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Atmospheric re-entry of orbital objects – can "Design For Non-Demise" be the optimal solution?

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Abstract
Satellite and upper-stage re-entries pose a dual challenge: fragments that survive to the surface create a finite casualty risk, while the ablation plume injects metals, aerosols and reactive gases that can alter ozone and climate, indirectly causing health effects. Design-for-demise (D4D) minimises ground risks by maximising re-entry burn-up; design-for-non-demise (D4ND) goal is to reduce high-altitude emissions, but it may require controlled descents and extra mass. We review current evidence on casualty risk, atmospheric chemistry, and other feedbacks, showing that no unified metric yet exists, and set out research priorities for choosing the better end-of-life strategy.

1. Introduction

The orbital activities in Low Earth Orbit (LEO = Perigee lower than 2.000 km) have drastically increased over the last 10 years and are expected to reach ceiling high values by the end of decade: there were 540 active satellites in 2003, 1 200 in 2015, 12 000 in June 2025 [1] and some 30 000 to 100 000 are expected by 2030, mostly in linked to the consolidation of the constellation networks in LEO. These activities are globally well regulated at international level thanks to a large set of Standards, Codes of Conduct, Guidelines or even Laws; these texts prescribe authorized in-orbit durations after the end of operational activities, as a function of altitude regime and type of satellite, and specify End-of-Life operations such as passivation and de-orbitation (refer to French Space Operations Act FSOA for instance [2]).

One constant can be established, whatever the operations in LEO: the End-of-Life of any Space Objects lead them through Earth atmosphere. Such objects may sometimes be recoverable, for instance when inhabited and/or aimed at reusability, in which case they are equipped with heatshields but most of the times the atmospheric re-entry is destructive. These manoeuvres can be controlled as generally required in most of the Standard documents, aiming at a specific geographical location on Earth, but most of them are uncontrolled, the object re-entering randomly at the end of its orbital phase.

Re-entry follows two phases: dynamic pressure fragments the structure, then high-velocity heating melts, vaporises and sublimates it. Roughly 20 % of the initial mass can survive to the Earth's ground [3], so international standards impose some casualty-risk limits. One response is Design-for-Demise (D4D), which modifies hardware to burn up fully during atmospheric re-entry [4].

A newer concern, however, is the 80 % of material that does not reach the ground. Metal vapours and aerosols, formed between 30 km and 70 km, may affect ozone and climate [5]. This raises a dilemma: favour complete ablation to remove immediate ground risk or adopt Design-for-Non-Demise (D4ND) to curb atmospheric emissions. The remainder of this paper examines that dilemma and outlines the research needed to resolve it.

2. Atmospheric re-entry

Controlled, guided, atmospheric re-entry is always preferable as End-of-Life manoeuvre as it enables to significantly reduce the impact area at the surface of Earth, enabling to aim at un-inhabited zone. Nevertheless, the effects of the atmospheric re-entry on the space object are very similar: a controlled re-entry will lead to higher peak thermal fluxes, as a random re-entry will mean higher time-integral fluxes, the effect of both greatly depending on the geometry and manufacturing of the re-entering objects.

A random, or uncontrolled re-entry, is the effect of dynamic pressure, hence the drag (1).

$$\frac{dV(t)}{dt} = \frac{1}{2}\frac{S(t).Cx(Z,M)}{m(t)}\rho(Z).V(t)^2 \quad (1)$$

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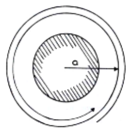
The induced deceleration depends on numerous factors, most of them associated to high dispersions or unknowns. The high-altitude atmospheric density ρ(Z) for instance, is directly linked to altitude Z of course, but also to Solar activity, in addition to geographical relations, leading to dispersions often reaching more than a factor 2. The same is true for the Drag Coefficient Cx (Z, M), function of Altitude and Mach number M, but also of many other parameters, as the temperature of the object, inducing in the best case a dispersion of as +/- 20%. The reference surface also depends on the attitude of the object at re-entry, which may strongly vary depending on aerodynamic coefficients, lift and drag, themselves function of altitude and Mach, specifically when the object is tumbling. Last, the mass m(t) itself of the object may be an unknown, depending for instance on the residual consumables, and varying during the re-entry phase. The reader may be interested by a much more detailed description form the application document of the tool STELA, re-entry freeware developed by CNES, today recognized as the reference tool at international level [6] adopted via the ISO standards family ISO 27852 [7].

Then one considers in addition the classical orbital movement formula (2) where "μ" expresses the gravitational constant of Earth and "a" the semi-major axis of the orbit, "R" being the Earth radius

$$\frac{V(t)^2}{2} - \frac{\mu}{R + Z(t)} = -\frac{\mu}{2a} \qquad (2)$$

The combination of the two leads to the equation (3) of the spiral which the orbital object will follow until the final phases of its atmospheric re-entry.

$$\frac{da(t)}{dt} = -\rho(Z)\sqrt{\mu a(t)}\frac{S(t)Cx(Z,M)}{m(t)} \qquad (3)$$



The main consequence of this spiral, when considering all the unknowns and dispersions, is the fact that the date of effective re-entry (say, at Z = 120 km for instance), is very hard to determine. One usually considers that the typical precision in the re-entry date is in the best case of the order of +/- 10% of the remaining time before impact. Considering the associated re-entry velocities, a lack of precision in the re-entry date induces a lack of precision in the re-entry location; typically, an error of 2 minutes in the re-entry date leads to a dispersion of the impact point of 1 000 km, the size of France. Fig (1) gives a real example of such dispersions, showing the predicted re-entry tracks of a space object, 16 hours before impact. Dedicated tools such as STELA [6] do a good job assessing the re-entry date, but the re-entry location remain widely dispersed.

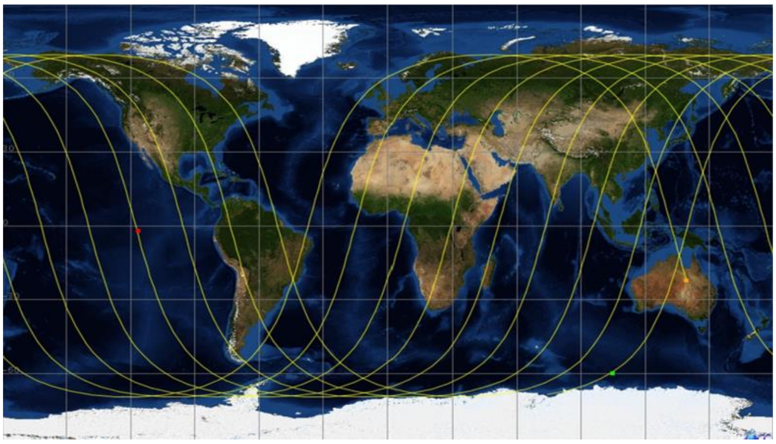


Fig. 1: example of random re-entry tracks, 16 hours before effective impact on Earth Surface (CNES)

During the atmospheric re-entry phase, random or controlled, the space objects will first be submitted to the dynamic pressure, proportional to the square of the velocity, inducing a significant fragmentation occurring typically between 90 and 70 km. Depending on the architecture and materials of the object, "fragile" objects such as Solar Panels, antennas, or even primary structures, may be broken and released when local stress becomes higher than strength.

Then, at lower altitudes, between 75 and 50 km, the thermal flux induced by the atmospheric friction (typically proportional to $V^{3.15}$ and to the inverse square root of local radius of the stagnation point), will lead to the weakening of the structural links adding to the fragmentation, then partial melting, ablation of some structures, depending on numerous parameters such as the optical properties of involved materials. Some observations of a complete atmospheric re-entry phase have done, but they are complex to perform, requiring dedicated airborne means with high performance sensors [8].

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Fig (2), courtesy of The Aerospace, from [9], describes the main phases of such a re-entry. The objects that survive this "thermal phase" and partial burn-up will impact the surface of the globe.

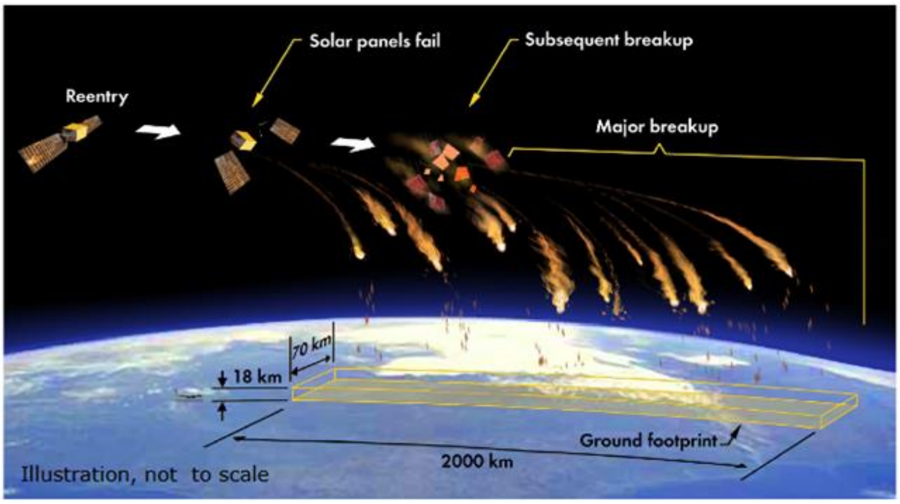

Fig. 2: Typical atmospheric re-entry phase – The Aerospace from [10]

3. Survivability of space objects following an atmospheric re-entry

The demise process occurring during the heat flux phase at re-entry is not quite complete. Depending on the references, authors consider that some 5 to 30% of a space object may survive re-entry and hit the Earth surface. These objects basically fall into 4 categories:

- The refractory objects, either composed of high-melting temperature materials (Titanium, Stainless Steel…) or presenting a higher optical emissivity that absorptivity, such as some CFRP structure.
- Dense objects which should melt and vaporize at re-entry but do not have time during the re-entry duration (typically 20 minutes) to do so due to high heat capacity.
- Highly intricated structured, nicknamed "matrioshkas", should melt, but the external structures protect the inner ones up to Earth impact.
- Last, very High Area-to-Mass (HAM) ratio objects, nicknamed "dead leaves" loose velocity at very high altitude, and end-up the re-entry at relatively low velocities, not feeling any heat flux.

The figure (3), composite of various observed examples of re-entries with surviving structures derived from [11], give examples of the four families, from Left to Right.

It is important to underline that such re-entry events with surviving artefacts hitting the Earth surface are extremely frequent: during the single year 2024 for instance, 2 205 catalogued objects (larger than 10 cm) re-entered atmosphere, among which 1,237 integer objects, satellite, or orbital stage, hence more than 3 per average day. Considering an average mass survivability of 20%, the "natural cleaning" of atmosphere brings a lot of "Sky falling on Chicken Little".

Some tools, quite complex, have been developed by the major space agencies to model this phase and predict the survivability of space objects during the atmospheric re-entry phase. A typical example of such tool, widely used in the "Mission safety files" is the freeware DEBRISK, from CNES [12].


Fig. 3: compound of typical surviving objects (derived from Paul Maley [11]*)*

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4. Casualty risk on ground

The surviving elements may wound or kill people on ground, either through direct impact (head…) or via an indirect impact leading to secondary consequences, as when hitting a plane, a train, a chemical plant, …

The international community has worked on the topic since a couple of decades, and has reached a good consensus on the modelling of such consequences; for instance, the ISO 27875 represents the typical approved methodology and thresholds [13]. A falling debris is considered to be potentially lethal when presenting a kinetic energy at impact higher than 15 Joules. Then the international rules specify an allowable casualty risk lower than 10^{-4} per re-entry, meaning that if the remains of a re-entering space object present a cumulated risk lower than 1 in 10 000 it is tolerable. Rough figures show that this threshold, as a first order of magnitude, corresponds to objects with a mass of 700 kg of a casualty area of 7 m² (definition and computation described in [13]). These requirements are widely shared in the Standards, Guidelines and Laws at worldwide level; examples such as the Chinese standard [14], ISO standards [15], French Space Operations Act [2], Japanese Space Debris Mitigation Standard or US Gov Orbital Debris Mitigation Standard Practices [16] among others may be quoted here.

Determination of the survivability of elements is complex. Numerous tests have been performed in High Enthalpy test facilities to evaluate what becomes of classical space objects elements during an atmospheric re-entry. The two composite figures (4) show typical results of such tests performed at the DLR-LBK arc-jet facility in Köln, with up to 16 kPa dynamic pressure combined with 3 MW/m² (a harsh re-entry), on typical elements composing a small satellite: left timely CubeSat test demise, right remains following such tests, showing partial survivability of elements such as batteries, inertia wheels, "protected" structures, electronics, etc.

Fig. 4: Typical results from tests in arc-jet facilities [17]

It is worth mentioning here the recent controversy concerning the risk associated to the re-entry of Starlink satellites. FAA published a report, based on a The Aerospace dedicated study attached to the reference [10]). This study claimed that there would be a risk of killing someone evaluated at 60% per year in 2035 due to random re-entries of Starlink satellites, and 0.07% risk of hitting a plane in flight. This result was contested by SpaceX, indicating that their satellites burn-up totally at re-entry, and stating that The Aerospace experts did not have elements concerning the technologies used on Starlink satellites [18]. This claim is interesting as there were recently some elements found on ground, believed to be associated to Starlink re-entries (potentially a piece of the antenna, 45 x 6 cm wide, Fig. (5))

Fig. 5: Debris potentially providing from a Starlink satellites, as claimed by [19]

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These findings consolidate a general trend in the current standards aiming at minimizing the casualty risk on ground through Design-for-Demise (D4D) which is generally strongly encouraged. This can be achieved by properly selecting the architecture and materials in order to minimize the number of surviving elements. There has been a very large amount of literature on the subject these last 15 years, so the practice appears to have reached a good consensus at international level (the reader can refer to [20]).

5. Atmospheric pollution

5.1 Description of physico-chemical phenomena governing anthropogenic atmospheric re-entry

As the space object enters into the atmosphere at an orbital velocity -around 8 km/s-, its surface temperature rises and it goes under a suite of ablation mechanisms, such as melting, sublimation, evaporation, non-equilibrium chemistry, and material spraying, leading to losses of mass [21]. There are three principal physical phenomena:

1. Shock-wave heating: the extreme velocities lead to a shock wave that compresses the surrounding air, leading to the dissociation of N_2 and O_2 through the Zeldovich mechanism, producing nitrogen oxides, or NO_x [22]. Certain surface coatings can also release chlorine radicals (Cl) [23]. The bow-shock layer appears mainly at altitudes between 60 km and 80 km [3].
2. Break-up and thermal ablation: when the dynamic pressure exceeds the structural strength, the object breaks-up, creating fragments that melt and then vaporize. Carbon-fibre-reinforced polymers (CFRP) may be subject to pyrolysis [24], while direct solid-to-gas transitions can occur for metals like aluminium alloys [25].
3. Sputtering, described as an ejection of surface atoms by energetic particles due to collision. It is dominant for micrometeoroids and is supposed to be negligible compared to thermal ablation for anthropogenic re-entries [26].

5.2 Particulate and gaseous emissions expressed as a percentage of the re-entering object's mass

Available measurements on particles and gas emitted from anthropogenic atmospheric re-entries remain sporadic, and NASA stresses that there is no available common formalism for describing by-products [27]. The limited assessments to date indicate that roughly 60% to 100% of a space object's mass is burnt during descent, and the major part above 50 km [3]**.** Schulz et al. (2021) estimate a demised mass of 80% for a spacecraft, 65% for upper stages, 30% for core stages, and they assume 100 % demise for large constellations satellites [28]; this last figure may be an over estimate, as a debris from a Starlink satellite was found on the ground in 2025 [29].

Nitrogen oxides form within the shock wave, between 60 and 80 km [3]. Reported data span from 17.5% of the vehicle mass into NO_x for the reusable Space Shuttle, with a peak abundance near 68 km [30]; expendable objects analysed in the ATISPADE study released around 35 to 40% of their mass into NO_x, a figure that applies whether the descent is controlled or not [23]; and when the shock chemistry is excluded, the ARA model finds a 9% of the object mass converted in NO_x [23]. Studies on meteoroid entries show that the NO_x formation is highly non-linear in object geometry, entry velocity, altitude, and incidence angle, and Larson and al. (2017) stress that the mechanism behind NO_x formation is exponentially dependent on temperature [31]. In addition, at lower altitudes, where O_2 is more abundant, dissociation happens more frequently to synthesise NO. Finally, the larger the cross-section, the higher the amount of NO_x at the same entry velocity [32]. Specific resins and coatings also introduce chlorine into the shock layer, with an average emission factor of about 2.3% of the object mass according to ATISPADE [23].

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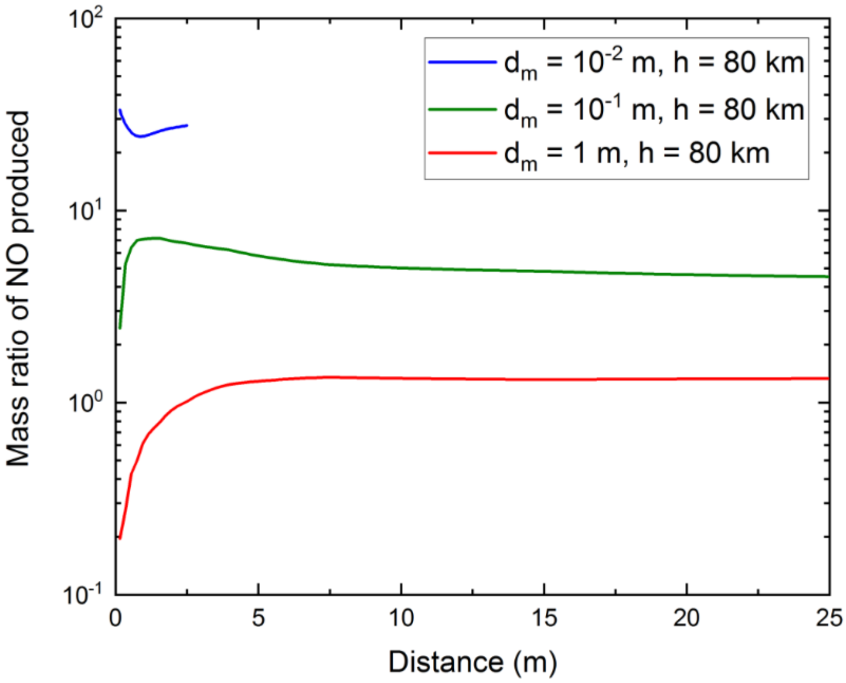

Fig. 6: Ratio of cumulative mass of NO produced between 10 km/s and 5 km/s by meteoroids travelling at 80 km altitude, from [32]*. This figure shows that for a 1-meter diameter meteoroid, the cumulative mass of NO produced at 10 km/s and 5 km/s is of the same order of magnitude.*

Oxidation and sublimation of reactive metals produce aerosols, mainly aluminium oxides. Worst-case analyses usually assume that 100% of the ablated aluminium is converted into Al_2O_3 [3]. Ferreira et al. (2023 & 2024) conducted a study on a 250 kg satellite containing 30 % aluminium, and estimated that roughly 32 % of that aluminium is actually transformed into aluminium oxides (AlO), which equals to 12% of the initial satellite mass [33] [26]. The Molecular Dynamic simulation used in the same study evaluates the creation of Aluminium Oxides clusters in the mesosphere, an oxygen-deficient environment [26], implying that if the ablation process happens at a lower altitude, it could generate more aluminium oxides. Similar physical phenomena inject oxides of copper, zinc, titanium, and other alloy compounds, although quantitative data remain sporadic [34]. Pyrolysis or combustion could form some by-products from graphite epoxies or carbon-fibre-reinforced polymers, like CO_2, CO, H_2O, and probably black carbon, but it is still unverified experimentally. Trace of particles can be emitted from Ti components, lithium-ion batteries, or niobium alloys [35] [36].

The diversity of species, the altitude-velocity-inclination-dependent chemistry, and the large disparities in reported data highlight the relevance and the need for multiplying research initiatives to better understand the mechanisms of anthropogenic atmospheric re-entry [27].

5.3 Atmospheric interactions, transport mechanisms, and resultant atmospheric effects

The discussion below concerns the possible environmental impacts of anthropogenic atmospheric re-entries. To date, the literature addressing impact generated by re-entry by-products is extremely sparse; existing research mainly focuses on emissions from rocket motors.

The behavior of alumina particles heavily depends on their size, injection location, and spatial distribution [37]. Molecular-dynamics simulation by Ferreira et al. (2023) resulted in freshly formed Al and AlO clusters measuring a few nanometers in diameter [26], whereas 2023 SABRE measurements detected aluminum aerosols of 120 to 600 nm in the stratosphere [36], implying that they coagulate through sulfuric acid or vapor condensation, as Ferreira et al. (2023) also suggests. Only particles below a certain diameter remain suspended in the atmosphere: Ross and Schaefer (2014) stated that diameters must by <1 µm to stay aloft in the stratosphere [37], but the dynamics in the mesosphere differ. A model conducted by Maloney et al. (2025) with particles from 0.01 µm to 17 µm in the mesosphere predicted that the alumina can take 1 to 3 years to descend to ozone-layer altitudes, and tend to accumulate at high latitudes in both hemispheres between 10 km and 30 km; indeed, all re-entry cases in the simulation show an accumulation over

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the southern high latitudes within the first five months [5]. Jan and Hastings (2023) likewise found that alumina released over the South-Pacific disposal zone remains mainly in the Southern Hemisphere for ~ 2 years [25]. The ARA study (2023) reported residence times of 24 days for Al_2O_3 and 15 days for TiO_2 for particle sizes were "relatively large", though that term was not specified [38].

Aluminum oxides influences ice nucleation, leading to the formation of stratospheric clouds in polar regions. These clouds release chlorine (Cl) that accelerates ozone-destructive reactions [33]. Other metal cations may similarly affect cloud formation and wider atmospheric processes [36]. Alumina aerosols can also perturb radiative forcing, while the exact consequences and orders of magnitude are still poorly understood and highly depend on the particles size distribution, with a most negative radiative forcing effect for size near ~240 nm radius [39]. Maloney et al. (2025) showed cooling in the lower stratosphere but heating higher up, with consequent changes in winds and chemistry; they reported both ozone-column gains and losses depending on scenario and noted that potentially important heterogeneous surface chemistry was omitted [5]. Sharma et al. (2024) found that the climate response to alumina injection is larger with low-latitude injections [27]. Black carbon, if emitted during re-entry, tend to warm the lower stratosphere, and the resulting temperature rise further accelerates ozone-destructive reactions, and its capacity to support ozone-destroying chemistry remains speculative [40]. Nitrogen oxides formed at high altitudes have relatively long residence time. Although their post re-entry chemistry needs further research, NO_x is known to deplete stratospheric ozone [41].

6. Overall atmospheric burden and prospects

6.1 Comparison with natural influx

Roughly 900 tons per year of anthropogenic material enters Earth's atmosphere from orbit, with approximately 350 tons injected in the atmosphere [28], while the natural influx stands from 6,000 to 25,000 tons per year [28], of which 93 % of particles having a mass inferior to 10 g.

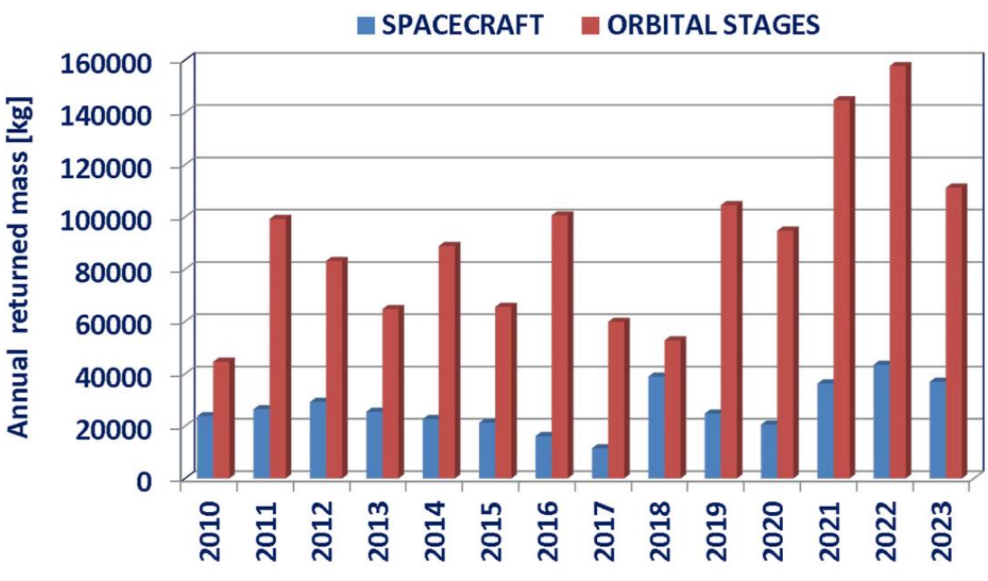

Fig. 7: Large spacecraft and orbital stages mass (kg) re-entered uncontrolled [42].

For nitrogen oxides, Fischer et al. (2024) conclude that the NOx generated by re-entering rocket structures remains below the meteoritic contribution, a statement derived using the customary assumption that 17.5 % of the incoming mass of a reusable vehicle converts to NOx during re-entry [35]. The picture is different when looking at ablation mechanisms, as the same study estimates that, given assumptions of ablation efficiencies exceeding 90 %, the aluminium delivered by re-entering launcher hardware already surpasses the meteoritic aluminium influx in the year 2021 [35]. At present, all anthropogenic re-entry material combined represents roughly 2.8 % of the natural meteoroid mass influx, yet modelling by Schulz & Glassmeier (2020) shows that this share could rise to nearly 40 % in future prospects. The same authors place today's anthropogenic-to-natural ratios at about 1.6 for aluminium, 7.2 for copper and 1 for titanium. By contrast, Ferreira (2023) derives a lower current ratio for aluminium (0.87), although he still notes an eight-fold rise since 2016 [26].

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Future scenarios diverge. The Schulz & Glassmeier (2020) worst-case forecast suggests mass factors of 19, 49 and 25 for aluminium, copper, and titanium, respectively, whereas Ferreira (2024) projects a more moderate aluminium excess of 6 × natural levels, corresponding to > 360 t yr^{-1} of Al_2O_3 clusters from satellites [33]. One year earlier, the same author estimated that respective contributions from launch vehicles and satellites could reach 500 t yr^{-1} and 910 t yr^{-1}, producing an overall excess ratio of about 10 × relative to meteoritic sources [26].

Observational evidence from SABRE measurements corroborates the growing anthropogenic injection into Earth's atmosphere: stratospheric aerosol sampling indicates that 10 % of particles already contain aluminium originating from space object demise. The authors warn that, with continuing growth in re-entry traffic, the fraction of stratospheric sulfuric-acid droplets bearing satellite-derived metals could approach the 50 % level presently associated with meteoric inputs [36].

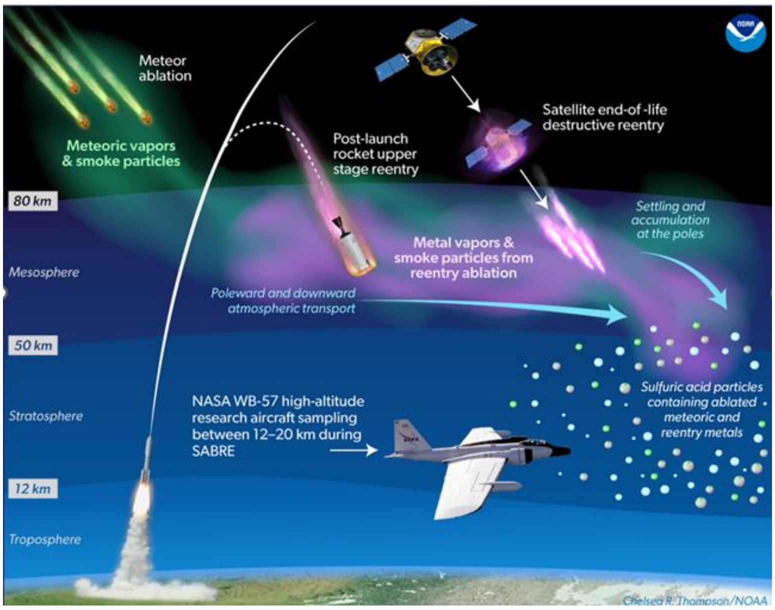

Fig. 8: SABRE measurements campaign, from [43].

6.2 Potential global atmospheric impacts

Modelling studies agree that re-entry emissions can perturb stratospheric chemistry, yet they diverge on the magnitude of that perturbation. The ATISPADE and ARA assessments, for instance, found that for a normal scenario the stratospheric ozone response remains negligible: column loss stayed below 0.005 % and relaxed to < 0.0001 % after a week, and < 0.001% for the cumulative global impact of 10 years of re-entry emissions. NOx and Cl species identified as the main drivers, for short and long-term scenarios [23]. Those conclusions, however, omit the enhanced alumina burdens expected from large satellite constellations. When such alumina is introduced, Ferreira et al. (2024) project that aluminium-oxide clusters can lead to significant ozone depletion in high-traffic LEO scenarios [33]. Other global models already register a non-negligible decline. Ryan et al. simulate a decade of launch growth at 5.6 % yr^{-1} and obtain a 0.01 % drop in total O_3—ten-fold larger than ATISPADE's estimate—, half of it attributable to re-entry NOx and half to Cl from solid motors. The study found a maximum loss of 0.15 % in the upper stratosphere in the northern high latitudes; and 0.24% when including prospective space-tourism flights [44]. The authors caution that decreasing use of solid propellants could moderate that upper bound, and that the actual share of space tourism remains speculative.

Climate interactions introduce additional variability in the atmospheric impacts. Maloney et al. (2025) show that, when re-entries deposit aerosols at low latitudes, mesospheric heating anomalies of around 1.5 K, followed by a seasonal warming of the stratospheric south pole and a local increase in the column ozone concentration. In contrast, mid-latitude or equatorial patterns with small particles injection reduce northern polar ozone, underscoring the sensitivity to both entry latitude and size distribution, with low latitude re-entry locations having a potential higher impact on the climate [5]. Jain & Hastings (2023) report that alumina primarily induces a localised cooling rather than a uniform effect, and warn that uneven distribution of these cooling effects could disrupt atmospheric circulation, that may induce regional or global climate consequences [25].

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Taken together, these results indicate that the potential global impact of re-entry emissions ranges from almost negligible to regionally significant, depending on assumptions about scenarios, aerosol size and quantity, atmospheric dynamics, and injection location.

7. Risk-management dilemma

7.1 Casualty risk versus upper-atmosphere degradation

Space object designing now face a question: should a vehicle be engineered to burn up completely, implying that surviving debris might increase casualty risk, or should it aim to minimize particle and gas emissions into the atmosphere, thereby limiting long-term environmental damage? As cited in section 4, Design-for-demise (D4D) was pushed to meet the current regulatory target of ≤ 10-4 expected casualties per re-entry and, empirically, no injuries have been recorded after more than 33 800 object re-entered [45] [46]. Yet, recent probabilistic studies indicate a cumulative casualty expectation approaching two (results are derived from past ESA studies and the IAA Space Debris Situation Report of 2016 [9]), and if today's launch cadence continues, the annual probability that an uncontrolled re-entry will cause at least one casualty could approach 20 % within a decade [47]. A total demise during re-entry, however, could maximise high-altitude emissions and have an impact on atmospheric circulation, radiative forcing, and ozone depletion. Damaging the ozone layer also endangers lives, albeit indirectly and on the long run, since increased UV exposure leads to well-documented and serious consequences: a rise in skin cancer rates in humans, disruption of plant photosynthesis, and harm to aquatic ecosystems due to the vulnerability of phytoplankton, which sits at the base of the food chain [48].

The dilemma is, however, non-binary. The next section pursues a thought experiment that traces the systemic consequences of adopting a Design-For-Non-Demise (D4ND) policy, revealing a multi-layered problem that goes beyond the dichotomy of on-ground casualty risk versus health risk.

7.2 Multi-dimensional implications of Designing for Non-Demise

Design-for-non-demise (D4ND) allows a space object to retain more coherent mass into the atmosphere during re-entry so as to prevent high-altitude ablation products. Assessing such a policy requires a holistic study of economic, social, safety and environmental trade-offs before any recommendation can be issued.

Choosing a Design-for-Non-Demise (D4ND) architecture would remove high-altitude ablation and fragmentation, and the surviving mass may affect the on-ground casualty risk. In some cases, adding propulsion for re-entering could be needed. The FAA already notes that "*the best mitigation to rising safety risks is avoiding random re-entries in favour of targeted, controlled re-entries*" [10].

Propulsion modules, thermal insulation or reshaped frames all add mass to the satellite; launchers must then lift more propellant, dragging extra costs and emissions into the life cycle. Three decades of work by Ross and co-authors show that launcher stages inject gas and particles that warm the stratosphere and perturbs ozone [37]; although the exact orders of magnitude are poorly understood and highly depend on the propellant type.

Material substitutions bring further externalities. Replacing primary aluminium with primary titanium for instance, to reduce the ablation mechanism, increases mass and related impacts. In addition, titanium is one of the EU's twenty critical raw materials [49]. Switching to carbon fibre reinforced polymers (CFRP) can lighten the structure and slow ablation, yet experimental data confirm that carbon-epoxy still ablates under entry heating [50].

Unless D4ND incorporates explicit deceleration, for example an inflatable device (such as IRDT [51]) that can lower the entry velocity, it does not necessarily reduce NO_x formation. Larger intact bodies should emit more NO_x, yet no study found the function linking NO_x to mass, geometry, and speed, so relative benefits versus D4D remain speculative.

Some controlled descents target the South-Pacific Ocean, in particular the SPOUA, also called the "Nemo point". Jain & Hastings (2023) showed that concentrating alumina injections over one hemisphere generates a radiative imbalance capable of intensifying tropical cyclones and altering Sahel rainfall [25]. Valdivia (2024), in an UNOOSA Workshop presentation, noted that cumulative spacecraft and debris injections at the "Nemo point" in the ocean may have an impact due to its interaction with oceanic currents, although it has yet to be quantified [52]; the mass involved is likely limited compared to the ~10,000 containers NOAA estimates are lost overboard each year [53].

In addition, space debris has raised diffuse sky-brightness by almost ten percent, which is the threshold set by the International Astronomical Union to define a sky as polluted for observations [54]. Luminous re-entry trails could

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add to this load by increasing the opacity of the Earth's atmosphere [55]. Whether the reduced fragmentation and burning from a D4ND policy lowers those trails or not is still an open question.

Conversely, a D4ND architecture may be selected to recover and reuse the space object: in this case, it would remove the potential marine impacts, could reduce the NO_x formation during re-entry, following the Space Shuttle model, and would reduce the raw material demand in the manufacturing phase.

The design trade-offs therefore extend across at least three distinct dimensions: (i) casualty probability, (ii) ozone-depletion potential, (iii) climate forcing on the upper atmosphere, and at the surface. No single design seems to find a minimum to all these indicators. Reducing re-entry emissions may shift the burden to the launch phase and casualty risks, while reducing the potential impact of the re-entry phase and the ozone. Jain & Hastings recognized the same dilemma, and judged D4D "tolerable" after studying the alumina injected by re-entering space objects [25], but their model omitted NO_x chemistry and ozone-depletion effects. Conversely, the American Astronomical Society (AAS) in September 2024 encouraged to use the precautionary principle to prevent the generation of re-entry aerosols [55].

Finally, shifting from D4D to D4ND may affect satellite performance and costs, raising questions about the business models of large and low-orbit constellations. This opens a new interdisciplinary field where engineering design, atmospheric science, policy, and business scenarios must converge before definitive guidance can emerge.

8. Recommendations and discussions

This analysis shows that neither complete demise nor full non-demise satisfies all safety, and environmental constraints. With the expected increase of launch activities, notably in the context of future mega-constellations deployment poised to multiply satellite and upper-stage re-entries by at least an order of magnitude, the community needs filling several knowledge gaps to allow responsible design and operations. Coordinated in-situ measurements, high-fidelity simulations, and harmonised indicators will give choice-makers the quantitative data they need to balance safety and environmental performance.

In particular, we recommend coordinated international research programmes, combining high-fidelity measures with simulations and standardized tools, through:

1. In-situ measurement with sounding balloon and aircraft campaigns, in particular in polar regions, to map the gas and particles produced both during launch (stratosphere) and during re-entry (mesosphere).
2. On-ground measurements to analyse ablated products, NO_x production, CFRP (including potential black carbon emission), heat shields, aluminium, and steel, to complement in-situ measurements.
3. Simulations to refine models on the re-entry by-products, including size-distribution and optical properties of the aerosols formed at high altitude, and to assess local and global atmospheric models to track how those emissions interact with circulation and influence radiative balance and ozone chemistry.
4. Studies to understand the astronomical consequences of re-entry light-trails and on the marine impacts of space objects re-entry, comparing D4D and D4ND scenarios.
5. Dedicated research programmes and working groups, including supporting already existing programmes such as the AIRL (Atmospheric Impact of Spacecraft Re-entries and Launches) working group that federates efforts from the European Science Foundation, the EU, ESA, NASA, NOAA, CNES, DLR, LATMOS, AAE, MaiaSpace and other stakeholders.
6. Development of harmonised indicators, linking casualty risk, ozone-depletion potential, climate forcing, brightness pollution and marine stress

Finally, this research should not omit taking into account the recovery, reusability and in-orbit recycling services as complementary system-level mitigation measures.

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