

Index

Page numbers in *italic* denote figures. Page numbers in **bold** denote tables.

- ABAQUS non-linear finite-element code 213, 222
- air entry value 51–52
- air-drying, concrete barriers, gas permeability 64, 65, 66, 70–71, 72
- aragonite mineralization 45
- argillite, hydrogen migration, modelling 178, 184, 186
- Äspö Hard Rock Laboratory, Lasgit 225
- backfill
 - GDF 2, 243
 - Nirex Reference Vault Backfill (NRVB) cement 35–46
- balance equations, two-phase flow 144–145
 - energy 145
 - mass 144–145
 - momentum 145
- Barcelona Basic Model 214
 - material properties **215**, 216
 - swelling property **215**, 217–218
- barriers
 - concrete 59–73
 - crystalline rock 95–105
 - engineered 2, 19
 - gas migration 3, 19–20
 - Japan
 - finite element model 218, 219
 - gas pressure and flow path 219–221
 - material properties 214–218
 - mechanical stability 221–223
 - numerical modelling 214–219
 - Lasgit 19, 225–227
 - geological 2
 - salt 107–121
- bentonite buffer 2, 19, 20
 - FEDEX 47–56, 194
 - hydrogen migration, geochemical modelling 189–200
 - Japan, low-permeability layer 213–218
 - consolidation properties 214–217
 - gas pressure and migration 219–221
 - mean effective stress 220–221, 223
 - mechanical properties 214, **215**
 - mechanical response 220, 221–222, 223
 - swelling property **215**, 217–218
 - Kunigel-GX 214, 216
 - Barcelona Basic Model 214, 217–218
 - Lasgit 19, 225–227
 - multiphase flow simulation 125, 126
 - MX 80 type 10, 192–200
 - thermal gradient 47
 - Volclay KWK, Boom Clay experiments 10, 14
- bentonite-sandblock assemblies
 - dry state shear strength testing 23–25
 - gas permeability 21, 25, 26, **30**
 - hydraulic properties **28**
 - hydromechanical properties 20–32
 - presaturation 22
- saturated state
 - gas-injection testing 27, 29–30, 32
 - healing 30–32
 - saturation 25–27, **28**
 - shear testing 21–22, 30–32
 - strength testing 21
- Bernberg salt mine, borehole injection tests **111**, 112–116
- bitumen, L-ILW disposal 2
- Boom Clay Formation 9–16
 - composition 10
 - favourable properties 9
 - gas breakthrough experiments 10–16
 - benonite 10, 14
 - displaced pore water 12, 13, 15
 - fractures 10, 13, 14–15
 - permeameter cells 10–11, 14, 15
- buffer medium 243
 - bentonite 2, 19, 20
 - blocks 19, 20
 - see also* bentonite buffer
- calcite evolution **195**, 198, 199
- calcite mineralization 35, 42, 44, 45
- Callovo-Oxfordian Clay
 - gas migration testing 15, 76–93
 - deviatoric loading 79–80
 - fracture sealing 82–83
 - gas breakthrough 83–86
 - permeability 88, 89, 90, 91, 92
 - pressure 87–88, 89, 91
 - shut-in pressure 92
 - impact of gas pressure rise 86–87
 - isostatic compression 77, 78
 - water-saturated and resealed fractures 81–93
- canisters
 - copper, Lasgit 225
 - corrosion 2, 3, 47, 192
 - HLW disposal 2, 243
 - upscaled numerical models 125, 127, 132
 - see also* super-canisters
- capillary pressure
 - hydrogen migration 169, 171, 186
 - mathematical upscaling 131–132, 134
- carbon dioxide
 - dissolved, hydraulic testing 40
 - formation in repository 2, 9, 35
 - NRVB cement 42–43
 - phase diagram 36
 - supercritical 36, **39**, 41–42
 - Werra Salt Formation 118
- carbonation
 - effect on buffering cement 35, 72
 - NRVB cement 42–46
 - reaction front propagation mechanism 43
 - implications for radioactive waste repository 45
 - PRECIP modelling 39, 44–45

- carnallite, rock burst 118–120
- cement, L-ILW disposal 2, 35
- Japan
- gas pressure and migration 219–221
 - low-diffusion layer 213, 214
 - mechanical response and stability 222, 223
- Nirex Reference Vault Backfill (NRVB) 35–46
- clay *see* Boom Clay Formation
- claystone
- effects of humidity on gas flow 80
 - gas migration 75–93
 - gas permeability 76, 78–81
 - hydrogen migration 167–178
 - sealing 78, 80–83
- Cluster Repository Project (CROP) 19
- CODE_BRIGHT, numerical modelling 143, 213, 219, 222
- COMPASS-PHREEQC model 190–191
- compressibility factor, FEBEX bentonite 49, 50
- compression
- deviatoric 23, 109
 - EDZ fractures, gas flow 79–80
 - isostatic, EDZ fractures, gas flow 76, 77, 78–79
- concrete barriers
- gas permeability 60–63, 64–66, 67, 70
 - and air-drying 64, 65, 66, 70–71, 72
 - Klinkenberg effect 67–70, 72–73
 - non-steady-state method 60, 62, 64, 72
 - pressure differential 65–66, 67, 68, 72
 - and saturation 64, 65, 66, 70–71, 72
 - steady-state method 62–63, 64–66, 72
 - hydraulic conductivity 63, 66–67, 68
 - intrinsic permeability 70–72
 - L-ILW disposal 59–73
 - relative permeability 71, 72
 - water permeability 63–64, 66–67, 68, 71–72
- consolidation properties, LPL bentonite 214–217
- constant flow injection test 95, 97, 98, 99, 100, 104
- constant head injection test 95, 97, 98, 99, 102, 104
- constitutive relationships, fluid flow modelling, Opalinus Clay EDZ 146–148
- corrosion
- anaerobic, waste containers 2, 3, 75, 123, 167, 192
 - Boom Clay 9
 - and carbonation 35
- Cortijo de Archidona deposit, FEBEX bentonite 47
- Couplex-Gaz simulation, two-phase flow 123
- creep, salt formations 108
- crystalline rock
- gas permeability 96–105
 - gas-injection tests 95–105
 - as host for radioactive waste disposal 95
 - pathway dilation 96–97
- Dalton's law 129, 148, 155, 156
- Darcy-Muskat flow 128, 168–169
- Darcy's law 76, 100, 146, 152–153, 154, 168, 191
- deformation, brittle to ductile 23, 24
- diffusion
- Fick-type 3, 169
 - gas 3, 9, 169, 244–245
 - iodide 11, 12, 13
- dilatancy 23
- salt formations 107, 108, 109–110
- double-packer gas injection tests 96, 98–99, 102–103, 113
- DuMu^X simulator 125, 133
- El Cabril disposal facility 59
- elasticity, isotropic linear, in plane strain and axisymmetry 159–162
- energy, balance equations 145
- engineered barrier systems *see*, barriers, engineered
- environment, Safety Case 1–2, 241–242
- equilibrium restrictions 145–146
- mechanical 145
 - phase-change 145–146
 - thermal 145
- European Commission
- Cluster Repository Project (CROP) 19
 - FORGE project *see* Fate Of Repository GasEs (FORGE) project
- event candidate investigation, Lasgit toolkit 229, 230, 231–238
- excavation damage zone 2
- gas migration 3, 9, 75
 - crystalline rock 95–105
 - effect of humidity 80
 - gas-injection tests 96–105
 - hydrogen FORGE cell-scale benchmark 178–186
 - Josef Underground Laboratory 103–105
 - multiphase flow simulation 125–127, 132–133
 - non-wetted 75–80
 - water pressure tests 103–104
 - water-saturated and resealed 81–93
- Opalinus Clay, fluid flow modelling 143–159
- salt formations 107
- exploratory data analysis, Lasgit 227–229
- toolkit 228, 229–231
- Fate Of Repository GasEs (FORGE) project** 1–4, 47, 242, 249–256
- cell-scale benchmark simulation
- hydrogen migration 175, 178–186
 - base case results 181
 - boundary conditions 179–180
 - deviation from original benchmark 180–181
 - drift boundary conditions 181, 183
 - gas entry pressure 183–184
 - initial conditions 180
 - outer boundary position 181
 - space and time discretization 178–179
- exclusions 252–253
- features, events and processes (FEPs) 1–2
- module-scale benchmark simulation 123–139
- mathematical model 127–129
 - numerical results 133–139
 - upscaling 129–133
- two-phase flow/pathway dilation models 255
- work packages 1, 3, 249–252
- 1 gas issues in Safety Case 3, 250–251, 255
 - 2 gas generation 3, 251, 253
 - 3 engineered barriers/seals 3, 59, 251, 253–254
 - 4 disturbed host-rock 3, 251–252, 254
 - 5 undisturbed host-rock 3, 252, 254–255
- FEBEX bentonite 47–56, 194
- air entry value 51–52
 - Cortijo de Archidona deposit 47

- gas breakthrough pressure 48–56
- gas permeability 50, 52–56
- pathway dilation 56
- physico-chemical properties 48
- saturation 49, 50, 51, 56
- testing 19
- two-phase flow 54, 56
- Fick-type diffusion 3, 169
- Fick's law 128, 147, 154, 168, 191
- flow properties, NRVB
 - carbon dioxide **39**, 40–41
 - inert gas **39**, 40
 - reaction zone 42
 - supercritical carbon dioxide **39**, 41–42
 - testing 36–42
- fluid flow
 - effect of NRVB carbonation 35–46
 - flow properties testing 36–38
 - modelling
 - Opalinus Clay EDZ 143–159
 - 1D modelling 150–159
 - balance equations 144–145
 - constitutive relationships 146–148
 - equilibrium restrictions 145–146
 - field equations 148–149
 - saturated-unsaturated transition 149–150
- FORGE project *see* Fate Of Repository GasEs (FORGE) project
- Fourier transform, discrete, Lasgit toolkit 229, 231
- fracture closure, compact claystone 78, 80–83
- fractures
 - Boom Clay gas breakthrough experiments 10, 13, 14–15
 - EDZ
 - effect of humidity on gas flow 80
 - non-wetted
 - gas flow 75–80
 - deviatoric compression 79–80
 - isostatic compression 76, 77, 78–79
 - water-saturated and resealed, gas flow 81–93
- fracturing
 - gas-induced 245–246
 - pneumatic
 - salt formations 108, 110, 112, 116, 120
 - see also* gas-frac scenario
- free gas phase formation 9
- frequency domain analysis, Lasgit toolkit 229, 231
- gas
 - generation and migration 2–4, 245
 - see also* gas migration
- gas breakthrough 9, 47
 - Boom Clay 10–16
 - Callovo-Oxfordian Clay 83–86
 - FEBEX bentonite 48–56
 - air entry value 51–52
 - Opalinus Clay 83–86
 - parameters
 - permeability 88, 89, 90, 91, 92
 - pressure 87–88, 89, 91
 - shut-in pressure 92, 108
 - salt formations 110, 113, 114, 118, 120
 - gas diffusion 3, 9, 169, 244–245
 - gas flow 245
 - EDZ fractures 247
 - effect of humidity 80
 - impact of gas-pressure rise 86–87
 - non-wetted 75–80
 - deviatoric compression 79–80
 - isostatic compression 76, 77, 78–79
 - water-saturated and resealed 81–93
 - second order events, Lasgit EDA 231–238
 - see also* two-phase flow
 - gas migration 245, 247, 254
 - bentonite buffer, reactive transport model 190–191
 - EBS, Japan 219–221
 - EDZ 75–93
 - crystalline rock 95–105
 - tests 99
 - see also* gas-injection tests; hydrogen
 - gas permeability
 - bentonite-sandblock assemblies 21, 25, 26, **30**
 - claystone 76, 78–81
 - concrete barriers 60–63, 64–66, 67, 68, 69–72
 - non-steady-state method 60, 62, 64, 72
 - steady-state method 62–63, 64–66, 72
 - crystalline rock 96–105
 - FEBEX bentonite 50, 52–56
 - gas reactivity 247
 - gas slippage *see* Klinkenberg effect
 - gas uptake 247
 - gas-frac scenario 108, 110, 120
 - Merkers natural analogue 118–120
 - gas-injection tests
 - bentonite-sandblock assemblies 25, 27, 29–30
 - concrete barriers 59–73
 - constant flow injection test 95, 97, 98, 99, 100, 104
 - constant head injection test 95, 97, 98, 99, 102, 104
 - crystalline rock 95–105
 - double-packer tests 96, 98–99, 102–103, 113
 - migration tests 99
 - single-packer tests 96, 97–98, 100–102
 - water permeability 103–104
 - NRVB cement 37–38
 - Opalinus Clay 143, 203–212
 - pressure drop test 95, 97, 99
 - salt formations
 - large-scale borehole 116–118
 - medium-scale borehole 112–116
 - small-scale laboratory 110–112
 - subsurface disposal facility, Japan 214–223, 216
 - see also* Large Scale Gas Injection Test (Lasgit)
 - gas-pressure rise
 - build-up 3, 9, 15, 47
 - compact claystone 86–87
 - EBS, Japan 219–221
 - pneumatic fracturing 108, 110, 213
 - salt formations 110–118
 - large-scale borehole injection tests 116–118
 - medium-scale borehole injection tests 112–116
 - small-scale laboratory injection tests 110–112
 - GASNET project 3, 249
 - geological disposal facility (GDF) 47
 - design strategies 123, 248, 255–256
 - NRVB 35–46

- geological disposal facility (GDF) (*Continued*)
 Safety Case 1–2, 241–242, 248–249
 FORGE project 1–4, 47, 242, 249–256
see also **Fate Of Repository GasEs** (FORGE)
 gas issues 243–249
 free gas-phase formation 245
 generation 244
 management and treatment 248–249
 microbial activity 248
 migration 244–245, 247, 254
 pathway dilation and fracturing 245–246
 reactivity 247
 redox reactions 247–248
 two-phase flow 245
 uptake 247
see also multiple barrier concept; **Fate Of Repository GasEs** (FORGE) project
- GETFLOWS flow analysis code 213, 214, 216
- glass, HLW disposal 2, 243
- granodiorite, gas-injection tests 95–105
- Grönaer shaft anticline 113
- groundwater, aqueous contamination 2, 3
- gypsum evolution 195, 198, 199
- HADES URL 10
 Boom Clay gas breakthrough experiments 10–16
 Praclay Seal 10
- halokinesis 108
- healing 30–32
 salt formations 107, 119, 120
- Henry's law 129, 145, 148, 155–156, 168, 170, 171, 184–186, 195
- HG-A test 143–159, 205–207, 209–210, 211
 ID modelling 163–165
- HG-B test 204, 205, 209, 210, 211
- Hooke's law 148, 160–161, 162
- host rock 2, 3
 crystalline 95
 interface with sealing material 19–20
- hydraulic conductivity, concrete barriers 63, 66–67, 68
- hydraulic tests
 NRVB cement 37, 38, 39–40
 dissolved carbon dioxide 40
- hydrogen
 formation in repository 2, 9, 123, 167
 multiphase flow simulation 123, 127
 mathematical model 127–129
 upscaling 129–133
 microbial activity 248
 migration in argillite
 modelling 167–178
 capillary pressure 169, 171, 186
 chemical reaction 169
 consistent thermodynamic model 170–171, 172
 Darcy-Muskat flow 168–169
 Fick-type diffusion 169
 FORGE cell-scale benchmark 175, 178–186
 hydrogen source 169–170
 MoMaS test cases 172–178
 physical model 168–170
 primary variables 171–172
 temperature 169
 migration in bentonite
 geochemical modelling 189–200
 gas evolution 196–197
 initial and boundary conditions 192–193, 194
 material parameters 193–194
 mineral evolution 195, 198, 199
 pH and redox 195, 197–198, 199
 reactions 195
 simulation results 195–200
 simulation scenarios 191–195
 redox reactions 247
 hysteresis, permeability-saturation curve 169
- ideal gas law 168
- interfaces
 bentonite-sandblock assemblies
 dry state shear strength testing 23–25
 oedometer pressure cell 22
 saturated, healing 30–32
 host rock-sealing material, gas-pathways 19–20
 iodide tracer, Boom clay 10, 11–13, 14–15
- Japan, subsurface radioactive waste disposal,
 hydromechanical modelling 213–223
- Josef Underground Laboratory
 crystalline rock, gas-injection tests 95–105
 EDZ permeability 103–105
- KBS-3 concept HLW repository 225, 226
- Kelvin's law 129
- Klinkenberg effect, gas permeability, concrete barriers
 67–70, 72–73
- Kozeny's model 214
- Krichevsky-Kasarnovsky equation 170, 185
- Kunigel-GX bentonite 214, 216, 217–218
- Large Scale Gas Injection Test (Lasgit) 19, 225–227
 exploratory data analysis 227–229
 event candidate investigation 231–238
 toolkit 228, 229–231
- lead-alloy, L-ILW disposal 2
- Leine salt 113
- mass balance equations 144–145
 mechanical equilibrium 145
- Merkers natural gas-frac analogue 118–120
- Merkers salt mine, borehole injection test 116–118
- methane
 formation in repository 2, 9
 migration 248
- microbial activity 2, 9, 248
- Mokrsko granodiorite, gas-injection tests 95–105
- MoMaS test cases, hydrogen migration in clays 172–178
- momentum, balance equations 145
- Mont Terri URL, Opalinus Clay
 gas-injection tests 204–207
 HG-A test 143–159, 204, 205–207, 209–210, 211
 HG-B test 204, 205, 209, 210, 211
 numerical modelling 207–212
- multiple barrier concept 2, 19, 123, 242–243
- MX 80 bentonite 10, 192–200
- Nirex Reference Vault Backfill (NRVB) cement 35–46
 carbonation 42–46
 implications for radioactive waste repository 45
 reaction front propagation mechanism 43, 45

- flow properties testing 36–42
 - gas injection testing 37–38
 - hydraulic testing 37, 38, 39–40
 - resaturation 37
- gas permeability 37, 38, 39
- hydraulic permeability 38, 39
- mineralogy 38–39, 42–43
- preparation 36
- nitrogen, in flow experiments 40, 49, 50, 60, 62–63, 81, 83
- oedometer cell 22
- Opalinus Clay
 - EDZ
 - fluid flow modelling 143–159
 - 1D modelling 150–159
 - boundary conditions 154–155, 156
 - field equations 153
 - geometry and coordinate system 150–151
 - hydraulic axisymmetry 151
 - initial conditions 153–154
 - mechanical axisymmetry 151
 - results 156–159
 - simplifying assumptions 151–153, 158–159
 - test input protocol 155–156
 - balance equations 144–145
 - constitutive relationships
 - gas phase 148
 - liquid phase 147–148
 - porous medium 146–147
 - solid phase 147
 - solid-phase skeleton 146, 148, 149, 158
 - equilibrium restrictions 145–146
 - field equations 148–149
 - saturated-unsaturated transition 149–150
 - gas migration testing 81–93
 - fracture sealing 82–83
 - gas breakthrough 83–86
 - permeability 88, 89, 90, 91, 92
 - pressure 87–88, 89, 91
 - shut-in pressure 92
 - injection tests 203–212
 - HG-A 143–159, 205–207, 209–210, 211
 - HG-B 204, 205, 209, 210, 211
 - laboratory 205, 208–209
 - numerical modelling 204, 207–212
 - water-saturated and resealed fractures 81–93
- pathway dilation 245–246
 - crystalline rocks 96–97
 - FEBEX bentonite 56
- permeability
 - gas
 - claystone 76, 78–81
 - concrete barriers 60–63, 64–66, 68, 69–72
 - crystalline rock 96–105
 - FEBEX bentonite 50, 52–56
 - MX 80 bentonite 194
 - intrinsic, concrete barriers 70–72
 - mathematical upscaling 131–132, 134
 - relative, concrete barriers 71, 72
 - salt formations 107, 111, 112, 115–116, 118, 120
 - water, concrete barriers 63–64, 66–67, 68
- permeameter
 - Boom Clay gas breakthrough experiments 10–11, 14, 15
 - constant head 63
- pH 197–198, 199–200
 - and carbonation 35
- phase-change equilibrium 145–146
- pneumatic fracturing 108, 110, 112, 116, 120
- Poisson's ratio 160, 162, 163
 - LPL bentonite 214, 215, 217
- polymer resin, L-ILW disposal 2
- poroelasticity, isotropic linear, in plane strain and axisymmetry 162–163
- porosity, mathematical upscaling 131
- portlandite 44, 45
- potash, Werra Salt Formation 118
- Praclay Seal 10
- PRECIP modelling 39, 44–45
- pressure drop test 95, 97, 99
- radioactive waste disposal
 - geological disposal facility 1–4, 241–242
 - FORGE project 1–4, 47, 241–256
 - high-level 2, 243
 - low- and intermediate-level 2, 59, 204, 243
- radiolysis, waste containers 9
- radionuclides
 - mobilization 2, 9
 - and carbonation 35
- Raoult-Kelvin law 168, 170, 171, 184–186
- reaction front propagation mechanism 43
- reactive transport model 190–191
- real gas law 49–50
- redox reactions 195, 197–198, 199, 247
- repository systems
 - gas generation and migration 2–4
 - multiphase flow simulation 125–139
 - bentonite 125, 126
 - EDZ 125–127
 - mathematical model 127–129
 - modules 125, 126
 - numerical results 133–139
 - upscaling 129–133
- resaturation
 - bentonite buffer 192
 - NRVB cement 37, 39
- resealing, claystone 75, 81–93
- rock burst, Werra Salt Formation 118–120
- rock salt *see* salt formations
- Safety Case, GDF 1–2, 241–242, 248–249
 - gas issues 243–249
 - see also* geological disposal facility, Safety Case
- salt formations 107–121
 - dilatancy 107, 108, 109–110
 - gas-frac scenario 108, 110, 120
 - impact of gas pressure 110–118
 - large-scale borehole injection tests 116–118
 - medium-scale borehole injection tests 112–116
 - small-scale laboratory injection tests 110–112
 - mass transport 109
 - permeability 107, 111, 112, 115–116, 118, 120
 - pneumatic fracturing 108, 110, 112, 116, 120

- salt formations (*Continued*)
 - tightness 108–110, 118
 - water content 109
- saturation
 - concrete barriers, gas permeability 64, 65, 66, 70–71, 72
 - FEBEX bentonite 49, 50, 51, 56
 - mathematical upscaling 131–132, 134
- sealing
 - fractures 75
 - Boom Clay Formation 10, 13–14
 - claystone 78, 80–83
 - see also* resealing, claystone
 - sealing materials 19
 - shear strength, LPL bentonite **215**
 - shut-in pressure 92, 108
 - single-packer gas injection tests 96, 97–98, 100–102
 - singular spectrum analysis, Lasgit toolkit 229
 - smoothing/weighted moving average functions, Lasgit
 - toolbox 229, 230
 - Sondershausen dam project 20
 - sorption 9, 247
 - spent nuclear fuel, disposal 2, 243
 - spike detection, Lasgit toolkit 229, 230
 - Staßfurt rock salt **111**, 112
 - sulphate reduction 199
 - super-canisters 19
 - swelling properties
 - FEBEX bentonite 48
 - LPL bentonite 214, **215**, 217–218
- Terzaghi's effective stress principle 162
- thermal equilibrium 145
- thermodynamic equilibrium, hydrogen migration
 - modelling 170–171, 172
 - tightness, salt formations 108–110, 118
 - tobermorite 44, 45
 - tortuosity, mathematical upscaling 132
 - transducer, LVDT 76, 77, 86
 - trend detection, Lasgit toolkit 229, 230–231
 - two-phase flow 245
 - FEBEX bentonite 54, 56
 - simulation 123–124
 - Couplex-Gaz 123
 - hydrogen migration in argillite 167–178
 - mathematical model 127–129
 - upscaling 124, 129–133
 - numerical results 133–139
 - UM1 135–139
 - UM2 137–139
 - UCODE_2005 214, 216
 - upscaling, two-phase flow simulation 124, 129–133
 - van Genuchten-Mualem model 127, 128, 172
 - vitrification, HLW disposal 2, 243
 - Volclay KWK bentonite, Boom Clay experiments 10
 - Waste Isolation Pilot Plant (WIPP) 109, 241
 - water permeability
 - concrete barriers 63–64, 66–67, 68
 - crystalline rock 103–104
 - Werra Salt Formation **111**, 116
 - carbon dioxide accumulation 118
 - rock burst 118–120
 - Young's modulus 160, 162, 163
 - LPL bentonite **214**, 215, 216, 217