A NEW BOOK: “LIGHT-WATER REACTOR MATERIALS”

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The contents of a new book currently in preparation are described. The dearth of books in the field of nuclear materials has left both students in nuclear materials classes and professionals in the same field without a resource for the broad fundamentals of this important sub-discipline of nuclear engineering. The new book is devoted entirely to materials problems in the core of light-water reactors, from the pressure vessel into the fuel. Key topics deal with the UO_2 fuel, Zircaloy cladding, stainless steel, and of course, water. The restriction to LWR materials does not mean a short monograph; the enormous quantity of experimental and theoretical work over the past 50 years on these materials presents a challenge of culling the most important features and explaining them in the simplest quantitative fashion. Moreover, LWRs will probably be the sole instrument of the return of nuclear energy in electric power production for the next decade or so. By that time, a new book will be needed.

KEYWORDS : Book, Nuclear Materials, Nuclear Fuels; Radiation Effects; Uranium Dioxide, Zircaloy

1. INTRODUCTION

This is not a book review; it is a book preview. Thirty years ago, “Fundamental Aspects of Nuclear Reactor Fuel Elements” was published [16]. The expected title was “Materials of Liquid-Metal Fast Breeder Reactors”; the last-minute change of title was intended to convey the sense that the book was broader than the old title suggested. Nevertheless, the old book was firmly tilted in the direction of LMFBRs. However, because the book used a fundamental approach to materials problems, it remained relevant even as the fast breeder program was cancelled.

This book, however, was only one of many that dealt in one way or another with nuclear materials. The hopefully exhaustive list is given chronologically as Refs 1–29. Several subspecialties under the broad rubric of nuclear materials can be discerned in this list.

The book by Dienes and Vineyard [2] was the first of three to deal with the atomistics of radiation damage in the language and mathematics of the physicist. This was followed in the next decade by Chadderton’s book [8], Thompson [14] and in the 70’s by the very useful book by Gittus [18]. The book by Robertson [13] dealt with radiation effects from an engineering point of view and the books by Kelly and Anno give an overview of irradiation effects [11, 20].

A second group of books concentrated on the metallic components of the primary circuit, with corrosion a central topic. The books in this category are Wilkinson and Murphy’s early work on metallurgy of nuclear components [3], Dawson and Sowden’s [6], Roberts’ [18] and most recently, translated from the Russian, Parshin’s, Alekseenko’s and Kritsky’s monographs [25-27].

The largest group includes a subgroup with general titles of “nuclear materials” [4], [12], [19] and [23,24]. These books feature discussions of nuclear fuels among other topics pertinent to the materials in the ensemble of the nuclear reactor. The second subgroup is devoted to nuclear fuels: The pre-eminent member of this group is Belle’s compendium on uranium dioxide [5]; French contributions concentrate mainly on uranium dioxide as a fuel [9, 28]; the fuels-related books commence with Gurinsky & Dienes’ [1], followed by Holdren’s [10], Olander’s [16], and Frost’s [22]. The volume by Simnad and Zumwalt [7] specializes in high-temperature graphite reactor fuel (probably associated with GA’s effort at Fort St. Vrain). The very useful volume on the thermodynamics of nuclear materials is a collection of the papers presented at an IAEA -sponsored meeting [15]. More recently Matzke wrote a monograph on LMFBR fuels [21].

Figure 1 shows the frequency of publication of books on nuclear materials since the 1950s. The peak activity was in the decade 1960 – 1970, and the frequency of publication has been declining ever since. The four books published in the 1990s were translations from French and Russian. No publications in this field have appeared in the first 5 years of this century.

Aside from the Olander work [16], none of the books in the list of references was intended as a textbook. This usage is signaled by problems for students worked out in the text or placed at the end of each chapter with solutions

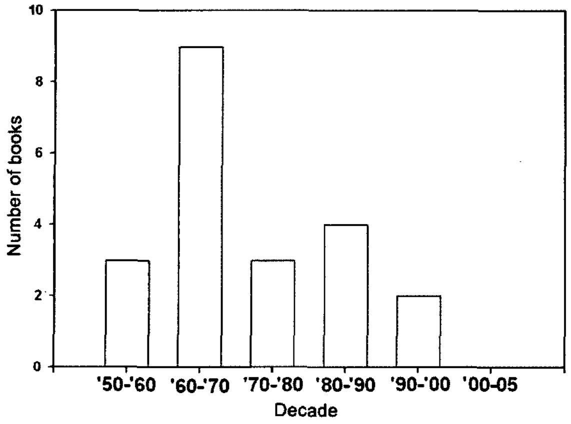

Fig. 1. Books on Nuclear Materials Published - by Decade

supplied in a companion volume.

Despite the total absence of new orders for power reactors in the U. S. since Ref. 16 was published, nuclear power has increased its contribution to the national production of electricity through increased capacity factors enabled by higher burnup fuel, fewer fuel failures, and longer operating cycles. In the process, substantial advances in the understanding of the fuel and core materials in LWRs have been made. The need to update the old book to reflect current developments in the field is beyond merely producing a second edition; a new book with a new outlook was clearly needed. The new book will retain the coverage of the basics of materials science that are important to the unique environment of nuclear reactors; this is in the *Fundamentals* section. This approach will be supplemented by extensive coverage of materials issues restricted to the performance of LWR fuel and core structures, in the *Applications* section. The distinction between *Fundamentals* and *Applications* is sharper here than in the old book.

The new book, like the earlier one, is intended primarily as a text for nuclear engineering students with only a lower-division introductory course in materials science. The targets for the nuclear materials courses are senior-level undergraduates and first-year graduate students. The book can also be used for a second course, either centered on environmental degradation of materials (stress corrosion cracking, corrosion, hydriding, etc.) or on radiation effects. The justification for the *Fundamentals* half of the new book is twofold: requiring materials science courses as prerequisites to the nuclear materials course that deals exclusively with reactor applications is not a viable option; at least two of the former would be needed, and the net result would be a drastic reduction in enrollment in the latter course; nor is directing students to other texts for the preparatory materials science a feasible substitute for including the *Fundamentals* in the new book – differences in notation and organization of subject matter from one text to another causes considerable trouble for students. The sole exception to this rule is the old book, upon which we rely for derivations which are not critical to the understanding of a topic[1]. There are many examples where the symbiotic relationship of the two books can be exploited.

The new book will feature solved problems in the text as well as homework problem statements at the end of each chapter. To the extent possible, references at the end of the chapter will cite original sources of important information, data, or analysis.

The coverage of the new book is intentionally narrow, restricted as it is to the core, internals, pressure vessel, and primary-circuit piping of LWRs. This choice is based on our judgment that LWRs are likely to be the main contributors to the nuclear electricity generation in the coming decades. Moreover, LWR technology contains the most extensive data and analysis knowledge base of any nuclear power system. This permits coverage of the important topics in a quantitative fashion, and avoids the qualitative, descriptive presentations that have characterized nuclear materials books in the past. Nor will fuels other than oxides be treated. Given the plethora of technical issues in LWR fuels, keeping the size of the book within reasonable bounds also precludes coverage of materials issues relevant to other nuclear systems, such as fusion reactors, space nuclear power, radioactive waste disposal sites and the Generation IV reactors [30]. However, there is much overlap of LWR materials analyses with the needs of other nuclear systems. For example, void swelling, which is treated in Chap. 27, is more important in fusion reactors than in LWRs; the mechanism of irradiation-induced diffusion of fission products in UO_2 is the same in operating fuel rods as in spent fuel in a geologic repository.

2. COMPARISON OF THE NEW AND OLD BOOKS

The Table of Contents for the new book is shown in Fig. 2. Twenty-nine chapters are planned, about equally divided between *Fundamentals and Applications*. To help understand the differences between the two books, Tables 1 and 2 show in very abbreviated fashion the coverage of *Fundamentals* (Table 1) and *Applications* (Table 2).

A significant omission in the new book is the topic of statistical thermodynamics and its application to ideal gases, the thermal properties of solids, and point defects. Experience in teaching nuclear materials has shown that the practical insights gained from this approach are very limited considering the time required to teach them. This shortcoming, when combined with the need to understand very different concepts, notation, and sophisticated statistical

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[1] For example, the derivation of the random walk relation between mean migration distance and time; derivation of the Nernst-Einstein equation expressing mobility of a species in terms of its diffusion coefficient

ideas, led us to eliminate statistical thermodynamics in the new book. This absence, however, does not mean that the microscopic basis underlying thermal and radiation effects on solids is abandoned: only the statistical approach to such phenomena is avoided[2].

Several topics that have either appeared since publication of the old book or have received greater emphasis in LWR materials technology are treated in the new book. These include an expanded discussion of grains and grain boundaries, rate theory for describing the evolution of the microstructure under irradiation, computational materials science, and aqueous corrosion.

The effects of irradiation on solids are given a more nuanced and complete coverage than in the old book. In the Fundamentals portion of the new book, treatment of this topic starts with the basic ideas of lattice atom displacements and transmutations (Chap. 12). Recent advances in atomistic simulations of the elementary processes in the interaction of radiation and matter are included (Chap. 14)[3]. Rate theory is applied to describe the subsequent effects on the microstructure (Chap. 13). These three basic features of radiation damage are followed in the Applications half of the book by a discussion of the consequences of such damage to LWR materials. In this package are mechanical property changes (Chap. 26), dimensional instability (Chap. 27) and phase transformations (Chap. 24).

In addition to understanding the microscopic basis of materials degradation phenomena, the new book also provides the wherewithal for understanding the engineering problems associated with the use of materials in the very demanding reactor environment. Because of this, the technology of fuel elements (Chaps. 16 and 17) and fuel assemblies (Chap. 18) are presented in the Applications half of the new book. Included are detailed descriptions of fabrication methods, nondestructive evaluation techniques, and cladding degradation processes arising from bundling fuel elements into fuel assemblies. Three chapters are devoted to various aspects of corrosion. Chapter 21 covers water chemistry in BWRs and PWRs, including radiation chemistry; Chapter 22 deals with waterside corrosion and hydriding of Zircaloy and the newer cladding alloys; Chapter 25 describes intergranular stress-corrosion cracking and irradiation-assisted stress-corrosion cracking.

The remaining chapters of the new book deal with fuel performance. Chapter 19 analyzes the thermal performance of fuel elements. Included are discussions of the thermal conductivity as affected by temperature and burnup, temperature distribution in the fuel and gap conductance. Chapter 20 encompasses the entire topic of fission product behavior: yields, thermochemistry, release, and swelling. This section is pulled together with a chapter (No. 29) on fuel behavior codes, to the extent that non-propriety literature is available.

Part I: Fundamentals

1. Introduction
2. Chemical Thermodynamics
3. Crystal Structures
4. Point Defects in Solids
5. Diffusion in Solids
6. Elasticity and Thermo-elasticity
7. Dislocations
8. Grains and Grain Boundaries
9. Cavities in solids
10. Phase Transformations
11. Mechanical Behavior of materials
12. Radiation Damage
13. Microstructure Evolution Under Irradiation
14. Computational materials (Brian Wirth)
15. Aqueous Corrosion

Part II. Applications

16. Oxide fuels
17. Zirconium Alloys and other metallic alloys
18. Fuel Elements and Assemblies
19. Thermal Performance
20. Fission Product Behavior
21. PWR and BWR Water Chemistry and its Influence on Corrosion
22. Waterside Corrosion and Hydriding of Zr Cladding
23. Fuel Rod Failure Mechanisms
24. Phase Transformations under irradiation
25. Inter Granular Stress-Corrosion Cracking (IGSCC)
26. Irradiation Induced Mechanical Property Changes: Hardening and Embrittlement
27. Dimensional instability under irradiation
28. High Burnup Effects/RIA/LOCA/Severe Accident Behavior
29. Fuel Performance Codes

Fig. 2. Tentative table of contents for the new book "Light Water Reactor Materials", by D. R. Olander and A. T. Motta

In practice, the relevant material issues are exacerbated by the ever-more severe fuel duty cycles and accident response at high burnup. Because of the importance of such issues in assuring the safe operation of nuclear power plants, various chapters cover the high-burnup structure, severe-accident behavior, the reactivity-initiated accident, and pressure-vessel embrittlement. Much of the emphasis of the later chapters of the book is on the synergistic effects of various stressors on the behavior of materials, producing phenomena such as stress-corrosion cracking and pressurized thermal shock.

3. DETAILED DESCRIPTION BY CHAPTER

Chapter 1 provides an introduction to the materials problems in light-water nuclear reactors. It contains a short

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[2] Even the entropy of mixing can be derived without recourse to the usual statistical techniques by considering two ideal gases.

[3] To be written by Professor Brian Wirth

review of light-water reactor types, as well as of the basic definitions and approximate magnitudes of linear heat rating, burnup and capacity factor. The chapter also contains a brief historical perspective, with examples of early materials problems and a review of the current ones (since circa 1985). The economic impact of these problems is discussed in terms of their effect on capacity factors. This coverage is designed to help students understand the importance of materials limitations in nuclear power plants.

3.1 Fundamentals

The *fundamentals* section starts with **Chapter 2**, chemical thermodynamics. This discipline underpins nearly every topic in the book. Examples include the driving force for corrosion by high-temperature water, the equilibria that determine phase stability, solution non-ideality and materials chemistry. The chapter covers basic thermodynamic properties and laws, the phase rule, phase equilibrium and ends with the thermodynamic aspects of ionic solutions and aqueous electrochemistry.

Although students in their senior year and graduate students should have been exposed to the principles of crystallography, we believe that it is necessary to review the basic concepts, both to refresh their memory and to discuss specific crystal structures relevant to LWR components, such as zirconium metal and UO_2. **Chapter 3** reviews

Table 1. Comparison of the Fundamentals Coverage of the Old and New Books on Nuclear Materials

Topic	Old Book	New Book	Comments
General Introduction	none	Chap. 1	Features of BWRs and PWRs; fuel, core structures, coolant
Statistical Thermodynamics	Chaps. 1 & 2	none	macroscopic thermodynamics exclusively used in new book; Debye heat capacity lost
Thermochemistry	Chap. 5	Chap. 2	Coverage in old book too brief; new book includes UO_2 chemistry and electrochemistry
Cohesive Energy	Chap. 4	Chap. 14	new chapter on computational materials
Crystal Structures	Chap. 3	Chap. 3	Extended coverage in new book; also contains discussion of interatomic potentials
Point Defects	Chap. 6	Chap. 4	New book adds point defects in UO_2; effects of impurities and nonstoichiometry
Diffusion in Solids	Chap. 7	Chap. 5	Coverage much more extensive in new book
Elasticity Theory	Appendix	Chap. 6	New book has applications; also thermal stresses
Dislocations	Chap. 8	Chap. 7	Coverage in new book is longer & more extensive
Grains & Grain Boundaries	none	Chap. 8	Old book has one page in Chap. 8
Equation of State of UO_2	Chap. 9	none	Omitted because of minor interest in LWRs
Cavities in Solids	none	Chap. 9	Reduced coverage in old book in chap. 13 on fission gas release & swelling
Phase Transformations	none	Chap. 10	not present in old book, covers different types of phase transformations, nucleation and growth
Mechanical Behavior	Chaps. 16, 18	Chap. 11	Old book did not have a stand-alone chapter
Radiation Damage	Chap. 17	Chaps 12 & 14	Coverage in new book updated to include molecular dynamics simulation and the SRIM code [31]
Radiation Effects on Microstructure	Chap. 18 (qualitative)	13	This topic is usually called "rate theory" – it appeared at about the same time as the old book
Computational Materials	Chap. 17	14	The improvement in computing power spawned ab initio and molecular dynamics methods
Aqueous Corrosion	none	15	Absent from the old book, which covered sodium corrosion instead

the rules for occupancy of space, unit cells and lattice parameters. The different crystal structures are illustrated and the symmetry elements of each are highlighted. Special emphasis is placed on the close-packed hcp and fcc structures, and on two-element ionic crystals.

Chapter 4 introduces zero-dimensional point defects. The equilibrium concentrations of vacancies and interstitials are determined by minimization of the Gibbs free energy. Ionic crystals additionally require electric charge balances, which restricts the type of defects to the Schottky and Frenkel types.

Chapter 5 demonstrates how point defects determine the rate of solid-state diffusion under thermal conditions (i.e. in the absence of irradiation). This process is often the rate-limiting step for phase transformations, creep and bubble or void growth. Diffusion is described from a microscopic view, including a derivation of the Einstein equation for the diffusion coefficient, and a macroscopic view, in which Fick's second law is solved for different geometries. The chapter also includes diffusion in ionic crystals, with special emphasis on UO_2.

The thermoelastic response of solids to applied loads, as expressed in terms of stresses and strains, is discussed in **Chapter 6**. The chapter covers stress-strain relationships and their microscopic origins, as well as calculation of stresses in various geometries. Particular attention is paid to thin-walled tubes, which is relevant to the behavior of reactor components, ranging from the centimeter-size fuel-element cladding to the meter-scale pressure vessel. Stresses also appear in components subject to large temperature gradients, such as the fuel pellets during ordinary operation and the rapidly-heated components in accident conditions.

The one-dimensional defects, in the form of dislocations are discussed in **Chapter 7**. The necessity of dislocations to explain the onset of plastic deformation is discussed. This is followed by a derivation of the characteristics of dislocations, whether edge or screw, the Burgers vector, slip plane, and its elastic strain energy. The interactions of dislocations, the forces between dislocations, their generation, and the impact of dislocations on the yield stress are also discussed. The chapter concludes with the explanation of dislocation climb, preparatory to the later analysis of creep.

Two-dimensional defects in the form of grain boundaries are discussed in **Chapter 8**. Many of the properties of solids are dependent on grain size, grain boundary type and orientation. Grain growth is described in terms of Hillert's model. Enhanced diffusion through grain boundaries is also discussed. The stacking fault and its effect on mechanical properties is analyzed.

Chapter 9 demonstrates how lattice defects control the growth of three-dimensional defect structures in the form

Table 2. Comparison of the Applications Coverage of the Old and New Books on Nuclear Materials

Topic	Old Book	New Book	Comments
Oxide Fuels (UO_2)	material in Ch. 9-16	Chap. 16	More extensive coverage in old book
Zr alloys	none	Ch. 17	Development of Zr alloys, microstructure and relation to properties
Thermal Performance	Ch.10	Ch. 19	Equivalent coverage
Fission Product Behavior	Ch. 12-15	Ch.20	More extensive coverage in old book
Reactor Water Chemistry	none	Ch. 21	Important topic now covered
Waterside Corrosion and Hydriding of Zr alloys	none	Ch. 22	Important topic now covered
Phase transformations Under irradiation	little specific coverage	Ch. 24	Many phenomena relevant to nuclear materials are controlled by phase formation or dissolution, so this is an important new topic covered.
High Burnup Effects on Fuel and Cladding	some in Chap. 21	Chap. 28	Most coverage in old book related to evolution of the fuel, but in the context of fuel performance codes
Intergranular Stress Corrosion Cracking	none	Ch. 25	New book covers IGSCC
Fuel Elements and Assemblies	some in Ch. 10 and 20	18	Explicit coverage of the materials issues related to fuel assembly design
Fuel Rod Failure Mechanisms	none	23	This will cover issues such as fretting, bowing etc.
Fuel behavior codes	An extinct LMFBR code	29	Will include the codes FRAPCON, TRANSURANUS, FEMAXI, ENIGMA

of cavities or bubbles. This topic is of particular relevance to the behavior of fission gases and to the mechanism of void swelling under irradiation.

The end state of phase transformations in the solids is dictated by the principle of minimization of the Gibbs free energy. However, there are many paths to the end state and these are described in **Chapter 10** by the kinetics of phase transformations. Phase transformations can occur by the sequential processes of nucleation and growth; they may or may not require long-range atomic transport by diffusion. The microstructures of commercial alloys result from such processes taking place during thermo-mechanical processing. This chapter contains the derivations of the critical embryo radius for nucleation, a discussion of the order of phase transformations, and of the different phase transformation mechanisms and the resulting microstructures.

The response of materials and components to different applied loads is one of the most important aspects of their behavior in service. In **Chapter 11** we review the basics of material deformation, including the stress-strain curve, plasticity, work hardening and failure. The change of the stress-strain curve due to precipitates in the alloy, and the effect of grain size are also discussed. We also review the theory of crack propagation, the concept of fracture toughness, thermal creep and life prediction rules. All of these concepts are presented first with the idea of explaining them in fundamental terms, such as dislocation multiplication being the underlying cause of work hardening. Summaries of important mechanical properties are given in the chapter.

Radiation damage resulting from atomic displacements caused by fast neutron collisions with lattice atoms is one of the distinguishing factors to which in-reactor components are subjected. **Chapter 12** describes the basis of damage production by energetic particle irradiation, starting from a review of the cross section concept and followed by analyses of primary-knock on atom (PKA) energy transfer, displacement cascade development and the number of displacements per collision. Together, these phenomena determine the overall number of displacements caused by a fast neutron flux.

The radiation effects discussed in the later chapters result from the interaction of atomic-scale radiation damage with the material's microstructure. **Chapter 13** describes how such an interaction produces totally unique microstructures exhibiting new material properties. Rate theory and point defect balances quantify the opposing processes of defect creation and annihilation. The resulting defect fluxes to sinks (two and three dimensional defects) cause the observed effects.

Recognizing the increasing importance of computational methods in understanding material properties, Prof. Brian Wirth will supply **Chapter 14** describing the application of "computational materials" to the detailed description of cascade development, diffusion in solids and dislocation properties. The basic techniques are "molecular dynamics" and "ab-initio" methodology.

The *Fundamentals* section finishes with **Chapter 15** on aqueous corrosion. Corrosion thermodynamics expressed by Pourbaix diagrams are essentially phase diagram for the stability of oxides and ionic solutions under different conditions of pH and electrochemical potential. Analysis of corrosion kinetics with the aid of Tafel diagrams follows with emphasis on regions of active corrosion and passivity. Special corrosion processes such as localized corrosion, crevice corrosion and stress-corrosion cracking complete this chapter.

3.2 Applications

Descriptions of the specific commercial and industrial materials used to fabricate nuclear fuel, reactor internals and the pressure vessel constitute the introduction to the *Applications* half of the book. The goal is to be specific enough in the description of the physical phenomena to understand of the underlying mechanisms of processes or problems of practical importance.

Coverage of the specific materials used in nuclear power plants begins with **Chapter 16**, which deals with the properties of oxide fuels. The uranium dioxide and mixed-oxide fuels have been extensively studied over the last fifty years and much experience has been acquired in their design, fabrication, and use. The rationale for using these fuels is first described, followed by a review of its properties, fuel-pellet design and fabrication.

Chapter 17 traces the historical development of the fabrication of Zircaloy used for nuclear fuel cladding. This includes the relevant phase diagrams and the precipitate phases that result from unique thermo-mechanical processing. It includes the notion of crystallographic texture of fabricated Zircaloy parts, and how this property is produced, measured and affects mechanical properties. Information on the microstructural evolution of Zircaloy under irradiation is presented. This chapter also reviews the microstructures and properties of several important non-fuel metallic alloys, such as stainless steels for primary-circuit piping, ferritic steels for the pressure vessel and specialty alloys for specific applications.

Chapter 18 describes the bundling of fuel rods into fuel assemblies. Many of the fuel failures that have occurred in recent years have resulted from problems related to fuel assemblies. These have to do more with mechanical design and vibration control than with irradiation-induced changes. Fuel rod spacing and the mechanical design of the spacer grids are also presented. The limits on fuel performance in terms of cladding temperature, burnup and corrosion are discussed.

Chapter 19 summarizes the properties of fuel and cladding and the analytical tools used to describe the thermal behavior of fuel rods. The heat conduction equation is applied to the series resistances to heat flow from the fuel to the coolant. The effects of temperature, burnup (impurities) and fission density on the thermal conductivity of ceramic oxide fuel are explained in the framework of phonon scattering theory. Models of the conductance of the fuel-cladding gap before and after closure are considered.

Chapter 20 summarizes the numerous effects of the over 100 different nuclides produced by fission of uranium and plutonium on the properties of the fuel. The elemental composition of fission products continuously changes with burnup by radioactive decay even as their concentrations increase. The chemical forms of individual fission product elements depend upon temperature and oxygen potential. The rare gases xenon and krypton are produced in one out of four fissions. These elements do not react chemically but exist as elements in the fuel either as single atoms in the crystal lattice or as intergranular or intragranular bubbles. The partition of the fission gas between these two states determines the volume expansion (swelling) of the fuel and the escape from the fuel (release). A considerable portion of this chapter is devoted to the complex processes that govern the release of stable fission gases to the gap and the plenum.

Chapter 21 details the roles of the various additives to the water coolant that flows through the primary circuit. The combination of the high temperature (300° C) and radiolytic decomposition by gamma rays and fast neutrons render the water especially corrosive, both to in-core structures and out-of-core components such as the primary piping and the steam generator. In both types of LWRs, hydrogen is added to the water to minimize the highly oxidizing state of the water. In BWRs, noble metals (e.g. Pt) are added to reduce radiation levels in the primary circuit. In PWRs, an acidic form of boron is dissolved in the coolant as a nuclear control agent. To increase the pH, lithium hydroxide is added. These two additives must be carefully controlled to avoid excessive cladding corrosion.

Waterside corrosion and associated hydriding of Zircaloy cladding is one of the factors limiting the maximum attainable burnuup in LWRs. In **Chapter 22** the mechanisms of the formation of the oxide scale and its growth are reviewed with explanations of the initial cubic growth law and the eventual transition to linear behavior. The chapter also covers the mechanisms of crud formation and its consequences, which include degradation of thermal conductivity and the "axial-offset anomaly". Because hydriding occurs in the bulk metal, its effect on mechanical performance is postponed until **Chapter 26.**

Failure of a single fuel rod among the ~40,000 in the core is an occasion for concern. The risk is not in the primary failure, which does little more that bleed a bit of fission gas and iodine into the coolant. Rather, the risk is the possibility of a massive split of the cladding due to internal hydriding of the cladding resulting from steam ingress through the primary defect. **Chapter 23** reviews the types of primary cladding failures and their causes. These include fretting of grids against fuel rods and excessive strain of the cladding fuel to intimate contact with swelling fuel pellets.

Chapter 24 reviews the mechanisms of phase changes that can occur in irradiated metals. Under irradiation, microstructures and phases in alloys behave in ways that contradict thermodynamic expectations. Such oddities as precipitation from an undersaturated solid solution, dissolution of precipitates that should be stable, and the amorphization of a crystalline phase are routinely observed. This reversal of normal equilibrium states results from the large input of energy by the energetic particles constantly bombarding the system during irradiation. Because no analytical methods exist that can describe such transformations from first principles, these transformations will be described using approximate methods that follow and predict the kinetics of transformations.

Chapter 25 discusses how the combination of water chemistry, irradiation damage, and applied stress renders metal components prone to failure by intergranular stress corrosion cracking (IGSCC). Radiation induces segregation of alloy components in steel, specifically by moving protective chromium away from the surfaces. A simple model for IGSCC – the slip-dissolution model - is then developed, with a view to illustrating the coupling between the three factors that cause IGSCC.

The mechanical properties of materials change significantly under neutron irradiation. The safety of nuclear power plants requires verification that the reactor pressure vessel has not become overly embrittled by fast neutrons. The methods used to monitor this form of degradation, (such as the Charpy V-notch test) are reviewed in **Chapter 26.** Embrittlement results from irradiation-induced production of Cu-rich precipitates and "matrix damage" in the form of defect clusters. The increased density of these obstacles to dislocation motion causes the yield stress to increase (hardening) and also causes the material to fail at lower strains (embrittlement).

Also of great importance to the operation of nuclear reactors prediction and control of changes in the dimensions of components subjected to irradiation. Such deformations include irradiation growth, irradiation creep and void swelling. These changes, which result from preferential interactions of point defect with microstructural sinks, are well-described by rate theory (developed in Chapter 13). **Chapter 27** analyzes a model of coupled irradiation swelling and irradiation creep that results from the separation of vacancies to voids and interstitials to dislocations. The stress-induced preferential absorption creep mechanism observed in Zr alloys is also covered. Irradiation growth, present in crystallographically anisotropic alloys such as uranium metal and Zr alloys that also show pronounced texture, is treated in detail.

Fuel-rod cladding that previously needed to survive burnups of ~30 MWd/kgU is now required to maintain integrity twice as long. Longer residence time implies greater radiation damage and increases in waterside corrosion and hydriding. Also fuel rods may be exposed to more aggressive chemistry and an increased incidence of boiling, both of which result in significant changes to the structure of the fuel and the cladding. **Chapter 28** reviews these high-burnup effects. Not only is normal operation affected, but the response of the core to the reactivity-initiated accident and the loss-of-coolant accident is altered. The genesis of both of these accidents and means of mitigating their unwanted consequences are explained.

In **Chapter 29** all of the phenomena described in the *Applications* part of the book are integrated into massive *fuel behavior codes*. These codes incorporate the effects of fuel temperature, burnup and fission density in an attempt to predict the changing properties and chemical and physical states of the entire fuel rod as power is varied in a prescribed manner. The international collection of fuel behavior codes includes TRANSURANUS (EU), METEOR (France), ENIGMA (UK), FEMAXI (Japan), and FALCON and FRAPCON (USA).

4. CONCLUSIONS

Since its publication in 1976, the original book has been cited in technical journals 350 times, and over 3600 copies have been sold. In the last 30 years, the LWR has become firmly ensconced in the nuclear power industry, and a new book devoted uniquely to this type of reactor is clearly needed. The book in preparation will describe in detail the issues associated with the use of materials in light water reactors. It will be divided into two roughly-equal parts, the first covering the *Fundamentals* of materials science relevant to the secord, *Applications,* that follows.

The new book is intended to serve primarily students, but should also be useful as a reference for professionals engaged in the research or application of nuclear materials.

The authors would appreciate greatly any input and/or feedback on the topics, and coverage of the new book.

REFERENCES

[1] D. Gurinsky & G. Dienes, *Nuclear Fuels*, Van Nostrand (1956)
[2] G. Dienes and G. Vineyard, *Radiation Effects in Solids*, Interscience (1957)
[3] W. Wilkinson & W. Murphy, *Nuclear Reactor Metallurgy* Van Nostrand (1958)
[4] A. McIntosh & T. Heal, *Materials for Nuclear Engineers*, Interscience (1960)
[5] J. Belle, *Uranium Dioxide: Properties and Nuclear Applications*, U.S. Atomic Energy Commission (1961)
[6] J. Dawson & R. Sowden, *Chemical Aspects of Nuclear Reactors*, Buttersworths (1963)
[7] M. T. Simnad and L. Zumwalt, *Materials and Fuels for High-temperature Nuclear Energy Applications*, M.I.T. Press (1964)
[8] L. Chadderton, *Radiation Damage in Crystals*, Methuen (1965)
[9] J. Sauteron, *Les Combustibles Nucléaires*, Hermann (1965)
[10] R. Holdren, *Ceramic Fuel Elements*, Gordon & Breach (1966)
[11] B. T. Kelly, *Irradiation damage to solids*: Pergamon Press (1966)
[12] C. Smith, *Nuclear Reactor Materials*, Addison-Wesley (1967)
[13] J. Robertson, *Irradiation Effects in Nuclear Fuels*, Gordon and Breach (1969)
[14] M. W. Thompson, *Defects and Radiation Damage in Metals*: Cambridge University Press (1969)
[15] *Thermodynamics of Nuclear Materials*, IAEA Vienna (1974)
[16] D. R. Olander, *Fundamental Aspects of Nuclear Reactor Fuel Elements*: National Technical Information Services, P26711-P1 (1976)
[17] J. Gittus, *Irradiation Effects in Crystalline Solids*, Applied Science (1978)
[18] J. T. A. Roberts, *Structural Materials in Nuclear Power Systems*, Plenum Press (1981)
[19] B. Ma, *Nuclear Reactor Materials*, Van Nostrand (1983)
[20] J. N. Anno, *Notes on radiation effects on materials*: Hemisphere Pub. Corp (1984)
[21] H. Matzke, *Science of Advanced LMFBR Fuels*: North-Holland (1986)
[22] B. T. Frost, *Nuclear Fuel Elements: design, fabrication and performance*, Pergamon (1987)
[23] C. Gupta, *Materials in Nuclear Energy Applications*, CRC Press (1989)
[24] B. R. T. Frost, *Nuclear Materials,* vol. I and II : VCH, Materials Science and Technology: a Comprehensive Treatment. (1992)
[25] A. M. Parshin, *Structure, strength, and radiation damage of corrosion-resistant steels*: American Nuclear Society, (1996)
[26] N. N. Alekseenko, A. Amaev, I Goryin, and V. A. Nikolaev, *Radiation damage of nuclear power plant pressure vessel steels*: American Nuclear Society, (1997)
[27] V. Kritsky, *Water Chemistry and Corrosion of Nuclear Power Plant Structural Materials*, American Nuclear Society (1999)
[28] H. Bailly, Ed, *The Nucleaer Fuel of Pressurized Water Reactors*, Lavoisier Publishing (1999)
[29] D. Olander, "Light-Water Reactor Fuel Design and Performance," in Encyclopedia of Materials Science and Technology, R. W. Cahn et al, Editors-in-Chief, Pergamon Press, (2001)
[30] T. Allen et.al., "Higher Temperature Materials Workshop," Argonne National Laboratory-West ANL-02/12, (2002)
[31] J. Ziegler, J. Biersack and U. Littmark, "The Stopping and Range of Ions in Solids," Pergamon Press (1985)