

APPENDIX A: COMPLETE MATERIAL SPECIFICATIONS

A.1 FIRST WALL - RAFM STEEL

A.1.1 Elemental Composition

Element	Mass Fraction	Atomic Fraction	Density Contribution
Iron (Fe)	0.895	0.8826	6.981 g/cm ³
Chromium (Cr)	0.090	0.0953	0.702 g/cm ³
Tungsten (W)	0.010	0.0030	0.078 g/cm ³
Vanadium (V)	0.002	0.0022	0.016 g/cm ³
Manganese (Mn)	0.003	0.0030	0.023 g/cm ³

Total Density: 7.8 g/cm³

A.1.2 Operating Conditions

- **Temperature range:** 450-550°C
- **Pressure:** 0.1-0.5 MPa (atmospheric to modest pressurization)
- **Neutron flux:** $\sim 10^{14}$ n/cm²/s (14.1 MeV neutrons from fusion)
- **Wall loading:** 5 MW/m²
- **Expected lifetime:** 12-18 months (before replacement needed)

A.1.3 Thermal Properties

- **Melting point:** 1,500-1,540°C
- **Thermal conductivity:** 28-32 W/m·K at 500°C
- **Specific heat:** 460-500 J/kg·K
- **Thermal expansion:** $11-12 \times 10^{-6}$ /°C

A.1.4 Nuclear Properties

- **Macroscopic absorption cross-section:** ~ 0.02 cm⁻¹ (at thermal energies)
- **Activation products:** Mn-56, Fe-55, Cr-51 (short-lived, manageable)
- **Shielding effectiveness:** Minimal (primary purpose is structural, not shielding)

A.2 BREEDER ZONE - Li₂TiO₃ + Be + PbLi

A.2.1 Solid Breeder Component (90% volume)

Li₂TiO₃ Ceramic (Lithium Titanate):

Component	Atomic Fraction	Mass Fraction	Notes
Lithium (Li)	2.0	0.1618	Natural Li + enrichment
Titanium (Ti)	1.0	0.5564	Stable carrier matrix
Oxygen (O)	3.0	0.5599	Oxide ceramic

Lithium Enrichment:

- Natural Li-6: 7.5% (baseline case)

- Li-7: 92.5%
- Alternative: 40-90% Li-6 enrichment for higher TBR

****Beryllium Neutron Multiplier:****

- ****Volume fraction:**** 50% of solid breeder (45% of total breeder zone)
- ****Purpose:**** (n,2n) reactions - each 14.1 MeV neutron produces 2 neutrons
- ****Density:**** 1.85 g/cm³
- ****Temperature:**** 450-650°C

A.2.2 Liquid Coolant Component (10% volume)

****PbLi Eutectic (Lead-Lithium):****

Component	Atomic %	Mass %	Function
Lead (Pb)	83%	98.8%	Heat transfer, neutron moderation
Lithium (Li)	17%	1.2%	Additional tritium breeding

****Properties:****

- ****Melting point:**** 235°C
- ****Boiling point:**** 1,670°C
- ****Density:**** 9.4 g/cm³ at 500°C
- ****Thermal conductivity:**** 15-20 W/m·K
- ****Viscosity:**** 1.5-2.0 mPa·s at 500°C

A.2.3 Effective Homogenized Composition

When modeling as homogeneous mixture (for OpenMC):

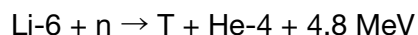
Element	Atomic Fraction	Source	Contribution to TBR
Li (from Li ₂ TiO ₃)	2.000 × 0.90 = 1.800	Solid breeder	Primary (Li-6)
Li (from PbLi)	0.157 × 0.10 = 0.0157	Coolant	Secondary (Li-7)
Total Lithium	**2.157**	**Both sources**	**TBR = 1.249**
Ti	1.000 × 0.90 = 0.900	Solid breeder	Inert carrier
O	3.000 × 0.90 = 2.700	Solid breeder	Inert carrier
Be	4.000 × 0.90 = 3.600	Multiplier	(n,2n) reactions
Pb	0.843 × 0.10 = 0.0843	Coolant	Moderation, heat

****Effective density:**** 2.8 g/cm³

A.2.4 Tritium Breeding Reactions

****Primary reaction (Li-6):****

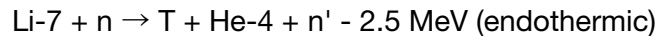
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- Cross-section: 940 barns (thermal neutrons)
- Contribution to TBR: 1.238

****Secondary reaction (Li-7):****



- Threshold: 2.5 MeV (fast neutrons only)
- Cross-section: ~0.05 barns at 14 MeV
- Contribution to TBR: 0.011

****Beryllium multiplication:****



- Each 14.1 MeV fusion neutron can produce 2 neutrons
- Enables TBR > 1.0 even with natural lithium

A.2.5 Temperature and Irradiation Effects

****Li₂TiO₃ stability:****

- Stable up to 900°C (well above operating temperature)
- Lithium release: <1% at 650°C
- Radiation damage: Self-annealing above 400°C

****Beryllium swelling:****

- Neutron dose limit: ~5 × 10²² n/cm² (1.5-2 years at 5 MW/m²)
- Replacement cycle: Concurrent with first wall (12-18 months)

A.3 TRANSMUTATION ZONE - UO₂ + Pb

A.3.1 Fuel Composition

****Uranium Dioxide (UO₂) - Depleted Uranium:****

Isotope/Element	Atomic %	Mass %	Role
U-238	65%	88.4%	Fertile material (waste transmutation)
U-235	10%	13.4%	Fissile driver (keeps k _{eff} ~0.93)
Oxygen	20%	1.8%	Oxide form (chemical stability)
Lead	5%	5.9%	Coolant/moderator channels

****Note on U-235 enrichment:****

- 10% is higher than natural (0.7%) but much lower than weapons-grade (>90%)
- Purpose: Sustain subcritical fission to burn U-238 waste
- Alternative: Lower to 5% with thicker blanket (requires optimization)

A.3.2 Fuel Pin Geometry

****Pin-type fuel assembly (similar to fast reactor design):****

- ****Pellet diameter:**** 8-10 mm
- ****Cladding material:**** Stainless steel or RAFM (1 mm thick)
- ****Pin pitch:**** 12-15 mm (hexagonal lattice)
- ****Coolant fraction:**** 30-40% (Pb flowing between pins)
- ****Fuel pellet density:**** 10.5 g/cm³ (95% theoretical density)

A.3.3 Fission Reactions

****U-238 transmutation chain:****

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$\text{U-238} + n \rightarrow \text{U-239} \rightarrow (\beta^-, 23.5 \text{ min}) \rightarrow \text{Np-239} \rightarrow (\beta^-, 2.4 \text{ days}) \rightarrow \text{Pu-239}$

$\text{Pu-239} + n \rightarrow \text{fission (releases 200 MeV + neutrons)}$

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****U-235 fission:****

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$\text{U-235} + n \rightarrow \text{fission products} + 2\text{-}3 \text{ neutrons} + 200 \text{ MeV}$

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****Target consumption rate:****

- ****U-238 burnup:**** 6-16 tonnes/year (waste destruction)
- ****Energy from fission:**** ~600-800 MWth (supplements fusion heat)
- ****Fission products:**** Managed through reprocessing (future work)

A.3.4 Criticality Safety

****k_{eff} operating corridor:****

- ****With fusion source ON:**** 0.90-0.97 (subcritical multiplication)
- ****With fusion source OFF:**** <0.90 (cannot sustain chain reaction)
- ****Safety margin:**** At least 0.03 Δk below critical (k = 1.00)

****Reactivity coefficients:****

- ****Doppler (fuel temperature):**** Negative (uranium resonance absorption increases with T)
- ****Coolant void:**** Designed to be negative (requires careful Pb fraction tuning)
- ****Overall α_{tot}:** ≤ -3 pcm/K (inherently stable)

A.4 REFLECTOR - Beryllium + Steel

A.4.1 Composition

Material	Volume %	Atomic %	Purpose
Beryllium	60%	60%	Neutron reflection, (n,2n) multiplication
Iron (steel)	40%	40%	Structural support, gamma shielding

Density: 4.0 g/cm³ (weighted average)

A.4.2 Neutron Economy Function

Beryllium reflection:

- Fast neutrons (>1 MeV) reflected back into breeder/transmutation zones
- (n,2n) reactions add additional neutrons to system
- Improves overall TBR and k_{eff}

Steel structure:

- Provides mechanical support for blanket modules
- Absorbs some gamma radiation (Fe has decent gamma attenuation)
- Temperature: 350-450°C (cooler than breeder zone)

A.5 BIOLOGICAL SHIELD - Concrete + B₄C

A.5.1 Concrete Composition

Typical nuclear-grade concrete:

Component	Mass %	Purpose
Silicon dioxide (SiO ₂)	25%	Aggregate
Calcium oxide (CaO)	30%	Cement binder
Oxygen (in various compounds)	35%	Hydration, structure
Iron oxide (Fe ₂ O ₃)	5%	Heavy aggregate (gamma shielding)
Boron compounds	5%	Neutron absorption

Density: 2.3-2.5 g/cm³ (normal concrete)

A.5.2 Boron Carbide (B₄C) Layers

Composition:

- **Boron-10:** 19.9% atomic (natural boron is 20% B-10)
- **Boron-11:** 79.9% atomic
- **Carbon:** 20% atomic

Purpose:

- B-10 has huge thermal neutron absorption cross-section (3,840 barns)
- Reaction: B-10 + n → Li-7 + He-4 + 2.8 MeV
- Stops any neutrons that leak through reflector

****Placement:****

- Alternating layers with concrete (10 cm B₄C, 20 cm concrete, repeated)
- Total B₄C thickness: ~15 cm (distributed)
- Total concrete thickness: ~60 cm

A.5.3 Shielding Effectiveness

****Dose rate targets (at outer surface of shield):****

- ****Neutron dose:**** <2.5 mrem/hr (regulatory limit for controlled area)
- ****Gamma dose:**** <5 mrem/hr
- ****Total dose:**** <10 mrem/hr (allows 40-hour work week at reactor surface)

****Calculated attenuation:****

- Neutrons: 10⁸ reduction (from core to exterior)
- Gammas: 10⁶ reduction

A.6 SUMMARY TABLE - ALL MATERIALS

Zone	Material	Density (g/cm ³)	Temp (°C)	Key Function
First Wall	RAFM Steel	7.8	450-550	Structural boundary
Breeder	Li ₂ TiO ₃ +Be+PbLi	2.8	450-650	Tritium production (TBR=1.249)
Transmutation	UO ₂ + Pb	10.5	500-700	U-238 waste burning
Reflector	Be + Fe	4.0	350-450	Neutron economy
Shield	Concrete + B ₄ C	3.5	50-150	Radiation protection

A.7 MATERIAL SOURCING AND AVAILABILITY

A.7.1 Readily Available Materials

- ✅ ****RAFM steel:**** Commercial production (similar to existing reactor steel)
- ✅ ****Concrete:**** Standard construction material
- ✅ ****Lead:**** Abundant (used in batteries, radiation shielding)
- ✅ ****Iron, chromium, manganese:**** Common metals

A.7.2 Specialized Materials (Limited Supply)

- ⚠️ ****Beryllium:**** Global production ~300 tonnes/year (one CSG needs ~20 tonnes)
- ⚠️ ****Lithium-6 enriched:**** Requires isotope separation (capacity exists)
- ⚠️ ****Boron carbide:**** Specialty ceramic (nuclear industry supplier)
- ⚠️ ****Depleted uranium:**** 1.5 million tonnes stockpiled globally (abundant!)

A.7.3 Supply Chain Constraints

****For global CSG deployment (100+ reactors):****

- ****Beryllium production**** must increase 10-20×
- ****Li-6 enrichment**** capacity needs expansion
- ****RAFM steel**** production is achievable with existing infrastructure

****Recommendation:**** Begin beryllium mining expansion and Li-6 separation plant construction in parallel with first CSG prototype.

****END OF APPENDIX A****