## 9. SHIELDING, CONTAINMENT AND SAFETY FEATURES

9.1. Shielding objectives (neutron and otherlimits at different important locations)
9.1.1. Reactor vessel (dpa)
9.1.2. Core support structure (dpa)
9.1.3. Above-core structure (dpa)
9.1.4. Activity of secondary sodium (Bq/kg)

### Experimental Fast Reactors

| Plant | 9.1.1. | 9.1.2. | 9.1.3. | 9.1.4. |
|---|---|---|---|---|
| Rapsodie (France) | | | | |
| KNK-II (Germany) | | | | |
| FBTR (India) | $7.17 \times 10^{-11}$ A/kg in accessible areas | | | |
| PEC (Italy) | $10^{21}$nvt (E > 0.1 Mev) | | | |
| JOYO (Japan) | below $2.10^{-5}$ Sv ($\gamma$ and n) in accessible areas | | | |
| DFR (UK) | | | | |
| BOR-60 (Russia) | $6.10^{21}$ | $12.10^{22}$ | $15.10^{22}$ | $<3,7.10^{4}$ |
| EBR-II (USA) | | | | |
| Fermi (USA) | | | | |
| FFTF (USA) | 10% TE* | 10% TE* | 10% TE* | |
| BR-10 (Russia) | 34 dpa ($7.10^{22}$ E>0,1 MeV) | | | |
| CEFR (China) | 2.0 | 2.0 | 2.0 | $5x10^{5}$ |

### Demonstration or Prototype Fast Reactors

| | | | | |
|---|---|---|---|---|
| Phenix (France) | | 2.0 | 0.1 | $10^{5}$ |
| SNR-300 (Germany) | | | | |
| PFBR (India) | $7.17 \times 10^{-9}$ A/kg on components (pump, IHX) | | | |
| MONJU (Japan) | | | | |
| PFR (UK) | $1.8 \times 10^{-10}$ A/kg above vessel roof and near secondary sodium pipes | | | |
| CRBRP (USA) | 10% TE* | | 10% TE* | |
| BN-350 (Kazakhstan) | $1.4\ 10^{21}$ | $1.6.10^{22}$ | $3.10^{21}$ | $<3,7.10^{4}$ |
| BN-600 (Russia) | $1,5.10^{19}$ | $4.5.10^{21}$ | $3.8.10^{21}$ | $1.7.10^{3}$ |
| ALMR (USA) | 4.1 | 4.1 | 4.1 | |

### Commercial Size Reactors

| | | | | |
|---|---|---|---|---|
| Super-Phenix 1 (France) | < 0.005 | < 1.5 | | $2x10^{4}$ |
| Super-Phenix 2 (France) | | | | |
| SNR 2 (Germany) | | | | |
| DFBR (Japan) | | | | $7.4x10^{4}$** |
| CDFR (UK) | 1/20 IAEA recommended limit | | | |
| BN-1600 (Russia) | $1.9.10^{17}$ | $7.1.10^{22}$ | $6.9.10^{22}$ | $1.4.10^{4}$ |
| BN-800 (Russia) | $4.5.10^{17}$ | $1.7.10^{22}$ (6.7dpa) | $4.2.10^{22}$(16dpa) | $4.4.10^{4}$ |
| EFR | | 1 | $1.9x10^{9}$n/cm$^2$/s | $3x10^{4}$ |
| ALMR (USA) | | | | |

* total elongation
** dose rate below 6 $\mu$Sv/h ($\gamma$ = n) in accessible areas

9.2. Shielding materials
9.2.1. Radial shield within primary vessel
9.2.2. Radial (biological) shield outside primary vessel

**Experimental Fast Reactors**

| Plant | 9.2.1. | 9.2.2. |
|---|---|---|
| Rapsodie (France) | stainless steel | concrete |
| KNK-II (Germany) | gray iron | high density concrete |
| FBTR (India) | stainless steel | concrete |
| PEC (Italy) | Nikel reflector elements and $B_4C$ shield elements | high density concrete |
| JOYO (Japan) | stainless steel | graphite and concrete |
| DFR (UK) | steel and borated graphite, top plugs only borated graphite | concrete |
| BOR-60 (Russia) | stainless steel | cast iron and high density concrete |
| EBR-II (USA) | graphite and borated graphite | borated graphite and reinforced concrete |
| Fermi (USA) | stainless steel | reinforced concrete |
| FFTF (USA) | stainless steel | high density concrete and $B_4C$ |
| BR-10 (Russia) | | cast iron, water concrete |
| CEFR (China) | SS + $B_4C$ covered by SS | reinforced concrete |

**Demonstration or Prototype Fast Reactors**

| | | |
|---|---|---|
| Phénix (France) | graphite and stainless steel | concrete |
| SNR-300 (Germany) | stainless steel | serpentine concrete |
| PFBR (India) | 316 & $B_4C$ | concrete |
| MONJU (Japan) | stainless steel | concrete and steel |
| PFR (UK) | graphite in steel | concrete and steel |
| CRBRP (USA) | SA-316 | concrete |
| BN-350 (Kazakhstan) | stainless steel | concrete and steel |
| BN-600 (Russia) | graphite and stainless steel | concrete |
| ALMR (USA) | 304 + $B_4C$ | concrete |

**Commercial Size Reactors**

| | | |
|---|---|---|
| Super-Phénix 1 (France) | stainless steel | concrete |
| Super-Phénix 2 (France) | SS + boron | concrete |
| SNR 2 (Germany) | steel | concrete and steel |
| DFBR (Japan) | SS + $B_4C$ | concrete and steel |
| CDFR (UK) | steel | concrete and steel |
| BN-1600 (Russia) | stainless steel | concrete |
| BN-800 (Russia) | SS+graphite and borated graphite | concrete |
| EFR | SS + $B_4C$ pins and blocks | concrete |
| ALMR (USA) | | |

9.2. Shielding materials
9.2.3. Axial shield inside primary vessel
9.2.4. Axial shield in or above the reactor roof

**Experimental Fast Reactors**

| Plant | 9.2.3. | 9.2.4. |
|---|---|---|
| Rapsodie (France) | | |
| KNK-II (Germany) | | |
| FBTR (India) | | |
| PEC (Italy) | | |
| JOYO (Japan) | | |
| DFR (UK) | | |
| BOR-60 (Russia) | SS | SS,CS, graphite |
| EBR-II (USA) | | |
| Fermi (USA) | | |
| FFTF (USA) | | |
| BR-10 (Russia) | SS, $B_4C$ | parafin, $B_4C$, SS |
| CEFR (China) | SS + $B_4C$ pins | SS + reinforced concrete |

**Demonstration or Prototype Fast Reactors**

| | | |
|---|---|---|
| Phénix (France) | SS, $B_4C$ | concrete and steel (CS) |
| SNR-300 (Germany) | | |
| PFBR (India) | | |
| MONJU (Japan) | SS | CS |
| PFR (UK) | | |
| CRBRP (USA) | | |
| BN-350 (Kazakhstan) | SS | SS, CS, graphite |
| BN-600 (Russia) | SS | SS, CS, graphite |
| ALMR (USA) | steel | steel |

**Commercial Size Reactors**

| | | |
|---|---|---|
| Super-Phénix 1 (France) | SS + $B_4C$ pins | CS |
| Super-Phénix 2 (France) | | |
| SNR 2 (Germany) | | |
| DFBR (Japan) | $B_4C$ | heavy concrete and steel |
| CDFR (UK) | | |
| BN-1600 (Russia) | SS | SS, CS, graphite |
| BN-800 (Russia) | SS | SS, CS, graphite |
| EFR | SS + $B_4C$ pins | 850 mm solid steel roof |
| ALMR (USA) | | |

9.3. Containment
9.3.1. Geometry of secondary containment building
9.3.2. Material
9.3.3. Vented (V) to atmosphere through filters or not vented (NV)

**Experimental Fast Reactors**

| Plant | 9.3.1. | 9.3.2. | 9.3.3. |
|---|---|---|---|
| Rapsodie (France) | cylindrical with dome | steel | |
| KNK-II (Germany) | cylindrical with dome | steel | |
| FBTR (India) | cylindrical with dome | concrete | |
| PEC (Italy) | cylindrical with dome | carbon steel | |
| JOYO (Japan) | cylindrical with dome | carbon steel | |
| DFR (UK) | sphere | steel | NV |
| BOR-60 (Russia) | rectangular building | concrete | |
| EBR-II (USA) | cylindrical with dome | carbon steel | |
| Fermi (USA) | cylindrical with dome | carbon steel | |
| FFTF (USA) | cylindrical with dome | carbon steel | |
| BR-10 (Russia) | | | |
| CEFR (China) | cylindrical with dome | concrete & steel | V |

**Demonstration or Prototype Fast Reactors**

| | | | |
|---|---|---|---|
| Phénix (France) | rectangular | concrete | NV |
| SNR-300 (Germany) | rectangular | steel and concrete | |
| PFBR (India) | cylindrical with dome | concrete | |
| MONJU (Japan) | cylindrical with dome | carbon steel | NV |
| PFR (UK) | rectangular | concrete and steel | NV |
| CRBRP (USA) | cylindrical with dome | carbon steel | |
| BN-350 (Kazakhstan) | ordinary rectangular bldg. | concrete | NV |
| BN-600 (Russia) | ordinary rectangular bldg. | concrete | NV |
| ALMR (USA) | cylindrical with dome | carbon steel | NV |

**Commercial Size Reactors**

| | | | |
|---|---|---|---|
| Super-Phénix 1 (France) | cylindrical with dome | concrete | NV |
| Super-Phénix 2 (France) | rectangular bldg. | concrete | |
| SNR 2 (Germany) | cylindrical | concrete | |
| DFBR (Japan) | rectangular building | steel and concrete | NV |
| CDFR (UK) | cylindrical with dome | steel and concrete | |
| BN-1600 (Russia) | cylindrical building | concrete | |
| BN-800 (Russia) | rectangular building | concrete | NV |
| EFR | cylindrical building | reinforced concrete | V |
| ALMR (USA) | | | |

9.3. Containment
9.3.4. Gross volume ($m^3$)
9.3.5. Maximum design pressure (MPa)

**Experimental Fast Reactors**

| Plant | 9.3.4. | 9.3.5. |
|---|---|---|
| Rapsodie (France) | 15000 | 0.235 |
| KNK-II (Germany) | 5000 | 0.25 |
| FBTR (India) | 15000 | 0.025 |
| PEC (Italy) | 18000 | 0.15 |
| JOYO (Japan) | 18600 | 0.15 |
| DFR (UK) | 11500 | 0.125 |
| BOR-60 (Russia) | | |
| EBR-II (USA) | 14000 | 0.166 |
| Fermi (USA) | 7900 | 0.32 |
| FFTF (USA) | 64100 | 0.067 |
| BR-10 (Russia) | | |
| CEFR (China) | 17000 | 0.1 |

**Demonstration or Prototype Fast Reactors**

| | | |
|---|---|---|
| Phénix (France) | 31000 | 0.040 |
| SNR-300 (Germany) | 323000 | 0.024 |
| PFBR (India) | leak tight containment not yet planned | |
| MONJU (Japan) | 130000 | 0.03 |
| PFR (UK) | 74000 | 0.005 |
| CRBRP (USA) | 170000 | 0.170 |
| BN-350 (Kazakhstan) | | |
| BN-600 (Russia) | | |
| ALMR (USA) | 112 | 0.172 |

**Commercial Size Reactors**

| | | |
|---|---|---|
| Super-Phénix 1 (France) | dome - 6500<br>containment - 170000 | dome - 0.3<br>containment - 0.004 |
| Super-Phénix 2 (France) | | |
| SNR 2 (Germany) | 180000 | * |
| DFBR (Japan) | 27000 | 0.05 |
| CDFR (UK) | 40200 | 0.1 |
| BN-1600 (Russia) | | |
| BN-800 (Russia) | | |
| EFR | 136000 | 0.05 |
| ALMR (USA) | | |

* structures are determined by large airplane crash considerations

9.3. Containment
9.3.6. Seismic acceleration (designed) (g): horizontal
9.3.7. : vertical

**Experimental Fast Reactors**

| Plant | 9.3.6. | 9.3.7. |
|---|---|---|
| Rapsodie (France) | 0.10-0.20 | 0.20-0.50 |
| KNK-II (Germany) | | |
| FBTR (India) | 0.1 | 0.05 |
| PEC (Italy) | 0.30 | 0.10 |
| JOYO (Japan) | 0.15 | 0.075 |
| DFR (UK) | | |
| BOR-60 (Russia) | 0.1 | 0.07 |
| EBR-II (USA) | containment designed in accordance with Uniform Building Code, in its contemporary version | |
| Fermi (USA) | 0.1 | |
| FFTF (USA) | 0.250 | 0.166 |
| BR-10 (Russia) | 0.1 | 0.07 |
| CEFR (China) | 0.107 | 0.071 |

**Demonstration or Prototype Fast Reactors**

| | | |
|---|---|---|
| Phénix (France) | 0.15-0.30 | 0.30-0.60 |
| SNR-300 (Germany) | 0.044 | 0.005 |
| PFBR (India) | | |
| MONJU (Japan) | | |
| PFR (UK) | | |
| CRBRP (USA) | 0.125 | 0.125 |
| BN-350 (Kazakhstan) | | |
| BN-600 (Russia) | 0.1 | 0.07 |
| ALMR (USA) | 0.3-0.5 | 0.3-0.5 |

**Commercial Size Reactors**

| | | |
|---|---|---|
| Super-Phénix 1 (France) | 0.1-0.2 | 0.07-0.14 |
| Super-Phénix 2 (France) | | |
| SNR 2 (Germany) | | |
| DFBR (Japan) | | |
| CDFR (UK) | 0.25 | 0.17 |
| BN-1600 (Russia) | | |
| BN-800 (Russia) | 0.1 | 0.07 |
| EFR | 0.25/0.2* | 0.17/0.13* |

* using UK/USNRC soil response spectr

9.4. Additional safety features

EP - elevated piping guard vessel to limit effect of pipe rupture
DW - double walls of primary loops
CI - containment isolation on increased radiation
TGV - reactor tank guard vessel
TPGV - tank and piping guard vessels
EC - elevations of the core, IHX dump HX to ensure natural convection cooling
NP - no penetrations below sodium level
PC - provision for collecting and cooling core debris following core meltdown or partial meltdown

**Experimental Fast Reactors**

| Plant | 9.4. |
|---|---|
| Rapsodie (France) | DW + TGV |
| KNK-II (Germany) | EP |
| FBTR (India) | DW |
| PEC (Italy) | EP,DW |
| JOYO (Japan) | DW,CI |
| DFR (UK) | DW |
| BOR-60 (Russia) | TPGV** |
| EBR-II (USA) | blast shield, isolation system with containment building |
| Fermi (USA) | DW,CI,TGV,EC,meltdown pan |
| FFTF (USA) | EP,EC |
| BR-10 (Russia) | TPGV |
| CEFR (China) | CI, TGV, EC, NP, PC |

**Demonstration or Prototype Fast Reactors**

| | |
|---|---|
| Phénix (France) | TGV |
| SNR-300 (Germany) | EP,TGV,EC,NP,CI,PC |
| PFBR (India) | DW,TPGV,EC,NP |
| MONJU (Japan) | EP,CI,TEV,EC |
| PFR (UK) | NP, leak jacket which would contain sodium above core level |
| CRBRP (USA) | EP,CI,TGV |
| BN-350 (Kazakhstan) | TPGV |
| BN-600 (Russia) | TGV,NP |
| ALMR (USA) | DW,CI,TGV,EC,NP,PC |

**Commercial Size Reactors**

| | |
|---|---|
| Super-Phénix 1 (France) | CI,TGV,PC |
| Super-Phénix 2 (France) | CI,TGV |
| SNR 2 (Germany) | CI,TGV,EC,NP |
| DFBR (Japan) | EP,DW,CI,TGV,NP |
| CDFR (UK) | TGV |
| BN-1600 (Russia) | TGV,NP |
| BN-800 (Russia) | TGV,NP,PC |
| EFR | CI,TGV,EC,NP,PC |
| ALMR (USA) | |

* i.e. additional to the shutdown and decay heat removal systems

** on parts of the primary loops to limit effect of pipe rupture