

Contents

Movies accompanying the text are located at: www.sitemaker.umich.edu/was.

Part I Radiation Damage

1	The Radiation Damage Event	3
1.1	Neutron–Nucleus Interactions	4
1.1.1	Elastic Scattering	4
1.1.2	Inelastic Scattering	11
1.1.3	(n, 2n) Reactions	14
1.1.4	(n, γ) Reactions	15
1.2	Interactions Between Ions and Atoms	17
1.2.1	Interatomic Potentials	17
1.2.2	Collision Kinematics	24
1.3	Ionization Collisions	44
1.3.1	Energy Loss Theory	44
1.3.2	Range Calculations	57
	Nomenclature	66
	Problems	68
	References	71
2	The Displacement of Atoms	73
2.1	Elementary Displacement Theory	73
2.1.1	Displacement Probability	74
2.1.2	The Kinchin and Pease Model for Atom Displacements	75
2.1.3	The Displacement Energy	78
2.1.4	The Electron Energy Loss Limit	83
2.2	Modifications to the K–P Displacement Model	85
2.2.1	Consideration of E_d in the Energy Balance	85
2.2.2	Realistic Energy Transfer Cross Sections	86
2.2.3	Energy Loss by Electronic Excitation	87
2.2.4	Effects of Crystallinity	91
2.3	The Displacement Cross Section	105
2.3.1	Elastic Scattering	106
2.3.2	Inelastic Scattering	107
2.3.3	(n, 2n) and (n, γ) Displacements	107
2.3.4	Modifications to the K–P Model and Total Displacement Cross Section	108

2.4	Displacement Rates	109
2.5	Correlation of Property Changes and Irradiation Dose	113
2.6	Displacements from Charged Particle Irradiation	115
	Nomenclature	119
	Problems	121
	References	123
3	The Damage Cascade	125
3.1	Displacement Mean Free Path	125
3.2	Primary Recoil Spectrum	126
3.3	Cascade Damage Energy and Cascade Volume	131
3.4	Computer Simulations of Radiation Damage	133
3.4.1	Binary Collision Approximation (BCA) Method	133
3.4.2	Molecular Dynamics (MD) Method	136
3.4.3	Kinetic Monte Carlo (KMC) Method	138
3.5	Stages of Cascade Development	140
3.6	Behavior of Defects within the Cascade	143
	Nomenclature	152
	Problems	153
	References	154
4	Point Defect Formation and Diffusion	155
4.1	Properties of Irradiation-Induced Defects	155
4.1.1	Interstitials	155
4.1.2	Multiple Interstitials	160
4.1.3	Interstitial-Impurity Complexes	161
4.1.4	Vacancies	162
4.1.5	Multiple Vacancies	162
4.1.6	Solute-Defect and Impurity-Defect Clusters	162
4.2	Thermodynamics of Point Defect Formation	164
4.3	Diffusion of Point Defects	167
4.3.1	Macroscopic Description of Diffusion	168
4.3.2	Mechanisms of Diffusion	169
4.3.3	Microscopic Description of Diffusion	172
4.3.4	Jump Frequency, Γ	174
4.3.5	Jump Frequency, ω	176
4.3.6	Equations for D	177
4.4	Correlated Diffusion	180
4.5	Diffusion in Multicomponent Systems	182
4.6	Diffusion along High Diffusivity Paths	184
	Nomenclature	187
	Problems	188
	References	190

5	Radiation-Enhanced and Diffusion Defect Reaction Rate Theory . . .	191
5.1	Point Defect Balance Equations	192
5.1.1	Case 1: Low Temperature, Low Sink Density	194
5.1.2	Case 2: Low Temperature, Intermediate Sink Density	196
5.1.3	Case 3: Low Temperature, High Sink Density	197
5.1.4	Case 4: High Temperature	199
5.1.5	Properties of the Point Defect Balance Equations	201
5.1.6	Deficiencies of the Simple Point Defect Balance Model . . .	203
5.2	Radiation-Enhanced Diffusion	203
5.3	Defect Reactions	206
5.3.1	Defect Production	209
5.3.2	Recombination	210
5.3.3	Loss to Sinks	210
5.3.4	Sink Strengths	211
5.4	Reaction Rate-Controlled Processes	211
5.4.1	Defect-Void Interaction	211
5.4.2	Defect-Dislocation Interaction	212
5.5	Diffusion-Limited Reactions	212
5.5.1	Defect-Void Reactions	213
5.5.2	Defect-Dislocation Reactions	215
5.6	Mixed Rate Control	217
5.7	Defect-Grain Boundary Reactions	218
5.8	Coherent Precipitates and Solutes	219
	Nomenclature	222
	Problems	223
	References	227

Part II Physical Effects of Radiation Damage

6	Radiation-Induced Segregation	231
6.1	Radiation-Induced Segregation in Concentrated Binary Alloys	233
6.1.1	Solution to the Coupled Partial Differential Equations	239
6.1.2	Interstitial Binding	240
6.1.3	Solute Size Effect	241
6.1.4	Effect of Temperature	242
6.1.5	Effect of Dose Rate	245
6.2	RIS in Ternary Alloys	246
6.3	Effect of Local Composition Changes on RIS	250
6.4	Effect of Solutes on RIS	253
6.5	Examples of RIS in Austenitic Alloys	256
6.6	RIS in Ferritic Alloys	259
	Nomenclature	263
	Problems	264
	References	265

7	Dislocation Microstructure	267
7.1	Dislocation Lines	267
7.1.1	Dislocation Motion	270
7.1.2	Description of a Dislocation	274
7.1.3	Displacements, Strains and Stresses	276
7.1.4	Energy of a Dislocation	280
7.1.5	Line Tension of a Dislocation	281
7.1.6	Forces on a Dislocation	283
7.1.7	Interactions Between Dislocations	289
7.1.8	Extended Dislocations	292
7.1.9	Kinks and Jogs	294
7.2	Faulted Loops and Stacking Fault Tetrahedra	294
7.3	Defect Clusters	298
7.3.1	Fraction of Defects Forming Clusters	298
7.3.2	Types of Clusters	300
7.3.3	Cluster Mobility	304
7.4	Extended Defects	306
7.5	Effective Defect Production	311
7.6	Nucleation and Growth of Dislocation Loops	313
7.6.1	Loop Nucleation	313
7.6.2	Clustering Theory	319
7.6.3	Production Bias-Driven Cluster Nucleation	321
7.7	Dislocation Loop Growth	325
7.8	Recovery	329
7.9	Evolution of the Interstitial Loop Microstructure	332
	Nomenclature	335
	Problems	338
	References	341
8	Irradiation-Induced Voids and Bubbles	343
8.1	Void Nucleation	343
8.1.1	Equilibrium Void Size Distribution	345
8.1.2	Void Nucleation Rate	348
8.1.3	Effect of Inert Gas	355
8.1.4	Void Nucleation with Production Bias	362
8.2	Void Growth	365
8.2.1	Defect Absorption Rates and Concentrations at Sink Surfaces	366
8.2.2	Point Defect Balances	370
8.3	Void Growth Equation	372
8.3.1	Temperature Dependence	377
8.3.2	Dose Dependence	380
8.3.3	Role of Dislocations as Biased Sinks	384
8.3.4	Dose Rate Dependence	385
8.3.5	Irradiation Variable Shifts	388

8.3.6	Stress Dependence	393
8.3.7	Effect of RIS	397
8.3.8	Effect of Production Bias	399
8.3.9	Void Lattices	402
8.3.10	Effect of Microstructure and Composition	404
8.3.11	Effect of Reactor Operating History	409
8.4	Bubble Growth	415
8.4.1	Bubble Mechanics	415
8.4.2	Growth Law	418
8.4.3	Bubble Growth by Dislocation Loop Punching	421
8.4.4	Bubble Lattices	422
8.4.5	Helium Production	423
	Nomenclature	423
	Problems	427
	References	430
9	Phase Stability Under Irradiation	433
9.1	Radiation-Induced Segregation and Radiation-Induced Precipitation	433
9.2	Recoil Dissolution	436
9.3	Radiation Disordering	445
9.4	Incoherent Precipitate Nucleation	450
9.5	Coherent Precipitate Nucleation	455
9.6	Metastable Phases	460
9.6.1	Order–Disorder Transformations	461
9.6.2	Crystal Structure Transformations	461
9.6.3	Quasicrystal Formation	463
9.7	Amorphization	463
9.7.1	Heat of Compound Formation and Crystal Structure Differences	464
9.7.2	Solubility Range of Compounds and Critical Defect Density	467
9.7.3	Thermodynamics and Kinetics of Amorphization	470
9.8	Phase Stability in Reactor Core Component Alloys	480
	Nomenclature	484
	Problems	487
	References	488
10	Unique Effects of Ion Irradiation	491
10.1	Ion Irradiation Techniques	491
10.2	Composition Changes	494
10.2.1	Sputtering	495
10.2.2	Gibbsian Adsorption	501
10.2.3	Recoil Implantation	503
10.2.4	Cascade (Isotropic, Displacement) Mixing	506

10.2.5	Combination of Processes Affecting Surface Compositional Changes	518
10.2.6	Implant Re-Distribution During Ion Implantation	522
10.3	Other Effects of Ion Implantation	525
10.3.1	Grain Growth	525
10.3.2	Texture	527
10.3.3	Dislocation Microstructure	528
10.4	High Dose Gas Loading: Blistering and Exfoliation	530
10.5	Solid Phases and Inert Gas Bubble Lattices	535
	Nomenclature	537
	Problems	540
	References	543
11	Simulation of Neutron Irradiation Effects with Ions	545
11.1	Motivation for Using Ion Irradiation as a Surrogate for Neutron Irradiation	545
11.2	Review of Aspects of Radiation Damage Relevant to Ion Irradiation	547
11.3	Particle Type Dependence of RIS	550
11.4	Advantages and Disadvantages of the Various Particle Types	557
11.4.1	Electrons	558
11.4.2	Heavy Ions	562
11.4.3	Protons	564
11.5	Irradiation Parameters for Particle Irradiations	565
11.6	Emulation of Neutron Irradiation Damage with Proton Irradiation . .	567
	Nomenclature	574
	Problems	575
	References	576
<hr/>		
Part III Mechanical Effects of Radiation Damage		
<hr/>		
12	Irradiation Hardening and Deformation	581
12.1	Elastic and Plastic Deformation	581
12.1.1	Elasticity	581
12.1.2	Plasticity	587
12.1.3	Tension Test	589
12.1.4	Yield Strength	592
12.2	Irradiation Hardening	594
12.2.1	Source Hardening	595
12.2.2	Friction Hardening	597
12.2.3	Superposition of Hardening Mechanisms	606
12.2.4	Hardening in Polycrystals	612
12.2.5	Saturation of Irradiation Hardening	613
12.2.6	Comparison of Measured and Predicted Hardening	617
12.2.7	Radiation Anneal Hardening	620

12.2.8	The Correlation Between Hardness and Yield Strength	622
12.3	Deformation in Irradiated Metals	626
12.3.1	Deformation Mechanism Maps	630
12.3.2	Localized Deformation	632
	Nomenclature	636
	Problems	638
	References	640
13	Fracture and Embrittlement	643
13.1	Types of Fracture	643
13.2	The Cohesive Strength of Metals	644
13.3	Fracture Mechanics	647
13.4	Fracture Mechanics Tests	653
13.5	Elastic-Plastic Fracture Mechanics	655
13.6	Brittle Fracture	658
13.7	Irradiation-Induced Embrittlement in Ferritic Steels	664
13.7.1	Notched Bar Impact Testing	664
13.7.2	DBTT and Reduction in the Upper Shelf Energy	666
13.7.3	Master Curve Approach	669
13.7.4	Factors Affecting the Degree of Embrittlement	673
13.7.5	Embrittlement of Ferritic-Martensitic Steels	677
13.7.6	Annealing and Re-Irradiation	678
13.7.7	Fatigue	679
13.8	Fracture and Fatigue of Austenitic Alloys at Low to Intermediate Temperatures	685
13.8.1	Effect of Irradiation on Fracture Toughness	686
13.8.2	Effect of Irradiation on Fatigue	689
13.9	High-Temperature Embrittlement	690
13.9.1	Grain Boundary Voids and Bubbles	692
13.9.2	Grain Boundary Sliding	697
13.9.3	Grain Boundary Crack Growth	700
13.9.4	Fracture Mechanism Maps	703
	Nomenclature	703
	Problems	705
	References	707
14	Irradiation Creep and Growth	711
14.1	Thermal Creep	712
14.1.1	Dislocation Creep	716
14.1.2	Diffusional Creep	723
14.2	Irradiation Creep	725
14.2.1	Stress-Induced Preferential Nucleation of Loops (SIPN)	726
14.2.2	Stress-Induced Preferential Absorption (SIPA)	729
14.2.3	Climb and Glide due to Preferential Absorption (PAG)	731
14.2.4	Climb and Glide Driven by Dislocation Bias	733

14.2.5	Transient Creep	734
14.2.6	Loop Unfaulting	738
14.2.7	Recovery Creep	739
14.2.8	Diffusional Creep: Why There is no Effect of Irradiation ..	740
14.2.9	Comparison of Theory with Creep Data	741
14.2.10	Irradiation-Modified Deformation Mechanism Map	744
14.3	Irradiation Growth and Creep in Zirconium Alloys	746
14.3.1	Microstructure of Irradiated Zirconium Alloys	747
14.3.2	Irradiation Growth	750
14.3.3	Irradiation Creep	753
	Nomenclature	758
	Problems	760
	References	762
15	Environmentally Assisted Cracking of Irradiated Metals and Alloys .	765
15.1	Stress Corrosion Cracking: A Tutorial	768
15.1.1	SCC Tests	770
15.1.2	SCC Processes	772
15.1.3	Metallurgical Condition	774
15.1.4	Crack Initiation and Crack Propagation	774
15.1.5	Mechanisms of Stress Corrosion Cracking	783
15.1.6	Predictive Model for Crack Propagation	786
15.1.7	Mechanical Fracture Models	788
15.1.8	Corrosion Fatigue	790
15.1.9	Hydrogen Embrittlement	790
15.2	Effects of Irradiation on Water Chemistry	791
15.2.1	Radiolysis and its Effect on Corrosion Potential	791
15.2.2	Effect of Corrosion Potential on IASCC	794
15.3	Service and Laboratory Observations of Irradiation Effects on SCC. 797	
15.3.1	Austenitic Alloys	797
15.3.2	Ferritic Alloys	802
15.4	Mechanisms of IASCC	805
15.4.1	Grain Boundary Chromium Depletion	805
15.4.2	Irradiation Hardening	806
15.4.3	Deformation Mode	807
15.4.4	Selective Internal Oxidation	809
15.4.5	Irradiation-Induced Creep	809
	Nomenclature	809
	Problems	811
	References	812
Index		815