## Subject Index

A	C
Alloy development, 805 Alloying element, redistribution, 242 Alpha-phase	CANDU reactor extrusion-billet preheating effects on microstructure and properties, 657
extrusion-billet preheating effects on microstructure, 657 niobium, 580	modelling in-reactor deformation of pressure tubes, 518 Carbon dating, CANDU pressure tube corrosion,
Amorphization, 557 precipitates, 541	265 Cathodic charging, 319
Analytical electron microscopy, zirconium alloys, 163	c dislocation loops, 628 Characterization, CANDU pressure tubes, 265
Anisotropic viscoplastic behavior, Zircaloy cladding tube model, cladding tubes, 373	Charged-particle irradiation, 557 Chromium anodic protection, 203
Annealing final, model for effect on in- and out-of-reactor	corrosion behavior and, 865 zirconium alloy development, 825
creep behavior, 448 parameter, nodular corrosion, 865 temperature, Zircaloys, 74	Cladding tubes, Zircaloy, 74 anisotropic viscoplastic behavior model, 373 effect of final annealing on in- and out-of-
Anodic polarization curve, zirconium alloys, 163	reactor creep behavior, 448 fracture toughness, 431
Anodic protection, precipitates in Zircaloys, 203	Composite, Zircaloy ductility, 407 Corrosion
Autoclave tests, 319, 710, 805	boric acid inhibition, 114 CANDU pressure tubes, 265
В	dependence on kind, size, and distribution of intermetallic precipitates, 541
Beta phase, 557	duplex and reference cladding, 805
extrusion-billet preheating effects on microstructure, 657	hydrogen pickup and redistribution, 338 in-reactor, Zircaloys, 726
Beta-solution treatment, Zircaloys, 74	LiOH acceleration, 114
Billet, effects on microstructure and properties, 657	long-term in situ investigation, zirconium alloys, 181
Boiling water reactors cladding materials, nodular corrosion, 865	long-time behavior, comparison of zirconium alloys, 850
long-time corrosion behavior, comparison of zirconium alloys, 850	modeling, PWR Zircaloy fuel cladding corrosion, 137
thermomechanical processing effects, Zircaloys, 726	nodular, in-BWR and out-of-pile, 865 post-transition, 295
Ziracloy lined zirconium barrier fuel cladding, 676	pressurized water reactor Zircaloy fuel cladding, 137
zirconium alloy development, 825	pretransition rates, 295
Boric acid, inhibition of degradation of zirconium alloys, 114	rate, zirconium alloys, hydrogen role, 319 steady-state, 295
Burnup, high, zirconium alloy development, 825	transition rates, 295

Corrosion—continued	Electrochemical impedance spectroscopy,
uniform, anodic protection, 203	CANDU pressure tubes, 265
Zircaloys, 12, 55	Electrochemical measurements, long-term in situ
zirconium alloys, 785	corrosion investigation, zirconium alloys
development, 825	181
in-pile grown films, 218	Electrochemical properties, correlation with
ZIRLO nuclear fuel cladding, 710	corrosion resistance of zirconium alloys,
Corrosion resistance	163
correlation with electrochemical properties of	Electron microscopy, in-pile grown corrosion
zirconium alloys, 163	films, 218
in-reactor Zircaloys, 726	Embrittlement
precipitates, 203	reactor core materials, 758
Zircaloy lined zirconium barrier fuel cladding,	Zircaloy cladding tubes, 431
676	Extrusion, effects on microstructure and
Zircaloys, 35, 74	properties, 657
Crack growth resistance	
irradiated zirconium alloy pressure tubes, 492	F
temperature and yield strength effect, 394	
Crack propagation, ziracloy lined zirconium	Fatigue, irradiated heat-treated zirconium alloys
barrier fuel cladding, 676	469
Creep	Film stress, oxide, 55
effect of final annealing, 448	Finite element code, 518
irradiated heat-treated zirconium alloys, 469	Fracture resistance, microstructure effects, 695
Zircaloys, 12	Fracture toughness
zirconium alloys, 785	extrusion-billet preheating effects, 657
Crystal structure, oxide on Zircaloys, 35	irradiated heat-treated zirconium alloys, 469
_	irradiated zirconium alloy pressure tubes, 492
D	irradiation effects, 758
T. 4	service life, 884
Deformation	Zircaloy cladding tubes, 431
in-reactor, 518	Fuel cladding
irradiated heat-treated zirconium alloys, 469	duplex and reference, 805
irradiated zirconium alloy pressure tubes, 492	in-pile grown corrosion films, 218
service life, 884	VVER and RBMK cores, 785
Deformation equation, 518	Zircaloy-2 lined zirconium barrier, 676
Delayed hydride cracking	ZIRLO, corrosion behavior, 710
delayed, temperature and yield strength effect	G
on, 394	G
irradiated heat-treated zirconium alloys, 469	Cassaus charging 310
service life, 884	Gaseous charging, 319 Grains, 603
Deuterium, irradiated zirconium alloys, 469 Dislocation	interaction stresses, 518
density, irradiation effects, 580, 603	Growth
structure, 518	breakaway, 623
effect of neutron irradiation, 603	zirconium alloys, 785
Ductility Ductility	Encomuni anoys, 700
irradiated Zircaloy, hydride precipitate	Н
localization and neutron fluence effects,	
407	Hafnium, embrittlement, 758
microstructure effects, 695	Heat treatment
111010011111111111111111111111111111111	effects on
${f E}$	creep behavior, 448
• • • • • • • • • • • • • • • • • • •	ductility and fracture resistance, 695
E110, 785	ZIRLO corrosion behavior, 710
E635, 785	zirconium alloy pressure tube properties, 469
EB zirconium, 203	High burnup fuel rods, Zircaloys, 137

High-temperature water, zirconium alloy	crystalline-to-amorphous transformation, 557
corrosion, 114	effects on
Hydrides	ductility and fracture resistance, 695
duplex and reference cladding, 805	in-PWR irradiation, 541
embrittlement, 758	PWR Zircaloy fuel cladding corrosion, 137
precipitate, localization effects on irradiated	irradiation effects, Zircaloys, 726
Zircaloy ductility, 407	structural changes during irradiation, 580
precipitation, 338	Internal variables model, anisotropic viscoplastic
at metal/oxide interface, 319	behavior, 373
Zircaloys	Iodine stress corrosion, Zircaloys, 12
delayed hydride cracking, 394	Iron
Hydride volume fraction, Zircaloy ductility, 407	anodic protection, 203
Hydriding	corrosion behavior and, 865
ductility of Zircaloy, 407	effects on
Zircaloy lined zirconium barrier fuel cladding,	ductility and fracture resistance, 695
676	nucleation of c component dislocation loops,
Hydrogen	628
concentration and service life, 884	redistribution, Zircaloy oxide layers, 242
embrittlement, Zircaloy cladding tubes, 431	supersaturation, 628
pickup and redistribution	zirconium alloy development, 825
alpha-annealed Zircaloy, 338	Irradiation
zirconium alloy development, 825	corrosion, duplex and reference cladding, 805
role on corrosion rate, zirconium alloys, 319	effects on, 12
solubility, 338	dislocation structure and phase composition,
uptake, CANDU pressure tubes, 265	603
Hydrogen thermal redistribution, effect on PWR	ductility of Zircaloy, 407
Zircaloy fuel cladding corrosion, 137	microstructure evolution, 580
	oxidation, 242
I	Zircaloy mechanical properties, 726
	ZIRLO corrosion behavior, 710
Impedance spectroscopy	embrittlement, 758
in-pile grown corrosion films, 218	in-PWR, effect on size, structure, and
Zircaloys, 181	composition of intermetallic precipitates,
oxide on, 55	541
Impurities, effect on Zircaloy aqueous corrosion,	long-time corrosion behavior, comparison of
295	zirconium alloys, 850
In-BWR corrosion, zirconium alloy comparison,	microstructure effects, Zircaloys, 726
850	nucleation of c component dislocation loops, 628
Infinite velocity, SIMS, 265	phase transformations, in situ studies, 557
Inner Zircaloy liner, 676	Zircaloy
In-pile corrosion, Zircaloys, 865	fracture toughness, 431
In-PWR corrosion, zirconium alloy comparison,	lined zirconium barrier fuel cladding, 676
850	zirconium alloy pressure tubes, 492
In-reactor	properties, 469
deformation, 518	Irradiation creep, in-reactor deformation, 518
E635 as fuel cladding material, 785	Irradiation growth, 603
final annealing effect on creep behavior, 448	iron effect, 628
ZIRLO fuel cladding, corrosion behavior, 710	non-linear, cold-worked Zircaloy, 623
In-reactor corrosion, 12	Zircaloys, 12
Zircaloys, 137	Irradiation hardening, Zircaloys, 726
In-reactor creep, 12	Irradiation precipitation, 557
In-reactor fuel performance, Zircaloy lined	manufoli prospimitori, 337
zirconium harrier fuel cladding 676	T.

in situ measurement, Zircaloy corrosion, 181

Intermetallic precipitates

anodic protection, 203

Laboratory tests, long-term corrosion behavior, zirconium alloy comparison, 850

Lattice peremeters 590	effect on ZIRLO corrosion behavior, 710
Lattice parameters, 580	zirconium alloy development, 825
Lauer phase, 557 Laves phase, 541	Nodular corrosion, zirconium alloys, 163
Light water reactors, operating conditions, 12	Nuclear fuel
Lithium, effect on oxidation rate, 94	case study, 3
Lithium hydroxide	history, 3
degradation of zirconium alloys, 114	nistory, 5
PWR Zircaloy fuel cladding corrosion, 137	0
Loops, 603	Ü
200ра, 003	Omega phase, 557
M	Out-of-pile corrosion, zirconium alloy comparison, 850
Manufacturing processes, Zircaloy lined	Oxidation
zirconium barrier fuel cladding, 676	irradiated heat-treated zirconium alloys, 469
Matrix effects, inside surface oxide, 265	kinetics, Zircaloys, 242
Matsuo creep model, 448	rate, lithium effect, 94
Mechanical properties, Zircaloys, 373	saturation, zirconium alloy development,
ductility, 407	825
post-irradiation, 726	Oxide
Metal/oxide examination, 319	characteristics, CANDU pressure tubes, 265
Microstructure	growth rate, zirconium alloys, 55
duplex and reference cladding, 805	microstructure, waterside corrosion of Zircaloy
effects on	cladding in lithiated environment, 94
ductility and fracture resistance, 695	morphology, Zircaloys, 74 waterside layer thickness, 407
microstructure and properties, 657	
evolution during irradiation, 557, 580	Oxide film, Zircaloys, 35 Oxide layers, Zircaloys
extrusion-billet preheating effects, 657 irradiation effects, Zircaloys, 726	microstructure evolution and iron redistribution
oxide films, 94	242
ZIRLO fuel cladding, corrosion behavior, 710	thickness, 181
Modeling	PWR Zircaloy fuel cladding corrosion, 137
anisotropic viscoplastic behavior, 373	Oxygen partitioning, mechanical properties, 657
in-reactor deformation, 518	r r
Molybdenum, zirconium alloy development,	P
825	
Morphology, oxide on Zircaloys, 35	Pellet clad interaction, 676
Multiaxial loadings, Zircaloys, 373	Phase composition, effect of neutron irradiation, 603
N	Phase structure, during irradiation, 580
	Phase transformations, under irradiation,
Neutron damage, oxide films, 137	zirconium alloys, in situ studies, 557
Neutron irradiation	Pin-loading tension test, 431
effects on	Porosity, zirconium alloys, 55
dislocation structure and phase composition, 603	Post-failure degradation, Zircaloy lined zirconium barrier fuel cladding, 676
irradiated Zircaloy ductility, 407	Precipitates
long-time corrosion behavior, comparison of	dissolution, 726
zirconium alloys, 850	intermetallic (see Intermetallic precipitates)
microstructure evolution, 580	irradiation, 557
Zircaloys, 12	effect on size, distribution, and composition, 541, 603
Nickel corrosion behavior and, 865	nodular corrosion, 865
zirconium alloy development, 825	Zircaloys, 12
Niobium	anodic protection, 203
in alpha-phase, 580	zirconium alloys, 163
	- ·

Pre-heat temperature, effects on microstructure Tensile strength, extrusion-billet preheating and properties, 657 effects, 657 Pressure tubes, zirconium allovs Test method, fracture toughness, 431 cold-worked, non-linear irradiation growth, Tetragonal phase, 55 Texture, crystallographic, 518 development, service life greater than 30 years, Thorium, effect on Zircaloy aqueous corrosion, 884 extrusion-billet preheating effects, 657 Threshold stress intensity, delayed hydride irradiated heat-treated, 469 cracking, 394 modelling in-reactor deformation, 518 Tit content Pressurized water reactor corrosion of zirconium alloys, 181 duplex and reference cladding, corrosion effect on ZIRLO corrosion behavior, 710 behavior, 805 PWR Zircaloy fuel cladding corrosion, 137 in-pile grown corrosion films, 218 Toughness tests, small- and large-scale, irradiated long-time corrosion behavior, comparison of zirconium alloy pressure tubes, 492 zirconium alloys, 850 Transmission electron microscopy Zircaloys in-pile grown corrosion films, 218 aqueous corrosion, 295 microstructure evolution, 580 corrosion kinetics, 242 oxide, 74 fuel cladding, 137 films, 94 hydrogen pickup and redistribution, 338 microstructure, 35 layers, Zircaloys, 242 R U Radiation (see Irradiation) Reactor core materials, embrittlement, 758 Uranium, effect on Zircaloy aqueous corrosion, Recrystallization, effect on creep behavior, 448 295 V Scanning electron microscopy Valences, zirconium alloy development, 825 in-pile grown corrosion films, 218 Voids, formation, 758 irradiated Zircaloys, 726 Volume-controlled fracture model, 492 oxide on Zircaloys, 55, 74 Science policy, 3  $\mathbf{x}$ Secondary ion mass spectrometry CANDU pressure tubes, 265 X-bar zirconium, 203 extrusion-billet preheating effects, 657 X-ray diffraction oxide films, 94 microstructure evolution, 580 Self-consistent model, anisotropic deformation, oxide on Zircaloys, 55 518 Service life, 30-year, 884 Y Soak time, effects on microstructure and properties, 657 Yield stress, effect on delayed hydride cracking, Steam, corrosion and, 319 394 Strain rates, 518 Stress intensity factor, delayed hydride cracking,  $\mathbf{Z}$ Zircaloys Т alpha-annealed, hydrogen pickup and redistribution, 338 Tellurium, zirconium alloy development, 825 annealing temperature effect on corrosion Tensile properties, irradiated zirconium alloys, behavior and oxide microstructure, 74 726 aqueous corrosion, trace impurity uranium heat-treated, 469 effect, 295

Zircaloys—continued	corrosion
behavior and properties in power reactors, 12	duplex and reference cladding, 805
cladding tube	effects of processing variables and alloy
anisotropic viscoplastic behavior model, 373	chemistry, 710
fracture toughness, 431	in-pile grown films, 218
VVER and RBMK cores, 785	long-time behavior, 850
cold-worked, non-linear irradiation growth,	long-term in situ investigation, 181
623	rate, hydrogen role, 319
hydrided, temperature and yield strength effect	tin content and, 181
on delayed hydride cracking, 394	development
in-BWR and out-of-pile nodular corrosion	boiling water reactors, 825
behavior, 865	service life greater than 30 years, 884
in-reactor corrosion and post-irradiation	extrusion-billet preheating effects on
mechanical properties, 726	microstructure and properties, 657
irradiated	fuel rod cladding, VVER and RBMK cores,
ductility, hydride precipitate localization and	785
neutron fluence effects, 407	hydrothermal redeposition, 114
iron effect on nucleation of $c$ component	in-PWR irradiation, effect on size, structure,
dislocation loops, 628	and composition of intermetallic
lined zirconium barrier fuel cladding, 676	precipitates, 541
model for effect of final annealing on in- and	irradiated heat-treated, pressure tube properties,
out-of-reactor creep behavior, 448	469
oxide	LiOH degradation mechanisms, 114
film microstructure, waterside corrosion in	microstructure effects on ductility and fracture
lithiated environment, 94	resistance, 695
layers, microstructure evolution and iron	neutron irradiation effect on dislocation
redistribution, 242	structure and phase composition, 603
microstructure, 35	oxide
precipitates, anodic protection, 203	microstructure, 35
pressurized water reactor fuel cladding, 137	morphology and oxidation rate, 55
reactor core, embrittlement, 758	phase transformations under irradiation, in situ
tin content and corrosion, 137	studies, 557
waterside corrosion in lithiated environment,	precipitates, anodic protection, 203
94	pressure tubes, modelling in-reactor
Zirconium alloys	deformation, 518
behavior and properties in power reactors, 12	Zircaloy lined zirconium barrier fuel cladding, 676
boric acid effect, 114	Zirconium barrier, Zircaloy lined, 676
CANDU pressure tubes, 265	ZIRLO, fuel cladding
correlation electrochemical properties and	corrosion behavior, 710
corrosion resistance, 163	E635 as material, 785