EXECUTIVE SUMMARY

The MRSEC at MIT was established in 1994 as the core program of the Center for Materials Science and Engineering (CMSE). CMSE, an interdepartmental center at MIT, promotes and facilitates interdisciplinary research and education in the science and engineering of materials. MIT has an exceptionally strong and broad effort in materials science and engineering. CMSE plays the critical role of bringing this diverse materials community together by encouraging and supporting collaborative research and innovative educational outreach programs. The clear and important mission of CMSE is to encourage fundamental research and education in the science and engineering of materials for long-range applications that will address the future needs of society. To accomplish this mission, CMSE enables collaborative interdisciplinary research among MIT faculty and between MIT faculty and the researchers of other universities, industry and government laboratories.

Collaborative research is encouraged through several mechanisms: interdisciplinary research groups (IRGs), seed and initiative projects, shared experimental facilities (SEFs), and outreach programs. Our SEFs are used by numerous research groups from MIT as well as from outside academic and industrial communities. Our educational outreach programs encompass a broad range of activities and age levels with participation from middle school students and teachers, undergraduates, and high-school students and teachers. Our industrial interactions have resulted in the establishment of new products, applied funding, licensed intellectual property, a new MIT center and numerous successful start-up companies. We estimate that more than 275 new jobs have been created as a result of CMSE-based start-up companies. All of our activities are highly integrated and often combine elements of research and educational and industrial outreach.

Research Programs: CMSE currently supports four IRGs, one initiative, and two seed projects involving 31 faculty principal investigators. Our current research program is summarized below.

**IRG-I: Microphotonic Materials and Structures (group leader, Prof. Joannopoulos).** The objective of this IRG is to explore materials issues and fundamental properties of photonic crystals, to discover physical phenomena associated with photon states that have never been possible before, and to exploit this knowledge with the ultimate aim of the design, fabrication, and characterization of novel microphotonic devices and components.

**IRG-II: Nanostructured Polymer Assemblies (group leader, Prof. Mayes).** This IRG seeks to gain a fundamental understanding of the factors that control the way multi-component, functionally active polymer systems organize at the molecular and nanoscale levels and then use this knowledge to control and significantly enhance the performance of electronic, magnetic, biosensor and optical devices based on these materials.

**IRG-III: Electronic Transport in Mesoscopic Semiconductor and Magnetic Structures (group leader, Prof. Bawendi).** The focus of this IRG is to explore charge and spin transport in solid-state electronic structures whose building blocks are in the nanometer size regime, in order to understand the fundamental physical principles governing transport through and between these potentially important building blocks of future electronic devices.

**IRG-IV: Science and Engineering of Solid-State Portable Power Sources (group leader, Prof. Ceder).** This IRG seeks to develop the basic science and engineering of materials for solid-state electrochemical power sources and to use this fundamental knowledge to design devices with capabilities far superior to those of anything available today.

**Initiative: Exotic States of Correlated Electrons in Single Crystals (group leaders, Profs. Lee and Nocera).** The objective of this initiative is to discover and understand the exotic phases that arise in materials with strongly interacting electron systems that may exhibit unusual properties such as superconductivity, anomalously high thermopower, or infinite ground-state degeneracy. **Seed Projects:** *Electron Transport Studies in Single-walled Carbon Nanotubes (J. Kong), Engineering Nanoscale Polymer Films as Tunable Mechanical Substrata (K. Van Vliet).*
During the past two years, we engaged in a major review of our MRSEC program that culminated in a MIT-wide open competition for new IRGs. In this competition, all existing IRGs competed head-on with newly proposed IRGs. Final decisions were based on a rigorous review process involving 2-3 external written reviews per IRG and a two-day review of all proposed IRGs (ten IRG groups were proposed) by our external advisory board (SEEAB). In the end, it was decided to phase out IRGs II and III and graduate a revised version of our current “correlated electron” initiative to IRG status. IRGs I and IV will be moving forward with substantially redirected efforts and many newly added (and eliminated) investigators. Pending the outcome of our MRSEC renewal proposal, our future research program will comprise the five IRGs listed below. This new program includes three new IRGs and two substantially modified and redirected IRGs. Some preliminary “seed” funding has been deployed to help launch these new groups. In total, 14 new faculty members will be participating in CMSE supported research.

1) Engineering Living Cells via Nanomaterials (Irvine and Rubner co-leaders)
2) Design of Nanomaterials for Electrochemical Energy Storage and Conversion (Shao-Horn and Ceder co-leaders)
3) New States of Frustrated and Correlated Materials (Lee and Nocera co-leaders)
4) Mechanomutable Heteronanomaterials (Ortiz and Cohen co-leaders)
5) Multimaterial Multifunctional Nano-Structured Fibers (Fink and Soljačić co-leaders)

Diversity Plan: During this funding cycle, we have continued implementation of our newly launched, multi-faceted diversity plan with the goal of further reinforcing our efforts to meet the diversity challenge in science and engineering. Our most recent activities in this arena include expansion of our new community college outreach program to include Bunker Hill Community College and the initiation of a new undergraduate exchange program with the Universidad Metropolitana (UMET) in San Juan, Puerto Rico. The objective of this latter program, which will start in the summer of 2008, is to contribute to an increase in the retention and graduation of science and math undergraduate students in Puerto Rico by engaging UMET students in our summer REU program. Our collaborative program directed at high school women (WTP), continues to be a highly successful vehicle for encouraging young women to pursue a career in engineering (sixty-nine percent of the women who have passed through this program and have chosen college majors are currently pursuing science, engineering or math degrees). Our diversity strategy has already had a significant and positive impact on the demographics of our outreach programs. Prior to the launching of these new programs, typically 30% women and 9% minorities participated in our programs. During this reporting period our outreach programs comprised 45% women and 13% underrepresented minority groups.

Important highlights during this past funding period include: 1) the participation of six teachers in our RET program from local urban school districts with significant minority student populations, including one from an all–female school; 2) the support of four underrepresented minority graduate students with our special earmarked funds; 3) the establishment of special earmarked funds (provided jointly by CMSE and various MIT academic departments) for potential faculty candidate, minority post-doctoral associates; and 4) the above mentioned expansion of our community college program to include Bunker Hill Community College (a college with 40% minority enrollment).

Education, Human Resources and Outreach: CMSE offers a wide variety of educational outreach programs directed at middle and high school students, K-12 teachers, minorities, undergraduates, and graduate students. During this funding period, a total of 118 people participated directly in our various core educational outreach programs including 17 middle, high school, and community college teachers, 59 K-12 students and 42 graduates and undergraduates. In addition, special activities enabled by our MRSEC program, including three public events involved about 792 people. Highlights of this past year are summarized below.
Funding of one of our MRET participants by the Siemens Foundation allowed us to support a total of five new teachers and four returning teachers. Summer activities resulted in the creation of four new lesson modules covering subjects ranging from biomimicry to nanoscintillators. After these new modules are tested in the classroom in the coming year and further refined by the teachers, they will be made available on the CMSE website. Our teacher enrichment program (STEP), in addition to a well-received, hands-on engineering workshop, included a presentation by CMSE faculty on energy issues and demonstrations of polymer science by one of our former MRET participants. Our collaborative WTP program served 40 high school women this past year. Feedback by participants indicates that this program was once again a resounding success. In our week-long middle school programs, eighteen students and their science teachers explored a wide range of topics and activities including glassblowing, metal casting and an enthusiastically received design contest. CMSE also hosted a number of K-12 student/teacher lab visits and activities during the course of the year including half-day visits to our SEFs. Our collaborative REU program continued its long-running tradition of engaging and challenging undergraduate students from across the country. This program is now integrated with our community college program and ends with a capstone poster event that more than 100 faculty, students and family members attended this year.

CMSE also contributed to three large public outreach events during the past year. In these specific events, CMSE graduate students, faculty and SEF staff contributed lectures, demonstrations and hands-on activities to more than 750 people, ranging from kids to grandparents. These events included 1) the MIT Museum sponsored “Family Adventures in Science and technology” afternoon 2) the first ever in the country city-wide Cambridge Science festival and 3) the MIT hosted “Space Odyssey Ball.”

**Shared Experimental Facilities:** Our SEFs are a critically important resource to our MRSEC program and to the MIT community, as well as to a number of outside academic and industrial organizations. Our SEFs also play a special role in the training and education of MIT students as well as participants in our educational outreach programs such as our MRET, RCC and REU participants. Currently we run four major facilities: Materials Analysis, Crystal Growth and Preparation, Electron Microscopy, and X-Ray Diffraction. During this past funding period, 675 different individuals utilized our facilities as well as about 150 students from MIT undergraduate lab subjects.

Key highlights/activities during this funding period include the following: 1) the running of a number of MIT-wide workshops, lectures and tutorials by our SEF staff, 2) our first ever SEF-sponsored seminar in which an outside expert presented a lecture on multivariate statistical analysis, and 3) participation of SEF staff in a remote access demonstration of scanning electron microscopy at the Cambridge Science Festival.

During this funding period, our newly purchased field-emission source scanning Auger microprobe was installed and activated. This new tool is capable of an ultimate spatial resolution of 7 nm and is the only instrument of its kind in the New England area. To date, sixteen researchers from both within MIT and outside MIT have utilized the instrument. We will shortly be taking possession of another one-of-a-kind capability: a cathode luminescence attachment for one of our transmission electron microscopes.

**Collaborations with Industry and Other Sectors:** Our MRSEC supported faculty has ongoing collaborations with numerous industrial partners that range from the funding of applied projects (often based on fundamental work carried out within the center) to the development of new technologies and products. We work effectively with MIT programs and centers, such as the Materials Processing Center (MPC) and MIT’s Industrial Liaison Program (ILP), designed to connect MIT research to industry. This past year, CMSE faculty participated in three ILP-
sponsored conferences that were attended by more than 500 industrial representatives. In addition, our faculty engaged in 90 ILP organized meetings with representatives from a broad range of different domestic and foreign companies, including 69 visits from industrial representatives; eight faculty visits to different firms; and 13 briefings to company executives. In this year’s MPC-hosted “Materials Day at MIT,” four CMSE supported faculty presented their latest results in a symposium entitled “Thin Films and Coatings: Designed and Processed to Enhance Function and Performance.” A new CMSE-originated industrial collaboration with Essilor Corporation was highlighted during the meeting, which was attended by about 130 people, many from industry, government labs and other universities. Our MRSEC supported faculty engaged in 67 collaborations this past year with researchers from other universities, industry and government labs.

**Administration and Management:** Our MRSEC program is administered by a proactive and effective management team capable of responding quickly to the emerging needs of the program. Our activities are guided and supported by five committees, including a Science and Engineering External Advisory Board (SEEAB) composed of leaders of industrial and government laboratories and key faculty from academic institutions. A key activity this past year was the previously mentioned MIT-wide IRG competition that was held in preparation for our renewal proposal.

**Key Scientific Accomplishments:**
**IRG-I** has played an important national role in establishing key computational tools for photonic crystal researchers. This past year they added to their 3D time-domain code support for anisotropic materials including magneto-optic and magnetic materials and materials with non-dispersive complex dielectric functions. The MIT 3D time-domain code is freely available, has been downloaded thousands of times and is used by researchers around the world. IRG-I researchers have successfully demonstrated large-scale supercollimation in a photonic crystal of silicon rods residing on a thick underlying layer of oxide. This new geometry is important as it limits the problem of coupling with the substrate. Supercollimation is important as it provides a means to direct light without the use of a waveguide and the inherent problems with coupling and cross talk. They have also introduced a new concept in fiber lasers: “dynamic surface-emitting fiber lasers.” In contrast to conventional fiber lasers where light only originates from fiber ends, these new fiber lasers can emit radiation radially from any predetermined position along the fiber. This new technology opens up exciting opportunities for enhanced capabilities in medical imaging, vapor detection, photodynamic therapies and fabric displays.

Research from IRG-II has established new processing techniques for creating nanodot arrays of magnetic materials. Using block copolymers as templates in conjunction with topographic features, they have demonstrated that highly ordered arrays of magnetic nanodots can be created with either patterned anti-reflective coatings or a sparse template of posts with dimensions commensurate with the size of the block copolymer domains. Magnetic measurements indicate that these arrays are excellent candidates for patterned magnetic recording devices. In the multilayer area, IRG-II researchers have created a functionally active thin film coating that can be loaded with multiple drugs that release in a controlled manner. Most importantly, since the multilayer coating is actually a nanoporous Bragg-stack similar to that found in hummingbird wings, the color of the coating changes dramatically as drugs are loaded and unloaded. Hence, these new coatings have a built-in self-monitoring capability. As a result of fundamental studies carried out by IRG-II researchers, five different companies are now funding efforts to develop multilayer coatings for anti-fogging, anti-reflection and structural color applications.

IRG-III research has revealed that charge transport in an array of PbSe quantum dots is very different from that observed in CdSe dots. In the PbSe case, charge transport was found to be the result of hole-majority carriers that are thermally released from acceptor states. This
important observation means that an n-type partner will be needed to create efficient light emitting devices from this material. This new discovery debunks current literature that suggests that p-type partners are preferred. Measurements of this quantum dot system also revealed a particular trap state on the surface of the PbSe dot surface: a possible route to tuning charge transport by passivating these trap states has been identified. This work opens the door to the fabrication of higher performance PbSe quantum dot based photodetectors and photovoltaic devices. This group has also demonstrated a novel approach to overcome the difficult challenge of “wiring” single nanoparticles in electro-optical devices. Using a layered organic electrode geometry, they were able to observed directly both the electroluminescence and photoluminescence signal from the same individual dots in a device.

**IRG-IV** researchers have used a genetically engineered M13 virus as a scaffold for templating the growth and assembly of nanoscale amorphous iron phosphate. These virus-generated nanoparticles look promising for use as the positive electrode material of a rechargeable battery. To date, electrochemical analysis indicates that close to 85% of the theoretical capacity of iron phosphate can be realized from the nanoscale version of this material. Working batteries were successfully assembled and tested. A virus-based approach to synthesizing new nanoscale battery materials is important as the replication process of a virus provides a means to easily and cheaply mass produce such materials. Research of this group also shed new light on the phase transformation dynamics of LiFePO$_4$ electrode materials. This work has resulted in a fundamental understanding of the lithiation patterns previously observed during battery recharging.

Members of the Initiative made an important breakthrough in their investigation of the fundamental physics of kagomé lattice systems. Utilizing our unique crystal growth facility, they have developed a hydrothermal crystal growth method that yields appreciably sized single crystalline samples of the S=1/2 kagomé lattice antiferromagnet ZnCu$_3$(OH)$_6$Cl$_2$. Crystals as large as 2 mm have been grown. Refinement of the growth technique and preliminary thermodynamic measurements are ongoing.

**Broader Impact:** CMSE-supported activities and facilities have enabled and promoted the integration of research and education in a number of significant ways. Our SEFs have contributed to the education and training of numerous undergraduate and graduate students, postdocs, and high school and middle school teachers and students, as well as visitors from many companies and local universities. Our SEFs also supported the research of a large number of non-CMSE affiliated MIT investigators and their students. To encourage additional participation from traditionally underrepresented minority groups, CMSE has embarked on a multi-faceted campaign that includes active participation in annual internship recruitment fairs targeted to minority students, attempts to establish new relationships with minority-rich colleges and universities, and the creation of a new internship program with local community colleges. Important research advances within our center have been communicated to the outside world through numerous publications in high impact journals, industry-targeted symposia and direct interactions with member companies of MIT’s Materials Processing Center (MPC) and Industrial Liaison Program (ILP).

**Long-Range Plans/Issues:** We are saddened to report that during the last year, Professor Mayes was forced to take an early retirement due to health reasons. Over the years, the contributions to our MRSEC by Professor Mayes have been significant and profound. Her leadership of IRG-II has been exemplary and will be sorely missed. She leaves MIT and our center with an amazing record of accomplishment and impact in place. Although Professor Mayes has officially retired, she will still remain intellectually engaged in IRG-II research from her home in Oklahoma. Since this IRG is currently being phased out, management of all remaining activities will be carried out by Rubner (member of IRG-II).
Overall Mission: MIT has an exceptionally strong and broad effort in materials science and engineering. CMSE, an interdisciplinary center at MIT, plays the critical role of bringing this diverse materials community together by encouraging and supporting collaborative research and innovative educational outreach programs. The clear and important mission of CMSE is to encourage fundamental research and education in the science and engineering of materials for long-range applications that will address the future needs of society. To accomplish this mission, CMSE enables collaborative interdisciplinary research among MIT faculty and between MIT faculty and the researchers of other universities, industry and government laboratories. Industrial and educational outreach efforts are fully integrated into all center activities. CMSE reports directly to the vice president for research. This insures that CMSE can effectively promote collaboration between researchers at MIT from both the Schools of Engineering and Science. Hence, CMSE is in a unique position to encourage faculty from different departments and schools to work together on new problems that require an interdisciplinary approach. Four internal and one external committee provide guidance and input to the director and monitor all critical aspects of center activities.

Research: CMSE’s research goal is to encourage collaborative research through several mechanisms: interdisciplinary research groups (IRGs), seed and initiative projects, shared experimental facilities (SEFs), and outreach programs. To insure that our research programs deliver the highest possible scientific and technological impact, we utilize an extensive review process involving internal and external evaluation of our programs. To become and remain a CMSE-supported researcher, it is necessary to successfully navigate this highly competitive, MIT-wide process. Regular meetings of our internal advisory board (IAC) insure that IRG leaders and our faculty educational outreach and SEF leaders understand and share a common vision for the center. Our Science and Engineering External Advisory Board (SEEAB) provides an outside perspective on the impact of our activities. This committee is composed of leaders of industrial, academic and government laboratories that support major efforts in long-range materials research and engineering. Important metrics utilized to evaluate our research programs include, for example, number, quality and impact of peer-reviewed publications, level and effectiveness of multi-investigator collaborative activities, engagement of graduate and undergraduate students in research, number of patents and licenses granted and effectiveness of knowledge transfer and outreach activities.

Education: CMSE offers a wide variety of educational outreach programs including programs directed at middle and high school students, K-12 teachers, women and minorities, undergraduates, and graduate students. The center’s educational goal is to provide a portfolio of effective and innovative educational outreach programs that are integrated into our research activities and benefit from wide participation of MIT faculty and students. In all of our programs, specific measures are in place to promote and enhance diversity within each participant pool. CMSE’s education committee consults on the direction of the education programs and facilitates the coordination of our programs with other outreach programs on campus. Assessment of our educational outreach programs against their objectives is accomplished by carefully crafted entrance and exit surveys and, where possible, by tracking of participant activities after completion of our programs. Another important metric is the level of subsequent involvement/collaborative interactions participants have with our center. We view our educational outreach activities as a vehicle for creating long-term relationships with, for example, local K-12 teachers and work to facilitate this process. To date, hundreds of students and teachers have taken advantage of the many resources available through our center.

Diversity: CMSE has a history of encouraging traditionally underrepresented minority groups and women to participate in materials research and education through its educational outreach programs, dedicated sponsorship of graduate research assistants, and efforts to coordinate
CMSE activities with other MIT programs. CMSE’s diversity goals include three key elements: 1) implementation of strategies to increase the diversity of participants in our existing education programs; 2) development of new outreach programs that specifically target underrepresented minority groups; and 3) initiation and execution of collaborations with other units at MIT that are working to address the diversity challenge in science and engineering. One key metric for assessing the impact of these activities is the number of women and minorities participating in our programs. At the start of our current grant, our programs typically involved about 30% women and 9% minorities. Over the past few years, these numbers have risen to about 45% women and have ranged from 12% to 21% minorities. However, it is not sufficient to simply increase numbers. We recognize that it is extremely important to provide an experience to our participants that is tailored and sensitive to their specific needs. Thus, an important goal is to establish a support infrastructure that insures that our program objectives are realized. As an example, in our recently launched community college program, we work closely with a faculty member from each college to monitor the progress of participants and better understand their needs. Close relationships of this type also help us track the subsequent progress of participants.

Shared Experimental Facilities: A key objective in this case is to establish state-of-the-art facilities that provide and maintain critically enabling instrumentation for our MRSEC investigators and, at the same time, serve as an important resource to the broader MIT materials community and beyond. An additional goal is to minimize the cost to users to make available an important educational training opportunity to all interested outreach participants, students and post-doctoral associates. To accomplish these important goals, we have assembled a highly motivated and engaged professional support staff and a substantial support infrastructure. Over the past five years or so, our user base has steadily increased from about 500 to 800 individual users. Long-term issues include the rising costs of modern instrumentation and service contracts. To address this important problem, we aggressively seek cost-sharing opportunities with other laboratories, departments and centers at MIT. This has allowed us to purchase, for example, expensive electron microscopes that vastly exceed our equipment budget. Faculty based users groups are utilized as needed to provide input on facilities performance and, in conjunction with our IAC, to make recommendations for new equipment purchases. To insure compliance with our long-term mission, the assistant director of our center manages directly all important aspects of the facilities.

Knowledge Transfer: MIT has a long-standing history of promoting collaboration with, and knowledge transfer to, industry. To facilitate the transfer of the fundamental knowledge generated within our program to the outside world, CMSE works effectively with MIT’s Materials Processing Center (MPC) and Industrial Liaison Program (ILP). Our goal is to keep industry, government laboratories and other universities aware of the latest developments and discoveries from within our center and where possible, facilitate technological developments that will impact society and the economy. This goal is accomplished through participation in MPC and ILP organized outreach events such as “Materials Day at MIT” and through numerous ILP arranged meetings at companies and with company researchers and technical managers. Start-up companies based on CMSE research are another important vehicle for knowledge transfer.