2006-2202: PROJECT-BASED INTRODUCTORY TO MATERIALS ENGINEERING MODULES ON BIOMATERIALS, SOLID OXIDE FUEL CELLS, NON-VOLATILE MEMORY, AND FIBER REINFORCED PLASTICS

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Project-Based Introductory to Materials Engineering Modules on Biomaterials, Solid Oxide Fuel Cells, Non-Volatile Memory, and Fiber Reinforced Plastics

Abstract

PRIME Modules, Project Based Resources for Introduction to Materials Engineering, are being developed that utilize modern materials science and engineering technologies and proven education methodologies of active learning and open ended projects. The modules are designed for use in a freshmen/ sophomore level Introduction to Materials Engineering course. This course is required by most engineering programs and is an ideal place to excite students about their engineering majors and expose them to real world engineering experiences.

Currently four of the classroom modules have been developed and utilized in Introduction to Materials classes. There is a non-volatile memory module where students are taught the fundamentals of electronic and magnetic properties in the context of learning about options for non-volatile memory in portable electronics. In another module, students learn about solid oxide fuel cells and the ceramic nanomaterials used to fabricate them. While being exposed to this emerging application, students learn the basics about ceramics, defects, and phase diagrams. A third module exposes students to fiber reinforced plastics used for civil infrastructure. This module covers mechanical properties, diffusion, polymers, and composites. The fourth module developed teaches students about crystal structure, mechanical properties of metals, and phase diagrams in the context of biomaterials (self-expanding stents made from shape memory alloys). Each classroom module contains background resources for faculty, lecture notes, active in class exercises, homework problems, and an open ended, team project.

Background

Most engineering programs require their students to take an introductory materials class. This includes community colleges with engineering transfer programs. In the U.S. alone, the "Introduction to Materials" course enrolls over 50,000 students a year.[1] The primary goal of the class is to provide a foundation in materials science and engineering that the students can build upon in their major classes and future careers. This freshman/ sophomore class is an ideal place to excite students about their engineering majors and expose them to real world engineering situations.

Project Based Resources for Introduction to Materials Engineering (PRIME) modules have been developed to teach the fundamental principles covered in a typical introductory materials course within the context of modern engineering technologies. The same fundamental principles of materials science and engineering that are typically delivered in a traditional lecture model of an Introduction to Materials course are taught. However, the fundamental topics are arranged in project based modules that center around a modern technology.

The use of relevant, industry examples expose freshman and sophomores to realistic engineering situations. The modules accurately inform and excite students about recent technological advances. By tying the fundamental material to technologies, students obtain a "bigger picture" view of the field. Placing the "Introduction to Materials" curriculum in a framework where the students can see its relevance to their interests and the world around them should increase their understanding and retention of the material.[2] Balancing the concrete and abstract content should cater to different learning styles, especially benefiting global learners who suffer in traditional forms of the class that do not emphasize the "bigger picture".[3] Cabral et al showed that placing the fundamental material within the context of an applied situation increases students motivation to learn.[4] Each lecture module will have an open ended project that student teams work on throughout the course of the module. The project is integrated into each module in order to increase student ownership of their learning and to deepen students' understanding between the connection of the fundamentals they are learning with real world engineering applications.[5] The fundamental material appears in multiple modules. This allows students to revisit the material over the course of the semester and build upon what they learned earlier to obtain a deeper understanding.

Table 1 lists the four modules developed to date along with the fundamental objectives they teach. These are classroom based modules that can be utilized within the framework of a traditional lecture only class. In addition, a lecture module on sports material and laboratory modules on failure analysis and materials selection are being developed and will be beta tested in Fall 2006.

Table 1: PRIME Modules developed to date to teach fundamental materials principles in the context of modern materials technologies.

AEC Module Technology	Fundamental Topics Covered
Biomaterials: Self-expanding stents made from shape memory alloys	Crystal structure of metals Defects Introduction to phase change & phase diagrams Mechanical properties of metals Processing & strengthening mechanisms in metals
Nanomaterials: Ceramic nanomaterials for solid oxide fuel cells	Crystal structure of ceramics Properties of ceramics Ionic defects Advanced phase diagrams Introduction to diffusion
Electronic & Magnetic Materials: Non-volatile memory devices for portable electronics	Atomic bonding and electron configurations Band structures of metals, semiconductors, and insulators Conductivity of metals and semiconductors Capacitance Introduction to transistor operation Magnetic moment, magnetic domains Hysteresis loops Solenoids
Composites: Fiber reinforced composites for civil infrastructure	Comparison of stress strain diagrams of all materials Polymer processing and properties Mechanical properties of composites Advanced diffusion

Overview of the Technologies

Each PRIME module is designed to take 3-5 weeks of class time. This modular format makes utilization of the curriculum more flexible. Instructors can choose anywhere from 1-4 modules for their class. They could cover all the fundamentals learning objectives of the course through this format or use the modular format for only a subset of the course. Modules could be chosen to target the specific interests of their student bodies or local economies.

Biomaterials Module: Self-expanding Stents

In the biomaterials module, students learn about NiTi (Nitinol) stents. These biomedical devices are used to permanently scaffold arteries. NiTi is a shape memory alloy that undergoes a phase change from austenite (B2, CsCl structure) to martensite (monoclinic). The phase change can be temperature or stress induced. There is a volume change between the two phases. There is also a change in the mechanical properties of the two phases with the martensitic phase exhibiting superelastic properties. In a self-expanding stent, the superelasticity is utilized. A stent is placed in the body with a surgical tool that crimps the stent shut. Due to the crimping, the stent is in the martensitic, superelastic phase. When released in the body, the stent expands dramatically. The superelasticity allows for the large expansion of the stent upon release and the continual flexing of the stent over its lifetime in the artery. Biomedical stents are a continually evolving technology with materials engineers making advances on the strength and reliability of the stents and improving their efficacy from a medical device's standpoint.[6]

In order to understand the fabrication and use of a Nitinol stent, students must learn about the crystal structures, phase changes, and mechanical properties of metals. These are taught over a 4 week module. Table 2 details the learning objectives covered in each class period of the module. Throughout the module, students work in teams on a project in which they utilize a shape memory alloy to improve on a biomedical application other than a stent. Students are given homework problems specific to the technology to help master the fundamental learning objectives and to guide them along the project.

Table 2: Learning objectives for each class period in the PRIME Biomaterials module.

Class 1 & 2: Overview of Biomaterials and Crystal Structure	Define lattice, unit cell, and basis. Draw the lattices for BCC and FCC. Determine the closest packed directions and planes for BCC and FCC. Calculate the ratio of lattice parameter to atomic radius in FCC, BCC, and simple cubic structures. Calculate atomic packing fraction of varying crystal structures. Define alloy and intermetallic compound. Draw the crystal structure for different phases of Ni-Ti alloys. Describe the phase change that takes place in memory metals.
Class 3: Defects	List examples of point, line, and interfacial defects. Calculate the concentration of vacancies as a function of temperature in a solid. Identify edge dislocations and describe their motion. Identify some of the specific properties of materials that are controlled by the presence and quantity of defects.

Class 4: Mechanical Properties	Calculate stress, strain, and/or modulus from applied force. Describe the difference between elastic and plastic deformation. Use a stress/strain diagram to determine yield point, ultimate tensile strength, Young's modulus, ductility, and toughness. Calculate strain in the y direction using Poisson's ratio. Differentiate between engineering stress and true stress. Define super-elasticity and identify it on stress strain plots for memory metals.
Class 5: Strengthening Mechanisms	Explain the process of slip. Determine the slip systems in FCC and BCC crystals. Describe strain hardening. Explain the influence of cold working on a metal's mechanical properties. Describe solid solution hardening. Describe strengthening by grain size reduction. Discuss processing methods used to strengthen biomedical stents.
Class 6 & 7: Phase Diagrams	Determine the equilibrium phases, microstructure, and composition of the phases as a function of temperature and overall composition from a phase diagram. Recognize and describe isomorphous and eutectic phase diagrams. Identify the invariant points and congruent transformations in a phase diagram. Calculate mole fraction and weight fraction of a phase using the lever rule. Utilize memory metal phase diagram to determine the operating temperature of a device.

Nanomaterials Module: Solid Oxide Fuel Cells

In the nanomaterials module, students learn about ceramics within the context of solid oxide fuel cells. A solid oxide fuel cell generates current and the harmless by-product of water from a hydrogen fuel source and air. The air is taken in on the cathode side and heated in order to break it down into to O^{2-} ions. The O^{2-} ions diffuse across a solid electrolyte to an anode. On the anode side, the O^{2-} ions undergo an electrochemical reaction with hydrogen atoms contained in a supplied fuel. Electrons and water are generated. A schematic of a solid oxide fuel cell is shown in Figure 1. The solid oxide fuel cell operates at high temperatures (around 1000 C) in order to increase the diffusion rate of the O^{2-} ions across the electrolyte. Due to this high operating temperature, ceramics are the material of choice for the anode, cathode, and electrolyte. Ceramic nanomaterials are used in the layers to make them as thin as possible and to increase the diffusion paths for the O^{2-} ions. Materials engineers are researching alternative materials and fabrication techniques to make efficient SOFC that operate at lower temperatures.[7]

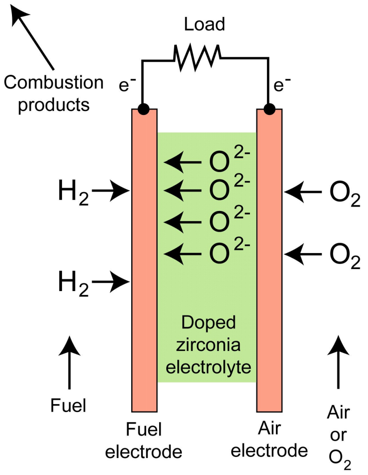

Figure 1: Schematic of a solid oxide fuel cell.

To understand the materials selection and optimization involved in designing and fabricating a solid oxide fuel cell, students must have knowledge of the fundamentals of ceramics. This includes ceramic crystal structures, defects, and thermal and mechanical properties. Students also need mastery of complex ceramic phase diagrams and diffusion. .These fundamentals are taught over a 3 week module. The learning objectives covered in each class period are detailed in Table 3. Throughout the module, students work on a team project where they choose materials and a fabrication process for the anode, cathode, and electrolyte of a SOFC. The materials selection and fabrication process need to be optimized in order to allow the SOFC to operate at as low a temperature as possible. Students are given homework problems related to SOFC to guide them through the major steps of the project.

Table 3: Learning objectives for each class period in the PRIME Nanomaterials module.

Class 1: Overview of SOFC	Draw the cross section of a SOFC. Describe how a SOFC operates. List materials used for anode, cathode, and electrode. Describe why ceramics are needed in SOFC. Describe why nanomaterials are needed in SOFC. List advantages of SOFC over other fuel cell types.
Class 2: Introduction to Ceramics	List the main properties of ceramics. Calculate the coordination number based on ionic radius. Determine the crystal structure from the coordination number. Draw the crystal structures for rock salt, cesium chloride, and zinc blend. Draw the crystal structure of common ceramics for the anode, cathode, and electrolyte in SOFC.
Class 3: Ceramic Defects	List the point defects. Determine the charge of a point defect in a ceramic. Define Frenkel and Schottky defects. Determine the point defect clusters in a SOFC electrolyte. List the bulk (interfacial) 3-D defects.

Class 4: Diffusion via defects	Explain the interstitial, vacancy, and fast path diffusion mechanisms. Describe how diffusion depends on temperature. Calculate the diffusion coefficient. Define sintering. Describe the role diffusion plays in sintering. Describe the role diffusion plays in the operation of a SOFC. List ways to increase diffusion across the electrolyte.
Class 5 & 6: Phase Diagrams	Define phase, component, and solubility. Calculate mole fraction and weight fraction of a phase using the lever rule. Determine the equilibrium phases, microstructure, and composition of the phases as a function of temperature and overall composition from a phase diagram. Recognize and describe isomorphous, eutectic, and eutectoid phase diagrams. Identify the invariant points and congruent transformations in a phase diagram. Utilize ceramic phase diagrams to explain Y-stabilized ZrO_2.

<u>Electronic & Magnetic Module: Emerging Devices for Non-volalite Memory</u>

Traditional non-volatile memory including magnetic hard drives, floppy discs, and Zip discs are not used in most portable electronic devices because of their relatively large size, the size of their read/write components, and the fact that they can't be integrated well with Si electronics. FLASH overcomes these problems and is currently the standard non-volatile memory technology used in portable, electronic devices. FLASH components are based on N-MOS transistors, see Figure 2. This memory technology creates 1s or 0s in memory by storing (or not storing) electrons on a floating gate. This affects the turn on voltage of the transistor which is how the memory state is read. Materials engineers are working on improving the memory density by scaling the size of the FLASH devices. Ultimately, there is a scaling limit to FLASH and engineers are researching the next generation of memory technology.[8]

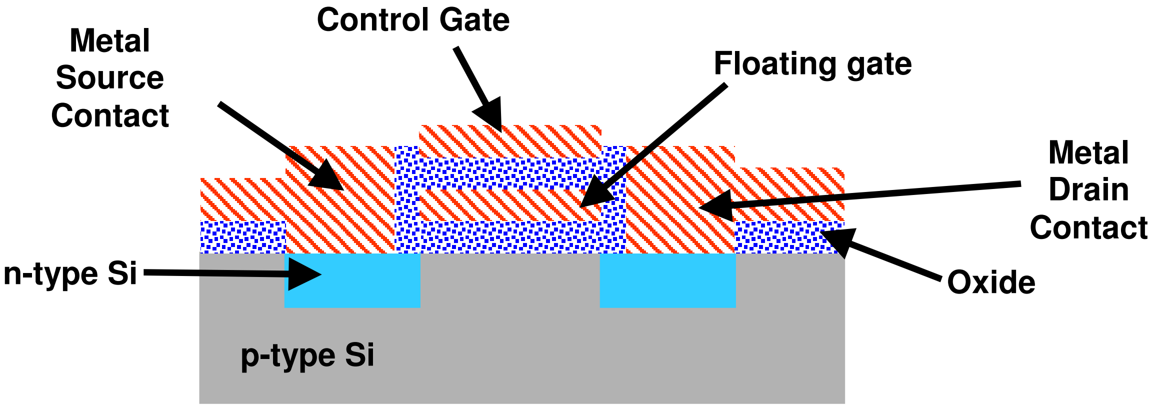

Figure 2: Cross section of a FLASH device.

This module emphasizes why FLASH is an attractive alternative to traditional magnetic hard drives and the limitations of FLASH that make it likely to be phased out in the next decade or two. Students are introduced to the fundamentals of metal, semiconductor, and insulator band structures and electronic properties. They also learn what makes a material magnetic. These fundamental learning objectives are covered over a 4 week module, Table 4. The team based project has students choose a portable electronic device such as a cell phone or MP3 player. The team researches the current memory technology in the device including the operation of this technology from a standpoint of basic electronic or magnetic properties. The students also research emerging memory technologies. Based on the constraints of the device, the students recommend the optimal memory technology for the device. Homework problems are utilized to assist students in the incremental steps of accomplishing the project.

Table 4: Learning objectives for each class period in the PRIME Electronic & Magnetic Materials module.

Class 1 & 2: Overview of non-volatile memory and crystal structure	Describe the difference between volatile and non-volatile memory. List several non-volatile memory devices. List constraints on memory technologies used in portable electronic devices. Define lattice, unit cell, and basis. Draw the lattices for SC, BCC, and FCC. Determine lattice type, atoms per lattice site (basis) and atoms per unit cell for varying crystal structures. Differentiate between single crystal and polycrystalline materials.
Class 3: Resistivity & Band Structures	Use Ohm's Law and equations for resistance to calculate current in a given setting. Describe the difference between conductivity, resistivity, and resistance. Describe the relationship between electronic orbitals in an atom and bands in a solid material. Differentiate between the conductivity of metals, semiconductors, and insulators. Relate these differences to their respective band structures.
Class 4: Semiconductor Doping & NMOS	Define intrinsic and extrinsic semiconductors. Explain how the addition of donors and acceptors alter the conductivity of a semiconductor. Draw a cross section of a NMOS transistor and explain the basic steps of operation.
Class 5: Capacitance and FLASH Operation	Define capacitance. Explain how charge is stored across a dielectric in a capacitor. Draw a cross section of a FLASH device and explain its basic operation in the on and off states.
Class 6: Fundamentals of Magnetism	Explain the basic classes of magnetic behavior: diamagnetic, paramagnetic, ferromagnetic, ferrimagnetic, and antiferromagnetic. Distinguish between B, M, and H. Calculate the magnetic field in a solenoid.
Class 7: Magnetic Domains and Hysteresis	Identify the following points on a hysteresis loop of a ferro- or ferrimagnetic material: remanent magnetization (M_R), remanence (B_R), coercivity (H_C), saturation magnetization (M_{sat}), and saturation induction (B_{sat}). Describe the operation to write a bit in a magnetic hard drive.

Composites Module: Fiber Reinforced Plastics for Civil Infrastructure

Fiber reinforced plastics (FRP) are composite materials with a polymer matrix and a glass, carbon or aramid fiber reinforcement. Common uses for FRPs generally occur in the aerospace, automotive and marine industries as low weight, high strength materials. The durability is a function of both the matrix and the fiber making them much more durable than the fibers on their own. The strength, however, is more influenced by the fibers making them very strong in tension. FRPs are used in civil infrastructure for reinforcement for concrete patching, cables on bridges, and complete bridges. The major advantages to FRPs over steel are that the material can be more specifically tailored to the loads for the system, a resistance to corrosion, an increase in material lifetime and durability, and a decrease in construction time and cost. Materials engineers are researching ways to improve the cost, strength to weight ratio, and long term reliability of FRP composites used in civil infrastructure.[9]

In order to successfully understand FRP applications, students must master the fundamentals of both polymers and composites. The structure, processing, and mechanical properties of these materials are covered in a 4 week module, Table 5. Student teams design an FRP based on given mechanical constraints. The students choose the matrix and fiber to optimize the mechanical design constraints and minimize the cost. Homework problems are utilized to help students master the calculations involved in analyzing the polymer and composite materials.

Table 5: Learning objectives for each class period in the PRIME Composites module.

Class 1: Overview of FRP in Civil Infrastructure and Comparison of Mechanical Properties of Different Classes of Materials	Describe types of composites and the materials used in them. Describe how composites are used in civil infrastructure. Calculate stress, strain, Young's modulus, and Poisson's ratio. Draw and identify stress-strain curves for different materials (metal, polymer, ceramic, and composites). Label the major points on each plot. Emphasize how the stress strain plots of metals and polymers differ in terms of definitions of yield stress and tensile strength. Describe the use of ASTM standards.
Class 2: Mechanical Properties of Composites	Define and give examples of particle, fiber, and structural composites. Calculate the limits of the modulus of elasticity in a particle reinforced composite. Calculate modulus and strength of a continuous fiber composite.
Class 3: Introduction to Polymers	Define a polymer and monomer. Describe the process of addition polymerization. Describe factors that control chain length. Calculate the number average and weight average molecular weight of a polymer sample. Classify a polymer based on linear, branched, cross linked and networked. Classify a co-polymer based on how the sub-units are arranged. Classify a polymer based on how the side groups are arranged. List factors affecting the mechanical properties of polymers.

Class 4 & 5: Polymer Crystallinity and Aging	Describe the morphology of polymers. Predict trends in crystallinity. List factors that influence aging in a polymer. Explain why temperature accelerates aging.
Class 6 & 7: Diffusion	Define diffusion Perform calculations for steady-state diffusion. Perform calculations for non-steady-state diffusion. Use the Arrhenius equation to predict long-term performance from accelerated aging data. Calculate the diffusion of water through an FRP. Predict the limits of accelerated aging from test data.

Module Format

The content of the modules include a range of resources developed for both faculty and students. These resources are outlined in Figure 3.

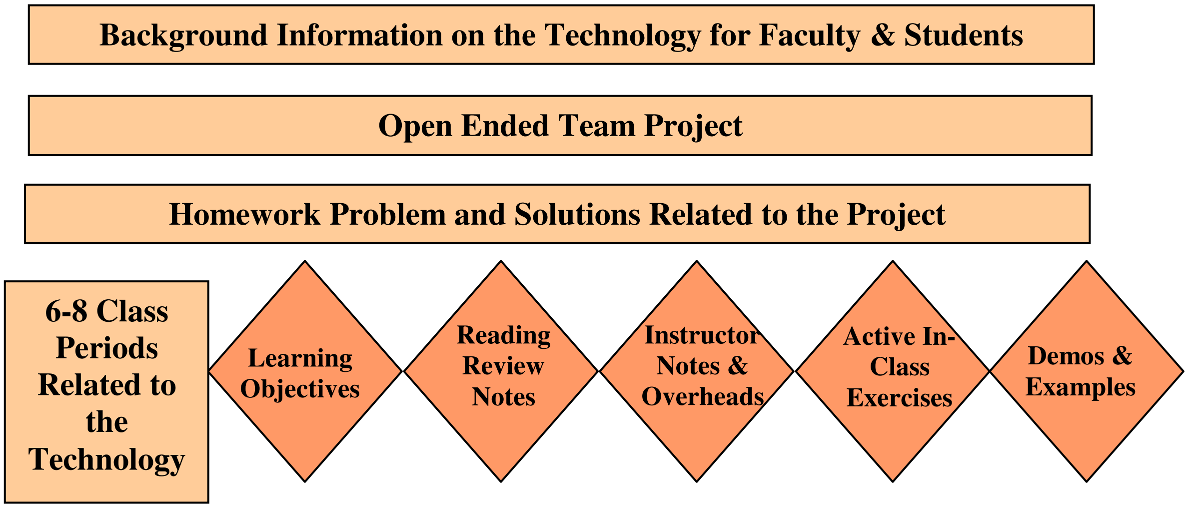

Figure 3: Overview of content developed for each PRIME Module.

Faculty receive a background document that briefly describes the overall technology, its relation to materials science and engineering, and current research issues related to the field. The background resource also includes a set of references for the faculty to gain a deeper understanding of the technology. This background document allows the modules to be utilized by faculty with differing expertise.

Each module also has an overarching project. The projects are designed to be done by teams of 3-4 students in a 3-5 week period. The projects are research based projects that can be accomplished within the framework of a lecture only class. Each project allows the student to articulate their mastery of the basic fundamentals and how those fundamentals relate to the technology. The projects have an open ended scope to them that allows the team to innovate on the ideas they learning about. The deliverables vary with the modules and include technical posters, product brochures, engineering memos, and online tutorials. They are designed to be fun and different from typical classroom assignments. A collection of homework problems and solutions have also been developed that help the students relate the fundamental material they are learning to the technology and provide foundation steps needed for the project.

The teams for the projects are assigned at the beginning of the semester. The 3-4 member teams are composed of a mix of engineering majors. As much as possible, the team members have similar, self-reported grades on their pre-requisite classes. The goal of this team make-up is to create teams where differing engineering majors bring different perspectives but similar levels of academic expertise. This hopefully minimizes the likelihood of one team member to dominate or to not contribute. At the start of the semester, the teams participate in a Materials Scavenger Hunt in the engineering building as a team building exercise.[10] Each project assignment contains suggestions on how to divide the work of the project between all the team members. Every student is given a teamwork evaluation form that has them quantitatively and qualitatively rate the performance of themselves and the other team mates. They are encouraged to fill this out over the course of the project. (Their individual grades are reduced if they do not submit a completed teamwork evaluation form with the project.) Upon completion of the project, students have the option to quit a team or fire a team member. The teams are then re-organized for the next project.

Each class period in the module has learning objectives and reading assignments the students need to do before class. The reading assignments utilize a traditional materials science text.[11] With each reading assignment, there is a list of main topics and review questions to highlight the relevant parts of the text. The students can view these online before the class period.[12]

PowerPoint lecture notes along with instructor notes have been developed. The lecture notes are structured in a clean, concise format that has been shown to improve student learning.[13] The students can view the lecture notes online.[12] The instructor notes include suggestions for demonstrations and places to utilize informal active learning in the classroom (such as surveying the students or having a quick “Pair & Share”).[2] The PowerPoint lecture notes are meant as a complement to the instructor’s own writing on the board and interaction with the class.

For each class period, there is a formal in-class exercise designed to actively engage the students through brainstorming or calculation. These exercises use 3-4 member groups based on where the students are sitting in lecture (not necessarily their project team). This group dynamic is chosen solely for the sake of organizational time. Each group is given one copy of the question. The worksheet details the role of each group member (typically a leader, recorder, and spokesperson). The exercise is designed to take about 10 minutes of class time. During that time, the instructor circulates the room answering individual group’s questions. Upon completion of the activity, groups are called on to discuss their questions and solutions. The solutions are posted online after class.[12]

Assessment Plans

To date only qualitative assessment of the modules have been carried out. Written feedback on student evaluations have indicated that, in general, most students enjoy learning about the technologies and working on the projects. Students also recognize and appreciate the fact that the fundamental material is repeated in the modules helping them see it from different perspectives and understand it at a deeper level. Negative comments indicate some students are bothered by not following the textbook order and having to learn extra material outside of the text. Extensive quantitative assessment is planned for the 2006-2007 academic year. The Materials Concept Inventory (MCI) quiz will be utilized to compare student learning of materials fundamentals before and after the modules. The MCI is a multiple choice test designed to gauge student understanding of fundamental materials concepts.[14] The impact of the modules on student's motivation to learn will be assessed with the Instructional Materials Motivation Survey (IMMS). This is a 36 item instrument in which students are asked to rate various statements regarding the instruction they have received using a Likert-type response set.[15] As a control, both surveys will also be used with class sections taught by the same instructor using a traditional class structure (not the modules).

Summary

Project based modules were developed for use in an Introduction to Materials Engineering course. The modules teach the fundamental concepts of materials science within the context of modern engineering applications. The main goals in integrating the fundamental concepts with advanced technologies is to help students see the connection between what they are learning and real world engineering issues and to motivate them to learn on their own.

To date, four lecture modules have been developed. Each is designed to take 3-5 weeks of class time. The technologies focused on the in the modules are biomaterials used in self-expanding stents, ceramic nanomaterials for solid oxide fuel cells, non-volatile memory options for portable electronic devices, and fiber reinforced plastics used in civil infrastructure. Throughout the course of each module, teams work on open ended projects that help them relate the fundamentals to the technology. The projects are used to increase student ownership and motivation in learning.

In addition to the projects, the module development includes background resources for faculty and students on the technology. This allows the modules to be taught by faculty with little or no experience in the technology area. Each class period of the module has learning objectives, a reading assignment with reading review notes, instructor notes and overheads, and active in-class exercises.

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