

Computational Reactors Textbook V1.0

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Computational Reactors was written to bridge the gap between computational science and reactor engineering. This textbook aims to equip readers with a thorough understanding of computational methods and their applications in reactor physics. It covers both traditional and emerging reactor technologies, providing a comprehensive guide to the modeling, simulation, and analysis of reactors. The book is intended for advanced undergraduate and graduate students, as well as professionals in nuclear engineering, physics, and related fields. By integrating theory with practical applications, the textbook addresses the complexities of reactor design, safety, and optimization.

Chapter 1: Introduction to Computational Reactors

The integration of computational modeling in reactor physics marks a transformative development in the field of nuclear engineering. By employing sophisticated computational methods, engineers and scientists can accurately simulate the behavior of nuclear reactors across a broad spectrum of operational conditions. This capability is critical for reactor design, safety analysis, performance optimization, and compliance with regulatory standards. Computational models provide invaluable insights into reactor behavior, allowing for predictions about how reactors will perform under various scenarios. This predictive power is crucial for ensuring that reactors operate efficiently and safely throughout their lifecycles.

Historically, the development of computational methods in reactor analysis began with relatively simple analytical solutions. Early nuclear reactors, which were less complex than modern designs, could be adequately modeled using straightforward mathematical equations. These early methods were sufficient for understanding basic reactor dynamics and designing early reactor prototypes. However, as nuclear technology evolved and reactors became more complex, the limitations of these simple models became apparent.

The evolution of reactor technology brought about more sophisticated designs, requiring more advanced computational approaches. The rise of digital computing significantly changed the landscape of reactor analysis. As computational power increased, it became possible to develop and employ more complex numerical models. These models could account for a wider range of variables and interactions, such as the detailed behavior of neutrons within the reactor core, the intricacies of heat transfer, and the effects of coolant flow. High-performance computing (HPC) has been a key driver in this advancement, enabling simulations that can capture the complex behaviors of modern reactors with high precision. The ability to run detailed simulations on supercomputers has revolutionized reactor design and analysis, providing deeper insights into reactor operations and improving the accuracy of predictions.

In recent years, the field of computational reactors has been characterized by several key trends. One prominent trend is the application of multiphysics simulations. These simulations integrate various physical phenomena, including neutron transport, heat transfer, and fluid dynamics, to provide a comprehensive understanding of reactor behavior. By combining these different aspects into a single simulation framework, multiphysics models offer a more holistic view of how reactors operate under different conditions. This approach is particularly useful for understanding complex interactions within the reactor core and for optimizing reactor performance.

Another significant trend is the application of machine learning (ML) techniques. Machine learning algorithms are employed to analyze large datasets generated from simulations and experimental data. These algorithms can identify patterns and make predictions that help optimize reactor performance and enhance safety. For example, ML techniques can be used to optimize reactor core configurations, predict fuel behavior, and detect anomalies or potential safety issues. By leveraging the power of data-driven analysis, machine learning is enhancing the capabilities of computational models and providing new insights into reactor operations.

The exploration of quantum computing also holds promise for the future of computational reactors. Quantum computing has the potential to solve complex problems that are currently beyond the reach of classical computing methods. For example, quantum algorithms could provide new ways to solve challenging problems in reactor physics, such as simulating neutron transport in highly complex reactor geometries or optimizing reactor designs with unprecedented precision. While quantum computing is still in its early stages, its future impact on reactor simulations could be substantial, offering new capabilities and insights that could drive further advancements in the field.

As we look to the future, the development of computational reactors will continue to be shaped by these advancements. The integration of multiphysics simulations, the application of machine learning techniques, and the exploration of quantum computing are all contributing to the evolution of reactor modeling and analysis. These advancements, combined with ongoing progress in high-performance computing and interdisciplinary research, will drive the continued improvement of reactor designs and safety practices. The future of computational reactors promises to bring even greater precision, efficiency, and safety to nuclear engineering, ensuring that reactors can meet the growing demands of energy production while adhering to the highest standards of safety and performance.

Chapter 2: Fundamentals of Reactor Physics

Neutron physics forms the cornerstone of reactor operation, as neutrons are essential for sustaining the chain reactions that generate power in nuclear reactors. At the heart of reactor physics is the neutron life cycle, which comprises three key phases: generation, moderation, and absorption. This life cycle is fundamental to understanding how reactors achieve and maintain criticality, as well as how they can be controlled and optimized.

Neutrons are produced during the fission process, where the nucleus of an atom splits into smaller nuclei, releasing a significant amount of energy along with additional neutrons. These neutrons initiate further fission reactions, creating a self-sustaining chain reaction that provides power. The fission process generates neutrons with a wide range of energies. To sustain a controlled and efficient chain reaction, these neutrons need to be moderated. Moderation involves slowing down the high-energy neutrons to thermal energies, where they are more likely to induce fission in the nuclear fuel. This is achieved using materials known as moderators, which are typically substances like water, heavy water, or graphite.

Once neutrons have been moderated, they interact with reactor materials, including the fuel, moderator, and control materials. The interactions between neutrons and these materials are crucial in shaping the reactor's operational characteristics. For instance, the fuel materials are designed to absorb neutrons and undergo fission, producing additional energy and more neutrons. The moderator's role is to ensure that neutrons are sufficiently slowed down to maintain the reaction, while the control materials, such as control rods or chemical shim systems, are used to adjust the reactivity of the reactor by absorbing neutrons and reducing the likelihood of further fission.

The design of the reactor core is a complex process that involves the strategic arrangement of these materials to achieve desired power levels while maintaining safety margins. Core design considerations include the selection of fuel types and the geometric arrangement of fuel rods within the core. The choice of fuel is critical as it affects the reactor's efficiency, safety, and operational lifespan. Fuel rods are arranged in a precise configuration to ensure a uniform distribution of power and to optimize the neutron flux within the core. Control rods, which are made from materials that absorb neutrons, are strategically positioned within the core to regulate reactivity and power output. By inserting or withdrawing control rods, operators can control the rate of the fission reaction, thus managing the reactor's power output and maintaining safe operating conditions.

The reactor core design must also account for the distribution of neutron flux, which varies throughout the core. Neutron flux distribution affects the efficiency of the fission process and the overall performance of the reactor. Additionally, the effects of fuel burnup must be considered. As the reactor operates, the fuel undergoes fission and gradually depletes. This changes the neutron economy within the core, impacting

reactivity and power distribution. Effective core design includes provisions for refueling and managing the impact of fuel burnup to ensure sustained reactor performance and safety.

Reactor kinetics and dynamics are essential for understanding the time-dependent behavior of reactors. One of the critical aspects of reactor kinetics is the role of delayed neutrons. Unlike prompt neutrons, which are emitted immediately following fission, delayed neutrons are released by fission products with a time delay. These delayed neutrons play a crucial role in reactor control because they provide a more extended time window for adjusting reactor power. Without delayed neutrons, reactors would be more challenging to control, as the response to changes in reactivity would be much quicker and less manageable.

Reactivity feedback mechanisms are integral to reactor dynamics. These mechanisms include temperature feedback, where changes in reactor temperature affect the reactivity, and power feedback, which involves changes in reactivity due to fluctuations in reactor power. For example, as the reactor heats up, the thermal expansion of the reactor materials and changes in the moderator density can affect neutron absorption and reactivity. Understanding and managing these feedback mechanisms are essential for maintaining reactor stability during transient conditions such as startup, shutdown, or load changes.

Overall, the fundamentals of reactor physics—encompassing neutron physics, core design, and reactor kinetics—provide a foundation for understanding how nuclear reactors operate. These principles guide the design, operation, and control of reactors, ensuring they operate efficiently and safely under a wide range of conditions. The careful consideration of neutron behavior, core configuration, and dynamic response is crucial for optimizing reactor performance and ensuring the safe and reliable operation of nuclear power plants.

Chapter 3: Mathematical Foundations for Computational Reactors

Partial Differential Equations (PDEs) are integral to reactor physics, providing the mathematical descriptions necessary to model the complex behavior of neutrons, heat, and fluids within a reactor core. These equations describe how physical quantities change with respect to spatial variables and time, offering insight into the dynamics of reactor operations.

One of the primary PDEs used in reactor physics is the neutron diffusion equation. This equation models the distribution of neutron flux within the reactor core, considering factors such as neutron production, absorption, and scattering. The heat conduction equation, another critical PDE, describes how heat generated by fission reactions is transferred through the reactor materials. Fluid flow within the reactor, which can affect both neutron behavior and heat transfer, is described by the Navier-Stokes equations. Each of these PDEs provides essential information about reactor behavior and is fundamental to designing and optimizing reactor systems.

To solve these PDEs, it is necessary to specify boundary and initial conditions that reflect the physical and operational environment of the reactor. Boundary conditions define the behavior of variables at the edges of the reactor or at interfaces between different materials. For instance, in neutron diffusion problems, boundary conditions might specify the neutron flux or current at the reactor's surface or at the boundary between the reactor core and the coolant. Initial conditions describe the state of the system at the start of the simulation, such as the initial distribution of temperature or neutron flux.

Given the complexity of the PDEs involved in reactor physics, analytical solutions are often impractical, necessitating the use of numerical methods to approximate solutions. Two widely employed numerical methods are the Finite Difference Method (FDM) and the Finite Element Method (FEM).

The Finite Difference Method involves discretizing the spatial domain into a grid and approximating derivatives using finite differences. This method converts the PDE into a system of algebraic equations that can be solved using standard numerical techniques. FDM is particularly useful for problems with simple geometries and boundary conditions, but its accuracy can be limited by the grid resolution and the stability of the difference schemes used.

In contrast, the Finite Element Method divides the domain into smaller, interconnected elements, applying variational methods to approximate solutions. FEM is highly versatile and can handle complex geometries and varying material properties more effectively than FDM. It is well-suited for problems involving irregular boundaries or heterogeneous materials. By applying FEM, the PDE is transformed into a system of linear equations that can be solved using various numerical techniques.

Both FDM and FEM require careful consideration to ensure convergence and stability. Convergence refers to the numerical solution approaching the exact solution as the discretization becomes finer, while stability ensures that the numerical method produces reliable results without significant errors. Techniques such as mesh refinement, time-stepping strategies, and error analysis are employed to enhance the accuracy and reliability of numerical solutions.

Linear algebra plays a crucial role in solving the large-scale systems of equations that arise in reactor modeling. Many reactor simulations involve matrices with thousands or millions of elements, making efficient solution techniques essential. Sparse matrix methods are particularly useful for handling matrices with numerous zero elements, a common feature in reactor simulations. These methods exploit the sparsity to reduce computational costs and storage requirements.

Eigenvalue problems are another critical aspect of reactor modeling, particularly in neutron flux calculations. Determining the eigenvalues and eigenvectors of large matrices is essential for understanding reactor behavior and stability. Specialized algorithms, such as the Lanczos method or the Arnoldi iteration, are used to solve these problems efficiently.

Iterative solvers are commonly employed for solving large systems of equations in reactor simulations. The Conjugate Gradient Method, for example, is an iterative technique used for solving systems of linear equations where the matrix is symmetric and positive-definite. This method is efficient for large, sparse matrices and is widely used in reactor physics simulations. Other iterative methods, such as GMRES (Generalized Minimal Residual) or BiCGSTAB (Biconjugate Gradient Stabilized), may also be used depending on the specific characteristics of the matrix and the problem at hand.

In summary, the mathematical framework and numerical methods used in reactor physics are essential for accurately modeling and analyzing reactor behavior. PDEs provide the foundational descriptions of neutron diffusion, heat conduction, and fluid flow, while numerical methods such as FDM and FEM offer practical approaches for solving these complex equations. Linear algebra techniques, including sparse matrix methods and iterative solvers, are crucial for managing the large-scale systems of equations encountered in reactor simulations. Together, these tools enable engineers and scientists to optimize reactor performance, ensure safety, and advance the field of nuclear reactor technology.

Chapter 4: Computational Methods in Reactor Physics

Neutron transport in reactors is a complex process involving the movement and interaction of neutrons with reactor materials. Understanding and predicting this behavior requires advanced computational methods. These methods can be broadly categorized into deterministic methods, stochastic methods, and hybrid methods. Each approach has its own strengths and is suitable for different aspects of reactor analysis.

Deterministic Methods

Deterministic methods solve the neutron transport equation by providing a systematic approach to model neutron behavior. These methods are characterized by their ability to provide detailed and accurate solutions for neutron flux distributions. Two key deterministic techniques are the Discrete Ordinates Method (SN) and the Method of Characteristics (MOC).

Discrete Ordinates Method (SN):

The Discrete Ordinates Method (SN) is a technique that discretizes the angular domain of neutron trajectories into a finite number of discrete directions. The neutron transport equation is solved separately for each direction, which allows for the calculation of neutron flux in various directions. This method involves several steps:

Angular Discretization: The solid angle is divided into a set of discrete directions, which can be represented by a set of ordinates. This discretization transforms the continuous angular dependence of the neutron transport equation into a finite set of discrete equations.

Spatial Discretization: The spatial domain of the reactor core is also divided into a grid, creating a finite number of spatial nodes. The neutron transport equation is then solved for each grid point in each discrete direction.

Solution of the Transport Equation: The resulting system of equations, which includes contributions from all discrete directions and spatial nodes, is solved to obtain the neutron flux distribution.

Advantages: The SN method is well-suited for problems with regular geometries and provides detailed information on neutron flux distribution. It can handle both homogeneous and heterogeneous media and is particularly effective for steady-state problems.

Method of Characteristics (MOC):

The Method of Characteristics (MOC) uses characteristic curves to trace neutron paths through the reactor. This method involves solving the neutron transport equation along these characteristic paths, which simplifies the problem by reducing the dimensionality of the equation.

Characteristic Curves: The neutron transport equation is reformulated along characteristic curves, which represent the paths that neutrons follow as they travel through the reactor core. This reformulation converts the PDE into a set of ordinary differential equations along these paths.

Numerical Solution: The solution along characteristic curves is computed, and the results are used to reconstruct the neutron flux distribution within the reactor. This approach often involves integrating along the characteristics and requires careful handling of boundary conditions.

Advantages: The MOC is particularly effective for complex geometries and can handle both spatial and angular dependencies of neutron transport. It is well-suited for problems with strong spatial variations in neutron flux.

Stochastic Methods

Stochastic methods, such as Monte Carlo simulations, use a probabilistic approach to model neutron transport. These methods are based on random sampling and are especially useful for complex geometries and materials.

Monte Carlo Simulations:

Monte Carlo methods rely on random sampling from probability distributions to simulate neutron interactions and transport. The steps involved in Monte Carlo simulations include:

Random Sampling: Neutron trajectories are simulated by randomly sampling from probability distributions that describe neutron interactions, such as scattering and absorption. This allows for the simulation of complex geometries and material compositions.

Tracking Neutrons: Neutrons are tracked as they move through the reactor core, interacting with materials and undergoing various physical processes. The simulation continues until a predefined number of neutrons have been tracked or a statistical convergence criterion is met.

Variance Reduction: Techniques such as importance sampling and biasing are used to minimize statistical variance and improve the accuracy of the simulations. These methods focus computational resources on important regions of the reactor where neutron interactions are most significant.

Parallelization: Monte Carlo simulations are often computationally intensive, and parallelization techniques are employed to distribute computations across multiple processors or computing nodes. This enhances the efficiency and speed of the simulations.

Advantages: Monte Carlo methods provide high accuracy and flexibility in modeling complex reactor geometries and materials. They are particularly useful for problems where deterministic methods are impractical due to their complexity.

Hybrid Methods

Hybrid methods combine deterministic and stochastic approaches to leverage the strengths of both techniques. These methods aim to achieve a balance between accuracy and computational efficiency by applying different methods to different parts of the problem.

Combining Deterministic and Stochastic Approaches:

Region-Based Approach: In a hybrid approach, deterministic methods may be used for regions of the reactor with relatively uniform or predictable neutron flux, while stochastic methods handle regions with complex geometries or materials. This combination allows for detailed analysis of critical areas while maintaining overall computational efficiency.

Multi-Scale Modeling: Hybrid methods can also be employed in multi-scale modeling, where deterministic methods are used for large-scale features of the reactor, and stochastic methods address fine-scale details. This approach provides a comprehensive view of reactor behavior without requiring exhaustive computations.

Advantages: Hybrid methods offer the flexibility to adapt to different problem characteristics and optimize computational resources. By combining the precision of deterministic methods with the versatility of stochastic approaches, hybrid methods provide a powerful tool for reactor analysis.

In summary, the computational methods used for neutron transport in reactors include deterministic methods such as the Discrete Ordinates Method (SN) and the Method of Characteristics (MOC), stochastic methods like Monte Carlo simulations, and hybrid methods that combine both approaches. Each method has its own strengths and is suited to different aspects of reactor analysis, allowing for accurate and efficient modeling of neutron behavior and reactor performance.

Chapter 5: Modeling Reactor Core Behavior

Core neutronics focuses on understanding power distribution, fuel burnup, and depletion within the reactor core. Accurate modeling of these aspects is crucial for predicting reactor behavior and optimizing fuel utilization. Fuel burnup refers to the gradual consumption of nuclear fuel during fission, which affects neutron flux and reactivity. Modeling these changes is essential for planning fuel replacements and managing the reactor's operational cycle.

Thermal-hydraulics examines the interaction between heat transfer and fluid flow within the reactor. Effective modeling involves analyzing how heat generated from fission reactions is transferred to the coolant and how coolant flow impacts the reactor's temperature and pressure. Integrating neutronics with thermal-hydraulics models provides a comprehensive understanding of reactor behavior, particularly during transient events like power changes or cooling system failures. This integration ensures that both thermal and neutron aspects are accurately represented.

Reactivity control methods are crucial for maintaining reactor stability and ensuring safe operation. Control rods are the primary means of regulating reactivity by being inserted or withdrawn from the reactor core. Other methods, such as boron injection or xenon oscillations, also contribute to reactivity management. Understanding these control mechanisms is essential for maintaining the desired power output and preventing uncontrolled reactions. Effective reactivity control is critical for safe and stable reactor operation throughout its lifecycle.

Chapter 6: Advanced Reactor Modeling Techniques

Multiphysics simulations represent an advanced approach that integrates various physical phenomena into a unified framework. These simulations combine neutronics with thermal-hydraulics, structural mechanics, and chemical interactions to offer a holistic view of reactor behavior. Multiphysics simulations are particularly valuable for designing advanced reactor systems and understanding complex interactions within the reactor. By integrating multiple processes, these simulations help optimize reactor performance and safety.

Uncertainty quantification is a key aspect of reactor modeling, assessing how uncertainties in model parameters impact simulation outcomes. Techniques such as sensitivity analysis and propagation of uncertainties are used to evaluate the effects of uncertainties on reactor simulations. Sensitivity analysis examines how changes in input parameters influence results, while uncertainty propagation estimates how uncertainties in input data affect the model. Managing and quantifying uncertainties allows for more informed decisions about reactor design and operation, ensuring the reliability and accuracy of simulations.

Machine learning (ML) is increasingly utilized to enhance reactor simulations. ML techniques, including regression analysis, clustering, and neural networks, are employed to predict reactor behavior, optimize design parameters, and detect anomalies. By analyzing large datasets from simulations or experimental data, ML algorithms can identify patterns and insights that improve reactor performance and safety. Applications of ML in reactor physics include predicting fuel behavior, optimizing reactor configurations, and detecting potential issues early.

Chapter 7: Case Studies and Applications

Pressurized Water Reactors (PWRs) are among the most commonly used nuclear reactors, and full-core modeling of PWRs involves simulating the entire reactor core to understand power distribution, neutron flux, and thermal-hydraulic behavior. This modeling is essential for optimizing performance, ensuring safety, and planning maintenance. Safety analysis for PWRs includes evaluating potential accident scenarios, such as loss-of-coolant accidents and control rod ejection, and implementing safety systems to mitigate risks. Case studies of PWRs illustrate the practical application of computational methods in addressing real-world challenges in reactor operation and design.

Boiling Water Reactors (BWRs) present unique modeling challenges. Full-core modeling of BWRs involves simulating the core, including steam generation and neutron flux distribution. Safety analysis for BWRs assesses the effects of changes in steam flow and coolant conditions on reactor stability. Case studies of BWRs demonstrate how computational methods are used to understand and address the specific characteristics of these reactors, such as the impact of steam voids on neutron flux and power distribution.

Advanced reactor designs, including Small Modular Reactors (SMRs) and Generation IV reactors, introduce new challenges and opportunities for computational modeling. SMRs are designed to be smaller and more flexible, making them suitable for decentralized power generation. Modeling SMRs involves simulating their unique core designs, safety features, and operational characteristics. Generation IV reactors aim to improve sustainability, safety, and efficiency, requiring advanced modeling techniques to address their innovative features, such as fast neutron spectra and closed fuel cycles. Case studies of advanced reactors highlight how computational methods are applied to emerging technologies and their potential benefits for future nuclear energy systems.

Chapter 8: Future Directions in Computational Reactor Physics

Emerging technologies in computational reactor physics include quantum computing and advanced machine learning techniques. Quantum computing holds the potential to revolutionize reactor simulations by solving complex problems that are currently intractable with classical computing methods. Quantum algorithms could provide new insights into reactor behavior and optimize designs more efficiently, potentially transforming the field of reactor physics.

Advanced machine learning techniques, such as deep learning and reinforcement learning, are also being explored to enhance reactor simulations. Deep learning models can analyze large datasets and identify complex patterns, while reinforcement learning algorithms can optimize reactor control strategies by learning from simulation data. These techniques have the potential to improve reactor performance, predict outcomes more accurately, and enhance decision-making processes.

Challenges and opportunities in computational reactor physics include managing the increasing complexity of reactor models, ensuring the accuracy of simulations, and integrating diverse physical phenomena. As reactor designs become more complex and involve multiple interacting systems, developing effective computational techniques and models becomes increasingly important. Opportunities lie in advancing computational methods, improving simulation accuracy, and exploring new technologies to address these challenges. Continued research and development in this field are crucial for advancing reactor technology and ensuring safe and efficient nuclear energy.

Chapter 9: Glossary of Terms

Absorption Cross Section: A measure of the probability that a neutron will be absorbed by a nucleus. It is used to describe the likelihood of neutron interactions with materials.

Active Core: The region of a nuclear reactor where fission reactions occur. It contains the fuel assemblies and is the primary site for neutron interactions and power generation.

Burnup: The amount of energy extracted from nuclear fuel, measured in gigawatt-days per metric ton of fuel (GWd/MTU). It indicates how much of the nuclear fuel has been consumed during reactor operation.

Control Rod: A device made of neutron-absorbing materials used to control the reactor's power output. By inserting or withdrawing control rods, operators can regulate the reactor's reactivity and maintain safe operation.

Criticality: The condition in which a nuclear reactor's chain reaction is self-sustaining. It occurs when the number of neutrons produced in each generation is equal to the number of neutrons lost, maintaining a constant power level.

Delayed Neutrons: Neutrons emitted by radioactive decay of fission products with a delay after the initial fission event. They are crucial for controlling reactor power and achieving a stable reaction.

Discontinuous Galerkin Method: A numerical technique used in computational reactor physics for solving differential equations. It is especially useful for handling complex geometries and heterogeneous materials.

Fuel Cycle: The series of processes involved in producing nuclear fuel, using it in reactors, and managing spent fuel. It includes mining, enrichment, fuel fabrication, reactor operation, and waste disposal.

Heat Transfer: The process of energy transfer from the reactor core to the coolant and then to the environment. It includes conduction, convection, and radiation mechanisms.

Keff (Effective Multiplication Factor): A parameter that indicates the neutron multiplication factor of a reactor. A Keff value of 1 signifies a critical state, while values less than or greater than 1 indicate subcritical or supercritical conditions, respectively.

Kinetics: The study of the time-dependent behavior of reactors, including how reactor power changes in response to various conditions. It involves understanding the effects of delayed neutrons and feedback mechanisms.

Latent Heat: The heat required to change the state of a substance without changing its temperature. In reactors, latent heat is associated with phase changes in coolant and fuel.

Monte Carlo Method: A stochastic technique used to solve complex problems by simulating random sampling of events. In reactor physics, it is used for neutron transport calculations and uncertainty analysis.

Neutron Flux: The rate of neutron flow through a given area, often expressed in neutrons per square centimeter per second. It provides information about the distribution of neutrons within the reactor.

Neutron Moderation: The process of slowing down fast neutrons to thermal energies through interactions with a moderator material. Moderated neutrons are more likely to induce fission in certain reactor fuels.

Power Distribution: The spatial variation of power output within the reactor core. It is influenced by fuel composition, reactor geometry, and neutron flux distribution.

Reactor Core: The central part of a nuclear reactor where the nuclear reactions take place. It contains the fuel assemblies, control rods, and other components necessary for maintaining the chain reaction.

Reactivity: A measure of the deviation of a reactor from criticality. Positive reactivity indicates that the reactor is supercritical and power is increasing, while negative reactivity indicates a subcritical state with decreasing power.

Safety Analysis: The process of evaluating potential accident scenarios and their impacts on reactor operation and safety. It involves modeling various failure modes and assessing the effectiveness of safety systems.

Sensitivity Analysis: A technique used to determine how variations in input parameters affect the outcome of a simulation. It helps identify which parameters are most critical to the accuracy and reliability of reactor models.

Thermal-Hydraulics: The study of heat transfer and fluid flow within the reactor system. It encompasses the behavior of the coolant, heat dissipation, and temperature distribution within the reactor core.

Transmutation: The process of changing one element into another through nuclear reactions. In reactors, transmutation can alter the isotopic composition of nuclear fuel and waste materials.

Uncertainty Quantification: The process of assessing and managing uncertainties in computational models and simulations. It involves evaluating how uncertainties in input data and model parameters impact simulation results.

Xenon Oscillations: Oscillations in reactor power caused by changes in xenon-135 concentration, a neutron-absorbing isotope. These oscillations can affect reactor stability and require careful management.