

Spacecraft Disposal Rosetta Stone

Parametric Tool for Orbital Lifetime, Disposal, and Cost Assessment

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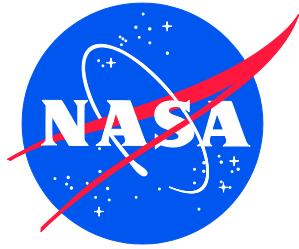
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Abstract

This Technical Memorandum documents a simplified, parametric method for evaluating spacecraft orbital lifetime, disposal compliance, and disposal-related cost impacts during early mission formulation and preliminary design. The method captures the dominant drivers of orbital decay—effective ballistic coefficient, operating altitude, and solar-cycle variability—using conservative bounding assumptions. Solar maximum conditions are used to bound achievable mission lifetime, while solar minimum conditions are used to bound disposal timelines and compliance with orbital debris requirements. A single tabulated dataset provides orbital lifetime under both solar-cycle extremes together with representative disposal ΔV required to ensure compliant disposal, enabling rapid assessment of disposal feasibility, cost sensitivity, and system-level impacts prior to committing to higher-fidelity analyses.

1.0 Executive Summary

This Technical Memorandum provides a compact planning framework to support early spacecraft disposal decisions for both government and commercial missions. By parameterizing orbital lifetime and disposal behavior in terms of effective ballistic coefficient, altitude, and solar-cycle extremes, the method enables rapid assessment of mission lifetime, end-of-life disposal compliance, and the trade space between passive decay, drag augmentation, and propulsion-based disposal. The approach is applicable to missions subject to NASA and Federal Communications Commission (FCC) orbital debris mitigation requirements, while remaining agnostic to specific disposal timelines. By emphasizing early architectural choices and realistic cost scaling, the method helps programs identify disposal risks and cost drivers early, when mitigation options are most flexible and least costly. The framework is intended to complement, not replace, higher-fidelity analyses and guidance described in a related NASA Engineering and Safety Center (NESC) Technical Assessment, SMD Post-Mission Disposal Support (TI-24-02050), final report, NESC-RP-24-0250, NASA/TM–20260001572 addressing orbital debris and end-of-life disposal considerations.

2.0 Purpose

The purpose of this Technical Memorandum is to provide a compact, transparent planning tool to support early trades involving orbit selection, spacecraft configuration, disposal strategy, and propulsion inclusion. The method is intended to inform architectural decisions, identify disposal-driven cost risk, and preserve schedule and cost flexibility.

3.0 Intended Use and Limitations

This method is intended for:

- Early architecture trades and concept studies
- First-order assessment of mission lifetime, disposal feasibility, and cost sensitivity
- Preliminary evaluation of whether propulsion-based disposal is warranted

Disposal compliance in this Technical Memorandum is evaluated relative to commonly applied orbital debris mitigation requirements, including U.S. Government requirements for NASA missions and U.S. FCC requirements for commercial missions. The method is agnostic to the specific requirement value and may be applied to alternative disposal timelines where applicable.

This method is not intended to replace:

- High-fidelity orbital lifetime tools
- Formal disposal compliance verification
- Detailed cost estimates or configuration-specific design analyses

Results are approximate and intentionally conservative.

4.0 Governing Parameters and Solar-Cycle Treatment

Orbital lifetime and disposal behavior are governed primarily by effective ballistic coefficient and atmospheric density variability driven by the solar cycle.

Two bounding solar-cycle cases are explicitly considered. Solar maximum produces higher atmospheric density and therefore the shortest orbital lifetimes, bounding achievable mission lifetime. Solar minimum produces lower atmospheric density and therefore the longest orbital decay times, governing disposal compliance and representing the controlling case for disposal design.

Both cases must be evaluated, as mission lifetime and disposal compliance are driven by opposite solar-cycle extremes.

5.0 Method Description

5.1 Ballistic Coefficient Estimation

An effective ballistic coefficient (BC) proxy is estimated as:

$$D = \frac{C_D \times A}{m} = \frac{1}{BC}$$

where m is spacecraft mass, C_D is drag coefficient, and A is effective cross-sectional area.

5.2 Operating Altitude and Table Selection

The spacecraft operating altitude and effective ballistic coefficient are used to select the corresponding row and column in Table 1, which serves as a planning-level lookup tool for bounding orbital lifetime and disposal feasibility. For each altitude and ballistic coefficient combination, the table provides estimated post-mission orbital lifetimes under both solar maximum and solar minimum atmospheric conditions, representing the minimum and maximum decay times, respectively.

Table entries are color-coded to indicate disposal compliance, with green cells meeting a 5-year disposal timeline, yellow and orange cells meeting a 25-year disposal timeline, and red cells exceeding a 25-year post-mission lifetime under worst-case (solar minimum) conditions. These

color codes are intended to provide rapid visual screening of disposal feasibility prior to detailed analysis.

When natural decay does not meet the applicable disposal requirement, Table 1 provides representative disposal ΔV values corresponding to two distinct disposal approaches: a single perigee-lowering terminal maneuver, and a two-burn maneuver that lowers the orbit and circularizes at a lower altitude in approximately 50-km increments. For planning purposes, the tabulated 50-km circularization ΔV values may be summed across successive altitude steps to estimate the total ΔV required to reach a desired lower disposal orbit. This approach enables rapid exploration of alternative end-of-life altitudes and disposal strategies during early mission design.

Table 1. Orbital Lifetime Under Solar Max. and Min. Conditions Representative Disposal ΔV

	dv Required (m/s)		Min, Max Time (years) to 100 km with Natural Decay (Solar Max F10.7 cm Range 175-275)																					
Orbit (km)	50km*	50km**	BC (m2/kg)																					
	Final Alt.	Decrement	0.005		0.010		0.015		0.020		0.025		0.030		0.035		0.040		0.045		0.050			
Starting Mission Altitude (circular)	400	102	N/A***	0.7	4.7	0.4	2.7	0.2	1.9	0.2	1.4	0.1	1.1	0.1	1.0	0.1	0.8	0.1	0.7	0.1	0.6	0.1	0.6	ISS ~400km
	450	116	28	1.5	8.1	0.8	5.6	0.5	4.4	0.4	3.5	0.3	2.9	0.3	2.5	0.2	2.2	0.2	2.0	0.2	1.8	0.2	1.6	
	500	130	28	3.1	16.0	1.5	8.8	1.0	7.2	0.7	6.3	0.6	5.5	0.5	5.0	0.4	4.6	0.4	4.2	0.3	3.9	0.3	3.5	HST ~510km
	550	143	28	11.3	30.9	2.9	17.3	1.8	10.4	1.3	9.1	1.1	8.2	0.9	7.5	0.8	7.0	0.7	6.7	0.6	6.3	0.5	6.0	Starlink ~550km
	600	157	27	18.7	60.5	8.0	31.0	3.5	20.8	2.5	17.5	2.0	12.2	1.6	10.5	1.4	9.7	1.2	9.2	1.1	8.7	0.9	8.4	
	650	170	27	35.7	112.7	15.4	56.1	11.9	39.9	5.3	30.3	3.7	22.5	2.9	20.4	2.5	18.7	2.2	17.0	1.9	14.5	1.7	11.3	Kuiper ~630km
	700	183	27	63.0	206.7	30.1	105.1	19.0	70.8	13.5	53.1	12.0	42.6	8.0	35.8	5.0	31.2	4.0	28.8	3.3	23.7	2.9	21.4	
	750	196	26	106.2	363.8	51.6	184.1	34.6	121.5	24.4	93.8	18.6	74.9	14.3	63.2	13.1	53.6	12.2	47.7	11.5	42.3	7.8	39.6	
	800	208	26	176.7	624.5	88.0	313.7	56.9	208.3	43.3	157.6	34.1	127.6	25.5	106.6	23.5	90.0	20.2	78.8	15.4	72.4	14.0	64.3	
850	221	26	278.6	1016.4	137.0	508.0	90.8	339.6	68.0	253.9	55.6	205.7	45.3	172.0	36.3	147.7	34.0	129.3	26.9	115.9	24.7	104.6		

dv* (m/s): Single burn with perigee set to 50km final altitude (and "immediate" disposal)
dv** (m/s): Two-burn circular disposal to decrease the operational orbit 50km (total)
N/A***: A single-burn perigee reduction can likely achieve desired outcome with lower ΔV

Green Cells: meet 5 year disposal requirement (FCC)
Orange, Yellow and Green Cells: meet 25 year disposal requirement
Red Cells: exceed 25 year disposal requirement (NASA)

5.3 Mission Lifetime Assessment (Solar Maximum)

Mission lifetime is evaluated using the solar maximum lifetime values provided in Table 1, which represent a conservative lower bound on achievable on-orbit lifetime for the selected altitude and ballistic coefficient.

5.4 Disposal Compliance Assessment (Solar Minimum)

Disposal compliance is evaluated using the solar minimum lifetime values in Table 1. If the predicted worst-case orbital lifetime meets the applicable disposal requirement, no disposal maneuver is required. If the predicted lifetime exceeds the requirement, an active disposal maneuver is required.

5.5 Disposal ΔV Selection

For cases requiring active disposal, Table 1 provides representative disposal ΔV values corresponding to the minimum altitude reduction required to meet disposal requirements under solar minimum conditions. The representative disposal ΔV is determined by estimating the impulsive velocity change required to lower the orbit perigee to the minimum altitude at which the corresponding solar minimum orbital lifetime meets the applicable disposal requirement, with

Table 1 providing ΔV values for both a single perigee-lowering terminal maneuver and a two-burn maneuver that lowers perigee and then circularizes the orbit at the lower altitude.

The tabulated ΔV values assume impulsive, two-body maneuvers and represent planning-level estimates suitable for early design trades. Execution of an active disposal maneuver assumes the spacecraft retains sufficient attitude determination and control capability at end of mission to orient thrust in the required direction.

5.6 Propulsion Sizing

The selected disposal ΔV from Table 1 is converted to propellant mass using the rocket equation:

$$\Delta V = g_o * I_{sp} * \ln \left(\frac{m_o}{m_f} \right)$$

Rearranging, the final spacecraft mass after the disposal maneuver is:

$$m_f = m_o * e^{(-\Delta V / (g_o * I_{sp}))}$$

The required propellant mass is then:

$$m_{prop} = m_o - m_f$$

where m_o is the spacecraft mass immediately prior to the disposal maneuver, including the propellant to be expended, and m_f is the spacecraft mass following the maneuver after that propellant has been consumed. The resulting propellant mass supports preliminary propulsion sizing with appropriate margin.

5.6.1 Propellant–Mass Coupling Considerations

Once a propulsion system is added, the spacecraft dry mass increases due to propulsion hardware, tanks, residual propellant, and associated components. This mass increase raises the propellant mass required to achieve the same disposal ΔV . As a result, disposal propellant sizing is inherently iterative.

For small disposal ΔV requirements, this feedback is typically modest and converges quickly. For larger disposal ΔV requirements or higher-mass spacecraft, the coupling between propulsion mass and propellant load can materially increase the total propellant required relative to an initial fixed-mass estimate. Early planning estimates should therefore include appropriate margin or perform a simple mass-closure iteration.

5.7 Application to Passive Drag Augmentation Devices

The parametric framework presented in this Technical Memorandum may also be used to evaluate passive drag augmentation devices, such as deployable drag sails, by adjusting the effective ballistic coefficient to reflect the deployed configuration. The post-deployment ballistic coefficient is used with Table 1 to estimate orbital lifetime under solar minimum conditions and assess disposal compliance.

From a space sustainability and operations perspective, the cumulative environmental impact of a spacecraft is often discussed in terms of the cross-product of effective collision cross-sectional area and post-mission orbital residence time. This cross-product framing highlights that increases in spacecraft size or deployed area must be considered in conjunction with achievable disposal

timelines, as large-area objects that persist in orbit for extended periods contribute disproportionately to long-term environmental risk.

This application provides a planning-level assessment only and does not capture effects such as attitude stability, deployment reliability, or aerodynamic variability.

5.8 Atmospheric Density Sensitivity and Drag Effectiveness

Atmospheric density in low Earth orbit decreases rapidly with altitude, causing orbital decay rates to be highly sensitive to relatively small changes in perigee altitude. As a result, modest altitude reductions can place a spacecraft in a significantly higher drag regime and produce large reductions in orbital lifetime.

The same behavior governs the effectiveness of passive drag augmentation devices. At lower altitudes, increased drag area can materially accelerate orbital decay, while at higher altitudes atmospheric density is sufficiently low that drag devices provide limited disposal benefit. The orbital lifetimes in Table 1 implicitly capture this transition and may be used to identify regimes where drag-based disposal approaches are effective.

6.0 Cost Implications of Propulsion-Based Disposal

6.1 Cost Scope Definition

For the purposes of early planning, total incremental propulsion system cost includes propulsion hardware, propellant and ground support equipment, software and fault protection changes, integration and test activities, safety and launch-site processing, compliance activities, and associated programmatic and schedule impacts.

For missions that already include propulsion capability sized to meet primary mission objectives, the incremental mass and cost impacts associated with disposal may be significantly reduced. In such cases, disposal may be achieved through allocation of existing propellant margin, modest increases in propellant load, or utilization of already-integrated hardware, rather than the addition of new propulsion subsystems. The framework presented herein remains applicable for assessing required disposal ΔV and propellant usage; however, the incremental mass, cost, and integration impacts may be substantially lower than for missions requiring propulsion to be added or significantly resized specifically for disposal.

6.2 Rough-Order-of-Magnitude Cost Relationship

Historical program experience indicates that propulsion hardware frequently represents a minority of the total incremental cost required to add a propulsion system. As a rough-order-of-magnitude planning estimate, propulsion system hardware often represents approximately 10–30 percent of the total incremental cost to add propulsion capability, and can be lower for late additions or in high-compliance environments, with the remainder driven by integration and test activities, safety and compliance requirements, software and operational changes, and programmatic impacts.

For clarity, this cost relationship applies to the entire propulsion system, not individual components. In a conservative, worst-case framing, the procurement cost of a single thruster typically represents on the order of 1 percent or less of the total incremental cost associated with adding propulsion-based disposal capability.

7.0 Lessons Learned

#1: Solar-cycle extremes bound different mission risks

Solar maximum and solar minimum conditions bound different aspects of spacecraft mission performance. Solar maximum drives the shortest achievable mission lifetimes due to increased atmospheric density, while solar minimum governs the longest orbital decay times and therefore controls end-of-life disposal compliance.

Mission lifetime and disposal compliance assessments should explicitly evaluate both solar maximum and solar minimum atmospheric conditions to ensure robust compliance across the full solar cycle.

#2: Atmospheric density nonlinearity creates strong leverage for disposal

Atmospheric density decreases rapidly with altitude, causing orbital decay rates to be highly sensitive to relatively small changes in perigee altitude.

Mission designs should preserve the ability to make small altitude adjustments or configuration changes that exploit atmospheric density gradients to achieve efficient disposal with minimal ΔV .

#3: Disposal cost is driven primarily by system- and program-level impacts

The total cost of implementing spacecraft disposal capability is often dominated by integration, test, safety, compliance, software, and operational impacts rather than by the procurement cost of individual propulsion components.

Disposal cost assessments should emphasize minimizing required disposal ΔV and overall system complexity, rather than optimizing individual component costs.

#4: Launch schedule uncertainty and solar-cycle variability couple mission lifetime, disposal compliance, and propulsion utilization

Launch availability constraints and schedule uncertainty can shift missions into unfavorable solar-cycle conditions, degrading achievable mission life during solar maximum or extending orbital persistence during solar minimum, thereby complicating disposal compliance.

Mission and disposal planning should treat solar-cycle phase and launch date as uncertain boundary conditions and explicitly account for the potential trade between using disposal-allocated propulsion for mission extension and preserving sufficient ΔV for compliant end-of-life disposal.

8.0 Currency and Maintenance

The tabulated results in Table 1, as well as the cost relationships presented herein, are sensitive to atmospheric models, solar-cycle assumptions, disposal policy requirements, and supplier maturity. Periodic review is recommended.

9.0 Conclusion

This Technical Memorandum provides a compact, conservative framework for evaluating spacecraft mission lifetime, disposal compliance, and disposal-driven cost risk during early design. By explicitly treating solar-cycle extremes, consolidating lifetime and disposal ΔV information into a single parametric table, and incorporating realistic cost scaling, the method enables informed architectural decisions and robust disposal planning with minimal analytical burden.

Appendix A. How to use the disposal Rosetta Stone

	dv Required (m/s)		Min, Max Time (years) to 100 km with Natural Decay (Solar Max F10.7 cm Range 175-275)																					
	Orbit (km)	50km* Final Alt.	50km** Decrement	BC (m2/kg)																				
				0.005		0.010		0.015		0.020		0.025		0.030		0.035		0.040		0.045		0.050		
Starting Mission Altitude (circular)	400	102	N/A***	0.7	4.7	0.4	2.7	0.2	1.9	0.2	1.4	0.1	1.1	0.1	1.0	0.1	0.8	0.1	0.7	0.1	0.6	0.1	0.6	ISS ~400km
	450	116	28	1.5	8.1	0.8	5.6	0.5	4.4	0.4	3.5	0.3	2.9	0.3	2.5	0.2	2.2	0.2	2.0	0.2	1.8	0.2	1.6	
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	550	143	28	11.3	30.9	2.9	17.3	1.8	10.4	1.3	9.1	1.1	8.2	0.9	7.5	0.8	7.0	0.7	6.7	0.6	6.3	0.5	6.0	Starlink ~550km
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	650	170	27	35.7	112.7	15.4	56.1	11.9	39.9	5.3	30.3	3.7	22.5	2.9	20.4	2.5	18.7	2.2	17.0	1.9	14.5	1.7	11.3	Kuiper ~630km
	700	183	27	63.0	206.7	30.1	105.1	19.0	70.8	13.5	53.1	12.0	42.6	8.0	35.8	5.0	31.2	4.0	28.8	3.3	23.7	2.9	21.4	
	750	196	26	106.2	363.8	51.6	184.1	34.6	121.5	24.4	93.8	18.6	74.9	14.3	63.2	13.1	53.6	12.2	47.7	11.5	42.3	7.8	39.6	
	800	208	26	176.7	624.5	88.0	313.7	56.9	208.3	43.3	157.6	34.1	127.6	25.5	106.6	23.5	90.0	20.2	78.8	15.4	72.4	14.0	64.3	
	850	221	26	278.6	1016.4	137.0	508.0	90.8	339.6	68.0	253.9	55.6	205.7	45.3	172.0	36.3	147.7	34.0	129.3	26.9	115.9	24.7	104.6	

dv* (m/s): Single burn with perigee set to 50km final altitude (and "immediate" disposal)
dv** (m/s): Two-burn circular disposal to decrease the operational orbit 50km (total)
N/A***: A single-burn perigee reduction can likely achieve desired outcome with lower ΔV

Green Cells: meet 5 year disposal requirement (FCC)
Orange, Yellow and Green Cells: meet 25 year disposal requirement
Red Cells: exceed 25 year disposal requirement (NASA)

1. Determine spacecraft lookup parameters:

Estimate spacecraft drag parameter (BC, ballistic coefficient proxy) using

$$D = \frac{C_d A}{m} = \frac{1}{BC}$$

where C_d is drag coefficient, A is effective cross-sectional area, and m is spacecraft mass.

2. Select operating altitude:

Choose the table row corresponding to the spacecraft's operating altitude.

3. Check disposal compliance:

Compare worst case predicted orbital lifetime (years) to disposal requirement.

- Meets requirement → no disposal maneuver required.
- Exceeds requirement → disposal maneuver required.

4. Determine altitude reduction:

Reduce effective starting altitude in 50-km increments until disposal requirement is met.

5. Select disposal ΔV:

From the ΔV columns for required altitude reduction, select lowest ΔV that satisfies mission constraints (single-burn perigee reduction or two-burn circular transfer as appropriate). ΔV values assume impulsive, two-body maneuvers.

6. Size propulsion system:

Convert the selected ΔV to propellant mass using the following equation

$$m_p = m_0 \left(1 - \exp \left(-\frac{\Delta V}{g_0 I_{sp}} \right) \right)$$

then select and size tanks, thrusters, and supporting hardware with appropriate margin.

Appendix B. An example calculation

Example Spacecraft (End of Mission)

- Mass, m : 850 kg
- Area, A : 5.8 m²
- Drag coefficient, C_D : 2.2
- Orbit: 700 km circular
- Mission life: 6 years
- Disposal: less than 25 years, post mission

Step 1: Ballistic Coefficient Proxy

$$D = \frac{1}{BC} = \frac{1}{\frac{m}{C_D A}} = \frac{1}{\frac{850}{2.2 \times 5.8}} \approx \frac{1}{66 \text{ kg/m}^2} \text{ or } 0.015$$

Select 700 km altitude and nearest BC proxy column (0.015) in Table 1.

Step 2: Mission Lifetime Assessment (from Table 1)

- Solar maximum: ~19 years → mission life feasible
- Solar minimum: ~71 years
- Post mission disposal = 71 - 6 = 65 years > 25 → passive decay is not compliant
Active disposal is required (without launch availability mission constraints).

Step 3: Disposal Strategy and ΔV

From Table 1, circularizing to ~600 km meets 25-year disposal under solar minimum.

- Single-burn terminal disposal: one perigee-lowering burn (183 km/s)
- Two-burn circularized disposal: perigee burn and circularize by ~100 km
Multiple (2) 50 km steps (27 m/s) may be summed (e.g., 700→600 km ≈ 54 m/s).

Step 4: Propellant Mass Estimate

Assume propellant system (for this example we'll use mono-prop):

$$I_{sp} = 220 \text{ s}, g_0 = 9.81 \text{ m/s}^2$$

$$m_{prop} \approx m_0 (1 - e^{-\Delta V / (g_0 I_{sp})})$$

and $\Delta V = 54 \text{ m/s}$:

$$m_{prop} \approx 850 (1 - e^{-54 / (9.81 \times 220)}) \approx 21 \text{ kg}$$

Step 5: Propulsion Dry Mass and Iteration

- ROM estimate for propulsion dry mass (tanks, feed system, structure, etc., and margin):

$$m_{dry prop} \approx 25 \text{ kg}$$

Updated mass prior to disposal:

$$m'_0 = 850 \text{ (Spacecraft)} + 21 \text{ (Propellant)} + 25 \text{ (Prop Dry Mass)} \approx 896 \text{ kg}$$

Recompute m_{prop} using m'_0 ; if change is small, typically converges in an iteration w/lower ΔV s.