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REAL-TIME HEALTH MONITORING FOR RELIABLE SATELLITE DISPOSAL

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The disposal readiness gap

A frozen baseline meets a more crowded sky

DECISIONS

End-of-life calls rely on **R**eliability **A**vailability **M**aintainability **S**afety (RAMS) models built on assumptions made during the CDR phase, years before the actual decommissioning.

WINDOW IS CLOSING

Zero Debris charter (signed May 2024), ISO 24113:2023, and the proposed EU space Act are tightening compliance expectations.

Disposal readiness needs to be auditable, not declared at CDR

NEW SPACE

~14,000 active payloads in orbit today, with launch cadence at record levels (ESA SER 2026).

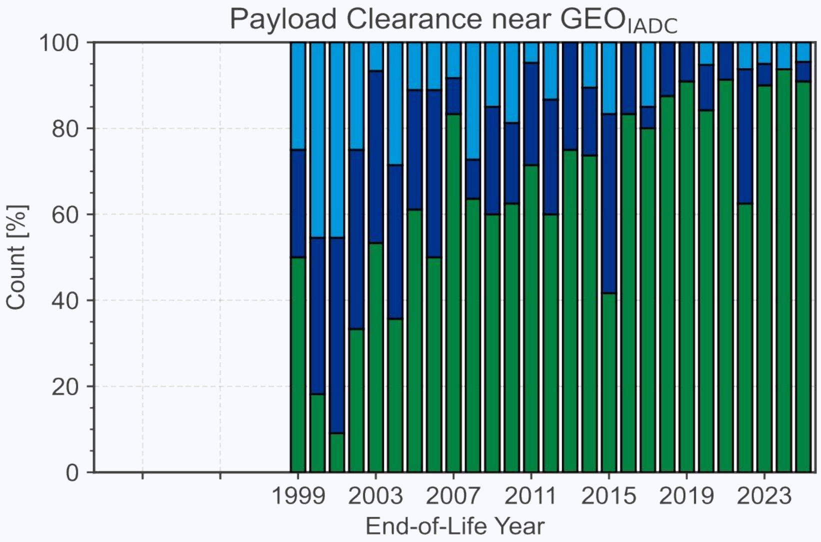
Disposal compliance has to scale with operators that have smaller ground RAMS teams.

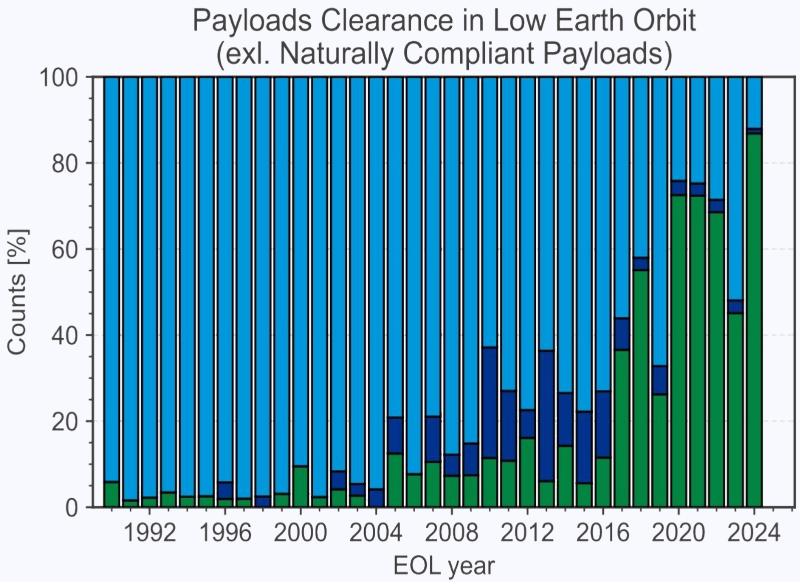
Disposal is treated as a deterministic outcome of a probabilistic process.

State of the art

Disposal compliance varies from 5% to 90% over the last 25 years.

- No attempt - Insufficient attempt - Successful attempt





Credit: ESA

The standards say what to do; very few tools say how to do it operationally. !

The gap is in the standard, not outside it

ESA RAMS already defines telemetry driven and prognostic disposal-readiness. Industry hasn’t moved.

ESA RAMS methodology (TN1-TN4, 2021)

Approach 0
CDR-frozen reliability model. Reassessed only on failure.

Approach 1
Failure occurred: updating RBD in case of failure, constant failure rates updated with real duty cycles and and redundancy schemes

Approach 2
Health-monitoring driven. Stress-aware lambda from telemetry. Continuous reassessment.

Approach 3
Prognostic. Forecast residual life and disposal-readiness over mission.

Credit: Thales Alenia Space, "Validated Reliability-Based Models for End of Life Operations", 2021.

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Prognostic. Forecast residual life and disposal-readiness over mission.

Thermal stress (primarily), redundancy schemes and actual duty cycles, with initial steps into prognostics.

Credit: Thales Alenia Space, "Validated Reliability-Based Models for End of Life Operations", 2021.

Our approach

What we replace the binary call with

A telemetry-driven reliability signal: an input for impact metrics

An operator sees **R(t) and its tier crossings every week**.

R(t) is a telemetry-grounded proxy for the post-mission disposal (PMD) success probability: CRITICAL ($R < 0.90$) marks the crossing of the ISO 24113 disposal-success threshold.

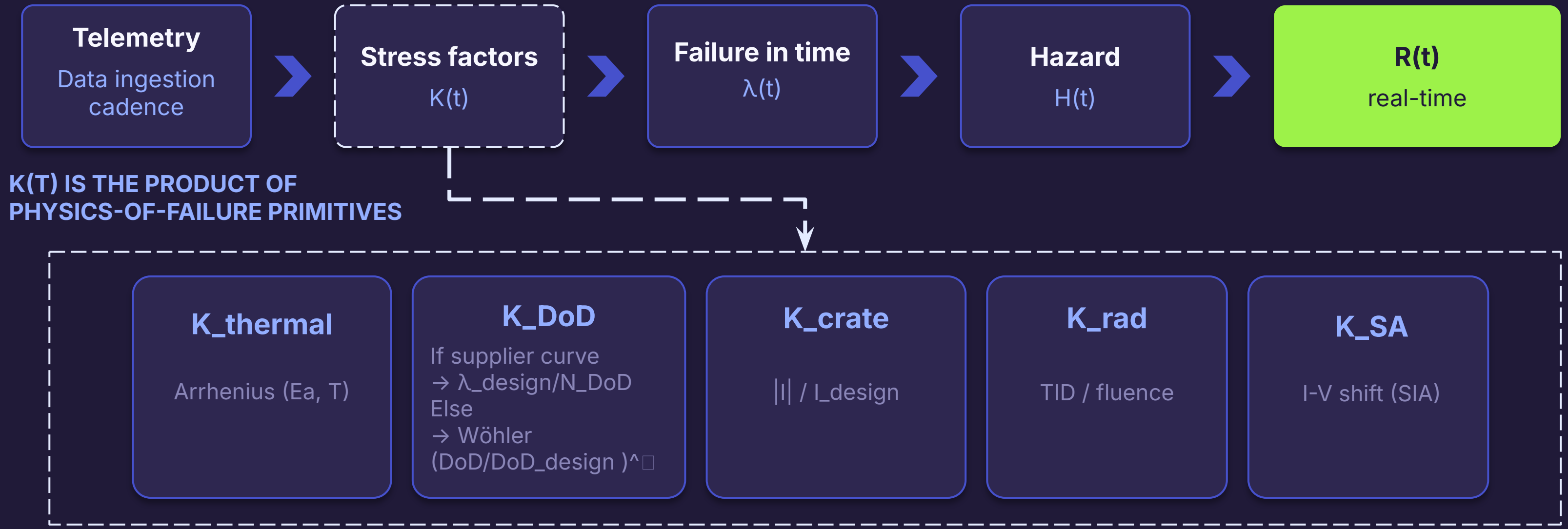
R(t) tiers

- **NOMINAL** $R \geq 0.99$
- **WARNING** $R < 0.99$
- **DEGRADED** $R < 0.95$
- **CRITICAL** $R < 0.90$

CRITICAL maps to the ECSS EoL disposal threshold.

Reliability Block Diagram

Telemetry-driven instantaneous failure rate, continuously re-assessed reliability

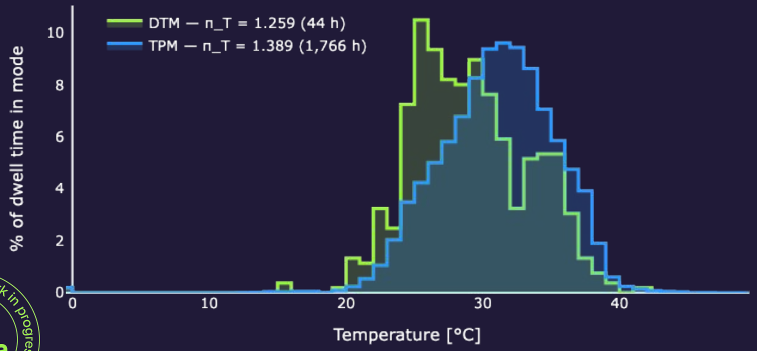


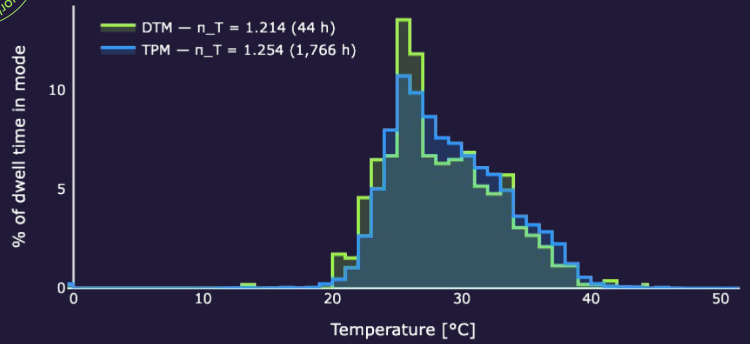
R(t) recomputed every bin. Redundancy via β-CCF (hot) or cold-standby per subsystem.

ECSS-Q-ST-30-09C, ECSS-E-ST-20-08C, FIDES.

Operational mode-aware temperature aggregation

Per-mode dwell-weighted Arrhenius integral feeds λ_eff.
Example: battery pack 1(top) & pack 2 (down), 7-day window.





ADCS MODES

DTM: Detumbling → post-separation rate damping
TPM: Target Pointing Mode → Dwell-dominant

π_T = thermal life adjustment factor
π_T > 1 → faster aging

Dwell-weighted Arrhenius per mode (h):

$$\pi\_T = \sum_i \frac{h_i}{\sum_j h_j} \times \exp\left(\frac{E_a}{k_B}\left(\frac{1}{T_{ref}} - \frac{1}{T_i}\right)\right)$$

E_a = 0.4 eV and T_ref = 25 °C

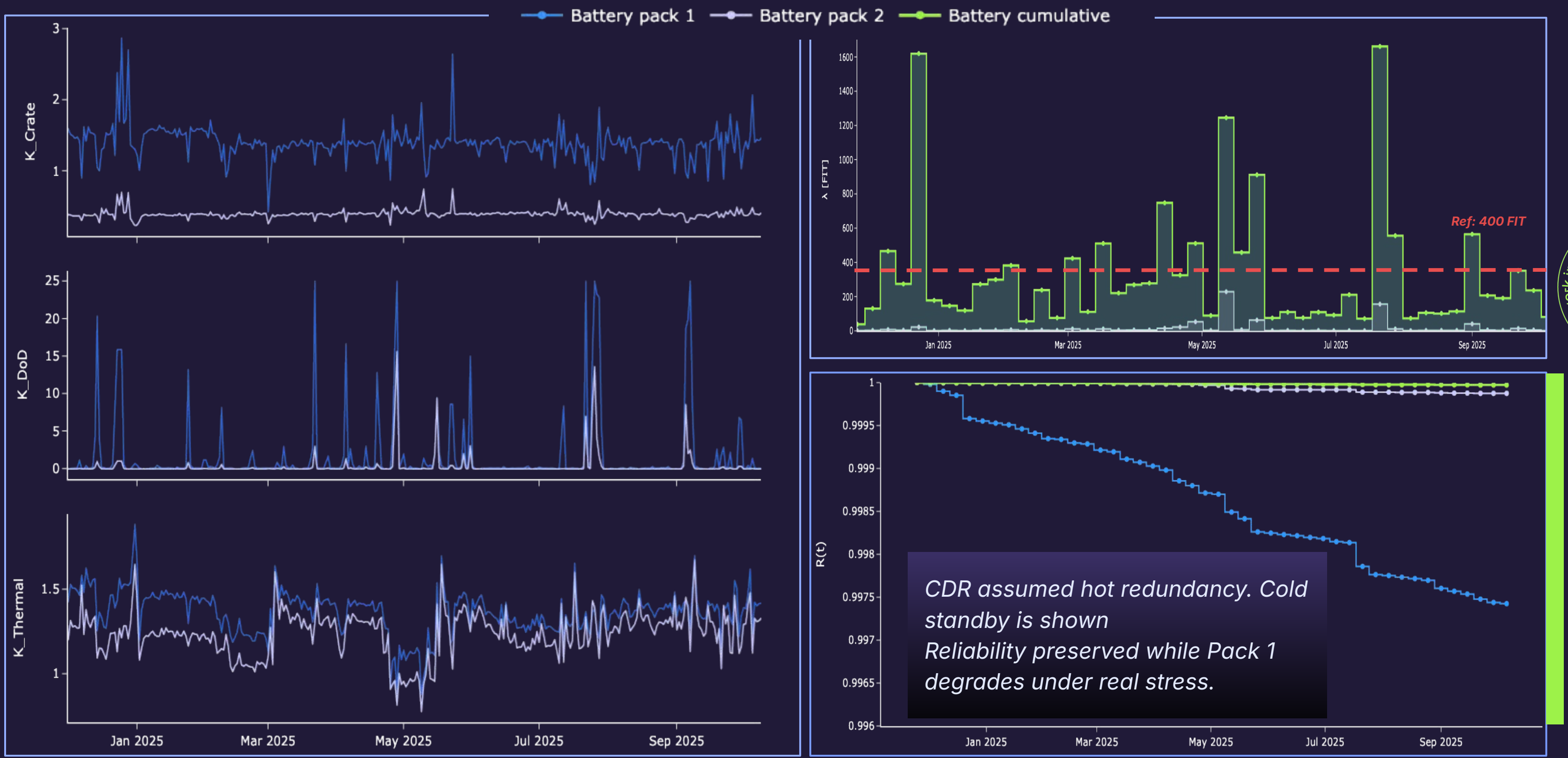
TPM causes 97% of the aging (NOMINAL)

Two battery packs, two thermal profiles, SAME operational schedule
→ RBD catches differences in λ

Preliminary results

An example | Instantaneous failure rate, cumulative aging

Weekly bins, stress-modulated FIT. Observed fluctuation tracks orbital DoD, thermal cycling and C-rate



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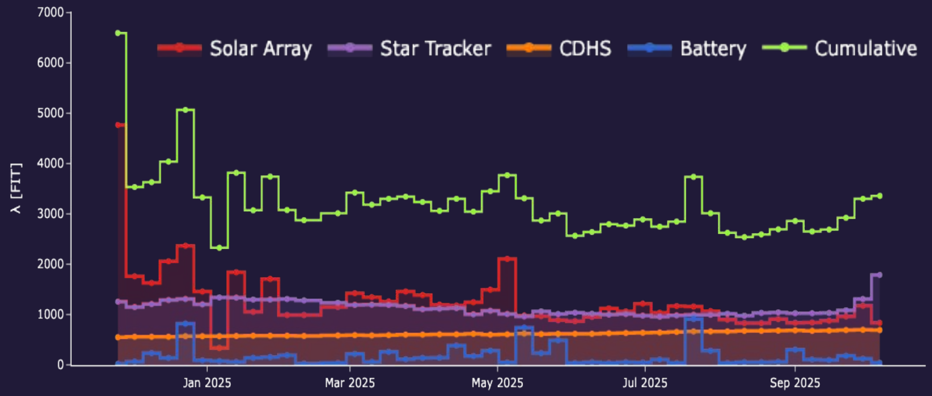
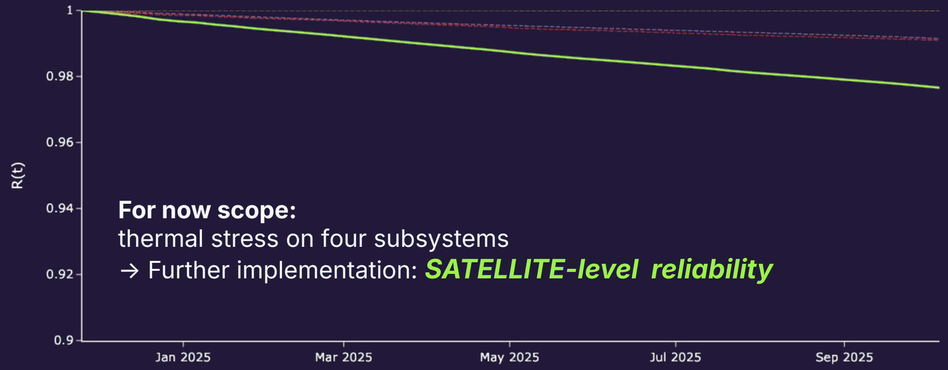


$$\lambda_{sat}(t) = \sum_i \lambda_i(t),\ H_{sat} = \int_0^t \lambda_{sat}\, d\tau,\ R_{sat}(t) = e^{-H_{sat}(t)} = \prod_i R_i(t)$$

Cumulative degradation

Same λ chain per subsystem telemetry-derived K-factors. Cumulative trace is the system λ, R(t) divergence is intended.



For now scope:
thermal stress on four subsystems
→ Further implementation: ***SATELLITE-level reliability***

NOMINAL
WARNING
DEGRADED
CRITICAL

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Reliability Block Diagram: monitor + forecaster

Per-K-factors-n-year-forecast with min/max envelope feeds R(t) projection

Telemetry Data ingestion cadence → **Stress factors** K(t) → **Failure in time** λ(t) → **Hazard** H(t) → **R(t)** Real-time

ESA approach 3-like

*CREDIT:
Giulia De Innocentiis*

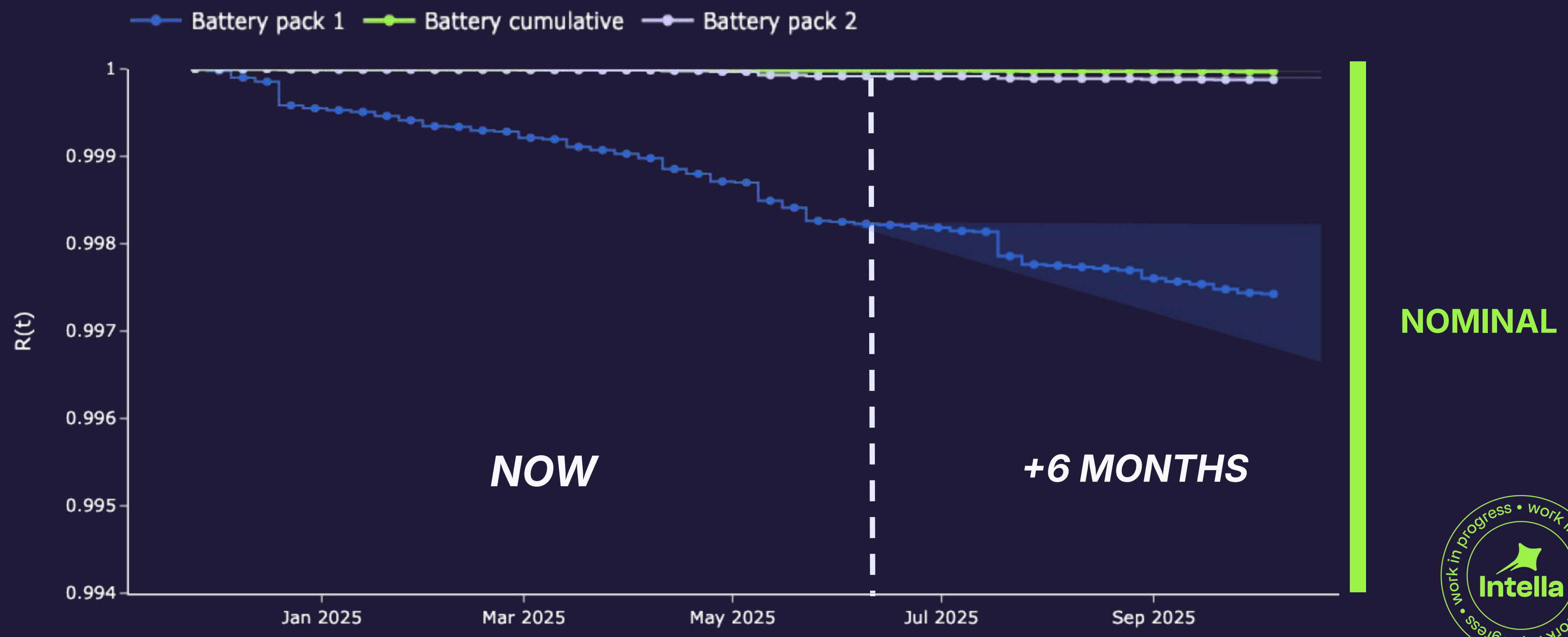
LTA K(t) forecast → **Failure rate** λ(t) forecast → **Hazard** H(t) forecast → **R(t)** Forecast

End of Life window

The chain K → lambda is the same in both tracks. Only the input changes: telemetry derived for today, LTA- projected for forecast

From past stress to future disposal-readiness

1-year R(t) projection with telemetry-driven uncertainty band. Asymmetric envelope: R(t) can only decay



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Highlights: two decisions, one engine

Operations today, strategic tomorrow

TODAY

Telemetry-grounded reliability

Per-subsystem λ(t) and R(t), reassessed from telemetry every time is requested.

Operators see tier crossings before disposal window closes.

Anticipate or delay decommissioning with evidence instead of CDR-frozen assumptions.

TOMORROW

From reliability to disposal capability

ΔV budget tracked alongside R(t): deterministic propellant computation &, probabilistic forecast next.

Fleet-level diagnostics to identify common failure modes across assets and separate root causes (design, manufacturing, operations) that better design can prevent.

Thank you!

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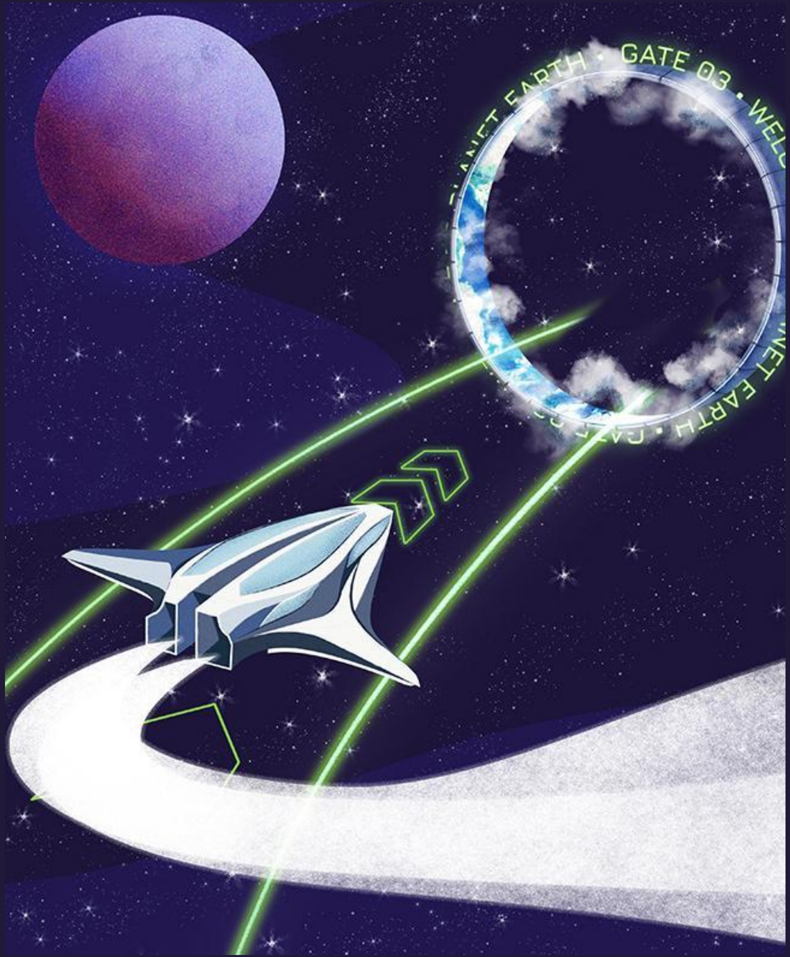

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