice. A

research program should focus on the application—distributed energy systems—instead of on a specific technology such as microtechnology.

4.2 Programmatic Conclusions

The workshop participants developed a set of specific programmatic suggestions for the development of a DOE energy systems miniaturization program. These suggestions stem from both positive and negative views of such a program. A major concern involved establishing proper links to existing stakeholders and preparing for collaboration in future efforts. Although DOE can establish a program, such a program must heavily involve universities and industry in addition to the national laboratories.

Key programmatic conclusions are summarized below. Although the workshop participants did not agree unanimously on all recommendations, the conclusions represent our understanding of the general areas of agreement resulting from the workshop.

- *DOE needs to provide the vision for energy applications of microtechnology.* Participants concluded that the most important role for DOE is in providing a vision for how miniaturized energy systems can revolutionize energy use in buildings, as well as leadership in developing the relevant technologies.
- *Stakeholders must be involved.* A successful program must address problems of interest to industrial partners and must be responsive to other stakeholders. The establishment of an industry advisory group was strongly recommended.
- *Teaming is critical to success.* It is clear that a successful program must involve teaming between universities, industry, and national laboratories, and between experts in applications and basic sciences as well as in microtechnology.
- *A microtechnology initiative must complement other related research efforts.* Any DOE program should coordinate with other research efforts such as at ARPA and NSF.

4.3 Implications for a Proposed Initiative in Microtechnology for Energy Applications

The workshop results have some strong implications for the proposed OBT initiative in microtechnology. Our review of the results has led to the following recommendations:

- *The technical focus of the proposed program should be on miniaturizing distributed heating and cooling systems and on sensor development.* The proposed initiative should include research on both sensors and distributed energy systems. Sensors offer the potential for a near-term impact with direct relevance to industry; distributed energy systems offer the potential for radical changes in buildings energy use.

- *Programmatic formation should focus on developing a vision for the initiative, developing teams, and developing linkages with related research efforts.* Program developers should focus on forming a vision for the program, including a solid evaluation of the value of distributed energy systems and sensors. In addition, we need to continue to develop linkages to potential microtechnology team members and with other programs in MEMS and microtechnology. Stakeholders must be included in program planning and execution.
- *Microtechnology offers important energy applications outside the buildings sector.* Workshop results identified a number of potential applications of microtechnology to other energy sectors. This suggests that other organizations within DOE should be made aware of the status and potential for microtechnology with the objective of developing collaborative research.

Appendix A

Microtechnologies Workshop Participants

Appendix A

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Appendix B

Microtechnologies Workshop Agenda and Working Groups

Appendix B

Microtechnologies Workshop Agenda and Working Groups

Wednesday Morning, May 25

- 8:00 Getting Started David Brenchley
- 8:15 Introduction, Logistics and Meeting Objectives David Brenchley
- 8:30 Is There a Role for MEMS/Microtechnology in Meeting Energy Challenges? Kevin Drost
- 9:00 MEMS Presentations (15 min each plus 5 min Q&A period)
- Jan Smits
Carlos Mastrangelo
Robert Warrington
Henry Guckel
Danka Petelenz
Paul McWhorter
Bob Wegeng
- 12:00 Working Lunch "How We See the Situation & Opportunities"
- Energy Panel Members Give Their Views
- 1:00 Open Discussion
- 1:45 Recorder's Report "Key Points to Remember" Ray Reilly
- 2:00 Parallel Working Groups (Groups A, B, & C)
- General Instructions: Brainstorm to identify and define opportunities for microtechnology in energy applications. For each application define problems and constraints and the research needs: what, why, benefits. Each group works using flip charts etc. and records results on PC disks.
- 4:00 Group Reports
- General Instructions: Groups A, B, and C provide shorts; and questions and discussion follow.
- 5:00 Adjourn

Thursday, May 26

8:00 Refocus—Open Discussion

9:00 Working Groups Reconvene (Groups A, B, and C)

General Instructions: Groups continue work from Day 1. Identify further potential applications and do writing. Do work on PCs and turn in disks to workshop leader. What research needs to be done? What?, Why?, When? Benefits? Cost? Who?

Need one team to develop the format for the workshop report, including the research write-ups.

10:30 Break

11:00 Writing Teams Continue Their Work

12:00 Lunch

1:00 Reports from Groups

2:00 Schedule for Workshop Report

2:30 Closing Comments, Thanks and Adjourn.

Working Groups

Group A

Tim Ameel
Norm Foss
Giri Venkataramanan
Henry Gunkel
Rob Pratt
Mark Zdeblick
Bob Wegeng

Group B

Jan Smits
Danka Petelenz
Keith Ramsey
Don Jarrell
Ray Reilly
Barry Penswick

Group C

Kevin Drost
Bob Warrington
Scott Butner
Joe Iannucci
Carlos Mastrangelo
Paul McWhorter

Appendix C

Descriptions of Potential Energy Applications of Microtechnologies

Appendix C

Descriptions of Potential Energy Applications of Microtechnologies

Eighteen potential energy applications of microtechnologies were identified and described during the workshop. Those applications are listed below. The following pages provide detailed descriptions of each application. The descriptions are included here using essentially the same phraseology used by workshop participants in formulating them.

Number	Application
1	Distributed Energy Conversion Systems in Buildings
2	Sensors and Actuators for Distributed Systems
3	Control of Boiler/Burner Combustion Processes
4	Power Distribution and Management
5	Regenerative Heat Exchangers
6	Piezoelectric Micropump
7	Microscale Cooling Technologies for Electronic Devices
8	Bimorph Energy Generator
9	Distributed Sensor Validation System
10	Integrated Occupancy-Sensor and Plenum Airflow Controller for HVAC ("Smart" Plenum)
11	Miniaturization Technologies Applied to Distributed Processes
11.1	Distributed Heating and Cooling
11.2	Building Air Quality
11.3	Hot Water Heater Power (Household Cogeneration)
11.4	Lighting
11.5	Windows
11.6	Transportation Comfort Control Distributed HVAC
11.7	Microscale Chemical and Biological Processes

1. Distributed Energy Conversion Systems in Buildings

Description

Devices that improve delivered efficiency of heating/cooling energy conversion systems in buildings by distributing the system throughout the building. This includes improved energy conversion efficiency itself as well as reduced or eliminated distribution overheads. Devices include heat pumps, air conditioning/refrigeration equipment, cogenerators, heat engines, and solar and low-temperature powered absorption chillers.

Benefits

1. Reduced distribution losses and power requirements.
2. Improved efficiency by allowing individual zone control.
3. Improved fundamental conversion efficiency from microscale processes.
4. Improved part-load efficiency by staging conversion modules so that they (individually) operate at full load and are (individually) optimized for the temperature conditions at which they will operate.
5. Utilize non-CFC/HCFC refrigerants.
6. Flexibility for partial peak shaving.
7. Redundancy from massively parallel systems.

Challenges

1. Sophisticated, robust control system for sophisticated, distributed HVAC system.
2. Cost of manufacturing and installation.
3. Is cooling practical, given latent loads (condensation)? Do we collect the moisture, or have a separate (desiccant, for example) dehumidification system?
4. Enhanced heat transfer, indoor and outdoor surfaces.
5. Compressor efficiency. For mini-compressors, lubrication/friction is an issue. For micro-compressors, technical feasibility is uncertain.
6. Reliability.

Research Needed

1. Systems analysis. We need to quantify the energy benefits of distributed systems, analyze the thermodynamics of various cycles, and develop functional component requirements.
2. Develop simulation capabilities and control strategies.
3. Conduct a manufacturing assessment.
4. Research fundamental principles of fluid dynamics and heat and mass transfer at the microscales.
5. Develop components, including compressors, pumps, valves, generators, heat exchangers, motors, and fans.
6. Develop and demonstrate systems.

2. Sensors and Actuators for Distributed Systems

Description

Development of sensors and actuators to enable operation and control of distributed energy conversion systems using microtechnology.

Long-Term Objective

Development of cost-effective sensors and actuators to ensure efficient operation of distributed energy systems.

Near-Term Objective

Utilize the sensors immediately in current industrial and building systems for improving energy efficiency.

Benefits

1. Reduced energy consumption.
2. Localized comfort control through
occupancy control
lighting control.
3. Local demand management through
localized peak shaving
prioritized cold load pick-up.
4. Improved indoor air quality.

3. Control of Boiler/Burner Combustion Processes

Long-Term Objective

Increase efficiency in boilers/burners through improved combustion control.

Benefits

1. Reduced energy consumption in power generation systems.
2. Reduced energy consumption in building boiler/burner systems.
3. Reduced pollution.
4. More accurate billing based on British thermal units (Btu).

Research Needed

1. Development of gas energy content sensors.
2. Fireball sensors for power generation system control.
3. Reliable oxygen sensors for air intake control of fuel/air mixture.
4. Boiler water quality sensors for improved heat transfer, reduced maintenance.

4. Power Distribution and Management

Long-Term Objective

Development of nonintrusive sensors for more efficient power systems control

Benefits

1. Improved distribution system reliability.
2. More accurate metering and billings, customer load research.
3. Preventive maintenance.
4. Control of localized generation.
5. Dynamic reconfiguration of distribution system.
6. Increased use of transmission and distribution equipment.
7. E-field and B-Field monitoring for health-related issues.

Research Needs

1. Wireless, accurate current/voltage/temperature sensors.
2. High bandwidth, wide dynamic range for preventive maintenance.
3. Low bandwidth, low cost, low dynamic range sensors monitoring.
4. Self power sensors.

5. Regenerative Heat Exchangers

Description

Regenerative heat exchangers in which thermal energy is transferred and stored in the solid material within the heat exchanger and then recovered during flow reversal. Specifically for 1) Stirling cycle heat engines/heat pumps, 2) miniaturized Brayton cycle, 3) air/air heat exchangers for ventilation, and 4) burner combustion air preheating - exhaust gas heat recovery.

Benefits

Efficiency improvements, cost reduction, and/or physical size reduction of energy conversion systems. Micromachining/fabrication may improve heat exchanger characteristics while tailoring thermal storage material properties along the flow path.

Challenges

1. Cost.
2. Large surface area micromachining.
3. Plugging/damage of flow passages.
4. Fabrication of materials with "optimum" thermophysical properties.

Research Needs

1. Understanding of heat exchange and fluid flow in microchannels.
2. Three-dimensional passage geometry fabrication.
3. Microscale channel fabrication in high-performance temperature-resistant materials such as ceramics, superalloys.

6. Piezoelectric Micropump

Description

Field of application: compressors, gas pumps, liquid pumps, heat pumps.

Benefits

Advantages: high efficiency, near 100%.

Research Needed

1. Basic Science: What materials are best for this application?
2. Materials Science: How to fabricate the good piezoelectric materials? Piezoelectric materials with high piezoelectric coefficients and low loss in thin film technology. Fatigue in constituent materials.
3. Conventional piezoelectric materials in thin film application are ZnO and PLZT. ZnO has rather low piezoelectric constants but is simple to manufacture; PLZT is much better but is of a very complex chemical nature. New materials such as the SbSI family, which has the highest piezoelectric constants known in nature, should be investigated as well.

Near-, Mid-, Far-Term

In the hybrid form in which piezoelectric ceramics are used in conjunction with micromachined silicon, this can be a near-term project that can be brought to the market in a very short time, maybe within 1 to 2 years.

In the fully integrated form, this is a mid-term project, that will come to fruition in 3 to 6 years after the start. The main problem is the deposition in thin film of a good piezoelectric.

Probability of Success

In hybrid form, these devices have been demonstrated around 10 years ago, so the chance of success in this field is very high, very close to 100%, even in the next 2 years.

In fully integrated form, they have been under investigation now for 5 years, with relatively low funding levels. Many problems have been solved, but some remain: what is the highest piezoelectric coefficient that can be reliably used? What is the efficiency of the material?

Probability of success in 4 years: 0.5

Probability of success in 5 years: 0.6

Probability of success in 6 years: 1

Required Levels of Funding

Around \$250,000 per year in university environment.

7. Microscale Cooling Technologies for Electronic Devices

Background

With continuing advances in electronic and computer technologies, enhanced capabilities bring with them more compact devices, higher internal frequencies, and inevitably higher rates of heat emission. The heat, if not effectively carried away, leads inevitably to early failure of the device. For example, the Intel pentium has significant cooling difficulties in several applications, resulting in early failures and the installation of large, noisy cooling systems. It is predicted that cooling of more than 100 W/cm² will be needed in the near future.

Description

It should be possible to develop cooling systems that are inherently designed as a substrate to or part of the electronic element (chip) requiring the cooling. Alternatively, the system could be included into the packaging for the chip, making the application more generic and widely usable. These cooling systems could then use solid or liquid heat transmission to heat exchangers external to the electronic instrument (computer), thus effectively moving the heat away from the critical electronic components and eliminating the need for separate cooling systems, eliminating the noise caused by the current family of cooling fans, and reducing the size of the overall system.

Research Needed

To make the device feasible, the following elements need to be accomplished:

1. Need to have specifications for the rate of cooling, allowable temperature ranges, suitable approaches for marrying the cooling system to the electronic device.
2. Need to understand whether the better approach is to implement as 1) an integral part of each electronic chip or 2) an associated packaging device.
3. Need to develop an approach for rejecting the collected heat to the environment. This approach includes a reliable, efficient way to deliver heat from the heat-collection device on the chip to the heat-rejection device on the rear, as well as the most efficient design for the heat-rejection device. Some kind of a vapor compression cycle or direct heat transfer may be required. Issues include single-phase versus two-phase heat transport and reliability of the heat transmission system (we can't have a leak leading to computer burnup). Other research issues may include the need for small temperature sensors.
4. Because such high temperatures and large amounts of heat are generated, it may be possible to capture this heat and generate electricity for recharging the battery system—especially important for portable systems.

Research Term

With the speed of development in the computer industry, computer power clearly will be very restricted unless the cooling requirements can be met. This leads to the need for solutions very quickly, and solutions whose cooling capacity can be quickly expanded to meet the growing needs of the computer industry.

Chance for Success

Success will be achieved in the short term. The only question is, What will the technology be and how expensive will it be? Evolutionary capability improvement (to meet steadily increasing needs) is likely, with perhaps a revolutionary change in the approach (from associated fan drives, to packaging on the chip, to integration with the chip...).

8. Bimorph Energy Generator

Field of Application

Generation of energy in remote area, using wind, water flow, etc.

Description

Wind flowing over the bimorph will bend it and generate a charge on the electrodes.

Research Needed

1. **Basic Sciences:** Energy conversion efficiency.

Different means of driving the bimorph may affect the efficiency; for instance, a mechanical moment generates more energy than a force, which generates more energy than a pressure wave, so the right way of "connecting" the wind or the flow to the bimorph has to be found.

2. **Material Science:** Piezoelectric materials with high piezoelectric coefficients and low loss in thin film technology. Fatigue in constituent materials: conventional piezoelectric materials in thin film application are ZnO and PLZT. ZnO has rather low piezoelectric constants but is simple to manufacture; PLZT is much better but is of a very complex chemical nature. New materials such as the SbSI family, which has the highest piezoelectric constants known in nature, should be investigated as well.

3. **System Science:** How to rectify, how to connect to the storage battery.

This generator delivers alternating current (ac) power that must be rectified and stored in a rechargeable battery. Each bimorph must have a set of diodes integrated with it to perform that task, which implies that the production process has to be closely matched with microelectronics fabrication.

Near-, Mid-, Far-Term

This is a mid-term project, which can be brought to the market in 4 to 6 years.

Probability of Success

The bimorphs have been fabricated and tested. The piezoelectric materials must be certified as truly dielectric, which has to be thoroughly investigated.

Probability in 4 years: 0.5

Probability in 5 years: 0.7

Probability in 6 years: 0.9

Probability in 7 years: 1.0

Funding Requirements

Implied requirements for funding in the probability of success estimates: level \$250,000/year.

9. Distributed Sensor Validation System

Background

A need now exists to get more effectiveness and efficiency out of the existing energy infrastructure. Generally, this means heavy instrumentation of existing physical systems for control and diagnosis. This involves large suites of sensors that 1) are expensive in themselves, 2) require continuous maintenance and calibration, and 3) require hookups for communications and controlling actuators. They can be so large as to hinder maintenance of the devices, and they can be invasive, leading to impaired functionality and perhaps more frequent failure of the device itself. Often the environments are hostile and lead to early sensor failure and expensive packaging. This is a generic need for all energy using systems including power plants, automobiles, electric T&D systems, and heat pumps.

Description

The required sensor suite is easily installed, accurate, reliable, and non-invasive, and provides for inexpensive communication with a central device. In general, low power consumption is also desirable. One approach to meet this need is a microsensor suite that provides for massive redundancy, onboard electronics to derive an accurate signal from the redundant sensors, signal processing, and communications approaches. The system could provide accuracy to a high degree, sense the rate at which individual sensors are failing, and predict overall failure of the device. The sensor suite would need to be packaged so as to be immune to the environment in which it is placed. It also should be easily attached to the system being sensed without being invasive. The system needs to be self-calibrating, or at least have the redundancy and control logic to make calibration unnecessary.

It may be possible to design one generic "chip" with the logic and communications capabilities into which one or more smaller sensor chips are plugged to meet the specific data requirement, accuracy, sampling rate, etc. Standardization will be very important, especially with respect to communications protocols, power requirements, and physical geometries of sensors with the overall parent chip.

Benefits

Low cost, small size, non-invasive, high reliability, low maintenance, high accuracy, appropriate for multiple applications.

Research Needed

1. Understanding the algorithms and control theory for delivering a signal from massively redundant sensors.
2. Packaging for hostile environments and different applications.

3. Standardization of power requirements, communication protocols, installation techniques, etc. Developing sensors to meet the sensing needs of industry (CO₂).

Time Scale

Will likely be evolutionary, putting more and more redundancy into smaller and smaller packages. To facilitate the rapid development of these devices, standards are required.

Success Probability

It will happen. It's only a question of when and to what degree...

10. Integrated Occupancy-Sensor and Plenum Airflow Controller for HVAC ("Smart" Plenum)

Description

An array of microsensors/microactuators would be installed in a room ceiling HVAC air delivery plenum. The sensors would detect area occupancy and open plenum dampers preferentially in the vicinity of room occupants. Such sensors might take the form of "smart" ceiling tiles in false ceilings.

Benefits

Room ventilation (heating or cooling) would be preferentially directed to occupied areas. Unoccupied areas within large rooms would not be fully conditioned, thus saving some HVAC power. Best applications may be in large assembly areas of commercial buildings.

Challenges

Microscale occupancy sensors must be developed and integrated with plenum actuators. Designs must be sufficiently low in cost so that a large number can be used cost-effectively within a room. Installation systems must be developed to allow distribution of HVAC air supply to a large portion of the full room ceiling area. Electrical power interconnections (between "smart" ceiling tiles) must be developed. Control algorithms must be developed to provide adequate conditioning (perhaps proportional to the area occupancy or level of activity in the area).

Research Needed

1. Microscale occupancy sensor design and development.
2. Microactuator design and integration with sensor.
3. Systems analysis to model room air quality under local ventilation control and to estimate energy savings.
4. Control algorithm development.
5. HVAC, conditioned air distribution system design compatible with "smart" plenums.
6. Laboratory-scale tests of (room-size) "smart" plenum operation.

11. Miniaturization Technologies Applied to Distributed Processes

Examples

Heat pumps, fuel cells, heat pipes, ventilation, cogeneration, generation, photovoltaic, storage, sensors and controls, display, chemical and biological processes.

Procedure

1. Develop functional criteria for functional process.
2. Perform comprehensive process screening and scale analysis resulting in functional criteria:
 - basic research issue identification
 - competing technologies; cost
 - performance
 - other barriers.
3. Survey existent technologies; identify cross-cutting basic research issues.
4. Conduct an early proof-of-concept demonstration using near-term technology with the goal of attracting potential funders.
5. Review selected approach and modify as necessary.
6. Develop enabling technology.
7. Conduct a field demonstration.
8. Analyzes for manufacturability and commercialization.

Benefits

Primary Goal:

Develop economically viable distributed HVAC system for buildings.

Short term:

Lightweight, small portable HVAC
High flux heat exchangers
New improved components for other applications

Mid-term:

New concepts for distributed HVAC
NASA/space/DOD thermal management

Long-term:

Novel compression techniques
Vacuum pumps
New processing technologies

Specific examples of technologies that would be evaluated as part of a program focused on miniaturizing energy technology are included in the following sections.

11.1 Distributed Heating and Cooling

Application

1. Small sources of heat or cooling
2. Microscale heat pumps
3. Distributed fuel cells
4. Local photovoltaic

Benefits

1. More efficient ?
2. Less expensive ?
3. Heat recovery from water drains
4. Spin-offs:
 - Personal HVAC
 - Portable HVAC
 - Vehicle HVAC
 - IC cooling

Challenges

1. Efficient compression
2. Microcompressor
3. Cost
4. Reliability
5. System integration
6. Marketing
7. Competing technologies
8. Codes and standards
9. Aesthetics
10. Safety
11. Air-side heat transfer

Research Needed

1. Compression technology
 - sealing
 - valving
 - actuators

11.2 Building Air Quality

Application

Sense, mitigate, remove, convert air pollutants in buildings:

1. carbon dioxide
2. air motion
3. formaldehyde
4. volatile organic compounds (VOCs)
5. carbon monoxide
6. natural gas
7. bioaerosols
8. particulates
9. mean radiant temperature
10. mitigate and remove contaminants
11. radon

Benefits

1. Quality of life
2. Safety
3. Costs
4. Energy savings
5. Liability
6. Health

Challenges

1. Low cost CO₂
2. Selectivity
3. Calibration
4. Cost
5. Removal technology
6. Controlled infiltration

Research Needed

1. New sensor mechanisms; e.g., mass spectrometer on a chip

11.3 Hot Water Heater Power (Household Cogeneration)

Application

1. Small fuel cell
2. Small heat pump
3. Use waste heat for hot water
4. Electric heat pump for in-line hot water heater

Benefits

1. Cost
2. Reliability
3. Efficiency
4. Clean power

Challenges

1. Downsizing fuel cell
2. Packaging
3. Operating hassles
4. Safety
5. Cost?
6. Hydrogen?
7. Life?
8. Balancing heat versus electricity

Research Needed

1. Materials
2. Fabrication

11.4 Lighting

Application

1. Distributed lights
2. Photosensors for quality and quantity
3. Occupancy sensors
4. Balance indoor/outdoor lights

Benefits

1. Quality of life
2. Productivity
3. Efficiency
4. Lower cost

Challenges

1. Miniaturization
2. Integration with HVAC
3. Cost

Research Needed

1. Microscale plasma lamp

11.5 Windows

Application

1. Light adjustments
2. Ventilation adjustments
3. Mechanical sensing

Benefits

1. Light heat/cool control
2. Energy savings
3. Increased utility light

Challenges

1. Actuation

Research Needed

1. Actuation/cost/optical properties

11.6 Transportation Comfort Control Distributed HVAC

Application

See building HVAC

Benefits

Weight
Volume
Waste heat utilization
Comfort
Reliability

Challenges

1. Same but cost constraint is not as bad
2. Must operate in moving car
3. Environment is more extreme
4. Different market drivers

Research Needed

Same as Building Applications

11.7 Microscale Chemical and Biological Processes

Application

1. Flow equivalent of logic?
2. Massively parallel
3. High-value-added reactors
analysis
pharmaceutical
possibly hybrid bio/chem reactor
mass transport increases with concentration gradient

Benefits

1. Tighter temp control
2. More selectivity
3. Important for recovery from dilute systems
4. Cost
5. Environmental applications
6. Materials efficiency
7. Embodied energy low waste

Challenges

1. Hardware lacking
pumps
valves
seals
sensors
systems integrations

Research Needed

See "Challenges"

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