

AC 2007-1244: DEVELOPMENT OF A NANOTECHNOLOGY CURRICULUM AT OREGON STATE UNIVERSITY

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Development of a Nanotechnology Curriculum at Oregon State University

Abstract

There is a need to adapt engineering and science curricula to equip students with the skills and attributes needed to contribute effectively in manufacturing based processes that rely on nanotechnology. Two activities have been undertaken at Oregon State University (OSU) in support of this goal: (1) development of a Nanotechnology Processes Option in the Chemical Engineering (ChE) Department and (2) development a survey course within the College of Engineering (CoE) that is broadly available to all engineering undergraduates. The hands-on based Option is designed to allow students both to develop an in-depth understanding of how the core skills of the ChE discipline can be applied towards manufacturing of nanotechnology based products as well as to provide them with multidisciplinary experiences.

The Nanotechnology Processes Option contains six courses, five required courses and an elective. Two entirely new sophomore level courses have been developed. The Science, Engineering and Social Impact of Nanotechnology (ENGR 221) is a general engineering survey course so that students from Biological, Electrical, Environmental, Industrial, Manufacturing and Mechanical Engineering will also be exposed to the field of nanotechnology. Thus, there will inherently be a multidisciplinary approach. This course includes several features to promote active learning, including (1) hands-on activities and demonstrations, (2) the integrated use of wireless laptops through an in-house developed web-based learning tool to promote metacognition and assessment of student learning, and (3) a capstone ethics project where students complete a risk assessment of the impact of nanotechnology on society. Additionally, this course will focus on synthesizing fundamental concepts in science and engineering towards applications in nanotechnology. The other new sophomore course, Material and Energy Balances in Nanotechnology (ChE 214), is a ChE specific laboratory-based course, emphasizing how the fundamental skills students have just learned couple to nanotechnology. For ChE students, the approach is to develop a complementary experience early in their undergraduate studies. One class provides the breadth of multidisciplinary experiences while the other provides depth of specific technical applications within the discipline. These sophomore level courses lead into three upper division courses and into the senior laboratory sequence. The duality (breadth and depth) is reinforced in senior laboratory (ChE 414/415/416) where students need to synthesize both aspects in the preparation of a white paper and in their capstone project, and, in certain cases, through an Honors College thesis. The curricular development leverages the growing research and commercialization activity of the Oregon Nanoscience and Microtechnologies Institute (ONAMI). ONAMI leadership is used to facilitate input on the content of the new courses, as a resource for guest lecturers, and in assistance in the evaluation of the effectiveness of the new courses in achieving their learning outcomes.

1. Introduction

There is a substantial investment into the development of nanotechnology infrastructure for the 21st century and beyond. For example, federal US funding in nanotechnology has increased from \$116 million in 1997 to over \$1 billion in 2005. It is expected to be funded at this level or greater in 2006 and beyond.¹ Such effort will provide new commercial opportunities in existing industries as well as lead to development of new technologies. Three industrial sectors have been identified as benefiting from the growth of nanotechnology:² (1) electronic materials (e.g., integrated circuit, information storage, optoelectronics); (2) traditional chemical based industries (bulk chemicals, pharmaceuticals); and (3) newly created industries based on these technologies (MEMS, nanobiotechnology). Commensurate with this effort is a need to adapt engineering and science curricula to equip students with the skills and attributes needed to contribute effectively in manufacturing based processes that rely on nanotechnology.³⁻⁵

The incorporation of nanotechnology into the undergraduate engineering curriculum represents both an opportunity and a challenge. On the one hand, nanotechnology can revitalize undergraduate programs by engaging students with interesting nanotechnology related concepts, examples, and experiments. On the other hand, due to its inherent interdisciplinary nature, programs will need to accommodate greater degrees of interdisciplinary teaching and research. In all three industrial sectors identified above, chemical and biological processes will play a significant role in the manufacturing operations. Chemical and biological engineers have the advantage of a solid background in chemical kinetics, reactor design, transport phenomena, thermodynamics and process control to undertake the challenges in the high volume manufacturing of nanotechnology-based products. Thus, these processes fall well within the purview of chemical and biological engineering undergraduate programs. However, at the same time, the products rely on principles based on other disciplines such as physics, mechanical engineering and electrical engineering. Thus research and development of new processes based on new products is inherently interdisciplinary in nature. The curricular challenge that needs to be addressed is how to design a program that reinforces the ChE undergraduate's core skills (*Depth*) in a way that can be applied towards manufacturing nanotechnology-based products while simultaneously providing the *Breadth* to interact effectively on the multidisciplinary teams which span the wide range of opportunities enabled by this emerging area.

While there has been considerable activity developing nanotechnology related courses and learning materials,⁶⁻¹¹ there are a few examples of nano-related Option-type curricula in US ChE programs. North Carolina State University has a "NanoScience Concentration."¹² However, a closer scrutiny of the degree requirements for this Concentration shows they differ from the core ChE curriculum by two classes, both electives. The lists of electives are very similar to those one would find in the *Microelectronics Processes and Materials Science Option* at Oregon State University (OSU). Thus, this represents more a repackaging than fundamental reform towards nanotechnology education. The University of Kentucky offers a "Nanoscale Engineering Certificate Program" available from four different departments in the College of Engineering.¹³ This program requires students to take four courses in nanoscale engineering, two of which are laboratory courses. They are also expected to attend a seminar series. This program is comprehensive, hands-on, and reflects the interdisciplinary nature of nanoscale engineering. However, this program does have its limitations. It does not offer a single ChE course so the

specific background ChEs can contribute to high volume manufacturing on the nanoscale is absent. Most courses are graduate level, only available to advanced undergraduates. Additionally, the content focuses heavily on semiconductor processing. The ChE department at the University of Massachusetts, Lowell, offers a “Nanomaterials Engineering Track” in its BS degree.¹⁴ This program consists of three nano-related courses, one semester in Nanomaterials Science and Engineering and two courses in Nanomaterials Characterization. However, these courses again come in the student’s senior year, and do not have a hands-on component. The University of Southern California has recently added a nanotechnology emphasis which primarily uses a survey course on nanotechnology and an independent research project during the senior year.¹⁵

This paper presents the plan to incorporate nanotechnology education in the College of Engineering (CoE) at OSU. The approach is twofold: (1) to develop a Nanotechnology Processes *Option* in the Chemical Engineering (ChE) Department at Oregon State University (OSU) and (2) to develop a survey course within the CoE that is broadly available to all engineering undergraduates at OSU. The curricular development fits in well with the growing research and commercialization activity of the Oregon Nanoscience and Microtechnologies Institute (ONAMI), and is consistent with the evolutionary vision developed by leading chemical engineering educators in the three-workshop series “New Frontiers in Chemical Engineering Education.”¹⁶

2. Nanotechnology Option

To meet all the ABET engineering topics and advanced science requirements, ChE students are required to take five to six technical elective classes outside the ChE core. These courses may be taken in any area as long as they have the appropriate engineering or science content as prescribed by ABET and AIChE. However, taken in an *ad hoc* manner, students were getting little satisfaction or career enhancement. The ChE department has established *Options* to aid students in selection of elective courses. This also helps to broaden and strengthen the undergraduate ChE curriculum, potentially attracting more students to the department. To be eligible for an *Option*, the student must fill out and present a Student Petition for *Option* Program in Chemical Engineering to the faculty “champion” for the desired area. The champion is a faculty member with expertise in the area of the *Option*. Additionally an *Option* must contain at least 21 credits. Three options have been available at OSU: (1) Biochemical Processes; (2) Environmental Processes and (3) Microelectronics Processes and Materials Science. These areas correspond to strengths in the OSU ChE program. A fourth option, the *Nanotechnology Processes Option*, has been developed. An outline of the curricular requirements is listed in Table 1. It contains six courses, five required courses and an elective, including two sophomore level courses. Four of the five required classes are laboratory-based and emphasize hands-on experience. Institutionalization of this new curriculum in nanotechnology is realized by casting it in terms of the established *Options* programs already in place in the ChE Department. The *Nanotechnology Processes Option* was approved at the university level in Fall 2006.

The Science, Engineering and Social Impact of Nanotechnology (ENGR 221) is a general engineering survey course that provides students from Chemical, Biological, Electrical,

Environmental, Industrial, Manufacturing and Mechanical Engineering exposure to the field of nanotechnology; therefore, there is inherently a multidisciplinary approach. On the other hand, *Material and Energy Balances in Nanotechnology* (ChE 214) is a ChE specific laboratory-based course, emphasizing how the fundamental skills students have learned couple to nanotechnology. For ChE students, the approach is to develop a novel *Breadth plus Depth Pedagogy* (breadth of multidisciplinary experiences and depth of specific technical applications within the discipline) in which students have complementary experiences early in their undergraduate studies. These sophomore level courses lead into three upper division courses already in place. This duality (*Breadth plus Depth Pedagogy*) is reinforced in senior laboratory (ChE 415), through which students synthesize both aspects in their capstone project, and potentially through their Honors College thesis.

Table 1. Nanotechnology Processes Option

Class#	Credits	Title
ENGR 221	3	The Science, Engineering and Social Impact of Nanotechnology (lec)
ChE 214	4	Material and Energy Balances in Nanotechnology (lec/lab)
ChE 415	3	Chemical Engineering Lab II (lab)*
ChE 417	4	Analytical Instrumentation in Chemical, Environmental and Biological Engineering (lec/lab)
ChE 444	4	Thin Film Materials Processing (lec/lab)
	3	Elective

*The capstone laboratory project will be in the area of nanotechnology

The curricular development fits in well with the growing research and commercialization activity of ONAMI, Oregon's first "Signature Research Center". The genesis of ONAMI began in 2000 with collaborations between the Center for Microtechnology-Based Energy, Chemical and Biological Systems at Oregon State University and the Materials Science Institute and Center for Advanced Materials Characterization at the University of Oregon. The partnership expanded in 2003 with an initiative at Portland State University's Center for Emerging Technologies. Among its industrial partners includes a leading nanoelectronics facility (Intel; Hillsboro, OR), and a leading MEMS/microfluidics facility (Hewlett-Packard, Corvallis, OR), one of the first partnerships in nanoelectronics for commercializing carbon nanotubes (LSI Logic/Nantero, Gresham, OR). Together, the ONAMI partners are performing research in nanoscale metrology, transparent and printed electronics, green nanoscience and nanomanufacturing, materials characterization, bulk microfluidics for energy/chemical and medical devices, process intensification and microfabrication; and applying this research to both short- and long-term commercial opportunities ranging from computers to healthcare, and energy systems to environmental remediation. Our curricular activities form the foundation for a much-needed educational infrastructure as ONAMI grows. Additionally, ONAMI leadership provides input on course content and is a resource for guest lecturers.

It has been proposed that as the chemical engineering profession takes its next evolutionary step towards applying molecular scale engineering to a set of new and emerging technologies, the core undergraduate curriculum needs associated reform.¹⁶ However, as topics from these emerging molecular-based technologies are incorporated, there is a legitimate concern of dilution of the core content due to staffing issues.¹⁷ At OSU, the Chemical, Biological and Environmental Engineering programs have recently joined into a single administrative structure. This structure

alleviates the staffing issue in two ways. First, a significant portion of the courses for all three programs are jointly taught. This set of eleven core courses covers fundamentals germane to all three disciplines (e.g., material and energy balances, transport processes, thermodynamics and process data analysis) while reducing the number of instructors needed. Second, the four *Option* areas in chemical engineering are taken from topics that have core research faculty. In two of the *Options*, biological processes and environmental processes, students take elective classes from amongst those offered by the other programs. In this way, some of the key elements identified in the “New Frontiers in Chemical Engineering Education” workshops are integrated into the undergraduate curriculum while, simultaneously, holding students accountable for the same depth of learning which has served OSU ChE graduates for many years. Moreover, this integration is accomplished in a reasonable scope commensurate with the resources of the program.

3. ENGR 221 - *The Science, Engineering and Social Impact of Nanotechnology*

ENGR 221 has been approved at the university level and was delivered for the first time in Winter 2007 with an enrollment of 31. The course is intended to be a general engineering survey course that ensures all engineering students have access to a course offering a basic understanding of the emerging field of nanotechnology. The course learning outcomes are presented in Figure 1. The concepts of nanotechnology have been divided in several sections, with each one spanning roughly one to two weeks. The outline is presented in Figure 2. The course includes several features intended to promote active learning including (1) hands-on activities and demonstrations, (2) the integrated use of wireless laptops through an in-house developed web-based learning tool to promote metacognition and assessment of student learning, and (3) a capstone ethics project where students complete a risk assessment of the impact of nanotechnology on society. Additionally, this course focuses on synthesizing fundamental concepts in science and engineering within the context of nanotechnology.

After successful completion of this course, students become able to:

1. Define nanotechnology. Identify existing and potential products based on nanostructured materials. Predict how these products might impact society.
2. Explain how the properties of nanostructured materials are different from their non-nanostructured bulk material counterparts.
3. Describe major manufacturing methods used to produce nanostructured materials. Explain the difference in approach of top-down vs. bottom-up manufacturing methods.
4. Identify the common methods used for nanomaterial characterization. Describe the principles by which each method works and the type of information obtained.
5. Explain how the unique properties of nanomaterials might impact human health and the environment. Identify the major areas of nanotoxicity research and summarize the status of each area.
6. Compare the two prevalent ethical theories, utilitarianism and absolutism. Develop an ethical framework to assist in conducting a risk assessment.
7. Perform a risk assessment to determine the best direction for nanotechnology development.

Figure 1. Course Learning Outcomes for ENGR 221

1. Introduction	<ul style="list-style-type: none"> - Definition of nanotechnology and a review of the scale of things natural and man-made - Review of existing nanotechnology products and possible future applications of nanotechnology
2. Characterization Methods	<ul style="list-style-type: none"> - Micro-imaging methods (AFM, STM, SEM, TEM) - Composition and phase characterization (XRF, EDX, XRD, TEM/ED) Concentration adjustments and measurements
3. Unique Properties of Nanostructured Materials	<ul style="list-style-type: none"> - Blend of quantum mechanics and classic physics; the electronic structure of nanoparticles vs bulk material - The surface area of nanoparticles vs micron-sized particles
4. Manufacturing Methods for Nanomaterials	<ul style="list-style-type: none"> - Top-Down Processing Methods (Lithography, Micromachining, Beam machining and laser machining) - Bottom-Up Processing Methods (Self assembly and other Selective additive processes)
5. Nanotoxicity	<ul style="list-style-type: none"> - Review potential health and safety concerns
6. Nano-ethics	<ul style="list-style-type: none"> - Review of ethical theories: utilitarianism and absolutism - Development of an ethical framework: value inventory, ethics assessment, risk assessment - Case study on asbestos
7. Final Project: risk assessment of nanotechnology development	

Figure 2. Course outline for ENGR 221

3.1 Hands-on activities

Each week, there is a two-hour recitation section in which hands-on activities are completed. Two hands-on activities were developed at OSU, while other hands-on activities utilize educational materials that were developed by other institutions. One activity developed for this class involves scanning electron microscopy (SEM), an important characterization method in nanotechnology. During this activity the students use a FEI Phenom SEM simulator software program to view a variety of SEM samples, from mosquitoes to a crystal of salt. A screenshot of this simulation software is shown in Figure 3. The simulation was followed-up by a hands-on activity where students in the class prepare actual SEM samples of their hair, examine these samples using a FEI Phenom benchtop SEM and analyze the results.

Another hands-on activity uses ferromagnetic fluid to demonstrate the unique properties that are found at the nano-level. This activity involves the preparation of nanocrystalline mixed valence iron oxide followed by addition of an ionic surfactant to create a ferrofluid. The concepts to be synthesized through these exercises include the importance of the understanding of the structure of matter (the difference between Fe_2O_3 and Fe_3O_4) and the importance of correct stoichiometry in materials synthesis.

Hands-on activities based upon educational materials developed elsewhere were also utilized. One such activity implemented in ENGR 221 was developed by University of Wisconsin-Madison Materials Research Science and Engineering Center (MRSEC) for Nanostructured Materials and Interfaces and is used to demonstrate different nanomaterial processing methods with LEGOS.¹⁰ Another hands-on activity used a video titled “When Things Get Small”,

produced at the University of California at San Diego¹⁸, coupled with a handout developed specifically for ENGR 221. This handout includes exercises intended to help integrate previous knowledge within the context of nanotechnologies such as the estimation of the volume in nanometers and the number of atoms in a 1 inch long strand of hair; to complete this calculation, students must explicitly state their assumptions and present the answer in an appropriate format (e.g., with significant figures accurately reflecting the uncertainty associated with the various assumptions made).



Figure 3. Screenshot of the FEI Phenom SEM Simulation Program

3.2 Active learning with wireless laptops

In a further effort to promote active learning and provide opportunities for formative assessment, the Web-based Interactive Science and Engineering (WISE), was utilized. This technology-enabled learning tool was developed at OSU to utilize the CoE's Wireless Laptop Initiative which requires all undergraduate engineering students to own a wireless laptop. The WISE learning tool allows an instructor to pose to the class questions that probe for conceptual understanding and supports a variety of student response types, from multiple choice answers to short answers. Interactive applets can also be used. After the students have submitted their response, the instructor can review a summary of the results with the class. A screenshot of the results screen is shown in Figure 4. The results shown by the orange and black bar graph represent the entire classes response to the multiple choice question posed. Selected written answers can also be selected by the instructor. This specific concept quest was included in a pre-assessment quiz for ENGR 221. Active learning was promoted during the preceding class discussion of quiz answers which was intended to prime students to look for specific concepts during the rest of the term.

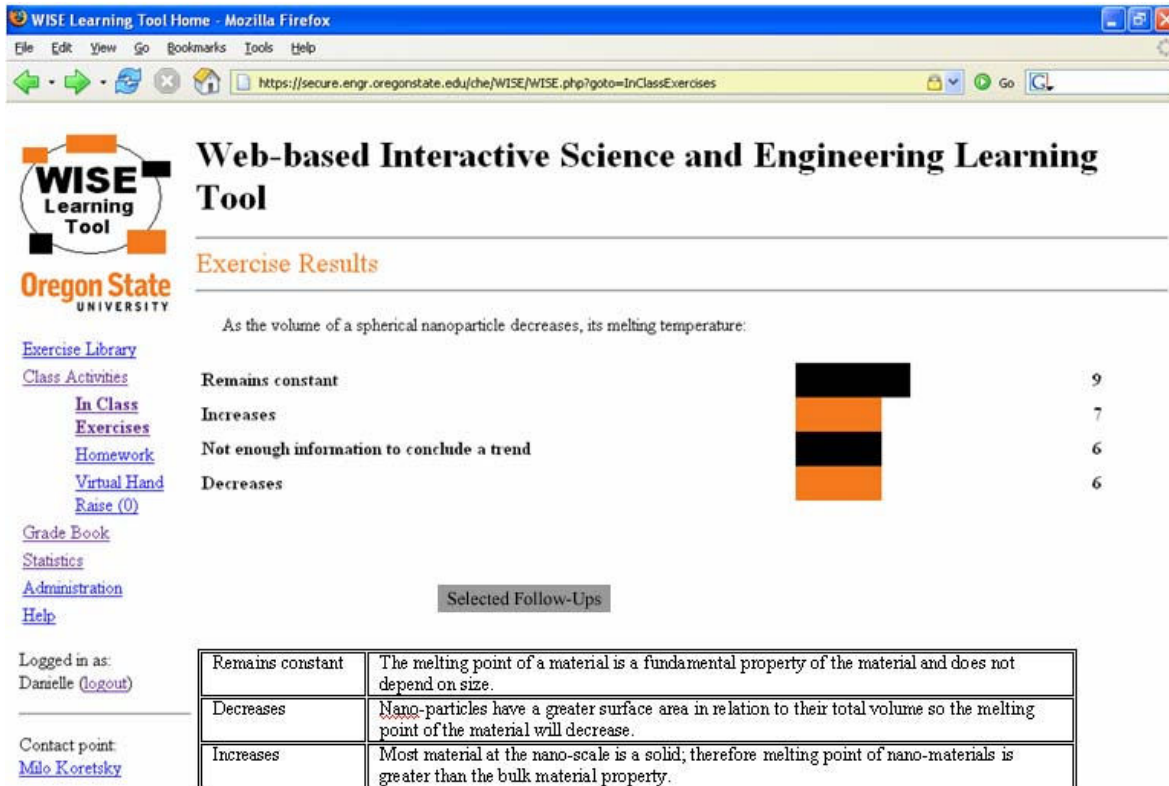


Figure 4. Screenshot from the web-based science and engineering (WISE) learning tool. The results shown by the orange and black bar graph represent the entire classes response to the multiple choice question posed.

3.3 Risk assessment project

Nanotechnology offers many exciting solutions to the challenges that face society in the 21st century. However, the potential benefits offered by this technology must be weighed against the potential impact on society, including possible health, safety and environmental risks. In an effort to engage students and promote the development of responsible and ethical nano-engineers, an ethics module was incorporated into ENGR 221. This module contained lectures that provided students with an ethical framework, including a discussion of the professional responsibility of engineers and conducting risk assessments. A case study based on the manufacture and use of asbestos was completed as a class to reflect on the impact of unethical decisions in industry. This case study led into a module covering nanotoxicity, an emerging field that is studying the potential health risks posed by nanomaterials. In conjunction with these activities, there was a term-long class assignment to view science fiction movies that show potential application of nanotechnology and write a paper that reflects on the impact that the futuristic nanotechnologies has on society. Students selected three of five pre-selected movies and had the option of viewing the movies alone, or attending a viewing of the movie on campus along with additional professors and graduate students who were not in the class. After these movie sessions, there was a discussion concerning the feasibility of the nanotechnology applications depicted in the movie, as well as the impact these applications had (or could have) on society. Combining these elements, the class culminated with a final project where each student completed a risk assessment for the responsible development of nanotechnology.

4. ChE 214 – *Material and Energy Balances in Nanotechnology*

Material and Energy Balances in Nanotechnology (ChE 214) is a ChE specific laboratory-based course, emphasizing how the fundamental skills students have just learned in the core ChE sophomore sequence apply to nanotechnology. The approach is to develop a complementary experience early in the undergraduate studies of Chemical Engineering students, providing them with depth of specific technical applications within the discipline. The course learning outcomes are presented in Figure 5. The outline is presented in Figure 6.

After successful completion of this course, students become able to:

1. Quantitatively describe the rate of reaction through real-time measurements of changes in the mass of product carbon nanotubes
2. Calculate molar and mass concentrations based on flow rates of mixture-gas components and correlate them to GC based concentrations
3. Calculate the extent of conversion based on the reactant inlet and outlet flow rates
4. Calculate product yields based on the gas-flow rates and correlate them to mass-based product yields
5. Describe the difference between endothermic and exothermic reactions based on the heats of formation of species involved in carbon nanotube synthesis reactions
6. Use temperature measurements at the reactor inlet and outlet to explain heats of reaction
7. Predict reactor outlet temperature and compare it to actual temperature measurements
8. Characterize carbon nanotubes by XRD, SEM and TEM in terms of their crystalline structures, diameters, length, and wall-layers

Figure 5. Course Learning Outcomes for ChE 214

1. Measurements of flow rate, temperature, and concentration
 - Calibration of mass-flow controllers
 - Adjustment of reactant gas concentrations based on flow-rate control
 - Concentration analysis by gas-chromatography
 - Calibration of thermocouples
2. Thermogravimetric analysis for measurements of rate of carbon nanotube synthesis in different gases (CH_4 , C_2H_4 , and C_2H_2) and concentrations
 - Concentration adjustments and measurements
 - Measurements of changes in product mass with time
 - Characterization of product carbon nanotubes (sizes, length, and wall-layers)
3. Carbon nanotube synthesis in a packed-bed reactor
 - Temperature measurements: inlet, in-the-bed, and outlet
 - Concentration measurements: inlet and outlet
 - Measurements of mass of product carbon nanotubes
 - Characterization of product carbon nanotubes (XRD, SEM, and TEM)
4. Data analysis and report
 - Engineering reporting
5. Safety consideration
 - Safety in the reactor operation
 - Safety in nano-product handling

Figure 6. Course outline for ChE 214

ChE 214, *Material and Energy Balances in Nanotechnology*, is a new, laboratory-based course β -offered in Spring 2007. It provides students with better understandings of material and energy

balances, covered in ChE 211/212, based on hands-on experience through carbon nanotube (CNT) synthesis from different carbon sources in different types of reactors. Students calibrate and measure flow rates of reactant gases, measure temperatures, analyze gas compositions, synthesize carbon nanotubes, measure the amount of product carbon nanotubes, characterize the product carbon nanotubes, and analyze data. The main laboratory equipment used is a set of TGA system and two sets of high-temperature reactors. The TGA set is rearranged so that sophomore students can use it for CNT growth experiment, measuring an increase in mass with time due to CNT growth. A 4-inch high-temperature reactor system, shown in Figure 7, capable of operating at 1400°C has been used for kinetic studies of gas-solid reactions, including fluidized-bed direct nitridation of silicon to produce silicon nitride, ammonolysis of SiO vapor for producing nano-sized silicon nitride powder, and carbon nanotube synthesis from several sources of hydrocarbons. The reactor system has been modified for easy, safe use by sophomore students, so that they can measure temperatures at several locations in the reactor as well as changes in the product gas composition between the inlet and outlet of the reactor. They also measure the mass of final product obtained after reaction operation. A 1.5-inch reactor system is also used for catalyst preparation and for testing catalyst performance in terms of product yields. A GC equipped with FID and TCD is available for in-line gas analysis for these high-temperature reactor systems.



Figure 7. High temperature reactor system for carbon nanotube growth

Operation manuals for the TGA and high-temperature reactor systems as well as a laboratory-instruction package were prepared to provide students a better understanding of what they are expected to do, what care they must take, what they are doing, and what they need to report. The facilities used for product CNT characterization are scanning electron microscopy (SEM), transmission electron microscopy (TEM), and X-ray diffraction (XRD). The compact SEM for undergraduate use has been described above. The TEM is housed at ONAMI, and a GTA is used to facilitate the use of TEM for undergraduate students. The XRD facilities are in the Chemistry Department at OSU. Prof. Yokochi, a co-PI of the NSF-funded project, has previously served as Director for the XRD facilities, and will arrange them for students' use in conjunction with *Analytical Instrumentation in Chemical, Environmental, and Biological Engineering* (ChE 417/517), a course first offered Spring 2005.

5. Senior level courses in the Nanotechnology Processes Option

Thin Film Materials Processing (ChE 444/544) was first introduced into the ChE curriculum in Fall 1994 and has been taught in every following school year. This course is well developed, but is similar to many nanotechnology-specific courses.^{19,20} Enrollment has varied between 22 to 36 senior undergraduate and graduate students enrolled from chemical engineering, chemistry, physics, and material science. The focus of this course is the application of core chemical engineering sciences (transport, kinetics, thermodynamics and reactor design) to thin film processes, one important example of which is integrated circuit technology. This approach creates a mind set in the process engineer to apply engineering skills in problem solving. It is particularly suited for the *Nanotechnology Processes Option* since it prepares students for emerging thin film technologies based on other materials.

In the lab component, students rotate through six experiments. Four core unit operations experiments, plasma etching and spin coating, silicon nitride chemical vapor deposition, silicon oxidation and copper electrodeposition. Additionally, students have a vacuum components lab and undergo a “virtual” lab based on the semiconductor device applets developed at SUNY Buffalo.²¹ In the processing labs (plasma, CVD, electrodeposition, and oxidation), students are introduced to the unit operations. For efficacy, these labs are conducted in a well-prescribed manner where the process parameters and lab procedure are given to the students. However, each group runs the process at different parameter settings, and once the entire class has rotated through a given unit operation, they are presented with the data collected from the entire class for analysis. For example, the silicon nitride chemical vapor deposition was run at three temperatures and three flow rates (NH₃ rich, stoichiometric, and NH₃ lean). Students measure growth rate, film thickness (from which they calculate density) and index of refraction for their particular run. Then they look at the entire data set of the (nine) groups in the class to explore the effect of temperature and concentration on nitride deposition. The vacuum lab gives students experience with constructing a vacuum system and shows them the basic components in any vacuum system including pumps, pressure measurement, mass flow control and different types of flanges. The virtual lab provides a workshop on carrier physics, crystal structure, and integrated circuit processing with subtractive pattern transfer. A worksheet has been developed to guide the students through the website in a directed manner and provoke connections with course content.

Analytical Instrumentation in Chemical, Environmental and Biological Engineering (ChE 417) provides a foundation in the principles of instrumental chemical analysis with a main emphasis on applications relevant to Chemical, Environmental and Biological Engineering. It was first offered in Spring 2005, and includes content relative to characterization in nanoscale systems, such as X-ray diffraction; X-ray fluorescence; optical, electron (SEM, TEM) and scanning probe microscopy (SPM: AFM, TEM). The intent is to equip students with a toolbox of instrumental techniques (understanding of analytical methods) and some of the knowledge required for determining the appropriate analytical technique to address a specific problem.

6. Capstone Project in Nanotechnology

Students who select the Nanotechnology Processes Option are required to do a nanotechnology-based capstone project, as the major project in Chemical Engineering Lab II (ChE 415). In 2005-2006 two student projects in the senior laboratory sequence related to nanotechnology were: (1) the assembly of a reactor for the production of well aligned films of carbon nanotubes using ethylene pyrolysis on iron catalysts; and (2) the study of the preparation of photovoltaic devices by spin coating nanocrystalline precursors onto polymeric substrates. The first project involved the growth of carbon nanotubes by ethylene pyrolysis and included the design and assembly of the reactor using a tube furnace. The substrates used were 1" edge Si squares cut from 6" wafers. The second project involved the preparation of photovoltaic devices by spin coating of nanostructured precursors and the study of the preparation of ITO films by spin coating onto conventional glass substrates (#1 square glass coverslips of 22mm edge) by understanding thickness and impedance resulting from spin speed and delivered solution concentration, followed by studies of the deposition of CdSe and CdTe films to complete the stack.

In 2006-2007, three student projects covered nanotechnology: (1) the assembly, testing and operation of a system designed to produce films of aligned carbon-nanotubes on a surface using pyrolysis of ethanol on molybdenum acetate (Mo_2OAc_4) based catalysts; (2) the use of diatom skeletons as masks to plasma-etch nanostructured designs onto polymeric surfaces; and (3) the production of Fe/Fe₂O₃ magnetic nanocomposites by sol-gel processing of Fe/Fe(acac)₃ precursors. Sample characterization are carried out using XRD, SEM/TEM and other spectroscopic techniques. These projects have been chosen due to the fact their wide scope can increase the probability that the student teams working on them will achieve results regardless of skill level. The process started with a request to the students to write an approximately 2000 word individual white paper on the topic to be explored, was followed by the assembly of students into teams, and continued with the actual project work. The deliverables for the capstone project include the participation in a poster session at the OSU CoE's "Engineering Week," where graduating seniors from all departments in the CoE display their senior project work, an oral presentation at an internal mini-symposium organized specifically for the purpose; and a final technical written report.

In addition to the projects, the instructors are offering a short subset of the lectures focused on a very brief survey of nanotechnology at a level appropriate for seniors, to ensure that those students that have not elected to work on a nanotechnology related project have a general understanding of nanotechnologies and their potential impacts.

7. Outreach

In addition to the integration of nanotechnology into the chemical engineering curriculum, this topic is introduced to K-12 students through existing outreach programs. One recipient of the newly developed nanotechnology modules is the Saturday Academy (SA). SA is a program that provides extracurricular enriched learning experiences to K-12 students through community professionals. During Winter 2007, a course was delivered to 10 high students through the Saturday Academy. This class used a theme of "saving the world with nanotechnology" to engage the students while they learn what nanotechnology is all about. It provided an overview

of nanotechnology applications, from the electronics industry to the medical field, and examined the potential benefits these technologies will have on our society. This class also exposed students to the potential health, safety and environmental risks posed by manufacturing on the nano-scale. Like the university level classes, the mode of delivery emphasized active learning with six hands-on activities ranging from modeling the assembly of nanomaterials using LEGOs to the manufacturing of nanoelectronics (both in a cleanroom and in a virtual fab). Students also performed a complete risk assessment where they balance the exciting opportunities offered by nanotechnology with potential risks that nanotechnology presents.

8. Assessment

In the first three months since the Nanotechnology Processes Option has been approved, three students have officially declared the option and over ten more have had serious discussions with the ChE Department Head Advisor. The assessment in this paper focuses on the delivery of ENGR 221 in Winter 2007, with an enrollment of 31 students. A pre/post assessment knowledge assessment, a survey of student perceptions of the hands-on activities and a discussion of the use of the WISE learning tool is presented.

8.1 Pre/Post Assessment

The pre and post assessment tests both consisted of twenty multiple-choice questions. These questions were designed to assess pre-existing knowledge of nanotechnology topics and to measure learning of the technical content corresponding to learning objectives 1-4. The pre-assessment was administered the second day of class via the WISE Learning Tool. The post-assessment was administered in the traditional paper and pen mode. The result of the pre and post assessment is displayed in Table 2. Student achievement of the intended learning outcomes is verified by a significant increase, about 35%, in the average class score. To validate the assessment design, the class performance on the post-assessment was compared to the performance on the midterm, which covered the same content as the post-assessment but was composed of short answer and calculation-based problems. Both of these assessments resulted in an average class score of 85%; therefore, the design of the post assessment should accurately depict student learning.

Table 2: Results from the Pre/Post Assessment

	Pre-Assessment	Post-assessment
Average Score	50.8 %	85.0 %
Standard Deviation	20.7 %	10.9 %
# of Students	31 (100% of students)	22 (82% of students)

8.2 Assessment of Hands-on Activities

The student perception of the effectiveness of the hands-on activities used in ENGR 221 was determined through completion of a questionnaire with a combination of closed-ended and open-ended responses. Specifically, the achievement of learning outcomes was determined through

Likert-scale (rating from 5, strongly agree, to 1, strongly disagree) responses; additionally, the students assigned a letter grade (A-F) to each hands-on activity. The questionnaire was completed by 22 students and the quantitative results are shown in Table 3. Each of the activities received a score of around 4, or agree, on the Likert-scale questions; this result suggests that the activities were generally perceived as beneficial. Inspection of the quantitative results and comments written by the students shows that two of the activities, ferrofluids and SEM, were the most valuable to the students in terms of learning and engagement. Both of these activities were developed specifically for use in this course. In contrast, the video, When Things Get Small, and the LEGO activity were both developed elsewhere and therefore, were not as tightly aligned with the content and audience of this class. Written comments suggested that although the students enjoyed these activities, the technical content was viewed as too simple. These activities were also used with high school students during the Saturday Academy course and were perceived to be very effective. This difference in perceived effectiveness suggests that the video and LEGO activities are better for a younger audience. These results highlight the importance of careful designing activities towards a specific audience, as well as to elicit specific learning outcomes.

Table 3: Results from the Assessment of Hands-on Activities

	Learning Outcome Likert-scale (1-5)	Grade (A-F)
When Things Get Small	4.1	B
Ferrofluid	4.5	A-
LEGO Processing	3.7	C
SEM	4.4	A-

8.3 WISE Use

WISE was used in five of the ten recitation sections in ENGR 221. Thirty-three questions were completed by the class using WISE. Question types included: multiple choice, multiple choice with short answer follow-up, and short answer. The use of WISE was limited due to some technical problems with the wireless network. One issue was that the classroom had a very low wireless signal; it was typical for one to two students to be unable to connect to the wireless network during class. In addition, some students did not own a laptop, and since they were seniors, the wireless laptop initiative did not apply to them; typically, four to five students did not have a laptop during class. These technical issues reduced the use of WISE and limited its effectiveness. However, in the same term, WISE was also used in ChE 312, *Chemical Engineering Thermodynamics*. This core class has been taught by the same instructor for 14 years. Additionally the classroom had a better connection to the wireless network and since most of the students were juniors, they were required to own laptops. The use of WISE was much more effective in this case. In the future, the technical barriers facing the use of WISE in ENGR 221 will be addressed.

9. Summary

A nanotechnology curriculum has been developed and implemented into the CoE at OSU. Chemical engineering students can choose a new Nanotechnology Processes *Option* where they learn the breadth of the field as well as how their discipline specific skills can be applied. The

Nanotechnology Processes Option culminates in an open ended senior capstone laboratory project in nanotechnology. Two entirely new, sophomore-level courses have been developed. A laboratory-based course, *Material and Energy Balances in Nanotechnology* (ChE 214), is a ChE specific laboratory-based course that promotes synthesis of fundamental concepts students have already learned and nanotechnology. Additionally, a survey course, *The Science, Engineering and Social Impact of Nanotechnology* (ENGR 221), was developed with the intent of providing an opportunity for any engineering undergraduate at OSU to learn about nanotechnology. Active learning is promoted in this course through weekly hands-on activities, interactions with a web-based learning tool and completion of a nanoethics project where the students complete a risk assessment of nanotechnology development. With a similar focus on active learning, this course was modified and delivered to high school students through the Saturday Academy.

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