
CONTENTS

PREFACE	v
CHAPTER 1 ENERGY FROM NUCLEAR FISSION	1
INTRODUCTION	1
The Demand for Electric Power, 1; Primary Sources of Energy, 2	
NUCLEAR ENERGY FUNDAMENTALS	3
Atomic Structure and Isotopes, 3; Nuclear Binding Energy, 5; Nuclear Stability, 8; Radioactivity, 10; Neutron Reactions, 12	
NUCLEAR FISSION	14
The Fission Process, 14; Fission Energy, 15; Critical Mass, 18	
NUCLEAR FISSION REACTORS	19
General Features of Nuclear Reactors, 19; Reactor Types, 20; The Nuclear Fuel Cycle, 22	
HISTORY OF REACTOR DEVELOPMENT	23
Plutonium Production, 23; Reactors for Experimental Purposes, 25; Experimental Fast Reactors, 26; Reactors for Power Production, 27	
POWER REACTORS IN THE UNITED STATES	29
Introduction, 29; Pressurized-Water Reactors, 30; Boiling-Water Reactors, 31; High-Temperature Gas-Cooled Reactors, 33; Fast Breeder Reactors, 34; Nuclear Reactor Safety, 35	
CHAPTER 2 NUCLEAR REACTIONS AND RADIATIONS	38
INTRODUCTION	38
RADIOACTIVITY	38
Radioactive Nuclides, 38; Rate of Radioactive Decay, 39; Radioactive Equilibrium, 41; Radioactivity Units, 44; Gamma Rays, 46; Bremsstrahlung, 48	
INTERACTION OF ALPHA AND BETA PARTICLES WITH MATTER	48
Ionizing Radiations, 48; Absorption of Alpha Particles, 50; Absorption of Beta Particles, 52; Čerenkov Radiation, 56	

INTERACTION OF GAMMA RAYS WITH MATTER	56
Introduction, 56; Photoelectric Effect, 56; Compton Effect, 57; Pair Production, 59; Attenuation of Gamma Rays, 59; Attenuation Coefficient and Gamma-Ray Energy, 61	
INTERACTION OF NEUTRONS WITH MATTER	65
The Production of Neutrons, 65; Neutron Reactions: Absorption, 66; Radiative Capture Reactions, 68; Emission of Alpha Particles, 68; Reactions with Fast Neutrons, 69; Inelastic Scattering, 70; Elastic Scattering, 71; The Maxwell-Boltzmann Distribution, 72; Departure from Maxwellian Distribution, 74; Structural Changes Caused by Neutron Interactions, 76	
CROSS SECTIONS FOR NEUTRON REACTIONS	77
Significance of Cross sections, 77; Macroscopic Cross Section, 78; Cross-Section Determination by the Transmission Method, 80; Rates of Neutron Reactions, 81; Cross-Section Determination by Activation Method, 82; Mean Free Path, 83; Polyenergetic Neutron Systems, 84; Thermal Neutron Systems, 86	
VARIATION OF CROSS SECTIONS WITH NEUTRON ENERGY	88
Experimental Results, 88; Resonance Absorption: Theoretical Interpretation, 91; The Breit-Wigner Formula, 92; The Doppler Effect, 94; Scattering Cross Sections, 95; Cross Sections at High Neutron Energies, 98; Cross Sections for Reactor Calculations, 99; Thermal-Neutron Cross Sections, 99	
THE FISSION PROCESS	100
Mechanism of Nuclear Fission, 100; Fission Cross Sections, 103; Fission Rate and Reactor Power, 105; Fission Neutrons and Gamma Rays, 107; Prompt Neutrons, 109; Delayed Neutrons, 110; Fission Gamma Rays, 112; Fission Products, 113; Amounts and Activities of Fission Products, 116; Fission-Product Activity After Shutdown, 120; Heat Generation After Shutdown, 122	
CHAPTER 3 DIFFUSION AND SLOWING DOWN OF NEUTRONS	129
NEUTRON DIFFUSION THEORY	129
Introduction, 129; One-Speed Neutron Conservation, 130; Calculation of Neutron Leakage, 131; The Diffusion Equation, 132; The Diffusion Coefficient and Diffusion Length, 134; Solution of the Diffusion Equation: Boundary Conditions, 135; The Linear Extrapolation Distance, 136; The Diffusion Equation in Nonmultiplying Media, 138; Diffusion of One-Speed Neutrons from a Point Source, 139; Infinite Plane Source and a Medium of Finite Thickness, 141; The Thermal Diffusion Length, 144	
DIFFUSION IN MULTIPLYING SYSTEMS	148
Infinite and Effective Multiplication Factors, 148; Geometric Buckling and the Spatial Flux Distribution, 150; The Nonleakage Probability, 154; The One-Group Critical Equation for a Bare Reactor, 155	
THE SLOWING DOWN OF NEUTRONS	157
Introduction, 157; Elastic Scattering, 158; Energy Change in Scattering, 161; Empirical Scattering Law, 162; The Average Logarithmic Energy Decrement, 164; Lethargy, 165	

SLOWING DOWN IN INFINITE MEDIA	166
Neutron Moderation without Absorption, 166; Neutron Moderation with Absorption, 169; Resonance Absorption in Heterogeneous Systems, 172; The Thermalization of Neutrons, 174	
SPATIAL DISTRIBUTION OF SLOWED-DOWN NEUTRONS	175
Fermi Age (Continuous Slowing-Down) Model, 175; Solution of the Age Equation: Significance of Age, 177; Slowing Down and Migration Lengths, 180	
CRITICAL EQUATIONS BASED ON DIFFUSION THEORY	181
Two-Group Critical Equation, 181; Reflected Reactors, 186; The Four-Factor Formula, 187	
CRITICALITY MEASUREMENTS	190
The Critical Assembly, 190; The Exponential Experiment, 191; Integral Experiments, 192	
CHAPTER 4 PRINCIPLES OF REACTOR ANALYSIS	196
MULTIGROUP DIFFUSION THEORY	196
Introduction, 196; The Group Diffusion Equation, 197; Strategy for Solving Multigroup Equations, 199; Evaluation of Group Constants, 200; The Group Fission Source Term, 202; Many-Group Calculations, 204; Few-Group (Macrogroup) Constants, 206; Heterogeneous Systems, 207; Space Dependent Group Fluxes, 208; The Multiplication Eigenvalue, 211; Solving the Few-Group Diffusion Equation, 211; Simplified Diffusion Theory Approximation, 213; Fast Reactors, 214	
FUEL DEPLETION CALCULATIONS	215
General Principles, 215; Simplifying Fuel Depletion Calculations, 217; Results of Fuel Depletion Calculations, 218	
THE NEUTRON TRANSPORT EQUATION AND ITS APPROXIMATION	220
Statement of the Transport Equation, 220; Approximating the Transport Equation, 222; The Diffusion Theory Approximation, 224; The Discrete Ordinates Method, 226; The Monte Carlo Method, 226	
CHAPTER 5 NUCLEAR REACTOR KINETICS AND CONTROL	229
REACTOR KINETICS	229
Introduction, 229; Kinetic Equations of Bare Reactor: One-Group Model, 230; Prompt Neutron Lifetime, 232; Step Change in Reactivity, 233; Stable Reactor Period, 234; One Group of Delayed Neutrons, 235; One Group of Delayed Neutrons: Negative Reactivity, 240; Reactivity and Period: Positive Reactivities, 242; Reactivity and Period: Negative Reactivities, 245; The Neutron Flux after Shutdown, 246; The Inhour Formula, 247; The Prompt-Critical Condition, 248	
FISSION PRODUCT POISONING	250
Effect of Poisons on Reactivity, 250; Xenon Poisoning During Operation, 253; Xenon Poisoning After Shutdown, 256; Xenon Spatial Oscillations, 259; Samarium Poisoning, 260; Other Poisons Produced by Fission, 261	

EFFECT OF TEMPERATURE ON REACTIVITY	262
General Considerations, 262; Thermal Reactors, 263; Prompt (Fuel) Temperature Coefficient, 264; Delayed (Moderator) Temperature Coefficient, 265; Temperature Coefficients in Thermal Reactors, 267; Fast Reactors: Doppler Effect, 268; Prompt Temperature Coefficient in Fast Reactors, 269; Delayed Temperature Coefficients in Fast Reactors, 270	
REACTIVITY STABILITY ANALYSIS	270
Reactivity Feedback, 270; Laplace Transform Representation, 272; Fuel-Moderator Time Constant, 273; Transfer Functions, 275; Open-Loop Reactor Transfer Function, 278; Negative Temperature Coefficient Feedback, 281; Coolant-Loop Transfer Functions, 284; Experimental Determination of Transfer Functions, 286; Reactor Stability Conditions, 287; Reactor Simulators, 288; Large Increase in Reactivity, 289	
GENERAL FEATURES OF REACTOR CONTROL	292
Introduction, 292; Methods of Control, 293; Control Loops, 294; Effectiveness of Control Rods, 295; Control Materials, 297; Control System Functions, 299; The Water-Gap Effect, 304; Range of the Control System, 305; Control-Rod Worth Evaluation, 306; Danger Coefficient and Pile Oscillator, 308	
CONTROL IN REACTOR OPERATION	309
Control Instrumentation, 309; Production of Ion-Pairs, 309; Behavior of Ion-Pairs in an Electric Field, 310; Ionization Chambers, 313; Proportional Counters, 318; Nonionization Neutron Sensors, 319; Out-of-Core and In-Core Sensors, 321; Instrumentation Ranges in Reactor Startup, 322; Reactor Startup, 324; Normal Operation of the Reactor, 326; Reactor Shutdown, 327	
CHAPTER 6 ENERGY REMOVAL	331
INTRODUCTION	331
Thermal Problems in Reactor Design, 331; Generation and Disposal of Heat in Reactor Systems, 332; Special Thermal Problems, 333; Thermal Transport, 334; Heat-Source Distribution, 334; Thermal Design Problems, 335	
HEAT SOURCES IN REACTOR SYSTEMS	337
Fission Energy, 337; Spatial Distribution of Energy Sources in Reactor Core, 339; Average and Maximum Power in Single Fuel Channel, 340; Power and Flux Flattening, 341; Heat Generation in Moderator, 342; Heat Generation in Reflector and Shield, 342	
HEAT -TRANSMISSION PRINCIPLES	343
Introduction, 343; Conduction of Heat, 343; Convection of Heat, 344; Conduction with Convection Boundary Conditions, 346; Radiation Heat Transfer, 349; Systems with Internal Heat Sources, 350; Conduction in Irregular Geometries, 360; Transient Heat Conduction, 361; Transient Heat Transfer, 365	
HEAT TRANSFER TO ORDINARY FLUIDS	365
Introduction, 365; Laminar and Turbulent Flow, 366; Heat-Transfer Coefficients of Ordinary Fluids, 369; Heat-Transfer Coefficients of Gases, 371	

CONTENTS

xi

HEAT TRANSFER TO LIQUID METALS	371
Introduction, 371; Heat-Transfer Coefficients of Liquid Metals, 372; Eddy Conductivity and Heat Transfer, 373; Slug-Flow Approximation for Liquid Metals, 379	
BOILING HEAT TRANSFER	380
Pool Boiling, 380; Flow Boiling, 382; Boiling Crisis, 383; Prediction of Burnout Conditions, 384; Boiling Heat-Transfer Coefficients, 385	
CORE HYDRAULICS	387
Pressure Drop in Laminar Flow, 387; Pressure Drop in Turbulent Flow, 388; Velocity Head Losses, 389; Two-Phase Flow, 391; Two-Phase Pres- sure Drop, 392; Limiting Flow with Compressible Fluids, 394; Free Con- vection Cooling, 395; Pumping Power in Coolant Systems, 396	
THERMAL-HYDRAULIC ANALYSIS	398
Introduction, 398; Temperature Distribution Along Path of Reactor Coolant, 399; Subchannel Analysis, 404	
CORE DESIGN CONSTRAINTS	405
General Considerations, 405; Hot-Channel Factors, 406; Combination of Subfactors, 408; Heat Flux Peaking Factor in Pressurized-Water Reactors, 409; Enthalpy Rise Hot-Channel Factor, 410; Heat Flux Related Limita- tions in Pressurized-Water Reactors, 412; Statistical Core Design Tech- niques, 414; Boiling-Water Reactors, 416; Fast Reactors, 418	
CHAPTER 7 NONFUEL REACTOR MATERIALS	422
INTRODUCTION	422
MECHANICAL PROPERTIES OF MATERIALS	423
Stress-Strain Relationships, 423; Ductile and Brittle Behavior, 424; Ductile to Brittle Transition, 425; Fatigue Failure, 425; Creep, 427	
STRESS ANALYSIS	428
Introduction, 428; Stress Intensity, 429; Thermal Stress, 430; Thermal Stress in Hollow Cylinder with No Heat Generation, 434; Thermal Stress in Hollow Cylinder with Exponential Heat Source, 435; Factors Affecting Thermal Stress, 437	
RADIATION EFFECTS IN MATERIALS	437
General Principles, 437; Atomic Displacements, 439; Indirect Atomic Dis- placements, 442; Mechanisms of Radiation Damage, 443; General Irradia- tion Effects in Metals, 444; Temperature-Dependent Swelling, 446; Helium Embrittlement, 448; Induced Radioactivity, 448	
CORROSION OF METALS	449
Electrochemical and Chemical Corrosion, 449; Erosion and Fretting Cor- rosion, 450; Stress-Corrosion Cracking, 450; Hydrogen Embrittlement, 451; Mass-Transfer Corrosion, 451	
STRUCTURAL AND CLADDING MATERIALS	452
General Requirements, 452; Stainless Steel, 453; Low-Alloy Steels, 457; Nickel Alloys, 459; Zirconium and Its Alloys, 460	

MODERATOR AND REFLECTOR MATERIALS	465
Introduction, 465; Graphite, 465; Beryllium and Beryllium Oxide, 469; Ordinary Water, 469; Heavy Water, 470; Radiation Decomposition of Water, 471; Zirconium Hydride, 472	
CHAPTER 8 THE REACTOR FUEL SYSTEM	476
INTRODUCTION	476
The Fuel Cycle, 476	
PRODUCTION OF REACTOR FUELS	478
Sources of Uranium, 478; Uranium Milling, 479; Production of Uranium and Its Compounds, 480; Thorium, 482; Plutonium, 482	
URANIUM ISOTOPE ENRICHMENT	483
Introduction, 483; The Gaseous-Diffusion Method, 483; The Gas-Centrifuge Method, 487; Isotopic Separation Work and Costs, 490; Diffusion Plant Tails Assay, 493; Other Isotope Separation Processes, 493	
PROPERTIES OF FUEL MATERIALS	494
Introduction, 494; Uranium Metal, 496; Uranium Dioxide, 499; Uranium Carbide, 503; Uranium Nitride Fuels, 505; Dispersion Type Fuels, 505; Plutonium Fuel Materials, 506; Thorium Fuel Materials, 507	
FUEL MODELING CODES	510
Introduction, 510; Phenomenological Models, 510; Microscopic Models, 511	
REPROCESSING OF SPENT FUELS	511
Introduction, 511; Cooling of Spent Fuel, 513; Head-End Treatment, 515; Solvent-Extraction Separation Processes, 517; Other Separation Processes, 521; Radioactive Wastes from Fuel Reprocessing, 521; High-Level Waste Solidification, 522; Characteristics of Wastes, 523; Characteristics of Spent Fuel, 525; Isolation of High-Level Wastes, 526; Long-Range Disposal Con- cepts, 527	
NUCLEAR FUEL MANAGEMENT	528
Introduction, 528; Fuel Burnup, 529; Core Management, 530; Control Management, 534; Other Reactor Types, 535	
NUCLEAR FUEL UTILIZATION	535
Introduction, 535; The Conversion Ratio, 537; The Breeding Ratio, 538; The Doubling Time, 541; Plutonium Utilization, 543; Thorium Utilization, 546; Proliferation Risk and Resource Utilization, 547	
NUCLEAR ENERGY COSTS	550
Introduction, 550; Capital Costs, 550; Operation and Maintenance Costs, 552; Fuel Costs, 552; Electric Power Generation Costs, 553	
NUCLEAR MATERIALS SAFEGUARDS	553
CHAPTER 9 RADIATION PROTECTION AND ENVIRONMENTAL EFFECTS	560
RADIATION HAZARDS	560
Health-Physics Activities, 560; Effects of Different Types of Radiation, 561; External and Internal Radiation Sources, 563; Protection from Radiation Hazards, 565	

RADIATION UNITS	566
The Roentgen and the Rad, 566; Photon Flux and Radiation Dose, 567; Dose Rate and Radioactive Source Strength, 568; Radiation Dose from Internal Source, 571; The Rem, 574	
RADIATION PROTECTION STANDARDS	576
Introduction, 576; Standards for Occupationally Exposed Individuals, 577; Standards for the General Population, 579; Maximum Concentrations of Radionuclides in Air and Water, 580; Radioactivity Levels "As Low As Is Reasonably Achievable", 582; Radiation Exposure Pathways, 583	
BIOLOGICAL EFFECTS OF RADIATION	585
Introduction, 585; Somatic Effects of Radiation, 586; Genetic Effects of Radiation, 588; The Radiation Background, 589; Radiation Dose from Nuclear Power Operations, 590; Estimates of Biological Consequences, 591	
RADWASTE TREATMENT SYSTEMS	592
Sources of Discharged Radioactivity, 592; Reactor Radwaste Systems, 593; Pressurized-Water Reactors, 593; Boiling-Water Reactors, 599; Fuel Reprocessing Plant Effluents, 602	
RADIATION MONITORING	603
Introduction, 603; Personnel Monitoring, 604; General Monitoring Instruments, 610; Area Monitoring: Fixed Instruments, 612; Radiation Survey: Portable Instruments, 612; Monitoring of Coolant and Effluent Systems, 616; Environmental Radiation Monitoring, 617	
THERMAL DISCHARGE	617
Condenser Cooling Requirements, 617; General Effects of the Condenser Cooling System, 619; The Aquatic Ecosystem, 620; Effects of Temperature and Entrainment, 621; Regulation of Thermal Discharges, 622; Treatment of the Thermal Discharge, 623; Aquatic Ecological Monitoring, 625	
CHAPTER 10 NUCLEAR REACTOR SHIELDING	631
REACTOR SHIELDING PRINCIPLES	631
Introduction, 631; Shield Design, 632; Radiations from Reactor Systems, 634; Thermal and Biological Shields, 636; Reactor Shielding Requirements, 637; Shielding Materials, 640	
RADIATION ATTENUATION CALCULATIONS	643
The Point-Kernel Technique, 643; Radiation Attenuation from a Uniform Plane Source, 644; The Exponential Point Kernel, 645; Buildup Factors, 647; Radiation Attenuation from a Line Source, 651; Radiation Attenuation from a Plane Source, 653; Volume-Distributed Source with Self Absorption, 655; Polyenergetic Gamma-Ray Sources, 658; Neutron Removal Cross Sections, 659; The Relaxation Length, 662	
REACTOR SHIELD ANALYSIS	663
Introduction, 663; Comparison of the Transport Problems in Core and Shield, 664; Simplifications in Shield Analysis, 665; General Approaches to Shield Analysis, 665; Secondary Gamma Rays, 667; Ducts and Voids, 670; Experimental Measurements, 672; Shielding Calculation Results, 673	

HEATING IN SHIELDS	673
Introduction, 673; Heating by Gamma Rays, 676; Heating by Neutrons, 678	
CHAPTER 11 NUCLEAR REACTOR SAFETY	683
GENERAL PRINCIPLES OF REACTOR SAFETY	683
Introduction, 683; Defense in Depth, 684; Inherent Reactor Stability, 685; Quality Assurance: Codes and Standards, 685; Redundancy and Diversity, 686; Barriers to the Escape of Radioactivity, 686	
REACTOR PROTECTION SYSTEM	687
General Description, 687; Reactor Trip Signals, 688; Shutdown Cooling, 689	
ENGINEERED SAFETY FEATURES	690
Introduction, 690; The Emergency Core-Cooling System, 690; Containment Systems, 693	
REACTOR SAFETY ANALYSIS	698
Categories of Abnormal Events, 698; Events of Moderate Frequency, 699; Events of Low Probability, 701; Design Basis Accidents, 703; Loss-of-Coolant Accident, 705; Emergency Core Cooling Criteria, 708; Thermal-Hydraulic Calculations, 710; Radiological Criteria of Site Acceptability, 714; Radiation Dose Calculations, 715	
RELIABILITY AND RISK ASSESSMENT	720
Fault Tree Analysis, 720; Quantitative Fault Tree Analysis, 722; Event Trees, 723	
PROBABILITIES AND CONSEQUENCES OF CLASS 9 ACCIDENTS	724
Introduction, 724; Core Meltdown Phenomena, 725; Modes of Containment Failure, 725; Accident Risk Assessment, 726; Health Effects and Probabilities, 728	
LICENSING AND REGULATION OF NUCLEAR PLANTS	729
Introduction, 729; Application for a Construction Permit, 729; Evaluation of the Safety Analysis Report, 731; Evaluation of the Environmental Report, 731; Public Hearings on Construction Permit, 731; Review of Construction Permit Decision, 732; Modification of Construction Permit Applications, 732; Application for an Operating License, 733; Technical Specifications, 734; Regulation of Plant Operation, 735	
NUCLEAR REACTOR SAFEGUARDS	735
Introduction, 735; Protection Against Sabotage, 736	
CHAPTER 12 POWER REACTOR SYSTEMS	740
INTRODUCTION	740
PRESSURIZED-WATER REACTORS	740
Typical Design Specifications, 740; Core and Reactor Vessel, 741; Control and Safety Systems, 744; Steam-Generating Systems, 745	
BOILING-WATER REACTORS	748
Typical Design Specifications, 748; Core and Vessel, 748; Coolant Recirculation System, 751; Control System, 751; Feedwater Temperature and Fuel Cycle Length, 753	

CONTENTS

xv

HEAVY-WATER MODERATED REACTORS	754
Introduction, 754; Design Specifications and Core Features, 754; Heat Removal, 757; Control System, 758; Safety Features, 758	
FAST BREEDER REACTORS	759
Introduction, 759; General Features, 759; Design Specifications, 760; The Reactor Core, 761; Control System, 762; Coolant Systems, 762; Steam Generators, 763; Fast Reactor Safety, 763; Severe Accidents of Very Low Probability, 765	
GAS-COOLED REACTORS	766
Introduction, 766; High-Temperature Gas-Cooled Reactors, 766; Gas-Cooled Fast Reactors, 769	
OTHER REACTOR TYPES	770
Light-Water Breeder Reactors, 770; Molten-Salt Breeder Reactors, 771; Pressure-Tube Reactors, 773	
APPENDIX	777
INDEX	791