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THE CURRICULUM OF THE OAK RIDGE SCHOOL OF REACTOR TECHNOLOGY

by

L. G. Alexander, R. K. Osborn, M. E. Whatley, W. O. Harms,
R. W. Peelle, C. S. Walker, and R. J. Carter

Oak Ridge National Laboratory

Abstract

The ORSORT curriculum, as it has evolved in six years under the direction of Dr. F. C. VonderLage, comprises courses in Reactor Analysis, Engineering, Materials, Chemical Technology, Shielding and Health Physics, Control and Instrumentation, Systems, Component Design and Special Topics, Reactor Physics Laboratory, and Project (group theses). The lecture courses are discussed from the standpoint of objectives, content, administration, and texts. Detailed outlines are given.

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THE ORSORT CURRICULUM

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It should be emphasized at the outset that nuclear engineering at present consists more of art than it does of science. Although a vast amount of theoretical and experimental work has been reported in the secret and open literature, this material has not been digested and organized around some conceptual framework in the way comparable material has been organized in conventional branches of engineering. A pattern is beginning to emerge, especially in the work of Stuart McLain⁽¹⁾, Samuel Glasstone⁽²⁾, and in the Reactor Handbook⁽³⁾, but much remains to be done, particularly on those topics dealing with the operational characteristics of reactors. It is, at present, difficult to generalize because nearly every reactor is in a class by itself, and there are so many types existing and proposed. The situation is similar to that which existed in the automobile industry in the early days when electric motors, steam engines, and internal combustion engines competed.

The ORSORT curriculum is the product of six years of development under the leadership of F. C. VonderLage. It is still undergoing change in order to better fulfill its objectives and boundary conditions, which are subject to change themselves. The primary objective of the ORSORT program is to produce graduates broadly trained in all phases of nuclear science and engineering. Lecture, laboratory, and thesis courses are offered. The laboratory and thesis courses will be described in other papers in this series; this paper deals with lecture courses.

At ORSORT, the general field of nuclear engineering is divided among several courses. There are separate courses in nuclear physics, reactor analysis, shielding, reactor control and instrumentation, reactor materials, and chemical technology. The art of reactor design is treated by implication in two courses; one dealing with the design of reactor components, and the other consisting of detailed descriptions and analyses of existing and building reactors. Mathematical methods involved in the thermal design of reactor cores is treated in still another course.

Classroom instruction is conducted in traditional university style, with two semesters of 18 weeks each. There are three 60-minute lectures per morning, Monday through Friday. Afternoons are devoted to laboratory, plant inspection

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trips, recitations, and study. The students are required to submit homework problems and laboratory reports. Tests and examinations are administered at appropriate times. The work of each student is carefully corrected and evaluated, and marks from A through F are awarded with approximately the normal distribution.

The prerequisites for admission to ORSORT are a bachelor's degree in mathematics, science, or engineering from an accredited school, and the equivalent of at least three semester hours of differential equations.

Lecture Courses

The number, names, duration, and content of the various lecture courses has varied each year since the inception of ORSORT. In the 1955-56 session just completed, the following courses were offered:

- Reactor Analysis and Nuclear Physics (180 hours)
- Reactor Engineering (108 hours)
- Reactor Materials (72 hours)
- Reactor Chemical Technology (54 hours)
- Reactor Shielding and Health Physics (36 hours)
- Reactor Control and Instrumentation (14 hours)
- Reactor Systems and Related Topics (40 hours)
- Reactor Component Design and Special Topics (36 hours)

Topic outlines of each of these courses are given in the Appendix. Outlines of each of these courses as given in the 1954-55 session will be found in a document entitled, "Course Outlines and Engineering Problems"⁽⁴⁾.

Reactor Analysis and Nuclear Physics

The primary objective of the Reactor Analysis course is to provide the student with a comprehensive qualitative understanding of the conditions required to initiate and control a self-sustaining, nuclear fission, chain reaction. The secondary objective is to enable the student to acquire facility in the employment of those mathematical techniques required for the formulation and quantitative solution of problems in reactor design.

The average student is barely qualified to take the course. It would be extremely desirable if all students were proficient in vector algebra, boundary value problems, probability theory, and infinite series.

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The subject matter is entirely unclassified. For text, "The Elements of Nuclear Reactor Theory", by S. Glasstone and M. Edlund⁽⁵⁾ is used, and "Notes on Reactor Analysis" by D. K. Holmes and R. V. Meghreblian⁽⁶⁾ is used for reference. The latter document was written during the 1953-54 and the 1954-55 sessions when the authors were, themselves, teaching the course.

Although beginning with elementary treatments, the instruction is carried forward to a level appropriate to an advanced course in theoretical physics; and while the course was not specifically designed to prepare the students for research in the field of reactor analysis, many ORSORT graduates have entered the field, and are making valuable contributions.

Reactor Engineering

The Reactor Engineering course was designed to instruct the students in those methods of calculating fluid flow, heat transfer, and thermal stress applicable to nuclear reactors, especially those not found in conventional engineering practice, and to illustrate the use of such techniques, and conventional techniques where applicable, in feasibility and economic evaluations of proposed reactor systems. It is possible to avoid almost entirely the use of classified material.

With few exceptions, attention is limited to engineering analysis and design of reactor components. Certain auxiliary components, such as heat exchangers, vapor separators, etc., which are treated in the conventional literature, are included because they are integral parts of the reactor system, and analysis cannot proceed without taking them into account.

Because of the diversity of backgrounds found among ORSORT students, and the absence of prerequisites for the engineering course, it is necessary to begin each topic with definitions and elementary relations. Introductory material, limited to that required as a basis for the advanced treatment, is presented to the students in unclassified lecture notes entitled, "Introduction to Fluid Flow and Heat Transfer for Reactor Engineers"⁽¹³⁾.

References used were Vol. 2 of the Reactor Handbook⁽³⁾, "Elements of Nuclear Engineering," by Samuel Glasstone and others⁽²⁾, "Conduction Heat Transfer" by P. J. Schneider⁽⁷⁾, and "Stress Analysis for ORSORT Students" by C. O. Smith of Oak Ridge National Laboratory⁽⁸⁾.

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It is believed that non-engineers achieve, in the engineering course, an understanding of the problems involved in thermal design of reactors and the limitations imposed by the thermal requirements on other aspects of reactor design. Students qualified as design engineers before entering ORSORT become competent to design reactor cores in detail sufficient for preliminary feasibility studies. No attempt is made to produce graduates qualified to perform engineering research and development in the nuclear field. However, many graduates already qualified for research and development by their previous training have undertaken research in the field of nuclear engineering with good success.

It would be extremely desirable for all the students entering ORSORT to have had elementary courses in fluid flow, heat transfer, stress analysis, engineering thermodynamics, vector analysis and engineering design. Introductory material could be eliminated from the ORSORT engineering course, and many more examples of application of engineering calculations to reactor systems could be explored.

It would be possible to produce graduates at the research and development level in one year only if the students were required to have had advanced courses in fluid flow and heat transfer, and a good course in advanced mathematics for engineers. In addition, it would probably also be necessary to have at ORSORT an engineering laboratory course, utilizing a reactor of low but appreciable power output, to accompany the lecture course.

Of the topics listed in the outline, only Heat Generation (Topic V) was unfamiliar to all the students. This topic has grown from a half-dozen lectures in the 1953-54 session to 25 in the most recent session. It shows great potential and pressing need for further development, both in theoretical and experimental. Also needing development are the subjects of transient behavior, breeding, and economic evaluation.

Guest lecturers and their topics included H. F. Poppendiek on forced convection in volume heat generation systems, P. C. Zmola on boiling heat transfer and boiling reactors, and Melvin Tobias on breeding systems.

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Reactor Chemical Technology

The Chemical Technology course has the major purpose of giving the student an understanding of the problems of processing spent reactor fuel as a basis for considering the chemical processing aspects of the design of a reactor complex. It is hoped the student will develop a feel for the chemical problems that arise in the reactor itself as a result of the presence of ionizing radiation, transmutation products, and the use of unusual materials and extreme conditions.

Also treated, though less intensively, are the production of fissionable materials, the separation of isotopes, and the methods of continuously processing fluid fuels.

It is assumed that the student has had little more than first-year chemistry, and that the subject is no longer fresh in his mind. It is deemed necessary to review the pertinent chemical and chemical engineering fundamentals as each specific application is covered. The presentation is made on a quantitative level sufficient only to assure an understanding of the principals involved.

Some half-dozen documents compiled, edited, or written by Sigfred Peterson were used for text material⁽⁹⁾. Many of these are classified.

Reactor Materials

The selection and development of suitable materials is one of the most difficult problems in the field of nuclear reactor technology. In fact, the materials problem is regarded by many reactor designers as the major limiting factor on progress in this field. A knowledge of materials--their applications and limitations--is indispensable to nuclear reactor design in regard to the selection of structural and operational components, as well as heat transfer, economics of power, and reactor reliability studies.

The purpose of the course in Materials in the Oak Ridge School of Reactor Technology is threefold: To acquaint the students with the requirements of nuclear reactor materials; to provide a basic understanding of the properties and behavior of materials suitable for use in nuclear reactors and of the methods used in their fabrication; and to describe the methods which have been or are being used and the basic principals involved in the solution of nuclear

reactor materials problems.

It is felt that the most expedient method by which reactor engineers can become adept at intelligently selecting materials and evaluating materials problems is by learning the basic principles of physical and extractive metallurgy and ceramics. It is recognized, of course, that a reactor engineer's training also should include a description of the various materials-testing methods, references to commercial alloys and their trade designations, and, in general, a familiarization with the materials terminology.

The course is arranged so that in no case will a student be thrown into a special topic without having been provided with an adequate background in the principals involved. For example, the subject of stainless steels is considered after a study of the effects of alloying elements on the behavior of steel, and in turn, is followed by a discussion of nickel base alloys.

Lectures devoted to specific reactor materials are presented in the form of reviews and summaries of behavior and properties, since the basic principals involved are treated in the introductory lectures. Guest lectures, by practicing engineers, on the materials considerations which have affected the design of actual nuclear reactors are included to prepare the students for the design problems which they undertake following their formal coursework.

The texts for the course are "Basic Engineering Metallurgy" by C. K. Keyser⁽¹⁾ and Vol. 3 of the Reactor Handbook⁽¹¹⁾.

Reactor Shielding and Health Physics

The shielding course was designed to impart an appreciation of, and respect for, the biological effects of reactor radiations, a knowledge of the significant sources of radiation in reactors, an understanding of the microscopic processes responsible for the attenuation of radiations, an insight into the principal analytic methods of shield design, and experience in the design of simple shields. In general, attention is confined to basic principles. Problems in shield optimization and shield design for special applications are left to guest speakers in the Reactor Component Design and Reactor Systems courses.

Reactor Controls

The Reactor Control course was designed to acquaint the students with some of the elementary considerations involved in the conception and design of control systems for nuclear reactors. First, the transient behavior of reactors is analyzed. Second, the construction and operation of the instruments used to measure nuclear performance of reactors are described. Third, the problem of designing control equipment and control systems is analyzed and illustrations from existing reactors are given. Finally, the problem of providing adequate protection against the hazards of faulty operation and accidents is considered.

The text, "Reactor Controls Lecture Notes"⁽¹²⁾, is unclassified. Distribution has been limited to the students at ORSORT.

The controls for specific reactors, hazards analysis, and safeguards are discussed in special lectures in the Reactor Component Design and Reactor Systems courses.

Since only 14 lecture periods are allotted to the subject of reactor control, the objectives are somewhat limited in comparison with those of other courses at ORSORT. The subject matter of the controls course has the characteristic that, as soon as one proceeds beyond the simplest cases, one is confronted with intractable non-linear, integro-differential equations. Although these are being studied by competent people at Oak Ridge National Laboratory and elsewhere, it does not seem feasible at the present time to extend the treatment of the subject at ORSORT.

Reactor Systems

In the latter part of the second semester, several series of lectures are presented by guest speakers on reactor systems of importance in this country. The number of lectures on a given system varies and runs as high as six. A list of topics and speakers is given in the Appendix, together with an outline of a typical lecture series. The lectures usually include a statement of the purpose of the reactor and its relation to the reactor program of the AEC or of the Defense Department. The reactor is described in considerable detail, usually with the aid of slides, models or printed materials. Design methods are indicated, and special problems analyzed. In reactors undergoing

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development, unsolved problems are outlined and methods of attack being used are described. In operating reactors, the performance is described and analyzed, and improvements in progress are discussed. About one-half of the material treated is classified.

The lectures are presented late in the school year in order that the students shall have a thorough background in all phases of reactor science and engineering. The talks are highly technical, and are prepared and presented with extreme care. The students are critically attentive, and ask many searching questions. In the 1954-55 session, several teams of students prepared secret notes on the lectures; in the most recent session, the lectures were recorded and then edited and distributed in unclassified form by R. W. Carter, of the ORSORT staff.

No homework is assigned in this course. Tests consist of multiple choice and partial completion questions.

The Systems course is, perhaps, second only to the thesis course, the most important in the ORSORT curriculum. In the first place, it helps the students to integrate and inter-relate the information they have received and the skills they have mastered in the other courses. They are instructed, in an authoritative and compelling way, in the application of those skills to reactor design and development. They become familiar with all types of reactors. They learn the details of latest developments and the nature of current difficulties. They learn these things from highly qualified people who are intimately and expertly informed in their subject, and who are, on the whole, not only good but contagiously enthusiastic speakers.

The Systems course is that ORSORT course the equivalent of which colleges and universities will be least able to provide in the foreseeable future. Mechanical difficulties of scheduling, the expense, the drain on the speakers' time, and the fact that the talks dealing with latest developments in civilian and military reactors must remain classified make it impractical to present the series in more than a few places.

Reactor Component Design

The Components course has become a catch-all for topics not readily incorporated in any other course. Its most important function is to permit the

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presentation of a group of related lectures on auxiliary equipment for reactors such as heat exchangers and gas recombiners. The selection of topics depends in part on the importance of the topic, in part on its degree of development and unsuitability for pedagogical treatment, but mostly on the availability of speakers. The lectures were designed primarily to illustrate the application of the methods developed in the Reactor Engineering course to the design of reactor components. An equally important object is to show the effect on design of limitations imposed by considerations other than thermal, such as the influence of fabrication methods and radiation-induced corrosion.

Some topics, such as nuclear excursions and effects, were extracted from the Reactor Systems lectures, where they logically belong, in order to give emphasis and provide a more detailed treatment. Other guest-lectures, which for lack of time or difficulty in scheduling cannot be given in the appropriate course, are assigned to the Components course. Finally, special topics, such as safeguard studies, which do not fit well into any of the other courses, are included.

The lectures are given by authorities and include discussion of unsolved problems as well as latest results. In the most recent session, the talks were recorded and then edited for distribution to the students by M. W. Whatley, of the ORSORT staff. In this way, a written record is being built up. This record, it is hoped, will provide valuable source material for students and teachers.

Summary

The ORSORT aim is to educate broadly. Some of the limitations encountered are lack of pedagogical development and integration of the various courses, inhomogeneity among the students and deficient preparation in one or more fields, and lack of time to cover the material available.

It is clear that responsibility for a large part of the present ORSORT program could be assumed by the colleges and universities, and this would be most desirable. Reactor engineers need a selection of basic courses in their undergraduate work appropriate to the nuclear field. They need to learn the elementary properties of the systems they will work with later, and they need

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to learn the appropriate vocabulary. Availability of college graduates having about the same degree of basic scientific education and specialized knowledge in the nuclear field as do those in conventional fields of engineering would free ORSORT to break new ground in the development of nuclear engineering education. Several possibilities exist. Engineers with B.S. or M.S. degrees could be upgraded rapidly in an intensive on-the-job-training type of program. Or, the development of a graduate curriculum and research program in the field of nuclear engineering appropriate and feasible for colleges and universities might be undertaken. The education of specialists for research by exhaustive, quantitative treatment of the specialty subject with qualitative courses in related fields could be attempted.

In short, it is believed that it is entirely appropriate and desirable for the National Laboratories to carry out for the benefit and guidance of our secondary schools a program of research and development in the field of nuclear engineering education using live students, operating reactors of significant power, and faculty actively engaged in the practice of nuclear science and engineering. The service performed would be analogous to that performed by these same laboratories for industry and the military in the reactor development program and is justified by the same needs.

Acknowledgment

The comments and suggestions of F. C. VonderLage, Lewis Nelson, R. V. Meghreblian, D. K. Holmes, D. A. Garrison, Murray Rosenthal, and many others are gratefully acknowledged. The personal opinions put forward herein are those of the first author only and do not necessarily reflect official policy of the Oak Ridge National Laboratory or the U. S. Atomic Energy Commission.

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APPENDIX: COURSE OUTLINES

NUCLEAR PHYSICS AND REACTOR ANALYSIS

R. K. Osborn

I. NUCLEAR PHYSICS

- A. Fundamental particles.
 - 1. Description of relevant properties.
 - 2. Designation of conventional units.
- B. Nuclear Stability.
 - 1. Mass-energy relationship.
 - 2. Packing fraction and binding energy.
 - 3. Beta decay.
 - 4. Empirical binding energy formula.
 - 5. Fission and fusion processes.
- C. Nuclear reactions (principally neutron induced).
 - 1. Qualitative description.
 - 2. Definitions of cross section
 - a. Microscopic vs. macroscopic.
 - b. Differential vs. total.
 - 3. Characteristics and examples of cross sections of importance in reactor analysis.

II. REACTOR ANALYSIS

- A. Model I: The infinite, homogeneous, one-speed reactor.
 - 1. Definitions of neutron density and flux.
 - 2. The Maxwell-Boltzmann distribution and its significance in reactor theory.
 - 3. The effect on reaction rates of atomic and neutron speed distribution.
 - 4. A critical equation.
- B. Model II: The infinite, homogeneous, multi-speed reactor.
 - 1. Elastic scattering of neutrons.
 - 2. Inelastic scattering of neutrons.
 - 3. The flux spectrum with no absorptions.
 - 4. The flux spectrum with absorptions.
 - 5. The flux spectrum in mixtures.
 - 6. The continuous slowing down approximation for the fast group.
 - 7. The concept of slowing down density and its relation to the neutron number density.
 - 8. The coupling between the fast and thermal neutron speed distribution.
 - 9. A critical equation (k_{∞}).
- C. Some mathematical tools.
 - 1. Vector algebra.
 - 2. Vector calculus.
 - a. Del and the Laplacian operator in diverse coordinates.
 - b. Stoke's theorem.

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- D. Model 3: The bare, homogeneous, one-speed, P_1 reactor.
 - 1. The neutron current in diffusion theory.
 - 2. The diffusion equation in the P_1 approximation.
 - 3. The transport correction to the diffusion coefficient.
 - 4. The boundary conditions.
 - 5. Steady-state solutions of the diffusion equation in diverse geometries.
 - a. Non-multiplying systems.
 - b. Multiplying systems.
 - c. Connection between solutions for multiplying and non-multiplying systems: Green's function.
- E. Model 4: The bare, homogeneous, multi-speed, P_1 reactor.
 - 1. The multi-group diffusion equations for the fast group in a P_1 approximation with continuous slowing down.
 - 2. The boundary conditions in space and lethargy.
 - 3. Solutions for various cases.
 - a. Point sources (by Fermi Age-theory).
 - b. Distributed sources in diverse symmetries.
 - 4. Coupling of the solutions to thermal diffusion.
- F. Model 5: The reflected, one-speed, P_1 reactor.
 - 1. The diffusion equations for core and reflector.
 - 2. The boundary conditions.
 - 3. The interfacial conditions.
 - 4. The solutions in various geometries.
 - 5. The concept and utilization of albedo.
- G. Model 6: The reflected, multi-speed, P_1 reactor.
 - 1. The multi-group diffusion equations for core and reflector.
 - 2. Boundary and interfacial conditions.
 - 3. Group calculations in various geometries.
- H. Time-dependent behavior.
 - 1. The diffusion equation with time dependence.
 - 2. Generation time.
 - a. Prompt.
 - b. Delayed.
 - 3. Effect of poisons.
 - 4. Power-temperature coupling and typical behavior.
- I. Heterogeneous reactors.
 - 1. Lattice theory.
 - 2. Rod theory.
 - a. Fuel rods.
 - b. Control rods.
 - 3. Perturbation theory.
- J. Present status of reactor analysis.
 - 1. Special methods.
 - a. Age calculations.
 - b. Resonance escape probability.
 - c. Thermal distributions.
 - 2. Techniques for solving higher approximations of the Boltzmann Equation.

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REACTOR ENGINEERING

L. G. Alexander

I. INTRODUCTION

- A. Nuclear reactors.
 - 1. Components of reactors and their function.
 - 2. Operation of reactors--the chain reaction, criticality, a typical fission.
 - 3. The reactor complex--the reactor, the thermal cycle, the fuel cycle.
- B. Classification of nuclear reactors.
 - 1. Purpose.
 - 2. Nuclear characteristics.
 - 3. Heat transfer characteristics.
- C. Outline of design of nuclear reactors.
 - 1. Determination of purpose of reactor and selection of power level, production level, etc.
 - 2. Selection of materials in respect to compatibility and performance.
 - 3. Selection of mode of heat transfer, heat utilization.
 - 4. Selection of power density.
 - 5. Calculation of core size from power density and heat transfer requirements.
 - 6. Calculation of enrichment required for criticality, control, and operation for extended period.
 - 7. Detailed design of reactor components.
 - 8. Design of reactor complex.
 - 9. Economic evaluation.

II. SURVEY OF HEAT TRANSFER, FLUID FLOW, AND THERMAL STRESS IN NUCLEAR REACTORS.

- A. Heat generation in nuclear reactors.
 - 1. Heat sources.
 - 2. Distribution of heat sources in reactor components.
 - 3. Distribution of heat sources in time.
- B. Fluid flow in nuclear reactors.
 - 1. Forced circulation.
 - 2. Natural circulation.
- C. Heat transfer in nuclear reactors.
 - 1. Heat transfer with internal generation.
 - 2. Generation and conduction in solid components, temperature distribution.
 - 3. Generation and convection in fluid components, temperature distribution.
 - 4. Other effects--radiative transfer, change of phase, dynamic stability.
 - 5. Kinetics of transient conduction, transient convection, thermal lags, coupling of thermal, hydrodynamic, and nuclear systems.

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- D. Distribution of mechanical and thermal stresses in reactor components--clad fuel elements, moderator, thermal shield, pressure shell, biological shield.

III. FLUID FLOW

- A. One-dimensional flow equations.
 - 1. Fundamental concepts.
 - 2. Total energy equations.
 - 3. Mechanical energy equation.
- B. Analysis of pressure losses and flow distribution through typical cores.

IV. HEAT TRANSFER

- A. One-dimensional conduction of heat.
 - 1. Simple conduction.
 - 2. Conduction with internal generation.
 - 3. Analysis of heat flow and temperature distribution in clad fuel plates, rods, cylinders, spheres.
- B. Forced convection heat transfer.
 - 1. Equivalent fluid film conductance--the stagnant film model.
 - 2. Heat exchanger design.
 - 3. Extended surfaces.
 - 4. Analysis of heat transfer in stationary fuel reactors.
 - 5. Analysis of boiling reactors.
- C. Boiling heat transfer.
 - 1. Surface boiling heat transfer.
 - 2. Two-phase flow.
 - 3. Boiling with internal heat source.
 - 4. Vapor separation.
 - 5. Analysis of boiling reactors.
- D. Gas cooling.
 - 1. Pressure drop in compressible flow.
 - 2. Heat transfer with compressible flow.
 - 3. Analysis of fluid flow and heat transfer in gas-cooled reactors.
- E. Radiative cooling.
 - 1. Radiative exchange.
 - 2. Analysis of heat transfer in high temperature, gas-cooled, ceramic reactor.
- F. General transfer equations.
 - 1. The transfer quantities.
 - 2. Transfer equations.
- G. Two dimensional conduction equation with internal generation.
 - 1. The heat conduction equation and analog solutions.
 - 2. Difference equations.
 - 3. Application of analytical, analog, and numerical methods.
- H. Transient conduction with internal generation.
 - 1. The transient equation - analytical solutions.
 - 2. The difference equation - numerical methods.

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- I. Forced convection with internal generation.
 1. Heat and momentum transfer equations.
 2. Laminar flow analysis.
 3. Turbulent flow analysis.
 4. Application to circulating fuel reactors.

V. HEAT GENERATION IN NUCLEAR REACTORS

- A. Energy sources.
 1. Fission fragments.
 2. Fission fragment beta decay.
 3. Neutron moderation.
 4. Capture beta decay energy.
 5. Gamma ray heating.
- B. Neutron flux density and spectral distribution.
 1. Continuous slowing down model.
 2. Multi-group methods.
 3. Monte Carlo technique.
- C. Gamma attenuation.
 1. Straight ahead scattering approximation and modifications.
 2. Moment method.
 3. Monte Carlo technique.
 4. Empirical attenuation kernels.
- D. Gamma flux and spectral distribution.
 1. The gamma sources.
 2. Construction of the gamma flux by integration over the gamma sources.
 3. Application to computation of gamma heating in moderator, structural materials, controls, thermal shields and pressure shells, biological shields, etc.

VI. STRESS ANALYSIS

- A. Mechanical stress.
- B. Thermal stress.
- C. Application to clad fuel plates, rods, cylinders, pressure shells, thermal shields, etc.

VII. TRANSIENT BEHAVIOR OF REACTOR SYSTEMS

- A. Coupling of thermal and hydrodynamic systems with nuclear system.
 1. Non-boiling circulating fuel reactor transients.
 2. Boiling reactor transients.
 3. Stationary fuel reactor transients.
 4. Shutdown transients.

VIII. POWER CYCLE ANALYSIS

- A. Fundamental concepts - vapor cycles, gas cycles.
- B. Analysis of various cycles for power reactors.

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IX. BREEDING

- A. Introduction.
- B. Description of reactor systems.
- C. Advanced designs.

X. ECONOMICS OF REACTOR DESIGN

- A. Basis for cost calculations.
- B. Economics of breeders and converters.
- C. Coupling of diffusion plant with reactor complex.

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REACTOR MATERIALS

W. O. Harms

I. INTRODUCTION TO REACTOR MATERIALS PROBLEM

- A. Introductory remarks--scope of course.
- B. Materials problems in power reactors.
- C. Materials problems in production and research reactors.

II. CHEMISTRY AND PHYSICS OF THE SOLID STATE

- A. Types of bonding in solids: physical properties of metals and non-metals.
- B. The structure of crystalline solids.
- C. The diffraction of x-rays, electrons, and neutrons by crystalline solids, applications.

III. PHYSICAL METALLURGY

- A. The solidification of metals.
- B. Equilibrium alloy phase diagrams.
- C. Diffusion in metals.
- D. Mechanical metallurgy.
- E. Kinetics of solid state transformations.
- F. Stainless steels.
- G. Nickel-base alloys.
- H. Metallurgy of welding.
- I. Powder metallurgy.
- J. Refractory metals.

IV. EXTRACTIVE METALLURGY

- A. Principles.
- B. Extractive metallurgy of reactor materials.
- C. Oxidation.
- D. Aqueous corrosion.
 - 1. Corrosion by hot water and slurries.
 - 2. Corrosion by aqueous fuels.
 - 3. Effect of radiation on corrosion by aqueous fuels.
- E. Corrosion by liquid metals and fused salts.

V. PROPERTIES AND BEHAVIOR OF SPECIFIC REACTOR MATERIALS

- A. Uranium.
- B. Thorium and plutonium.
- C. Beryllium.
- D. Zirconium and titanium.
- E. Aluminum.
- F. Ceramics.

VI. EFFECT OF RADIATION ON MATERIALS

- A. Effect of radiation on ceramics.
- B. Effect of radiation on metals.
- C. Effect of radiation on the properties of engineering materials.
- D. Effect of radiation on non-metals.
- E. Effect of radiation on organic compounds.

VII. MATERIALS SELECTION FOR SPECIFIC REACTORS

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CHEMICAL TECHNOLOGY

M. E. Whatley

I. ROLE OF CHEMICAL PROCESSING

- A. Contrast of purity of fuel in nuclear power plants with conventional power plants.
- B. Limitation on burnup and requirement for recovery.
- C. Recovery of valuable by-products.
- D. Disposal of dangerous by-products.
- E. The reactor complex.

II. MATERIALS AND PROBLEMS ENCOUNTERED IN REACTOR CHEMICAL TECHNOLOGY

- A. Fission products: Yield curves and decay chains, location in periodic chart, nature of nuclear instability, fission product radiation heating, fission product poisoning, most important fission products based on yield, cross section, and half-life.
- B. Heavy isotope buildup: Growth from U^{235} , growth from U^{233} , U^{237} limitation on decontamination, U^{232} activity buildup, long term effects with and without loss.
- C. Problems unique to radiochemical processing: Shielding, remote operation, criticality, maintenance, waste disposal, radiation damage, radiation heating, very dilute solutions, high value of product, S. F. accountability.
- D. Description of typical solvent extraction plant flow sheet.

III. GENERAL CHEMISTRY REVIEW

- A. Stoichiometry: Chemical formulas, laws of chemical combinations, Avogadro's number, use of various concentration units.
- B. The periodic chart: Atomic structure as a basis for grouping, oxidation states by groups, various properties as a function of position in the chart, the rare earths and actinide elements.
- C. Oxidation and reduction reactions: Balancing chemical equations, oxidation potential, Nernst equation.
- D. Equilibrium: Criteria for equilibrium, general equation, ionization constant, pH, hydrolysis, solubility product, oxidation and reduction reactions.

IV. CHEMISTRY OF THE FISSION PRODUCTS

- A. Discussion of all of the fission products, taking them according to their groups in the periodic table.
- B. Discussion of the most important fission products with respect to their yields, half-lives, chemical behavior, and biological effects.

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- V. CHEMISTRY OF THE HEAVY ELEMENTS (Atomic Number Above 88)
 - A. Oxidation states and oxidation potentials of the heavy elements, and comparison to corresponding elements in the lanthanide series.
 - B. Tendency of the ions to hydrolyze and form complexes.
 - C. Chemical properties of the metals, oxides, and halides.
- VI. RADIATION CHEMISTRY
 - A. Effect of heavy particles on crystalline materials.
 - B. Effect of ionizing radiation on co-valent bonds, organic materials and water.
 - C. Transmutation
 - D. Effect of ionizing radiation on aqueous solutions: oxidizing effects from peroxides and direct effects on solutes, catalytic effects of solute on radiolytic decomposition products.
 - E. Effect of radiation on corrosion.
- VII. RAW MATERIALS
 - A. Sources of uranium: Pitchblende and uranite deposits, domestic ores, low grade ores.
 - B. Treatment of ores: Acid leach, carbonate leach, new processing techniques.
 - C. Thorium: Sources and treatment of ores.
 - D. Feed material preparation (purification techniques).
- VIII. GENERAL PRINCIPLES OF SEPARATION PROCESSES
 - A. Dependence of chemical separations on the physical separation of two phases.
 - B. Equilibrium distribution between phases.
 - C. Mechanical methods of operations: Batch versus continuous processes, multistage versus single stage, multiple parallel passes versus countercurrent multi-stage, concept of the differential process.
 - D. General material balance equations.
 - E. Single solute assumption.
 - F. Separation of two very similar solutes and the concept of the separation factor.

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IX. PRECIPITATION

- A. Necessity for carrier: Solubility limitations, sorption effects, mechanical handling limitations.
- B. Mechanism of carrying.
- C. Development of the logarithmic distribution law as a differential batch process.
- D. Bismuth phosphate process for plutonium separation.
- E. Application in radioactive isotope production.

X. DISTILLATION

- A. Distillation systems: Relative volatility as a separation factor, equilibrium diagrams, azeotropes.
- B. Constant molal overflow assumption: Deviations and inherent limitations.
- C. McCabe Thiele graphical method: Minimum reflux, minimum stages, separation calculation.
- D. Application to radiochemical processing: Plutonium removal from uranium metal, UF_6 volatilization - BrF_3 , ClF_3 , and SbF_5 processes.
- E. Application to isotope separation: Heavy water, deuterium, O^{18} , B^{10} .
- F. Chemical exchange cascades.
- G. Sublimation and molecular distillation.

XI. SOLVENT EXTRACTION

- A. Single solute, immiscible solvents assumptions: The application and limitation of the distribution coefficient, equilibrium diagrams.
- B. Representation of material balances by operating lines in simple and compound columns.
- C. Separation of two independent solutes.
- D. Adjustment of equilibrium conditions by choice of solvent, oxidation state of solute, and use of salting agents.
- E. "25" process.
- F. "Redox" and "Purex".
- G. "Thorex".

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XII. GASEOUS DIFFUSION

- A. Mechanism of separation by diffusion, separation factors, application to uranium isotope separation.
- B. Material balances in multistage operations: Differential process approximation.
- C. Total reflux: Ideal cascades, square cascades.
- D. Relative power requirements.

XIII. ION EXCHANGE

- A. Mechanism of sorption by ion exchange: Chemical nature of the resin, capacity of the resin.
- B. Separation of the two solutes: Relative affinity for the resin.
- C. Batch operations: Differential loading and eluting, the multi-stage concept.
- D. Continuous ion exchange operations.
- E. Isolation of uranium and plutonium in radiochemical processing, advantage of high affinity and selectivity, limitations in high radiation fields.
- F. Application to ore processing: Existing bucket operations, continuous moving bed and resin cloth belt developments.

XIV. DESIGN OF RADIOCHEMICAL PROCESSING PLANTS

- A. Reactor variables influencing chemical processing, physical and chemical nature of the fuel elements, transmutation products to be recovered, and irradiation level of fuel elements.
- B. Choice of chemical flowsheet.
- C. Maintenance: Importance of minimizing maintenance, remote maintenance, direct maintenance, and underwater maintenance as alternate methods, illustration of application of each of these.
- D. Criticality: Uniqueness of the problem, effects on design, the application of geometry, concentration, total mass of fissionable material, and neutron poisons as a means of criticality control.
- E. Shielding: Dependence on maintenance philosophy, effect on piping layouts, bulk versus unit shielding, relative advantage of concrete, lead, and water as shields, general effects of shielding on plant design.
- F. Remote operation: Necessity for complete instrumentation and specially developed techniques.

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- G. Waste disposal, : Tolerances and philosophy, heat generation problem, current methods of concentrating and handling liquid wastes, possible alternatives for disposing of liquid wastes, gaseous wastes.
 - H. Other unique problems: Radiation damage to materials of construction, heat generation, high value of product, low concentrations of solutions, health physics monitoring, accountability.
 - I. Description of existing chemical processing plants.
- XV. HIGH TEMPERATURE FUEL PROCESSING
- A. Slagging.
 - B. Fused salt extraction.
 - C. Liquid metal solvent extraction.
 - D. Metal distillation.
 - E. Zone melting.
- XVI. AQUEOUS HOMOGENEOUS REACTORS
- A. Specific chemical problems.
 - B. Continuous processing techniques.
- XVII. FUSED SALT REACTORS
- XVIII. LIQUID METAL REACTORS
- A. Specific chemical problems.
 - B. Continuous processing techniques.

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REACTOR SHIELDING AND HEALTH PHYSICS

R. Peelle

I. INTRODUCTION

II. CHARACTERIZATION OF THE SHIELDING PROBLEM

- A. Important properties of nuclear radiation.
- B. Generalized definition of shielding.
- C. The magnitude of the attenuation required.
- D. The genealogy of reactor radiations.
- E. Biological dose, "tolerance".
- F. Outline of a simple shielding problem.

III. INTERACTIONS OF CHARGED PARTICLES WITH MATTER

- A. Distinction between range and exponential attenuation.
- B. Stopping power and range for heavy particles.
- C. Stopping power and range for electrons, multiple scattering, bremsstrahlung.

IV. INTERACTIONS OF PHOTONS WITH MATTER

- A. The Compton effect, description and discussion of cross section.
- B. The photo-electric effect, description and discussion of behavior of the cross-sections.
- C. The pair production effect, description and discussion of behavior of the cross-sections.
- D. The combined effect of the photon cross-sections.
- E. The definition of the energy absorption cross section.

V. INTERACTIONS OF NEUTRONS WITH MATTER

- A. The possible interactions.
- B. Neutron energy loss in tissue.
- C. Geometrical neutron-reaction cross sections.
- D. Elastic scattering.
- E. Inelastic scattering.
- F. Absorption.
- G. The importance of hydrogen for neutron attenuation.

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VI. HEALTH PHYSICS

- A. The pharmacology of radiation.
- B. The philosophy of radiation exposure.
- C. Types of radiation injury.
- D. Partial recovery from radiation injury.
- E. Short range damage problems.
- F. Long-term damage, genetic and shortening of life.
- G. Chemical protection from radiation effects.
- H. Health physics instrumentation, the Bragg-Gray principle.
- I. Internal dose problems.

VII. APPROXIMATIONS TO THE EXACT ATTENUATION LAWS

- A. Exponential approximation.
- B. Approximations to the scattering laws for the simple calculation of complex situations.
- C. Effective removal cross sections for neutrons.
- D. Machine calculation techniques.
- E. The build-up factor, its behavior as a function of the parameters.
- F. Analytical calculation of the build-up factor under the linear approximation.

VIII. REACTOR SOURCES OF RADIATION

- A. Prompt fission gammas.
- B. Fission product gammas.
- C. Inelastic scattering gammas.
- D. Capture gammas, classification of the nuclides.

IX. DESIGN METHODS FOR THE BASIC SHIELD

- A. The direct method vs. the comparison method.
- B. Geometrical transformations between hypothetical surface source distributions.
- C. Calculations of reactor leakage, the determination of the surface source strength.
- D. The comparison method for non-homogeneous shields.
- E. The semi-analytic method of shield design.

X. SHIELD DESIGN OPTIMIZATION, THE GENERAL METHOD

XI. THE PRACTICAL SHIELD

- A. Dusts and voids, the resulting decrease in attenuation.
- B. Discussion of reactor shields that have been designed.
- C. Examples of shield design materials.

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REACTOR CONTROL AND INSTRUMENTATION

C. Walker

I. REACTOR KINETICS

- A. Without delayed neutrons.
- B. With delayed neutrons.
- C. With source.
- D. Range of power levels.
- E. Nonlinear behavior.
 - 1. Temperature coefficient.
 - 2. Poisons.
 - 3. Circulating fuel reactors.
- F. Analog computers.

II. INSTRUMENTATION

- A. Detectors.
 - 1. Requirements.
 - 2. Reactions used.
 - 3. Ion chambers, pulse and integrating types.
 - 4. Compensated chambers.
 - 5. Detectors other than ion chambers.
- B. Instruments.
 - 1. Pulse amplifiers.
 - 2. Counting rate amplifiers.
 - 3. DC amplifiers.
 - 4. Log N and period amplifiers.
 - 5. Galvanometers.
- C. Applications of instrumentation.

III. PHILOSOPHY OF CONTROL

- A. Safety criteria.
- B. Operational criteria.

IV. EXAMPLES OF SYSTEMS

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REACTOR SYSTEMS AND RELATED TOPICS

R. J. Carter

THE AEC, ITS ORGANIZATION AND PROGRAMS, by Nathan H. Woodruff, Oak Ridge Office of the A.E.C.

HISTORY AND NUCLEAR DESIGN OF THE HANFORD REACTORS, 1940-45, by Alvin M. Weinberg, Oak Ridge National Laboratory.

HANFORD ENGINEERING DESIGN, 1940-45; HANFORD REACTORS, 1954-56, by Paul Gast, General Electric Company.

SAVANNAH RIVER REACTORS, by Edward J. Hennell, E. I. DuPont de Nemours, Inc.

FOREIGN REACTOR PROGRAMS, U. S. INDUSTRIAL POWER PROGRAM, U. S. MILITARY REACTOR PROGRAM, RESEARCH REACTOR PROGRAMS, by J. A. Lane, Oak Ridge National Laboratory.

NAVAL REACTOR PROGRAMS, by J. M. Dunford, Naval Reactors Branch, U. S. N.

HOMOGENEOUS REACTOR PROJECT, by R. B. Briggs, S. Beall, and R. Kormeyer, Oak Ridge National Laboratory.

MATERIALS TESTING REACTOR DESIGN AND OPERATION, by J. Huffman, Phillips Petroleum Company.

OAK RIDGE RESEARCH REACTOR, by T. Cole, Oak Ridge National Laboratory.

EXPERIMENTAL BOILING WATER REACTOR, by J. A. Thie and L. W. Fromm, Argonne National Laboratory.

LIQUID METAL FUEL REACTOR, by F. Miles, Brookhaven National Laboratory.

ARMY POWER PACKAGE REACTOR, by F. Neill, Oak Ridge National Laboratory.

EXPERIMENTAL BREEDER REACTOR, by H. O. Monson and W. B. Loewenstein, Argonne National Laboratory

SUBMARINE INTERMEDIATE REACTOR AND SUBMARINE ADVANCED REACTOR, by C. Stahl and H. Stevens, Knolls Atomic Power Laboratory.

PRESSURIZED WATER REACTOR, by A. Henry, N. J. Palladino, and P. N. Ross, Westinghouse Corporation.

HIGH TEMPERATURE REACTORS, by A. P. Fraas and W. K. Ergen, Oak Ridge National Laboratory.

SODIUM GRAPHITE REACTOR, by W. Parkins, North American Aviation, Incorporated.

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OUTLINE FOR TYPICAL REACTOR SYSTEMS LECTURE

R. B. Briggs

I. EARLY PROJECT HISTORY

- A. Purpose for building reactor.
- B. Basic requirements.
- C. Survey of reactors studied before final selection of particular reactor.
- D. Basis for selection of particular reactor.

II. GENERAL DESCRIPTION OF REACTOR.

- A. Design basis.
- B. Reactor core.
 - 1. Fuel elements.
 - 2. Control elements.
 - 3. Moderator and reflector.
 - 4. Container.
- C. Thermal and biological shielding.
- D. Controls.
- E. Coolant system.
- F. Site, buildings, and associated facilities.

III. REACTOR PHYSICS

- A. Critical mass calculations.
- B. Neutron flux distribution.
- C. Heat production distribution.
- D. Reactivity losses.
- E. Reactor control and dynamics.
- F. Shielding.
- G. Critical experiments.

IV. ENGINEERING DESIGN OF REACTOR

- A. Design data.
- B. Reactor core.
 - 1. Heat transfer.
 - 2. Fluid flow.
 - 3. Materials.
 - a. Neutron absorption.
 - b. Corrosion.
 - c. Radiation stability.

- 4. Mechanical design.
 - a. Fuel elements.
 - b. Control elements.
 - c. Moderator and reflector elements.
- C. Reactor tank design.
 - 1. Temperature, pressure, and radiation problems.
 - 2. Mechanical design.
- D. Thermal shield.
 - 1. Heat production and cooling problems.
 - 2. Mechanical design.
- E. Biological shield.
 - 1. Materials.
 - 2. Mechanical design.
 - 3. Special problems.
- F. Special facilities.
 - 1. Experimental.
 - 2. Production.
 - 3. Monitoring.
 - 4. Maintenance.
 - 5. Charging and discharging.

V. REACTOR CONTROL SYSTEM

- A. Design basis.
- B. Nuclear instrumentation.
- C. Control mechanisms.
- D. Reactor operation.
 - 1. Start-up.
 - 2. Manipulation of operating level.
 - 3. Operation in face of difficulty.
 - 4. Shut-down.
- E. Process instrumentation and control.
- F. General control facilities.

VI. REACTOR COOLANT SYSTEMS

- A. Design basis, flowsheets, and special requirements.
- B. Quality requirements.
- C. Induced activity and shielding.
- D. Provisions for maintenance.
- E. Disposal problems.
- F. Emergency cooling.
- G. Description of systems and equipment.
- H. Generating equipment (for power reactors).

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VII. FACILITIES FOR HANDLING AND DISPOSAL OF RADIOACTIVE MATERIALS.

VIII. SITE

A. Requirements:

B. Reactor building.

C. Associated buildings and facilities.

IX. DEVELOPMENT STUDIES AND RESULTS

X. CONSTRUCTION EXPERIENCE

XI. OPERATIONAL EXPERIENCE

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REACTOR COMPONENT DESIGN AND SPECIAL TOPICS

M. W. Whatley

HEAT EXCHANGERS, by W. L. Ross.

RECOMBINERS, OFF-GAS SYSTEMS, by P. H. Harley.

CANNED ROTOR PUMPS, DIAPHRAGM PUMPS, by C. B. Graham.

HOMOGENEOUS REACTOR CORE DEVELOPMENT, GAS SEPARATORS, by I. Spiewak.

SLURRIES: PHYSICAL AND MECHANICAL ENGINEERING ASPECTS OF HANDLING,
EQUIPMENT DESIGN, by R. Lyon.

SOLID FUEL ELEMENT DESIGN AND FABRICATION, by J. E. Cunningham.

PRESSURE VESSELS: METALLURGICAL ASPECTS, BOILER CODES, SPECIFICATION,
by E. C. Miller.

PRESSURE VESSELS: DESIGN, FABRICATION, CLOSURES, by W. R. Gall.

NATURAL CONVECTION WITH INTERNAL GENERATION, by D. C. Hamilton.

REACTOR SAFEGUARDS: CONTAINMENT, by S. Beall.

REACTOR SAFEGUARDS: NUCLEAR EXCURSIONS AND EFFECTS, by P. Kasten.

BIOLOGICAL EFFECTS OF RADIATION, by G. E. Stapleton.

EFFECTS OF RADIATION ON MAMMALS, by A. G. Upton.

GENETIC EFFECTS OF RADIATION, by W. L. Russell.

"BACK-OF-ENVELOPE" CALCULATIONS , by P. Kasten.

REACTOR SAFEGUARD STUDIES AND REPORTS, by E. P. Blizard.

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