The Thermodynamics of Permanence

Open Systems, Propellantless Propulsion, and the Physics of Persistence

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Strange Loops LLC · March 2026

Every system that carries its own fuel is a countdown. The Tsiolkovsky rocket equation makes the mathematics explicit: the velocity change a spacecraft can achieve depends on the logarithm of its mass ratio — the proportion of its total mass that is propellant. Doubling the desired velocity change does not require twice the fuel; it requires the fuel mass to increase exponentially. A chemical rocket achieving a velocity change equal to its exhaust velocity needs to be 63 percent propellant by mass. Achieving twice that velocity change requires 86 percent. Three times: 95 percent. The payload shrinks toward zero as the ambition grows. This is not an engineering limitation. It is a thermodynamic boundary condition. A system that carries its own energy store is a closed system with respect to the resource it consumes, and a closed system's lifetime is bounded by the second law.

Ilya Prigogine's Nobel Prize-winning work established the alternative. Thermodynamically open systems operating far from equilibrium maintain order through continuous entropy export: they take in energy and matter from their environment, perform work, and export disorder. The total entropy of the system can decrease locally — order can increase — as long as the entropy exported exceeds the entropy generated internally. Prigogine called these "dissipative structures": systems that persist not despite thermodynamic law but through it, by maintaining the flow of energy and matter that keeps them far from the equilibrium that would be their death. Erwin Schrödinger anticipated the insight in 1944: organisms maintain order by continually drawing orderliness from their environment — consuming Gibbs free energy and exporting entropy as waste heat. Life is the paradigmatic open system.

This essay applies Prigogine's framework to two domains simultaneously: biological aging and orbital infrastructure. The argument is that the same thermodynamic principle governs persistence at both scales, that the technologies emerging in both domains converge on the same solution — restoring thermodynamic openness to systems sliding toward equilibrium — and that the Immortal Systems Architecture framework provides the vocabulary for this convergence.

Aging as thermodynamic closure

The Toussaint-Remacle model of cellular aging, published across a series of papers from 1991 to 2002, applies Prigogine’s framework directly to the cell. Their central finding: cells transition through defined morphological types — seven identified in human fibroblasts — each representing a distinct thermodynamic steady state with lower entropy production and higher internal error levels than the last. External stresses accelerate transitions between morphotypes, confirming that fluctuations speed the approach to equilibrium. Senescent cells represent the terminal state: a system that has lost the ability to maintain its far-from-equilibrium dissipative condition. They persist briefly in a near-equilibrium twilight, consuming resources and emitting inflammatory waste, before the system reaches true equilibrium — cell death or, in the absence of apoptotic clearance, indefinite toxic persistence.

Leonard Hayflick argued in 2007 that entropy explains aging — that aging is stochastic thermodynamic degradation of biomolecular structure. More recent work has made this quantitative. Pyrkov and colleagues developed a thermodynamic biological age metric tracking entropy produced and information lost, demonstrating that this thermodynamic measure increases with chronological age, reduces resilience, and drives exponential acceleration of disease and death risk. The parallel to material science is direct: Khonsari and Bryant showed that all damage mechanisms in engineered materials — fatigue, corrosion, wear — share a common feature of energy dissipation quantified by entropy generation, with failure occurring at a constant fracture fatigue entropy independent of loading conditions.

The implication is precise. A senescent cell is not merely a biological inconvenience. It is a region of the organism that has transitioned from the far-from-equilibrium state that constitutes life to the near-equilibrium state that constitutes decay. The SASP it emits is the thermodynamic consequence of this transition: disordered molecular signals that drive neighboring cells toward the same equilibrium. Senolytic therapy — whether through FOXO4-DRI’s disruption of the FOXO4-p53 interaction, dasatinib-plus-quercetin’s inhibition of anti-apoptotic pathways, or the newer ES2 peptide series — works by removing the regions of thermodynamic closure, allowing the remaining tissue to maintain its dissipative state. Mitochondrial repair through elamipretide works by restoring the organelle’s capacity to process energy gradients efficiently — directly restoring the cell’s ability to maintain itself far from equilibrium. The peptide protocol described in the companion research report is, read through Prigogine’s lens, a program for restoring thermodynamic openness at the cellular scale.

The Tsiolkovsky trap: orbital infrastructure as closed system

A satellite carrying chemical propellant obeys the same thermodynamic logic as a senescent cell, inverted in time. The cell starts open and closes as it ages; the satellite starts with a finite store and depletes it. But the end state is identical: a system that has lost the capacity to maintain itself against perturbation. When a satellite exhausts its propellant, it becomes debris — persisting in orbit but unable to maneuver, avoid collisions, or maintain its assigned position. It is a senescent object: consuming space, generating collision risk through close approaches, and emitting the orbital equivalent of SASP — fragment clouds from micrometeorite impacts that degrade the environment for functional neighbors.

The ESA Space Environment Report 2025 documents the condition. Over 40,000 tracked objects now orbit Earth, with an estimated 1.2 million debris fragments larger than one centimeter and 130 million larger than one millimeter. At 550 kilometers — Starlink's primary operational altitude — debris density now equals active satellite density. ESA states unequivocally that even without any additional launches, the number of space debris objects would continue to grow autonomously. This is the Kessler Syndrome threshold: the point at which collision-generated fragments produce more new fragments than atmospheric drag removes, and the orbital environment transitions irreversibly from order to disorder. It is the heat death of orbital space — the thermodynamic equilibrium that Prigogine's framework predicts for any system that loses its energy throughput.

SpaceX's January 2026 FCC filing for one million solar-powered orbital data center satellites operating between 500 and 2,000 kilometers makes the Kessler math acute. The company's existing Starlink fleet of over 8,000 satellites performed nearly 150,000 collision-avoidance maneuvers in a six-month window in late 2025. An eightfold increase in the number of active objects produces a 64-fold increase in close-approach frequency. A single fragmentation event from a defunct satellite or rocket body creates a debris cloud transiting multiple orbital shells. The CRASH Clock — a metric of the interval between predicted catastrophic collisions — has contracted from over 120 days to approximately 5.5 days. A 24-hour loss of maneuverability now carries a 30 percent probability of catastrophic collision. Every satellite that exhausts its propellant and becomes a passive object accelerates this convergence. The architecture of managed oblivion has an orbital analogue: the assumption that finite resources can sustain infinite infrastructure.

Propellantless propulsion as thermodynamic openness

The solution is the same at the orbital scale as at the cellular: restore coupling to environmental energy gradients. Three technology families accomplish this.

The magnetic sail generates a miniature magnetosphere that deflects the solar wind — a plasma of protons and electrons flowing outward from the sun at 200 to 600 kilometers per second. The momentum exchange between the high-velocity ions and the magnetic field produces thrust on the spacecraft without consuming any onboard propellant. The Mini-Magnetospheric Plasma Propulsion system injects a small amount of plasma into a modest magnetic field, inflating the effective magnetospheric radius to kilometers. The force scales with the dynamic pressure of the solar wind and the area of the magnetic bubble. Kinetic simulations have revised the original MHD estimates downward, showing 1/r-squared rather than 1/r field falloff near the source, but the principle remains sound: a spacecraft with a sufficiently strong magnetic field source can extract momentum from a plasma stream that will persist for the remaining lifetime of the sun.

Air-breathing electric propulsion converts the very medium that threatens low-orbit satellites — residual atmospheric gases — into propellant. An electromagnetic intake funnels ambient oxygen and nitrogen ions into an electrodeless thruster powered by solar panels. The ESA DISCOVERER project demonstrated the concept with the SOAR CubeSat mission and developed cathode-less inductive plasma thrusters resistant to atomic oxygen erosion. Gridded ion thrusters with titanium optics achieved stable operation projections exceeding 60,000 hours. DARPA's Otter program, with its $44 million Phase 2 contract to Redwire, targets in-orbit ABEP demonstration lasting over one year. A satellite using ABEP is metabolically open in exactly the Prigoginean sense: it ingests environmental matter, processes it through an electric thruster, and exports momentum, maintaining its orbital position indefinitely as long as the sun provides energy and the atmosphere provides mass.

The enabling technology for both architectures is the miniaturized superconducting magnet. The National High Magnetic Field Laboratory's LBC9, achieving 48.7 Tesla in a salt-shaker-sized REBCO coil with no-insulation winding, demonstrates that the field strengths required for magnetic sails and plasma intakes are achievable within CubeSat mass and power budgets. A 2.1-kilogram Sunpower CryoTel MT cryocooler can maintain operating temperature at 40 watts of input power — well within the capacity of the kilowatt-class solar arrays that SpaceX's orbital data centers will require for their AI processors. The same magnet that generates thrust from the solar wind also provides radiation shielding and Lorentz-force attitude control through interaction with Earth's geomagnetic field. REBCO superconductors are additionally immune to neutron radiation damage, lacking the organic insulating materials that degrade in the space radiation environment. The hardware is converging.

Dissipative structures at every scale

The thermodynamic framework unifies these domains more tightly than analogy alone would suggest. Prigogine identified three regimes: thermodynamic equilibrium (maximum entropy, death for biological systems, debris cloud for orbital systems), near-equilibrium (linear response, the senescent cell's twilight zone, the fuel-depleted satellite's uncontrolled drift), and far-from-equilibrium (the regime where dissipative structures emerge, healthy cells function, and propellantless satellites maintain their orbits through continuous environmental coupling).

Jeremy England's dissipation-driven adaptation, derived from fluctuation theorems, predicts that matter under external energy input spontaneously self-organizes to better absorb and dissipate that energy. Computer simulations of chemical reaction networks confirmed that strongly driven systems frequently evolve toward states of exceptional structure — ordered configurations that maximize entropy production. Life, in this framework, is as thermodynamically unsurprising as rocks rolling downhill. The implication for infrastructure is direct: systems designed to maximize their coupling to ambient energy flows will spontaneously develop ordered, persistent configurations. A satellite constellation designed around propellantless propulsion is not fighting thermodynamics; it is riding the same gradient that produced life itself.

The Kessler Syndrome, in this framework, represents the heat death of orbital space: the transition from an ordered state (operational satellites with controlled trajectories, maintained by energy throughput from solar panels and propellant expenditure) to a disordered state (random debris in chaotic orbits, approaching maximum entropy). Active debris removal missions — Astroscale's ADRAS-J, ClearSpace-1, the ELSA-M servicer — are the orbital equivalent of senolytic therapy: clearing dysfunctional objects that generate disorder faster than the environment can absorb it. Propellantless propulsion is the orbital equivalent of mitochondrial repair: restoring the energy-processing capacity that keeps the system far from equilibrium. The combination — debris removal plus propellantless maintenance — is the orbital Regenerative Pivot.

The permanence gradient

A spectrum of persistence emerges from this analysis, ranging from pure closure to pure openness.

At one extreme: a chemical rocket stage, fully closed, consuming stored propellant until exhaustion, then becoming debris. Its ISA equivalent is the organism that cannot clear senescent cells — sclerosing until systemic failure. At the other extreme: a propellantless satellite coupled to the solar wind and ionospheric plasma through superconducting magnets and air-breathing thrusters, maintaining orbit indefinitely as long as the sun shines and the atmosphere persists. Its ISA equivalent is the organism that cycles continuously between AMPK-driven cleanup and mTOR-driven growth — the phased peptide protocol's oscillation between dissolution and renewal, sustaining a far-from-equilibrium state through managed entropy export.

Every real system occupies a position on this gradient. The engineering challenge — at every scale, in every domain — is to shift systems toward the open end. In biology, this means clearing senescent cells, repairing mitochondria, and restoring the metabolic throughput that keeps tissue far from equilibrium. In orbital mechanics, it means replacing finite propellant with ambient-resource coupling and removing debris that has already transitioned to the closed-system state. In both cases, the enabling technologies are the same: precision molecular engineering (synthetic peptides or REBCO superconductors), energy harvesting from environmental gradients (mitochondrial oxidative phosphorylation or solar-powered electric propulsion), and selective elimination of dysfunctional components (senolysis or active debris removal).

The million-satellite constellation is either the ultimate expression of the Sclerotic Singularity — a million closed systems counting down to a Kessler catastrophe — or the first instantiation of genuinely permanent space infrastructure — a million open systems coupled to the solar wind, breathing the ionosphere, and maintaining their positions through the same thermodynamic principle that keeps living cells alive. The difference is not ambition but architecture. And the architecture, at every scale, reduces to a single thermodynamic question: is the system open or closed? Prigogine answered it fifty years ago. The engineering is finally catching up.