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/cm^3

A.1.2 Operating Conditions

- **Temperature range:** 450-550°C
- **Pressure:** 0.1-0.5 MPa (atmospheric to modest pressurization)
- **Neutron flux:** ~10^{14} $n/cm^2/s$ (14.1 MeV neutrons from fusion)
- **Wall loading:** 5 MW/m^2
- **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 × 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 - Li_2TiO_3 + Be + PbLi

A.2.1 Solid Breeder Component (90% volume)

Li_2TiO_3 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_2TiO_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):

```
Li-6 + n → T + He-4 + 4.8 MeV
```

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

Secondary reaction (Li-7):

```
Li-7 + n → T + He-4 + n' - 2.5 MeV (endothermic)
```

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

Beryllium multiplication:

```
Be-9 + n (>1.85 MeV) → 2n + 2(He-4)
```

- 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

Li_2TiO_3 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: ~5×10^{22} n/cm^2 (1.5-2 years at 5 MW/m^2)
- Replacement cycle: Concurrent with first wall (12-18 months)

A.3 TRANSMUTATION ZONE - UO_2 + Pb

A.3.1 Fuel Composition

Uranium Dioxide (UO_2) - 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/cm^3 (95% theoretical density)

A.3.3 Fission Reactions

U-238 transmutation chain:

```
U-238 + n → U-239 → (β-, 23.5 min) → Np-239 → (β-, 2.4 days) → Pu-239
Pu-239 + n → fission (releases 200 MeV + neutrons)
```

U-235 fission:

```
U-235 + n → fission products + 2-3 neutrons + 200 MeV
```

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 + B_4C

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_2O_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 (B_4C) 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 B_4C, 20 cm concrete, repeated)
- Total B_4C 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: 10^8 reduction (from core to exterior)
- Gammas: 10^6 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_2TiO_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_4C	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