Subject Index

A

Absorbed specific energy until fracture (ASFE) measurement, 118–123
Accidents (see Loss of coolant accidents; Over-cooling accidents; Reactor pressure vessels)
Accelerated irradiation experiments, 26
Aging
  strain, 14, 16, 17, 23, 24
  thermal, 14, 16, 17, 22, 28
Aluminum content, 28, 201
American Nuclear Society seminar (1983), 149
American Society of Mechanical Engineers (ASME)
  Code, 134, 144
  Section XI, 170
  Specification for A508 Class 3 steel, 14, 15
Annealing
  behavior, 66, 68
  irradiated steels, 66–68
  postirradiation, 9, 235, 242
  reirradiation response and, 242–259
Antimony, 22
Arsenic, 22
ASTM Committee E-10, Subcommittee 6 Task Groups, 149
ASTM Standards
  E 23-82, 58, 97, 112, 262
  E 185-82, 6, 7, 17, 107, 178, 179, 183
  E 208-81, 40
  E 399-83, 74, 262
  E 560-77, 10
  E 693-79, 8, 39
  E 813-81, 74, 76, 89, 122, 244
  E 853-81, 10
ASTM-EURATOM Symposium on Reactor Dosimetry, 66, 162
Atomic Energy Act, German (Atomgesetz), Article 20, 181
Atomic Energy Agency, International (IAEA)
  Coordinated Research Programme (CRP), 22–25, 31, 58, 62, 71
  Specialists Meeting (1981), 19
Atomic Energy Commission (French), 71

B

Bainite microstructure, 260–262, 265–268, 273–275
Boiling water reactor (BWR) pressure vessel surveillance program, 106–117

C

Central Electricity Generating Board, 14, 17, 26
Charpy specimens, ASFE measurement of, 118–122
Charpy upper-shelf energy, 245–252, 272–277
Charpy V-notch (CVN) data trends analysis, 207–228
mechanical property-CVN parameter relationships, 217
structure-property relationships, 217
synthesis, 228–234
Charpy V-notch impact testing, 7, 23, 58, 62, 243–252
microstructure, 272–275
results, 112, 113, 116
transition temperature and, 82
Chemistry factor, 150, 152–155, 207, 210
Cladding
austenitic, 136
effects of, 167, 175
Code of Federal Regulations, U.S., 18
Coolant temperature variation, 169, 170, 174
Copper
content, 99–105, 150–159, 178, 179, 199–201, 204, 208
diffusion in iron, 255
distribution, 188–190, 217
embrittlement effects of, 15, 19, 24–26, 252–255, 258
nickel and, 101–105, 150–155, 159, 229, 234, 235
damage due to, 252–255, 258
temperature shift and, 207, 212–215, 218–223, 234, 235
Copper sulfide, 192, 195, 204
formation of, 201, 203
Crack (see also Flaws)
arrest, 136, 144, 167, 169
geometries, 136, 140, 141, 147
crazed pattern, 167
growth, 89
initiation, 168, 174
propagation and fracture toughness, 8
Crack-opening displacement (COD) measurement, 118
Crack tip opening (CTOD) monitoring, 62

D
Damage
attenuation of, 161, 162
prediction, U.S. regulatory position on, 18–22
rates (see also Embrittlement, rates; Re-embrittlement rate), 258
Danish Reactor DR 3, Riso National Laboratory, 262
Design Codes, 18
Directorate for Safety and Protection (DISP), 97
Displacements per atom (dpa), 8, 9
equivalent formula, 162
Dosimetry
component integrity testing, 38, 39
embrittlement-neutron, 10–12
embrittlement-related, 6
neutron, 182
Drop-weight testing (see also Impact testing), 40, 43, 45

E
Elasto-plastic toughness, 70–95
Electric Power Research Institute (EPRI) annealing research, 243
surveillance data, 29, 30, 152, 210
Embrittlement
aspects of, 7
levels, 244, 245
monitoring in light-water reactors, 177–183
neutron irradiation studies, 13–33, 55–69
NRC regulatory requirements for, 6, 7
prediction, 255
rates, 60, 258
reactor pressure vessel structural implica-
tions of, 163–176
residual elements influence on, 59
Embrittlement-neutron dosimetry, 10, 11
Energy, Charpy upper-shelf, 245–252, 272–277
Energy criteria (see also Absorbed spe-
cific energy until fracture (ASFE) measurement), 119

F
Failure criteria, 169
Ferrite, composition of small regions, 199–201, 223
Ferrite-perlrite structure, 260–262, 267, 268, 274, 275
Flaws (see also Crack)
evaluation, outside, 8, 9
finite length, 166, 167
infinitely long, 167
influences on, 168–175
Fluence
attenuation, 172
distribution, 38, 39, 130
embrittlement effects, 59
end-of-life (EOL), 132, 133, 211
factor, 150, 153, 155–159
hardening and, 219–221
monitoring, 63–66
predictions, 8, 10
temperature shift and, 207–209, 211, 212
Fluence-embrittlement extrapolation model, 8
Flux
distribution, 131, 132
hardening and, 221, 223
level shifts, 10, 11, 211
Fracture behavior, brittle, of pressure vessel, 127–148
Fracture criteria evaluation, static, 118–124
Fracture mechanics behavior of flaws, 165
Fracture stress, 272
Fracture testing, dynamic, 118
Fracture theory, stress-controlled cleavage, 217
Fracture toughness
change in, 8
determining, 134, 136
effective, 147
radiation-induced loss of, 242
testing, 26, 35, 39, 243–247
upper shelf, 16, 243, 247
French Atomic Energy Commission (CEA), 71

G
German KTA Rule 3203, 49, 177–183
Guthrie data base, 150–155
Guthrie formula, 49, 98–99, 171

H
Hardening mechanism, 229, 238, 239
irradiation-induced, 254, 275
Hardness properties (see also Vickers hardness), 40, 43
changes, 218–223
irradiated steel, 66–68
prediction, 230, 232
Hardness testing, 35, 40
rehardening studies, 67
Heavy-Section Steel Technology (HSST) program, 165–167

I
Impact energy of materials, 37, 43–49
measurements, 118
Impact testing (see also Charpy V-notch impact testing; Drop-weight testing), 26
fracture toughness and, 35
instrumented, 43, 44
results, 112, 113, 115, 116
Impurity, effect on material, 230, 231, 236, 237
Indian Point-2 reactor, 9
Iron
   content, 199
   copper diffusion in, 255
   isotopes, 132, 147
Irradiation, effect of microstructure on Ni-Mo-Cr response to, 260–278
Irradiation effects, 5–12
   embrittlement (see also Embrittlement), 14
   on elasto-plastic toughness, 70–95
Irradiation experiments, 74–76
Italian Comitato Nazionale per l’Energia Nucleare ed Energie Alternative (ENEA), 97
   predictions, 103–105

J
   \( J_c \), determination of, 89, 90, 94
   \( J_K \), measurement, 118, 122–123
   fracture toughness tests, 243–247
   \( J-R \) resistance curves, 74, 76–89, 94

K
   Kerntechnischer Ausschuss (KTA) (see also KTA Rule 3203), 177
   KTA Rule 3202 (German), 49, 177–183

L
   Lead factor, 181, 183
   Least square fit (LSF) regression analysis, 236, 239
   Light Water Reactor Study Group, 14–17
   Light-Water reactors
      embrittlement of pressure vessels, 187
      monitoring embrittlement in, 177–183
   Linear elastic fracture mechanics method, 134, 141, 144
      applicability of, 165–167, 174, 175
   Loviisa Nuclear Power Plant embrittlement research, 55–69
   Loadings
      critical transient, 134–136
      dynamic and static, 119
      embrittlement from, 8
      stress intensity and, 142, 143
      thermal-shock, 166
   Loss of coolant accidents (LOCAs), 134, 136, 137, 170

M
   Manganese content, 199–203
   Manganese silicate inclusions, 192–195, 202, 203
   Martensite microstructure, 260–264, 267, 268, 273–275
   Material degradation, mechanisms of, 14, 15
   Metallographic techniques, 189–192, 223
   Metallurgical microstructure effects, 160–178
   Microanalysis of pressure vessel weld materials, 187–205
   Microscopy
      field ion (FIM), 217, 228
      scanning electron (SEM), 189, 201
      scanning transmission electron (STEM), 189
      transmission electron (TEM), 217, 223, 227
   Microstructures, metallurgical, 260–278
   Microvoids, 216–218, 229
   Molybdenum carbide, 195
   Molybdenum content, 199

N
   National Energy Plan (PEN) (Italy), 97
   National Nuclear Corporation (England), 14, 17
Neutron irradiation (see also Irradia-
tion; Irradiation effects)
reference transition temperature in-
crease due to, 96–105
studies in United Kingdom, 13–
33
Nickel
beneficial effects of, 104
content, 19, 24–26, 30, 99–105, 192,
195, 198–203, 208
copper and, 101–105, 150–155, 159,
229, 234, 235
depletion, 192
distribution, 188
embrittlement due to, 253, 254
hardness and, 238, 239
temperature shift and, 207, 213, 214,
218, 219, 234, 235, 238, 239
Niobium, 63, 65, 66, 132
Notch strength ratio (NSR), 272, 277
Nuclear Regulatory Commission, U.S.,
242
Guides, 6
Appendix G, 6, 7, 160
Appendix H, 6
draft proposal, 22
General Design Criterion, 31, 6
Guide 1.99, 14, 179
Revision 1, 10, 18–20, 22, 102,
103, 149, 171
Revision 2, 7, 10, 102, 149–162
trend curves, 45, 49, 50, 116, 117
perspective on irradiation effects in
reactors, 5–12
regulation and licensing of reactors, 5, 149
requirements for embrittlement, 6, 7
screening criteria (SC), 165, 171, 174
Unresolved Safety Issue A-49, 164,
165
Nuclear Safety Standards Commission
in Federal Republic of Germany
(see Kerntechnischer Aus-
schuss)

O
Odette data base, 152–155
Ostwald ripening process, 253, 254
Over-cooling accidents (OCAs), 164,
165, 174

P
Parametric analysis, 165–175
Phosphorus
content, 178, 179
embrittlement effects, 15, 18, 19, 22,
25, 31
shift and, 212, 214, 215, 234
Positron annihilation studies, 25
Precipitate growth model, 237
Pressure-temperature limits, 7
Pressure vessel steels
boiling water reactor surveillance
program, 106–117
elasto-plastic toughness of, 70–95
integrity (see also Reactor pressure
vessel, safety), 136–147
irradiation embrittlement
mechanisms, models, and data
correlations, 206–241
studies of, 13–33
regulatory considerations (see also
Nuclear Regulatory Commission, Guides), 149–162
reirradiation response of and anneal-
ing, 242–259
weld materials, 187–205
Pressure water reactors (PWR), 97
Italian Design Criteria, 97, 98
safety of against brittle fracture, 127–
148
threat to integrity, 164
Pressurized-thermal-shock (PTS) (see
also Thermal shock)
accidents, 8, 9, 11
analyses, 7, 8, 243
equation, 98, 99 (see also Guthrie
equation)
Pressurized-thermal-shock (PTS) (continued)
issue, resolution of, 149, 160, 161
reactor pressure vessel structural implications of embrittlement to, 163–176

R
Rancho Seco accident, 169
Reactor heatup and cool-down limits, 150
cool-down rates, 169, 170
Reactor pressure vessels (see also Pressure vessel steels)
accidents, ability to withstand, 96, 97
attenuation of damage in walls, 161, 162
brittle fracture behavior, evaluation of, 127–148
component integrity research, 34–51
embrittlement aspects, 7
end-of-lifetime, 114, 177
irradiation behavior, 34–51
irradiation effects in, 5–12
irradiation embrittlement of, 206–241
Loviisa, Finland, 56–68
monitoring embrittlement of, 177–183
safety analyses, 11
PWRs against brittle fracture, 127–148
regulations (see also Nuclear Regulatory Commission, 5, 6
standards, 177–183
structural implications of embrittlement, 163–176
surveillance program, Loviisa, 56–68
wall temperature cool-down rates, 169, 170
Reactor vessel beltline definition, 6
effect of irradiation in, 182
Re-embrittlement rate, 247, 252, 254, 255, 258
Reirradiation response, 247–258
Residual elements (see also Copper, Nickel, Phosphorus), 59, 161
micro-distribution of, 187–205
Runge-Kutta technique, 141
Russell-Brown hardening model, 228, 237

S
Silicon content, 28, 192, 199
Safety (see also Nuclear Regulatory Commission, Guides)
German KTA 3203 standard, 49, 177–183
PWR pressure vessel against brittle fracture, 127–148
Sizewell pressure vessel reactor (Suffolk), 14, 15, 19–21
studies on, 17
Small-angle neutron scattering techniques, 24, 25, 28, 29, 218, 224, 226–229, 237
Small specimen, static fracture criteria evaluation of, 118–124
Static fracture criteria evaluation, 118–124
Steels
A302 B, 97, 98, 107
chemical composition, 108
constant chemistry analysis, 99–104
A508 Class 3, 14, 15, 22, 23, 35, 71, 90–94, 97, 127
chemical composition, 72
constant chemistry analysis, 99–104
J-R curves, 78, 87
tensile properties, 73
A533 B Class 1, 22, 23, 35, 71, 90–94, 97
chemical composition, 72
constant chemistry analysis, 99–104
J-R curves, 77, 80, 83
plate material, 243
tensile properties, 73
Cr-Mo-V, 56
ferritic type, 106
15H2MFA, 120, 121
Linde 80 welds, 244
Magnox, 14, 26–30
manganese-molybdenum-nickel weld wire, 243
20 MnMoNi 5 5, 35, 36, 40, 179
NiCrMo 1, 179
22 NiMoCr 3 7, 35, 36, 40, 127, 179
nickel-molybdenum-chromium BH 70, 260–278
reactor pressure vessel (see also Pressure vessel steels)
component integrity, 34–51
elasto-plastic toughness of, 70–95
embrittlement studies in United Kingdom, 13–33
irradiation behavior, 34–51
irradiation effects in, 5–12
S3 NiMo 1, 179
weld material properties, 72, 73, 79, 81, 82, 84–86
Stress intensity factors, 136, 140–147
Sulfur content, 28
Surveillance data
analysis of, 206, 207
trends, 207–211
commercial power reactor, 150–152
Surveillance programs, 17, 23, 31
boiling water reactor, 106–117
German program, 179, 180
plan of, 181, 182
requirements for, 178, 179
in-service inspections, 147
Lovisa Nuclear Power Plant research, 55–69
Surveillance testing, 119, 122
irradiation tests, 10, 18
T
Tarapur Atomic Power Station (TAPS) reactors, 107–116
Technical University of Budapest tests, 119
Temperature
adjusted reference, 150
hardness and, 219–223
impurity-induced shift, 230, 231
monitoring, 182
transition
Charpy-V tests, 82, 250, 252, 253, 255, 257, 258, 275, 277
ductile-brittle shifts, 22, 29, 30, 243
impact energy and, 43–50
index, 112–117
influence of, 88, 89, 93, 94, 121
prediction of increase, 96–105
reference, 97–99, 150
shifts in, 16, 17, 58, 60, 61
Temperature-pressure limits, 7
Tensile properties, 40–42
BH 70 steel, 270–272
Tension testing, 35, 39, 74, 243, 244, 247
determination of $J_c$ from, 89, 90
microstructure, 269, 272
results, 112, 115
static, 119, 120
Thermal shock (see also Pressurized-thermal-shock), 141, 146, 147
Tin, 22
U
Ultrasonic investigations, 147
United Kingdom, neutron irradiation embrittlement studies, 13–33
University of Virginia Research Reactor, 244, 247
Vickers hardness (see also Hardness properties), 40
microhardness, 218
of BH 70 steel, 261, 272

Warm prestressing (WPS), 168, 175
path, 145, 147
Weld materials
microanalysis of, 187–205
properties, 72, 73, 79, 81, 82, 84–86

Weld versus base metal data, 155–161
Weld seam, end-of-life, 144, 148
Westinghouse capsule, 17, 18

X-ray energy dispersive detectors (EDX), 189

Yield strength, 40, 42
copper precipitation and, 26–30
recovery, 245, 247, 249
Yield stress, 252, 253, 256, 258