Chapter

Introductory Chapter: The Key Role of Materials in Nuclear Technology Options and Pathways

Pavel V. Tsvetkov

1. Introduction

In this book we are focusing on a broad range of nuclear technologies. In particular, we would like to give special attention to energy systems. The feasible way to utilize nuclear energy today is via deployment of fission reactors. While fusion reactors are technically possible and their physics has been demonstrated, it will take a much longer time to bring fusion systems into the feasible and competitive energy engineering domain of commercially viable systems. However, material developments targeting performance under extreme conditions is relevant to both pathways enabling options for fission and fusion technologies. As such, this book discusses developments broadly relevant to nuclear energy systems, fission and fusion.

Materials play the key role in the nuclear energy system feasibility. So much so, they are among the key classification factors and metrics for nuclear systems:

Nuclear system type (fission or fusion)

- Purpose and functionality,
- Moderator type,
- Coolant type,
- Fuel type,
- Structural materials options,
- Neutron-energy classification,
- Core design options (homogeneous or heterogeneous, and etc.),
- Energy conversion process type and implementation options,
- Environmental interfaces.

Focusing on nuclear fission systems as the near term and already available commercial option, there are a few well-explored directions as well as emerging new technologies. Materials play the enabling role for contemporary nuclear reactors creating possibilities for extending their lifetimes. Materials are also the key factor making emerging new technologies viable. As notable examples, there are developments of paramount significance offering accident tolerant fuels and robust structural materials performing under extreme conditions due to high temperatures and high energy radiation effects.

2. Performance conditions and materials options

There are many options for material selections. The contemporary nuclear reactors utilize mostly light water (light water reactors) that is prevented from boiling (in pressurized water reactors) or allowed to boil (in boiling water reactors). All nuclear reactors utilizing water pressurize their primary system to achieve needed performance characteristics. The pressure levels range from about 6 MPa in boiling water reactors to 15 MPa in pressurized water reactors. A number of contemporary commercial nuclear reactors utilize heavy water (CANDU reactors).

The alternative options for primary coolant choices are liquid metals, such as molten sodium, and gasses, such as helium. Respectively, the reactor types are called liquid-metal-cooled reactors and gas-cooled reactors. Depending on the choice of a liquid metal, an expensive intermediate loop might be needed to isolate the working-fluid energy conversion loop from high radioactivity levels induced in the primary loop. The dramatically different option is offered by liquid salt configurations found in molten salt reactors. In all of these advanced reactor options, material interactions, compatibility, and performance in their ability to support and withstand internal conditions while offering needed characteristics are vital for successful developments towards increasing commercial feasibility levels in competition with contemporary options.

Moderators and structural materials include both solid and liquid options. Graphite, beryllium, steels, and composites are among solid form options. Light and heavy water and liquid salts are among solid form options. The choice of moderators and structural materials is driven by internal conditions and performance characteristics. Most of the time, materials are expected to remain compatible and perform under extreme conditions over prolonged periods of time.

Some material choices offer unique traits and opportunities not found in others. For example, due to characteristics of liquid metals such as high boiling points and very low vapor pressures, the pressurization is not required or very low. This is an important distinction and advantage compare to light water and gasses which do require pressurization to achieve needed performance characteristics in a system. As noted above, typical pressures in light water systems are between 6 and 15 MPa. Typical pressures in gas systems are between 4 and 7 MPa. The need to support these pressure levels poses requirements on structural materials for primary systems including vessels for components and connecting piping. Absence of the need for pressurization is a significant relaxation of the demand on materials.

Notably, liquid salts take advanced nuclear systems even further by eliminating requirements for solid structural materials to withstand prolonged direct proximity to nuclear fuel. This offers significant advantages from the system longevity point as well as from the system safety point. Molten salt reactors do require unique technologies in support of salt environments that would not be found in other nuclear reactor configurations.

3. Materials selection and the system design

The choice of materials in nuclear energy systems determines attainable neutron energies within their reactor cores. Consequently, it defines these systems as either thermal or fast nuclear reactors or systems. The contemporary nuclear fleet is predominantly composed of thermal reactors although a number of fast reactors have been built and operated over the years, several fast reactors are in operation today. Thermal reactors use water, heavy water, helium, carbon dioxide, and graphite as material options. Fast reactors use sodium, lead, and steels.

Considering the importance of fast reactors for sustainable nuclear energy future pathways, let us summarize advantages of liquid metals over other in-core material choices accounting for their heat removal capabilities:

- Liquid metals have excellent heat-transfer characteristics.
- Liquid metals are characterized by wide ranges of temperatures in which they remain in the liquid state and can offer high temperature performance matching characteristics of gas-cooled reactors.
- Liquid metals, helium, and heavy salts are the coolant types for fast reactors.
- Liquid metals have excellent resistance to nuclear radiation damage.
- Liquid metals have high thermal conductivities and low specific heats due to the temperature gradients in the coolant system to be low. Coupled with high boiling temperatures, local hot spots are inherently minimized in fast reactor configurations.

From the challenges side, liquid metals are chemically active and corrosive, requiring the use of special, and often costly, structural materials and handling technologies. Oxygen, present even in small quantities, oxidizes sodium to Na_2O, which is highly soluble in Na. It later precipitates on cold walls and causes clogging problems. The relatively high freezing point of sodium necessitates the use of electric or other heaters to keep the coolant from freezing during low-power operation or extended shutdown. In addition, liquid metals are not universally available and are costly. All of these challenges are engineering challenges. They have been overcome and resolved through the use of advanced materials designed to perform in liquid metal environment.

Gas coolants is another option for advanced nuclear reactors. Because they have very small moderation capabilities at reactor pressures, separate moderators, such as graphite or heavy water, are needed in thermal reactors. Although there have never been a gas-cooled fast reactor in operation, there are significant interests in industry to develop and deploy a number of gas-cooled fast reactor technologies. Gaseous coolants are generally available, cheap, safe, and manageable. They allow operation modes with high reactor outlet temperatures, resulting in high plant thermal efficiencies. Furthermore, gas coolants allow high-efficiency direct thermodynamic cycles. When purified, they do not present a serious activation problem. Gases, however, have poor heat-transfer characteristics and low volumetric heat capacities, and they require greater pumping powers and larger ducts than do liquid coolants. Pressurizing is necessary to reduce pumping requirements. Leak-proof systems are needed, especially for low-molecular-mass gases such as He. Because of the poor heat transfer, high fuel temperatures are required if high heat-removal rates from the reactor are to be achieved. Similar to liquid metal configurations, these challenges are engineering challenges. They have also been resolved by development and deployment of advanced materials that are suitable for gas environments.

Thus, it can be asserted that the very selection of materials and materials availability are the key factors determining nuclear reactor feasibility, both from technology side and from commercial deployment side. Fortunately, advances in materials make a wide range of nuclear reactors possible today. This book describes many key contemporary developments in nuclear materials targeting contemporary and advanced nuclear energy systems as well as outlines the enabling technologies and approaches for the future.

Author details

Pavel V. Tsvetkov
Department of Nuclear Engineering, Texas A&M University, College Station, Texas, USA

*Address all correspondence to: tsvetkov@tamu.edu