Lecture Notes in Energy 56

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Nuclear Batteries and Radioisotopes

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As a gesture to the fading concepts of academic integrity and excellence, the authors wish to dedicate this book to the students, alums, staff, and faculty of the Nuclear Science and Engineering Institute (NSEI) at the University of Missouri. Its history began in 1957 when the university offered its first course in nuclear engineering through the chemical engineering department. The university began hiring dedicated nuclear engineering faculty who then designed and built the University of Missouri Research Reactor. Unlike other programs of the era where the reactor remained in the nuclear engineering department, the research reactor management structure was moved to the University of Missouri System where it was a shared resource for the system's four campuses. In 1964 NSEI's first Masters of Science student graduated and the university formally established a degree program in nuclear engineering. It offered MS and PhDs in Nuclear Engineering with a traditional emphasis and a health physics emphasis. In 1980, it developed one of the first and most *prestigious nationally accredited programs in medical physics through its offering of MS and PhD degrees with medical physics emphasis. NSEI's approximately 600 alumni have served in government, the military, industry, hospitals, the health professions and academia in the US and internationally with great honor. Many NSEI alumni have walked the halls of power serving as corporate leaders, entrepreneurs, a Chairman of the Nuclear Regulatory Commission, an Assistant Secretary of Defense, Generals, academic program chairs, deans, respected faculty, medial physicists at prestigious hospitals such as MD Anderson, Washington University, and many more of the greatest hospitals in the US. A significant fraction of the PhDs awarded in the nuclear engineering community nationally graduated from NSEI and its predecessor (the nuclear engineering program at MU). This book has five authors from the last group of NSEI graduate students.*

Remember: NSEI, 1958–2012

Preface

Nuclear Batteries and Radioisotopes and its sister book, Nuclear-Pumped Lasers (published by Springer in 2016), examine the direct conversion of nuclear energy into other useful energy forms. What these two books demonstrate is that all types of nuclear energy conversion have common features. These include the principles of the interaction of ionizing radiation with matter (covered as a chapter in Nuclear-Pumped Lasers), the matching up of the range of the ionizing radiation with the scale length of the transducer, the concept of reaction rates, the concept of power density, as well as many other shared principles. Another shared commonality between the two texts is that both were originated from graduate level courses. Nuclear Batteries and Radioisotopes was developed from a graduate level course of the same title taught by Prof. Prelas during the fall semester 2015. Five of the students who participated in this course assisted in the writing of this text as authors.

Nuclear Batteries and Radioisotopes was undertaken to provide researchers and students in the field a resource which can be used as a tool to identify the critical engineering issues in nuclear battery design. This book expands upon the fundamental aspects of radiation transport and the physics of transducers. Ionizing radiation transports through matter with a characteristic scale length Called the range. Transducers also have basic scale lengths over which they absorb power and convert that power into another useful form. The matchup between the transducer scale length and the range of the ionizing radiation is one of the dominant factors in determining the system efficiency of the nuclear battery design. The complexities of nuclear battery design are difficult to comprehend even for skilled practitioners. The field seems to gain a new life and renewed interest every 20 years or so which so happens to coincide with generational changes in the scientific community. The driving force of this cycle of renewed interest is the enormity of amount of energy that is stored in radioisotopes. Often times the lessons learned from the previous cycles are lost in the enthusiasm of the current cycle. More so, it is the complex nature of the designs that make the lessons from previous works hard to interpret.

The goal of this book is to help simplify the factors which make the design of nuclear batteries so complex. In Chap. 1, the physical parameters of the radioisotope sources themselves are explored. Compounds can be formed which contain the radioisotope atoms. Chemically, there is a compound which maximizes the atomic number density of the radioisotope. This compound then has the highest possible concentration of the radioisotope and thus has the maximum thermal power density that is feasible for that radioisotope. By taking the inverse of the maximum thermal power density, the minimum volume of the compound able to produce 1 W of power can be found. This minimum volume provides the reader a feel for the scale of a device fueled by a specific radioisotope.

Chapter 2 looks at the radioisotopes and where they come from or how they can be made. There are two fundamental sources of radioisotopes: naturally occurring; and man-made. In choosing a radioisotope for a nuclear battery design, the designer will have questions. Are the isotopes readily available? How much do the isotopes cost? These two fundamental questions are addressed.

Chapter 3 focuses on the ranges of ionizing radiation in matter as well as the scale length of the transducers of interest. The scale length match up of the ionizing radiation range to the scale of the transducer is an important issue. If the matchup is poor, the efficiency of the nuclear battery will be low. The power deposition efficiency in the transducer is dependent upon the scale length matchup between the charged particles ranges and the transducer.

Chapter 4 covers the atomic dilution factor, which is the ratio of the number of radioisotope atoms in the volume of the nuclear battery versus the number of radioisotope atoms in the same volume of the compound which maximizes the atomic density of radioisotope. The way the source is interfaced with the transducer in the nuclear battery design will determine how large the dilution factor will be. A surface source interface will have large dilution factors relative to volume interfaces. However, even volume interfaces will have some level of dilution factor. The dilution factor is a measure of how much the power density in a nuclear battery will be diminished from the optimum possible value.

Transducer and system efficiency of the nuclear battery is covered in Chap. 5. Specific examples of transducers are discussed and the reader is given a methodology of making such determinations for new transducer concepts beyond those that are already known. In addition the effects of radiation damage on components of a nuclear battery are examined. The goal of this chapter is to consider the integrated nuclear battery system. A section on problems and issues in nuclear battery literature is included. The purpose of this section is to provide the reader with ability to evaluate reported systems in the literature and to develop the necessary skills to use the tools developed in prior chapters to accurately determine the validity of claims that are made.

In Chap. 6, a host of projected applications are discussed and the capability of nuclear battery systems is examined to determine the viability of batteries to meet the challenges presented by the specific applications. A brief discussion of the transition from radioisotopes to fission reactors is discussed which examines the benefits of the control of the power density which fission reactors offer.

Appendix A has valuable data on the range of ionizing radiation from viable radioisotopes that may be used for applications in nuclear batteries. The range data helps the reader understand the scale length of the ionizing radiation ranges.

Appendix B has formulas which represent the energy spectra of beta particles emitted from key radioisotopes.

Appendix C looks at advanced theoretical concepts for the purpose of presenting methodologies for the reader to be able to use the tools presented in the book to tackle never-seen-before designs and to understand the potential of the design.

The concepts from the chapters of this text demonstrate the sophistication and subtleties of nuclear battery design. There are numerous difficulties involved in integrating these concepts into a nuclear battery system and at least in part is a reason why this technology seems to be enthusiastically rediscovered every generation with high expectations solely based on the energy storage potential of radioisotopes. It is the humble hope of the authors that this text will help the reader to focus on the fundamental engineering limitations which underlie nuclear battery design and will temper expectations of the technology. It is only through a full understanding of limitations that real breakthroughs can be made.

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Chapter 1
Introduction to Nuclear Batteries and Radioisotopes

Abstract This chapter provides the reader with background and fundamental information on the subject of nuclear batteries. The approach used in this chapter is to describe the characteristics of a nuclear battery relying on easy to understand physical properties. For example, a commonly used descriptive parameter is the maximum power density. However, a more intuitive parameter is to use the inverse of maximum power density and define a quantity of minimum volume per Watt for a radioisotope volume source or minimum surface area per Watt for a radioisotope surface source. This approach gives the reader a feel for actual dimensional limitations of the technology as well as other constraints.

Keywords Energy conversion · Scaling · Surface source · Volume source · Interfaces

Nuclear batteries have long been thought of as potential long-lived small power supplies for host of critical applications. The quest for a viable nuclear battery began soon after the discovery of radiation in the early 1900s [1] and continues today because of one factor: the potential for a long battery lifetime. The reasons that a viable micro-battery has yet to materialize can be explained. This chapter introduces the reader to some fundamental concepts which will provide the foundation for understanding the difficulties in using radioisotopes with various types of nuclear battery energy conversion schemes. There are many competing types of nuclear batteries: thermoelectric, thermophotoelectric, direct charge collection, thermionic, scintillation intermediate, alphavoltaics, and betavoltaics. These battery types depend on ionizing radiation for heat production (e.g., thermoelectric, thermophotoelectric, and thermionic), for the production of ions and excited states (e.g., alphavoltaic, betavoltaic, and scintillation intermediate) or the conversion of kinetic energy into potential energy contained in electrostatic fields (e.g., direct charge collection). For the past 40 years the dominant nuclear battery technology has been the radioisotope thermoelectric generator, or RTG, which converts the decay heat of radioisotopes into electricity through the Seebeck effect [2–4]. RTGs have been deployed in numerous deep space missions [5] and their demonstrated success

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