

# Subject Index

**A**

- Accumulated annealing parameter, 437
- Amorphization, 521, 687
- Analytical scanning, 687
- Anion vacancy migration, 760
- Anisotropy, pressure tubes, 202, 469
- Annealing parameter, 307, 328, 663, 760
- Applied stress, 559

**ASTM STANDARDS**

- B-531-92, 80

Autoclave testing, 307, 351, 483, 579,  
724, 760

Axial fatigue, 499

**B**

- Barrier fuel, 3
- Barrier layer, 615
- Beta quenched phase, 663
- Boiling water reactors
  - boiling conditions, 351
  - corrosion behavior of zircaloy, 400, 599
  - corrosion environment, 709
  - creep anisotropy in zircaloy cladding, 469
  - fatigue behavior of zircaloy and zirconium, 499
  - heat treated pressure tube, 183
  - zirconium barrier fuel, 3
- Boric acid, 378
- Boron, 378
- Burnups, in pressurized water reactors, 438, 521, 760
- Burst strength, welds in zirconium, 264

**C**

- CANDU (Canada Deuterium Uranium) pressure tubes, 62, 116, 135, 168, 202
- Calandria tubes in CANDU reactor, 264
- Carbon, 221
- Chemical composition, zircaloy oxidation, 80
- Chlorine, 221
- Chromium, in zirconium alloys, 438

Cladding, fuel, 3, 19

Cladding tubes, 549, 599

Cladding, zircaloy, 245, 285, 307, 328, 469, 599, 687, 745, 760

Cold pilgering, 245, 285

Compact tension specimen, fatigue behavior, 499

Contractile strain ratio, 469

Coolant chemistry in water reactors, effects on zircaloy corrosion behavior, 779

Corrosion, 19, 98, 116, 183

Corrosion acceleration, 378

Corrosion enhancement, 745

Corrosion inhibition, 378

Corrosion mechanism of zirconium alloys, 615, 644, 724, 760, 779

Corrosion modeling, 760

Corrosion resistance, zircaloy, 285, 307

Corrosion resistance, zirconium based alloys, 437, 483, 579, 709

Corrosion, zircaloy-2, 599

Corrosion, zircaloy-4, 351

Crack driving force, 35

Crack growth resistance, 135

Crack propagation of zircaloy-4, 559

Crack velocity, 35

Cracking, 35

Cracks (materials), zircaloy-2 tubing, 285

Creep (materials), 202, 469, 483, 521, 724

Crystallographic orientation, 559

Cumulative annealing parameter, 307, 328

**D**

Damage (materials), 245

Defected rods, 745

Deformation (materials), 419, 469

Delayed hydride cracking, 35, 264

Deuterium concentration, 62, 116

Diffusion, 116

Dislocations, 521

Dissolution, 521

**E-F**

Elongation, 168

Electron microscopy, 116

Examination methods, corrosion  
mechanism, 615, 644  
Fabrication process, corrosion resistant  
zircaloy, 285, 307, 328  
Failure mechanisms, nuclear fuel, 3  
Fatigue behavior, zircaloy-4 tubes, 549  
Fatigue crack growth, 499  
Fatigue testing, 549  
Fracture (materials), 221  
Fracture resistance, 221  
Fracture toughness, 135, 183  
Fretting corrosion, 19  
Fuel rods, cladding, 599, 709, 724, 745,  
760  
Fuel rod defects, 19  
Fuel utilization in pressurized water  
reactors, 483  
Fugen (165MWe), heavy water, boiling  
light water cooled reactor, 183

**G–H**

Granular oxides, 745  
Growth, in-reactor corrosion performance  
of zircaloy, 724  
Heat affected zone, 264  
Heat treated pressure tube, 183  
High pressure, 450  
High temperature oxidation of  
zircaloy-4, 450  
High temperature pressurized water  
reactors, 760  
Hot rolling and annealing conditions, 307  
Hydride cracking, 264  
Hydride morphology, 98  
Hydrides, 745  
Hydriding, 19, 35, 80, 98, 599, 709  
Hydrogen absorption, 579  
Hydrogen analysis, 80, 116  
Hydrogen concentration, 98  
Hydrogen diffusion, 62, 116  
Hydrogen in pressure tubes, 221  
Hydrogen ingress, 62  
Hydrogen mobility, 62  
Hydrogen pickup, irradiation, 19, 183, 483  
Hydrogen uptake in zirconium alloys, 62,  
116, 760  
Hydroxide, 724

**I–K**

In pile tests, 779  
In reactor behavior, 328, 709  
In reactor deformation, 469  
In reactor fuel tests, 3  
In reactor uniform corrosion, 745  
Inspection process in manufacturing, 328  
Intermetallic compounds, 307  
Intermetallic precipitates  
corrosion mechanism of zirconium  
alloys, 615  
microstructure analysis, 419, 437, 483  
oxidation, 664, 687  
Investigation methods, corrosion  
mechanism of zirconium alloys,  
615, 644  
Iodine stress corrosion cracking of  
zircaloy-4, 559  
Ion mass spectroscopy, 116  
Iron, 168  
Iron, in zirconium alloys, 438  
Irradiation, 135, 168, 183, 549, 687  
Irradiation enhancement of corrosion and  
hydrogen pickup, 19  
Irradiation fluence, 35  
Irradiation growth, 521  
Irradiation temperature, 35  
J-R curves, 135  
Kinetics, oxidation in zircaloy-4, 687

**L–M**

Large scale demonstration, 3  
Light water reactors, 19, 400, 469  
Lithium, 351, 378  
Lithium hydroxide, 378, 779  
Lithium hydroxide boric acid aqueous  
chemistry, 378  
Loops, 351  
Loss of coolant accidents, 19  
Manufacturing process  
corrosion and stress behavior of  
zircaloy, 285, 307, 328  
pressure tubes, 221  
zircaloy, 285, 307, 328  
Material chemistry effect, 709  
Material samples, 709  
Mechanical modeling, 245  
Microchemistry, 400  
Microscopy, 116

**Microstructure**

- corrosion parameters, 351, 483, 615, 709
  - effects of irradiation, 521
  - in-reactor corrosion performance, 724
  - oxide layers, 579
- Model prediction, 779**

**N**

- Neutron fluence, 168, 183, 202, 499**
- Neutron irradiation, 521**
- Nickel, in zirconium alloys, 438**
- Niobium, zirconium- alloys, 116, 437, 579**
- Nodular corrosion, zircaloy, 285, 400, 419, 709**
- Nondestructive testing, 328**
- Nuclear applications**
- anisotropy of pressure tubes, 202
  - corrosion behavior, irradiated zircaloy, 400
  - corrosion behavior, zircaloy, 285, 307, 599, 724, 760
  - corrosion environment for boiling water reactors, 709, 745, 779
  - corrosion mechanism of zirconium alloys, 615, 644
  - corrosion of zircaloy-4, 351, 378, 400
  - corrosion resistant zirconium based alloys, 437, 483
  - crack propagation of zircaloy-4, 559
  - creep anisotropy, 469
  - damage in cold pilgering, 245
  - fatigue behavior of zircaloy and zirconium, 499, 549
  - fracture toughness, 135
  - heat treated pressure tubes, 183
  - hydride cracking, 35
  - hydrogen absorption, 80
  - hydrogen uptake, 62
  - in-reactor corrosion performance of zircaloy, 724, 745
  - iodine stress corrosion cracking of zircaloy-4, 559
  - irradiation effect on zircaloy-4, 521
  - irradiation growth in pressure tubes, 168
  - light water reactors, 19
  - microstructure analysis, 419
  - nodular corrosion behavior, 419

- oxidation of zircaloy-4, 450, 687
- oxide layers, microstructure, 579
- pressure tubes, anisotropy, 202
- pressure tubes, fabrication, 221
- pressure tubes, fracture toughness, 135
- pressure tubes, heat treated, 183
- pressure tubes, irradiation growth, 168
- scanning electron microscope techniques, 98

- welds in zirconium, mitigation, 264
- zircaloy corrosion behavior, 98, 285, 307, 328, 400
- zirconium barrier fuel cladding, 3
- zirconium, oxide films, 116

**Nuclear electricity, 549****Nuclear fuel**

- hydride cracking, 35
- hydrogen absorption, 80
- hydrogen uptake, 62
- light water reactors, 19
- zirconium barrier cladding, 3, 19

**Nuclear materials**

- anisotropy of tubes, 202
- corrosion behavior of zircaloy, 285, 307, 328, 400, 760
- corrosion environment for boiling water reactors, 709
- corrosion mechanism of zirconium alloys, 615, 644, 724, 779
- corrosion of zircaloy-4, 351, 378
- corrosion resistant zirconium based alloys, 437, 483
- crack propagation of zircaloy-4, 559
- creep anisotropy, 469
- damage in cold pilgering, 245
- fatigue behavior of zircaloy and zirconium, 499, 549
- fracture toughness, 135
- fuel cladding, 3
- heat treated pressure tubes, 183
- hydride cracking, 35
- hydrogen absorption, 80
- in-reactor corrosion performance of zircaloy, 724
- irradiation effect on zircaloy-4, 521
- irradiation in pressure tubes, 168
- light water reactors, 19
- microstructure analysis, 419
- nodular corrosion behavior, 419
- oxidation of zircaloy-4, 450, 687

oxide layers, microstructure, 579  
 pressure tubes, anisotropy, 202  
 pressure tubes, fabrication, 221  
 pressure tubes, fracture toughness, 135  
 pressure tubes, irradiation growth, 168  
 pressure tubes, heat treated, 183  
 scanning electron microscopy  
     techniques, 98  
 stress, zircaloy tubes, 328  
 welds in zirconium, mitigation, 264  
 zircaloy corrosion and hydriding, 98,  
     307, 328  
 zirconium, oxide films, 116  
 Nuclear reaction analysis, 116  
 Nuclear reactors, 202  
 Nuclear submarines, fuel elements, 19  
 Neutron irradiation, 19, 35

## O-P

Oxidation behavior of zircaloy-4, 351,  
     378, 450, 687  
 Oxide barrier, hydrogen uptake in  
     zirconium, 62  
 Oxide growth, 579  
 Oxide layers, corrosion mechanism of  
     zirconium alloys, 615, 663,  
     709, 779  
 Oxide layers, microstructure, 579  
 Oxide lithium hydroxide, 724  
 Oxide metal interface, 579  
 Oxide scale, 307  
 Oxides, 116  
 Oxygen, 221  
 Oxygen reactivity, 644  
 Pellet cladding interaction, 3, 19  
 Phosphorous, 221  
 Photoelectron spectroscopy, 116  
 Pilgering, cold, 245, 285  
 Porosity, 62, 116  
 Post irradiation examination, 183  
 Post weld heat treatment, 264  
 Power cycling effects, 549  
 Power reactors, 351  
 Precipitates, 328, 400, 521  
 Pressure tubes  
     anisotropy of reactor creep, 202  
     fracture toughness, 135  
     hydrogen uptake in zircaloy, 62  
     irradiation growth, 168, 183

Pressure tubes, cold pilgering, 245  
 Pressure tubes, corrosion resistant  
     zircaloy, 285, 328  
 Pressure tubes, manufacturing and  
     inspection process, 328  
 Pressure tubes, trace elements, 221  
 Pressure tubes, zirconium alloy welds, 264  
 Pressurization, repeated, 549  
 Pressurized water reactors  
     corrosion performance of zirconium  
     alloys, 351, 483, 599, 709,  
     760, 779  
     fatigue behavior, 499, 521  
     fuel rods, cladding, 579, 760  
     in reactor uniform corrosion, 745  
     microstructure of oxide layers, 579  
     oxidation of intermetallic precipitates,  
     687  
     stress corrosion, 549  
 Processing creep, 724  
 Processing route, hydrogen absorption, 80

## Q-R

Quenching, 285, 328  
*Q*-value, 285  
 Radiation effects  
     anisotropy of tubes, 202  
     corrosion behavior of zircaloy, 285,  
     307, 328, 400, 779  
     corrosion mechanism of zirconium  
     alloys, 615, 644, 709, 760  
     corrosion of zircaloy-3, 599  
     corrosion of zircaloy-4, 351, 724  
     crack propagation of zircaloy-4, 559  
     creep anisotropy, 469  
     damage in cold pilgering, 245  
     effect on microstructure of zircaloy-4,  
     521  
     fatigue behavior of zircaloy and  
     zirconium, 499, 549  
     fracture toughness, pressure tubes, 135  
     fuel elements, boiling water reactors,  
     709  
     heat treated pressure tubes, 183  
     hydride cracking, 35  
     hydrogen absorption, 80  
     hydrogen uptake, 62  
     in-reactor corrosion of zircaloy, 724  
     irradiation growth in pressure tubes,  
     168

light water reactors, 19  
 lithium hydroxide and boric acid,  
     corrosion of zircaloy-4, 378, 724  
 microstructure and properties of  
     zirconium based alloys, 483  
 oxidation of zircaloy-4, 450, 687  
 oxide films on zirconium-niobium  
     alloys, 116  
 oxide layers, microstructure, 579  
 pressure tubes, anisotropy, 202  
 pressure tubes, fabrication, 221  
 pressure tubes, fracture toughness, 135  
 pressure tubes, heat treated, 183  
 pressure tubes, irradiation growth, 168  
 scanning electron microscope  
     techniques, 98  
 welds in zirconium, 264  
 zircaloy corrosion and hydriding, 98  
 zirconium barrier cladding, 3, 19  
 Reactor fuel, 3, 19  
 Recrystallized state, 663  
 Reduction in area, zircaloy tubing, 285  
 Repeated pressurization, 549  
 Residual stress, 264, 663

**S-T**

Scanning electron microscope techniques,  
     98, 116  
 Second phase particles, 599s  
 Secondary ion mass spectrometry, 62  
 Single crystals, 559  
 Solutes, 400  
 Spectroscopy, 116  
 Steam corrosion, zircaloy oxidation, 80,  
     450  
 Stress corrosion, 3, 19, 328, 559  
 Stress gradients, 663  
 Surface boiling, 779  
 Surface defects, 245  
 Surveillance specimens, 183  
 Temperature, 168  
 Tensile properties, corrosion resistant  
     zirconium based alloys, 437, 483  
 Tensile strength, 183  
 Tensile stress, 663  
 Tensile stress, welds in zirconium  
     alloys, 264  
 Tetragonal zirconia, 663  
 Texture (materials), 202, 419

Thermal reactor, 183  
 Threshold stress intensity factor, 35  
 Tin content, zircaloy-4 cladding, 760  
 Tin, effect on corrosion resistance under  
     irradiation, 328  
 Tin, in zirconium alloys, 438  
 Tool design, 245  
 Trace elements, 221  
 Transmission electron microscopy, 307,  
     419, 579, 615, 687  
 Tube shells, 285  
 Tubes, 202  
 Twin boundaries, 559

**U-X**

Uniform corrosion  
     in reactor, 745, 760  
     irradiated zircaloy, 400  
     manufacturing and inspection process,  
         328  
     oxide layers, 579  
     under hot rolling and annealing  
         conditions, 307  
     zirconium based alloys, 437, 483, 615  
 Uniform protective oxide, 400  
 Water cooled nuclear reactors, 521  
 Water, in-reactor corrosion performance of  
     zircaloy, 724  
 Water rods, 285  
 Welds, in zirconium alloy components,  
     264, 400  
 X-ray absorption spectroscopy, 644  
 X-ray diffraction, 663  
 X-ray microanalysis, 98, 116  
 X-ray photoelectron spectroscopy, 644

**Z**

Zr-2.5Nb pressure tubes  
     anisotropy of in reactor creep, 202  
     corrosion, 378  
     fabrication, 221  
     fracture toughness, 135  
     heat treated, 183  
     hydrogen uptake, 62  
     irradiation growth, 168  
     oxide films, 116  
 Zircaloy corrosion and hydriding, 98  
 Zircaloy-4 cladding, 285, 307, 328, 378,  
     760

- Zircaloy-4, corrosion performance, 724, 745, 779  
 Zircaloy-4, effect of irradiation on microstructure, 521, 687  
 Zirconia, 687, 760  
**Zirconium**  
 anisotropy of pressure tubes, 202  
 cladding tubes, 307, 328, 351, 599  
 coolant chemistry in water reactor, effect on zircaloy corrosion, 779  
 corrosion behavior, 307, 351, 378, 400, 599, 724, 760  
 corrosion environment for boiling water reactors, 709, 724  
 corrosion mechanism of alloys, 615, 644, 663  
 corrosion resistant alloys, 437, 483  
 corrosion resistant tubing, 285  
 crack propagation, 559  
 creep anisotropy in zircaloy cladding, 469  
 damage in cold pilgering, 245  
 fatigue behavior, 499, 549  
 fracture toughness, 135  
 heat treated pressure tube, 183  
 hydride cracking, 35  
 hydrogen absorption kinetics, 80  
 hydrogen uptake, 62  
 in reactor corrosion, 745  
 intermetallic precipitates, 687  
 iodine stress corrosion cracking, 559  
 irradiation effect on microstructure, 521, 687  
 irradiation growth in pressure tubes, 168  
 light water reactors, 19  
 manufacturing and inspection process, 328  
 microstructure analysis, 419  
 nodular corrosion behavior, 419  
 oxidation in steam, 80  
 oxidation of zircaloy-4, 450, 687  
 oxide films, 116  
 oxide formation, 644, 663  
 oxide layers, 579  
 pressure tubes, anisotropy, 202  
 pressure tubes, fracture toughness, 135  
 pressure tubes, heat treated, 183  
 scanning electron microscope techniques, 98  
 trace elements in pressure tubes, 221  
 welds, mitigation of harmful effects, 264  
 zirconium barrier cladding, 3, 19  
**Zirconium alloys**  
 anisotropy of pressure tubes, 202  
 cladding tubes, 307, 328, 351, 599  
 composition, 499  
 coolant chemistry in water reactors, effect on zircaloy corrosion, 779  
 corrosion behavior, 307, 351, 378, 400, 599, 724, 760  
 corrosion environment for boiling water reactors, 709, 724, 779  
 corrosion mechanism, 615, 644, 663  
 corrosion resistance, 437, 483  
 corrosion resistant tubing, 285  
 crack propagation mechanisms, 559  
 creep anisotropy in cladding, 469  
 damage in cold pilgering, 245  
 fatigue behavior, 499, 549  
 fracture toughness of pressure tubes, 135,  
 fuel cladding, 3  
 heat treated pressure tube, 183  
 hydride cracking, 35  
 hydrogen absorption kinetics, 80  
 hydrogen uptake, 62  
 in reactor corrosion of zircaloy-4, 745  
 intermetallic precipitates, 687  
 iodine stress corrosion cracking, 559  
 irradiation effect on microstructure, 521, 687  
 irradiation growth in pressure tubes, 168  
 microstructure analysis, 419  
 nodular corrosion behavior, 419  
 oxidation in steam, 80  
 oxidation of zircaloy-4, 450, 687  
 oxide films on zirconium-niobium, 116  
 oxide formation, 644, 663  
 oxide layers, 579  
 oxides, 116  
 performance in light water reactors, 19  
 pressure tubes, 135, 168, 183, 202  
 scanning electron microscope techniques, 98  
 stress corrosion cracking, 559  
 trace elements in Zr-2.5Nb pressure tubes, 221

- welds, mitigation of harmful effects, 264
- Zirconium barrier fuel cladding, 3
- Zirconium niobium alloys, 116
- Zirconium oxide surface chemistry, 378
- Zirconium oxides, 62
- Zirconium X-bar, 437
- ZIRLO. *See* Zircaloy-4.