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THE FIVE-YEAR RULE AS A DESIGN CONSTRAINT

DECAY PHYSICS, DISPOSAL RELIABILITY, AND THE COST OF COMPLIANCE FOR SMALL LEO CONSTELLATIONS

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Scope and method

Published by Apogee Ventures LLC in a series on the rules governing satellite spectrum and orbit. Each paper states the regulatory requirement, reviews the published work bearing on it, reproduces the governing calculation, and sets out the consequences for design, licensing, and diligence. Calculations use the models published on the Tools page at apogee-ventures.com: an exponential atmosphere with a solar-activity scaling factor, a circular-orbit drag integrator, Hohmann transfer delta-v, free-space path loss, and ITU-R P.838 rain coefficients with the P.618 path reduction. They are sized for decisions; a filing uses the full recommendation and the applicant's own parameters.

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Sources and images

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ABSTRACT

The FCC's five-year post-mission disposal rule, adopted in September 2022 with its two-year grace period ended in September 2024, is usually filed under regulatory affairs. This paper argues it belongs with the propulsion, structures, and reliability leads. Using the same drag model published on this site, it maps the altitude below which a spacecraft complies passively as a function of ballistic coefficient and solar activity, sizes the delta-v and propellant fraction required above that line, and shows, following Kawamoto et al. and Lewis and Yazadzhiyan, that the disposal success rate matters more to the long-term environment than the residual lifetime itself. It closes with the questions a licensing engineer and an investor should each be asking of a small-constellation design.

PRINCIPAL RESULTS

- At 50 kg/m² and mean solar activity the passive-compliance altitude is about 540 km; it falls to about 485 km at solar minimum and rises to about 627 km at maximum. Each 50 km above the line roughly doubles the natural lifetime.
- The environment responds to the fraction of satellites that fail to dispose, not to the nominal lifetime of the ones that succeed. A 1,000-satellite system at 90 percent disposal reliability leaves 100 derelicts; at 99 percent, ten.
- Propellant is not the cost. Lowering perigee to 350 km from 600 to 1,200 km takes 3 to 10 percent of mass with monopropellant and 0.5 to 1.5 percent with electric propulsion; the cost is end-of-life reliability and the operations during descent.
- A disposal plan has to close at low solar activity, which is the case in which it fails.

SECTION 1

Regulatory requirement

On September 29, 2022 the Commission adopted FCC 22-74, replacing the 25-year post-mission disposal guideline for satellites ending their mission in, or passing through, low Earth orbit below 2,000 km with a requirement to complete disposal as soon as practicable and no later than five years after mission end [10]. The rule applies to US-licensed systems and to non-US systems seeking US market access. Satellites already authorized but not yet launched were given two years; that grace period ended on September 29, 2024, and new applications since then must show a disposal plan that closes within the five years.

The disposal requirement sits on top of the disclosure regime the Commission built two years earlier. FCC 20-54, the first comprehensive rewrite of the orbital debris rules since 2004, requires applicants to describe collision risk, trackability, and the reliability of the disposal method, and opened a further notice on maneuverability, casualty risk, and performance bonds [11]. A five-year disposal plan is therefore not a paragraph in an application. It is a claim about propulsion reliability at end of life, about the area-to-mass ratio the spacecraft will actually present once passivated, and about what happens if the spacecraft fails before it can be commanded.

SECTION 2

Prior work

The research record on large constellations predates the rule and explains it. Bastida Virgili et al. modeled the response of the LEO population to constellations of several thousand satellites and identified failed satellites, those that cannot execute their disposal, as the dominant driver of long-term environmental harm [1]. Radtke, Kebschull, and Stoll reached the same conclusion using OneWeb's architecture as the worked example, showing that the constellation's effect on the environment is governed by the fraction of satellites that fail to deorbit rather than by the nominal design [2]. Lewis et al. had already shown in 2012 that the 25-year rule, adequate for the launch rates of the early 2000s, would not stabilize the population under the deployment rates then being proposed [3], and Liou's NASA update confirmed that the effectiveness of post-mission disposal depends on both compliance rate and mission duration [4].

Two studies published after the rule test it directly. Kawamoto et al., using the NEODEEM evolutionary model developed by JAXA and Kyushu University, shortened the post-mission lifetime from 25 years to five and to one and found that the shorter lifetimes improve short-term safety below 700 km by reducing collision rates and avoidance maneuvers, but that the long-term stability of the environment is set by the compliance rate, not the residual lifetime [5]. Lewis and Yazadzhiyan, using Southampton's DAMAGE model, found a 45 percent reduction in conjunctions under the five-year rule relative to the 25-year rule, 90 percent under a one-year rule, and 95 percent when satellites used continuous thrust to bring perigee to 300 km, which is what large operators actually do [6]. The same study flags the cost: disposal orbits are lower, so delta-v is higher, and conjunction frequency at low altitudes rises as more objects pass through on their way down.

Boley and Byers widened the frame to the atmosphere and the ground, estimating that re-entries from a single large constellation could exceed the meteoroid input of aluminum to the upper atmosphere [7], and Pardini and Anselmo quantified the cumulative casualty expectation from uncontrolled re-entries, which the per-event 10^{-4} threshold does not capture [9]. Letizia, Bastida Virgili, and Lemmens introduced the notion of orbital capacity thresholds, a way of asking how much a shell can hold before disposal and collision rates make it unusable [8]. ESA's own Zero Debris analysis assumes a five-year disposal lifetime with a 90 percent success rate, rising to 95 percent for members of large constellations [12]. The design question is therefore not whether five years is the correct threshold. It is where the five-year line falls for a particular spacecraft, and what it costs to get below it reliably.

SECTION 3

Passive compliance altitude

Natural decay is governed by the ballistic coefficient, the ratio of mass to drag area times drag coefficient, and by the atmospheric density, which at constellation altitudes varies by roughly an order of magnitude across the solar cycle. Table 1 gives the natural decay lifetime from a circular orbit for four ballistic coefficients spanning the range from a deployed-array smallsat (25 kg/m²) to a dense bus (200 kg/m²), at low, mean, and high solar activity, using the exponential atmosphere model on this site's Tools page with density scaled by 0.4, 1, and 4. A recent analytical treatment of the same problem reaches similar conclusions about the altitude below which passive compliance is achievable [13].

Table 1. Natural decay lifetime (years) from a circular orbit, by ballistic coefficient $m/(C_dA)$ and solar activity. Entries under one year are shown in months.

Altitude	Mean solar activity				Low (0.4x)				High (4x)			
km	25	50	100	200	25	50	100	200	25	50	100	200
450	6.5 mo	1.1	2.2	4.3	1.4	2.7	5.4	11	1.6 mo	3.3 mo	6.5 mo	1.1
500	1.3	2.6	5.2	10	3.2	6.5	13	26	3.9 mo	7.8 mo	1.3	2.6
550	3.0	5.9	12	24	7.4	15	29	59	8.9 mo	1.5	3.0	5.9
600	6.6	13	26	52	16	33	65	130	1.7	3.3	6.6	13
650	14	28	56	112	35	70	140	>200	3.5	7.1	14	28
700	29	58	116	>200	72	145	>200	>200	7.3	15	29	58
800	105	>200	>200	>200	>200	>200	>200	>200	26	53	105	>200

Three things stand out. First, the line is steep: at mean activity and a ballistic coefficient of 50 kg/m^2, the five-year altitude is about 540 km, and each 50 km above it roughly doubles the lifetime. Second, the ballistic coefficient moves the line by 40 to 45 km per doubling: about 583 km at 25 kg/m^2, 540 km at 50, 498 km at 100, and 458 km at 200. A spacecraft that stows its arrays at end of life, or that fails with them feathered, has changed its own compliance altitude. Third, solar activity moves the line more than the design does: for the 50 kg/m^2 case the five-year altitude is about 485 km at low activity and 627 km at high activity. A disposal plan written against mean activity and a mission that ends at solar minimum are two different plans.

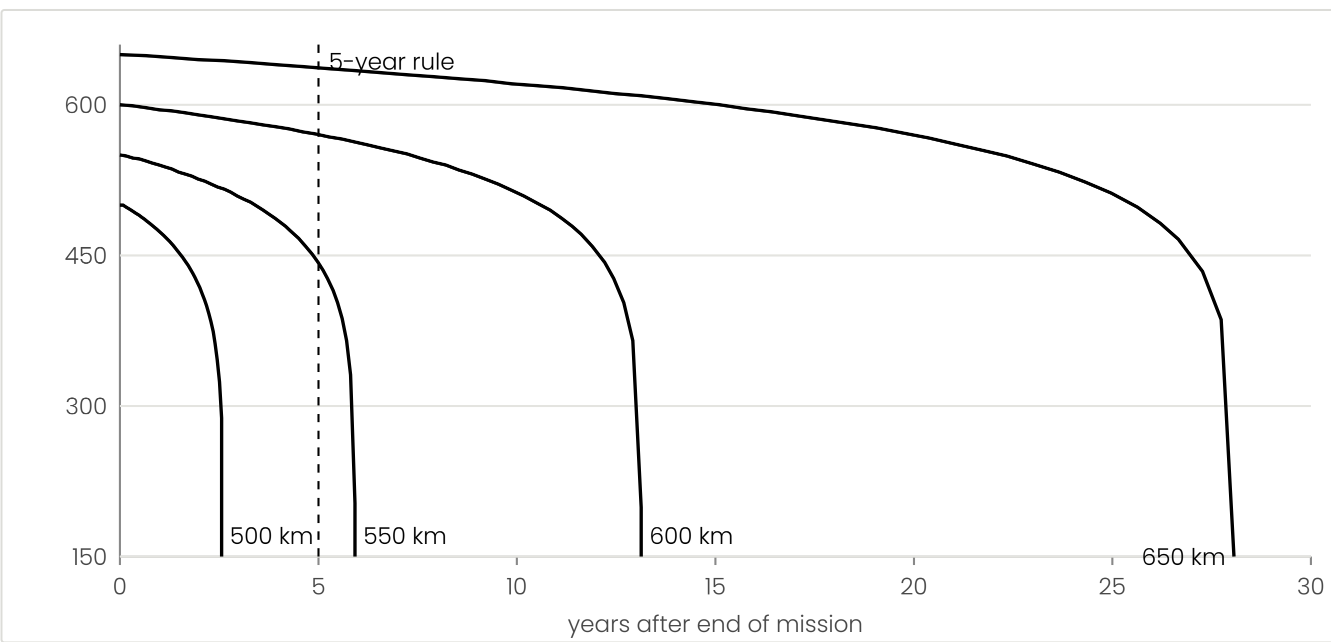

Figure 1. Altitude versus time after end of mission for a spacecraft with $m/(C_dA)$ of 50 kg/m^2 at mean solar activity, starting from 500, 550, 600, and 650 km. Only the 500 and 550 km cases pass the five-year line without a maneuver.

SECTION 4

Sensitivity to disposal reliability

Every evolutionary study cited above converges on the same sensitivity: the environment responds to the fraction of satellites that fail to dispose, not to the nominal lifetime of the ones that succeed. For a constellation of N satellites with disposal success rate r, the expected number of derelicts is N(1 - r). A 1,000-satellite system at 90 percent leaves 100 uncontrolled objects at operational altitude; at 99 percent it leaves 10. If the operational shell is above the passive-compliance line, those derelicts are the long-lived population the models are worried about, and their number scales with the constellation, not with the rule.

This reframes the engineering. A propulsion system that performs the disposal burn with 99 percent reliability after five years of operation is a harder requirement than the burn itself. It implies propellant margin held in reserve and never touched for station keeping, thruster and valve reliability assessed at end of life rather than at acceptance, a power and attitude system that can still execute the burn after partial failures, and passivation that does not leave a pressurized tank behind. The FCC's disclosure rules ask for exactly these things because the models say they are what counts [11]. An operator who cannot answer them with numbers is not ready to file.

SECTION 5

Cost of active disposal

Above the passive line the operator has two choices: carry propellant for a disposal maneuver, or carry a drag device that raises the area-to-mass ratio at end of life. Table 2 gives the Hohmann delta-v to lower perigee from a circular operational altitude to a 350 km disposal perigee, which for the 50 kg/m² case yields a residual lifetime of a few months, and the propellant fraction that burn consumes at two representative specific impulses.

Table 2. Delta-v and propellant fraction to lower perigee to 350 km from a circular orbit, and total delta-v if the orbit is also circularized at 350 km.

Operational altitude	Perigee-lowering burn	Both burns	Propellant, I_{sp} 225 s	Propellant, I_{sp} 1,500 s
600 km	69 m/s	139 m/s	3.1%	0.5%
700 km	96 m/s	193 m/s	4.3%	0.6%
800 km	122 m/s	245 m/s	5.4%	0.8%
1,000 km	172 m/s	347 m/s	7.5%	1.2%
1,200 km	219 m/s	445 m/s	9.5%	1.5%

The propellant fractions are modest for monopropellant and small for electric propulsion, which is why the FCC treated the requirement as achievable [10]. The cost is not the propellant. It is the reliability of executing the burn late in life, the schedule and testing that reliability requires, and, for electric systems, the months of thrusting during which the spacecraft is still a maneuvering object at intermediate altitudes. Lewis and Yazadzhiyan's finding that conjunction frequency rises at low altitudes as more spacecraft transit them is the operational consequence: the disposal phase is itself a period of elevated conjunction workload [6].

Drag devices avoid the reliability problem of a late burn but introduce another: a mechanism that must deploy after years in vacuum, from a spacecraft that may be tumbling, and whose deployed area must be predictable enough to support a lifetime estimate the Commission will accept. Either way, the disposal plan has to be validated against the low-activity column of Table 1, because that is the case in which it fails.

SECTION 6

Implications for design and diligence

For the licensing engineer, the five-year rule collapses to five questions. Where is the passive-compliance line for this spacecraft at low solar activity? What is the disposal method above it, and what is its demonstrated reliability at end of life? What is the expected number of derelicts across the constellation, and how does the collision risk disclosure account for them? What is the casualty expectation on re-entry, per event and cumulative across the fleet? And how does the plan change if the mission ends early, or late?

For the investor, the same questions translate into cost and schedule. A design that sits above its passive line has committed to a propulsion reliability program and a disposal operations budget for every satellite it launches. A design that sits below it has accepted a shorter mission or a lower altitude, with the capacity and coverage consequences that follow. A design that has not decided is carrying a licensing risk that surfaces at the worst time, when the application is on public notice and a competitor files a petition to deny.

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SECTION 7

Conclusion

The five-year rule changed a guideline into a design constraint. The physics puts the passive-compliance line between roughly 460 and 630 km depending on ballistic coefficient and solar activity, which is exactly the band where most new constellations want to operate. The literature is unambiguous that what protects the environment is the fraction of spacecraft that actually dispose, so the requirement is in effect a reliability requirement on end-of-life propulsion or deployable drag. Treating it as a paperwork item is the most expensive way to meet it.

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