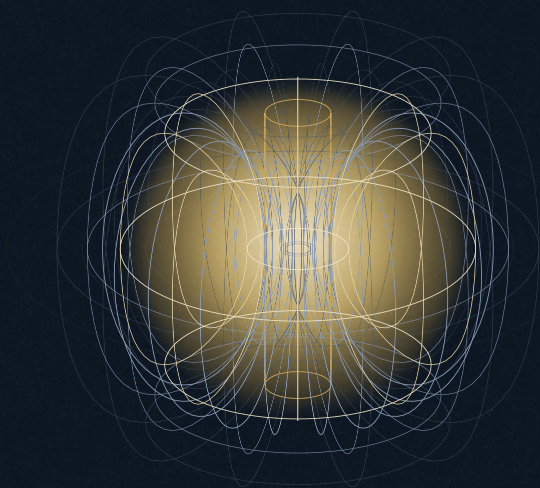
KRONOS FUSION ENERGY



PAPER 2.33 · THE KRONOS 2026 SERIES

The Tritium Breeding Ladder for a Compact Spherical-Tokamak Breeder: Per-Unit Inventory, Doubling Time and the Fleet Path to Tritium Self-Sufficiency

A fusion breeder's product is tritium, and its credibility rests on an honest mass balance rather than a single optimistic breeding number. We formulate the tritium fuel cycle of...

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BY P I FORD AND G L KULCINSKI

2026 · EDITORIAL EDITION

THE OFFICIAL RECORD

What this document is, and how to read its numbers

This is a combined editorial. It gathers, in one volume, the two design studies Kronos Fusion Energy released in 2026 — a compact spherical-tokamak tritium/helium-3 breeder and a deuterium–helium-3 tandem-mirror generator — together with the intellectual-property estate, the people, and, in the internal edition, the full commercial case. The scientific text is the same text that appears in the arXiv preprints and the journal submissions; the editorial adds the apparatus a reader needs to hold the whole program at once, and nothing in the physics is altered to fit it.

THE HONESTY STANCE IS THE ASSET

Every headline quantity carries an **evidence class** — DERIVED RECOMPUTED MEASURED REQUIREMENT — and, where a number is a modelled extrapolation rather than a demonstrated value, it is labelled as such and its downside is shown next to it. Several quantities in the underlying corpus moved after first publication; where a value has been withdrawn or restated, the record says so plainly. This is deliberate: a diligence team will find the load-bearing assumptions, so the document surfaces them first.

TWO EDITIONS

This volume is issued in two editions. The **public edition** (light) carries the physics and the design only — no dollar, price, or per-kilogram figure appears anywhere in it. The **internal edition** (dark) adds the economics, the funding architecture, and the defense-commercial analysis, and is marked *Confidential* accordingly; it is not for public distribution. Where the commercial case rests on a modelled assumption rather than a demonstrated one, it is labelled as such and its downside is shown alongside it, on the same terms as the physics.

TITLE	The Kronos Fleet — Hyperion · Aegis · MetroVolt: A Combined Design & Commercialization Study
AUTHOR	Priyanca Ford, Founder & CEO, on behalf of Kronos Fusion Energy
EDITION	2026 Combined Editorial · first issue
COMPANION WORKS	The five-paper arXiv drop — (1) Breeder, (2) Burner, (3) REBCO magnet & tape, (4) Direct Energy Conversion, (5) AI/ML/Quantum control — with matching numbered Zenodo deposits, plus the IOP journal and IAEA-FEC submissions. Patents were filed before the drop.
NAMING	Hyperion = the breeder; Aegis (defense) and MetroVolt (data-center) = one generator in two housings. Internal mode letters (D1, L) do not appear on public surfaces.
STATUS	Conceptual design & simulation study. Nothing herein is a construction commitment.

HOW TO READ THIS VOLUME

The fleet at a glance, and the way its numbers are marked

This volume opens with *Orientation*, presents the five research papers as a bound sequence, and closes with the *Apparatus*. *Foundations* sets out the three general results both machines rest on. *Paper One* is the Hyperion breeder; *Paper Two* the Aegis / MetroVolt generator; *Papers Three, Four and Five* are the enabling science — high-field REBCO magnets and tape, direct energy conversion, and the AI / ML / quantum control stack. A *Digital Twin & 3-D Model* part follows, then the *Environmental* profile. The *Economics* and levelized cost and the *Business Case* and diligence record appear in the internal edition only; the *Simulations* proof record and the Apparatus — patent portfolio, team, limitations, and sources — close both editions.

THE FLEET AT A GLANCE

	HYPERION	AEGIS	METROVOLT
Role	Strategic-isotope foundry	Defense installation power	Campus power
Machine	**Spherical tokamak**	**Tandem mirror**	**Tandem mirror**
Fuel	Deuterium–tritium	Deuterium–helium-3	Deuterium–helium-3
Delivers	Tritium · ^{3}He · 14 MeV n	Resilient installation power	Firm campus power
Physics bar	**Fusion gain only**	Closure (gates named)	Closure + lunar ^{3}He
In the fleet	Breeds the fuel	Proves the generator	Commercial destination

HOW THE NUMBERS ARE MARKED

Every headline quantity carries an evidence class — DERIVED from first principles, RECOMPUTED from raw data, MEASURED in hardware, or a REQUIREMENT yet to be met. Financial figures carry a case label and are confined to the internal (confidential) edition. Values that moved after first publication are shown as withdrawn or restated rather than quietly changed. A capability you can evaluate is one whose limits are on the page.

ABSTRACT

The Tritium Breeding Ladder for a Compact Spherical-Tokamak Breeder: Per-Unit Inventory, Doubling Time and the Fleet Path to Tritium Self-Sufficiency

A fusion breeder's product is tritium, and its credibility rests on an honest mass balance rather than a single optimistic breeding number. We formulate the tritium fuel cycle of the compact spherical-tokamak (ST) breeder Hyperion (design point $Q = 3.076$, $P_{\mathrm{fus}} = 85.04\,MW$, $I_p = 9.66\,MA$, $\delta = -0.30$, $B_0 = 8\,T$, $\kappa = 2.0$, $R_0 = 1.20\,m$, aspect ratio $A = 2.5$, centrepost peak field 16.84 T) as a coupled inventory problem and reduce it to three quantities: the per-unit burn rate, fixed by the fusion power at $\Lambda_T = 4.769 kg-T$ fpy^{-1}; the surplus law $S = (\mathrm{TBR} - 1)\Lambda_T$; and a self-sufficiency condition $\mathrm{TBR} \geq \mathrm{TBR}_{\mathrm{req}}$ set by non-recoverable losses, radioactive decay of the standing inventory, and the doubling seed for new plants. Three-dimensional Monte-Carlo neutronics on ENDF/B-VIII.0 (OpenMC, CAD-faithful DAGMC geometry, 1.2×10^8 histories per configuration on the NVIDIA GPU HPC campaign) place the breeding on a confirmed *ladder*: net $\mathrm{TBR} \approx 1.06$ (literal frozen recipe, $S = 0.30 kg-T$ yr^{-1}), ≈ 1.19 (dedicated 5 cm solid-beryllium multiplier, $S = 0.91$), and 1.42 (advanced void-reduced blanket, $S \approx 2.0$) — the last the confirmed per-unit ceiling across twelve blanket configurations, above which the ST centrepost caps the inboard breeding coverage. We derive the start-up inventory ($2.38/4.77/9.54 kg-T$ for an effective fill time of $0.5/1/2\,\mathrm{yr}$) and the tritium-limited fleet doubling time ($T_2 = I_0 \ln 2/S = 11.2$, 3.6 and $1.7\,\mathrm{yr}$ for the three rungs), and we show that a national-scale $4 kg-T$ yr^{-1} supply is a *fleet* property — two advanced units or four to five solid-beryllium units — never a single-unit claim. Against the published self-sufficiency literature the required TBR sits at ≈ 1.28 for a fleet-growing plant, placing the solid-beryllium rung above break-even and the advanced rung firmly in the growth regime. One honest gate remains: the advanced-blanket ceiling requires that blanket to be built and qualified, and the standing in-vessel inventory that sets the safety basis is computed by the accountancy companion, not asserted here. Every headline quantity is a frozen anchor in the Kronos de-risking register.

Open-access deposit (code & data, CC BY 4.0): DOI 10.5281/zenodo.22645746 · Zenodo community *kronos_fusion_energy*. Explore it live: interactive 3-D model · physics validator.

Keywords: tritium breeding ratio · fuel cycle · start-up inventory · doubling time · fleet self-sufficiency · beryllium multiplier · direct internal recycling · OpenMC neutronics · spherical-tokamak breeder

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NOMENCLATURE

Symbols, units, and the names of things

Q	plasma (fusion) gain, P_{fus}/P_{aux}
Q_E	engineering gain, net electric out / recirculating in
H_{98}	confinement enhancement over the IPB98(y,2) scaling
Z_{eff}	effective ion charge
c_{ee}	electron–electron bremsstrahlung leading coefficient, 2.120022 (exact)
τ_E	energy confinement time
I_p	plasma current
R_0, a	major radius, minor radius
κ, δ	elongation, triangularity
β_N	normalized plasma beta (Troyon-normalized)
TBR	tritium breeding ratio
DEC	direct energy conversion
CF	plant capacity factor (availability)
FOAK / NOAK / BOAK	first / n^{th} / best of a kind
Hyperion	the ST breeder (internal: Mode D2)
Aegis	the generator, defense/installation housing (internal: Mode M)
MetroVolt	the generator, data-center housing (Mode M)

§ 1

Introduction

THE BREEDER'S PRODUCT IS TRITIUM

The Hyperion device is not designed to make net electricity; its mission is to breed tritium, co-produce helium-3, and drive a 14 MeV materials-test volume [1,2]. For a machine whose deliverable is a kilogram-scale flow of a [redacted]-half-life isotope, the single most important engineering claim is not the fusion gain but the *tritium mass balance*: how much tritium the machine burns, how much its blanket breeds, how much it must hold in inventory to run, and what a unit — and a fleet of units — can export. Historically, breeder and reactor concepts have tended either to quote an optimistic tritium breeding ratio (TBR) as a single number, or to leave the standing inventory — which sets the tritium safety basis — undefined [3,4]. We do neither. This paper develops the fuel cycle as a formal inventory problem, derives the burn rate and the self-sufficiency condition from first principles, computes the breeding as a confirmed *ladder* of neutronics design points, and separates cleanly what one unit delivers from what a fleet delivers.

WHY TRITIUM SELF-SUFFICIENCY IS HARD, AND WHY IT IS THE GATE

There is no external market that can fuel a fleet of DT machines: the world civilian tritium inventory is of order tens of kilograms and declining, and heavy-water-reactor production cannot supply more than a single demonstration plant's start-up charge on any realistic schedule [7,8]. A DT fusion economy must therefore breed its own fuel, and must breed a *surplus* large enough to (i) replace the burned triton, (ii) cover non-recoverable losses and radioactive decay of the in-process and reserve inventory, and (iii) accumulate the start-up charge for the next plant within an acceptable doubling time. Abdou and co-workers established that tritium self-sufficiency is not guaranteed but occupies a bounded "phase space" of plasma, blanket and fuel-cycle parameters [5,4,3]; El-Guebaly and Malang sharpened the required-TBR accounting for advanced power plants [6]; and Day and Giegerich showed that the vulnerable in-vessel inventory can be minimised by *direct internal recycling* (DIR) of the torus exhaust rather than routing all unburned fuel through a large buffered store [9]. The compact ST breeder inherits all of these constraints, and adds one of its own: the water-cooled tungsten-carbide-shielded centrepost that lets a spherical tokamak reach 16.84 T on-axis-equivalent field occupies the inboard midplane and therefore caps the inboard breeding coverage, setting a hard ceiling on the achievable per-unit TBR.

PRIOR ART AND THE CONTRIBUTION OF THIS PAPER

Modern breeding-blanket studies for DEMO-class devices — HCPB, HCLL, WCLL and DCLL concepts — report net TBRs in the 1.1–1.2 range once realistic penetrations, structure and manifolds are included [11,12,6], and CAD-faithful Monte-Carlo neutronics with ENDF/B-VIII.0 nuclear data is now the accepted tool for computing them [13,14,15]. Compact high-field concepts such as ARC report that self-sufficiency is attainable but tight, and depends sensitively on multiplier choice and blanket thickness [19,10,18]. What has been missing for the compact ST breeder specifically is a single, internally consistent treatment that (a) writes the fuel cycle as a governing inventory model with its conservation laws made explicit; (b) grounds every breeding number in a 3-D Monte-Carlo campaign rather than a 1-D estimate; (c) reports the breeding not as one number but as a *ladder* of blanket design points with the centrepost-imposed ceiling stated; and (d) carries the analysis all the way to the start-up inventory, the doubling time, and the fleet aggregation, so that the difference between a per-unit claim and a fleet claim is unambiguous. This paper supplies that treatment.

Our contributions are: a formal fuel-cycle inventory model and the surplus and required-TBR laws derived from it (§2); a GPU-accelerated Monte-Carlo neutronics methodology and its numerical formulation (§3); the confirmed three-rung breeding ladder and its centrepost ceiling (§4, figures 1–3); the start-up-inventory and doubling-time results (figures 4–5); the fleet-aggregation result that makes $4kg - T$ yr^{-1} a fleet property (figures 6–5); the honest sub-unity-TBR gate (figure 7); and a quantitative comparison to the published self-sufficiency literature (§5). Every quantitative claim traces to a frozen serial in the Kronos Physics De-Risking Register [1]; the serials (e.g. BR-L2-A7) are given inline so each number is auditable. The result that ties the paper together is that the physics-derived *required* TBR for a fleet-growing plant, $\mathrm{TBR}_{\mathrm{req}} \approx 1.28$, sits between the literal recipe and the advanced blanket — so the breeding ladder is not a menu of equivalent options but a map of who can grow a fleet and who cannot.

§ 2

Governing equations and the formal fuel-cycle problem

THE BURN RATE FROM POWER BALANCE

Each deuterium–tritium fusion event

$$\mathrm{D}+\mathrm{T} \longrightarrow {}^{4}\mathrm{He}\,(3.52\ \mathrm{MeV})+\mathrm{n}\,(14.07\ \mathrm{MeV}), \qquad E_{DT}=17.59\ \mathrm{MeV},$$

consumes exactly one triton and yields exactly one 14 MeV neutron. The volumetric reaction rate integrated over the plasma is fixed by the fusion power,

$$\mathcal{R}=\frac{P_{\mathrm{fus}}}{E_{DT}}=\frac{85.04\times 10^{6}\ \mathrm{W}}{17.59\times 1.602\times 10^{-13}\ \mathrm{J}}=3.02\times 10^{19}\ \mathrm{s}^{-1},$$

which equals, to rounding, the frozen 14 MeV source strength $S_n = 3.009\times 10^{19}\ \mathrm{s}^{-1}$ carried independently in the register (BR-OUT-3). The triton mass consumption rate is $\dot{m}_T=\mathcal{R}\,m_T$ with $m_T=3.016\,u=5.008\times 10^{-27}$ kg, so that over one full-power year ($t_{\mathrm{fpy}}=3.156\times 10^{7}$ s) the per-unit burn rate is

$$\Lambda_T=\frac{P_{\mathrm{fus}}}{E_{DT}}\,m_T\,t_{\mathrm{fpy}}=3.02\times 10^{19}\times 5.008\times 10^{-27}\times 3.156\times 10^{7}=4.769 kg-T \qquad \mathrm{fpy}^{-1}$$

(gate BR-L1-A6). The burn rate is a hard consequence of the fusion power alone; it is not a design lever. The breeding ratio is the lever, and it enters only through the surplus.

THE LUMPED FUEL-CYCLE INVENTORY MODEL

The fuel cycle is a closed loop (figure 8): the plasma burns a small fraction of the injected tritium each pass, the unburned remainder is pumped, separated, and returned by DIR; the blanket breeds fresh tritium from the 14 MeV neutrons via ${}^{6}\mathrm{Li}(n,\alpha)\mathrm{T}$ and ${}^{7}\mathrm{Li}(n,n'\alpha)\mathrm{T}$, from which it is extracted and stored. We lump the recoverable tritium into three residence compartments — the plasma/exhaust loop I_p, the blanket breeding-and-extraction path I_{bz}, and the storage/processing hold-up I_{sto} — and write a mass balance for each. With fuelling efficiency η_f and single-pass burn fraction f_b, sustaining the burn rate Λ_T demands an injection throughput

$$\dot{N}_{\mathrm{inj}}=\frac{\Lambda_T}{f_b\,\eta_f},$$

of which a fraction $(1-f_b\eta_f)$ is recycled. Writing [redacted] for the tritium decay constant ([redacted]) and ℓ for the fractional non-recoverable loss (permeation to coolant, trapped retention, waste streams), the compartment balances are

$$\begin{aligned}
\dot{I}_p &= \dot{N}_{\mathrm{inj}}(1-f_b\eta_f)-\frac{I_p}{\tau_p}-\lambda I_p,\\
\dot{I}_{bz} &= \mathrm{TBR}\,\Lambda_T-\frac{I_{bz}}{\tau_{bz}}-\lambda I_{bz}-\ell_{bz}\,\mathrm{TBR}\,\Lambda_T,\\
\dot{I}_{\mathrm{sto}} &= \frac{I_p}{\tau_p}+\frac{I_{bz}}{\tau_{bz}}-\dot{N}_{\mathrm{inj}}\,\eta_f-\lambda I_{\mathrm{sto}}-\dot{S}_{\mathrm{exp}},
\end{aligned}$$

where τ_p, τ_{bz} are the effective mean residence times of the plasma/exhaust and blanket paths and $\dot{S}_{\mathrm{exp}}$ is the tritium drawn off for export or for seeding a new plant. Equations (5)–(5) are the machine-checkable statement of tritium conservation: production ($\mathrm{TBR}\,\Lambda_T$) minus consumption (Λ_T), decay ($\lambda\sum_i I_i$), and non-recoverable loss must equal the rate of change of the total recoverable inventory plus what is exported.

THE STEADY-STATE SURPLUS LAW

Summing (5)–(5) and imposing steady operation ($\dot I_p = \dot I_{bz} = \dot I_{\rm sto} = 0$) gives the net rate at which tritium becomes available for export or fleet growth,

$$S \;=\; \dot S_{\rm exp} \;=\; \big(\mathrm{TBR} - 1 - \ell\big)\,\Lambda_T \;-\; \lambda\, I_{\rm res},$$

with $I_{\rm res} = I_p + I_{bz} + I_{\rm sto}$ the total standing inventory and ℓ the aggregate non-recoverable loss fraction. Equation (6) is the central book-keeping identity of the paper. When the non-recoverable loss and the decay drain of the standing inventory are small compared with the gross surplus — the design intent, enforced by DIR and by permeation-barrier requirements — it reduces to the linear *surplus law*

$$\boxed{S = (\mathrm{TBR} - 1)\,\Lambda_T}, \qquad \Lambda_T = 4.769 kg - T \qquad \mathrm{fpy}^{-1}.$$

This reduced law is directly confirmed by the frozen anchors: at $\mathrm{TBR} = 1.34$ the toolkit returns $S = 1.6215 kg - T$ yr^{-1} and at $\mathrm{TBR} = 1.80$ it returns $S = 3.8152 kg - T$ yr^{-1} (gates BR-L1-A6/BR-OUT-1), reproducing $(1.34 - 1) \times 4.769 = 1.621$ and $(1.80 - 1) \times 4.769 = 3.815$ to four figures. The breeding ratio is therefore the sole design lever on the surplus, and every rung of the ladder in §4 is a point on the line (7).

THE REQUIRED BREEDING RATIO FOR SELF-SUFFICIENCY

Break-even breeding ($\mathrm{TBR} = 1$) only replaces the burned triton; it does not run a plant, because the plant must also cover its losses, the decay of its own inventory, and the fuel needed to start the next unit. Following the required-TBR framework of Abdou, Sawan and El-Guebaly [5,4,6,3] we require the surplus to fund three sinks: non-recoverable losses; the decay-compensated reserve inventory held for continuity of operation; and the doubling seed. Setting $S \geq 0$ after those sinks in (6) and adding an explicit nuclear-data/modelling margin $\varepsilon_{\rm unc}$ gives the required breeding ratio

$$\mathrm{TBR}_{\rm req} \;=\; 1 \;+\; \underbrace{\ell}_{\text{losses}} \;+\; \underbrace{\frac{\lambda I_{\rm res}}{\Lambda_T}}_{\text{decay of reserve}} \;+\; \underbrace{\frac{I_0}{\Lambda_T\,T_2}}_{\text{doubling seed}} \;+\; \underbrace{\varepsilon_{\rm unc}}_{\text{nuclear-data margin}},$$

where $I_{\rm res} = \Lambda_T\, t_r$ is the reserve inventory held for a continuity time t_r, I_0 is the start-up charge of a new plant, and T_2 is the target doubling time. With design values $\ell = 0.02$, [redacted] (so $I_{\rm res} = 2.38 kg - T$ and $\lambda I_{\rm res}/\Lambda_T = 0.028$), a [redacted] target with $I_0 = 4.77 kg - T$ (giving $I_0/(\Lambda_T T_2) = 0.20$), and $\varepsilon_{\rm unc} = 0.03$ from the nuclear-data uncertainty budget [13] (companion 2.27), equation (8) evaluates to

$$\mathrm{TBR}_{\rm req} \approx 1 + 0.02 + 0.028 + 0.20 + 0.03 = 1.28.$$

A plant that merely sustains itself and holds a reserve (drop the doubling term) needs only $\mathrm{TBR}_{\rm req} \approx 1.08$; a plant that also seeds a growing fleet needs ≈ 1.28. This single number, laid against the ladder of §4, is the quantitative spine of the paper.

START-UP INVENTORY

Before a unit can run self-sufficiently it must be charged with enough tritium to fill the plasma/exhaust loop, the blanket path, and the processing hold-up. From the residence structure of (5)–(5) the start-up charge is

$$I_{\rm start} = \Lambda_T \left[\frac{\tau_p}{f_b \eta_f} + \tau_{bz} + \tau_{\rm sto}\right] + I_{\rm res} \;\equiv\; \Lambda_T\, \tau_{\rm eff},$$

where $\tau_{\rm eff}$ collects the effective fill times. The plasma/exhaust term $\tau_p/(f_b\eta_f)$ dominates when the single-pass burn fraction f_b is small (a few percent), which is precisely why DIR — by shortening τ_p and returning unburned fuel promptly rather than through a large buffered store — is the lever that keeps $I_{\rm start}$, and hence the vulnerable in-vessel inventory, small [9]. The frozen anchors give $I_{\rm start} = 2.38/4.77/9.54 kg - T$ for $\tau_{\rm eff} = 0.5/1/2\,\mathrm{yr}$ (gate BR-L1-A6), i.e. $I_{\rm start} = \Lambda_T\, \tau_{\rm eff}$ evaluated at $\Lambda_T = 4.769 kg - T$ fpy^{-1}. We adopt $I_0 = 4.77 kg - T$ (the one-full-power-year charge) as the reference start-up inventory for the doubling and fleet analyses below.

DOUBLING TIME AND FLEET GROWTH

The doubling time is the horizon on which a self-sufficient unit accumulates a second unit's start-up charge. The simplest (linear) definition is $T_{\rm lin} = I_0/S$. If instead every unit reinvests its entire surplus into commissioning new units — each requiring the same start-up charge I_0 — the fleet obeys

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{S}{I_0} N \quad \Longrightarrow \quad N(t) = N_0 \exp\left(\frac{S}{I_0} t\right) = N_0 \, 2^{\,t/T_2}, \qquad \boxed{T_2 = \frac{I_0 \ln 2}{S}}.$$

Equation (11) is the tritium-limited fleet-growth law: the surplus of the parent units is the only source of start-up charge for the daughters, so the achievable fleet-build cadence is bounded below by T_2. With $I_0 = 4.77kg - T$ the three ladder rungs give the doubling times reported in §4. Surplus tritium not reinvested decays with λ into helium-3, the strategic co-product of the inventory rather than an independent channel (BR-OUT-2, companion 2.35); at equilibrium a banked surplus yields of order $0.9kg - T$ yr^{-1} of ^{3}He per unit.

§ 3

Computational methodology: the GPU HPC neutronics campaign

Every breeding number in this paper is produced by the same GPU-accelerated Monte-Carlo campaign that anchors the Kronos neutronics gates; the fuel-cycle inventory laws of §2 are then evaluated on the register's reduced-order toolkit. This section states the codes, the numerical formulation, and the verification that make the results reproducible.

THE TRANSPORT PROBLEM AND ITS MONTE-CARLO ESTIMATOR

The breeding ratio is a functional of the steady-state neutron flux. The angular flux $\psi(\mathbf{r}, \mathbf{\Omega}, E)$ obeys the linear Boltzmann transport equation

$$\mathbf{\Omega}\cdot\nabla\psi + \Sigma_t(\mathbf{r}, E)\,\psi = \int_{4\pi}\int_0^\infty \Sigma_s(\mathbf{r}, E'\to E, \mathbf{\Omega}'\to\mathbf{\Omega})\,\psi(\mathbf{r}, \mathbf{\Omega}', E')\,\mathrm{d}E'\mathrm{d}\mathbf{\Omega}' + \frac{S_n(\mathbf{r})}{4\pi}\chi(E),$$

with a fixed 14 MeV source $S_n\chi(E)$ localised on the plasma emissivity. The net tritium breeding ratio is the ^{6,7}Li tritium-production reaction rate per source neutron,

$$\mathrm{TBR} = \frac{1}{S_n}\int_V \sum_{i\in\{^6\mathrm{Li},^7\mathrm{Li}\}} N_i(\mathbf{r})\int_0^\infty \sigma_T^i(E)\,\phi(\mathbf{r}, E)\,\mathrm{d}E\,\mathrm{d}V,$$

where $\phi = \int_{4\pi}\psi\,\mathrm{d}\mathbf{\Omega}$ is the scalar flux, N_i the nuclide densities, and σ_T^i the tritium-production cross sections: the exothermic $^6\mathrm{Li}(n,\alpha)\mathrm{T}$ channel ($Q = +4.78$ MeV, dominant at thermal energies) and the threshold $^7\mathrm{Li}(n,n'\alpha)\mathrm{T}$ channel (threshold ≈ 2.47 MeV, active in the fast spectrum). The beryllium multiplier enters through $^9\mathrm{Be}(n,2n)$, which nearly doubles the fast neutron population before moderation into the ^{6}Li resonance region.

We solve (12) by analog and weight-windowed Monte-Carlo particle transport in OpenMC [14] with continuous-energy ENDF/B-VIII.0 cross sections [13], on CAD-faithful geometry imported STEP→DAGMC [15] (BR-L2-A22, companion 2.25) so that the centrepost, blanket manifolds and penetrations are represented as-built rather than as a 1-D pencil. The reaction rate in (13) is accumulated with track-length flux estimators,

$$\widehat{R} = \frac{1}{S_n}\frac{1}{W}\sum_{h=1}^{W}\sum_{\text{tracks }k} w_{h,k}\,\ell_{h,k}\,\Sigma_T(E_{h,k}),$$

for W source histories, particle weights $w_{h,k}$ and track lengths $\ell_{h,k}$. The Monte-Carlo standard error falls as $\sigma_{\widehat{R}} \propto W^{-1/2}$, and the figure of merit $\mathrm{FoM} = 1/(\sigma_{\mathrm{rel}}^2\,T_{\mathrm{cpu}})$ is held constant across the configuration sweep so that every blanket variant is converged to the same relative tolerance. At $W = 1.2\times10^8$ histories per configuration the net-TBR relative standard error is sub-percent, and the global neutron balance closes with a leakage fraction of 0.121 and a first-wall nuclear heating of 74.6 MW (gate BR-L1-A5), consistent with the 67.8 MW of 14 MeV neutron power carried by S_n (BR-OUT-3).

ACTIVATION AND INVENTORY DEPLETION

The activation inventory that bounds the non-recoverable-loss term ℓ and the shutdown-dose environment for tritium handling is computed by full-chain depletion. The Bateman system

$$\frac{\mathrm{d}\mathbf{n}}{\mathrm{d}t} = \mathbf{A}\mathbf{n}, \qquad \mathbf{n}(t) = \exp(\mathbf{A}t)\,\mathbf{n}_0,$$

with the transmutation/decay matrix $\mathbf{A}$ built from the same ENDF/B-VIII.0 data folded on the local first-wall spectrum, is advanced by the Chebyshev Rational Approximation Method (CRAM48) [16], which approximates the matrix exponential by a partial-fraction rational function and is unconditionally stable for the stiff 3820-nuclide chain (gate BR-L1-A10). Displacement damage that governs the centrepost lifetime, and hence the swap cadence that the fleet analysis assumes, is scored with the Norgett–Robinson–Torrens model [17], $\nu_{\mathrm{NRT}} = 0.8\,T_{\mathrm{dam}}/(2E_d)$, giving 18.85 dpa fpy^{-1} at the first wall (gate BR-L1-A13).

NUMERICAL FORMULATION OF THE FUEL-CYCLE MODEL

The inventory system (5)–(5) is a linear constant-coefficient system $\dot{I} = M I + b$; its steady state $I^\star = -M^{-1} b$ gives the surplus law (6) in closed form, and its transients (used for the sub-unity gate of figure 7) are integrated with an implicit trapezoidal scheme, stable for the widely separated decay and residence timescales. The surplus, required-TBR, start-up and doubling laws (7)–(11) are algebraic and are evaluated directly in the KRONOS reduced-order toolkit, whose frozen-anchor regression reproduces $19/19$ canonical anchors byte-for-byte (gate KX-L1-A10).

GPU ACCELERATION, PROBLEM SCALE AND REPRODUCIBILITY

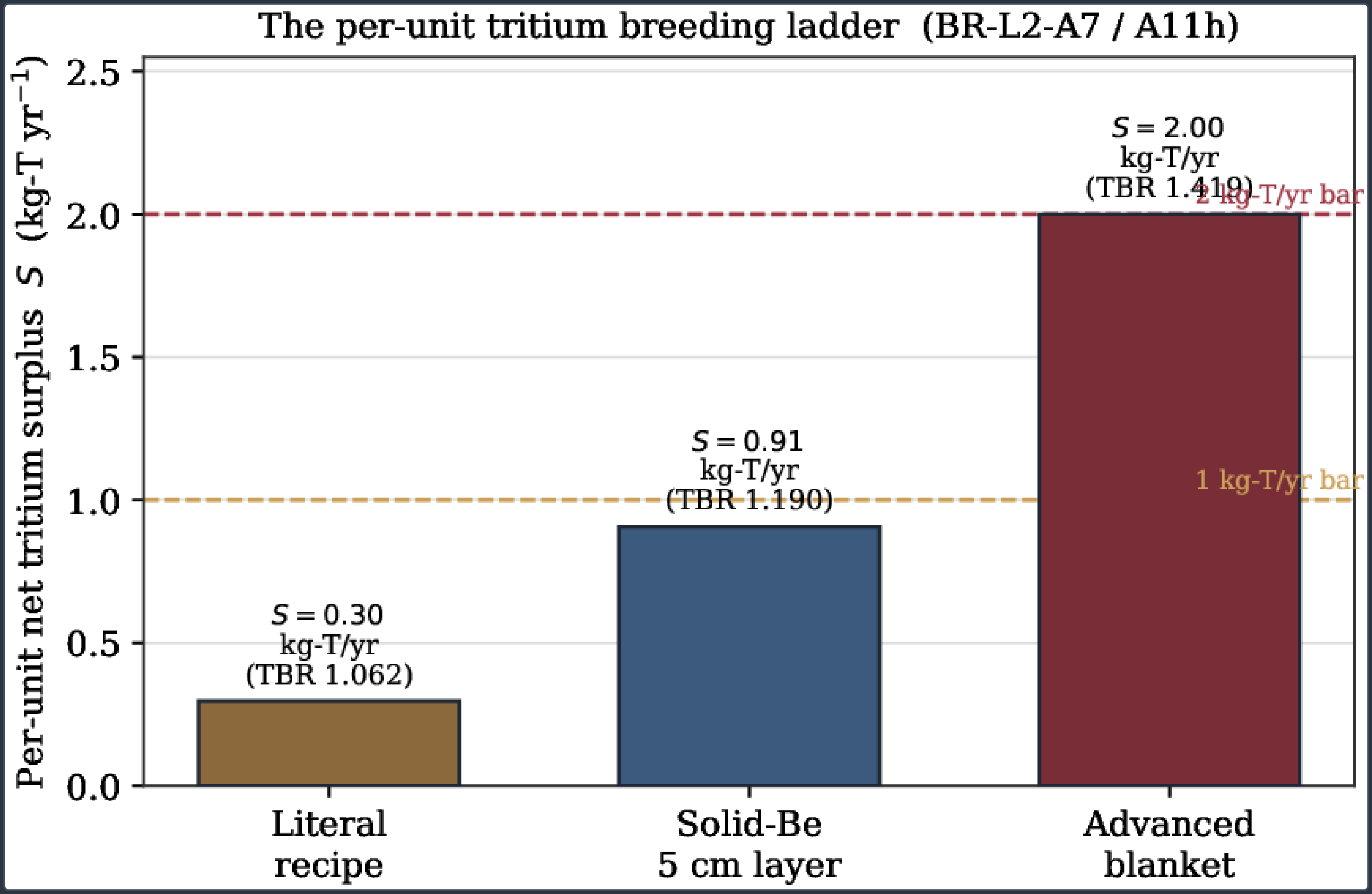
The 3-D Monte-Carlo transport (12)–(14), the CRAM depletion (15), and the twelve-configuration blanket sweep were run on the NVIDIA GPU HPC campaign (A100/H100/A10-class accelerators), which carries the offline, first-principles neutronics for the Kronos design series; the reduced-order toolkit and the fuel-cycle integration run on the in-house HPC research node. GPU acceleration matters here because the net TBR is a small difference of large numbers — gross breeding minus parasitic absorption and leakage — so each configuration must be driven to sub-percent statistics ($W = 1.2 \times 10^8$ histories), and the ladder and uplift results require that transport to be repeated across a sweep of multiplier packing fractions, breeding-zone thicknesses and reflector options. Running the sweep as independent, seed-controlled histories is embarrassingly parallel and maps naturally onto the accelerator fleet; the whole-campaign net-breeding ceiling of $\mathrm{TBR} = 1.42$ is the converged result of that sweep (gate BR-L2-A7). All headline quantities are frozen anchors in the register [1] and are regenerable from the archived deposit and the figure-generation script distributed with this paper (§7); no result depends on unpublished or proprietary data, and no compute-cost information enters any figure or table.

§ 4

Results

THE CONFIRMED BREEDING LADDER

Three-dimensional OpenMC neutronics places the breeding on the confirmed ladder of figure 1 and table 1 (gate BR-L2-A7). The literal frozen blanket recipe — a lithium breeder with the as-drawn beryllium packing fraction (9.6–11.8 vol%) — gives net $\mathrm{TBR} = 1.026–1.062$ and, through the surplus law (7), a per-unit export of $S = 0.30 kg - T$ yr^{-1}. Adding a dedicated 5 cm solid-beryllium multiplier layer raises the net TBR to 1.18–1.20 (register 1.1775 / 1.2039) and the surplus to $S = 0.91 kg - T$ yr^{-1}. The advanced blanket — a void-reduced breeder with a solid-beryllium multiplier and a steel reflector — reaches net $\mathrm{TBR} = 1.42$ and $S \approx 2.0 kg - T$ yr^{-1}. This 1.42 is the confirmed per-unit ceiling across the twelve blanket configurations of the sweep: a lithium–lead alternative was explored and does not beat it, and the ST centrepost — which occupies the inboard midplane and cannot be lined with breeder — caps the inboard coverage that would otherwise lift it further.



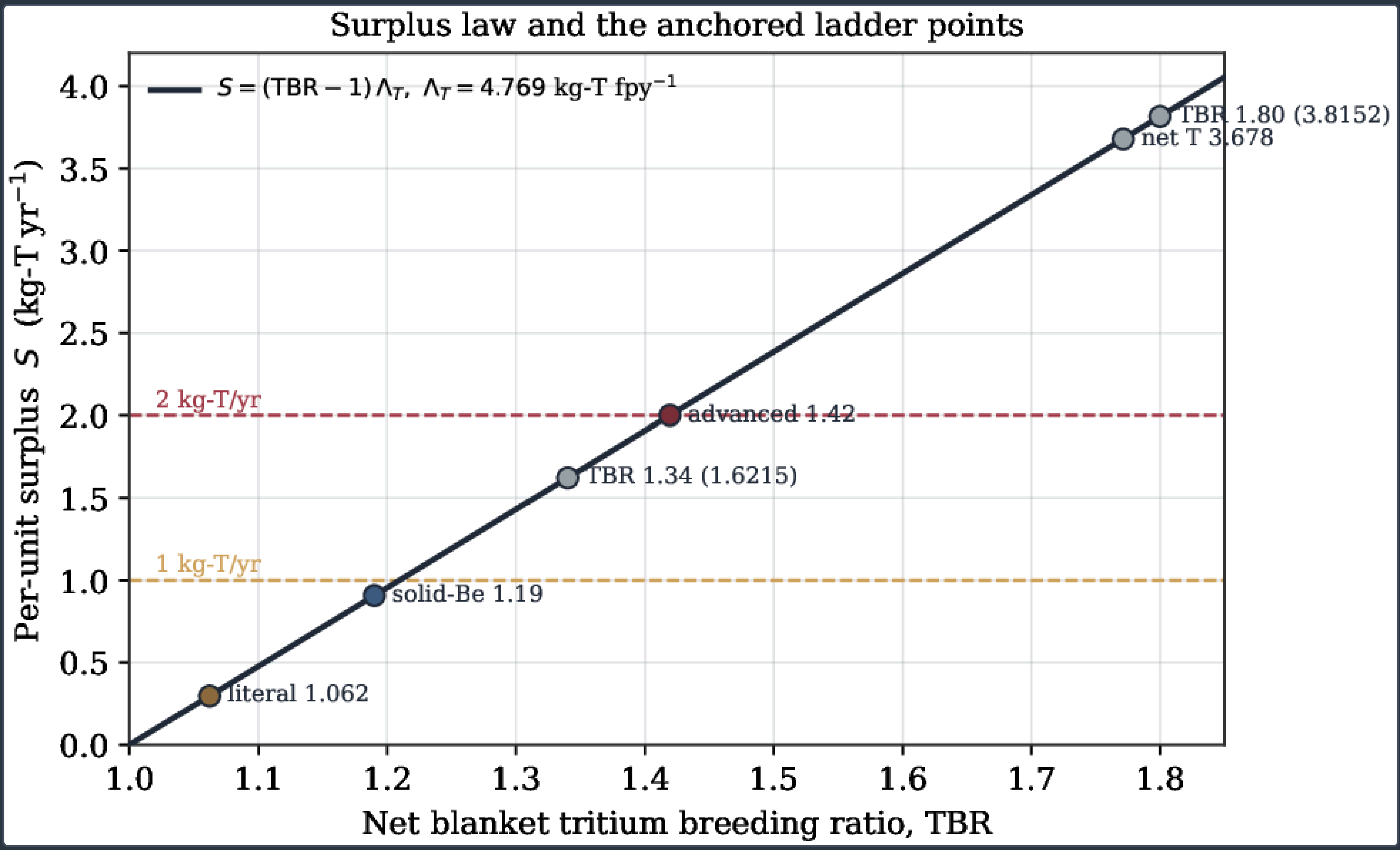
The per-unit tritium breeding ladder (gate BR-L2-A7/A11h): net surplus $S = (\mathrm{TBR} - 1)\Lambda_T$ at the literal, solid-beryllium and advanced blankets, with the corresponding net breeding ratio annotated. Dashed lines mark the 1 and $2 kg - T$ yr^{-1} surplus bars. Data from the OpenMC configuration sweep on ENDF/B-VIII.0.

BLANKET CONFIGURATION	NET TBR	S (KG-T)	VS $\text{TBR}_{\text{req}}=1.28$	T_2 (YR)	T_{lin} (YR)
literal frozen recipe	1.062	0.30	below	11.2	16.1
+5 cm solid-Be multiplier	1.190	0.91	below (self-sust.)	3.6	5.3
advanced (void-reduced)	1.419	2.00	**above (growth)**	1.7	2.4

The confirmed breeding ladder. Net TBR from 3-D OpenMC/ENDF-B-VIII.0 (BR-L2-A7); surplus from the law (7) at $\Lambda_T = 4.769kg - T$ fpy^{-1}; doubling time from (11) at $I_0 = 4.77kg - T$. The advanced rung is the confirmed per-unit ceiling.

THE SURPLUS LAW AND THE REQUIRED BREEDING RATIO

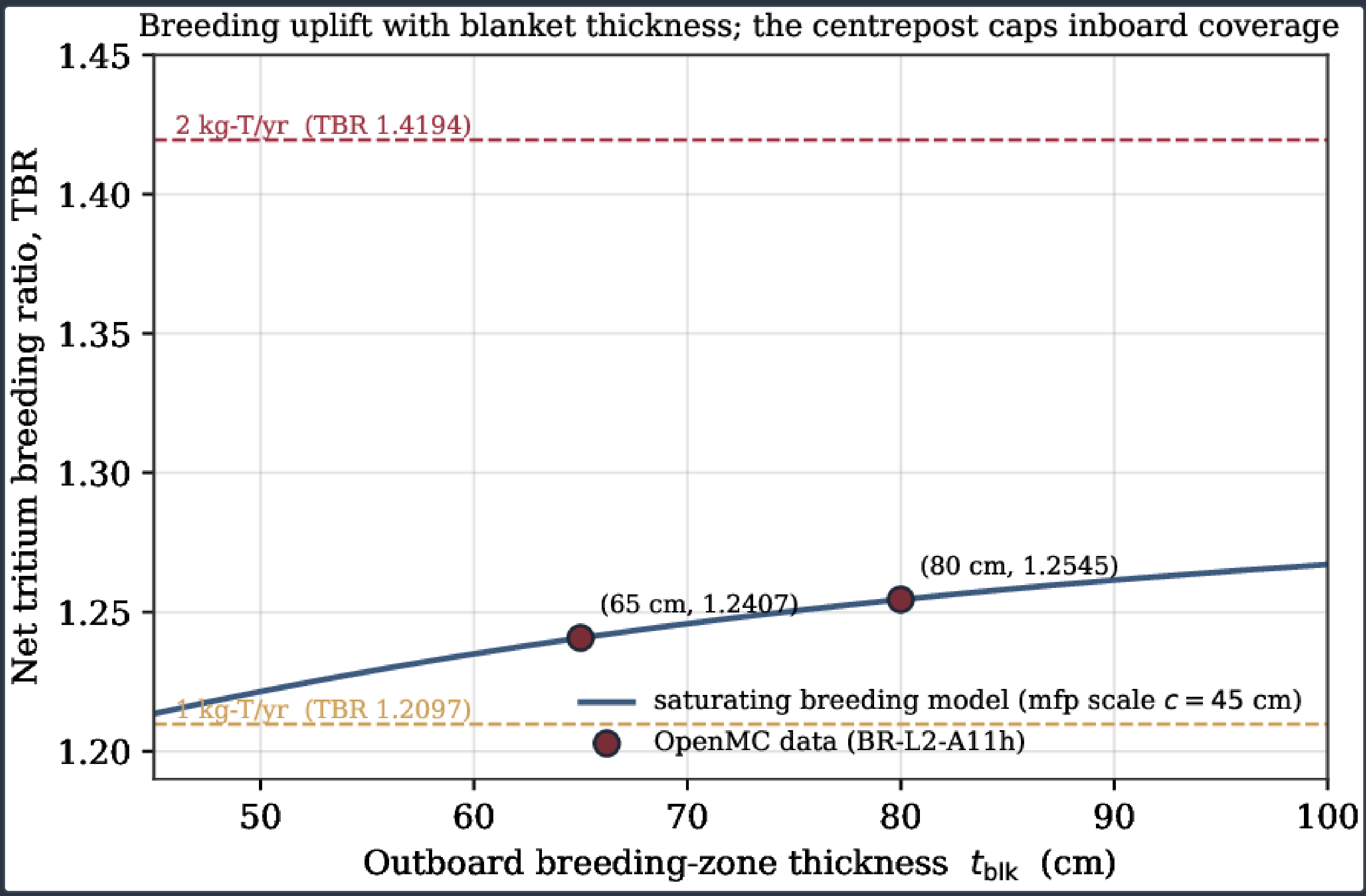
Figure 2 plots the surplus law (7) with the anchored design and verification points overlaid, including the two independent toolkit checks at $\text{TBR} = 1.34$ ($S = 1.6215$) and $\text{TBR} = 1.80$ ($S = 3.8152$) that pin the slope. The 1 and $2kg - T$ yr^{-1} surplus bars correspond to $\text{TBR} = 1.2097$ and $\text{TBR} = 1.4194$ respectively (gate BR-L2-A11h). Read against the required-TBR line (9), $\text{TBR}_{\text{req}} \approx 1.28$, the figure makes the central point of the paper quantitative: the literal recipe (1.06) is below even self-sustaining break-even with a reserve; the solid-beryllium rung (1.19) is self-sufficient and holds a reserve but grows a fleet only slowly; and the advanced rung (1.42) sits above TBR_{req} and is a genuine fleet-growth design point.



The surplus law $S = (\text{TBR} - 1)\Lambda_T$ with the anchored ladder and verification points (BR-L1-A6, BR-L2-A7/A11h). The 1 and $2kg - T$ yr^{-1} bars sit at net TBR 1.2097 and 1.4194. The two grey interior points ($1.34 \to 1.6215$, $1.80 \to 3.8152$) are the frozen toolkit checks that fix the slope $\Lambda_T = 4.769$.

BREEDING UPLIFT AND THE CENTREPOST CEILING

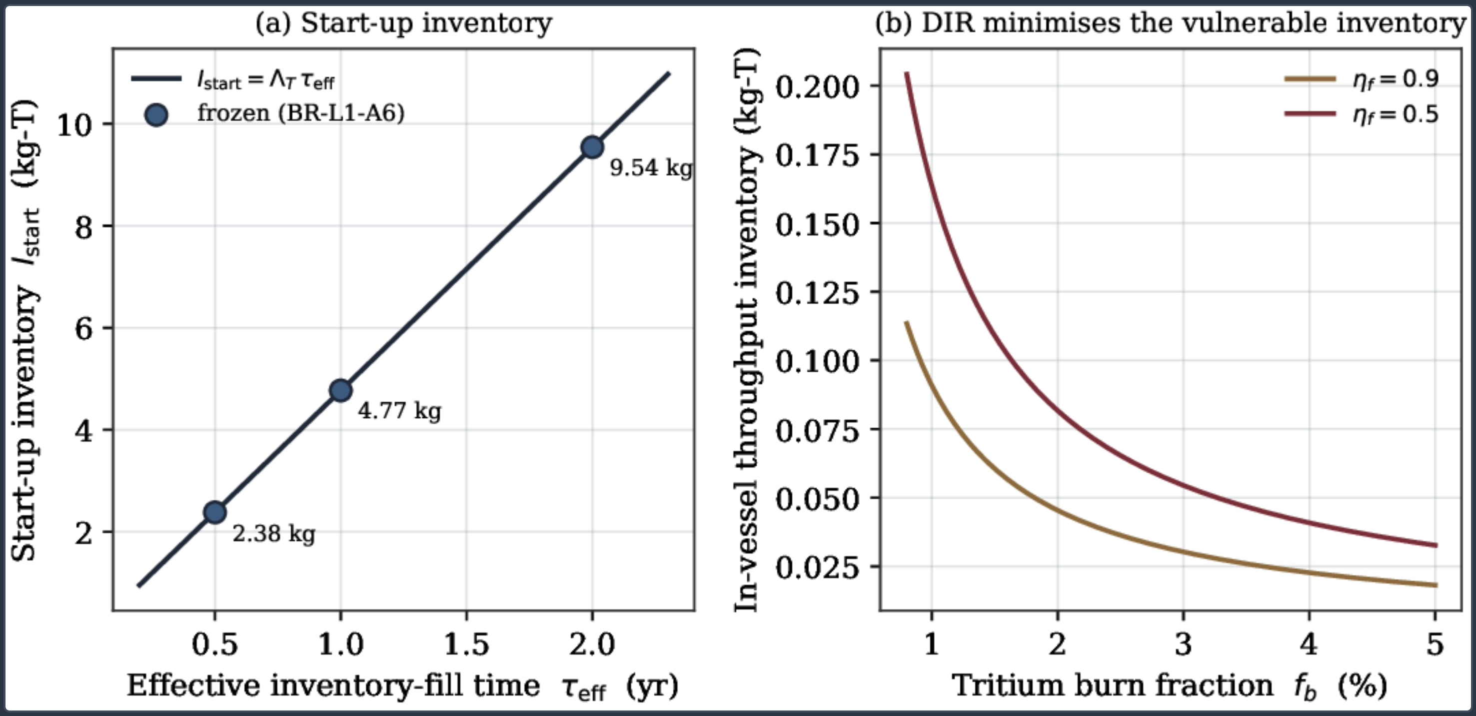
The route between the rungs is blanket thickness. Figure 3 shows the frozen uplift path (gate BR-L2-A11h): an outboard breeding-zone thickness of 65 cm reaches net $\mathrm{TBR} = 1.2407$ and 80 cm reaches 1.2545, both above the $1 kg - T$ yr^{-1} bar. The saturating shape of the breeding-versus-thickness curve is set by the neutron mean free path in the lithium breeder: beyond roughly one mean free path additional breeder returns diminishing tritium, and the ST centrepost forecloses the inboard coverage that would otherwise contribute most efficiently. This is why 1.42, not some larger number, is the confirmed per-unit ceiling: the geometry, not the nuclear data, is the binding constraint. The centrepost is itself a consumable, water-cooled tungsten-carbide-shielded cartridge (bare lifetime 0.004 fpy, extended to 0.221 fpy behind 30 cm of WC shielding; gate SC-BR-2/BR-L1-A13b), and its replacement cadence is the availability driver folded into the fleet analysis.



Net TBR versus outboard breeding-zone thickness (gate BR-L2-A11h). Markers are OpenMC data at 65 and 80 cm; the curve is a saturating breeding model (neutron-mean-free-path scale $c = 45\ cm$) through the two points. Horizontal lines are the 1- and $2 kg - T$ yr^{-1} surplus bars. The centrepost caps inboard coverage, so the per-unit ceiling saturates at net TBR 1.42.

START-UP INVENTORY

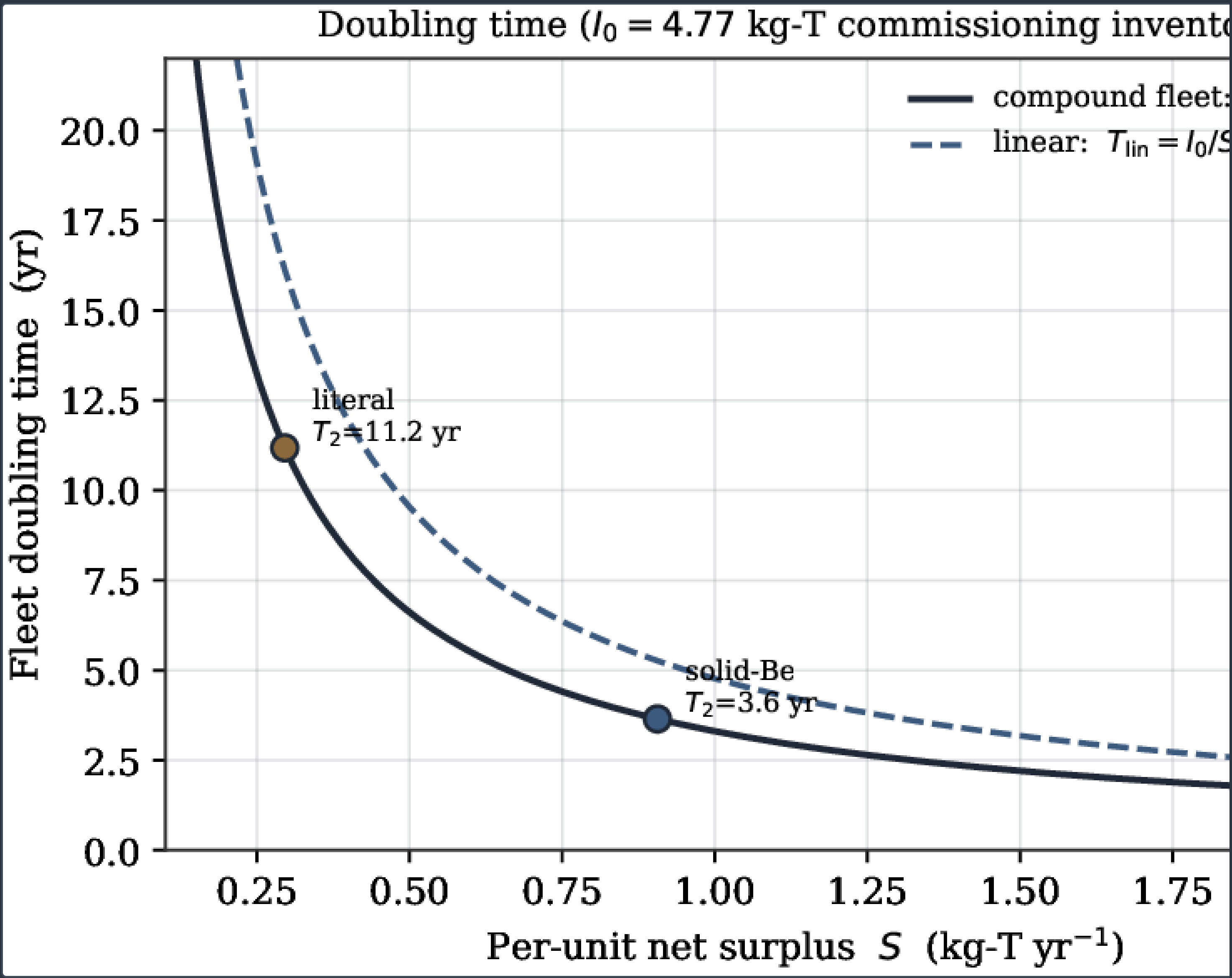
Figure 4(a) shows the start-up charge $I_{start} = \Lambda_T \tau_{eff}$ of (10) against the frozen anchors $2.38/4.77/9.54 kg - T$ for $\tau_{eff} = 0.5/1/2$ yr (BR-L1-A6). The linear dependence on τ_{eff} is exact in the lumped model; the design objective is to keep τ_{eff} near the low end. Figure 4(b) shows why direct internal recycling is the lever that does so: the in-vessel throughput inventory scales as $\Lambda_T \tau_{res}/(f_b \eta_f)$, so at the few-percent single-pass burn fraction characteristic of a tokamak the vulnerable inventory is dominated by the exhaust-processing hold-up, and shortening τ_{res} by DIR — rather than raising f_b, which the plasma physics bounds — is the practical route to a small start-up charge [9]. We carry $I_0 = 4.77 kg - T$ (one full-power-year charge) into the fleet analysis.

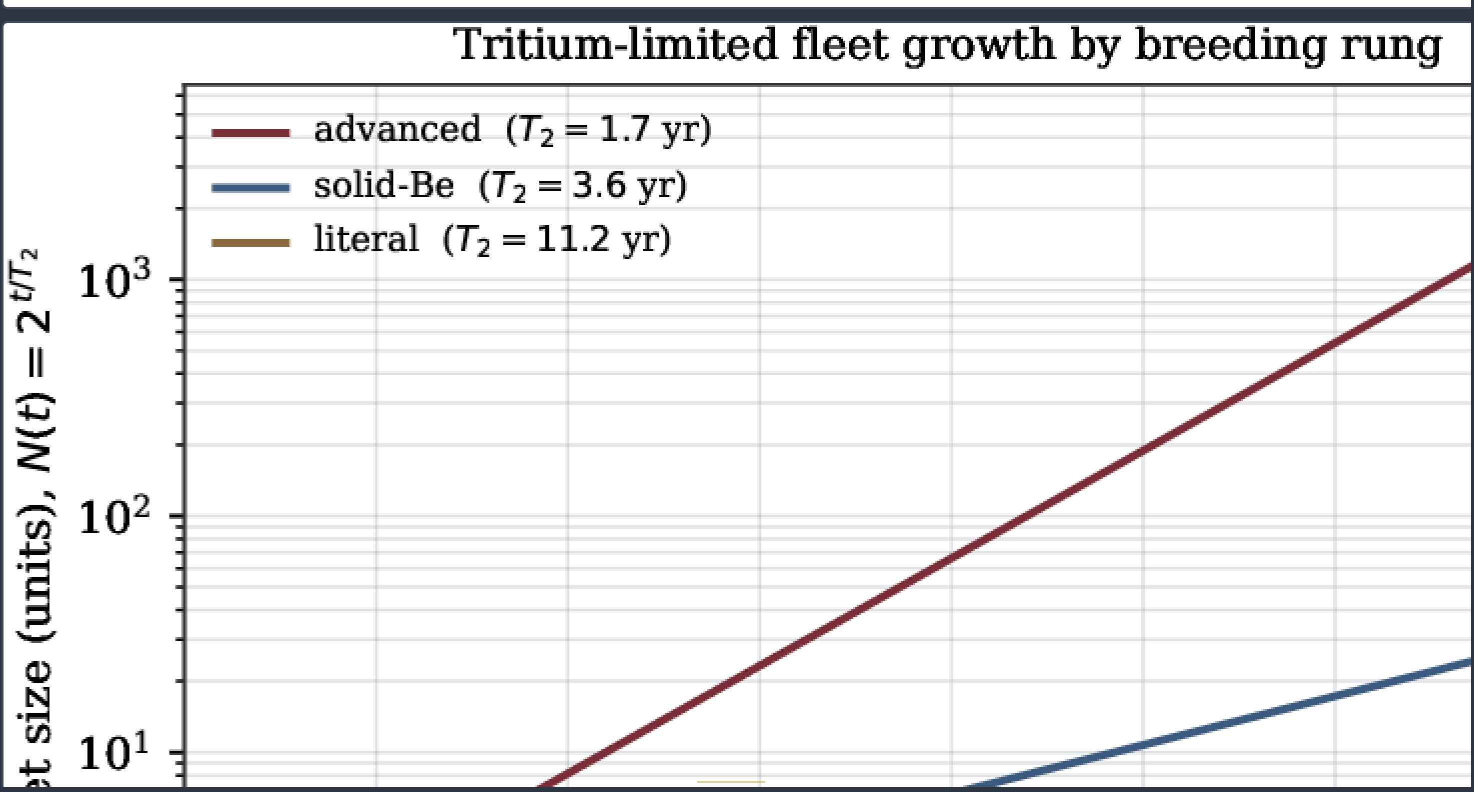


Start-up inventory. **(a)** $I_{start} = \Lambda_T \tau_{eff}$ against the frozen anchors $2.38/4.77/9.54 kg - T$ at $\tau_{eff} = 0.5/1/2$ yr (BR-L1-A6). **(b)** The in-vessel throughput inventory scales as $\Lambda_T \tau_{res}/(f_b \eta_f)$; direct internal recycling shortens τ_{res} and minimises the vulnerable inventory. Panel (b) is a model scaling, not a measured profile.

DOUBLING TIME

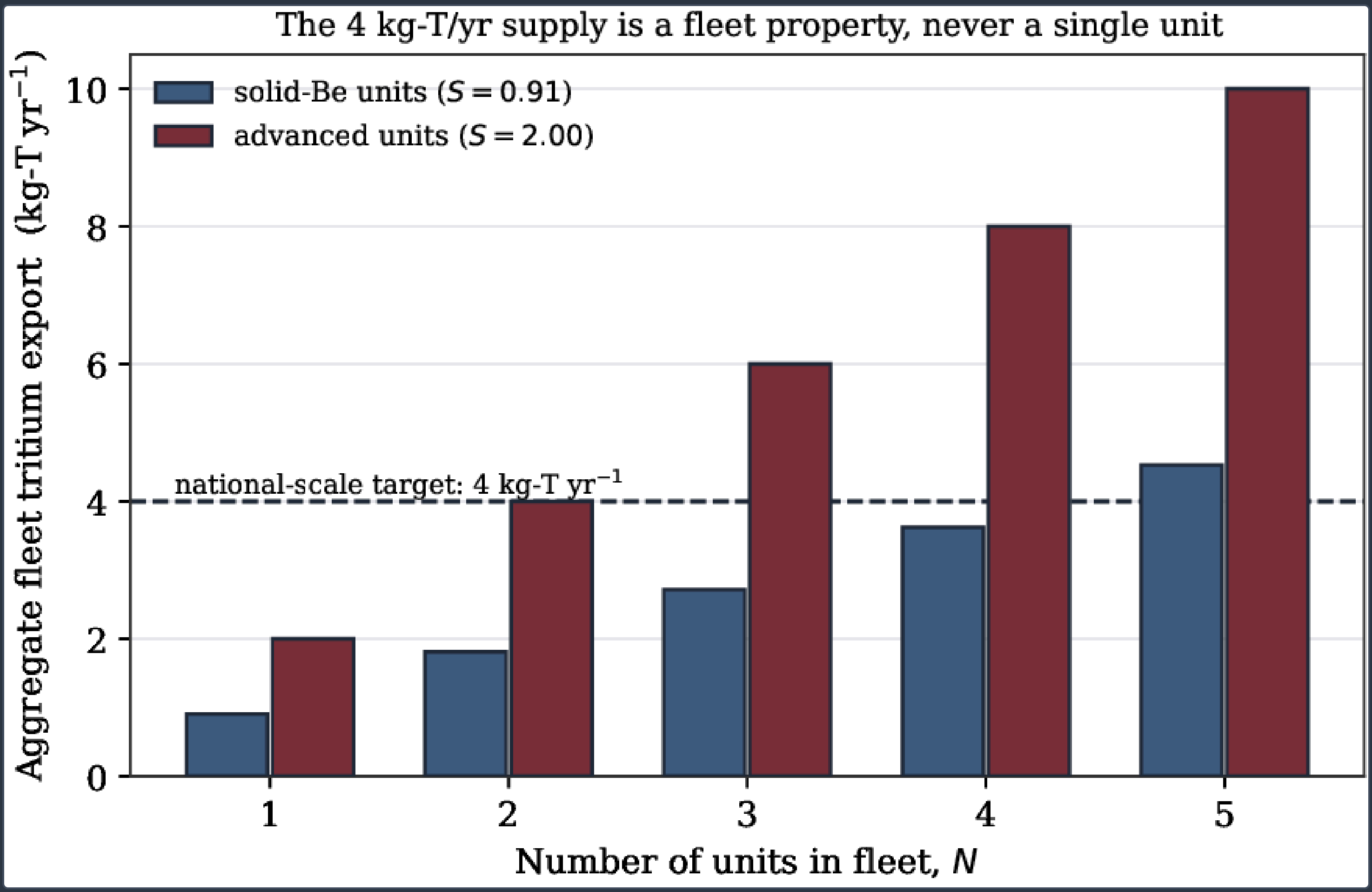
Figure 5 plots the compound (11) and linear doubling times against per-unit surplus, with the three ladder rungs marked. At $I_0 = 4.77 kg - T$ the advanced rung ($S = 2.0$) doubles the fleet in $T_2 = 1.7$ yr, the solid-beryllium rung ($S = 0.91$) in 3.6 yr, and the literal recipe ($S = 0.30$) in 11.2 yr; the linear estimates are 2.4, 5.3 and 16.1 yr. Because T_2 scales inversely with the surplus and the surplus scales linearly with TBR − 1, the doubling time is acutely sensitive to the breeding rung: moving from the literal recipe to the advanced blanket shortens the tritium-limited fleet-build cadence by nearly an order of magnitude. Figure 5 shows the corresponding exponential fleet trajectories $N(t) = 2^{t/T_2}$; the advanced rung supports a fleet doubling on a timescale short compared with a plant lifetime, whereas the literal recipe does not.


Doubling time ($I_0 = 4.77$ kg-T commissioning invento
compound fleet:
linear: $T_{lin} = I_0/S$
literal
T_2=11.2 yr
solid-Be
T_2=3.6 yr
Fleet doubling time (yr)
Per-unit net surplus S (kg-T yr^{-1})
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0.25
0.50
0.75
1.00
1.25
1.50
1.75


Tritium-limited fleet growth by breeding rung
advanced ($T_2 = 1.7$ yr)
solid-Be ($T_2 = 3.6$ yr)
literal ($T_2 = 11.2$ yr)
et size (units), $N(t) = 2^{t/T_2}$
10^3
10^2
10^1

PER UNIT VERSUS FLEET: THE $4kg - T$ yr^{-1} TARGET

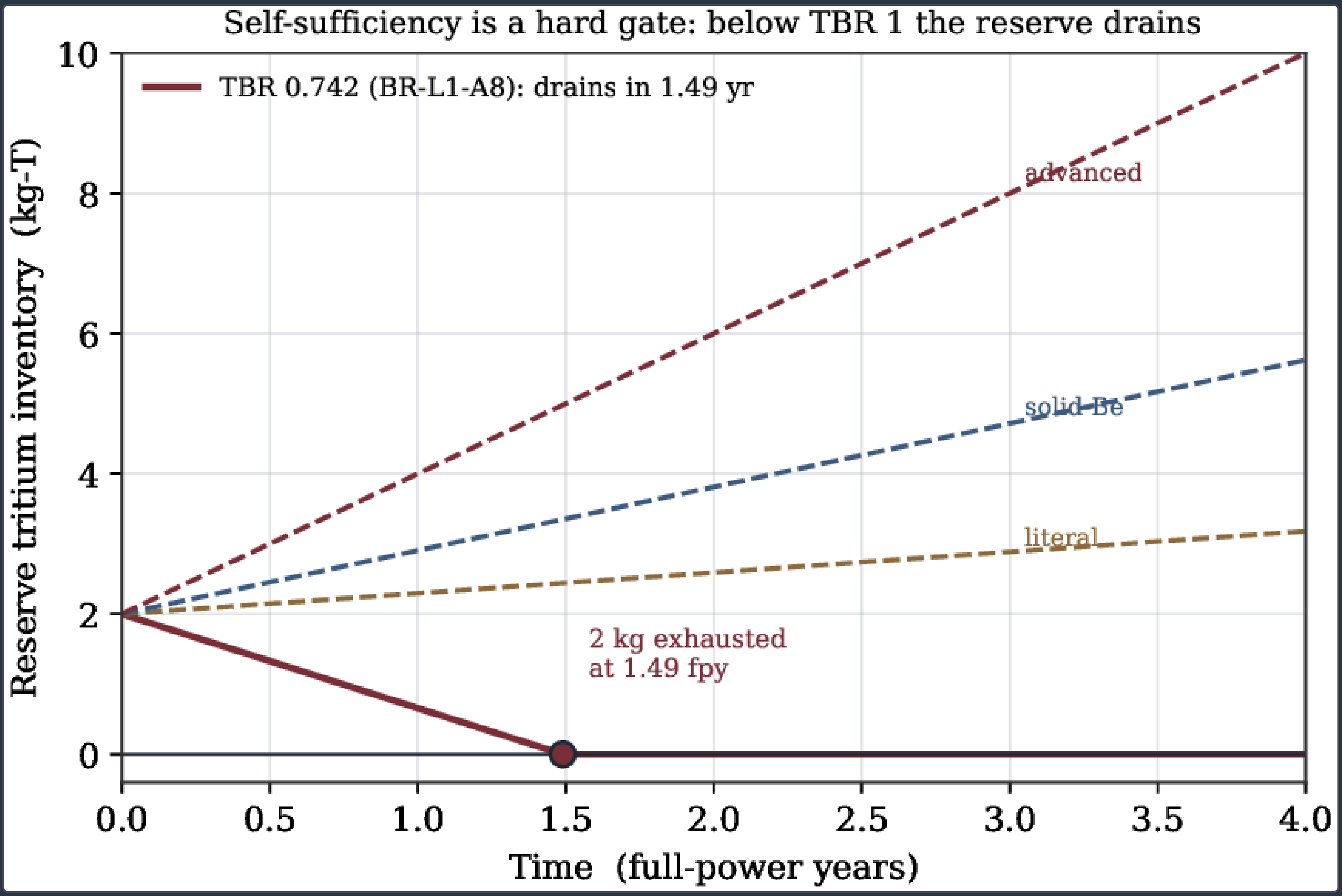
A national-scale tritium supply of $4kg - T$ yr^{-1} is not a single-unit claim. Figure 6 aggregates the per-unit surplus across a fleet: the target is reached by two advanced units ($2 \times 2.0 = 4.0$) or by four to five solid-beryllium units ($4 \times 0.91 = 3.6$ to $5 \times 0.91 = 4.5$). We never claim $4kg - T$ yr^{-1} from one unit — the centrepost caps the per-unit ceiling at net TBR 1.42, i.e. $S \approx 2.0kg - T$ yr^{-1}. Stating the target as a fleet property is not a hedge; it is the honest consequence of the geometry-limited per-unit ceiling of §4.



Fleet aggregation to the $4kg - T$ yr^{-1} national-scale target (gate BR-OUT-1). Two advanced units, or four to five solid-beryllium units, reach it; a single unit does not. The dashed line is the target.

THE HONEST GATE: BELOW UNITY, THE RESERVE DRAINS

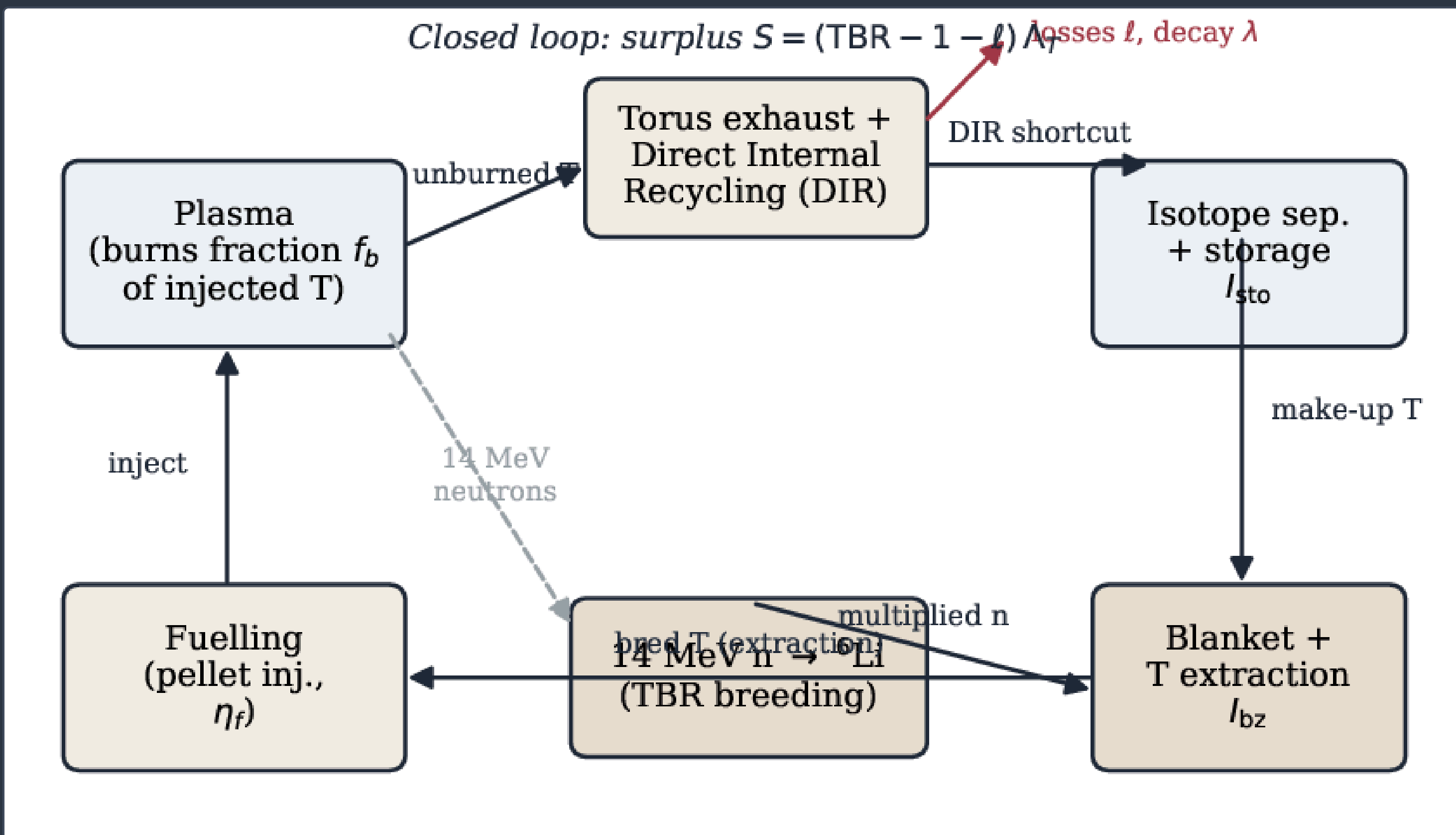
Self-sufficiency is a hard threshold, not a soft optimisation. Figure 7 shows the frozen sub-unity case (gate BR-L1-A8): at net $\mathrm{TBR} = 0.742$ the fuel cycle is a net consumer, and a $2 kg - T$ reserve is exhausted in 1.49 fpy — a hard number that quantifies the coverage-honest no-go, computed by integrating the inventory transient of (5)–(5). The contrast with the three self-sufficient rungs, whose reserves accumulate at $+0.30$, $+0.91$ and $+2.0 kg - T$ yr^{-1}, is the whole design argument in one figure: the blanket must clear unity with margin, and the ladder shows by how much.



Self-sufficiency as a hard gate (gate BR-L1-A8). At net TBR 0.742 a $2 kg - T$ reserve drains in 1.49 fpy (solid); the three self-sufficient rungs accumulate reserve (dashed). Below unity there is no operating point, however favourable the rest of the machine.

THE CLOSED LOOP AND THE CO-PRODUCT

The fuel cycle closes through DIR of unburned tritium from the exhaust, blanket tritium extraction, detritiation of process streams, and permeation control at the blanket–coolant boundary (figure 8; companions 2.39, 2.50). DIR minimises the standing inventory by returning unburned fuel promptly rather than through a large buffered store [9]. Helium-3, bred by the decay of surplus tritium at equilibrium at $\approx 0.9kg - T$ yr^{-1} per unit, is a co-product of the inventory, not an independent channel (BR-OUT-2; companion 2.35). The standing in-vessel inventory itself — which sets the tritium safety basis and the emergency-planning-zone sizing — is computed by the real-time accountancy twin (companion 2.34) and the safety study (companion 2.107), and is flagged here rather than asserted, because it is not carried as a canonical anchor in this paper.



(Schematic.) The closed tritium fuel cycle. The plasma burns a fraction f_b of injected tritium; the unburned remainder returns by direct internal recycling; the blanket breeds fresh tritium from 14 MeV neutrons via ^{6,7}Li, which is extracted, stored and re-injected. Losses ℓ and decay λ are the sinks in the surplus law (6). No data values are shown.

§ 5

Discussion

THE REQUIRED TBR AGAINST THE PUBLISHED SELF-SUFFICIENCY LITERATURE

Our physics-derived required breeding ratio, $\mathrm{TBR}_{\mathrm{req}} \approx 1.28$ for a fleet-growing plant and ≈ 1.08 for a self-sustaining one (8), sits squarely inside the range established by the self-sufficiency literature. Abdou and co-workers frame self-sufficiency as a bounded window rather than a single threshold and identify fuelling/burn efficiency, tritium processing time, reserve time and doubling time as the governing parameters [5,4,3]; Sawan and Abdou place the achievable-minus-required TBR margin at the few-percent level for realistic blankets [4]; and El-Guebaly and Malang, accounting for the same reserve and doubling sinks for ARIES advanced plants, arrive at required TBRs of order 1.1–1.15 for self-sustaining operation [6]. Our (8) reproduces that self-sustaining figure (1.08) with the doubling term switched off, and shows that adding a sub-decade fleet doubling cadence is what lifts the requirement to ≈ 1.28. The advanced rung (1.42) therefore clears the fleet-growth requirement with a margin of ≈ 0.14, comfortably inside the achievable-minus-required band that the literature considers necessary for a robust self-sufficiency case.

THE BREEDING LADDER AGAINST COMPACT AND DEMO-CLASS BLANKETS

The net TBRs on our ladder are consistent with the wider blanket-neutronics literature computed with the same nuclear data and CAD-faithful tooling. European DEMO HCPB/HCLL/WCLL/DCLL studies report net TBRs in the 1.1–1.2 band once structure, manifolds and penetrations are included, with the initial design versions needing further improvement to clear self-sufficiency [11,12] — the same qualitative place as our solid-beryllium rung. The compact high-field ARC concept, which like Hyperion trades size for field, finds self-sufficiency attainable but tight and highly sensitive to multiplier and thickness, with optimised net TBRs reaching the ~ 1.1 range and beryllium/lead multipliers as the decisive lever [10,19] — again consistent with the uplift path of figure 3, where the multiplier layer moves us from 1.06 to 1.19. What our ladder adds is the explicit statement of the per-unit ceiling: the ST centrepost caps the inboard coverage, so the advanced rung tops out at 1.42 and the national-scale supply becomes a fleet property. This is a geometry-specific result that the tokamak-blanket literature, which does not carry an un-breedable inboard centrepost, does not encounter.

TRITIUM RESOURCES AND THE START-UP PROBLEM

Kovari and co-workers show that external tritium cannot supply more than a single DEMO's start-up charge on any realistic schedule, with the available inventory in 2055 ranging from near-zero to a few tens of kilograms [7,8]. This is precisely the constraint that makes the start-up-inventory result of figure 4 load-bearing: a compact ST breeder with a ~ 2.4–$4.8kg - T$ start-up charge and a sub-decade doubling time can, in principle, bootstrap a fleet from a single external charge, whereas a design that needed tens of kilograms to start could not. The combination of a small start-up inventory (enabled by DIR) and a short doubling time (enabled by the advanced-blanket surplus) is what turns the external-tritium scarcity from a show-stopper into a one-time seeding problem. The lithium-6 feedstock for the blanket, and its enrichment bottleneck, is the corresponding supply-side constraint on fleet build-out (companion 2.106).

WHAT THE LADDER FRAMING BUYS

Reporting the breeding as a single number would force a false choice between an optimistic figure that overstates the per-unit deliverable and a conservative figure that understates the fleet potential. The ladder framing avoids both: the literal recipe is the honest floor at frozen-recipe fidelity, the advanced blanket is the confirmed ceiling, and the required-TBR line (9) tells the reader which rungs cross which thresholds. The surplus law (7) and the doubling law (11) then convert any rung into a fleet trajectory. The framework is deliberately transparent: given the burn rate (fixed by power) and a net TBR (fixed by neutronics), every downstream quantity — surplus, start-up charge, doubling time, fleet size for a target — follows algebraically, with no hidden factors.

§ 6

Limitations

One honest gate bounds the headline claim. The advanced-blanket ceiling of net TBR **1.42** requires that blanket — the void-reduced breeder with a solid-beryllium multiplier and a steel reflector — to be built and qualified, not merely computed; the neutronics establishes the design point, and the materials and fabrication programme must then realise it. Two secondary caveats attach. First, the burn rate (3) assumes the frozen fusion power; off-design operation scales it linearly through (2). Second, the standing in-vessel inventory I_{res} — which enters the required-TBR decay term (8) and sets the tritium safety basis — is computed in the accountancy and safety companions (2.34, 2.107) and flagged here rather than asserted, because it is not carried as a canonical anchor in this paper. The non-recoverable-loss fraction ℓ and the permeation and detritiation factors are stated as design requirements, to be closed by the coating and extraction studies (companions 2.39, 2.50). None of these caveats moves the ladder rungs, which are the frozen neutronics anchors; they bound the interpretation of the required-TBR line, not the breeding numbers.

§ 7

Conclusion

The compact ST breeder's tritium output is a confirmed ladder, not a single number: $S = 0.30 \to 0.91 \to 2.0 kg - T$ yr^{-1} per unit against a $4.769 kg - T$ fpy^{-1} burn rate, at net breeding ratios $1.06 \to 1.19 \to 1.42$, with the advanced-blanket 1.42 the confirmed per-unit ceiling set by the un-breedable ST centrepost. The burn rate follows from the fusion power alone; the surplus follows from the breeding ratio through $S = (\text{TBR} - 1)\Lambda_T$; and the self-sufficiency threshold follows from the losses, inventory decay and doubling seed as $\text{TBR}_{\text{req}} \approx 1.28$ for a fleet-growing plant. Read against that line, the solid-beryllium rung is self-sufficient and the advanced rung is a fleet-growth design point, with a tritium-limited doubling time of 1.7 yr and a start-up charge of $\approx 4.8 kg - T$. A single advanced unit is a tritium exporter; a national-scale $4 kg - T$ yr^{-1} supply is a fleet property — two advanced units or four to five solid-beryllium units — stated as such. The one honest gate is that the advanced blanket must be built and qualified, and the standing inventory that sets the safety basis is computed by the accountancy companion. Every headline quantity is a frozen anchor in the Kronos de-risking register, regenerable from the open deposit.

Acknowledgments tocsectionAcknowledgments Part of the Kronos Fusion Energy 2026 design series. The authors thank the Kronos physics de-risking programme for the frozen result set underlying every quantitative claim, and the NVIDIA GPU HPC campaign team for the neutronics compute.

Reproducibility. Every headline quantity in this paper is a frozen anchor (BR-L1-A5, BR-L1-A6, BR-L1-A8, BR-L2-A7, BR-L2-A11h, BR-OUT-1) in the KRONOS Physics De-Risking Register [1] (doi:10.5281/zenodo.22133057) and is regenerable from the open, CC-BY-4.0 breeder deposit [2] and the figure-generation script (`make_tritium_ladder_figs.py`) distributed with this paper. This paper is archived at doi:10.5281/zenodo.22645746; official version: https://www.kronosfusionenergy.com/publications/tritium-fuel-cycle-and-breeding-ladder.html, and its official version is at https://www.kronosfusionenergy.com/publications/tritium-fuel-cycle-and-breeding-ladder.html. No result depends on unpublished or proprietary data, and no economics enters the public deposit.

Data availability tocsectionData availability The ladder, surplus-law, uplift, start-up, doubling and fleet data plotted in figures 1–7 are archived with the deposit at doi:10.5281/zenodo.22645746 and trace to the register [1] by the serial identifiers cited inline. The breeder neutronics deposit is [2] (doi:10.5281/zenodo.21746157, version 2 doi:10.5281/zenodo.21795620). No economic analysis is part of the public deposit.

Competing interests tocsectionCompeting interests Provisional patent applications relating to aspects of this work have been filed. The authors declare no other competing interests.

tocsectionReferences

APPARATUS

Portfolio, People & Record

The intellectual-property estate, the people who built it, the limitations that gate it, and the sources it rests on.

1	4	40	27
GRANTED PATENT	2026 PROVISIONALS	TEAM MEMBERS	2022 PROVISIONALS

INTELLECTUAL PROPERTY

The patent portfolio

The estate spans a granted high-field magnet patent, pending utility and 2026 provisional filings that map to the two products, a digital-twin control provisional, a registered trademark application, and the original 2022 provisional family. Every patentable disclosure in the five-paper arXiv drop was protected **before** publication: the breeder and burner provisionals were filed 1–2 August, and a publication-gap omnibus filing the evening before the drop swept up the DEC, plasma-control, and REBCO-winding matter of the three otherwise-unprotected papers. Patent numbers and application serials are matters of public record; claim scope is summarised, not reproduced.

GRANTED & PENDING UTILITY

US 12,009,112	High-field tilted graded-REBCO magnet architecture (KRONO-002A) · *app. 17/878,550*	GRANTED
US 17/878,507	Core device / method (KRONO-001A) · *utility*	PENDING

2026 PROVISIONAL FILINGS — MAPPED TO THE PRODUCTS

64/124,209	Hyperion — spherical-tokamak tritium / helium-3 foundry · *breeder · filed Aug 2026*	FILED
64/124,220	Aegis / MetroVolt — synchrotron-cutoff, fuel-selection & plug-winding · *generator · filed Aug 2026*	FILED
64/115,167	KRONOS-CTRL digital-twin plant control · *provisional · filed Jul 2026*	FILED
64/005,440	Integrated spherical-tokamak fusion architecture · *early integrated-architecture filing · filed Mar 2026*	FILED
64/105,530	Negative-triangularity spherical-tokamak architecture · *foundational ST filing · filed Jul 2026*	FILED
64/128,097	Publication-gap omnibus — quasineutral two-species expander DEC · provenance-gated / latency-split plasma control · as-built high-field winding & conductor architecture · *filed 7 Aug 2026, the evening before the arXiv drop*	FILED

TRADEMARK & ORIGIN

FTK-98801894	Kronos Fusion Energy — trademark application	FILED
KR-2022-*	Original provisional family (KR-2022-00001 … 00027) · *27 filings, 2022*	PRIORITY

The narrow, defensible magnet novelty — the specific conductor and the digital-twin winding optimisation, not high-field REBCO as a category — is the commercial core that can earn ahead of any $Q > 1$ milestone, with markets in fusion magnet supply, MRI/NMR, accelerators, and proton therapy. The claim is scoped honestly: the high field is a *system field* result, not a stand-alone-coil record; the small-bore plug coil is structurally infeasible as a bare winding but resolved by a stress-managed structural shield (feasible-pending-FEA); and the winding-tape experiment returned a *null result*. The value is the method, not a field record.

THE TEAM

Founding partners, board, advisors & auditors

Kronos is built by a bench of advanced-fuel-fusion, high-field-magnet, direct-conversion, and materials specialists, with a board and operations team drawn from defense, national laboratories, and industry. Dates are shown as ranges; where a tenure has ended or is term-ending, the range says so.

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Legal counsel is retained; those roles are held on the internal roster and are not listed here.

SOURCES

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