Towards a Sustainable Space: Addressing the Challenges of the Final Frontier

Atmospheric reentry of orbital objects: Can "Design for Non-Demise" D4ND be the optimal solution?

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1. Any object in LEO will reenter atmosphere

1. Controlled reentry

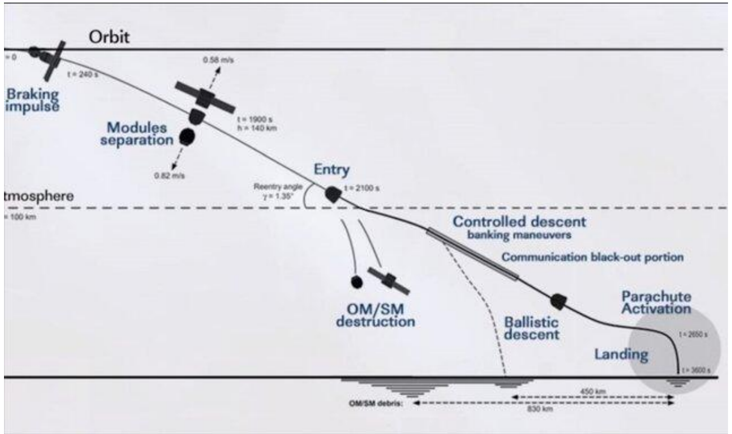
Dedicated deorbiting maneuver at end of life

atmospheric capture

➪ Enables dedicated geographical reentry zone

Object can be recoverable with potentially further reuse

➪ Ad-hoc thermal protection and recovery systems



Example of Soyuz capsule deorbiting and recovery [1]

2. Random reentry

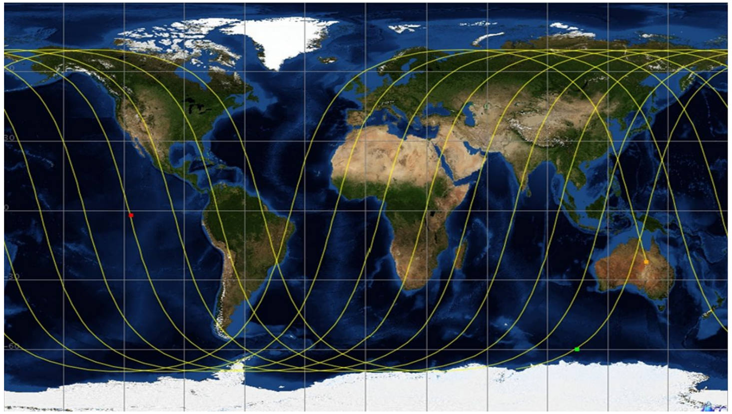
May follow a deorbiting maneuver
Usually induced by atmospheric drag integrated over time

Date and location of reentry very dispersed

➪ Random reentry area within ± Inclination band

➪ Typical precision ±10% of remaining time

□ **Dedicated tools to estimate the orbital lifetime of objects** [2]



Example of random reentry tracks, 16 hours before reentry [2]

[1] A. Fedele, 'A Deployable Aerobraking System for Atmospheric Re-entry', (2020), DOI: 10.13140/RG.2.2.34074.36801

[2] CNES Reentry freeware STELA, https://www.connectbycnes.fr/en/stela

2. Atmospheric reentry leads to fragmentation and demise

Objects demise at reentry

Re-entry mission phases [1]

Reentry steps

1. **Initial decay:** Reentry interface at 120 km altitude.
2. **Break-up:** Occurs between 90–70 km
3. **Demising objects:** Major ablation and fragmentation from 80–45 km.
4. **Ground impact:** Fragments that survive atmospheric burn-up.

Key phenomena

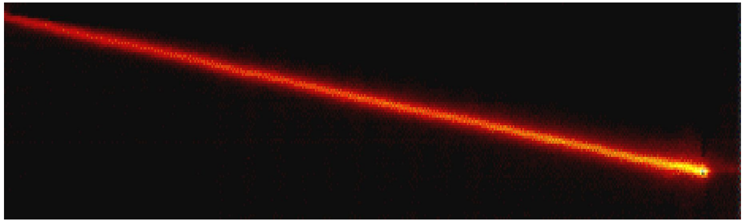
1. **Fragmentation**
   - Due to dynamic pressure α V^2
   - Depends on architecture and materials
2. **Partially burn-up**
   - Due to atmospheric friction α $V^{3.15}$
   - Depends on architecture and materials
   - Typically, 5-30% of the mass survives reentry

□ **Dedicated tools to estimate the demise process [3]**

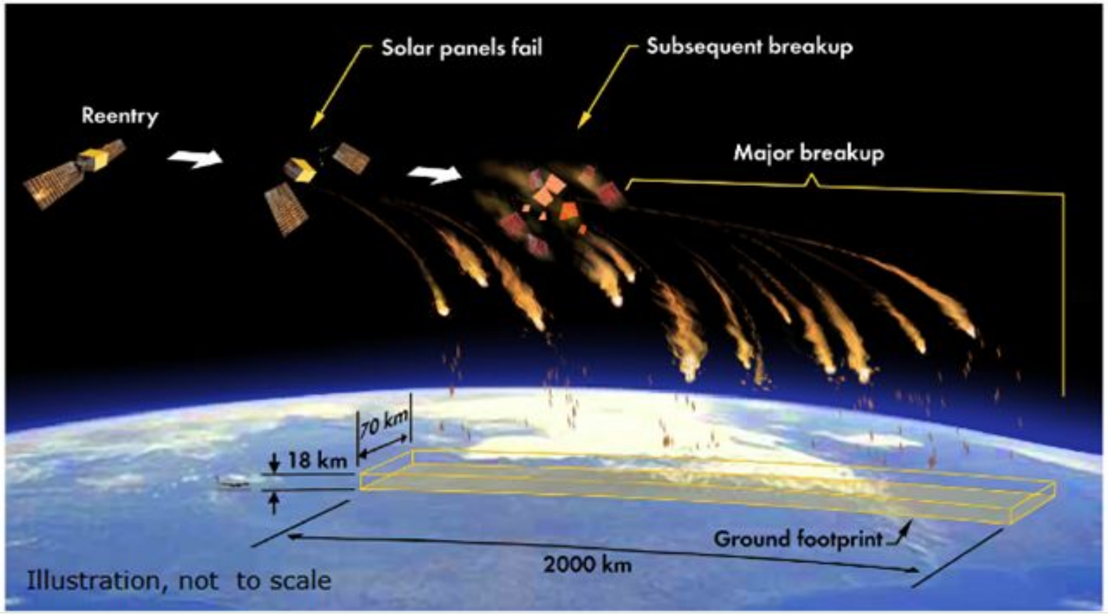
[1] J.-S. Fischer, A. Pagan, and S. Fasoulas, 'Ecological impact of re-entering launcher structures in comparison to natural sources' (2022)
[2] Ch. Bonnal et al. 'Observation of the reentry of the main cryotechnic stage of Ariane 5: Application to reentry prediction of large orbital objects, (1999), IAF-99-V.2.08
[3] CNES Demise freeware DEBRISK, https://www.connectbycnes.fr/en/debrisk
[4] S.-H. Park, S. Mischler, P. Leyland, 'Re-entry analysis of critical components and materials for design-for-demise techniques', Advances in Space Research 68 (2021) 1–24

Uncontrolled atmospheric reentry

- Fragmentation (90 – 60 km) due to dynamic pressure α V^2
- Partial fusion-sublimation (70 – 50 km) due to thermal flux α $V^{3.15}$
- Typical reentry sequence:



$V \approx 8\ km/s$



Chinese Long-March 7 upper-stage over Los Angeles

2. Atmospheric reentry leads to fragmentation and demise

Some objects survive reentry

- **Refractory materials**

  Titanium, Stainless Steel, Carbon, CFRP, COPV…

  (Example: PSLV upper stage – CFRP tank)

- **Dense objects**

  Melt and vaporize, but not completely before impact

  (Example: ISS battery support – Inconel – 10 x 3 cm, 800 g)

- **"Russian dolls"**

  Intricated structures, external protecting internal ones

  (Example: remains of SpaceX Falcon 9 computer)

- **"Dead leaves"**

  Objects with very high Area to Mass ratio

  Debris loses velocity at very high altitude, then doesn't feel thermal flux

  (Example: Mrs. L. Williams with a Delta 2 thermal protection debris)

[1] From P. Maley, 'History of space and launch debris recoveries', with numerous similar examples, https://pauldmaley.com/

CASUALTY RISK LINKED TO RANDOM ATMOSPHERIC REENTRY

Titanium casing of the STAR-48B solid rocket motor found in northeastern Argentina.

CASUALTY RISK LINKED TO RANDOM ATMOSPHERIC REENTRY

A man stands next to the piece of metal that Graham Sheppard and his son Ian first saw in 1975 while transporting missionaries to an airstrip in western Zambia. Graham took this photo when he returned to the airstrip in 1976.

CASUALTY RISK LINKED TO RANDOM ATMOSPHERIC REENTRY

Special SpaceX page... ☺️

3. Surviving elements induce a casualty risk to populations

Surviving elements may wound or kill people on ground


Fig. 25. CubeSat remains.

A surviving element can have a direct impact, or an indirect impact
(plane, train, roof collapse, chemical plant…)

Dedicated methods to compute the risk as a function of debris surface hitting ground
Minimal impact energy to be lethal ≅ 15 Joules
International standards and National rules specify a casualty risk ≤ 10^{-4} per reentry [1]
Very rough order of magnitude: 500 kg or 7 m^2 leads to a 10^{-4} casualty

Determination of the survivability of elements is complex

- Example [2] ESA test campaign at DLR 16 kPa à 3 MW/m^2
  Partial survivability of batteries, inertia wheels, electronics…

Recent controversy concerning the risk associated to Starlink reentries

FAA based on work from The Aerospace [3]
. 60% risk killing someone, per year, in 2035, due to random reentries of Starlink - 0.07% risk hitting a plane in flight
. Highly contested results by SpaceX, indicating that satellites burn-up totally at reentry [4]

Notion of D4D Design for Demise

- Proper selection of architecture and materials to minimize surviving elements
- Recommended in most of the current standards

[1] Numerous laws, standards, guidelines… Example: Chinese GB/T 43224-2023; ISO-24113-2023; French Space Operations Act; US Gov Orbital Debris Mitigation Standard Practices…
[2] James Beck et al., 'Improved representation of destructive spacecraft re-entry', Acta Astronautica 164(2019) 287-296
[3] https://www.faa.gov/sites/faa.gov/files/Report_to_Congress_Reentry_Disposal_of_Satellites.pdf - Report from The Aerospace attached to this reference
[4] SpaceX letter to FCC, David Goldman, Director of Satellite Policy, 10 Aug 2021

4. Demised elements may lead to atmospheric pollution

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Demisable materials and by-products of reentry

Atmospheric release: [1]

- 70–95% of the mass of reentering objects is vaporized in the high atmosphere.

Gas chemistry: [2]

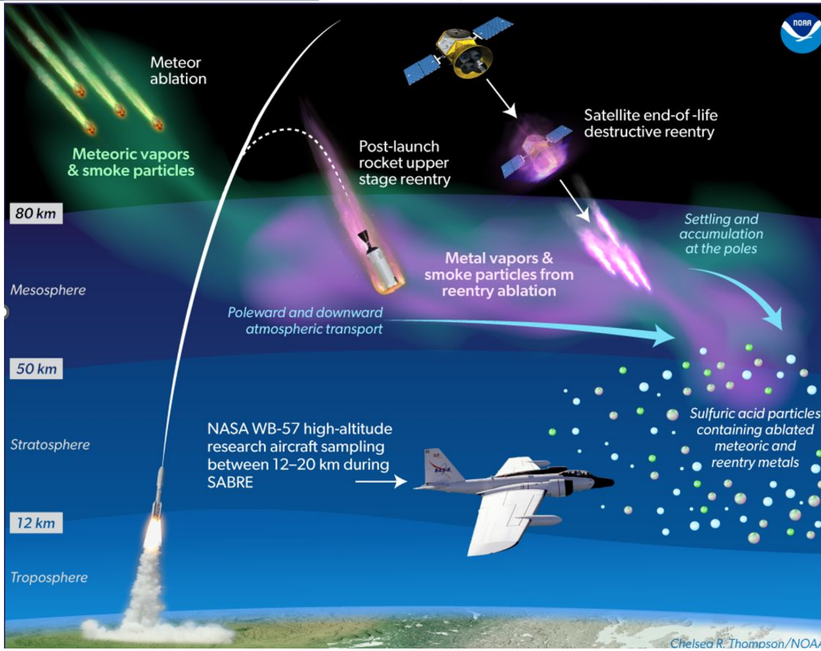
- High temperatures lead to nitrogen oxides (NOx), peaking at ~50 km altitude.
- High-speed reentry also generates chlorine (Cl).

Metal oxidation:

- Reactive metals (e.g., aluminum) form oxides like alumina (Al_2O_3).
- Sublimation of alloys at sufficiently high temperatures releases elements like copper, zinc, and titanium.

Transport and deposition:

- Metallic compounds aggregate with sulfuric acid particles, forming aerosols.
- Winds transport these gases and particles towards polar regions, where they accumulate in the stratosphere.



Incorporation of Metals from Reentry into Stratospheric Particles [3]

Other possible ablation products:

- Black carbon (BC) from CFRP (to be confirmed).
- Particles from materials such as titanium, lithium (batteries), and niobium. [4]

[1] esa-csid-21-bekki
[2] Park et al., 'Re-entry survival analysis and ground risk assessment of space debris considering by-products generation', Acta Astronautica 179 (2021) 604-618
[3] NOAA scientists link exotic metal particles in the upper atmosphere to rockets, satellites - NOAA Research
[4] D.M. Murphy et al., 'Metals from spacecraft reentry in stratospheric aerosol particles', Proc. Natl. Acad. Sci. U.S.A. (2023).

4. Demised elements may lead to atmospheric pollution

Environmental impacts and knowledge gaps

Aluminum and other metals

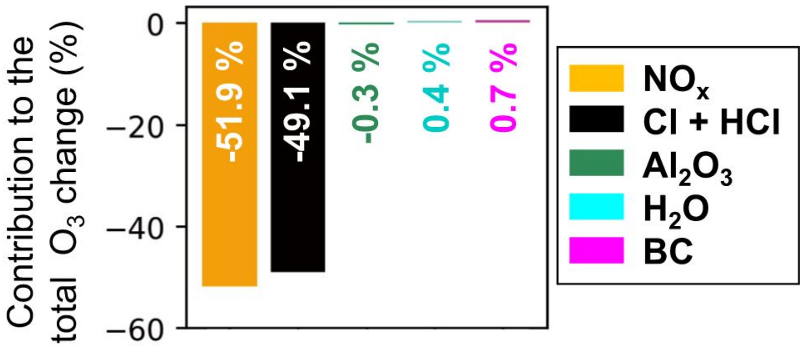
- Aluminum influences ice nucleation, leading to the formation of stratospheric clouds in polar regions.
- These clouds release chlorine (Cl) that accelerates ozone-destructive reactions. [3]
- It is possible that other metal cations also affect cloud formation and atmospheric processes. [1]

Black carbon (BC)

Contributes to stratospheric warming, which accelerates ozone-depleting reactions. [3]

Nitrogen oxides (NOx)

- NOx has prolonged residence times at high altitudes, amplifying its environmental impacts. [4]
- Promotes tropospheric ozone formation, contributing to global warming.
- Could deplete the ozone layer by increasing polar stratospheric clouds (PSCs). [1]



Contribution of individual pollutants to stratospheric O3 depletion. [2]

Knowledge gaps

- Most research examines rocket launches impact rather than spacecraft reentry.
- Difficult to differentiate between meteoritic and anthropogenic materials in high-altitude samples. [1]
- The persistence of metal oxides in sulfuric acid aerosols (weeks to months) remains unclear. [1]
- Ablation by-products still present a lot of data gaps, in addition to their interaction with the atmosphere.

[1] D.M. Murphy et al., ‘Metals from spacecraft reentry in stratospheric aerosol particles’, Proc. Natl. Acad. Sci. U.S.A. (2023).
[2] R. G. Ryan et al., ‘Impact of Rocket Launch and Space Debris Air Pollutant Emissions on Stratospheric Ozone and Global Climate’, *Earth’s Future*, vol. 10, no. 6 (2022)
[3] J. P. Ferreira et al., ‘Potential Ozone Depletion From Satellite Demise During Atmospheric Reentry’, *Geophysical Research Letters*, vol. 51, no. 11 (2024)
[4] G. Lammel G, H. Graßl, ‘Greenhouse effect of NOX’. Environ Sci Pollut Res Int., Vol.2 (1995) 40-45

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Vaporized elements may lead to atmospheric pollution

Available Global Warming Potential (GWP) coefficients

(Very preliminary…)

- *Unit is kg CO2eq*
- *CH4 = 28 whatever the altitude*
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Ground-based and aviation-based climate change characterization factors (GWP100) as a function of altitude + filled with in-house methodology

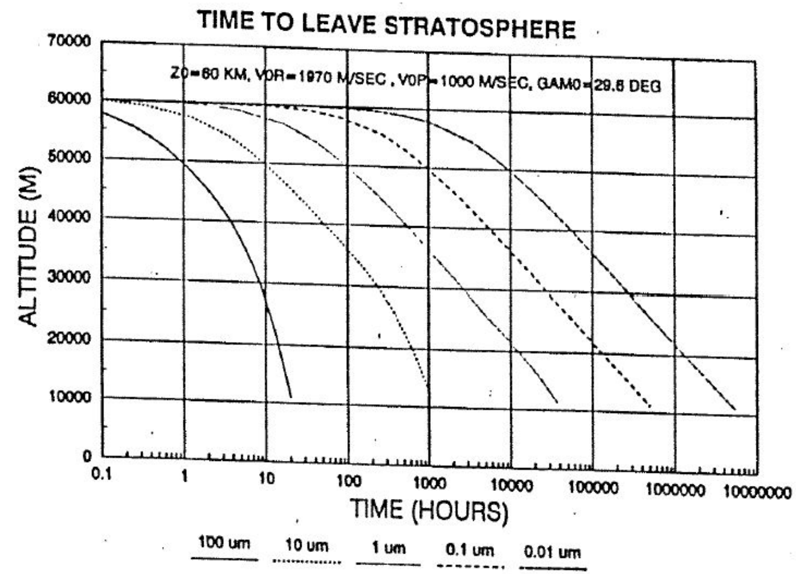
	Altitude (km)	BC	Al2O3	H2O	NOx
Lower troposphere	0-5	460	1.23	~0	8.5
Upper troposphere	5-15	1166	? -> 1.23	0.06	114
Stratosphere	15-50	310906	60156	854	? -> 114
Mesosphere	50-85	310906	60156	854	? -> 114
Space	>85	0	0	0	0

[1] L. Miraux, 'Update of the implementation of LCA', 2023 ESA Clean Space Industry Days, 18/10/2023

4. Demised elements may lead to atmospheric pollution

Vaporized elements may lead to atmospheric pollution

Environmental impact depends on Species and Timescale which themselves depend on the particulate sizes



Species	Impact	Timescales
Chlorine	Stratospheric ozone	2-3 years
Nitrogen oxides	Stratospheric ozone	2-3 years
Carbon monoxide	Stratospheric ozone	~1 month
Water	Stratospheric ozone, climate	2-3 years
Hydrogen	Stratospheric ozone	2-3 years
Methane	Stratospheric ozone	2-3 years
Carbon (soot)	Stratospheric ozone, climate	<1 week to 2-3 years (depends on size)
Metal/metal oxide	Stratospheric ozone, climate	<1 week to 2-3 years (depends on size)
Carbon Dioxide	Climate	>100 years

Table 1: Relevant Species for Environmental Impact

[1] J. Beck et al., 'Aerothemodynamic assessment of atmospheric emissions from re-entry demise'
[2] P.D. Lohn & E. Y. Wong, 'The impacts of deorbiting space debris on stratospheric ozone', TRW 1994

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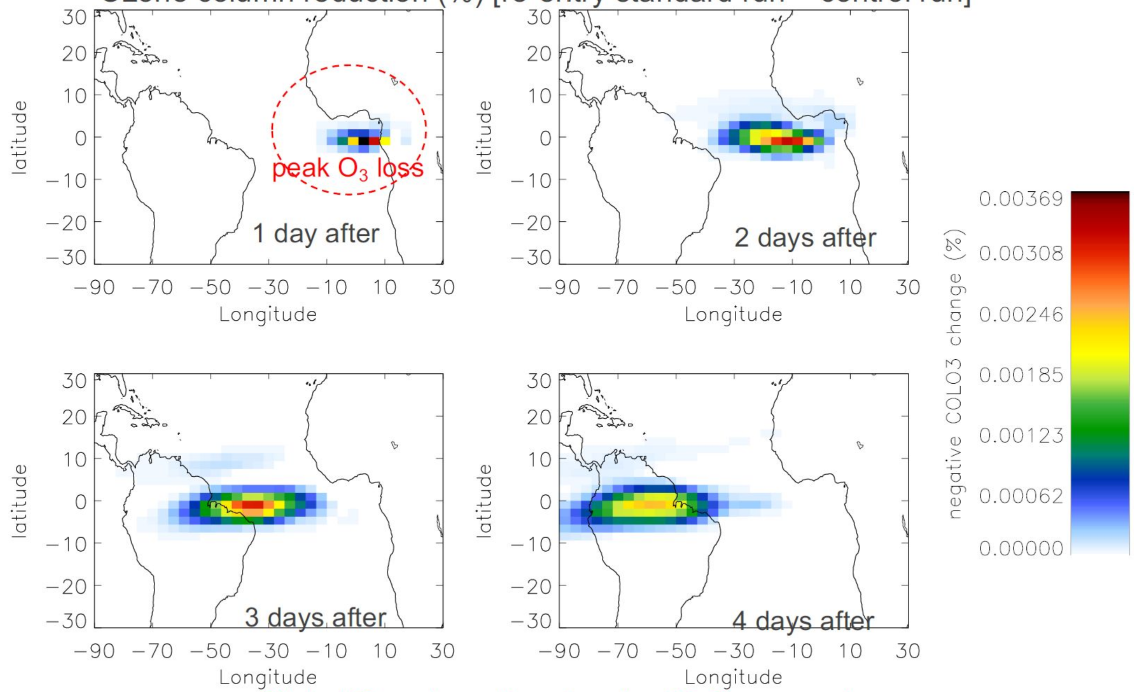
Vaporized elements may lead to atmospheric pollution

Typical Ozone layer impact following the reentry of one single large object

Atmospheric chemistry-transport simulations:

Impact of single re-entry event (20 T S/C)

Ozone column reduction (%) [re-entry standard run – control run]



Global O_3 column loss levels off after a week

8

[1] S. Bekki et al., 'Environmental impacts of atmospheric emissions from spacecraft re-entry demise' – ESA Project: ATmospheric Impact of SPAcecraft Demise (ATISPADE)

4. Global perspectives and future outlook

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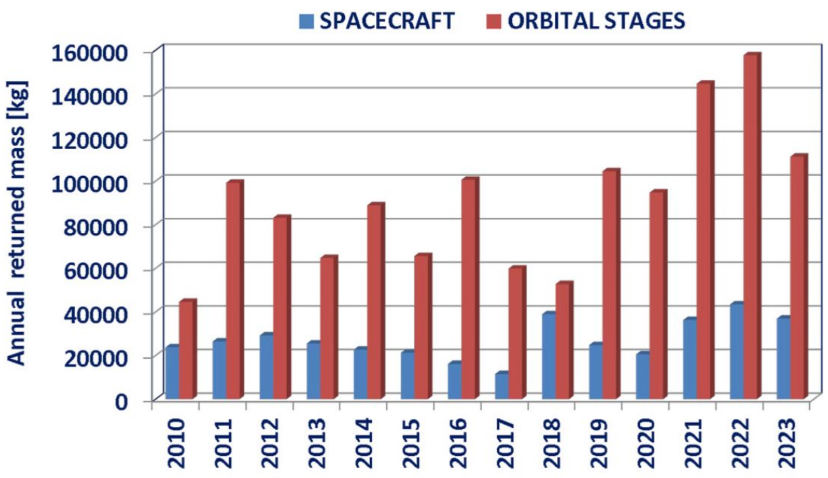
Vaporized elements may lead to atmospheric pollution

Current contributions [1]

- Roughly 90-180 tons/year of anthropogenic material enters Earth's atmosphere <u>from orbit</u> (900 when including suborbital stages)
- The demise of a typical 250-kg satellite can generate around 30 kg of aluminum oxide nanoparticles, which may endure for decades in the atmosphere [2]



Large spacecraft and <u>orbital</u> stages mass (kg) re-entered uncontrolled [1]

Comparison with natural influx

- Natural influx: 6,000–25,000 tons/year. [2]
  93% particles with mass < 10 g
- Reentries in 2022 generated a 29.5% increase of aluminum in the atmosphere above the natural level [3]
- 10% of stratospheric aerosols contain reentry metals [4]

☐ **<u>Significant lack of consolidated coherent reliable data…</u>**

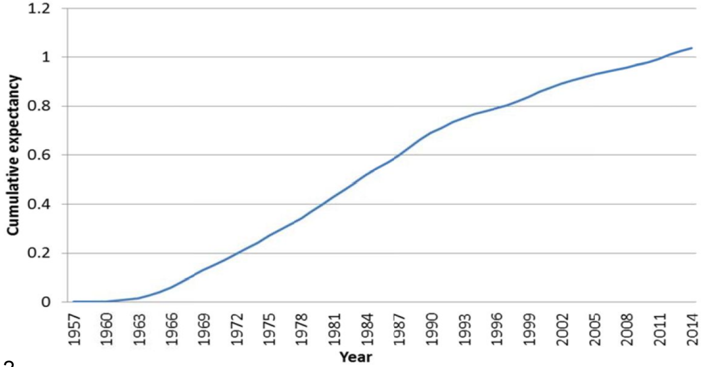
Future outlook

- Annual anthropogenic mass could double by 2030, reaching levels comparable to natural influx.
- Projections with planned mega-constellations lead to 360 tons Alumina injected into atmosphere per year [3]
- Metals and aerosols from reentry could equal 90–95% of natural contributions in the near future. [2]

[1] C. Pardini and L. Anselmo, 'On the need to assess and mitigate the risk from uncontrolled re-entries of artificial space objects…', Acta Astronautica, 219(2024) 662–669
[2] Schulz, et al. (2021). 'On the anthropogenic and natural injection of matter into Earth's atmosphere'. Advances in Space Research. 67 (2021)1002-1025.
[3] J. P. Ferreira et al., 'Potential Ozone Depletion From Satellite Demise During Atmospheric Reentry', *Geophysical Research Letters*, vol. 51, no. 11 (2024)
[4] D.M. Murphy et al., 'Metals from spacecraft reentry in stratospheric aerosol particles', Proc. Natl. Acad. Sci. U.S.A. (2023).

Orbital objects atmospheric reentry raises a dilemma:

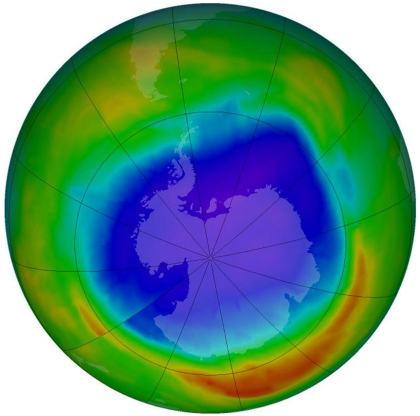
- **Shall we give priority to casualty risk minimization?**
- **Shall we prevent risk of atmospheric pollution?**



Cumulative on-ground casualty expectancy [2]

Concerning casualty risk:

. Casualty doesn't mean death, but serious wound or more
. There has never been a casualty reported so far
No death, no wounds, despite 32,118 reentries to date [1]
Cumulative on-ground casualty expectancy: 1 in 2014, probably < 2 today [2]
. 71% of Earth = Water, 20% = Deserts & Forests, <10% inhabited
. Evaluation methods may be too conservative:
Lethal energy, shielding effects, casualty area computation…



Concerning atmospheric pollution due to reentries:

. No evidence yet that it is indeed problematic
. Comparison with Natural environment: Orders of Magnitude?
. Effects such as Ozone hole may take long time to recover
. Need to adopt a precautionary principle?
. Notion of Long-Term Sustainability

[1] Cataloged objects, from www.space-track.org
[2] ESA Debris Risk Assessment and Mitigation Analysis Software, Documentation and Software, https://sdup.esoc.esa.int

6. Recommendations for addressing reentry impacts

Priority should be given to atmosphere (opinion of the authors 😊)

Proposal to evaluate transition from "Design for Demise" to "Design for Non-Demise" (D4ND)

Selection of architectures and materials surviving atmospheric reentry
Selection of shapes minimizing NOx production
Associated to "Recommendation to perform controlled reentry over uninhabited areas (SPOUA)"

⇨ **Explore the economic, social, and safety implications of adopting D4ND strategies.**

Proposal to stimulate more research on the topic, coordinated at worldwide level

Simulations

Develop and refine ablation and atmospheric chemistry models to better predict reentry products effects, such as the interaction of alumina particles with HCl or their role in producing polar stratospheric clouds.

Ground-based measurements

Analyze ablated products, NOx production, CFRP (including black carbon emission), heat shields, aluminum, or steel.

In situ measurements

Conduct aircraft and sounding balloon campaigns, in particular in polar regions, to measure atmospheric particles and gases.

Dedicated working Group on-going at international level

AIRL (Atmospheric Impact of Spacecraft Reentries and Launches
European Science Foundation, EU, ESA, NASA, NOAA, CNES, DLR, LATMOS, AAE, …

In parallel study other possibilities at system level: recovery, reusability, recycling, In-Orbit-Servicing…

Clear need for appropriate recommendations before further Mega-constellations deployment

Thank you for your kind attention