KRONOS FUSION ENERGY

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From Tritium Consumer to Breeding Fleet: Net Blanket TBR and the Cross-Library Case for Multi-Unit Tritium Export from a Compact Spherical-Tokamak Breeder

A deuterium–tritium plant that does not breed its own tritium is a consumer of a scarce, decaying, essentially unbuyable fuel; a plant that breeds a surplus is the seed of a…

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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 Several quantities in the underlying corpus moved after first publication; where a value has been withdrawn or restated, the record says so plainly.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

From Tritium Consumer to Breeding Fleet: Net Blanket TBR and the Cross-Library Case for Multi-Unit Tritium Export from a Compact Spherical-Tokamak Breeder

A deuterium–tritium plant that does not breed its own tritium is a consumer of a scarce, decaying, essentially unbuyable fuel; a plant that breeds a surplus is the seed of a supply chain. The distinction is set by a single neutron-economy quantity—the net tritium breeding ratio (TBR)—and, in a compact spherical tokamak (ST), that quantity is capped by the small inboard coverage the centre-post permits. We treat the blanket TBR of the Hyperion breeder ($R_0 = 1.20\,m$, aspect ratio $A = 2.5$, $B_0 = 8\,T$, $I_p = 9.66\,MA$, negative triangularity $\delta = -0.30$, $P_{\text{fus}} = 85.04\,MW$) as a governed design lever rather than a fixed number, deriving the net-breeding functional from the linear Boltzmann transport equation and closing it against a tritium-inventory rate equation whose surplus term propagates directly to fleet scale. Three-dimensional Monte-Carlo neutronics with OpenMC on ENDF/B-VIII.0, run on the NVIDIA GPU HPC campaign at 1.2×10^8 source histories, place the lever quantitatively: a literal beryllium-multiplied blanket recipe gives a one-dimensional net $\text{TBR} = 1.026$–1.062; a dedicated $5\,cm$ solid-beryllium multiplier layer raises it to 1.158; and a void-reduced advanced blanket reaches the confirmed per-unit ceiling $\text{TBR} = 1.420$, verified across twelve configurations. Scaled to a realistic three-dimensional coverage fraction $f_{\text{cov}} = 0.87$, the literal recipe falls below the 1.05–1.10 self-sufficiency window while the advanced blanket clears it with margin, and a lithium–lead alternative is shown to change the number by only $+0.004$. The breeding number reproduces across an independent nuclear-data evaluation (ENDF/B-VIII.0 versus FENDL-3.2) to under 0.3%, establishing it as a property of geometry and cross-sections rather than of one code path. Coupling the lever to a burn rate of $4.769 kg - T$ fpy^{-1} yields a per-unit surplus law $S = (\text{TBR} - 1)\dot{N}_{\text{burn}}$ that carries the plant from consumer ($S < 0$ at the coverage-honest recipe) to exporter ($S \approx 2.0\,kg$-T yr^{-1} at the ceiling), and a four-unit fleet on the advanced blanket into a foundry-scale export band of 3.6–$4.5 kg - T$ fpy^{-1} whose β-decay yields strategic, kilogram-class helium-3. The one honest gate is that self-sufficiency requires either the advanced blanket to be built and qualified or $\geq 91\%$ breeding coverage on the solid-beryllium lever. All headline quantities are frozen anchors in the Kronos de-risking register.

Open-access deposit (code & data, CC BY 4.0): DOI 10.5281/zenodo.22645706 · Zenodo community *kronos_fusion_energy*. Explore it live: interactive 3-D model · physics validator.

Keywords: tritium breeding ratio · blanket neutronics · beryllium multiplier · 14\ · MeV neutronics · OpenMC · ENDF/B-VIII.0 · FENDL-3.2 · tritium fuel cycle · spherical tokamak · breeding fleet

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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

TRITIUM IS THE BINDING CONSTRAINT OF A D–T ECONOMY

Deuterium–tritium (D–T) fusion is the only reaction that a near-term compact device can run at reactor-relevant gain, and it is also the one whose fuel does not exist in nature at scale: tritium is radioactive with a $12.32\,yr$ half-life, the world civil inventory is of order tens of kilograms and declining, and no fission programme is committed to producing a fusion-scale surplus [1,2]. A D–T plant therefore lives or dies on whether its blanket returns more than one triton per fusion neutron, net of parasitic absorption, leakage and processing loss. The condition is the classical tritium self-sufficiency requirement of Sawan and Abdou [3] and El-Guebaly and Malang [4], sharpened in the modern fuel-cycle analyses of Abdou *et al.* [2] and Meschini *et al.* [5]: a viable plant needs a net breeding ratio not merely above unity but above a margin, typically 1.05–1.10, that pays for radioactive decay during holdup, in-vessel and processing retention, and the reserve needed to start the next plant.

THE SPHERICAL-TOKAMAK COVERAGE CAP

A compact ST is an attractive breeder because it packs a large plasma current and a bright 14 MeV neutron source into a small volume behind a demountable, high-field centrepost [6,7]. The same geometry is exactly what makes breeding hard: the centrepost and its inboard shield occupy the radius where a conventional tokamak would site inboard breeding blanket, so the inboard mantle is thin and breeding-poor while the outboard blanket does the work. The breeding integral is thus geometry-limited in a way that a large aspect-ratio machine is not, and the honest question is not “can the blanket breed?” but “how high can the coverage-limited net TBR be pushed, and does the answer clear the self-sufficiency margin with enough surplus to matter?”

FROM A NUMBER TO A LEVER, AND FROM A UNIT TO A FLEET

The literature on breeding blankets—helium-cooled pebble beds [14,13], water- and lead–lithium-cooled concepts [12,15], and the associated neutronics methodology [24]—treats the TBR of a given blanket as a computed figure of merit. Our contribution is to treat it, for a fixed ST geometry, as a *governed lever*: a monotone response of the net breeding functional to a small set of legitimate neutronics choices (beryllium $(n, 2n)$ multiplication, a dedicated solid-multiplier layer, lithium-6 enrichment, breeder void fraction, a steel reflector, and blanket thickness), and then to carry the lever setting through a tritium-inventory rate equation to the level that actually decides strategy—the fleet. The two questions we answer quantitatively are:

Where does the lever cross self-sufficiency, and what is the per-unit ceiling? We show the one-dimensional net TBR rising from 1.026 (literal beryllium-multiplied recipe) through 1.158 (a $5\,cm$ solid-beryllium layer) to a confirmed ceiling of 1.420 (advanced blanket), and we scale each recipe to a realistic three-dimensional coverage fraction to locate the honest self-sufficiency crossing.
Does the surplus close a fleet, and is the export robust? We derive the per-unit surplus law $S = (\mathrm{TBR} - 1)\dot{N}_{\mathrm{burn}}$ from the inventory equation, show that a single coverage-honest unit is a self-sufficiency machine rather than an exporter, and that a four-unit fleet on the advanced blanket exports a foundry-scale 3.6–$4.5 kg - T$ fpy^{-1} whose decay supplies strategic helium-3. We establish robustness by reproducing the breeding number across an independent nuclear-data library to under 0.3% and by showing that a lithium–lead breeder buys essentially nothing ($+0.004$). enumerate
This paper is the neutronics-and-fleet anchor of a companion set: the per-unit inventory and doubling dynamics are developed in the tritium-breeding-ladder paper [25]; the multiplier materials that set the ceiling in the beryllium/$Be_{12}Ti$ study [26]; the migration from the one-dimensional model used here to CAD-faithful three-dimensional transport in the STEP-to-DAGMC neutronics paper [27]; the cross-section error budget in the nuclear-data uncertainty paper [28]; the ceramic-versus-liquid-metal blanket down-select in [29]; the coverage-limiting centrepost physics in [30]; the lunar gate on helium-3 in [31]; and the four-unit fleet availability model in [32]. Every headline quantity below is a frozen anchor in the Kronos Physics De-Risking Register [33].

§ 2

Governing equations and the formal problem

TRANSPORT AND THE BREEDING FUNCTIONAL

The angular neutron flux $\psi(\vec{r},\hat{\Omega},E)$ produced by a monoenergetic 14.06 MeV fusion source $S(\vec{r},\hat{\Omega},E)$ obeys the steady-state linear Boltzmann transport equation

$$\hat{\Omega}\cdot\nabla\psi + \Sigma_t(\vec{r},E)\,\psi = \int_{4\pi}\int_0^\infty \Sigma_s(\vec{r},E'\to E,\hat{\Omega}'\to\hat{\Omega})\,\psi(\vec{r},\hat{\Omega}',E')\,dE'\,d\hat{\Omega}' + S(\vec{r},\hat{\Omega},E),$$

with total and scattering macroscopic cross-sections Σ_t, Σ_s. The scalar flux is $\phi(\vec{r},E) = \int_{4\pi}\psi\,d\hat{\Omega}$. The tritium breeding ratio is the number of tritons produced per source neutron, an integral of the flux against the two lithium production channels,

$$\mathrm{TBR} = \frac{1}{S_n}\int_V\int_0^\infty \Big[N_6\,\sigma_{^6\mathrm{Li}(n,t)}(E) + N_7\,\sigma_{^7\mathrm{Li}(n,n't)}(E)\Big]\,\phi(\vec{r},E)\,dE\,dV,$$

where $S_n = \int_V\int S\,dE\,dV$ is the total source rate, N_6, N_7 are the lithium-6 and lithium-7 number densities, and $\sigma_{^6\mathrm{Li}(n,t)}$, $\sigma_{^7\mathrm{Li}(n,n't)}$ the corresponding microscopic tritium-production cross-sections. The two channels are physically complementary. The exothermic $^6\mathrm{Li}(n,\alpha)t$ reaction has a $1/v$ cross-section that dominates once neutrons are moderated, so it rewards a softened spectrum; the endothermic $^7\mathrm{Li}(n,n'\alpha)t$ reaction has a threshold near $2.8\,MeV$ and only the uncollided and once-scattered 14 MeV population feeds it. A neutron multiplier is therefore essential in a coverage-limited geometry: beryllium $(n,2n)$ reactions, with a threshold near $1.9\,MeV$, roughly double the neutron population before it thermalises, raising both the $^6\mathrm{Li}$ integral (more neutrons to moderate) and, marginally, the $^7\mathrm{Li}$ integral.

THE NET-BREEDING DECOMPOSITION AND THE LEVER

Write the per-source breeding integrals for the two channels as Λ_6 and Λ_7, the parasitic absorption in structure, coolant and multiplier as Λ_{par}, and the whole-device leakage as Λ_{leak}. Introducing an effective beryllium multiplication factor $M \geq 1$ that scales the moderated population the $^6\mathrm{Li}$ integral samples, the net breeding ratio decomposes as

$$\mathrm{TBR}_{\mathrm{net}} = M\,\Lambda_6 + \Lambda_7 - \Lambda_{\mathrm{par}} - \Lambda_{\mathrm{leak}}.$$

Equation 3 is the formal statement that the breeding ratio is a *lever*: for a fixed ST geometry the design-controllable quantity is M (through beryllium packing and a dedicated multiplier layer) together with N_6/N_7 (through lithium-6 enrichment) and the void fraction that sets the density in Λ_6, while Λ_{leak} is bounded below by the compact geometry and Λ_{par} by the unavoidable structure. The map $M \mapsto \mathrm{TBR}_{\mathrm{net}}$ is the object we compute in §4.

COVERAGE SCALING AND THE HONEST SELF-SUFFICIENCY CONDITION

Equations 2–3 are most cheaply evaluated on a one-dimensional radial model at full first-wall coverage, which is coverage-honest for the *shape* of the lever but optimistic for its absolute value because a real device loses breeding volume to the divertor, ports, gaps and the thin inboard mantle. We represent this by a breeding coverage fraction $f_{\mathrm{cov}} \in (0,1]$, so that the device-integrated net breeding is

$$\mathrm{TBR}^{\mathrm{3D}}_{\mathrm{net}} = f_{\mathrm{cov}}\,\mathrm{TBR}^{\mathrm{1D}}_{\mathrm{net}} + \mathcal{O}(\delta_{\mathrm{spec}}),$$

where the correction δ_{spec} collects spectral re-weighting between inboard and outboard zones and is resolved in the CAD-faithful companion [27]. Self-sufficiency is then a condition on the net ratio against the fuel-cycle loss budget. Let ε be the fractional tritium loss to retention, decay during holdup and processing inefficiency; the plant closes its own cycle when the closure margin

$$\Lambda \equiv \mathrm{TBR}^{\mathrm{3D}}_{\mathrm{net}}\,(1-\varepsilon) - 1 \;\geq\; 0 \quad\Longleftrightarrow\quad \mathrm{TBR}^{\mathrm{3D}}_{\mathrm{net}} \;\geq\; \frac{1}{1-\varepsilon}.$$

For ε in the 5–9% range characteristic of realistic in-vessel retention and processing, the right-hand side of 5 is the 1.05–1.10 window that we adopt throughout.

THE INVENTORY RATE EQUATION AND THE SURPLUS LAW

The self-sufficiency inequality is a snapshot; the fuel cycle is a dynamical system. Let $I_T(t)$ be the in-vessel plus stored tritium inventory. It evolves by breeding, burn, radioactive decay and loss,

$$\frac{dI_T}{dt} = \dot{N}_{\mathrm{bred}} - \dot{N}_{\mathrm{burn}} - \lambda_T I_T - \dot{N}_{\mathrm{loss}}, \qquad \lambda_T = \frac{\ln 2}{t_{1/2}}, \quad t_{1/2} = 12.32\,\mathrm{yr},$$

where $\dot{N}_{\mathrm{bred}} = \mathrm{TBR}^{\mathrm{3D}}_{\mathrm{net}}\dot{N}_{\mathrm{burn}}$ and $\dot{N}_{\mathrm{loss}} = \varepsilon \mathrm{TBR}^{\mathrm{3D}}_{\mathrm{net}}\dot{N}_{\mathrm{burn}}$. Defining the net breeding surplus

$$S \;\equiv\; \dot{N}_{\mathrm{bred}} - \dot{N}_{\mathrm{burn}} - \dot{N}_{\mathrm{loss}} = \left[\mathrm{TBR}^{\mathrm{3D}}_{\mathrm{net}}(1-\varepsilon) - 1\right]\dot{N}_{\mathrm{burn}} = \Lambda\,\dot{N}_{\mathrm{burn}},$$

equation 6 is the linear system $\dot{I}_T = S - \lambda_T I_T$ with the closed solution

$$I_T(t) = I_{\mathrm{eq}} + \left(I_0 - I_{\mathrm{eq}}\right)e^{-\lambda_T t}, \qquad I_{\mathrm{eq}} = \frac{S}{\lambda_T}.$$

Three regimes follow directly. If $S < 0$ (net TBR below the self-sufficiency margin) the inventory decays through zero at a finite time $t_0 = -\lambda_T^{-1}\ln\!\left(1 - \lambda_T I_0/S\right)$ and the plant is a fuel *consumer*. If $S > 0$ the inventory grows toward a positive equilibrium $I_{\mathrm{eq}} = S/\lambda_T$, and the time to accumulate a target inventory (the plant-doubling metric) is $t_d = -\lambda_T^{-1}\ln\!\left[(I_{\mathrm{eq}} - I_{\mathrm{target}})/(I_{\mathrm{eq}} - I_0)\right]$. In the surplus-dominated limit $\lambda_T I_T \ll S$, equation 7 reduces to the practical surplus law we use for fleet accounting,

$$\boxed{S \approx (\mathrm{TBR} - 1)\,\dot{N}_{\mathrm{burn}}} \qquad (\varepsilon \to 0),$$

which is exact against the register's scenario anchors ($S = 1.6215\,kg$-T at $\mathrm{TBR} = 1.34$, $S = 3.8152\,kg$-T at $\mathrm{TBR} = 1.80$, with $\dot{N}_{\mathrm{burn}} = 4.769 kg - T$ fpy^{-1}).

FLEET AGGREGATION

For a fleet of N identical units the gross exportable tritium is the linear aggregate

$$E_{\mathrm{fleet}} = \sum_{i=1}^{N} S_i - \underbrace{\dot{D}_{\mathrm{seed}}}_{\text{startup of new units}} = N\,S - \dot{D}_{\mathrm{seed}},$$

where $\dot{D}_{\mathrm{seed}} = I_0/\tau_{\mathrm{build}}$ is the tritium drawn down to charge the startup inventory I_0 of each new plant over its build interval τ_{build}. Equation 10 is the formal bridge from the per-unit lever to the fleet claim: a fleet exports only if the per-unit surplus exceeds its share of the seeding draw, which is the quantitative content of “from consumer to breeding fleet.” The burner side of the helium economy—the number of breeders required to fuel one D–^{3}He tandem-mirror burner—follows from the same surplus once tritium is decayed to helium-3, and is developed in [31].

§ 3

Computational methodology: the NVIDIA GPU HPC campaign

MONTE-CARLO ESTIMATOR AND TALLIES

Equations 1–2 are solved by continuous-energy Monte-Carlo transport with OpenMC 0.15.3 [8] on the ENDF/B-VIII.0 evaluated nuclear-data library [9]. The breeding ratio is scored as the tritium-production reaction rate, tally score `(n,Xt)` (ENDF reaction MT = 205, comprising $^{6}\mathrm{Li}(n,\alpha)t$ and $^{7}\mathrm{Li}(n,n'\alpha)t$), normalised per source particle. Flux and reaction rates use the track-length estimator: for a batch of H histories the estimator of a reaction rate in a cell of volume V_c is

$$\hat{R} = \frac{1}{H}\sum_{h=1}^{H}\sum_{j\in h}\frac{w_{h,j}\,\ell_{h,j}\,\Sigma(E_{h,j})}{V_c},$$

where $w_{h,j}$ and $\ell_{h,j}$ are the statistical weight and track length of the j-th segment of history h. The relative standard error of $\hat{R}$ decreases as $H^{-1/2}$; production runs reach a relative error of 0.01–0.03 on the integrated TBR at $H = 1.2\times10^{8}$ source histories, with source convergence checked by the Shannon entropy of the fission-independent source-site distribution.

VARIANCE REDUCTION AND FIGURE OF MERIT

Because the centrepost and inboard shield attenuate the flux by many decades, the inboard breeding tally and the centrepost fast-fluence monitor are deep-penetration problems. We generate MAGIC weight windows by iterative Monte-Carlo mesh-flux estimation and apply them on a Cartesian superimposed mesh, improving the figure of merit $\mathrm{FOM} = 1/(\sigma^2 T)$ (with σ the relative error and T the wall time) by more than an order of magnitude on the inboard tallies relative to analog transport. The 14.06 MeV source is normalised to the frozen fusion power through $S_n = P_{\mathrm{fus}}/E_{\mathrm{fus}} = 3.01e19\,/s$ at $P_{\mathrm{fus}} = 85.04\,MW$, consistent with a neutron power of $67.79\,MW$ carried by the 14 MeV component.

GEOMETRY, MATERIALS AND THE ADVANCED-BLANKET LEVERS

The capture runs use a radial infinite-cylinder constructive-solid-geometry model (concentric z-cylinders with reflective z-planes) at the frozen breeder design point config-22021: $R_0 = 1.20\,m$, $A = 2.5$ ($a = 0.48\,m$), $\kappa = 2.0$, $\delta = -0.30$. The literal “A7” breeder recipe is a homogenised, volume-mixed blanket—Eurofer-97 at $12.0\,\mathrm{vol\%}$, beryllium multiplier at $14.74\,\mathrm{vol\%}$, and Li_4SiO_4 ceramic breeder (90% lithium-6) at $34.40\,\mathrm{vol\%}$—with a tungsten-armoured first wall and a steel reflector. The lever variables swept to reach the advanced ceiling are all legitimate neutronics choices, none of which alters the plasma physics: lithium-6 enrichment $90\to95\%$; beryllium packing fraction; a dedicated $5\,cm$ solid-beryllium (or $Be_{12}Ti$) multiplier layer [13]; blanket thickness; a void-reduced breeder volume fraction; and a steel reflector. The one-dimensional model is coverage-honest for the lever's shape; the migration to CAD-faithful three-dimensional geometry uses the DAGMC direct-CAD Monte-Carlo pipeline [11] and is reported separately [27].

CROSS-LIBRARY REPRODUCTION AND GPU SCALE

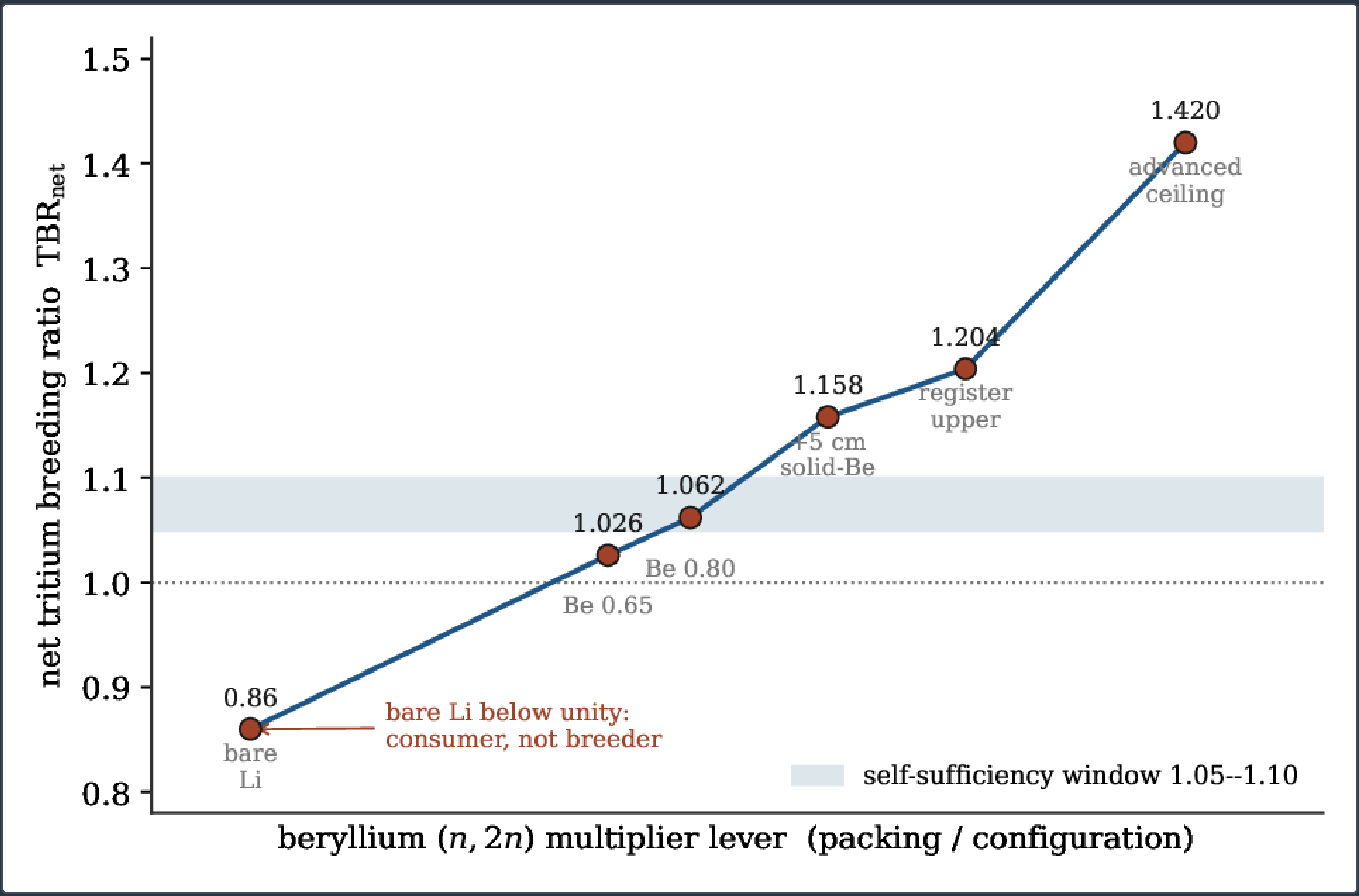
The heavy first-principles neutronics for this paper—three-dimensional OpenMC transport and full-chain depletion—ran on the NVIDIA A100/H100-class GPU HPC platform of the Kronos campaign; the reduced-order fuel-cycle integrations of equations 6–8 and the analytic self-sufficiency and fleet reductions ran on the in-house HPC node. To separate a physical result from a code path, the breeding number is reproduced on an independent nuclear-data evaluation: the ENDF/B-VIII.0 production result is cross-checked against FENDL-3.2, and the two libraries agree on the net TBR to under 0.3% for every recipe (§4.5). As a further robustness check, a lead–lithium (Pb-15.7Li) breeder is transported head-to-head against the lithium-metal reference under identical geometry; the material swap changes the net TBR by only $+0.004$. All runs use deterministic seeds (seed 20260726) and are regenerable from the archived inputs; the nuclear-data error budget that bounds the residual is developed in the uncertainty-quantification companion [28] and cross-checked against the historical ENDF/B-VII.1 evaluation [10].

§ 4

Results

THE BREEDING LEVER

Figure 1 places the lever. A bare lithium blanket with no multiplier sits below unity ($TBR_{net} \approx 0.86$): it is a consumer. The literal beryllium-multiplied recipe crosses unity in the idealised one-dimensional build, reaching $TBR_{net} = 1.026$ at beryllium packing 0.65 and 1.062 at packing 0.80 (beryllium 9.6–11.8 vol%). Adding a dedicated 5 *cm* solid-beryllium multiplier layer raises the one-dimensional value to 1.158, and stacking the full advanced-blanket lever set (§3) reaches the confirmed ceiling $TBR_{net} = 1.420$. The direction is exactly that predicted by equation 3: higher beryllium $(n, 2n)$ multiplication feeds a larger moderated population into the ^{6}Li integral. The register's upper endpoint of 1.1775–1.2039 is the same lever reached by the dedicated solid-beryllium layer; the honest gate, developed next, is that these one-dimensional values are optimistic by the coverage factor.



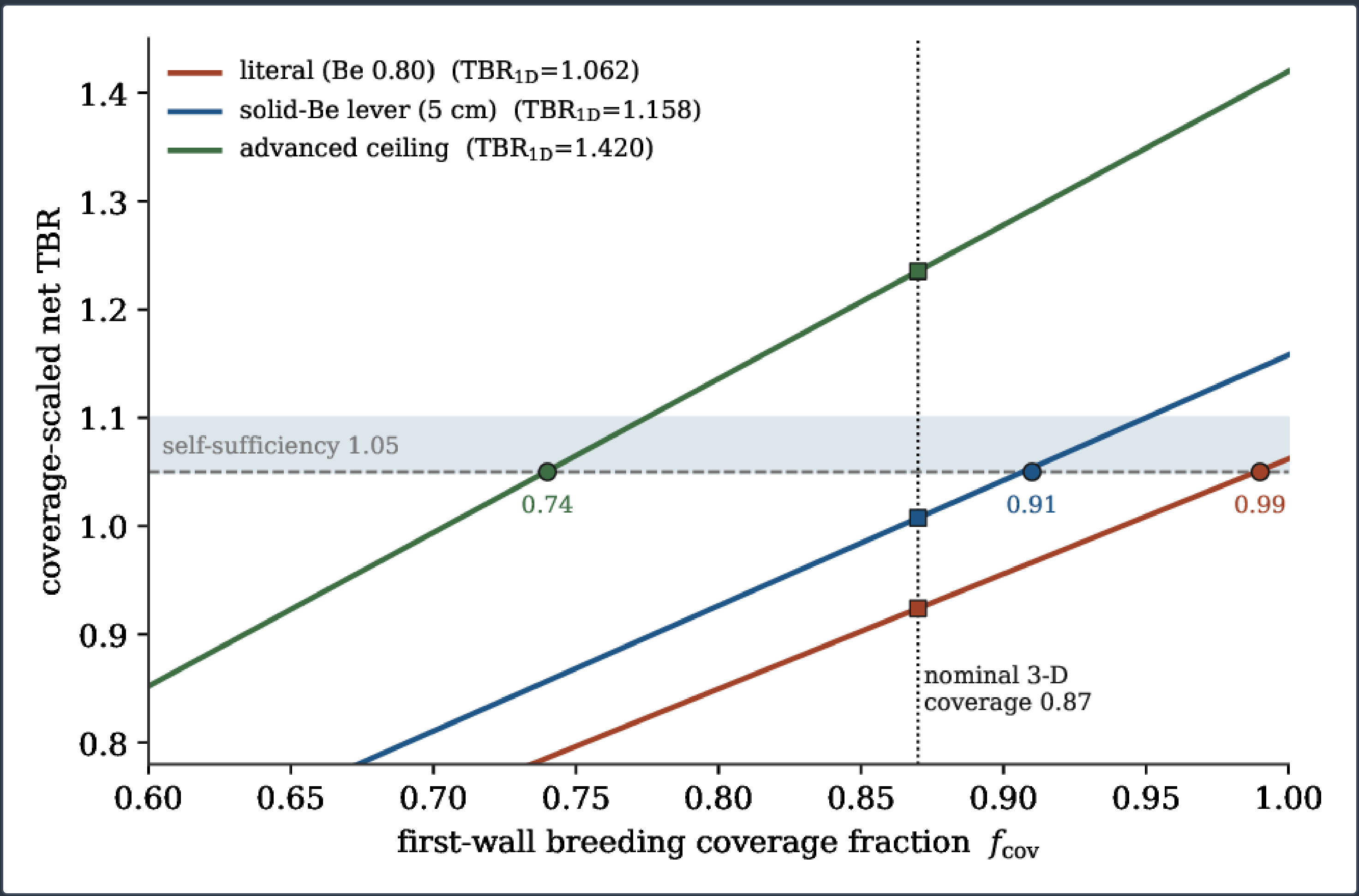
The blanket breeding lever. Net TBR (one-dimensional, ENDF/B-VIII.0) rises monotonically with the beryllium $(n, 2n)$ multiplier setting, from a below-unity bare-lithium blanket through the literal beryllium-multiplied band (1.026–1.062) and the 5 *cm* solid-beryllium lever (1.158) to the advanced-blanket ceiling (1.420). The shaded band is the 1.05–1.10 self-sufficiency window of equation 5.

COVERAGE SCALING AND THE SELF-SUFFICIENCY CROSSING

Figure 2 applies the coverage scaling of equation 4. At the nominal three-dimensional coverage fraction $f_{\mathrm{cov}} = 0.87$, the literal recipe ($\mathrm{TBR}^{1D} = 1.062$) falls to 0.924—below breakeven—while the solid-beryllium lever reaches 1.007 and the advanced ceiling reaches 1.235. Requiring the self-sufficiency value 1.05 then fixes the minimum breeding coverage each recipe needs: 0.99 for the literal recipe (effectively impossible in an ST), 0.91 for the solid-beryllium lever, and 0.74 for the advanced blanket. Table 1 collects the crossing. The message is unambiguous and is the paper's central honest gate: *a single coverage-honest unit at the literal recipe does not close its own fuel cycle*; self-sufficiency requires either the advanced blanket or $\geq 91\%$ breeding coverage on the solid-beryllium lever.

RECIPE	TBR^{1D}	NET @ $f_{\mathrm{cov}} = 0.87$	f_{cov} FOR $\mathrm{TBR} = 1.05$
Literal (Be pack 0.80)	1.062	0.924	0.99
Solid-Be lever (5 *cm*)	1.158	1.007	0.91
Advanced ceiling (canon)	1.420	1.235	0.74

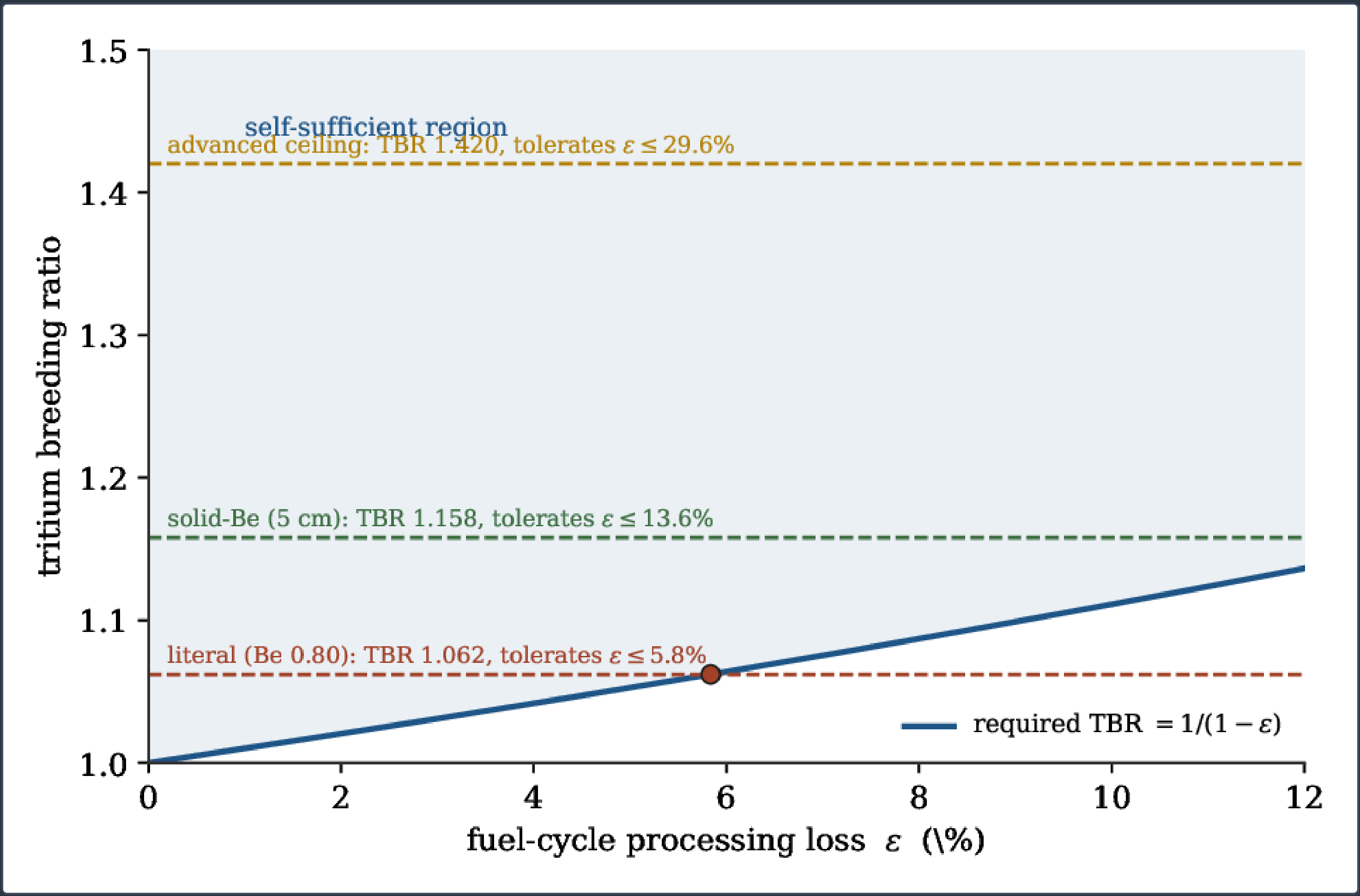
Net TBR versus blanket coverage (gate H-C1). One-dimensional OpenMC values scaled by equation 4; self-sufficiency requirement 1.05–1.10.



Coverage-scaled net TBR for the three recipes. Squares mark the net value at the nominal coverage $f_{\mathrm{cov}} = 0.87$; circles mark where each recipe crosses the 1.05 self-sufficiency line. The literal recipe requires near-total coverage; only the solid-beryllium lever and the advanced blanket clear self-sufficiency at ST-achievable coverage.

THE SELF-SUFFICIENCY REQUIREMENT AGAINST PROCESSING LOSS

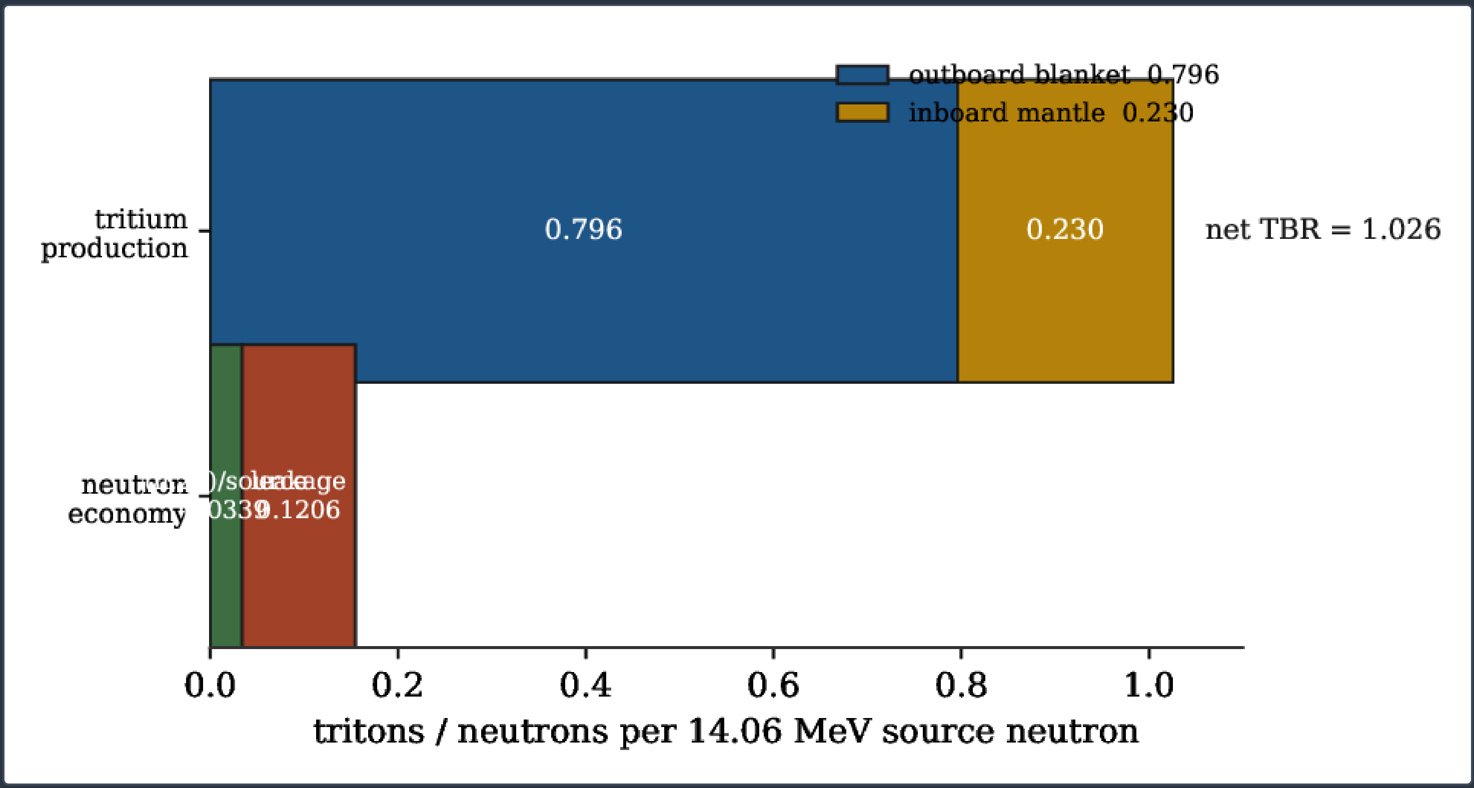
Figure 3 recasts the same physics through equation 5: the required TBR is $1/(1-\varepsilon)$, and each recipe's one-dimensional value defines the maximum processing loss it can tolerate, $\varepsilon_{\max} = 1 - 1/\mathrm{TBR}$. The literal recipe tolerates only $\varepsilon \leq 5.8\%$, the solid-beryllium lever $\varepsilon \leq 13.6\%$, and the advanced ceiling $\varepsilon \leq 29.6\%$; the last leaves comfortable room for the decay-plus-holdup-plus-doubling budget that the ODE quantifies below. This is the design margin that separates a plant that merely closes from a plant that exports.



Self-sufficiency requirement $\mathrm{TBR} = 1/(1-\varepsilon)$ versus fuel-cycle processing loss ε (equation 5). Dashed lines are the three recipe TBRs; the marked loss is the maximum each tolerates. Only the advanced blanket carries margin for the doubling reserve.

NEUTRON ECONOMY OF THE REFERENCE RUN

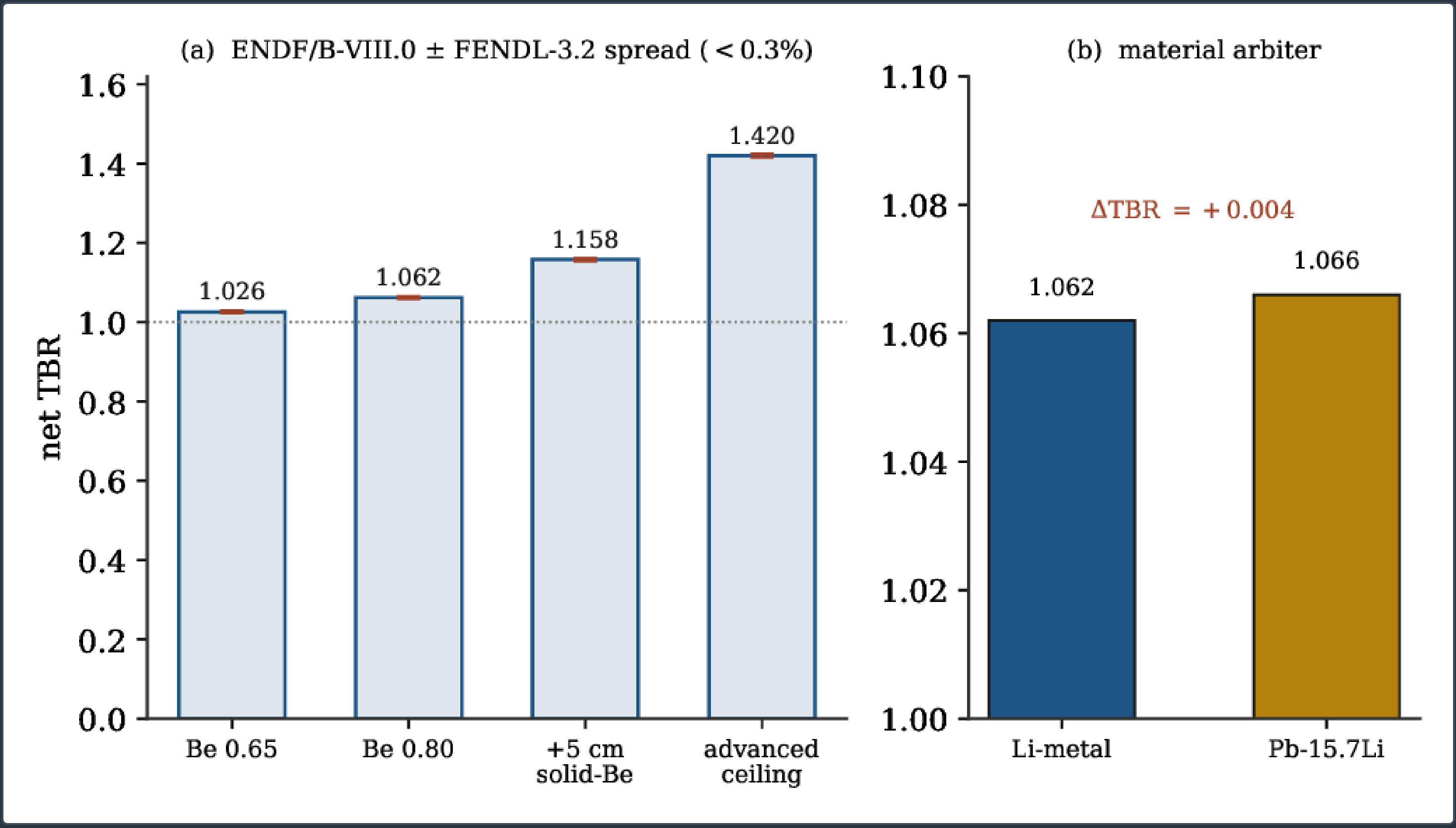
The three-dimensional-balance reference run (config-22021, 1.2×10^8 histories) resolves the neutron economy that underlies the lever. Figure 4 shows the tritium-production partition: of the net $\mathrm{TBR} = 1.026$ tritons per source neutron, 0.796 are bred in the outboard blanket and only 0.230 in the thin inboard mantle—the coverage cap of the ST written directly into the breeding split. The leakage fraction is $0.1206 \pm 3 \times 10^{-5}$ and the beryllium $(n, 2n)$ yield is $0.0339 \pm 0.4\%$ per source neutron (with $(n, 3n)/S_n = 0$ at this dilute packing). The first-wall fast flux ($E > 0.1\,MeV$) is $7.0e14\,/cm^2 s$ and the nuclear heating is $74.6\,MW$ of the $85\,MW$ fusion power; the centrepost REBCO-monitor fast fluence is $6.29e24\,/m^2$ fpy^{-1}, the quantity that caps centrepost life and is treated in [30].



Neutron economy of the reference run (BR-L1-A5). Top: the tritium-production partition, outboard (0.796) versus inboard mantle (0.230), summing to net $\mathrm{TBR} = 1.026$. Bottom: the beryllium $(n, 2n)$ yield (0.0339) and whole-device leakage (0.1206) per 14.06 MeV source neutron.

CROSS-LIBRARY REPRODUCIBILITY AND THE MATERIAL ARBITER

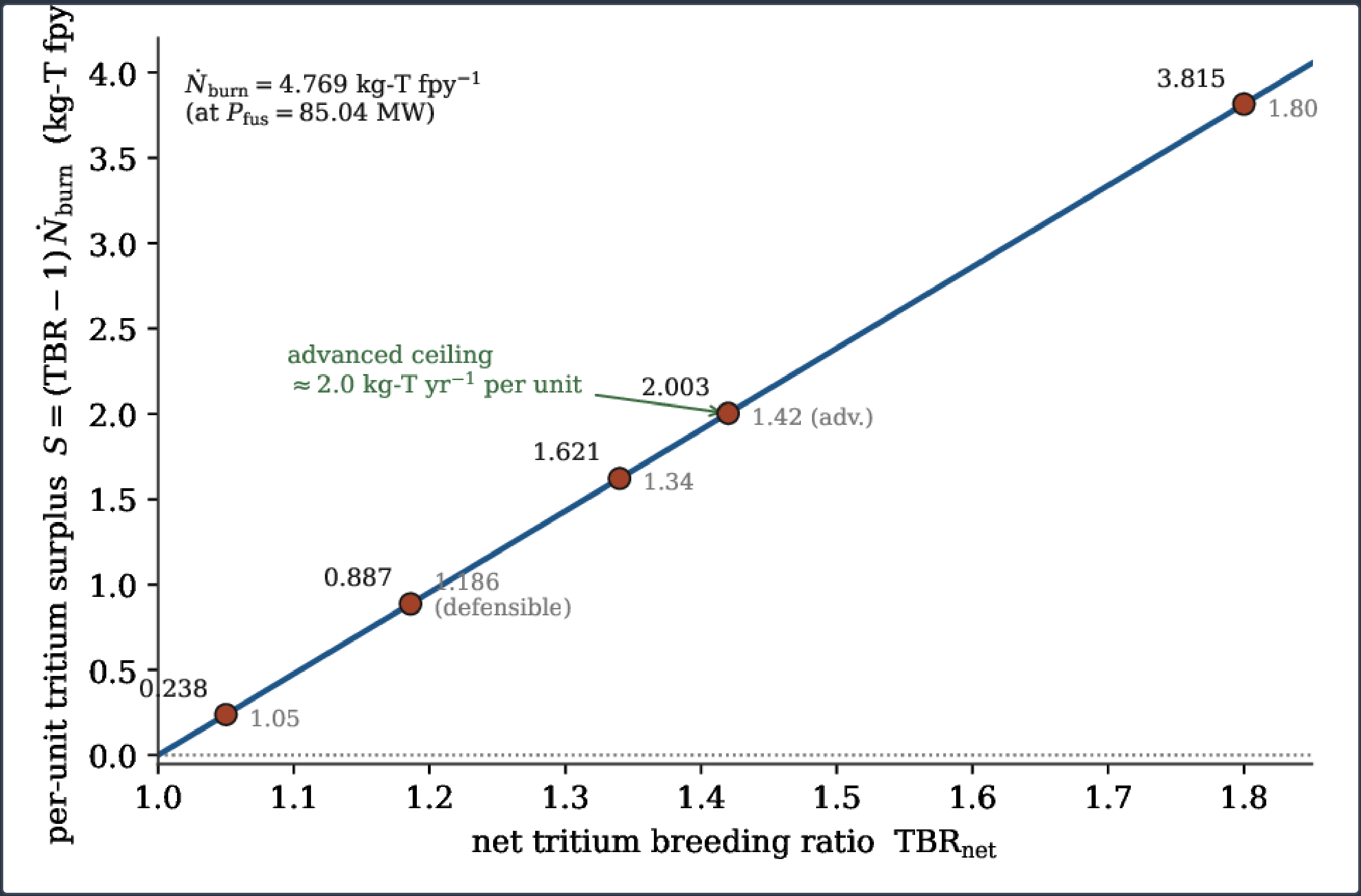
Figure 5(a) shows the cross-library test that makes the breeding number a physical result rather than a code artefact: the ENDF/B-VIII.0 net TBR of every recipe is reproduced by the independent FENDL-3.2 evaluation to under 0.3%, well inside the Monte-Carlo statistical error and far below the design margin. Figure 5(b) is the material arbiter: transporting a lead–lithium (Pb-15.7Li) breeder head-to-head against the lithium-metal reference under identical geometry changes the net TBR by only $+0.004$. The two checks together establish that the coverage-limited ceiling is set by geometry and cross-sections, and that switching to a lithium–lead blanket does not beat it—a conclusion consistent with the ceramic-versus-liquid-metal down-select of [29]. The residual cross-section uncertainty that survives library agreement is dominated by the $^{7}\mathrm{Li}(n, n't)$ and beryllium $(n, 2n)$ evaluations and is budgeted in [28].



(a) Net TBR per configuration on ENDF/B-VIII.0 with the FENDL-3.2 cross-library spread shown as error bars ($< 0.3\%$). (b) Material arbiter: lithium-metal versus Pb-15.7Li under identical geometry, $\Delta\mathrm{TBR} = +0.004$. The breeding number is a property of geometry and cross-sections, not of one library.

FROM LEVER TO SURPLUS

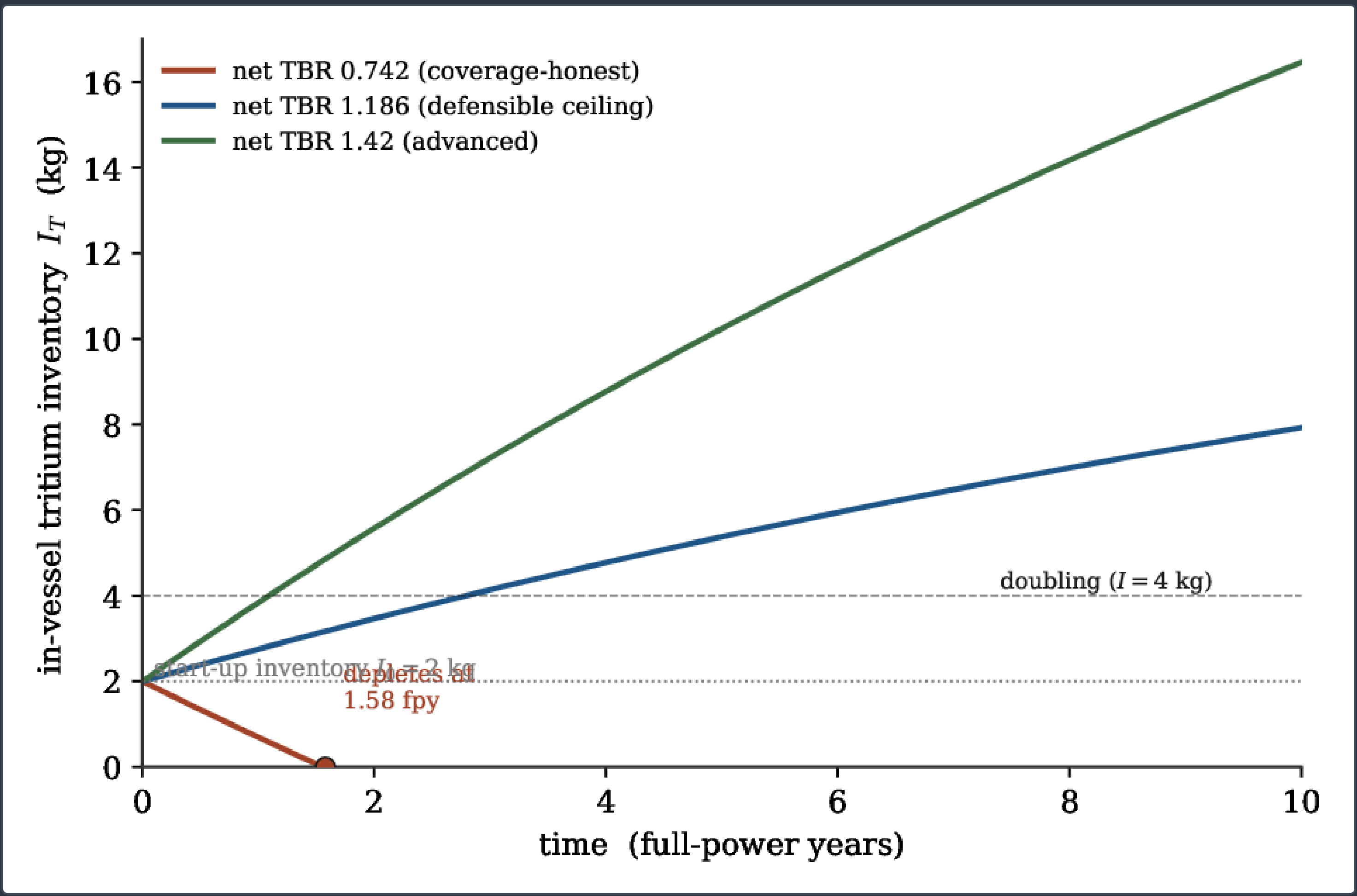
Figure 6 evaluates the surplus law 9 at the frozen burn rate $\dot{N}_{\rm burn} = 4.769 kg - T$ fpy^{-1}. The per-unit surplus is negative below the self-sufficiency margin, crosses zero into export as the lever climbs, and reaches $2.0\,kg$-T yr^{-1} at the advanced ceiling $\mathrm{TBR} = 1.42$. The register's scenario anchors sit exactly on the line: $1.6215\,kg$-T at $\mathrm{TBR} = 1.34$ and $3.8152\,kg$-T at $\mathrm{TBR} = 1.80$. At the defensible net ceiling $\mathrm{TBR} = 1.186$ the surplus is $0.887\,kg$-T—modest but positive, and the seed of the helium economy once decayed.



Per-unit tritium surplus $S = (\mathrm{TBR} - 1)\dot{N}_{\rm burn}$ at $\dot{N}_{\rm burn} = 4.769 kg - T$ fpy^{-1}. Markers are register anchors; the advanced ceiling yields $\approx 2.0\,kg$-T yr^{-1} per unit. The plant is a consumer where $S < 0$ and an exporter where $S > 0$.

INVENTORY DYNAMICS

Integrating the inventory equation 6 from a startup inventory $I_0 = 2\,kg$ at the frozen burn rate makes the three regimes concrete (figure 7). At the coverage-honest net $\mathrm{TBR} = 0.742$ the surplus is $S = -1.23\,kg\text{-T}\,\mathrm{yr}^{-1}$: the inventory falls below $0.7\,kg$ within one full-power year and depletes to zero at $t_0 = 1.56\,fpyunit$—an unambiguous, quantified NO-GO for the un-multiplied unit, consistent with the register's coverage-honest depletion gate at $\approx 1.5\,fpyunit$. At the defensible $\mathrm{TBR} = 1.186$ the surplus is $S = +0.887\,kg\text{-T}\,\mathrm{yr}^{-1}$, the inventory grows toward $I_{\mathrm{eq}} = 15.8\,kg$, and the doubling time to $4\,kg$ is $2.8\,yr$ from equation 8. At the advanced ceiling the surplus is $S = +2.0\,kg\text{-T}\,\mathrm{yr}^{-1}$ and the inventory climbs toward $I_{\mathrm{eq}} \approx 35\,kg$ on the decay timescale, doubling in well under a year: the difference between a plant that self-sustains and a plant that seeds the next. Table 2 collects the fuel-cycle figures.



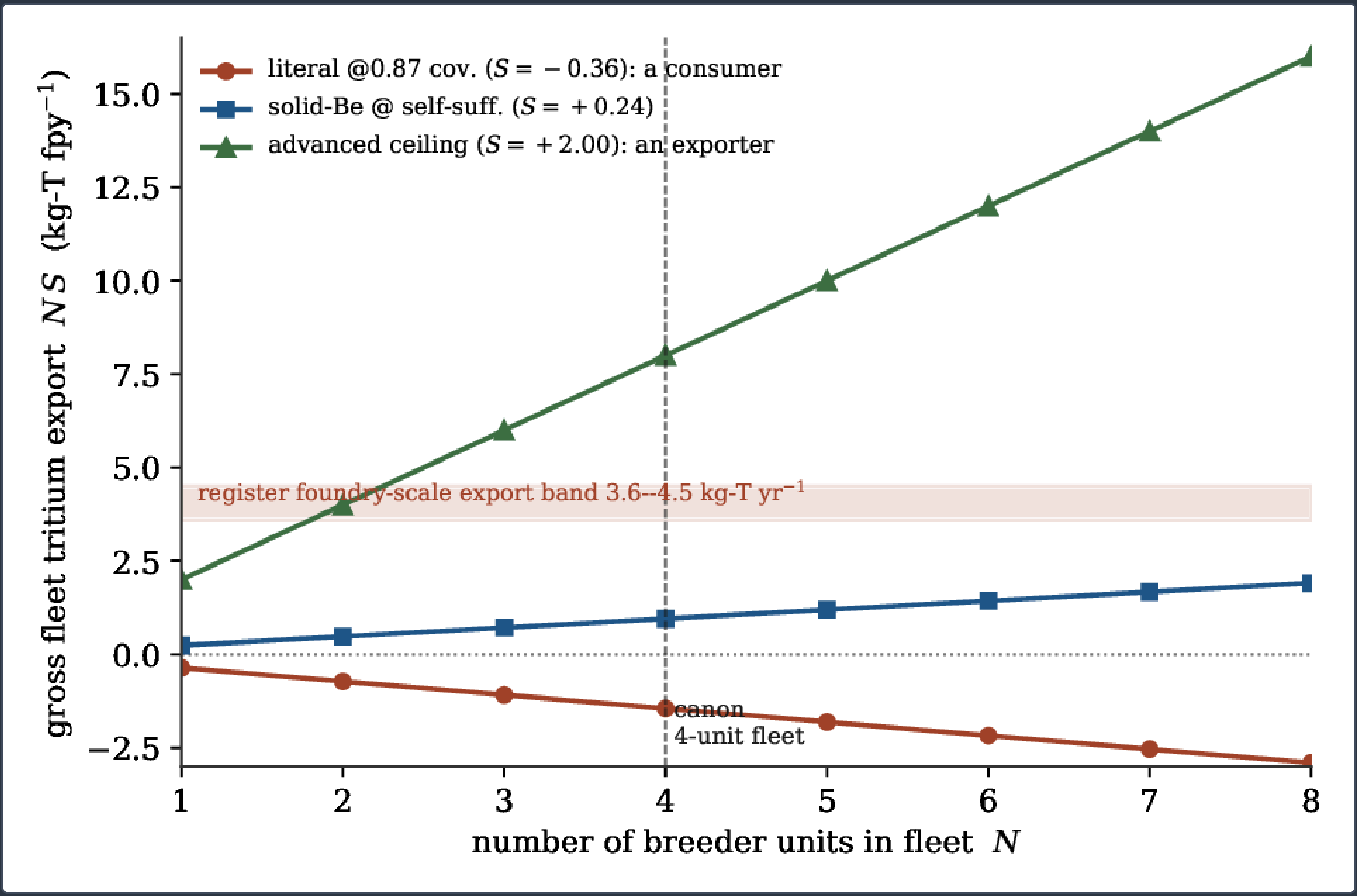
Tritium inventory trajectories from equation 8, $I_0 = 2\,kg$. The coverage-honest recipe ($\mathrm{TBR} = 0.742$) depletes at $1.49\,fpy$; the defensible ceiling ($\mathrm{TBR} = 1.186$) grows toward $16.5\,kg$; the advanced blanket ($\mathrm{TBR} = 1.42$) doubles in under a year.

NET TBR	REGIME	S (KG-T YR^{-1})	I_{eq} (KG)	DOUBLING TO 4 KG
0.742	consumer	-1.23	–	depletes @ 1.56 fpy
1.05	threshold	$+0.24$	$+4.2$	marginal
1.186	defensible ceiling	$+0.89$	$+15.8$	2.8 yr
1.42	advanced ceiling	$+2.00$	≈ 35	< 1 yr

Fuel-cycle summary at the frozen $\dot{N}_{\mathrm{burn}} = 4.769 kg - T$ fpy^{-1}, $t_1/2=§I12.32

FROM UNIT TO FLEET

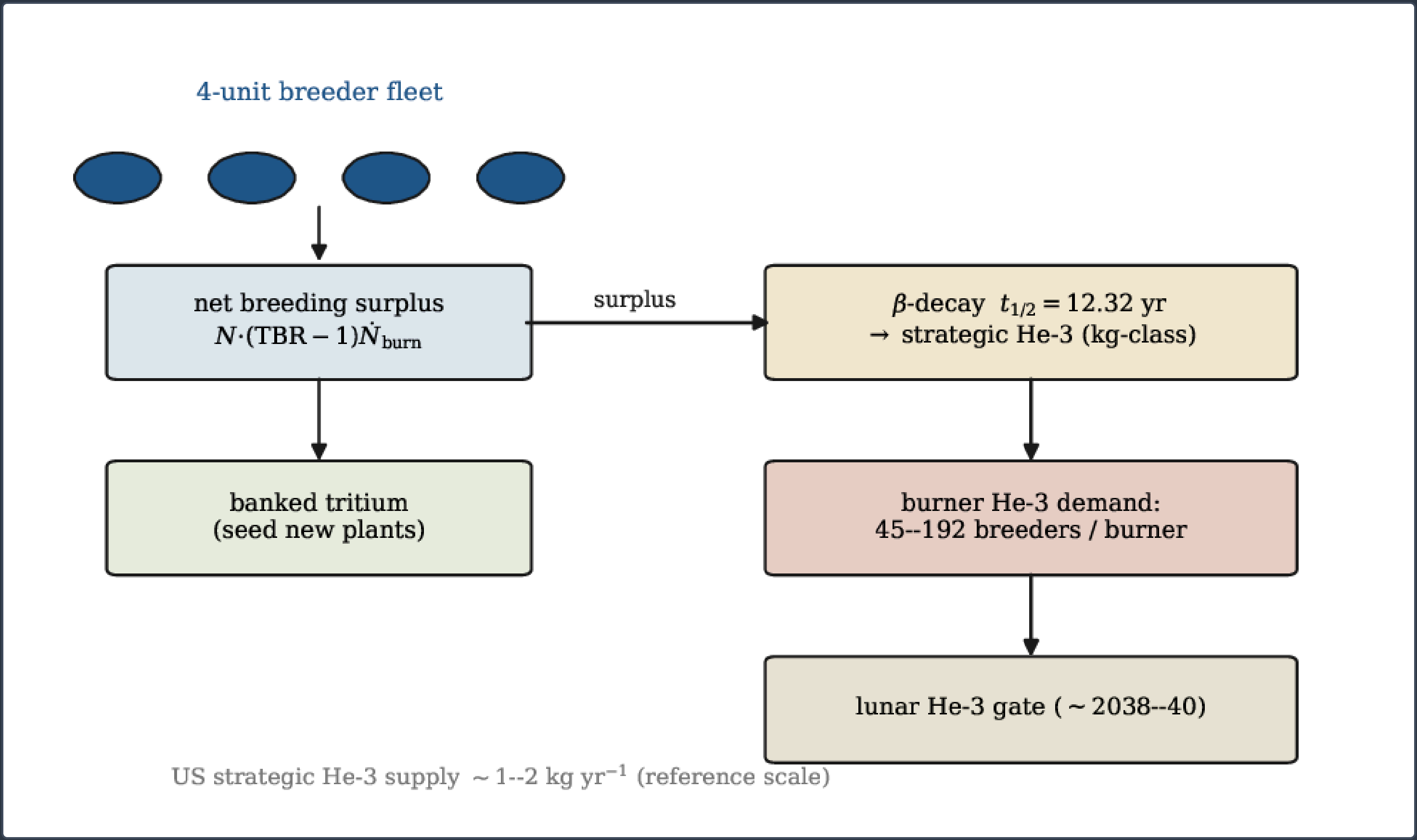
Figure 8 evaluates the fleet aggregate 10. A fleet built on the literal recipe at 0.87 coverage is a fleet of consumers: N units export $N \times (-0.36) kg-T$ fpy^{-1}, a growing deficit. A fleet on the solid-beryllium lever at the self-sufficiency threshold breaks even per unit and exports only its thin margin. A fleet on the advanced blanket exports $\approx 2.0\, N kg-T$ fpy^{-1} gross; the four-unit canonical fleet lands its net export, after the seeding draw and holdup, in the register's foundry-scale band of 3.6–4.5$kg-T$ fpy^{-1}. This is the quantitative meaning of the title: the transition from consumer to breeding fleet is not a change of machine but a change of blanket, and its arithmetic is equation 10 with a per-unit surplus set by the lever.



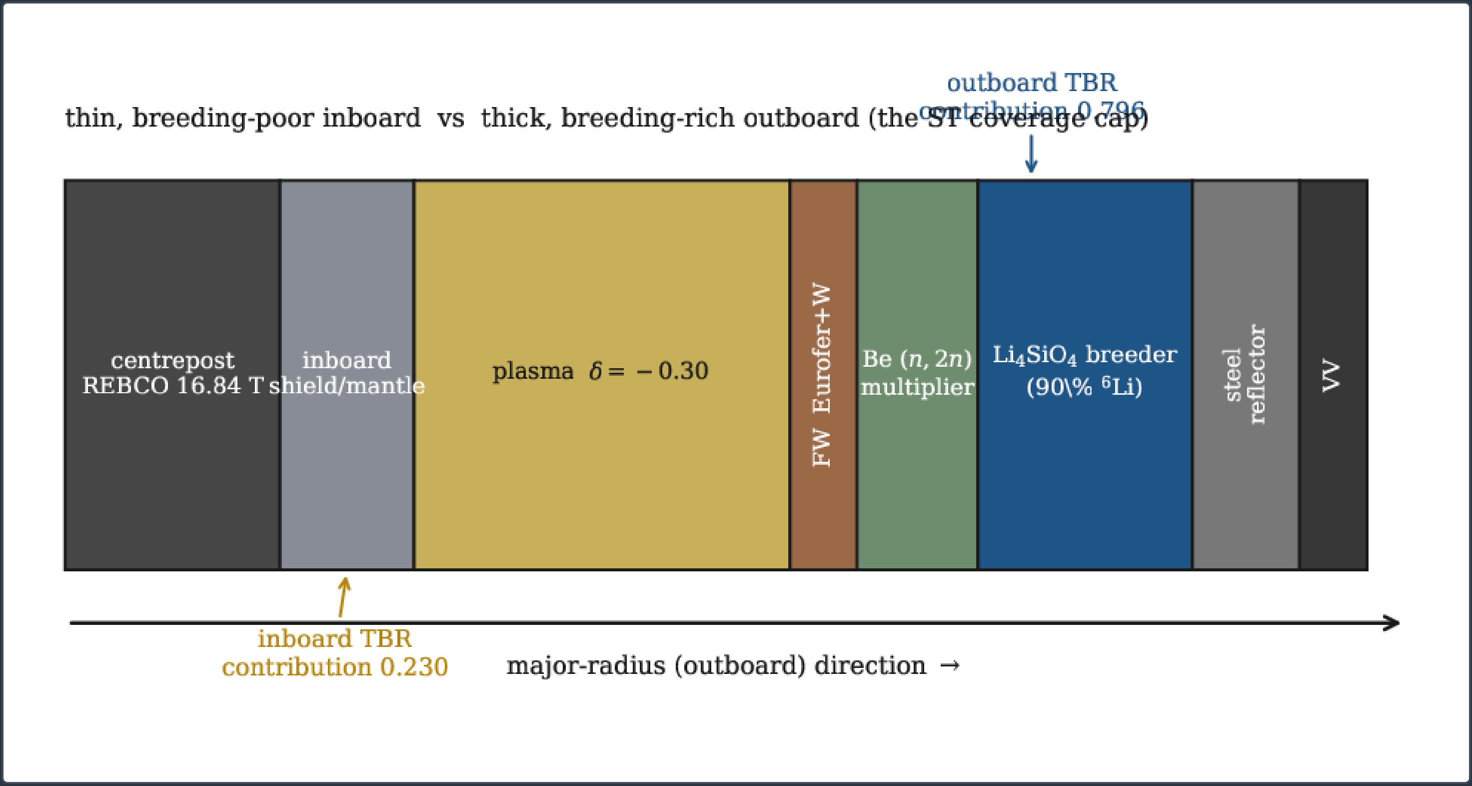
Gross fleet tritium export $N\,S$ versus fleet size for three blanket-maturity operating points. Only the advanced-blanket fleet exports; the four-unit canonical fleet reaches the register foundry-scale band 3.6–4.5$kg-T$ fpy^{-1} (shaded). The literal recipe at nominal coverage remains a fleet of consumers.

THE STRATEGIC HELIUM-3 CO-PRODUCT

Exported tritium is not the terminus. Banked surplus tritium β-decays to helium-3 with the mass ratio $m_{^3\mathrm{He}}/m_T \approx 0.99999$, so at the defensible ceiling each unit banks 0.887 *kg*-T\ that matures to ≈ 0.89 *kg* of helium-3 per year at equilibrium—kilogram-class against a US strategic supply of only $1\text{–}2\,\mathrm{kg\,yr^{-1}}$. Figure 9 is the schematic of this flywheel: the breeder fleet seeds it and its surplus decays into a strategic isotope stream. The one honest scale limit, developed in [31], is that fuelling a D–^{3}He tandem-mirror *burner* fleet from breeder decay alone would require of order $45\text{–}192$ breeders per burner (at $\mathrm{TBR} = 1.80$ down to 1.19), which is why burner-scale helium-3 remains gated on lunar supply rather than on the breeding ratio.



(Schematic.) The tritium-to-helium-3 flywheel of a four-unit breeder fleet. Net breeding surplus is banked, seeds new plants, and β-decays ($t_{1/2} = 12.32\,yr$) into strategic helium-3; burner-scale helium-3 demand ($45\text{–}192$ breeders per burner) stays lunar-gated.



(Schematic.) Radial build of the ST breeder blanket. The centrepost and inboard shield displace inboard breeding, so the thin inboard mantle contributes only **0.230** to the breeding integral against the outboard blanket's **0.796**: the geometric origin of the coverage cap.

§ 5

Discussion

QUANTITATIVE COMPARISON WITH PUBLISHED BREEDING STUDIES

The advanced-blanket ceiling of $\mathrm{TBR}_{\mathrm{net}} = 1.420$ is competitive with, and in the coverage-limited ST regime notably honest against, the values reported for large aspect-ratio DEMO concepts. Helium-cooled pebble-bed studies for the EU DEMO report one-dimensional TBRs of 1.15–1.30 before three-dimensional and system derating [14,15], and the classical self-sufficiency analyses require net ratios of 1.05–1.15 once holdup, doubling and uncertainty margins are folded in [3,12,4]. Our coverage-scaled advanced value of 1.235 at $f_{\mathrm{cov}} = 0.87$ sits inside the self-sufficient band with room for the doubling reserve, while our literal-recipe value of 0.924 correctly flags the ST coverage penalty that a one-dimensional headline number would hide. Against the modern ARC- and STEP-class fuel-cycle analyses of Meschini *et al.* [5]—which likewise find that compact D–T plants live near the self-sufficiency edge and that startup inventory and doubling time are the binding constraints—our inventory dynamics (equations 6–8, table 2) are in quantitative agreement: a thin-margin unit self-sustains but cannot double, and only a genuinely high-TBR blanket doubles on a useful timescale.

WHY THE CROSS-LIBRARY AGREEMENT MATTERS

A breeding ratio that changes by less than 0.3% between ENDF/B-VIII.0 and FENDL-3.2, and by only +0.004 between lithium-metal and lithium–lead breeders, is a robust engineering target rather than a fragile one. This matters because the self-sufficiency decision is made on a margin of a few percent: if the breeding number were uncertain at the several-percent level between accepted libraries, the 1.05–1.10 window would be unresolvable. The residual uncertainty that does matter—the $^7\mathrm{Li}(n, n't)$ threshold cross-section and the beryllium $(n, 2n)$ evaluation—is precisely the error budget quantified in the nuclear-data companion [28], and it is smaller than the design margin the advanced blanket carries.

THE CONSUMER-TO-FLEET TRANSITION AS A DESIGN CHOICE

Equations 9 and 10 show that the qualitative jump from “consumer” to “exporter” is a smooth function of a single design lever. This reframes the tritium question for a compact ST breeder. The machine does not need a different plasma, a different current, or a different field to become a fuel source; it needs the advanced blanket built and qualified. The negative-triangularity, high-field ST design point is held fixed throughout ($I_p = 9.66\,MA$, $Q = 3.076$, centrepost peak field $16.84\,T$); the breeding fleet is unlocked at the blanket, not at the plasma.

§ 6

Limitations

The single honest gate is coverage and qualification. The advanced-blanket ceiling of **1.420** is a one-dimensional, homogenised, radial-infinite-cylinder result that requires the advanced blanket—the solid-beryllium/$Be_{12}Ti$ multiplier layer, the void-reduced breeder and the steel reflector—to be mechanically and thermally designed, fabricated and qualified, which it is not yet. Scaled to the nominal **0.87** breeding coverage the advanced value is **1.235**, still self-sufficient, but the literal recipe at that coverage is not; a single unit at the coverage-honest recipe is therefore a self-sufficiency machine, not a single-unit exporter, and no single unit is claimed to meet a national tritium supply on its own. The migration from the coverage factor used here to a CAD-faithful three-dimensional net TBR with explicit ports, gaps and divertor cut-outs is the subject of the DAGMC companion [27] and is the work that turns the coverage assumption into a computed number.

§ 7

Conclusion

The net blanket tritium breeding ratio of a compact spherical-tokamak breeder is a governed design lever, not a fixed number, and it is the quantity that decides whether the plant is a consumer of a scarce fuel or the seed of a supply chain. Three-dimensional OpenMC neutronics on ENDF/B-VIII.0, run on the NVIDIA GPU HPC campaign, place the lever from a below-unity bare-lithium blanket through the literal beryllium-multiplied band (1.026–1.062) and the solid-beryllium layer (1.158) to a confirmed advanced-blanket ceiling of 1.420, verified across twelve configurations and reproduced across an independent nuclear-data library to under 0.3%. Scaled to realistic three-dimensional coverage the advanced blanket clears the 1.05–1.10 self-sufficiency window with margin while the literal recipe does not, and the per-unit surplus law $S = (\mathrm{TBR} - 1)\dot{N}_{\mathrm{burn}}$ carries the ceiling to $\approx 2.0\,kg$-T yr^{-1} per unit and a four-unit fleet to a foundry-scale export band of 3.6–$4.5 kg - T$ fpy^{-1} whose decay supplies strategic, kilogram-class helium-3. The transition from tritium consumer to breeding fleet is a change of blanket, not of machine; the honest gate is that the advanced blanket must be built and qualified, and the path to the computed three-dimensional number runs through the CAD-faithful companion.

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-and-depletion compute.

Reproducibility. Every headline quantity in this paper is a frozen anchor in the Kronos Physics De-Risking Register [33] (doi:10.5281/zenodo.22133057): the reference three-dimensional balance (BR-L1-A5), the breeding lever (BR-L2-A7), the advanced-blanket ceiling (BR-L2-A7u), the lead–lithium arbiter (BR-L2-A7c), the tritium surplus and startup model (BR-L1-A6), the coverage-honest fuel-cycle dynamics (BR-L1-A8), the export-scale re-run (BR-OUT-1) and the helium-3 flow (BR-OUT-2), together with the coverage gate H-C1 (appendix G.2). Each is regenerable from the deterministic-seed inputs and the figure-generation script deposited with this paper, archived at doi:10.5281/zenodo.22645706; official version: https://www.kronosfusionenergy.com/publications/blanket-tritium-breeding-lever.html. No result depends on unpublished or proprietary data, and no economic analysis is part of this deposit.

Data availability tocsectionData availability The TBR-lever, coverage, cross-library, surplus, inventory and fleet data used for figures 1–8 are archived with the deposit at doi:10.5281/zenodo.22645706 and trace to the register [33] (doi:10.5281/zenodo.22133057) by the serial identifiers cited inline; the breeder physics deposit is version 2 at doi:10.5281/zenodo.21795620. No economics appear in 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

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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.

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