Laboratory for Electromagnetic and Electronic Systems

The mission of the Laboratory for Electromagnetic and Electronic Systems (LEES) is to engage in research and teaching in efficient electric energy production, distribution, utilization, and storage and in electromechanics from the macroscopic through the nanoscopic levels. Electric energy and electromechanics are defined broadly to include power systems design, monitoring, and operation; electrical energy storage; automatic control; power electronics; high-voltage engineering; and conventional, continuum, and biological electromechanics. Much of the work of the laboratory is experimental, and industrial sponsorship represents a large fraction of its support.

The laboratory's professional staff consists of 8 faculty members from the Department of Electrical Engineering and Computer Science (EECS), 1 principal research engineer, 1 principal research scientist, 2 postdoctoral associates, and approximately 50 graduate students. The laboratory faculty and most of the staff are heavily involved in both undergraduate and graduate teaching. Faculty from the Departments of Mechanical Engineering, Chemical Engineering, and Materials Science and Engineering are collaborators in many of the laboratory's programs, and extensive joint activities are conducted with the Microsystems Technology Laboratories, the Gas Turbine Laboratory, the Materials Processing Center, the Laboratory for Information and Decision Systems, and the Harvard–MIT Division of Health Sciences and Technology (HST). Each term, a substantial number of Undergraduate Research Opportunities Program (UROP) and senior projects are carried out in LEES.

Automotive Consortium

Since its establishment in 1998, LEES has also managed the activities of the MIT/Industry Consortium on Advanced Automotive Electrical/Electronic Components and Systems, directed by principal research engineer Dr. Thomas Keim. The consortium, with more than 20 member companies, sponsors meetings and research projects related to improving automobile performance through electricity. Several projects begun with consortium funding have attracted independent funding from Toyota Motor Corporation, the Ford-MIT Alliance, the Draper Laboratory, and the Sheila and Emmanuel Landsman Foundation.

Research Emphasis

The LEES research emphasis has broadened from traditional applications of electrical power and energy and now includes several exciting nontraditional and cross-disciplinary areas that show great promise. In recognition of this evolution, we have grouped our projects into the following areas:

- Nano-enhanced energy systems for electric power generation and storage
- Increased energy conversion efficiency for automobile and other applications
- Improved reliability for automotive and other applications
- Power electronics and electromechanics

- Micro-sized energy systems
- Magnetic fluids and particle suspension
- Application of network analysis and control tools to biomedicine and biology

Nano-Enhanced Energy Systems: Combining the Old and the New

A very promising, timely, and possibly revolutionary new thrust in the laboratory's work is the use of nanotechnology to enhance "discarded" energy conversion and storage technologies to the point that they may exceed the efficiency of existing approaches. This is accomplished by using nanotechnology to alter the properties of materials by sculpting their surface on a microscopic scale. Two programs within LEES are based on this principle, one involving the enhancement of thermophotovoltaic (TPV) electrical power generation and the other involving a structure for a nonchemical battery wherein an engineered nanotube lattice replaces the chemical lattice that forms the electrode of a traditional battery.

Thermophotovoltaic Project

TPV electrical power generation, developed in 1956 by Dr. Henry H. Kolm at the MIT Lincoln Laboratory, is notoriously inefficient, primarily because only a small portion of the blackbody spectrum from the thermal heat source is matched to the energy of the semiconductor band gap. However, it is now possible to greatly improve this efficiency by etching the emitter surface to form a frequency-selective photonic crystal. Professors John Kassakian and David Perreault, Dr. Thomas Keim, and doctoral students Natalija Jovanovic and Ivan Celanovic (now a postdoctoral researcher) have fabricated a two-dimensional photonic crystal with submicron periodicity on a single-crystal tungsten substrate. Emittance measurements show excellent correlation with simulation results and are significantly improved compared with results obtained from the polycrystalline sputtered tungsten substrate described in last year's report.

In addition, continued work with the vertical cavity enhanced resonant thermal emitter (VERTE) developed by the TPV program—in collaboration with Professor John Joannopoulos, Professor Marin Soljacic, and doctoral student David Chan from the Department of Physics—has resulted in surprising new findings in the relatively uncharted territory of resonant thermal radiation phenomena. We believe we have discovered, designed, and demonstrated a new class of resonant thermal emission sources based on a two-dimensional silicon photonic crystal slab, as shown in Figure 1. In addition to spatial and temporal coherence properties, this

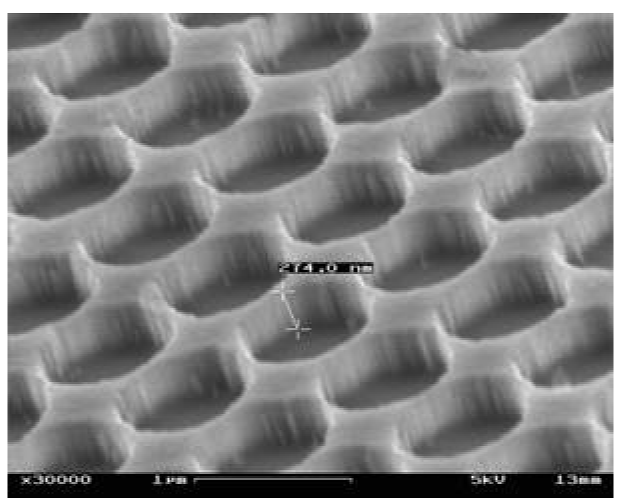

Figure 1. Scanning electron microscopy image of a two-dimensional silicon photonic crystal slab resonant thermal emitter.

source was shown to exhibit non-blackbody radiation behavior that, to the best of our knowledge, has never been reported before. The anomalous behavior shown in Figure 2 is the increased energy in the shorter wavelength (higher energy) emission peak as the temperature is reduced, contrary to the behavior of a blackbody. The emitter in this figure is the structured photonic crystal of Figure 1 on a sapphire substrate. These spatially coherent and nearly monochromatic emitters, with the radiation patterns shown in Figure 3, show great promise for a range of applications ranging from highly efficient TPV systems to improved near-infrared and infrared sensors.

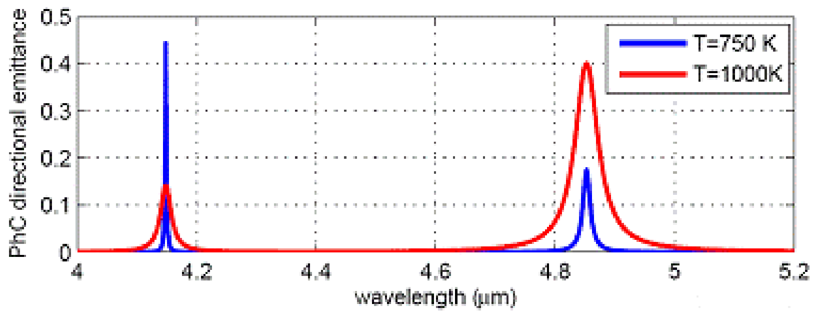

Figure 2. A two-dimensional silicon photonic crystal slab displaying anomalous emittance (non-blackbody) and thermal radiation intensity at 750 K and 1000 K.

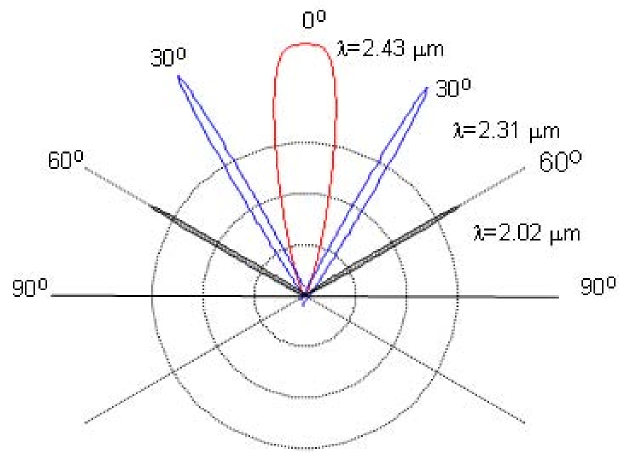

Figure 3. Vertical cavity enhanced resonant thermal emitter (VERTE) emission pattern showing strong spatial coherence for three different wavelengths.

Nanotube-Enhanced Ultracapacitor

The ultimate goal of this project, conducted by Professor Joel Schindall, Professor Kassakian, and graduate student Riccardo Signorelli, is to develop a practical electrical energy storage device that combines the long life and rapid charge–discharge capability of a capacitor with the much higher energy storage capacity of a rechargeable battery. We believe that this can be achieved through increasing the energy storage capacity of a commercial electrical energy storage device, that is, a double-layer capacitor or ultracapacitor, by replacing the activated carbon electrode coating with an array of vertically aligned nanotubes (Figure 4).

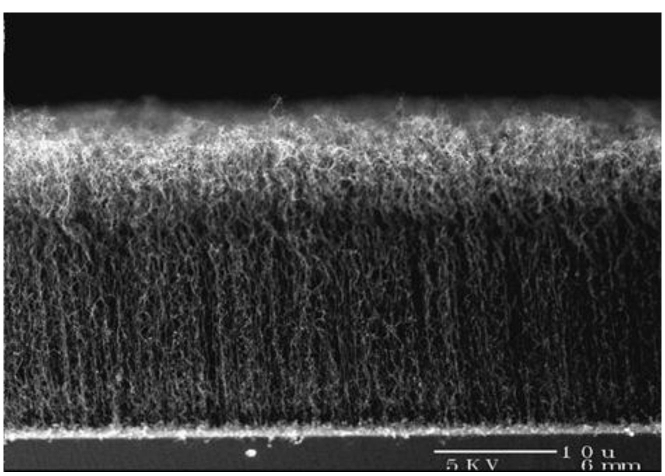

Figure 4. Nanotube array cross section.

Capacitors store electrical energy in an electric field that forms between two electrodes separated by an insulator. They can be charged and discharged very rapidly and have an almost unlimited lifetime, but they store perhaps a millionth of the energy of a comparably sized rechargeable chemical battery. Ultracapacitors achieve an enormous increase in storage capacity by coating the electrode with highly porous activated carbon to greatly increase the surface area and incorporating an electrolyte whose ions are electrostatically attracted into the pores of the carbon as the ultracapacitor is charged. This large surface area, in conjunction with the small ionic charge separation at the carbon surface, creates a capacitance measured in farads rather than microfarads, with a corresponding energy storage density in the order of several watt-hours per kilogram. However, despite their improved storage capacity, ultracapacitors typically store only 1/25 of the energy of the best rechargeable chemical batteries (lithium ion).

The predicted performance of the nanotube-enhanced ultracapacitor using the vertically aligned nanotube array is significantly higher (30 to 60 Wh/Kg) because of its improved electrical characteristics and because the diameter and spacing of the nanotubes are matched to the dimensions of the electrolyte ions, in contrast to the irregular pores exhibited by activated carbon. Calculations indicated that this structure could achieve an energy storage density equivalent to that of a lithium battery.

We now realize that the predicted similarity to the energy storage density of a battery is not a coincidence. A chemical battery stores an electrical charge by transferring charged ions in and out of a chemical lattice that forms the battery electrode. In effect, our goal is to build a new device wherein this chemical lattice is replaced by a synthesized or "engineered" nanotube lattice of equivalent dimensions. This lattice is expected to provide an ion storage structure equivalent to that of a battery but without the many disadvantages that are characteristic of the reduction and oxidation processes of a chemical battery. In a way, this is a "synthetic battery."

Our initial work resulted in successful electrode fabrication via catalyst-induced growth of the desired nanotube arrays using acetylene gas in a high-temperature, low-pressure vapor deposition furnace. However, this initial growth was achieved on a nonconducting substrate. This year we have successfully used a conducting substrate. The current focus of our work is on assembling a test cell using this electrode material to experimentally validate the predicted storage density. Ongoing funding for this activity is being provided by the Ford–MIT Alliance.

Increased Energy Conversion Efficiency

Another focus of the laboratory's activity is the use of advanced electronic and electromechanical techniques to promote increased energy efficiency for automotive and other applications. Three LEES programs address this area. The first is the use of electromechanical valve actuators designed to allow increased engine efficiency through more complete control of valve operation. The second involves the development of a more efficient alternator. The third, described further in the section on power electronics, entails a very-high-frequency DC–DC converter that offers small size and high efficiency.

Electromechanical Engine Valve

This project uses electromechanical valve actuators to increase engine efficiency through enhanced control of valve operation. This year the staff included Professors Perreault and Kassakian, Dr. Keim, graduate student Yihui Qiu, and UROP student James Otten. Through a series of control and design refinements, we have been able to reduce the power consumption of our prototype valve from 140 Watts (per valve, averaged over a complete engine cycle at full speed) to 49 Watts while reducing the instantaneous peak drive torque requirement from 1.33 N-m to 0.40 N-m and decreasing the transition time from 3.3 to 2.7 milliseconds. The reduction in peak torque enables our next step, which is the introduction of a much smaller drive actuator. We have built an apparatus that makes it possible for us to demonstrate the opening of an exhaust valve against cylinder pressure.

Improved Automotive Alternators

Two of the laboratory's projects involve simple and inexpensive improvements to standard automobile alternators that provide significantly improved power output and efficiency. Professor Perreault, Dr. Keim, principal research engineer David Otten, and former postdoctoral associate Dr. Sai Chun Tang have extended the laboratory's work on the use of switched-mode rectification and load-matching control to further enhance alternator power, efficiency, and transient performance. This year, an alternator has been developed that implements this approach with fully integrated power electronics and controls. In addition to demonstrating the feasibility of integrating the power electronics with the electric machine, this design illustrates the use of synchronous rectification for increased efficiency and takes advantage of interleaving to minimize passive filter size. This work has resulted in four publications over the past year.

In addition, Professors Jeffrey Lang and David Perreault, Dr. Keim, and former LEES graduate student Dr. Leandro Lorilla completed the development and demonstration of a Lundell alternator with a new type of field design that results in a greatly increased field copper packing factor. This new approach, which involves power electronic controls, enables substantial improvement (30%) in field ampere turns to be achieved, along with commensurate improvements in alternator power and efficiency.

Improved Reliability for Automotive and Other Applications

Our work on automotive reliability issues has led us to develop a new method to analyze the consequences of failures in redundant systems. This new method provides more detailed and useful information about system reliability. It has proven useful not only for X-by-wire systems but also for more complex systems of the type studied at the Draper Laboratory.

Fault-Tolerant Systems

Professors Kassakian and Schindall and graduate student Alejandro Dominguez-Garcia continue to work on advances in the theory of fault-tolerant systems. This work was initiated as a study of reliability in critical automotive X-by-wire (steer-by-wire, brake-by-wire) systems. What has evolved is a new method of analyzing the consequences of failures in fault-tolerant systems. Classical methods describe the system as existing in one of a finite number of states and describe the failure process as a transition from state to state. Markov methods are used to analyze such systems. By combining the present discipline with a consideration of the dynamic processes that occur in the immediate aftermath of a failure, the new method provides more detailed and useful information about system reliability.

The group has also assembled a prototype of a brake-actuated steering system that can serve as an independent steer-by-wire backup system. Such an independent backup is vital to achieve the near-perfect reliability that will be required before steer-by-wire systems can be deployed in automotive applications. This work is receiving collaborative and financial support from the Draper Laboratory via its Industry Independent Research and Development support program, and it has also received support from the LEES/Industry Automotive Consortium and the Bosch Corporation.

Circuit Board Degradation Analysis

The new materials required for eco-friendly products (such as lead-free systems) require improved testing processes to ensure reliability. Dr. Chathan Cooke and Dr. Keim have been working with graduate student Vasanth Sarathy (now graduated) to identify physical models that accurately quantify the impact of electrochemical processes on the degradation of electric printed circuit boards such as those used in automotive electronics. The work has shown that standard printed circuit board materials exhibit an Arrhenius-type thermally activated electrochemical process. Furthermore, the impact of water as absorbed moisture has been shown to be a strong accelerator for enhanced electrochemical activity. A new model designed to quantify the effects of moisture has been developed, and this model can be useful in developing reliability testing for new product development.

Electrolyte Stratification in Lead Acid Batteries

Because of the central role that lead acid batteries play in the automotive world, a good understanding of battery failure mechanisms is beneficial. Electrolyte stratification is one of the major mechanisms that reduce performance and cause failure of flooded lead acid batteries. Graduate student James Geraci, supervised by Dr. Keim, is developing electrochemistry-based numerical models to quantify the effects of stratification on battery performance and comparing the predictions of these numerical models with experimental data. While other studies have considered how electrode usage can create a stratification profile, the nanofluids used in this research allow us to study how a known stratification profile affects electrode performance.

Power Electronics, Power Systems, and Electromechanics: VHF Electrical Power Converters

Higher frequency DC–DC converters are desirable because they reduce energy storage requirements, enabling miniaturization, integration, and increased control bandwidth. Professor Perreault and graduate students Juan Rivas, Yehui Han, Anthony Sagneri, Robert Pilawa, and Olivia Leitermann have continued the development of power conversion circuits that operate at very high frequencies (30–300 MHz), two orders of magnitude higher than conventional designs. Advances this year include the development of new converter topologies that reduce component count and device stress and improve response speed. These new topologies have been demonstrated in converters operating at frequencies up to 110 MHz, and efficiencies and power densities have been higher than those previously achieved at these frequencies. This work has resulted in one patent filing, one provisional patent filing, three conference publications, and one journal publication this year, with two additional journal publications in press.

Improved Filters Using Parasitic Inductance Cancellation

Professor Perreault and graduate student Brandon Pierquet have continued the development of filters and passive components incorporating parasitic inductance cancellation. Advances this year include the development of methods designed to achieve parasitic compensation of multiple capacitors with a single magnetic winding. This approach has been demonstrated in the design of electromagnetic interference filters having greatly reduced weight and size relative to commercial designs. Another advance in the past year has been the experimental validation of new low-cost manufacturing methods for integrated filter elements providing inductance cancellation. These methods yield power filter components with improvements of up to a factor of 30 in filtering performance over conventional components of comparable weight and size. This work was the subject of a patent application and a conference publication this year, along with two journal publications in press.

Shipboard Power Systems

Professor James Kirtley supervised five master's-level projects on shipboard power systems. Steve Englebretson studied and designed excitation systems for high-speed induction generators. Jon Rucker designed a high-speed permanent magnet generator at a rating suitable for a particular type of electric ship. Andy Johnson investigated end effects in electromagnetic aircraft launch systems. Bryan Miller designed and prototyped a charging system for an autonomous undersea vehicle with a separable transformer so that the vehicle can be charged while in the water without ohmic contacts. Ed West studied power quality issues in ships with electric propulsion systems.

Rotating Field Windmill Generator

The US Navy is interested in using the design concept of the windmill generator being developed by Professor Kirtley for ship propulsion. In the coming year we expect, with support from the Navy, to complete the experimental machine with a new frame, balance the rotors, and get it running. In addition, we plan to do a design evaluation to determine how well it might function as a propulsion machine.

Dynamics of Networked Systems

Professor George Verghese and doctoral student William Richoux have completed a substantial generalization of the "influence model" that was developed in previous LEES work to describe, at an aggregated level, the dynamics of networked systems. The influence model represents the interaction of components that can each be in one of several possible statuses at a given time, with component status transitions that depend in a quasi-linear fashion on the current statuses of neighbors on the network. The model was originally developed to capture features of cascading failure in infrastructure networks such as power systems. The generalization allows dependence in the selection of influencing neighbors while maintaining the computational tractability of the earlier version, which had assumed independence in the selection of influencing neighbors. The generalization substantially increases the modeling power of the influence model and maintains its fundamental tractability.

Power System Diagnostics and Monitoring

Professor Steven Leeb's team has continued its work on power system diagnostics and monitoring, both for load health monitoring and for energy scorekeeping and optimization. They have conducted conclusive field studies on board the USCGC *Seneca* to demonstrate the value of one of their trial diagnostic indicators for the *Seneca*'s vacuum waste disposal system. On the basis of this and other work, they have been invited by the US Navy to continue studies of the application of this system to DDG-51 destroyer main engine plants, including experiments they are conducting at the Philadelphia Navy Yard. In the near future, they plan to shift this work to the forthcoming DDX destroyer and to expand their interactions with the Coast Guard. In addition, they have received new funding from the National Aeronautics and Space Administration (NASA) to expand this work to satellites and aerospace systems.

Multiwound Motor Stators

Also during the past year, Professor Leeb and his team have demonstrated the application of their new multiwound motor stator technique for reducing power supply requirements in multibus power electronic systems. They have successfully demonstrated the technique with full closed loop control on both the output voltage stages and the mechanical shaft parameters of a drive system.

Data Multiplexing over Power Cables

Dr. Cooke, working with industry and graduate student Jose Mendez-Alcazar (now graduated), has been exploring the use of electric power cables, such as those supplying power to motors, for carrying control and position data. The "data-over-power" approach reduces costs and enhances flexibility. A demonstration system has been built and tested in which digital data were transferred from the motor end of a cable to the controller end while pulse-width modulation power signals were simultaneously transported on the same copper wires from the controller end to the motor end of the cable. Plans are in development to further optimize the data encoding/modulation process to achieve better data communications. Power efficiency and low error rates are key parameters that must be controlled.

Stress-Induced Conduction in Insulators

Dr. Cooke, working with the electric power apparatus industry, has applied ultrasonic diagnostics to quantify space charges and internal stresses in high-voltage epoxy dielectrics. This work has been extended to create a simultaneous thermal and electrical gradient. These multistress test results have recently been shown to induce conduction-driven space charges and enhanced internal fields. Measurement values are being compared with theoretical values to establish a clear model for stress-induced conduction. The purpose of this effort is to improve the long-term reliability of materials used in electric power systems and other high-voltage applications. Additional work has been directed at determining the influence of materials and processing on resultant conduction characteristics.

High-Voltage Electron Beam Facility

Dr. Cooke and research scientist Kenneth Wright have been improving the instrumentation of the electron beam facility at LEES. Beam position and control of energy and intensity are each being improved. The facility has been used for a variety of measurements, including the processing of silicon wafers for improved radio frequency windows, the production of gamma rays for the stimulation of nuclear fluorescence radiation, and polymer processing for biocompatible materials.

Micro-Dimension Energy Systems

Micro Gas Turbine Project

As part of the MIT Micro Gas Turbine Engine Project, Professor Lang and former doctoral student Sauparna Das, together with colleagues from the MIT Gas Turbine Laboratory and the Georgia Institute of Technology, have pushed their microelectromechanical systems (MEMS) permanent-magnet synchronous generators to deliver substantially increased power, near 10 W. This continues to be the largest known power output from any MEMS generator. As part of the same project, Professor Lang and graduate student Bernard Yen, in collaboration with Professor Zoltan Spakovsky of the Department of Aeronautics and Astronautics, have completed a redesign of the MEMS generators and a variety of supporting fabrication experiments. The results of this effort should enable the fabrication of a fully packaged generator, driven by an integrated air turbine, that will produce approximately 20 W of electrical output power. Fabrication of the new generator will begin shortly, with demonstration expected within a year.

Micro Electrical Relay Development

Professor Lang and graduate student Alexis Weber, in collaboration with Professor Alex Slocum of the Department of Mechanical Engineering, have fabricated and demonstrated MEMS relays that are capable of hot switching electric power at levels up to several hundred volts. During the next year, their goal is to improve the current handling capability of the relays so that electric power can be hot switched simultaneously at currents in the range of 1–10 A.

Magnetic Fluids, Nanoparticle Suspensions, and Moisture

Magnetic Fluids

Ferrofluids consist of three components: single-domain magnetic nanoparticles, a stabilizing surface coating on these nanoparticles to prevent particle agglomeration by steric or coulombic repulsion, and a carrier fluid. Professor Markus Zahn has continued his research on magnetic fluids, exploring new behavior and applications of ferrofluids in rotating magnetic fields. These fields cause magnetic nanoparticles to spin owing to a magnetic torque on the fluid resulting from the magnetization and magnetic field being in different directions. Such suspensions of spinning magnetic nanoparticles function in a manner similar to nanosized gyroscopes that stir and mix the fluid. This is useful in microfluidic and nanofluidic applications or for heat generation due to viscous dissipation of spinning nanoparticles.

Ferrofluids

Shihab Elborai, working with Professor Zahn, has recently completed his PhD research, demonstrating that, in the case of a ferrofluid in a rotating uniform magnetic field with a top free surface, surface velocity rotates in the opposite direction to bulk velocity. PhD student Xiaowei (Tony) He is trying to further model this phenomenon and is extending the theory and measurements of ferrofluid torque and flow velocity profiles to nonuniform oscillating and rotating magnetic fields. This work is directed toward microfluidic device applications.

Nanoparticle Suspensions and Electrical Breakdown

PhD student Francis O'Sullivan, working with Professor Zahn, is developing the theory and numerical simulations of the initiation and propagation of electrical breakdown streamers in transformer oil with suspensions of nanoparticles. In pure transformer oil, positive streamers form at lower voltages and travel at greater velocities than negative streamers. Transformer oil with nanoparticle suspensions has approximately unchanged negative streamer breakdown strength, while positive streamers have increased breakdown voltage by about a factor of 2. Negative streamers increase their velocity by approximately 50 percent, while positive streamer velocities decrease by about a factor of 1.5 to 2. The purpose of this project, funded by ABB Corporate Research, is to understand how nanoparticle suspensions in transformer oil can be used to improve power transformer performance.

Dielectrometry Analysis of Insulator Breakdown

PhD student Zachary Thomas, working with Professor Zahn, is using interdigital dielectrometry sensors to monitor moisture dynamics in oil/paper insulated power cables as part of an Electric Power Research Institute project designed to understand failures in these cables due to the presence of moisture.

Electrodynamic Screens

Professor Zahn is working on a Jet Propulsion Laboratory project with Malay Mazumder, visiting professor from the University of Arkansas at Little Rock, on developing an electrodynamic screen to prevent dust from coating solar cell arrays on Mars. Theory and experiments are in progress for using traveling wave electric fields to prevent dust accumulation on surfaces.

Biomedicine and Biology: A Parallel Universe

The study of electrical power networks has created a rich body of expertise in the modeling, identification, and control of complex systems. Professor Verghese is leading a promising initiative to apply this expertise to biology and medical monitoring. In addition, some of Professor Zahn's work on ferrofluids, including nanoparticle-enhanced ferrofluids, has promising biological applications.

Model-Based Monitoring of Human Physiological States

Professor Verghese and postdoctoral associate Dr. Thomas Heldt have expanded their research in the area of model-based monitoring of human physiological state, with a focus on applications in critical care as well as in space medicine. This work, partly funded by the National Institutes of Health and NASA, as well as by the medical division of Philips (developer of the instrumentation), is being conducted in collaboration with Professor Roger Mark of HST and Professor Peter Szolovits of the Computer Science and Artificial Intelligence Laboratory, and involves doctoral student Tushar Parlikar; master's students Said Francis, Shirley Li, and Ahmad Zamanian; and UROP student Gireeja Ranade. In addition, Jennifer Roberts recently completed her master's thesis in the group.

The objectives of the critical-care component of this research are to take advantage of dynamic models from physiology to correlate the different data streams collected in intensive care units, to make inferences regarding patient state and parameters, to generate alarms based on inferred parameters and state rather than simply on high/low thresholds for individual measured signals, and to generate suitable clinical hypotheses. One direction of the research has focused on state and parameter estimation using electrical circuit analogs for cardiovascular flow operating at timescales of seconds to minutes. This work has also involved the construction of cycle-averaged models, motivated by ideas familiar from power electronics but requiring different development in the context of cardiovascular models. A second direction, developed in Jennifer Roberts's master's thesis, is built around probabilistic Bayesian network models operating at timescales of minutes to hours and involving additional clinical variables relevant to the cardiovascular system.

Initial results for both of these directions of work have been encouraging and have been accepted for presentation at conferences of the Institute of Electrical and Electronics Engineers (IEEE). The results on averaging have been accepted for publication in a special issue of *IEEE Transactions on Circuits and Systems* devoted to biomedicine. The space medicine thrust of this research has led to the development of models of cardiovascular dynamics for humans on "personal centrifuges" being developed at MIT's Man Vehicle Laboratory (MVL) for use in future space stations. The predictions of these models will be compared with actual data collected from experiments conducted at MVL.

Dynamic Network Models for Epidemics

Other research carried out by Professor Verghese, working with doctoral student Laura Zager, has been devoted to developing and studying dynamic models for epidemics on networks wherein transmission of the disease vector or movement of the hosts is restricted to neighboring nodes on a particular graph structure. An essay/proposal on this topic written by Zager resulted in her being selected by the Laboratory for Energy and Environment as a Martin Fellow for sustainability and the environment. Doctoral student Victor Preciado's continuing work on synchronization phenomena in networks turns out to have interesting points of similarity to the models used in the study of network epidemics.

Models for Protein Signaling Cascades in Cells

The research of doctoral student Carlos Gomez-Uribe, jointly supervised by Professors Verghese and Leonid Mirny (HST), has produced new understandings of models of protein signaling cascades in cells. Two new and potentially interesting regimes of operation have been identified, and their transmission properties for both signals and noise have been characterized. The work has been presented at a number of conferences, and journal publications are in preparation. Dynamic equations for efficiently tracking the fluctuations of mean concentration and variance of the chemical species in such signaling have also been constructed. Again, potentially fruitful connections have been found with the models used for studying epidemics on networks.

Ferrofluids for Cancer Therapy and Improved MRI

Professor Zahn has continued his research on magnetic fluids for microfluidic and biomedical applications. The ferrofluid surface coating can also serve a secondary purpose of selective adsorption to a surface or molecule. This has led to research, in collaboration with Professor Elfar Adalsteinsson, involving the use of magnetic fluids as a possible cancer therapy combined with improved magnetic resonance imaging (MRI). In a rotating magnetic field, the magnetic susceptibility of the ferrofluid becomes a tensor that depends on the rotating magnetic field frequency. This allows external magnetic field control of MRI contrast, which can be modulated so that the location of the magnetic nanoparticles can be easily visible by causing a “twinkling” effect. If the magnetic nanoparticles are selectively adsorbing to tumor cells, the location of the nanoparticles identifies the location of a tumor. Then, with further application of an oscillating or rotating magnetic field, the particles can be heated to a range of 42°–44°C, which kills tumor cells without harming healthy cells. Doctoral student Padraig Cantillon-Murphy has been investigating the theory of magnetic fluid effects on MRI contrast and is designing experiments to verify the theory.

Electromagnetic Therapy for Brain Treatment

Professor Zahn is collaborating with the Center for Non-Invasive Brain Stimulation at the Beth Israel Deaconess Medical Center on modeling electromagnetic effects on the brain during exposure to DC and transient magnetic fields. Such magnetic fields have been found to have therapeutic effects in treating major depression, stroke, and other brain injuries and illnesses.

Educational Initiatives

Professors Leeb, Kirtley, and Les Norford (of MIT’s Department of Architecture) are developing and teaching a new “Physics of Energy” class for freshmen. Course development is supported by a d’Arbeloff grant and funding from the Cambridge–MIT Institute and the Grainger Foundation. Students are exposed to discussions of thermodynamics, heat transfer, electric machinery, and some of the principles of electric power. This is expected to evolve into one of the proposed “project-based” first-year subjects contemplated by the Task Force on the Educational Commons.

Professors Verghese and Vincent Blondel (on sabbatical from the Catholic University of Louvain) ran a graduate seminar on network structure and dynamics in spring 2006 that attracted interest and participation well beyond the area of power systems.

Honors and Awards

Professor Verghese received a Distinguished Advising Award from MIT's IEEE/ Association for Computing Machinery student chapter. Professor Leeb received a Distinguished Teaching Award from Eta Kappa Nu.

Joel Schindall
Associate and Acting Director
Professor of Electrical Engineering and Computer Science

More information about the Laboratory for Electromagnetic and Electronic Systems can be found at http://lees.mit.edu/lees/.