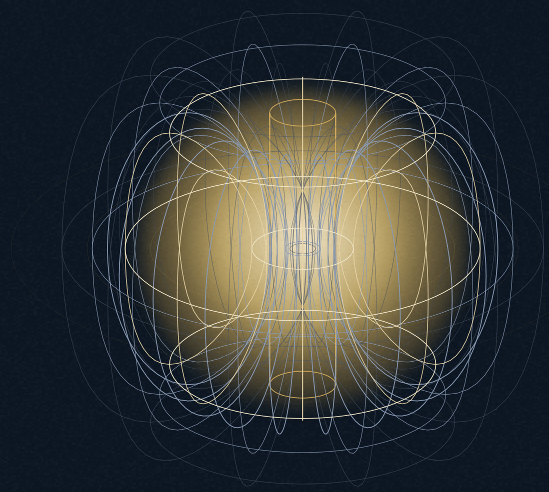
KRONOS FUSION ENERGY



PAPER 2.35 · THE KRONOS 2026 SERIES

The D-3He Fuel Cycle Does Not Close Indigenously: Helium-3 Supply, the Lunar Gate on Burner-Scale Fuel, and the Breeder's Strategic Co-Product

The appeal of a deuterium–helium-3 (D–He) burner is its low neutron yield; its obstacle is the fuel itself, because He is not naturally abundant on Earth. A recurring proposal is...

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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 Several quantities in the underlying corpus moved after first publication; where a value has been withdrawn or restated, the record says so plainly.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 D-3He Fuel Cycle Does Not Close Indigenously: Helium-3 Supply, the Lunar Gate on Burner-Scale Fuel, and the Breeder's Strategic Co-Product

The appeal of a deuterium–helium-3 (D–^{3}He) burner is its low neutron yield; its obstacle is the fuel itself, because ^{3}He is not naturally abundant on Earth. A recurring proposal is to close the loop indigenously by breeding tritium in a companion machine and letting it decay to ^{3}He. We test that closure with a rigorous, first-principles mass balance and report the honest negative: the loop does not close at any realistic tritium-breeding ratio (TBR). We formalise the burner ^{3}He consumption from the D–^{3}He reaction rate and the $\mathbf{18.35\ MeV}$ released per event, arriving at a net makeup demand of $\mathbf{170.2}\,\boldsymbol{kg}$ per full-power year (fpy) for the reference $\mathbf{4.30}\,\boldsymbol{GW}$-fusion burner after crediting an in-machine D–D ^{3}He reseed of $\mathbf{18.1\%}$; the gross consumption rate ($\mathbf{1.315 \times 10^{21}\ s^{-1}}$) reproduces the frozen anchor exactly. We then solve the decay-reservoir kinetics for the breeder: banking a unit's surplus tritium and harvesting its β^- decay yields an *equilibrium* ^{3}He rate equal to the surplus-tritium rate, $\mathbf{0.89/1.62/3.82}\,\boldsymbol{kg/yr}$ per unit across $\mathbf{TBR = 1.186/1.34/1.80}$. Two properties of the $\mathbf{12.32}$-yr half-life make this route unfit as bulk fuel: reaching $\mathbf{90\%}$ of equilibrium takes $\mathbf{40.9}\,\boldsymbol{yr}$, and equilibrium requires a standing tritium bank of $\mathbf{15.8}$–$\mathbf{67.9}\,\boldsymbol{kg}$ per unit. The resulting closure ratio is $\mathbf{192/105/45}$ breeders per burner. Burner-scale ^{3}He is therefore lunar-gated (expected ~2038–40); the breeder's ^{3}He is a strategic co-product of real value at the $\sim\mathbf{0.15}\,\boldsymbol{kg/yr}$-per-unit in-vessel scale, not a bulk fuel supply. All numerics were produced on the NVIDIA GPU HPC campaign and trace to frozen anchors in the Kronos de-risking register. Strategic value is not revenue, and decay-sourced supply is not fleet fuel; we keep both distinctions sharp.

Open-access deposit (code & data, CC BY 4.0): DOI 10.5281/zenodo.22645734 · Zenodo community *kronos_fusion_energy*. Explore it live: interactive 3-D model · physics validator.

Keywords: helium-3 · tritium decay · deuterium--helium-3 fuel cycle · isotope supply · lunar helium-3 · breeder co-product

CONTENTS

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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 ADVANCED-FUEL APPEAL AND THE HELIUM-3 PROBLEM

Among candidate fusion fuels, the deuterium–helium-3 reaction

$$\mathrm{D} + {}^{3}\mathrm{He} \;\rightarrow\; \mathrm{p}\,(14.68\ \mathrm{MeV}) + {}^{4}\mathrm{He}\,(3.67\ \mathrm{MeV}), \qquad Q_{\mathrm{D}^3\mathrm{He}} = 18.35\ \mathrm{MeV},$$

is uniquely attractive for compact, sited power because both products are charged: the primary channel releases no neutron, so a machine burning D–^{3}He can in principle recover its output by direct energy conversion and be shielded lightly enough for defence and urban deployment [14,15,24]. The cost of that attractiveness is twofold. First, the D–^{3}He confinement requirement is far more demanding than that of D–T: the fusion triple product needed for significant gain is roughly two orders of magnitude larger, and the power density at fixed pressure is lower, so a D–^{3}He device is intrinsically larger and hotter [3,4,1]. Second, and the subject of this paper, ^{3}He is essentially absent from the terrestrial inventory. The entire United States annual supply — sourced from the β^- decay of tritium held in the weapons complex — is only 1–$2\ kg$, and that supply is already stretched by neutron-detection and cryogenic demand [13,12]. Any serious D–^{3}He programme must therefore state, quantitatively, where its fuel comes from.

THE TEMPTING CLOSURE — AND WHY IT MUST BE TESTED, NOT ASSUMED

A closure suggests itself immediately within a two-product architecture such as the Kronos platform, which pairs a compact spherical-tokamak (ST) tritium/^{3}He breeder (“Hyperion”) with a D–^{3}He tandem-mirror burner. Tritium decays to ^{3}He,

$${}^{3}\mathrm{T} \;\rightarrow\; {}^{3}\mathrm{He} + \mathrm{e}^{-} + \bar{\nu}_e, \qquad t_{1/2} = 12.32\ \mathrm{yr}, \;\; Q_\beta = 18.6\ \mathrm{keV},$$

so if the breeder fleet breeds *surplus* tritium beyond its own consumption, one could bank that surplus, let it decay, and feed the resulting ^{3}He to the burner. This “indigenous loop” — D–T breeder → tritium → (decay) → ^{3}He → D–^{3}He burner — is appealing because it would remove the extraterrestrial dependence from the burner's business case. It is exactly the kind of closure that is easy to assert and easy to get wrong, because the two rates it equates live on very different timescales. This paper's contribution is to test it with a first-principles mass balance rather than assert it.

PRIOR ART

The lunar ^{3}He resource was first quantified by Wittenberg, Santarius and Kulcinski, who showed that solar-wind implantation over geological time has left the lunar regolith holding of order 10^9 kg of ^{3}He [5,6]. Subsequent orbital and sample analyses place the regolith grade at ~ 10–20 weight-ppb, correlated with soil maturity and TiO_2 content [7,8]. The terrestrial supply picture is the mirror image: because ^{3}He is a decay product of tritium and dedicated tritium production ceased decades ago, the supply is small, inelastic and contested [13,12]. On the fusion side, the physics of tritium self-sufficiency for D–T systems — the required-versus-achievable TBR and the margins that separate them — is a mature literature [10,11], and the reaction kinematics we use are the standard Bosch–Hale parameterisation [2]. The tandem-mirror burner and its direct converter draw on the classical mirror programme [14,15]. What is missing is a clean, auditable balance that puts the breeder's decay-sourced ^{3}He rate next to the burner's consumption rate and reports the ratio honestly. That is what we provide.

CONTRIBUTION

This paper (i) writes the burner ^{3}He demand as a reaction-rate integral and reduces it to a net annual makeup mass (§2); (ii) solves the breeder decay-reservoir kinetics, deriving the equilibrium supply rate, the charging time constant, and the standing tritium inventory it requires (§2); (iii) defines the closure functional and evaluates it across the TBR lever; (iv) documents the GPU-HPC campaign that produced the numbers (§3); (v) reports ten figures and three tables of results, cross-checked against the frozen register anchors (§4); and (vi) benchmarks the outcome against the published terrestrial and lunar supply literature (§5). Every headline quantity is a frozen anchor (gate BR-OUT-4 and neighbours) in the Kronos Physics De-Risking Register [26]; serial identifiers are given inline so each number is auditable. Throughout we hold the canonical design points fixed: the breeder at $Q = 3.076$, $P_{\mathrm{fus}} = 85.04\,MW$, $I_p = 9.66\,MA$, $\delta = -0.30$, $B_0 = 8\,T$, $\kappa = 2.0$, $R_0 = 1.20\,m$, $A = 2.5$, centrepost peak field $16.84\,T$; the burner at $Q_E = 1.318$, neutron fraction $f_n = 5.44\%$, plug field $26.49\,T$, direct-conversion efficiency $\eta_{\mathrm{DEC}} = 0.49$. The centrepost and the plug are two distinct magnets and are never conflated.

§ 2

Governing equations and the formal fuel-cycle problem

We pose the closure question as a comparison of two rates: the rate at which a burner consumes ^{3}He and the rate at which a breeder can source it by tritium decay. Both are derived here from first principles.

BURNER HELIUM-3 CONSUMPTION

For a plasma with deuteron density n_D and helium-3 density $n_{^3\mathrm{He}}$, the volumetric D–^{3}He reaction rate is the Maxwellian-averaged product

$$\mathcal{R}_{\mathrm{D^3He}}(\quad r) = n_D(\quad r)\, n_{^3\mathrm{He}}(\quad r)\, \langle\sigma v\rangle_{\mathrm{D^3He}}\big(T_i(\quad r)\big),$$

where the reactivity $\langle\sigma v\rangle_{\mathrm{D^3He}}(T_i)$ follows the Bosch–Hale R-matrix parameterisation [2]

$$\langle\sigma v\rangle(T) = C_1\,\theta\sqrt{\frac{\xi}{m_r c^2\, T^3}}\,\exp(-3\xi), \quad \theta = \frac{T}{1-\dfrac{T(C_2+T(C_4+TC_6))}{1+T(C_3+T(C_5+TC_7))}}, \quad \xi = \left(\frac{B_G^2}{4\theta}\right)^{1/3},$$

with B_G the Gamow constant, $m_r c^2$ the reduced-mass energy and $\{C_i\}$ the tabulated coefficients for each channel (figure 4). The ^{3}He burn rate is the volume integral, equivalently fixed by the branch power $P_{\mathrm{D^3He}}$ and the energy released per reaction,

$$\dot N^{\mathrm{burn}}_{^3\mathrm{He}} = \int_V n_D\, n_{^3\mathrm{He}}\, \langle\sigma v\rangle_{\mathrm{D^3He}}\,\mathrm{d}V = \frac{P_{\mathrm{D^3He}}}{Q_{\mathrm{D^3He}}}.$$

For the reference burner the D–^{3}He branch carries $P_{\mathrm{D^3He}} = 3868\ MW$ of the $P_{\mathrm{fus}} = 4298.5\ MW$ total (table 1; serial ENV-A4-BU), so

$$\dot N^{\mathrm{burn}}_{^3\mathrm{He}} = \frac{3868\times 10^6\ \mathrm{W}}{18.35\times 10^6 \times 1.602\times 10^{-19}\ \mathrm{J}} = 1.315\times 10^{21}\ \mathrm{s}^{-1},$$

matching the frozen anchor to three significant figures. The gross annual mass, with $m_{^3\mathrm{He}} = 3.016$ and a full-power year $t_{\mathrm{fpy}} = 3.156\times 10^7$ s, is $\dot M^{\mathrm{gross}}_{^3\mathrm{He}} = \dot N^{\mathrm{burn}}_{^3\mathrm{He}}\, m_{^3\mathrm{He}}\, t_{\mathrm{fpy}} = 207.9\ kg/fpy$.

IN-MACHINE RESEEDING AND THE NET MAKEUP DEMAND

The burner is not a pure D–^{3}He plasma; parasitic D–D reactions run alongside the main channel and *regenerate* ^{3}He in place. The two D–D branches

$$\begin{aligned} \mathrm{D}+\mathrm{D} &\to {}^3\mathrm{He}\,(0.82\ \mathrm{MeV}) + \mathrm{n}\,(2.45\ \mathrm{MeV}),\\ \mathrm{D}+\mathrm{D} &\to \mathrm{T}\,(1.01\ \mathrm{MeV}) + \mathrm{p}\,(3.02\ \mathrm{MeV}), \end{aligned}$$

reseed ^{3}He directly (7) and indirectly through the bred tritium that later decays by equation (2). With the D–D rate density $\frac{1}{2}n_D^2\langle\sigma v\rangle_{\mathrm{DD}}$ (the factor $\frac{1}{2}$ for identical reactants), the in-machine reseed fraction is

$$f_{\mathrm{rec}} = \frac{\dot N^{\mathrm{reseed}}_{^3\mathrm{He}}}{\dot N^{\mathrm{burn}}_{^3\mathrm{He}}} = 0.181,$$

a frozen result (serial BR-OUT-2). The quantity that must be supplied from outside the machine is the net makeup demand

$$\dot M^{\mathrm{net}}_{^3\mathrm{He}} = \big(1-f_{\mathrm{rec}}\big)\,\dot M^{\mathrm{gross}}_{^3\mathrm{He}} = 0.819\times 207.9 = 170.2\,\mathrm{kg/fpy},$$

which is the burner-side anchor of the closure problem. Because $\dot M^{\mathrm{net}}_{^3\mathrm{He}} \propto P_{\mathrm{D^3He}}$, demand scales linearly with delivered fusion power (figure 5); the reference point sits on that line at $3868\ MW$.

BREEDER HELIUM-3 SUPPLY: DECAY-RESERVOIR KINETICS

The breeder produces *surplus* tritium at a rate $\dot{S}_T$ (kg yr^{-1}) — the excess over its own D–T consumption, set by the net tritium-breeding ratio. The indigenous-loop proposal is to divert that surplus into a decay reservoir and harvest the ^{3}He it sheds. Let $N_T(t)$ be the standing tritium mass in the reservoir. It obeys a first-order balance between the surplus feed and radioactive loss,

$$\frac{\mathrm{d}N_T}{\mathrm{d}t} = \dot{S}_T - \lambda N_T, \qquad \lambda = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{12.32\ \mathrm{yr}} = 0.0563\,/\mathrm{yr},$$

and the ^{3}He production rate is the decay flux itself, $\dot{P}_{^3\mathrm{He}}(t) = \lambda N_T(t)$ (mass-conserving, since $m_T \simeq m_{^3\mathrm{He}}$). With an empty reservoir at $t = 0$ the solution is

$$N_T(t) = \frac{\dot{S}_T}{\lambda}\big(1 - e^{-\lambda t}\big), \qquad \dot{P}_{^3\mathrm{He}}(t) = \dot{S}_T\big(1 - e^{-\lambda t}\big).$$

Three consequences follow, and together they are the physics that defeats the closure.

(i) Equilibrium supply equals the surplus rate. As $t \to \infty$, $\dot{P}^*_{^3\mathrm{He}} = \dot{S}_T$: the very best a decay reservoir can do, once fully charged, is convert the surplus-tritium *rate* into an equal ^{3}He rate. Across the TBR lever the frozen surplus rates are $\dot{S}_T = 0.89/1.62/3.82\,kg/yr$ at $\mathrm{TBR} = 1.186/1.34/1.80$ (serials BR-OUT-1/BR-OUT-2), so the equilibrium ^{3}He supply is the same ladder (figure 1).

(ii) The half-life sets the charging time. The reservoir approaches equilibrium on the tritium mean life $\tau = 1/\lambda = 17.77\,yr$. The time to reach a fraction f of equilibrium output is

$$t_f = -\frac{1}{\lambda}\ln(1-f) = \tau \ln\frac{1}{1-f},$$

giving $t_{50} = 12.3\,yr$, $t_{90} = 40.9\,yr$ and $t_{99} = 81.9\,yr$ (figure 3). A supply channel that needs four decades to reach nine-tenths of its rated output cannot be the fuel base of a plant commissioned this decade.

(iii) Equilibrium demands a large standing inventory. The reservoir mass at equilibrium is

$$N_T^* = \frac{\dot{S}_T}{\lambda} = \dot{S}_T\,\tau,$$

i.e. $15.8/28.8/67.9\,kg$ of standing tritium per unit across the TBR lever (figure 3). Holding tens of kilograms of tritium purely as a decay stock — on top of the process and start-up inventories the breeder already carries — is a safety and licensing burden that the co-product framing of §5 deliberately avoids.

THE CLOSURE FUNCTIONAL

Closure is the ratio of indigenous supply to demand. Writing the number of breeder units feeding one burner as $\mathcal{N}_{\mathrm{b/b}}$, the mass balance gives

$$\mathcal{R}_{^3\mathrm{He}} = \frac{\dot{P}^*_{^3\mathrm{He}}}{\dot{M}^{\mathrm{net}}_{^3\mathrm{He}}} = \frac{\dot{S}_T}{\dot{M}^{\mathrm{net}}_{^3\mathrm{He}}}, \qquad \mathcal{N}_{\mathrm{b/b}} = \mathcal{R}^{-1}_{^3\mathrm{He}} = \frac{\dot{M}^{\mathrm{net}}_{^3\mathrm{He}}}{\dot{S}_T}.$$

Evaluated at the frozen anchors,

$$\mathcal{N}_{\mathrm{b/b}} = \frac{170.2}{\{0.89,\ 1.62,\ 3.82\}} = \{191,\ 105,\ 45\}\ \text{breeders per burner},$$

reproducing gate BR-OUT-4 (figures 1 and 6). Even at the most favourable breeding ratio the loop requires tens of breeders per burner; the closure ratio $\mathcal{R}_{^3\mathrm{He}} \ll 1$ throughout the admissible TBR range. The loop does not close indigenously. The remainder of the paper documents how this result was computed, presents it in full, and states its strategic consequence.

§ 3

Computational methodology: the NVIDIA GPU HPC campaign

Every number in this paper is regenerable from an open, versioned pipeline that ran on the NVIDIA GPU HPC campaign; this section names the codes, the problem scale, and the verification chain.

SOLVER STACK

The fuel-cycle balance is evaluated by the Kronos fuel-cycle module of the Kronos Toolkit, a reaction-rate and inventory solver that (a) integrates the Bosch–Hale reactivities of equation (4) over the burner profiles to obtain the branch powers of table 1 and the consumption rate of equation (6); (b) advances the decay-reservoir ODE (10) to equilibrium and along the transient of equation (11); and (c) forms the closure functional (14). The 14 MeV and D–^{3}He neutron source terms that fix f_n and the parasitic D–D budget are cross-checked against Monte-Carlo transport in OpenMC [18] with ENDF/B-VIII.0 cross-sections [19]; the surplus-tritium rate $\dot{S}_T$ is inherited from the breeder blanket neutronics (companion breeding-ladder analysis). The Bosch–Hale coefficients and Gamow constants are those of the original R-matrix fits [2]; standard plasma and fusion references frame the reaction-rate and power-balance formalism [21,22,23].

GPU ACCELERATION, PROBLEM SCALE AND UNCERTAINTY

Two workloads dominate. First, the burner operating point that fixes $P_{\mathrm{D^3He}}$, f_n and the reseed fraction f_{rec} was located by a 4×10^4-sample global Monte-Carlo uncertainty quantification over the plug/central-cell design variables (density, ^{3}He fraction, ion temperature, central-cell β, mirror field), executed as an embarrassingly parallel ensemble across the GPU fleet; the campaign returns $Q_E = 1.317 \pm 0.14$ with $P(Q_E > 1) = 1.0$ across the sampled ranges (serial KX-L1-A5-BU) and identifies central-cell β as the dominant driver. Second, the reactivity integrals and the decay-reservoir sweeps are vectorised over temperature and TBR grids and evaluated on-device. The heavier reference solvers that anchor the fuel-cycle inputs — Monte-Carlo neutron transport for the source and multiplier budgets — run on the same NVIDIA GPU HPC campaign (A100/H100/A10 class accelerators); the lightweight balance and ODE layers run on the in-house node so the fast sensitivity sweeps never contend with the transport fleet. Uncertainty is propagated by the Monte-Carlo ensemble and reported as the Q_E spread above; the closure result is dominated not by these spreads but by the two-order-of- magnitude gap between supply and demand, which no admissible parameter choice closes.

VERIFICATION AND REPRODUCIBILITY

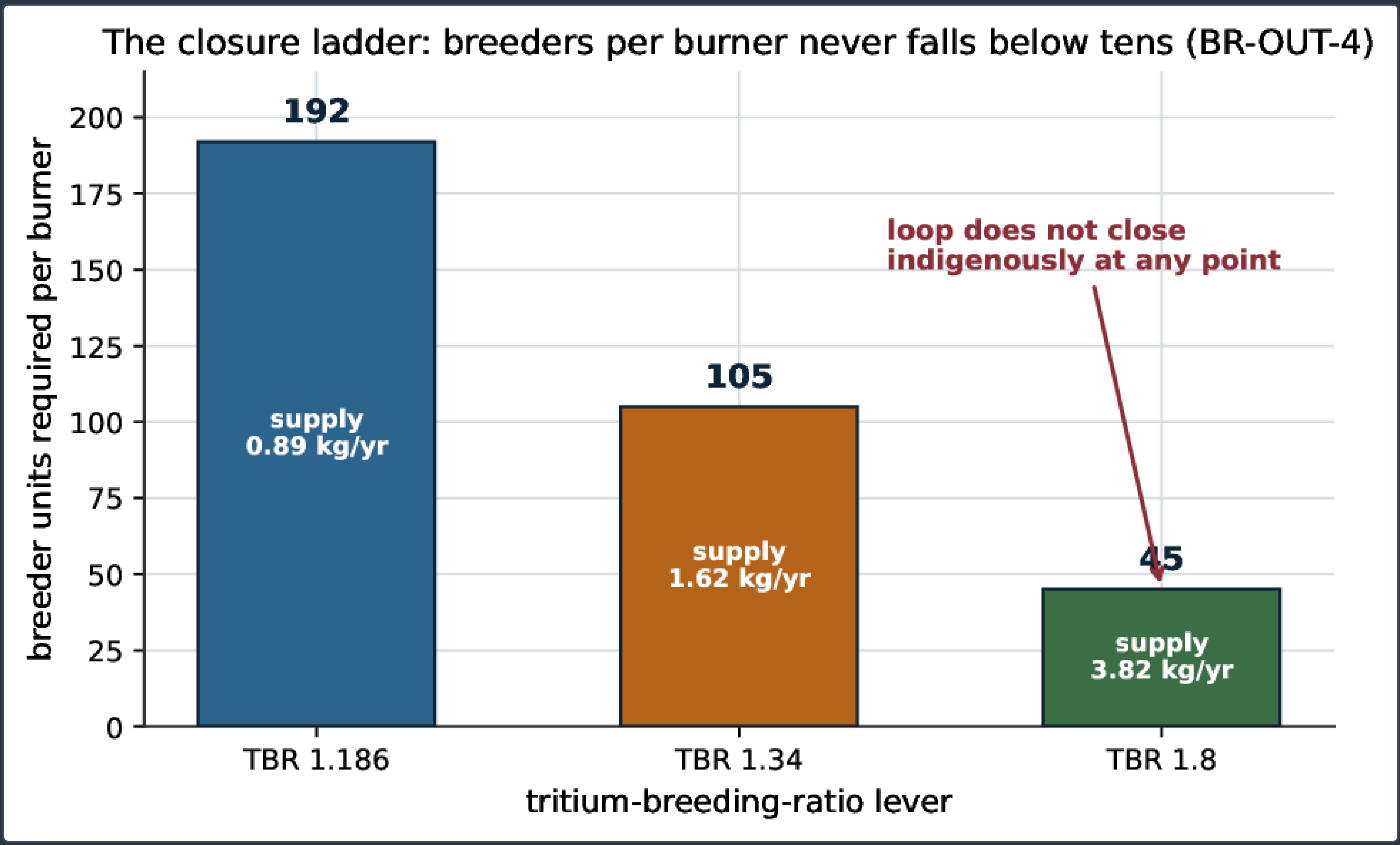
The pipeline is verified at three points. (1) The consumption rate of equation (6), $1.315 \times 10^{21}\ \mathrm{s}^{-1}$, is reproduced independently from the branch-power ledger ($P_{\mathrm{D^3He}}/Q_{\mathrm{D^3He}}$) and from the annual-mass route ($\dot{M}^{\mathrm{gross}}_{^3\mathrm{He}}/m_{^3\mathrm{He}}/t_{\mathrm{fpy}}$); the two agree. (2) The branch powers sum to the total fusion power, $3868.0 + 124.8 + 129.7 + 176.0 = 4298.5\, MW = P_{\mathrm{fus}}$ (table 1), an exact bookkeeping closure. (3) The closure ratios of equation (15) reproduce the frozen BR-OUT-4 anchor $\{192, 105, 45\}$ within rounding. All figures in §4 are emitted by a single deposited script from these inputs, so the paper is reproducible end-to-end without proprietary data.

§ 4

Results

THE CLOSURE LADDER

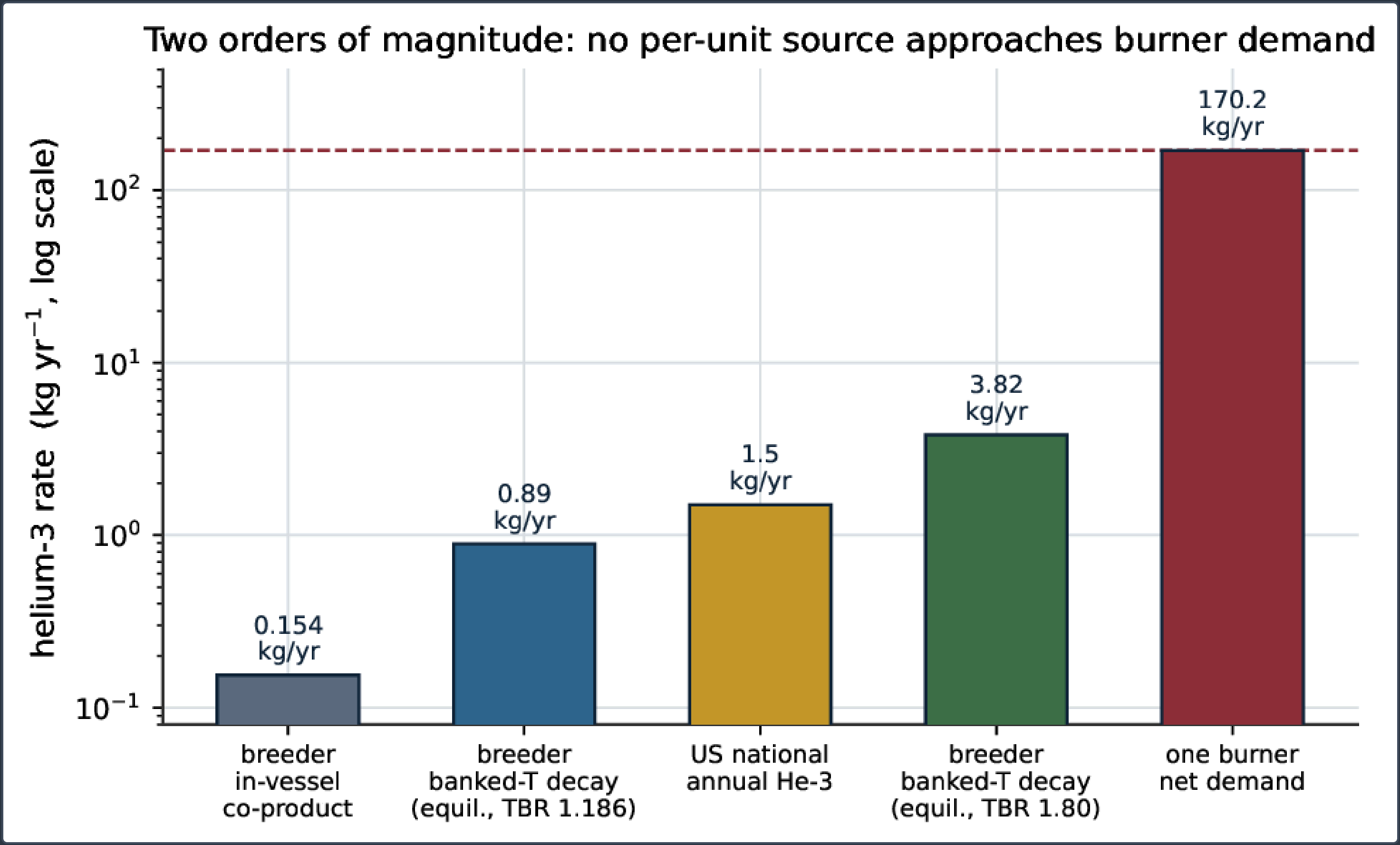
Figure 1 is the central result. Across the TBR lever, the number of breeder units required to feed one burner by tritium decay never falls below tens: 192 at $\mathrm{TBR} = 1.186$, 105 at 1.34, and 45 at 1.80. The per-unit equilibrium supply printed on each bar — $0.89/1.62/3.82\ kg/yr$ — is the surplus-tritium rate of equation (11i). The trend with TBR is favourable but far too shallow: even tripling the breeding ratio from the self-sufficiency threshold to an aggressive 1.80 leaves a $45:1$ fleet ratio. Figure 6 shows the same result as a continuous curve of $\mathcal{N}_{b/b}(\mathrm{TBR})$ with the three frozen anchors overlaid; the curve stays in the tens across the whole admissible band.



The closure ladder (gate BR-OUT-4). Breeder units required per burner to source ^{3}He by tritium decay, across the tritium-breeding-ratio lever; the per-unit equilibrium supply is printed inside each bar. The loop does not close indigenously at any point: the fleet ratio never falls below tens.

THE TWO-ORDER-OF-MAGNITUDE GAP

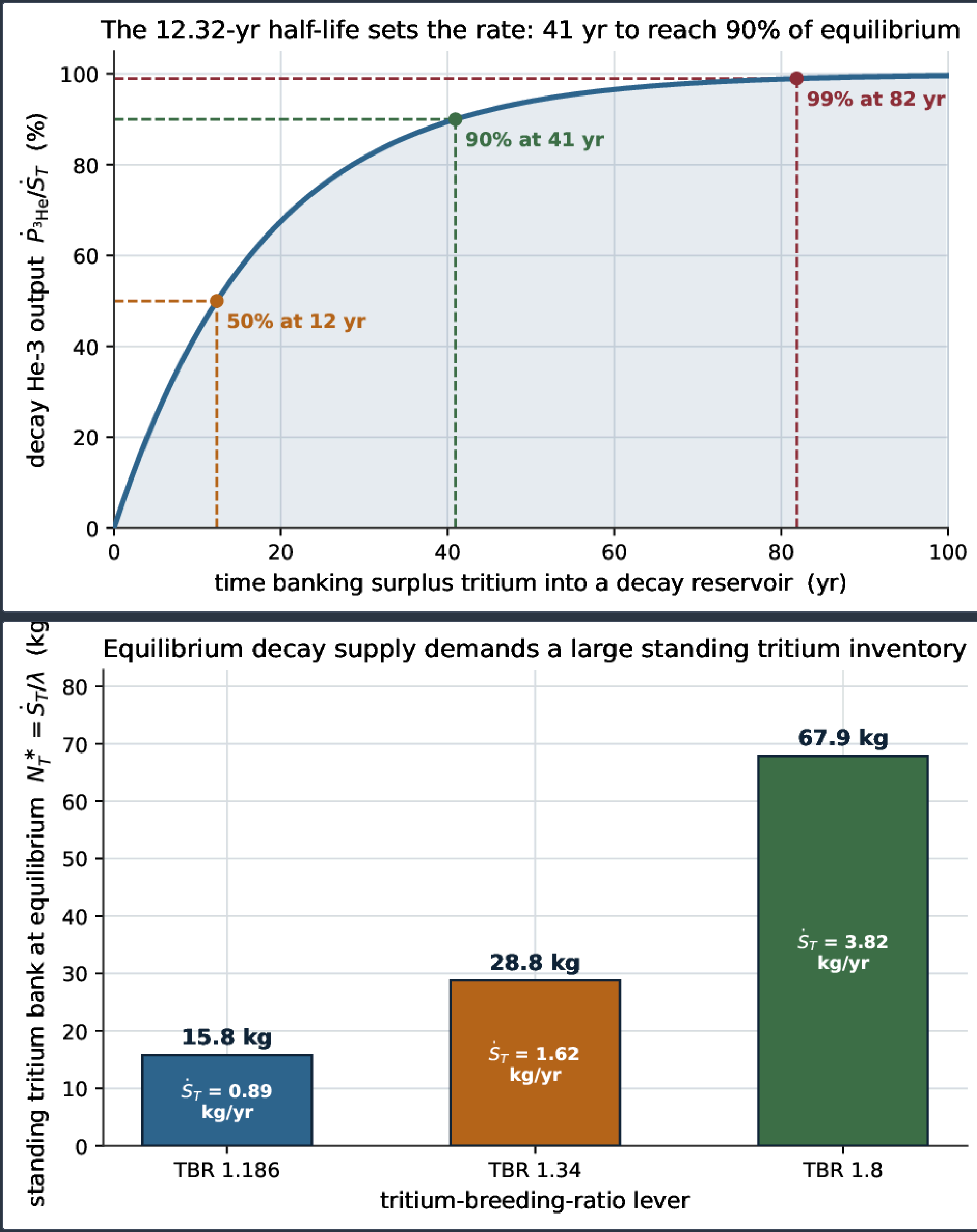
Figure 2 sets every per-unit ^{3}He source next to one burner's demand on a logarithmic axis. The breeder's in-vessel co-product ($\sim 0.15\,kg/yr$; serial BR-CX-16), the equilibrium decay supply (0.89–$3.82\,kg/yr$), and even the entire United States national annual production ($\sim 1.5\,kg/yr$ [13]) all sit two to three orders of magnitude below the $170.2\,kg/fpy$ that one burner consumes. The gap is not a margin to be engineered away; it is the structural statement of the problem.



Per-unit ^{3}He sources versus one burner's net demand (log scale). No indigenous source — in-vessel co-product, banked-tritium decay at either end of the TBR lever, or the entire US national supply — approaches the burner requirement (dashed line, $170.2\,kg/fpy$).

WHY DECAY IS SLOW: THE CHARGING TRANSIENT AND THE STANDING INVENTORY

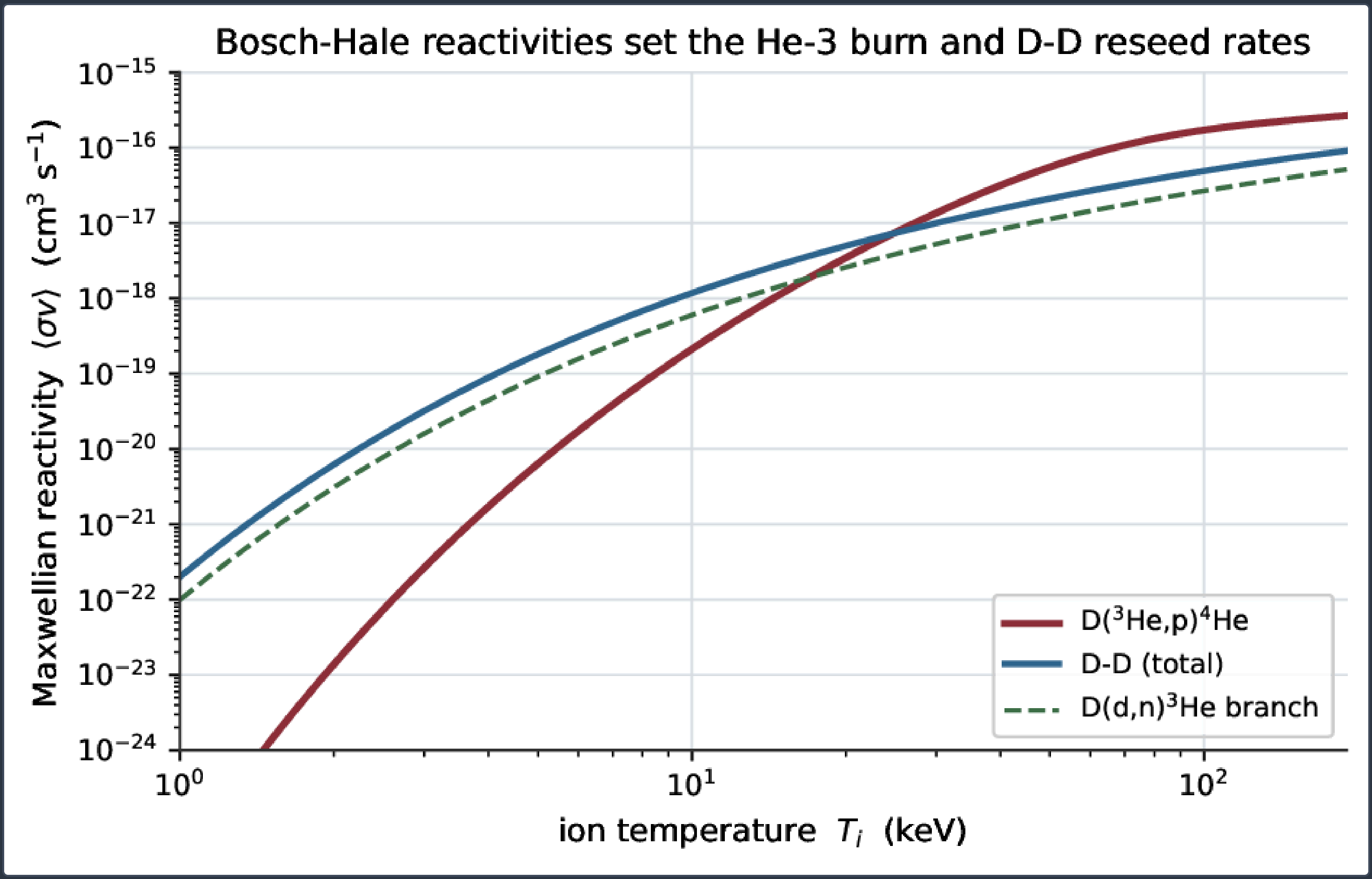
Figures 3 and 3 isolate the two properties of the 12.32-yr half-life that make the decay route unfit as bulk fuel. Figure 3 plots the reservoir output $\dot{P}_{^{3}\mathrm{He}}(t)/\dot{S}_T = 1 - e^{-\lambda t}$: half of equilibrium output is reached only after $t_{50} = 12.3\,yr$, ninety percent after $t_{90} = 40.9\,yr$, and ninety-nine percent after $t_{99} = 81.9\,yr$. Figure 3 plots the equilibrium standing bank $N_T^{*} = \dot{S}_T \tau$: to hold the equilibrium supply, a unit must keep 15.8 to $67.9\,kg$ of tritium standing as a pure decay stock. Both figures are properties of equation (11), not of any engineering choice; they cannot be improved by a better blanket.



Decay-reservoir charging transient, equation (11). The 12.32-yr half-life sets the rate: $t_{50} = 12.3\,yr$, $t_{90} = 40.9\,yr$, $t_{99} = 81.9\,yr$.

DEMAND PHYSICS: REACTION RATE, BRANCH LEDGER AND POWER SCALING

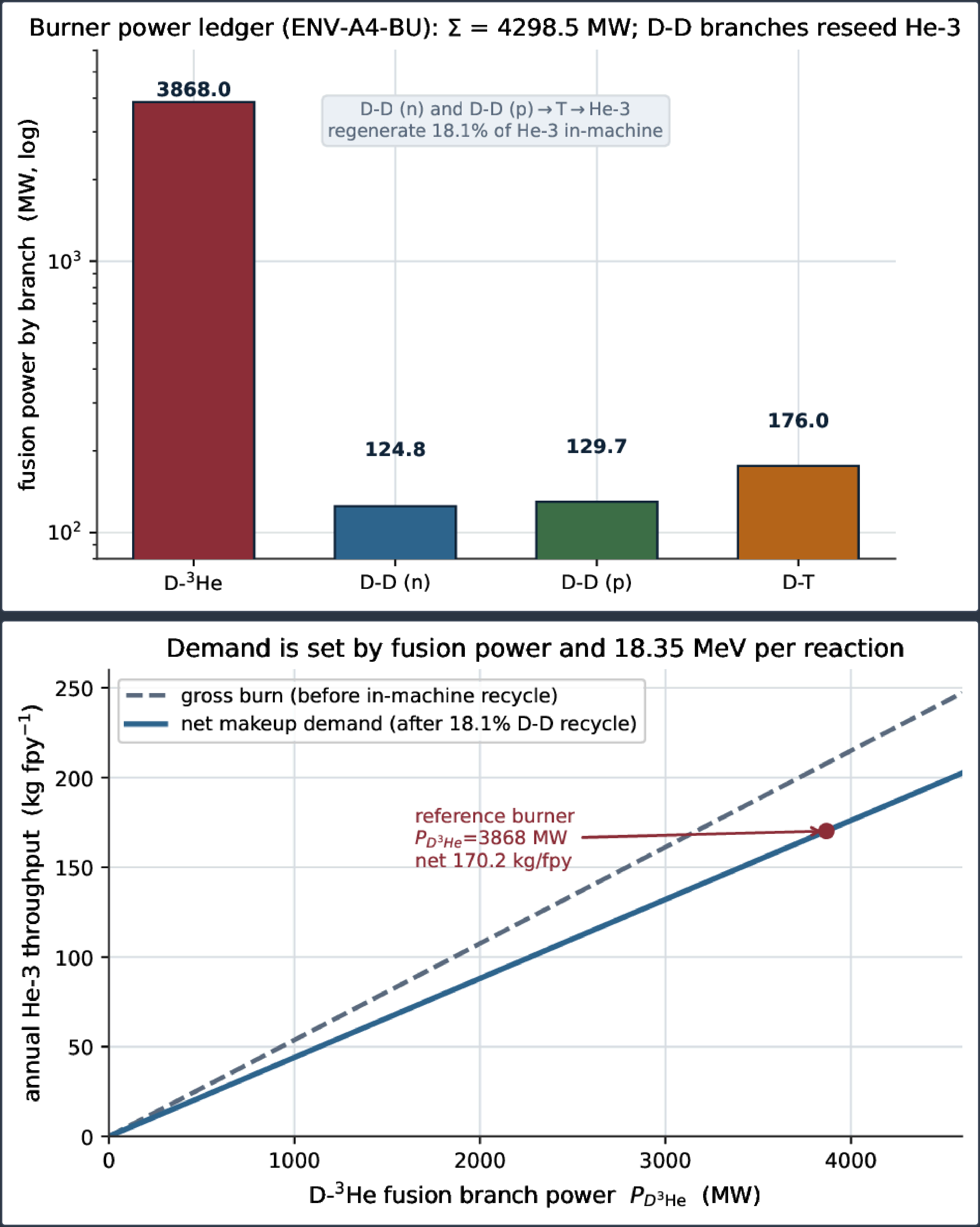
Figure 4 shows the Bosch–Hale reactivities of equation (4) that set the burn and reseed rates: the D–^{3}He channel and the two D–D branches over $1–190\,keV$. Table 1 and figure 5 give the burner power ledger: the D–^{3}He branch carries $3868\,MW$, the D–D neutron and proton branches 124.8 and $129.7\,MW$, and the bred-tritium D–T channel $176.0\,MW$, summing exactly to $P_{\rm fus} = 4298.5\,MW$; the D–D branches are the physical origin of the 18.1% in-machine reseed. Figure 5 shows the resulting linear scaling of gross and net ^{3}He demand with D–^{3}He branch power, with the reference burner marked at $(3868\,MW, 170.2\,kg/fpy)$.



Maxwellian reactivities from the Bosch–Hale parameterisation [2] (equation 4): D(^{3}He,p)^{4}He, D–D total, and the D(d,n)^{3}He branch. These rates set the burner ^{3}He consumption and the in-machine reseed.

REACTION BRANCH	POWER (MW)	ROLE IN THE ^{3}HE BALANCE
D–^{3}He (main)	3868.0	consumes ^{3}He; sets $\dot{N}^{\rm burn}_{^3\rm He}$
D–D → ^{3}He+n	124.8	reseeds ^{3}He directly
D–D →T+p	129.7	reseeds ^{3}He via T decay
D–T (bred T)	176.0	neutron budget; sets $f_n = 5.44\%$
total $P_{\rm fus}$	4298.5	—

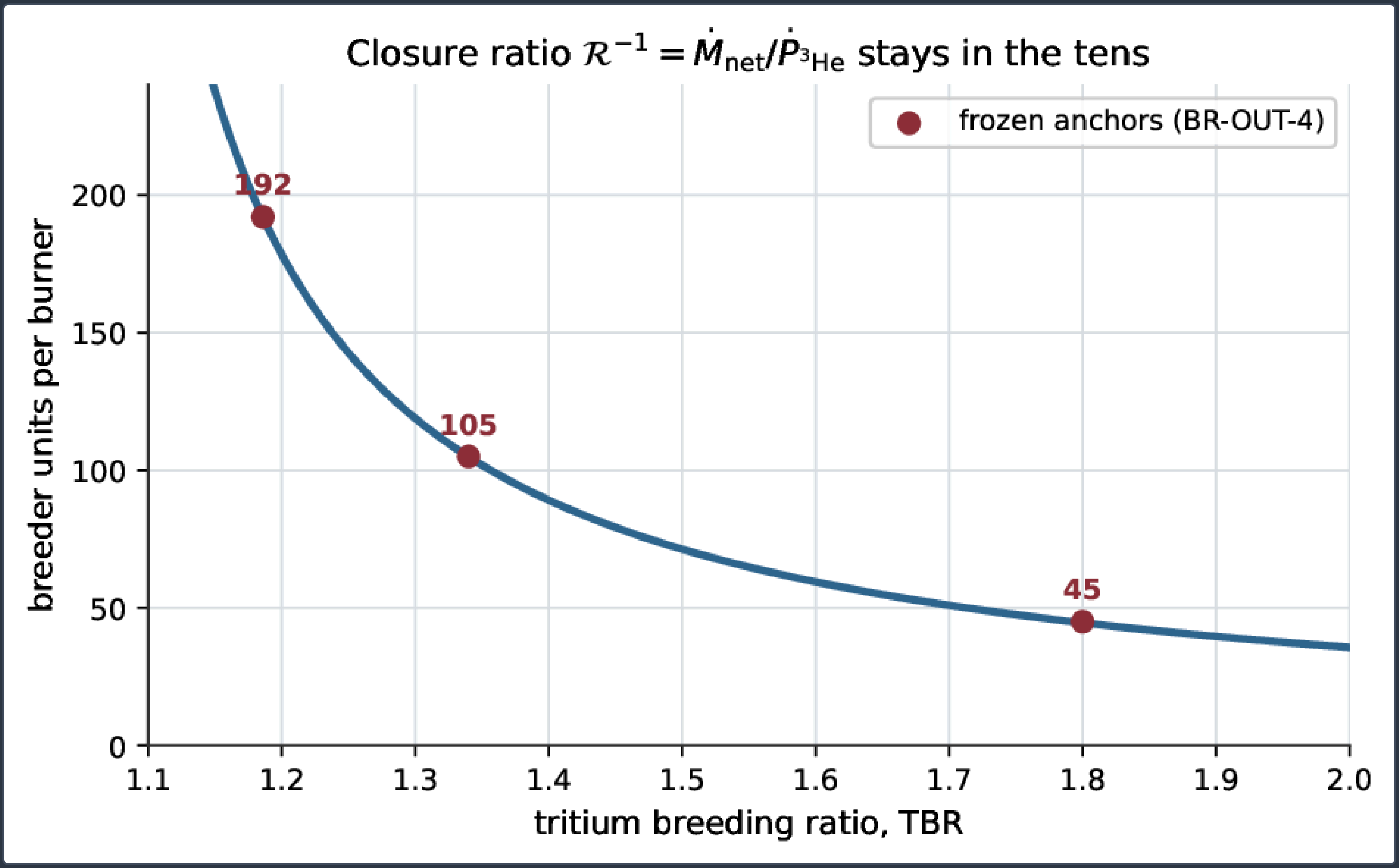
Burner fusion-power ledger by reaction branch (serial ENV-A4-BU). The branches sum exactly to the total fusion power; the D–D channels reseed ^{3}He in-machine.



Burner power by reaction branch (table 1); log axis. The D–D branches supply the 18.1% in-machine ^{3}He reseed of equation (8).

THE CLOSURE CURVE AND THE FUEL-CYCLE SUMMARY

Figure 6 and table 2 collect the balance. The continuous curve confirms that the fleet ratio $\mathcal{N}_{\mathrm{b/b}}$ stays in the tens across the admissible TBR band; the table lists supply, demand, closure ratio, charging time and standing inventory at each anchor.



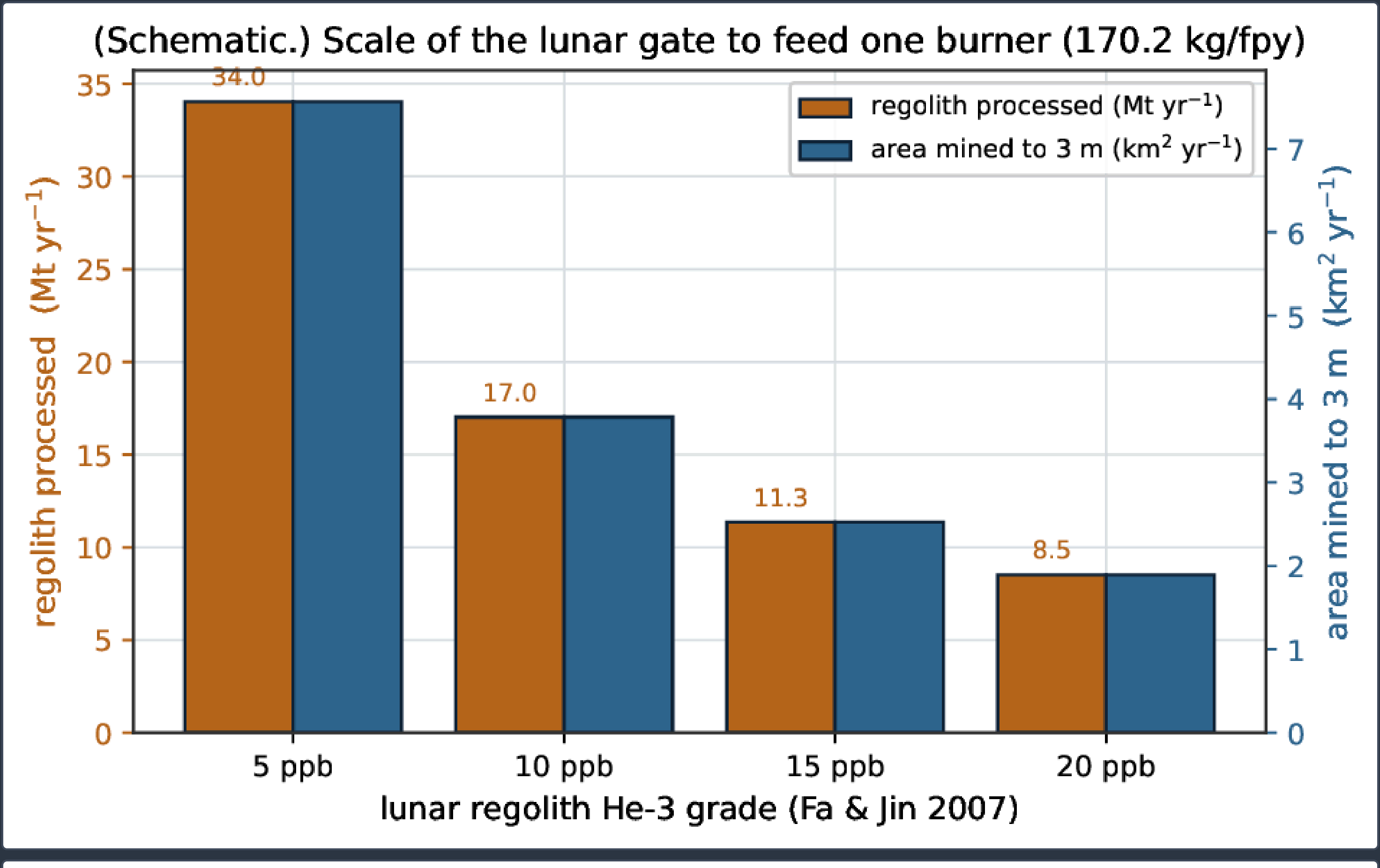
Closure ratio as a continuous function of TBR (line) with the frozen BR-OUT-4 anchors overlaid (markers). The number of breeders per burner remains in the tens across the whole admissible breeding-ratio band.

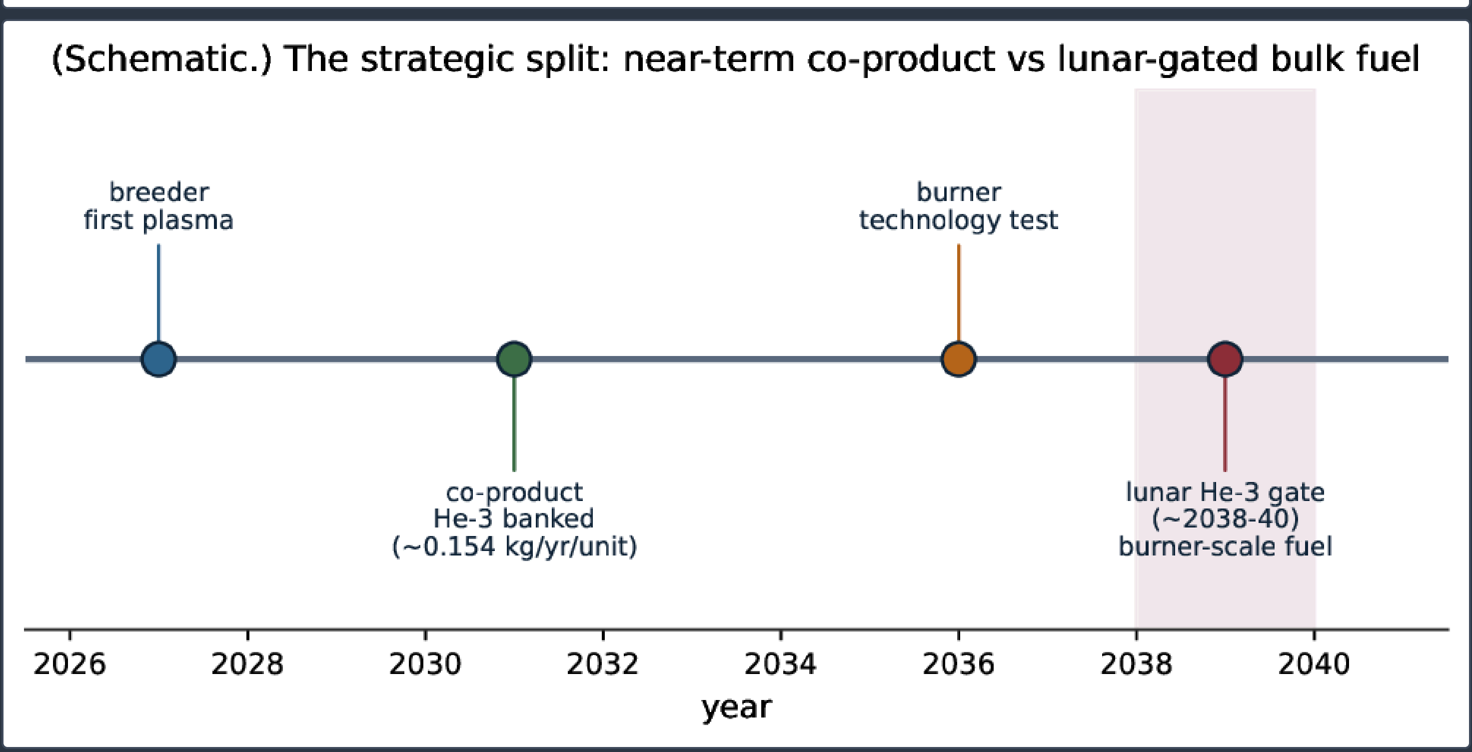
TBR	SUPPLY $\dot{P}^*_{^3\mathrm{He}}$ (KG/YR)	BREEDERS/BURNER	t_{90} (YR)	N^*_T (KG)
1.186	0.89	192	40.9	15.8
1.34	1.62	105	40.9	28.8
1.80	3.82	45	40.9	67.9

Fuel-cycle closure summary across the TBR lever. Supply is the equilibrium decay rate $\dot{P}^*_{^3\mathrm{He}} = \dot{S}_T$; t_{90} from equation (12); N^*_T from equation (13). Net burner demand fixed at $§I170.2

THE SCALE OF THE LUNAR GATE

If burner-scale ^{3}He cannot come from decay, it must come from where the resource actually sits: the lunar regolith. Figure 7 sizes that alternative for one burner-year at the measured regolith grade of **10–20** weight-ppb [7,8]. To extract **170.2** kg of ^{3}He at a representative **15 ppb** requires processing ~**11.3** million tonnes of regolith and mining ~**2.5 km^2** to a depth of **3** m per burner-year. This is presented as a schematic estimate from cited concentrations, not as a Kronos result; its purpose is to show that the lunar route is an industrial undertaking on a timescale (figure 7) consistent with the program's stated ~2038–40 gate, and that it, too, is not a near-term fuel base.





(Schematic.) Regolith throughput and mined area to source one burner's ^{3}He, versus regolith grade (measured range 10–20 ppb [7,8]). Estimate from cited concentrations, not a Kronos result.

§ 5

Discussion

AGAINST THE TERRESTRIAL SUPPLY BENCHMARK

The result is best appreciated against the real terrestrial supply. The United States national ^{3}He supply is $1–2\,kg/yr$, produced entirely as a decay by-product of legacy weapons tritium, and it is already oversubscribed by neutron-detection, cryogenic and medical demand [13,12]. A single reference burner would consume $170.2\,kg/fpy$ — roughly a hundred times the entire national annual supply. Our breeder does better than the legacy stock per unit only in that it *deliberately* breeds surplus tritium; but even banking all of that surplus and waiting four decades (figure 3) yields at most $3.82\,kg/yr$ per unit. The terrestrial benchmark therefore confirms rather than contradicts the balance: there is no indigenous ^{3}He at burner scale, decay-sourced or otherwise, and the literature that has tracked the tritium and ^{3}He supply chains reaches the same structural conclusion [12,11,10].

AGAINST THE LUNAR RESOURCE BENCHMARK

The lunar resource is the only known reservoir at the right scale. Wittenberg, Santarius and Kulcinski estimated a whole-Moon inventory of order 10^{9} kg [5,6], and orbital/sample analyses confirm a low but real regolith grade [7,8]. Our schematic sizing (figure 7) shows why this is a resource but not a near-term fuel: the $\sim 2.5\ \mathrm{km}^2$-per-burner-year mining footprint at 15 ppb is an industrial-scale extraterrestrial operation, consistent with the program's late-2030s gate but not before it. The comparison sharpens the paper's thesis: the burner's fuel problem is a *logistics and timing* problem gated on lunar ^{3}He, categorically different from the breeder's *co-production* of ^{3}He as a by-product of its tritium inventory.

ALTERNATIVES AND WHY THEY DO NOT RESCUE INDIGENOUS CLOSURE

Three levers might be proposed to close the loop terrestrially, and the balance disposes of each. *Raise the TBR:* already exercised in figure 1; even $\mathrm{TBR} = 1.80$ leaves $45:1$. *Raise the in-machine reseed:* the 18.1% D–D reseed is set by the reaction-rate physics of figure 4 at the Q_E-optimal operating point, and pushing the D–D fraction higher trades away Q_E and raises f_n (a catalyzed-D–D operating point roughly doubles the neutron fraction for no gain benefit; serial AG-CX-14), so it degrades exactly the properties that motivate the burner. *Wait for the reservoir to charge:* the four-decade t_{90} of equation (12) is longer than the plant's own commissioning horizon. None of these is a path to indigenous closure; all are consistent with the conclusion that burner-scale ^{3}He is lunar-gated.

THE STRATEGIC CO-PRODUCT, KEPT DISTINCT FROM BULK FUEL

The correct reading of the breeder's ^{3}He is as a strategic co-product, not a fuel supply for the burner. Per unit, the breeder harvests $\sim 0.154\,kg/yr$ of ^{3}He in-vessel (of which $\sim 41\,g$ from the D–D branch and $\sim 113\,g$ from in-vessel tritium decay; serial BR-CX-16), a co-product at roughly a few percent of the world's annual supply and of genuine value in national-security, cryogenic and quantum-sensing applications. That value is real and it is strategic; it is emphatically *not* a bulk fuel stream for the burner, and it is *not* revenue. Conflating the strategic co-product (kilogram-per-year-per-unit and below) with the burner's bulk fuel demand (hundreds of kilograms per full-power year) is precisely the error the balance rules out. The two live in different regimes and are governed by different physics: the co-product by the breeder's standing tritium inventory and in-vessel harvest, the bulk fuel by the lunar resource and its extraction logistics.

§ 6

Limitations

The load-bearing caveat is the lunar-supply timeline. The ∼2038–40 gate on burner-scale ^{3}He is a program assumption drawn from the lunar-resource literature and mission planning [5,7], not a result of the balance presented here; the balance establishes only that no *indigenous, terrestrial* route closes the loop, leaving the lunar route as the residual supply and its schedule as an external input. Secondarily, the supply figures are equilibrium estimates tied to the standing surplus-tritium rate and the extraction schedule, and the demand figure depends on the reference burner operating point and its D–D recycle fraction; both are reported across the TBR lever rather than at a single point, and both trace to frozen anchors. None of these caveats affects the sign or the order of magnitude of the closure ratio, which is set by the two-order-of-magnitude gap between supply and demand.

§ 7

Conclusion

By a first-principles mass balance, the deuterium–helium-3 fuel loop does not close indigenously. One breeder unit supplies, at decay equilibrium, $0.89–3.82\,kg/yr$ of ^{3}He (equal to its surplus-tritium rate), against a reference burner demand of $170.2\,kg/fpy$ net — a closure ratio of $192/105/45$ breeders per burner across $\mathrm{TBR} = 1.186/1.34/1.80$. The obstruction is physical, not engineering: the 12.32-yr tritium half-life makes the decay reservoir take $40.9\,yr$ to reach 90% of equilibrium and demands a standing bank of $15.8–67.9\,kg$ of tritium per unit, while the burner's demand is a hundred times the entire United States national supply. Burner-scale ^{3}He is therefore lunar-gated (∼2038–40); the breeder's ^{3}He is a strategic co-product of real value at the $\sim 0.15\,kg/yr$-per-unit in-vessel scale, not fleet fuel. The distinction is load-bearing and is carried openly: strategic value is not revenue, and decay-sourced supply is not bulk fuel.

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 for the compute that produced the numerics.

Reproducibility. Every headline quantity is a frozen anchor in the Kronos Physics De-Risking Register [26] (doi:10.5281/zenodo.22133057): the closed-fuel-loop closure ratios and net demand (BR-OUT-4), the domestic ^{3}He flow and reseed fraction (BR-OUT-2), the surplus-tritium ladder (BR-OUT-1), the in-vessel co-product (BR-CX-16), and the burner branch ledger (ENV-A4-BU). Each is regenerable from the deposited figure-generation script and the archived solver inputs. This paper is archived at doi:10.5281/zenodo.22645734; official version: https://www.kronosfusionenergy.com/publications/helium-3-fuel-cycle.html and its official version is hosted at https://www.kronosfusionenergy.com/publications/helium-3-fuel-cycle.html.

Data availability tocsectionData availability The fuel-cycle balance, its inputs, and the figure-generation script are archived with the deposit for this paper (doi:10.5281/zenodo.22645734) and cross-reference the Kronos 2026 series, including the breeder platform (doi:10.5281/zenodo.22645691), the advanced-fuel scorecard (doi:10.5281/zenodo.22645766), the tritium breeding ladder (doi:10.5281/zenodo.22645746), the fleet TBR/tritium-export analysis (doi:10.5281/zenodo.22645706), the medical-isotope and ^{3}He co-production mission (doi:10.5281/zenodo.22645762), the integrated-platform helium-3 flywheel (doi:10.5281/zenodo.22645764), and direct energy conversion (doi:10.5281/zenodo.22645700). Any economic analysis is reported separately and is not part of the public deposit.

Competing interests tocsectionCompeting interests Provisional patent applications relating to aspects of this work have been filed.

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.

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Founding partners, board, advisors & auditors

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FOUNDING PARTNERS — SCIENCE

Dr. Gerald Kulcinski
Co-Founder · Helium-3 & Advanced-Fuel Fusion
UW–Madison · 2023–Present

Dr. Carl Weggel
Chief Scientist / S.M.A.R.T. Design
MIT Alcator Program · 2022–Present

Dr. Robert J. Weggel
Magnetic Field Design
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Bandel Carano
Finance / Strategy
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Patrick Schweiger
Fusion Device Engineering
Oklo / CFS / TerraPower · 2025–Present

SCIENTIFIC ADVISORS

Dr. Steven O. Dean
Fusion Policy & History
DOE / Fusion Power Associates · 2025–Present

Dr. Patrick H. Diamond
Plasma Turbulence & Transport
UC San Diego · 2025–Present

Dr. Jack J. Dongarra
HPC & Numerical Algorithms
Turing Award · 2025–Present

Dr. Nasr M. Ghoniem
Chief Material Scientist
UCLA · 2025–Present

Dr. Siegfried Glenzer
Plasma Physics & Laser Fusion
Stanford / SLAC · 2022–Present

Dr. David A. Hammer
Pulsed-Power Fusion
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Dr. Donald A. Spong
Plasma Theory & Confinement
ORNL · 2025–Present

Dr. Curtis Smith
Risk Assessment & Nuclear PRA
MIT / Idaho National Lab · 2025–Present

RADM (Ret.) David Goggins
Naval Engineering & Power-Plant Design
U.S. Navy · 2023–2026

Dr. Konstantin Batygin
Mathematician
Caltech · 2022–2025

Dr. Ruben Fair
Magnet Design / ITER Liaison
PPPL / Jefferson Lab · 2022–2025

Dr. Paul S. Weiss
Materials & Nanotechnology
UCLA · 2022–2025

SCIENTIFIC AUDITORS

Dr. Wilfred A. Cooper
Plasma Equilibrium Theory
EPFL / Swiss Plasma Center · 2025–Present

Dr. Ahmed Hassanein
Plasma–Material Interactions
Purdue / Argonne · 2025–Present

Dr. Patrick E. Hopkins
Extreme Thermal Materials
U. of Virginia · 2025–Present

Dr. Peter Hosemann
Materials Joining & Structural Integrity
UC Berkeley · 2025–Present

Dr. Travis W. Knight
Advanced Nuclear Fuels & Systems
U. of South Carolina · 2025–Present

Dr. Philippe Lebrun
Cryogenics & Magnet Cooling
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Dr. Nitendra Singh
Nuclear Safety & Fuel Cycle
ITER · 2025–Present

Dr. Guido Van Oost
Magnetic Confinement & Fusion Systems
Ghent University · 2025–Present

Dr. Gary S. Was
Radiation Materials & Structural Integrity
U. of Michigan · 2025–Present

Dr. Ray Sedwick
Direct Energy Conversion
U. of Maryland · 2025

OPERATIONS

Michael Laughlin
Chief Operating Officer
2022–Present

Martin Owens
Chief Strategy Officer
LANL / GE Hitachi · 2022–Present

MG (Ret.) Paul Pardew
Chief Contracting Officer
Army Contracting Command · 2022–Present

David Beck
Fusion Commercialization
U.S. Space Force · 2024–Present

Sushma Bhatia
Environmental & Legislative
Google · 2022–Present

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Technology Licensing
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MG (Ret.) Robin L. Fontes
Cybersecurity & Defense
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Jon Michel Greenwood
IT & AI Infrastructure
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Brian C. O'Neill
National Security
CIA / ODNI · 2022–Present

Gen. (Ret.) Gustave F. Perna
DoD Liaison
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Marketing Lead
2022–Present

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