Broadening the Knowledge Base of Nuclear Engineering Students: The Development of a Course in Radiation Sources and Applications

Nolan E. Hertel, Michael P. Shannon

Neely Nuclear Research Center, Georgia Institute of Technology, Atlanta, GA/
Department of Physics, United States Military Academy, West Point, NY

Abstract

Nuclear engineering curricula have undergone significant revisions over the past ten years, in response to both declining enrollments in the early 1990s and to broaden the visions of nuclear engineering students beyond nuclear power applications. The keystone of traditional nuclear engineering curricula was the need for competence in the design, modeling and operation of nuclear reactors, particularly power reactors. As the resurgence in demand for BS-level nuclear engineering graduates has indicated, this emphasis is still paramount. However, the nuclear engineering graduate of today should have a basic understanding of other opportunities and technologies to which their discipline can be applied. In 1997, in order to add a radiological engineering flavor to the nuclear engineering curriculum at the Georgia Institute of Technology, two one-quarter long courses were added to the curriculum. They were a radiation sources course and a radiation applications course. In 1999 a conversion was made to the semester system at Georgia Tech and initially two semester long courses were created, one of which was adapted from its quarter version to include some fuel cycle and nuclear chemical engineering topics. Subsequently, in 2002, the two courses were merged into a one-semester long course entitled “Radiation Sources and Applications”. The course has seen some dynamic changes over its first two years of being taught. It offers nuclear engineering undergraduate students with an overall foundation for success in many areas where radiation and nuclear physics are applied to non-power problems. This paper will discuss the development of the course, the topics covered in it, the course goals and expectations as well as the impact of the course on Georgia Tech BSNRE graduates.

Introduction

The nuclear engineering profession has undergone significant changes over the past 20 years. With a shift from full-scale development of reactor-based power plants, the focus of nuclear engineers has shifted into a broad array of nuclear-based applications. These applications range from industrial uses of radioisotopes, i.e. gauges, tools and manufacturing imaging machines to food sterilization to diagnostic and therapeutic processes used in nuclear medicine. The need for nuclear engineers to have an understanding of these applications is apparent in a 1998 report of the Nuclear Engineering Department Heads Organization entitled "Nuclear Engineering in Transition: A Vision for the 21st Century."[1] In this report, the heads of nuclear engineering departments around the country concur that nuclear science and engineering programs should continue to broaden their educational emphasis beyond just fission power to a wider range of nuclear science applications such as national defense, medical technology and health care, materials processing, advanced industrial applications and nuclear waste management and remediation.[1]

There is no question that paucity exists in the number of nuclear engineers entering the workforce. In November 2002, the American Nuclear Society published a position statement entitled "Human Capital in Nuclear Science and Technology."[2] In this statement, ANS makes it clear that "serious personnel shortages in nuclear power, nuclear medical and health applications, and research related to applications of nuclear science and technology to defense and space applications appear to be likely unless new circumstances intervene to change these trends."[2] As well, in August 2001, the Health Physics Society issued a position statement entitled "Human Capital Crisis in Radiation Safety."[3] The HPS statement contends that "a critical shortage exists in the supply of qualified radiation safety professionals throughout a broad spectrum of activities within the United States including medical practice and research, regulatory oversight, academic research, environmental protection, occupational safety, and the research and application of nuclear technologies."[3] Based on both the ANS and HPS statements, there is no question that nuclear engineering curricula must emphasize the applications of radiation science technology in addition to its traditional fission power approach.

With seemingly strategic vision and in response to the need to provide more formal instruction in non-power related nuclear applications, the Georgia Institute of Technology modified its existing nuclear engineering (BSNE) major to include a course in radiation sources and a course in radiation applications in 1997. This change allowed for graduates to be more rounded in radiological engineering. Therefore, the bachelor's degree was changed from nuclear engineering to nuclear and radiological engineering. Over the past 6 years, these courses have changed and continue to change. This paper will discuss the evolution of this change as well as the need for this type of a course in the curriculum. Finally, the current state of the course will be presented as well as recommendations for future offerings of the course.

Transformation from BSNE to BSNRE

During the winter of 1996, the Nuclear Engineering/Health Physics faculty of the George Woodruff School of Mechanical Engineering at Georgia Institute of Technology embarked upon a revision of the then existing bachelor of science in nuclear engineering degree.[4] The changes in the curriculum resulted in the development of a new bachelor's degree in nuclear and radiological engineering. This change was prompted by the then changing job market and technical needs in the nuclear industry as well as to provide graduates at the undergraduate level with great professional flexibility.[4] During this new curriculum development, the faculty used the following working definition of radiological engineering. Radiological engineering is an emerging engineering discipline that combines a broad-based knowledge of applied atomic, nuclear, and radiation physics; nuclear and radioactive materials; radiation detection; radiation dosimetry and shielding; nuclear energy production; and engineering fundamentals to

a. design and analyze radiation sources and/or detection instruments for medical, agricultural, industrial, research and environmental applications;
b. apply radiation protection engineering principles to ensure the safe uses of atomic and nuclear technology;
c. address the problems of the nuclear fuel cycle; nuclear and radioactive materials management; the production and processing of nuclear source materials and radioisotopes; materials transportation and storage; and disposal of waste materials, including assay, criticality safety, worker protection, cost, and optimization of facility management;
d. assess the environmental impact of nuclear facilities using the principles of radiological assessment.[4]

Note that the radiological engineering degree was not meant to be a degree in health physics or radiological health engineering, although it does cover those areas. The degree was intended to give graduates the ability to seek nuclear-based jobs in non-power areas. With this change came the reorganization of numerous courses, however, the greatest effect on the overall curriculum was the addition of two courses, one in radiation sources and the second in radiation applications. Additionally, in 1997, the 34 Georgia state colleges and universities, to include Georgia Tech, were still operating under the quarter system. The quarter system consisted of four quarters which broke down into 10 weeks of classes and a week of final exams. So each course, was offered during a back-to-back 10 week quarters.

NE 4315 Radiation Sources (Quarter System)

The first offering of the radiation sources course was in the fall of 1997. A big challenge in the development of the course was that no one comprehensive textbook exists that adequately covers each topic presented in the course. In order to remedy this, the students were given numerous handouts throughout the course. The handouts were lecture-based and provided the students with enough information to understand the course content. The main focus of the course was in three main areas; overview of the theory of particle accelerators, basic types of sources and the monitoring/cooling considerations in source design. This course served as prerequisite to the radiation applications course. Figure 1 shows the course description and course goals from the 1997 Georgia Tech General Catalog and Table 1 presents the breakdown of lectures for the course.[5]

Course Credit	3 Credit Hours (3 Lecture / 0 Laboratory)
Course Description	Particle Accelerators; radiation sources for applications; source design considerations
Course Goals	To provide students with an overview of the understanding of various radiation sources and the design principles for radiation sources tailored for applications.

Figure 1. NE 4315 Catalog Description

Table 1. NE 4315 Lecture Breakdown

Lecture Topic	*Number of Lectures*
Particle Accelerator Characteristics Radiation Environments Shielding	5
Neutron Sources: Radioisotope-based	1
Neutron Sources: Accelerator-based	5
Neutron Sources: Reactor-based	4
Neutron Sources: Plasma-based	1
Neutron Sources: Neutron Multipliers	1
Photon Sources	4
Electron & Beta Sources	1
Positron Sources	1
Source Cooling and Other Considerations	2
Source Monitoring and Characterization	1
Total Number of Lectures	**28**

NE 4325 Radiation Applications (Quarter System)

The first offering of the radiation applications course was in 1998. As in NE 4315, no comprehensive textbook existed, so once again students were given handouts throughout the course. The main focus of this course was in two main areas; the industrial applications of radiation and the medical applications of radiation. This course, unlike NE 4315, was a laboratory course so the focus was directed toward hands-on learning. Students were also expected to complete 4 major laboratory projects as well as perform Monte Carlo simulations and deconvolution (unfolding) simulations. Figure 2 shows the course description, goals and credit from the 1997 Georgia Tech General Catalog and Table 2 presents the breakdown of lectures for the course.[5]

Course Credit	3 Credit Hours (2 Lecture / 3 Laboratory)
Course Description	Numerical and experimental methods for the application of radiation in industry and medicine.
Course Goals	To give students background in the use of numerical and experimental methods to address industrial and medical applications of radiation technology.

Figure 2. NE 4325 Catalog Description

Table 2. NE 4325 Lecture Breakdown

Lecture Topic	*Number of Lectures*
Radiation Imaging Techniques	3
Radiation Interrogation of Materials	4
Industrial Radiation Processes	3
Radiotracers	2
Radiation Instruments	3
Medical Applications	3
Total Number of Lectures	**18**

Conversion to Semester System

In 1999, Georgia Tech converted from the quarter system to the semester system. Now instead of being able to complete courses in 10 weeks, courses took 15 weeks to complete. Once again this caused a realignment of the BSNRE curriculum which resulted in a major reshuffling of many courses in the program. Both of the previously mentioned quarter-based courses became semester-based courses which meant that there was much more time (5 additional weeks) to cover many more topics. The resulting courses, with changes, are described below.

NRE 4316 Radiation Sources and Radioactive Materials Management (Semester System)

The new course, as the title suggests, was significantly changed to include nuclear fuel cycle topics as well as various chemical engineering topics. Once again, handouts were used to cover the radiation topics, however, a text was used for the fuel cycle topics (*The Nuclear Fuel Cycle: Analysis and Management.* R.G. Cochran and N. Tsoulfanidis, American Nuclear Society, 1990). In this course, students were expected to be able to run isotope growth and depletion modeling codes in order to make fuel cycle predictions. Figure 3 shows the course description, goals and credit from the 1999 Georgia Tech General Catalog and Table 3 presents the breakdown of lectures for the course.[6]

Course Credit	3 Credit Hours (3 Lecture / 0 Laboratory)
Course Description	Radiation sources; methods of isotope build-up and depletion in nuclear systems; isotope enrichment; nuclear reactor fuel cycle; isotope trajectories; radioisotope production; high and low level radioactive waste management.
Course Goals	To provide students with necessary background to analyze isotope trajectories as well as an understanding of the nuclear reactor fuel cycle and waste management

Figure 3. NE 4316 Catalog Description

Table 3. NE 4316 Lecture Breakdown

Lecture Topic	*Number of Lectures*
Neutron Sources: Radioisotope-based	1
Neutron Sources: Accelerator-based	5
Neutron Sources: Reactor-based	4
Neutron Sources: Plasma-based	1
Neutron Sources: Neutron multipliers	2
Isotope Growth, Depletion and Decay	3
Isotope Enrichment	2
Nuclear Reactor Fuel Cycle	
Exploration, Mining and Milling	1
Uranium Enrichment Methods	1
Fuel Fabrication	1
Burn-up and In-core Fuel Management	2
Irradiated Fuel Properties	1
Reprocessing of Spent Fuel	1
Economics	1
Criticality Safety	2
Inventory Models	4
Radioisotope Production	2
High-Level Waste Management	2
Low-Level Waste Management	2
Regulatory Issues	2
Total Number of Lectures	**40**

NRE 4326 Methods for Radiation Applications (Semester System)

The course description and course goals for this course remained the same as in NE 4325. The major change in this course was that more radiation source specific topics in addition to medical and industrial applications were included. Table 4 presents the breakdown of lectures for the course.[6]

Table 4. NE 4326 Lecture Breakdown

Lecture Topic	*Number of Lectures*
Photon Sources and Uses	4
Electron and Beta Sources and Uses	2
Positron sources and Uses	2
Radiation Imaging Techniques	4
Radiation Interrogation of Materials	4
Industrial Radiation Processes	3
Radiotracers	2
Radiation Instruments	4
Medical Applications	3
Total Number of Lectures	**28**

NRE 4328 Radiation Sources and Applications (Current-course)

In 2002, after teaching a few iterations of the two semester-long courses, a decision was made to merge both courses into one, NRE 4328 Radiation Sources and Applications. The new course, which is still offered every fall to NRE students, is an evolution of the original courses taught under the quarter system (NE 4315 and NE 4325). The current course only covers radiation sources and radiation applications. The nuclear fuel cycle and waste management topics are now briefly covered since they are taught in detail in an elective course. The resulting course is one focused on the fundamentals of each type of radiation source as well as some very current and relevant applications. Furthermore, the laboratory component was removed from the course and such coverage is offered in other places in the curriculum. As in each of the other courses discussed, no one single textbook discusses all of the topics covered in the course. Therefore a large list of selected references is offered to the students on reserve in the Georgia Tech library as well as from the instructor. The three major areas of emphasis of the course are; radiation sources, nuclear fuel cycle and radiation applications. Figure 4 shows the major topical areas covered in the new course.

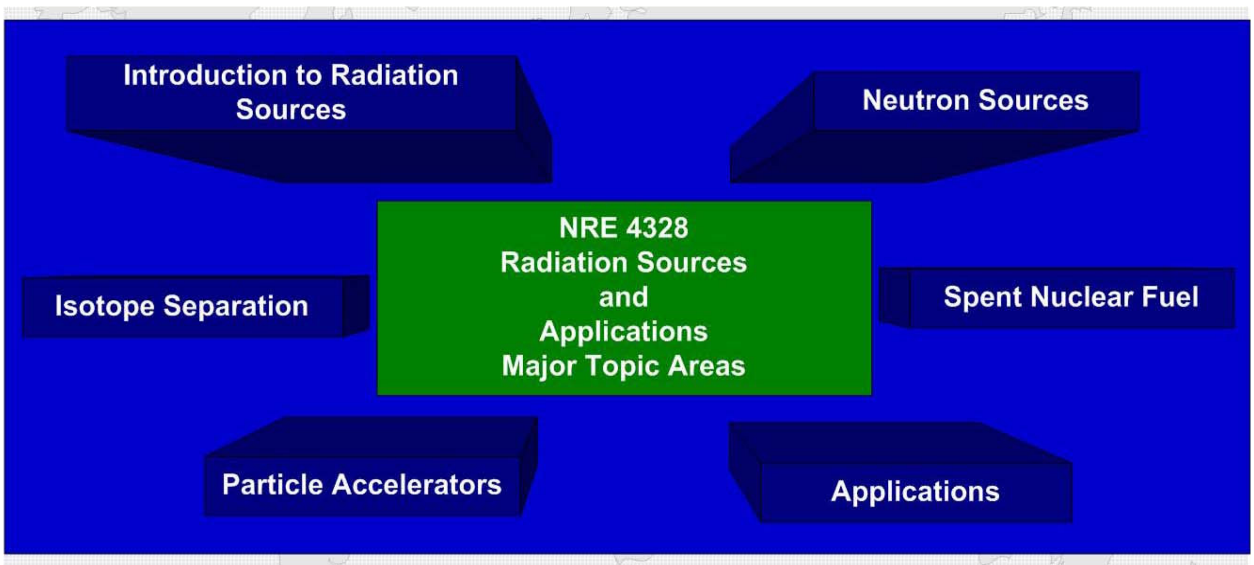

Figure 4. NRE 4328 Major Topic Areas

Within each topical area, a number of lectures are presented which expose the students to not only the practical aspects of a certain source/application but also the associated physics. The radiation sources component contains lectures in all types of radiation sources to include neutron, photon, positron and electron. The nuclear fuel component contains lectures in spent nuclear fuel and isotope separation. The applications component contains lectures in particle accelerators as well as industrial and medical applications.

During the radiation sources component of the course, students explore the physical basis of radioactive decay, transformation kinetics, constant production and shutdown, and activity. They also look at the physics peculiar to each particle type. Next, different types of sources are presented, i.e. photon sources, positron sources, etc. This is followed by a great deal of time spent on neutron sources. The students learn about spontaneous fission sources such as ^{241}Am and ^{252}Cf, as well as D-D and D-T reaction-based sources. When learning about monoenergetic neutron sources, concepts such as monchromacity, angular resolution and neutron yield are discussed. Next, deuteron and proton induced reactions are discussed as well as pulsed reactor sources where students look at nuclide filters as well as neutron choppers. The major concepts covered in the radiation sources component are shown in Figure 5.

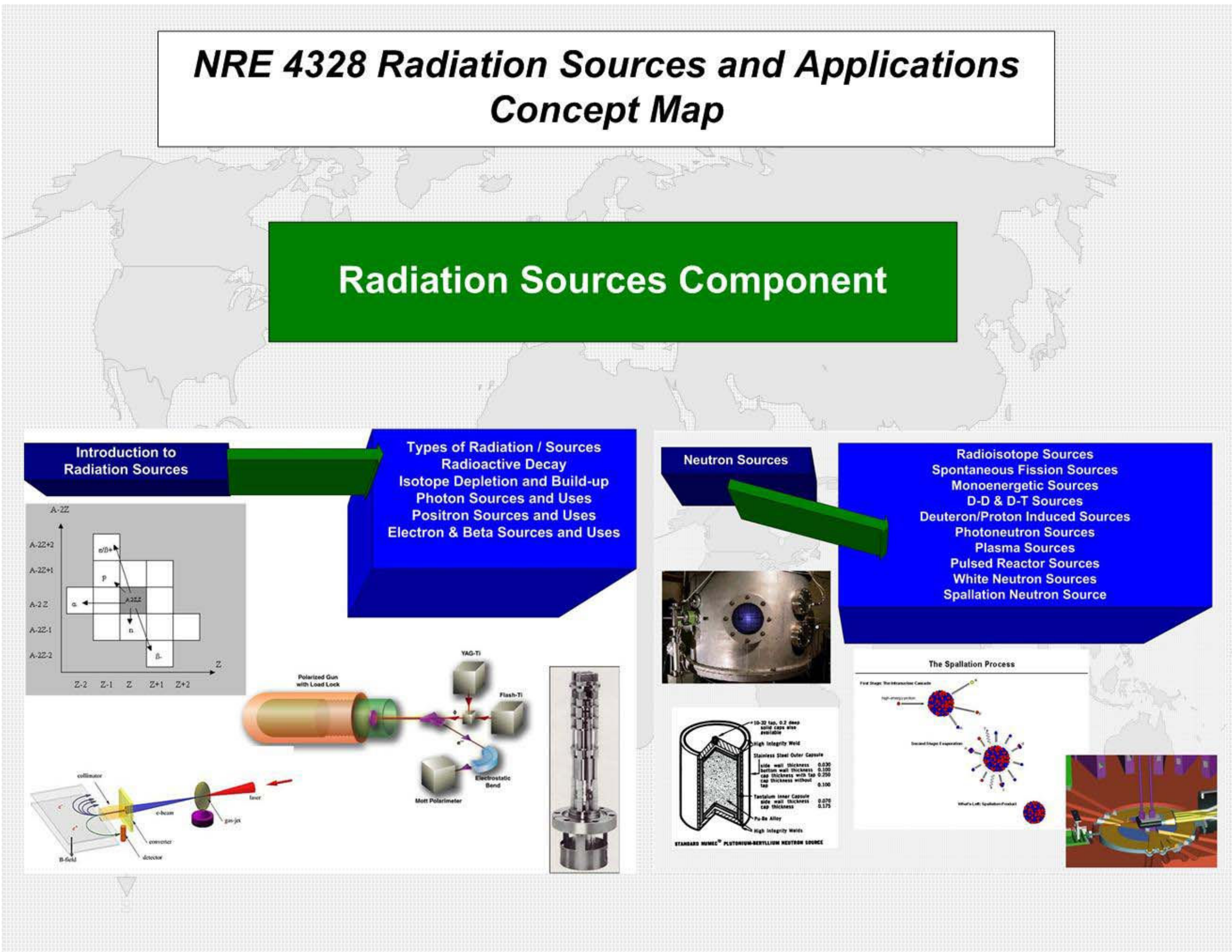

Figure 5. Radiation Sources Component

The next course component, nuclear fuel, covers a short list of concepts. Students learn about burn-up and depletion, transmutation, breeding, conversion as well as the toxicity index which is of concern in nuclear waste disposal. A lecture is also spent discussing the three major modalities of isotope separation as well as a historical perspective of the emergence of the major separation facilities during the Manhattan Project. The major concepts covered in the nuclear fuel component are shown in Figure 6.

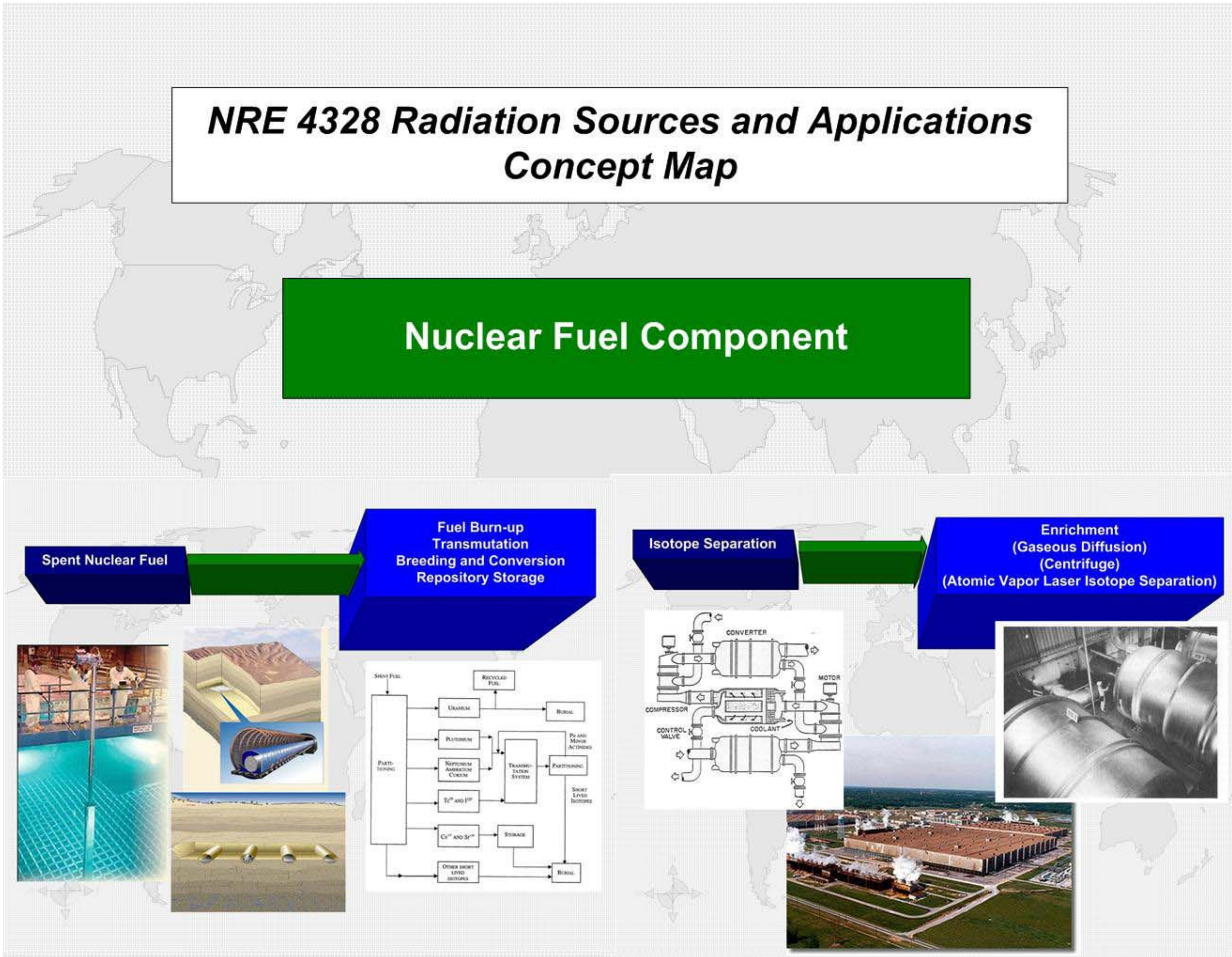

Figure 6. Nuclear Fuel Component

The remainder of the course is spent on the applications component. This component of the course evolves every time the course is offered because of the constantly changing applications of radiation science. Students spend time learning concepts such as the use of radiation in the non-destructive interrogation and assay of materials. They learn about how the use of ion implantation modifies the electrical, optical, magnetic and mechanical properties of the substrate as well as the specific application of semi-conductors development. A great deal of time is spent on radiation processing such as cross-linking and scission in electron beam accelerators as well as food sterilization. A great deal of time is also committed to the diagnostic and therapeutic uses of radiation in cancer treatment ranging from proton therapy on the eye to the use of BNCT. There are never too many topics to cover in this component. Finally, the basic physics associated with particle accelerators is presented. Students learn about the electric and magnetic fields associated with most accelerators, the challenges of building different types of accelerators as well as concerns associated with building targets (i.e. dose and heating). This set of lectures is intended to give the students an overview of how these devices work. The major concepts covered in the applications component are shown in Figure 7.

Figure 7. Applications Component

Conclusion

When one does an analysis of the types of jobs that nuclear engineers are currently performing, the need for an undergraduate course in radiation sources and applications is apparent. The nuclear and radiological engineering program at Georgia Tech has responded to this need by offering a radiation sources and applications course which is dynamic, relevant and technically rigorous. Presented in this paper is a broad overview of the approach taken to offer such a course. Although always evolving, the course is consistently a favorite among the students. This course will continue to be enhanced in order to provide our undergraduate students with the best education possible. There are two recommendations that the authors would like to make in order to improve the course; 1. In the future, we would like to cover more applications of radiation used in industries around the world. The main obstacle to overcome is finding enough data on the application in order to present a rigorous lecture to our students. The charge to the nuclear community is to continue to publish data concerning their specific application so that it can be effectively presented in the classroom; and 2. The authors would like to add a condensed design component to the course where the students work on an actual application and look at the design and economic factors influencing that specific application.

Bibliography

1. Feidberg, J., M. Kazimi, G. Emmert, W. Kastenberg, J. Poston, V. Ransome, J. Tulenko, G. Was and D. Woodall. Nuclear Engineering in Transition: A Vision for the 21st Century. Report of the Nuclear Engineering Department Heads Organization, December 1998.

2. Human Capital in Nuclear Science and Technology. Position statement of the American Nuclear Society, November 2002.

3. Human Capital Crisis in Radiation Safety. Position statement of the Health Physics Society, August 2001.

4. Hertel, Nolan E., Farzad Rahnema. Revision of Georgia Tech's BNE Degree to a BNRE Degree. *Transactions of the American Nuclear Society,* 76, 24-27, 1997.

5. Georgia Institute of Technology 1997 General Catalog. Georgia Tech, 1997.

6. Georgia Institute of Technology 1999 General Catalog. Georgia Tech, 1999.

NOLAN E. HERTEL is a professor of Nuclear and Radiological Engineering at Georgia Tech. Dr. Hertel has been actively engaged in nuclear engineering education and research as a university professor for over 24 years. His main research interests are in radiation shielding and dosimetry. He currently serves on the eight-person Joint Japanese-American Senior Review Group charged with reviewing the newly revised Japanese Atomic Bomb Survivor Study.

CPT MICHAEL SHANNON is an instructor in the Department of Physics at the United States Military Academy. CPT Shannon received an Army ROTC commission and a Bachelor of Science degree in Aerospace Engineering at Embry-Riddle Aeronautical University (ERAU) in Prescott, AZ. CPT Shannon holds a Master of Science degree in Aeronautics from ERAU as well as a Master of Science degree in Health Physics from Georgia Tech.