Atmospheric ablation: the potential environmental impact of space debris re-entering Earth's upper atmosphere

Beyond the Burning: *Researching and Implementing Policy Solutions for Sustainable Debris Ablation*

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TN-03 Report on critical landscape analysis

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1 Introduction

This project seeks to establish a comprehensive research framework aimed at mitigating the environmental risks associated with atmospheric ablation of end-of-life spacecraft. By integrating a deep understanding of current atmospheric ablation research with a broad perspective encompassing technical, geopolitical, and socio-ecological factors, we will develop a robust research program with cascading short, medium, and long-term goals. Our focus will be on identifying and addressing critical knowledge gaps and challenges within the field of atmospheric ablation modelling and prediction. This holistic approach will enable us to explore the multifaceted implications of atmospheric ablation and pave the way for the UK to assume a leadership role in space sustainability.

1.1 Scope

This document, TN-03, successfully meets the requirements outlined in Milestone 2 (MS3) by critically analysing these interconnected landscapes. TN-03 develops 2 comprehensive scenarios with concrete recommendations for viable mitigation strategies and non-binding/regulatory instruments. In addition, TN-03 evaluates the potential environmental impacts of atmospheric ablation and explore the societal benefits of adopting Design for Demise (D4D) solutions.

1.2 Applicable Documents

Applicable documents are identified as ADn, where "n" denotes the document number from the table below.

Ref.	Document ID	Title	Rev.
[AD1]	G23A.001.PP.01	Project proposal	N/A
[AD2]	G23A.001.GFA.01	Fully executed Grant Funding Agreement	N/A

1.3 Reference Documents

Reference documents are identified as RDn, where "n" denotes the document number from the table below.

Ref.	Document ID	Title	Rev.	Date
[RD1]	ST/SPACE/61/Rev.2	International Space Law: United Nations Instruments	2	2017
[RD2]	IADC-02-01	IADC Space Debris Mitigation Guidelines	2	March/2020
[RD3]	United Nations Office for Outer Space Affairs	Long-term sustainability of outer space activities: implementation experiences, opportunities for	1	June/2024

		capacity-building and challenges.		

1.4 Acronyms and Abbreviations

Tag	Description
BNNT	Boron nitride nanotube
CFRP	Carbon fibre reinforced polymer
D4D	Design for Demise
EoL	End-of-Life
GEM	Gibbs Energy Minimisation
GO	Graphene oxide
LEO	Low Earth Orbits
MEO	Medium Earth orbits
MLI	Multi-layer insulation
TPS	Thermal protection system
VLEO	Very Low Earth Orbits

2 Technical Landscape

2.1 Design for Demise (D4D)

With the adoption of space debris mitigation guidelines by most space agencies, spacecraft in Low Earth Orbit (LEO) protected regions must be removed from their operational orbit within 25 years post-mission, resulting in atmospheric re-entry. Although most satellite equipment disintegrates during re-entry, certain critical components may survive and reach the ground, either fragmented or intact (e.g., propellant tanks, reaction wheels, magnetorquers, and optical payloads). Such events pose significant risks, especially over densely populated areas.

Per ESA's ESSB-ST-U-004 and other agency safety regulations, the estimated on-ground casualty risk for any re-entering space object must be lower than 10^{-4}. This risk assessment accounts for all fragments impacting the surface with kinetic energy equal to or exceeding 15J. For systems with high predicted casualty risks, controlled re-entries are often conducted to comply with these guidelines, ensuring that surviving fragments impact unpopulated areas. However, this approach significantly increases mass, complexity, and costs. Alternatively, uncontrolled re-entries may be used if the satellite can naturally decay within 25 years and is expected to demise upon re-entry. This strategy has fewer system-level impacts but requires additional measures to meet on-ground casualty risk requirements, often achieved through Design for Demise (D4D), which ensures spacecraft disintegration during re-entry.

D4D methods are classified into system-level approaches, impacting the entire spacecraft, and equipment-level methods, targeting specific components. Demise assessments involve computational simulations, on-ground testing, and re-entry flight experiments. Simulations attempt to model re-entry processes based on the thermal properties of common materials, while on-ground testing aims to replicate aerothermal and mechanical phenomena, enabling partial validation of simulation models. Despite the complementary nature of these methods, significant gaps and approximations remain, indicating the need for further research.

2.1.1 Previous research activities

Previous studies collectively advance D4D by exploring material choices, enhancing thermal designs, and developing new simulation methods, contributing to safer re-entry practices for future spacecraft.

2.1.1.1 ESA's Clean Space Initiative on Space Debris Mitigation

Previously, B.M. Cattani et al. explored how D4D can be integrated into mission designs to comply with space debris mitigation policies [1]This study emphasises the need for intentional design changes, such as using demisable materials for critical components and enhancing the disintegration probability during re-entry. It has been identified D4D can be achieved by using the heat required to ablate the components. This research also highlights the balance required between implementing D4D features and maintaining mission performance, aiming to make D4D a standard practice for reducing ground casualty risks.

2.1.1.2 Thermite-for-Demise (T4D): Thermite-Based Enhancements for D4D

In 2023, A. Finazzi proposed the concept of Thermite-for-Demise (T4D), where thermite materials are integrated into spacecraft to facilitate more efficient disintegration upon re-entry [2]. The study tests thermite's characteristics to optimise thermal and structural degradation processes. This innovative approach shows potential in enhancing the D4D process by maximising internal heating, which helps ensure that large structural components break down completely before reaching Earth's surface.

2.1.1.3 H2020 ReDSHIFT

The EU's ReDSHIFT project, led by A. Rossi et al., aimed to create a sustainable debris mitigation strategy by combining D4D with computational simulations and testing on materials commonly used in satellites [3]. The project evaluated the thermal and structural properties of various materials to identify those that could achieve complete demise during re-entry. ReDSHIFT's findings have informed ESA's policies and set benchmarks for developing safer, demisable materials and structures.

2.1.1.4 Early Phase Re-Entry Analysis

Previously, C. Velarde conduced early-phase re-entry analyses for ESA Earth observation missions, assessing how different configurations impact D4D compliance [4]. The research introduces simulation-based methods for testing component disintegration probabilities and optimizing component materials. This study demonstrates the importance of early-stage re-entry modelling in achieving compliance with casualty risk limits, showing that structural design choices made during mission planning can significantly enhance D4D outcomes.

2.1.2 Current research activities

Recent research projects on Design for Demise (D4D) are advancing methods for safely managing space debris during re-entry by designing spacecraft and components to disintegrate effectively in Earth's atmosphere. Current research activities represent efforts to advance D4D by integrating aerothermal modelling, structural adjustments, and experimental validations to ensure controlled and safe re-entry of space objects. Each contributes to building a foundation for safer, more predictable space debris mitigation

2.1.2.1 Destructive Re-entry Analysis Tools and Developments

Recently, C. Persis and S. Lemmens explore the latest advancements in destructive re-entry analysis tools in Europe, highlighting significant progress in the intentional design of structural components for D4D [5]. This study emphasises European efforts to improve predictive accuracy for debris disintegration during re-entry, which remains challenging due to complex interactions of spacecraft materials with atmospheric conditions. The study also suggests that enhanced simulations and experimental facilities are helping to mitigate uncertainties and strengthen safety in debris re-entry pathways.

2.1.2.2 ClearSpace One Platform and Structural Panel Demise Research

A. Looten focuses on applying D4D principles to structural panels for the ClearSpace-1 mission and has investigated the design and material choices that improve predictability in re-entry disintegration, which is vital for minimising on-ground risks [6]. This study contributes to setting safer guidelines for the demise of various spacecraft structures, supporting future missions in achieving compliance with safety requirements.

2.1.2.3 Aerodynamic Stability and Re-Entry Capsule Design for D4D

D. Massari addresses aerodynamic stability and demise-oriented design for a re-entry capsule [7]. This study investigates aerodynamic configurations and stability factors that ensure predictable disintegration upon atmospheric entry, focusing on the spacecraft's response to high temperatures and mechanical stresses. The study provides insights into capsule shapes and materials that could enhance D4D effectiveness, potentially reducing uncontrolled debris risks in future re-entry events.

2.1.3 Future Research Activities

Future research in Design for Demise (D4D) will focus on advancing safe re-entry methods through innovative design and material testing. It will involve extensive testing of materials and configurations to improve casualty risk assessments and make D4D methods applicable across a broader range of missions and satellite components.

2.2 Mitigation Pathways

2.2.1 Limiting the Total Amount

The total mass flux of meteoroids into Earth's upper atmosphere, though varying depending on measurement methods and assumptions, is typically estimated to be between 2,900 and 7,300 tons per year [8], [9], [10]. The metal content in meteoroids depends on their composition, which is generally classified as either chondritic or achondritic. While iron meteorites are almost entirely metallic, they are relatively rare. On average, meteoroids entering Earth's atmosphere contain approximately 10–20% metal, primarily in the form of iron-nickel alloys, with the remaining composition consisting of silicates and other minerals. Ordinary chondrites—the most common type of meteorite—typically contain 15–20% metal by mass, mainly iron [11], [12], [13].

Using a conservative estimate, the annual mass of naturally ablated metal in Earth's upper atmosphere is approximately 1,460 tons per year. Although the threshold of metal flux that the Earth's upper atmosphere can tolerate without causing harmful environmental impacts is not fully understood, the naturally occurring meteoroid metal flux can serve as a reference for evaluating acceptable levels of metal input from artificial sources.

2.2.1.1 Number of Satellite Launched

The most direct way to reduce the amount of material ablated in Earth's upper atmosphere, particularly metal, is to limit the number of satellites launched. Although the mass of a Low Earth Orbit (LEO) satellite varies with size, the Starlink V1.5 satellite can serve as a useful reference, as it currently constitutes around 40% of active satellites in LEO. Typically, around 50% of a satellite's total mass is structural and often composed of aluminium [14]. Given that the Starlink V2 satellite has a mass of 800 kg, this would equate to approximately 400 kg of metal flux per satellite upon re-entry. Consequently, the metal flux generated by around 3,650 Starlink V2 satellites (See Figure 1) would be equivalent to the natural metal flux from meteoroid entry.

Figure 1. Picture of Starlink V2-mini having a mass of 800 kg.

Each Starlink satellite has an estimated lifespan of about five years, and SpaceX aims to deploy as many as 39,396 satellites for their Starlink Gen2 constellation. The total metal flux contributed by meteoroid entry, therefore, would only support a single mega-constellation of a similar scale to Starlink. As outlined in TN01, there are several other large constellations currently in development, including:

- Kuiper (U.S., 3,232 satellites)
- Guo Wang (China, 12,992 satellites)
- Astra (U.S., 13,620 satellites)
- Semaphore-C (EU, 116,640 satellites)
- E-Space (France, 300,000 satellites)

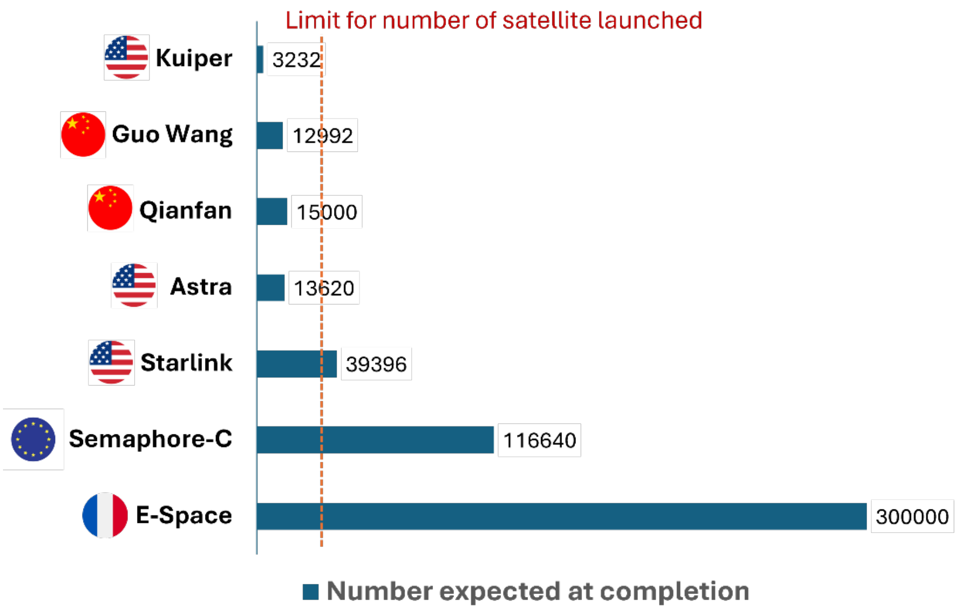

Figure 2. Planned major mega-constellations

Restricting the number of satellite launches to limit metal flux in the upper atmosphere would have significant implications for the future of mega-constellations and could constrain the use of LEO for services that rely on large satellite networks, such as communications and remote sensing.

While limiting satellite launches has no technical obstacles and directly reduces ablated metal flux, it would restrict humanity's ability to utilise outer space, impacting technology development and scientific research. Such a limitation could also stifle the growth of the space industry by capping the market, potentially leading to a future space sector dominated by a few large corporations. This could hinder market entry for small and medium-sized enterprises (SMEs), thus limiting technological innovation in the space sector.

Determining how launch mass would be allocated (e.g. across country, sector or company lines) would also likely be an extremely complex multi-country regulatory implementation challenge.

2.2.1.2 Satellite Material

Up to 90% of spacecraft re-entering the atmosphere are vaporised [15]. While little attention has been given to the fate of the ablated material, a significant environmental concern in Earth's upper atmosphere is the deposition of aluminium and other metals from spacecraft ablation during re-entry. The total amount of ablated metal flux could be reduced by replacing some metallic components with non-metallic or organic materials, which are less polluting when burned up on re-entry.

Recently, a wood-panelled satellite (See Figure 2) was launched to evaluate the feasibility of using wood in spacecraft [16]. Organic materials like wood burn more readily at higher altitudes than metals, reducing the flux of metal oxides into the stratosphere, where they pose a threat to the ozone layer. By minimizing metal usage, more spacecraft could be safely disposed of through atmospheric re-entry without exceeding acceptable metal flux limits in Earth's upper atmosphere.

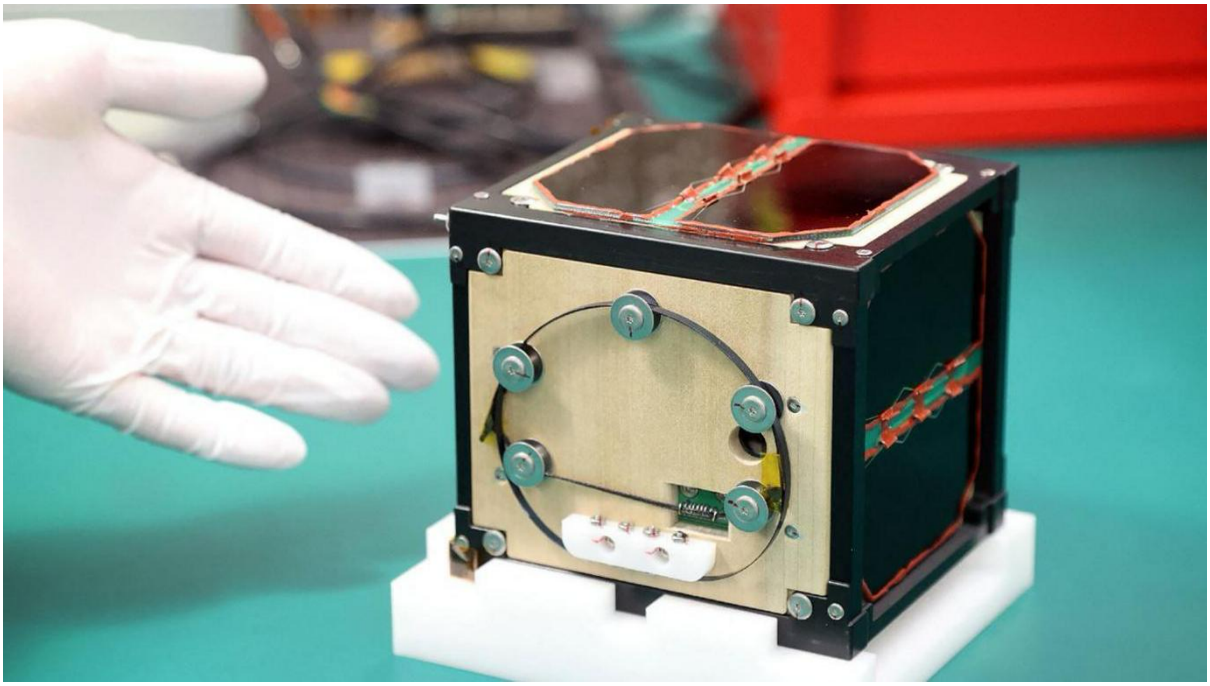

Figure 3. Picture of a wood-panelled 1U CubeSat developed by the Kyoto University.

However, material properties play a critical role in spacecraft design and manufacturing, directly affecting launch costs and system reliability. Spacecraft materials must withstand the harsh space environment, including vacuum, thermal cycling, charged particle and ultraviolet radiation, plasma effects, and atomic oxygen. These factors significantly influence the required properties of materials used in spacecraft. Improper material selection or defects can lead to catastrophic failures. For instance, the failure of Hughes HS-601 commercial communications satellites was attributed to conductive filament growth in pure tin plating on an electronic assembly [17].

Material performance can also be affected when manufacturers change materials formulations or manufacturing process steps. Numerous occurrences were noted during the Space Shuttle Program when unreported manufacturing changes resulted in unexpected materials performance during flight. What manufacturers or raw material suppliers may consider as insignificant changes can require expensive hardware rework or disposition rationale development when discovered downstream in the manufacturing or launch preparation flow.

The primary role of the structure in a spacecraft is to maintain stiffness during launch and provide a high conductivity thermal pathway of internally power dissipating components to external surfaces where the heat can be radiated. It is not yet clear if alternative approaches, such as wood, could meet the demanding thermal and structural requirements of an operational satellite.

Changing spacecraft materials mean redeveloping all manufacturing and assembly processes, including environmental qualifications. Spacecraft materials should be selected based on the environment and the time of exposure, with either durability in that environment or known degradation for appropriate endurance and end-of-life properties. They should be correctly assembled and maintained, with proper compatibility with surrounding materials and corrosion prevention. While reducing metal can minimise the environmental damage caused by ablated metal flux, the space industry will require significant effort and resources to develop and verify manufacturing and assembly procedures with new materials.

2.2.1.3 D4D

Design for Demise (D4D) approach has emerged as a critical strategy for mitigating space debris propulsion in LEO (Low Earth Orbit) environment. By ensuring that spacecraft components are designed to disintegrate completely during atmospheric re-entry, the approach minimises the uncontrolled re-entry casualty risk to people caused by space debris. Current D4D approach aims to modify a spacecraft design and conception process to achieve the safest destructive re-entry possible by material substitution, specific geometries, or dedicated subsystems.

The amount of ablated material flux entering Earth's atmosphere can be significantly reduced by designing spacecraft to demise at lower altitudes, where atmospheric density is higher, and heating rates are more intense. Materials such as aluminium and titanium, commonly used in spacecraft structures, tend to ablate at higher altitudes, contributing metal flux into the mesosphere and stratosphere, where they may have long-term environmental impacts, including ozone layer depletion [18]. Using materials that burn up more readily and modifying component geometries to enhance aerothermal loading can help ensure more complete disintegration at lower altitudes, reducing the deposition of harmful metallic oxides.

While shifting the demise altitude downward can minimise ablated material flux in the upper atmosphere, it introduces the risk of surviving debris reaching the ground. Components with high melting points or low surface-area-to-mass ratios, such as propellant tanks or reaction wheels, may not completely burn up even at lower altitudes [19]. Such surviving debris poses potential hazards to populated areas. Studies have shown that uncontrolled re-entries account for most of the on-ground casualty risks associated with space operations, with critical components surviving re-entry being the primary contributors [20].

For addressing this challenge, the D4D approach must strike a balance between reducing ablated material flux and ensuring public safety. Strategies could include:

- **Enhanced Component Design**: Utilizing materials with lower melting points and higher susceptibility to aerodynamic forces for components with high demise resistance.
- **Self-Destructive Structures:** Using structural fixtures which are designed to come apart at preset altitudes to expose internal components to re-entry heating.
- **Controlled Re-Entry**: Employing controlled re-entry manoeuvres to direct surviving debris toward unpopulated areas, such as oceans, minimizing the risk to human life.
- **Risk Modelling and Analysis**: Incorporating advanced modelling tools to predict the likelihood of debris surviving re-entry and assessing ground impact risks [21]

Advancing the D4D approach with reducing harmful environmental impact by ablated spacecraft materials requires continued research into materials science, re-entry dynamics, and risk mitigation strategies. Collaborations between industry and regulatory bodies, such as ESA and NASA, can help refine standards for spacecraft demise while addressing both environmental and safety concerns. Integrating these measures into future spacecraft designs can ensure sustainable use of Earth's orbital and atmospheric environments.

2.2.1.4 Post-mission Disposal Practice

Modifying post-mission disposal practices offers potential strategies to mitigate this flux. Key approaches include **controlled re-entry disposal methods**, **in-orbit disposal**, **in-orbit reuse and controlled non-destructive re-entry**. While each method has distinct advantages, challenges related to feasibility, cost, and practicality remain critical factors in their adoption.

Controlled destructive re-entry involves guiding the spacecraft to re-enter Earth's atmosphere in a planned and predictable manner, typically targeting remote and unpopulated regions such as the Pacific Ocean's "spacecraft cemetery." By ensuring re-entry occurs over these safe zones, controlled re-entry minimises the risk of harmful debris reaching populated areas. Additionally, by tailoring the re-entry trajectory and timing, it is possible to maximise the demise of materials at lower altitudes, reducing the deposition of ablated material in the mesosphere and stratosphere.

While controlled destructive re-entry offers a significant reduction in environmental and safety risks, it is energy-intensive and often requires additional onboard propellant and control systems. For small satellites and CubeSats, which often lack onboard propulsion systems, implementing controlled re-entry would necessitate design modifications that increase mission complexity and costs [22]. Particularly for CubeSat smaller than 6U, it will have very limited capability for controlled destructive re-entry as a propulsion system required for controlled re-entry is bigger than 2U.

Alternatively, in-orbit disposal can be considered, which involves moving defunct spacecraft to designated graveyard orbits or other orbital regions where they are unlikely to pose hazards to operational satellites or generate debris. By avoiding re-entry, this method eliminates ablated material flux entirely. However, in-orbit disposal is primarily suitable for high-altitude spacecraft, such as those in geostationary orbits, where moving to a graveyard orbit requires less energy than a controlled descent to Earth.

For low Earth orbit (LEO) satellites, in-orbit disposal presents significant challenges. Moving satellites to higher orbits where they do not re-enter naturally requires additional propellant and larger propulsion systems, leading to increased launch mass and mission costs. These added expenses make in-orbit disposal impractical for most commercial LEO satellites, especially large constellations like Starlink or Kuiper, which rely on cost efficiency to remain viable. For example, the Starlink V2 satellite operating at 550 km altitude requires about 334 m/s of delta-V to dispose it beyond the LEO protected region at the end of mission. Compared to about 100 m/s of delta-V required for disposing it by atmospheric re-entry, in-orbit disposal beyond the LEO protected region will require significantly more propellant. Furthermore, leaving defunct spacecraft in higher orbits contributes to long-term debris risks, as after any fragmentation event the debris will pass down through the LEO protected region, undermining the sustainability of orbital operations.

In-orbit reuse can also be considered, which involves repurposing spacecraft components or systems to extend their functional life or support new missions. This approach is gaining traction with technologies like on-orbit servicing and manufacturing. For instance, spacecraft could be designed with modular components that can be retrieved and reused to construct new platforms or repair operational satellites. Alternatively satellite structures can be recycled and 3D printed into new structures, as demonstrated by ESA in 2024 [23]. By keeping materials in orbit, this method eliminates ablated material flux entirely and supports sustainable space operations.

While promising, in-orbit reuse faces several technical and economic barriers. The development of in-orbit servicing and manufacturing infrastructure is still in its infancy, and retrieving spacecraft components for reuse is costly and complex. Moreover, retrofitting satellites with modular designs for future reuse or optimising for recycling requires significant upfront investment and could increase mission costs beyond the reach of smaller operators. Thus, while in-orbit reuse aligns with long-term sustainability goals, its widespread adoption may be limited to large-scale or government-funded programs in the near term.

Controlled non-destructive re-entry methods attempt to safely protect the spacecraft as it goes through re-entry to significantly reduce the amount of ablated material being released. Given the size of most spacecraft doing an uncontrolled non-destructive re-entry would likely be in breach of the ESA casualty probability limits and so a controlled re-entry to a safe surface location is required. If parachutes or soft-landing devices are also included then the spacecraft can be recovered for recycling or refurbished to fly again. Previous examples of this method include the US Space Shuttle, X-37B and SpaceX Dragon, which return the majority of their orbital element.

This method is significantly more complex than the above options because it requires a heat shield and controlled re-entry systems, however there are benefits to industry in terms of reduced rebuild costs and faster constellation replenishment time. As well as these benefits it has the potential to reduce the metal-oxide emissions to near zero and also reduce the in-orbit collision risk as spacecraft would be returned soon after their end of mission. It may also be possible to return partially failed spacecraft, reducing fragmentation risks and enabling post recovery investigations to improve future reliability. This method has the greatest possible environmental benefits but likely the highest technological hurdles to overcome as adapting mega-constellations for safe return will be a challenge.

Each post-mission disposal practice offers unique opportunities to reduce ablated material flux, but requires trade-offs between environmental benefits and practical feasibility. While controlled destructive re-entry can reduce both ablated material flux and ground impact risk, it requires additional onboard systems and propellant. Controlled non-destructive re-entry can eliminate metal-oxide emissions but as well as propulsion also requires a heat shield and landing protection systems. The use of in-orbit disposal can eliminate ablated material flux at the Earth's upper atmosphere but increases costs significantly and contributes to orbital debris risks in long-term space use. Although in-orbit reuse offers long-term sustainability with avoiding the ablation of spacecraft materials at the Earth's upper atmosphere, it will require substantial technological advancement and upfront investment.

Therefore, a hybrid approach that combines these methods, tailored to mission-specific needs, may provide a balanced solution. For instance, reusable systems could be prioritised for high-value spacecraft, while controlled destructive re-entry could be mandated for small satellites to mitigate environmental risks.

2.2.2 Limiting the Presence Time

The aerosol particles in the stratosphere contain aluminium and other metals are considered as problematic as their long-term presence in the stratosphere is affecting the ozone layer and Earth radiation balance. While the influence of metallic aerosol particles on the stratosphere is unknown, limiting their presence time on the Earth’s upper atmosphere can minimise their long-term environmental impact.

2.2.2.1 D4D

The D4D approach can provide a promising pathway to reduce the environmental impact of spacecraft re-entry by enhancing the disintegration of spacecraft materials in Earth's atmosphere thus limiting the presence time of ablated metal particles, such as aluminium and titanium oxides, in the upper atmosphere. These particles, which are by-products of spacecraft ablation, can persist in the mesosphere and stratosphere, contributing to ozone depletion and other atmospheric changes [23]. However, implementing D4D for this purpose introduces several technical and practical challenges for spacecraft manufacturers, because a significant number of spacecraft materials/systems have not been characterised during re-entry, and their high temperature chemistry is not well known.

D4D strategies can be adapted to ensure that spacecraft materials either burn up more completely or ablate at lower altitudes, where atmospheric density facilitates faster deposition and sedimentation of metal particles. Metals such as aluminium, commonly used in spacecraft structures, typically ablate at high altitudes due to their high melting points and resilience to aerodynamic heating [6]. By modifying material composition and spacecraft design, the altitude at which ablation occurs can be lowered, reducing the time metal particles remain suspended in the atmosphere. This can be achieved by replacing high-melting-point metals with lower-melting-point materials or metal composites that disintegrate at higher heating rates. We can also alter spacecraft geometry to maximise aerodynamic heating and enhance material demise at lower altitudes. Moreover, we can achieve this by designing spacecraft components with sacrificial layers that ablate early, exposing less resilient inner layers that demise quickly. These D4D strategies can limit the residence time of metallic oxides, preventing their accumulation in atmospheric layers where they could catalyse ozone depletion or influence the radiation balance of the Earth.

However, D4D minimising the residence time of the ablated spacecraft materials introduces technical challenges. First, substituting high-performance metals like aluminium or titanium with lower-melting-point materials could compromise structural integrity and thermal resistance. As spacecraft will be exposed to vacuum, extreme thermal cycling, and high radiation levels, the required material properties with exceptional durability limit the choice of suitable replacements. Therefore, D4D should trade-off between material performance and their demisability at low altitude.

Second, thermal fragmentation could be an issue. Compared to current materials, lower melting point materials may fragment into larger debris during re-entry rather than vaporising completely, increasing the risk of ground impact or residual orbital debris. This is particularly problematic for components with low surface-area-to-mass ratios, such as propellant tanks and reaction wheels.

Finally, altering D4D for limiting the presence time of ablated materials will increase the testing and certification requirement and cause competitivity issue with existing manufacturing process. Additional testing to validate the demise characteristics of alternative materials under re-entry conditions could delay spacecraft development timeline. For example, integrating hybrid components or sacrificial layers could require entirely new assembly and quality assurance workflows.

In addition to these technical challenges, altering D4D could impact space industry by increasing spacecraft production cost. Developing and qualifying new materials or hybrid designs can significantly increase research and development expenditures. For small-scale manufacturers, these costs may become prohibitive. Moreover, the introduction of specialised materials, such as composites tailored for demise, may require sourcing from niche suppliers, potentially increasing procurement lead times and costs. High-performance satellites in LEO constellations may not prioritise D4D features if they reduce mission capabilities.

To balance environmental objectives with practical feasibility, therefore, the implementation of D4D requires:

- **Material Research**: Increase investment in R&D for materials with controlled degradation properties that meet structural and thermal performance requirements.
- **Component-Level Optimisation**: Focus on high-risk components (e.g., tanks, payloads) for D4D modifications, rather than retrofitting entire spacecraft.
- **Collaborative Testing Facilities**: Develop shared facilities for simulating re-entry conditions, reducing the cost burden on individual manufacturers.

By addressing these challenges, D4D can become an effective tool for reducing the presence time of ablated metal particles in Earth's atmosphere, supporting sustainable space operations while balancing industry needs.

2.2.2.2 Re-entry Practice

Altering spacecraft re-entry practices offers another pathway to limit the presence time of ablated material, such as metallic oxides, in Earth's upper atmosphere. By modifying re-entry methods, including adjusting the angle of entry and increasing the survivability of spacecraft components, it is possible to influence the altitude and distribution of material deposition. While such changes can reduce the time these particles remain suspended, they also introduce heightened risks of surviving debris impacting the ground, requiring careful consideration of safety and environmental trade-offs.

As discussed in previous TN01, the angle at which a spacecraft enters the Earth's atmosphere significantly affects the heating rate, altitude of peak ablation, and material demise characteristics. Controlling entry angles leads to longer re-entry trajectories with gradual heating, allowing more material to burn up at lower altitudes where atmospheric density facilitates faster deposition and sedimentation of ablated particles. By increasing the time spent in dense atmospheric layers, controlled re-entries reduce the likelihood of metallic oxides persisting in the mesosphere or stratosphere, where their presence can contribute to long-term environmental effects, such as ozone layer depletion. However, this approach requires precise trajectory control to ensure the spacecraft does not skip off the atmosphere or impact remaining debris the ground, which could exacerbate safety risks.

Another approach involves designing spacecraft components with increased survivability during re-entry to enable ground recovery. Materials with high melting points, such as titanium or stainless steel, can be used to withstand the intense heat and aerodynamic forces during re-entry, ensuring that critical components survive intact. This would allow for targeted retrieval and proper disposal or recycling of debris, preventing the release of ablated material into the atmosphere. While enhancing survivability has clear environmental benefits, it significantly increases the risk of ground impact hazards. Surviving spacecraft components pose a direct threat to human life and property if they fall in populated areas. For example, the re-entry of the Chinese Long March 5B rocket core in 2021 caused widespread concern as large fragments survived and landed near inhabited regions. Moreover, it could increase unpredictable debris dispersion thus complicating risk assessments and ground recovery operations.

Modifying re-entry practices, therefore, must balance the environmental benefits of limiting ablated material presence time with the safety risks posed by surviving debris. The combination of altering re-entry angles and selective survivability could provide a feasible technical solution. For example, components containing high-risk metals or toxic substances, such as aluminium, should be designed to burn up completely at lower altitudes to reduce atmospheric and ground-level hazards. Developing advanced predictive models integrating atmospheric dynamics and material fragmentation behaviour will help identify optimal re-entry angles and trajectories, minimising both atmospheric persistence and ground impact risks.

However, implementing precise re-entry trajectories requires onboard propulsion systems and guidance mechanisms, adding cost and complexity to satellite design, particularly for CubeSats and small satellites. Enhancing component survivability or implementing ground recovery systems necessitates material redesigns and extensive testing, increasing production and operational expenses in space industries. Therefore, we need to have international collaboration to develop standardised re-entry guidelines and shared ground recovery protocols, reducing the burden on individual operators. In parallel, safe re-entry zones should be established, which are designate unpopulated regions for controlled re-entries to minimise ground impact risks from surviving debris.

3 Navigating the Geopolitical Terrain Within Space Governance

The objective of this section is to review the geopolitical and strategic implications of potential policy and regulatory responses or mitigations associate with the impact of atmospheric ablation of spacecraft (including revised post-mission disposal (PMD) guidelines) and from there to pinpoint obstacles to knowledge sharing among stakeholders. The current space governance and space sustainability policy landscape was extensively reviewed in TN01 and TN02, so the analysis here builds upon that work and refers to it for supporting details, rather them repeating analysis.

In general, from a space-sector regulatory and policy standpoint it has been implicitly assumed that impacts on terrestrial atmospheric values from resulting from spaceflight activities are "minimal." In the context of broader anthropogenic climate changes emissions from other industrial sector have received much more attention, and have been assumed to be larger. This assumption is amplified by the low level of scientific data and understanding on the potential impacts from space activities.[25] As described in TN01 and TN02, national interests, in terms of economic, security, societal, and diplomatic benefit of space activities are the primary interests driving space policy. In recent years space sustainability has increased in prevalence and importance as a supporting goal of space policy work. Traditionally these national interests have "[outweighed] concerns regarding the environmental impacts of space activities."[26]

Essentially the space sector has benefitted from a "free pass" on assessment of, and policy and regulatory response to, this issue.[27] This policy baseline may now be changing. As the amount and pace of space activity increases policymakers, and the general public, are beginning to question if this implicit assumption of minimal impacts is true.[28] As researchers at the Aerospace Corporation have expressed, this creates risk of operating into "a policy void without direction, analogous to the recognition that space debris presented a serious hazard to newly launched spacecraft."[29]

Atmospheric impacts resulting from space activities – as with other aspects of climate policy – is clearly of global consequence, suggesting the need for a global level response. However, the primary international governance forum with responsibilities for space sustainability and other civil space cooperation discussions, the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) faces a number of challenges in keeping pace and relevance to the current context of the space sector. These include structural barriers to including private and non-governmental participation, expanding membership and geopolitical tensions affecting the ability to achieve consensus in discussions, and the increasing cross-cutting nature of space governance issues that require coordination with other UN bodies including the International Telecommunication Union (ITU) and the Conference on Disarmament (CD).[30] In the current geopolitical environment COPUOS is also essentially unable to develop binding international law – it has shifted from a era of treaty making in the first decades of the Committee to an era of guidelines and recommendations.[31] The evolution and current context of COPUOS was discussed in further detail in TN01 and TN02.

These trends suggest that the role of international space governance forums in addressing or mitigation potential atmospheric impacts of space activities is likely to focus on coordination and information sharing, while implementation of any regulatory or policy tools are more likely to implemented at national level (inclusive of regional bodies like the European Union).

National regulators and policymakers are operating in state of uncertainty with regards to atmospheric impacts from spaceflight activities. In general regulation and policy should seek to follow a precautionary approach – seeking to guard against the worst-case outcomes within the information available. However, at same time regulators and policymakers seek to not cause unnecessary harm to an emerging industry and sector of national interest. These trade-offs, coupled with a lack of robust information, creates potential for policy inertia or lack of movement on this topic. This is further complicated by the entanglement with broader climate change policy governance and politics. As Jones and Jain describe: "Industrial strategy in the United States and other nations is still forming in the era of climate change. Inevitably, there is a tension between the economic self-interests of a growing space sector and regulatory efforts to internalize negative externalities. But there are options available to incorporate environmental policy considerations through government space stakeholders motivated by national interests"[32]

Recent work by the Organisation for Economic Co-operation and Development (OECD), in the context of a project evaluating *The Economics of Space Sustainability,* has identified three broad categories of environmental policy interventions options or approaches typically used by national level policymakers.[33] These intervention types are summarized in Table 1, below.

Table 1. Types of Environmental Policy Instruments, as Described by the OECD

Incentive-based measures	Command-and-control regulation	Voluntary approaches
Address the economic incentives of commercial actors and include charges (deposit-refund, taxes and fees), tradeable permits, subsidies and market friction reductions (e.g. liability rules)	Direct government regulation accompanied by negative sanctions in the case of non-compliance, e.g. technology and performance standards, emission targets, product bans	Non-binding approaches to engage stakeholders and build consensus, e.g. guidelines, industry commitments and environmental labels

Each of these approaches will have a role in potential mitigation strategies in response to the atmospheric impact of ablating spacecraft. And each will have specific drawbacks limitations and political considerations. As Joanne Wheeler described, during a presentation at the workshop held under this project at Southampton University on September 23, 2024: "Overall the ecosystem of international guidelines, national implementation and commercial environmental, social and corporate governance linked to investment – is a powerful one. But it is not a complete panacea."[34]

3.1 Potential Space Policy Tools and Strategies for Intervention

There are a variety of potential space policy (and regulatory) tools and strategies which will form part of this ecosystem of response. Table 2, on the following page, maps these potential policy tools to the technical mitigation strategies which were identified earlier in TN03. Discussion in the remained of this section will review these policy tools to review to identify political pros/cons and potential lessons for their applicability to migration of atmospheric ablation impacts on the atmosphere. This review will then inform the recommendations to be presented in TN04.

Table 2. Mapping Potential Policy Interventions to Technical Mitigation Approaches

TECHNICAL MITIGATION METHOD	POTENTIAL TOOLS FOR INTERVENTION: Space Debris Mitigation Guidelines	Voluntary Practices and Standards	Environmental Life Cycle Assessments (LCA)	Environmental impact assessments	Application of Environmental Law	Develop circular economy in space	Rationalize number of satellites
Limit the total amount of ablated material							
Reduce the Number of Satellite Launched			■			■	■
Change Satellite Materials		■	■	■		■	
Change Re-entry Practices	■	■					
• Limit Re-entry Method / Emissions	■	■		■			
• Dispose in Orbit	■	■					
• Re-use in orbit	■	■				■	
Limiting the presence time of ablated material at upper atmosphere							
Change Re-entry Practices	■	■					
• Limit Re-entry Method / Angle	■	■					
• Increase Survivability (inc. reuse on ground)	■	■					

3.1.1 Space Debris Mitigation Guidelines

The global approach to development, adoption, and implementation of space debris mitigation guidelines (including post-mission disposal practices) was described in detail in TN01 and TN02. Space debris mitigation guidelines are expressed at the international level through voluntary international guidelines, further refined and elucidated in further detail in national-level standards and policies as well as industry-level practices, and implemented in both non-binding and binding ways through regulation, procurement and contract requirements, and standards. Many of the elements included in space debris mitigation guidance seems relevant to mitigation of atmospheric impacts, including potentially ability to inform approaches to conducting re-entry, increasing survivability, and influencing materials and other spacecraft design practices.

However, trends in the objectives and specificity of space debris mitigation practices in recent years may instead create a tension point: placing emphasis on increasing atmospheric entry. Lead by technical experts within space agencies and the IADC, and reinforced by industry space safety practices, recent revisions to the space debris mitigation requirements have focused largely on decreasing the amount of time space objects spend in orbit after service life ends and on increasing compliance with post mission disposal (PMD) guidelines. A key overarching motivation in space debris mitigation is the recognition that "the trends in the compliance to space debris mitigation practices at a global level slowly increasing, it is of importance to note that the successful implementation is still at a too low level to ensure a sustainable environment in the long run."[35] One of the core principles of the space debris mitigation guidelines is to remove objects from the LEO and GEO protected regions with a high success rate for those orbits where a natural disposal mechanism is absent.[36]

A recent review of space debris mitigation instruments, guidelines, requirements, and standards conducted by the European Space Policy Institute (ESPI) finds that the overall trend in updates to these policies is characterized "evolution towards greater stringency."[37] This stringency is reflected in several ways: including the increasing shift from a 25-year post mission disposal goal to a 5-year post mission disposal goal. It also includes an emphasis on reliability in post-mission disposal. As the IADC has suggest regarding post mission disposal in large constellations: "Each spacecraft in a large constellation should have a probability of successful post mission disposal at a level greater than 0.9 with a goal of 0.99 or better." Many commercial spacecraft operators have made post-mission disposal reliability a key requirement in their design practices, and this requirement is a strong element of most voluntary industry space debris mitigation practices. A second key objective consistently reflected in space debris mitigation guidance is avoidance of human causality risk on the ground. Spacecraft re-entry disposal guidelines consistently reflect a re-entry casual risk requirement of <0.0001 or better (and some are more stringent: ESA's 2023 updated space debris mitigation requirements include a <0.000001 threshold for spacecraft in a constellation).[38] Design for demise practices for spacecraft have taken these requirements into account and practice.

Proposals or strategies to reduce the rate of atmospheric re-entry and to increase survivability of re-entering objects are, at face value, counter in theme to emerging best practices and emphasis in space debris mitigation. Efforts to leverage space debris mitigation guidelines to include these technical mitigation strategies related to atmospheric ablation impacts will need to consider this trade-off.

However, other elements of ongoing discussion and revisions withing space debris mitigation efforts are more directly related to implementing mitigation approaches for atmospheric ablation. A key trend (as discussed in the TN01 and TN02 deliverables) is development of guidance and requirements at the national level (and in voluntary industry commitments) that goes beyond the international consensus guidelines and standards. A key example of this in the increasing acknowledgement of role of external Active Debris Removal (ADR) and satellite End of Life services (EOL) as means to compliance with post mission disposal requirements. This allows for operators to contract with service providers to provide removal services instead of conducting direct disposal operations. Currently these services are mostly focused on atmospheric re-entry and are designed as back up to direct re-entry. However, in the medium and long run acceptance of these methods will contribute to recognition of circular economy and in-orbit reuse as an alternative to atmospheric disposal. Space debris mitigation requirements, as well as voluntary commitments, also are increasingly calling for conducting controlled re-entry as a standard practice. This clearly relates to mitigation approaches which might dependent on changing the angle and/or speed of re-entry.

ESPI notes that in addition to the increasing stringency of space debris mitigation instruments there is also some expansion of scope of topics included under them, which in some cases includes "Environmental sustainability of the space industry, in relation to its harmful environmental effects on Earth's environment." The IADC Space Debris Mitigation Guidelines do state that "Also, ground environmental pollution, caused by radioactive substances, toxic substances or any other environmental pollutants resulting from on-board articles, should be prevented or minimised in order to be accepted as permissible."[39] In this regard the technical community involved in space debris mitigation has a research role that might be leveraged to help advance knowledge gaps related to ablation. For example, the IADC, through its Protection Working Group, has research functions in materials, impacts, and re-entry observations. The European Space Agency (ESA) has also conducted data campaigns around re-entering space objects. In the United States the 2022 Orbital Debris Implementation plan, a national level strategy document development by the White House, noted the potential for the US government to "Sponsor R&D for determining material properties, shape, and orientation of existing debris objects. Steps may include leveraging existing facilities and radiation chambers to study material properties and structure when exposed to different radiation levels observed at different altitudes."

One final element of the structure around global implementation of space debris mitigation guidelines is instructive for consideration of policy implementation approaches to mitigation of atmospheric impacts of spacecraft reentry: the value of regular reporting: The IADC notes that "While mitigation measures have found broad consensus, today, it is of increasing importance to verify their effect in practice and to monitor their level of implementation. Therefore, the members of the IADC have decided on a collaborative effort in analysing and documenting the state of the environment in this comprehensive report and publish it in regular intervals for the awareness of space farers, decision takers and the interested public."[40] Space debris mitigation guidelines and requirements are referenced to key space environmental models (e.g. DRAMA, ORDEM). Reference models for the impact of spacecraft-derived particles on global atmospheric composition and chemistry don't yet exist. This is a key challenge in developing global guidelines for mitigation.

3.1.2 Voluntary Practices and Standards

In Section 3.1.3.3 of TN02 the current trend of significant efforts have been made by a number of industry, non-government, and civil-society groups to develop and promulgate voluntary guidelines, principles, and practices for space sustainability and/or space operations. This trend, coupled with the emphasis on non-binding and coordination principles in the work of COPUOS, suggests that voluntary guidance developed from the bottom-up will likely be part the strategies used to implement technical mitigation approaches, and their role should be considered in the context of policy and regulatory strategies.

The experience of the Dark and Quiet Skies community suggests a pathway for how issues of concern might be integrated into voluntary industry sustainability efforts and commitments. As the impacts of satellite constellations on optical and radio astronomy begam more apparent, the International Astronomical Union (IAU) and other actors in the astronomy community began a concerted effort to engage with the satellite operator community to raise awareness and develop joint mitigation process. This effort was paired with other lines of effort to engage governance and regulatory forums. (the Dark and Quiet Skies efforts are described in further detail in Section 3.1.4.3 of TN02). One of the outcomes of this efforts has been reflection of mitigation commitments from constellations on astronomy in the satellite-industry lead GSOA Code of Conduct on Space Sustainability. It has also been reflected in industry-led implementation guidance being development under the ESA Zero Debris Charter.

A similar path of engagement may be a fruitful effort in implementing mitigation strategies for impacts of spacecraft re-entry on the atmosphere. During the workshop held under this project at Southampton University on September 23 and 24 it was reported that two industry-led voluntary space sustainability initiatives have already begun consideration of this issue, as part of efforts to further develop voluntary space sustainability practices:

- A working group, under the AstraCarta initiative and led by the Earth Space Sustainability Initiative (ESSI) is being established to look at "leveraging of industry innovation to reduce environmental impact and emissions."[41]
- Re-entry emissions are also part of working discussion under the ESA Zero Debris Charter.[42]

Voluntary practices or commitments of this type can be ultimately be reflected in procurement requirements and in some cases regulation. Market factors – such as consumer pressure and trade dynamics – can also encourage adoption and follow-through on voluntary commitments. For example, the European Commission is considering developing EU Space Label, which would serve as voluntary rating and labelling scheme to assess sustainability in space operators. Preparatory studies have suggested that this label might recogniSes or rate space operators based on efforts "to asses and reduce the impacts of space activities on the environment in line with EU Green Deal targets"[43] (among other themes). The methodology behind such a rating would likely consider or encourage adherence to voluntary initiatives and standards as part of the rating scheme. This approach to rating provides means to link sustainability performance in the space sector to broader environmental performance and governance policies, and may provide market incentive (through potential connection to sustainability motivated investment and financial performance requirements). However, the space industry remains driven primarily by government markets; and the end-user consumer-responsibility motivations which have contributed to adoption of sustainability ratings in other sectors are not as developed in the space industry.

In addition to voluntary initiatives, formal industry standards can play a important role in addressing governance or regulatory gaps. Formal standards play several roles including[44]:

- Allow for implementation in national law, policy, licensing and market access requirements.
- Providing a basis for consistency and objective criteria to apply in regulations and licensing systems, across different national jurisdictions
- Provides transparent due diligence criteria for investors to conduct due diligence and stimulate investment.

TN01 and TN 02 provided a brief review of existing standards which might relate to ablation of space objects, both at the international level through the International Organization for Standardization (ISO), and in selected examples of national-level standards organization. Within the ISO *Technical Committee on Space Systems and Operations* (ISO/TC 20/SC 14) several ongoing working groups have technical scopes with encompass topics that might include elements related to the identified technical mitigation approaches for ablation impacts.[45] These include *Working Group 4 space environment (natural and artificial)*, *Working Group 6 materials and processes*, *Working Group 7, orbital debris*, and *Working Group, Downstream space services and space-based applications.*

The standards development process through ISO is a well-defined intuitional process that might offer some advantages for initiation of work on implementation of mitigation approaches to reduce the impact of spacecraft re-entry.[46] ISO working groups provide for national representation from experts nominated by national standards bodies, and can include government and industry experts. Working groups are generally able to interact on a technical basis, with a degree of independence or separation from political considerations which are part of diplomatic forums. Preparatory discussions within working groups can build socialization and familiarization of the technical realties of a problem or challenge, and the associated mitigation strategies, withing affected stakeholders even if no standard results. There are also mechanisms in which sectoral expertise can be exchange between different ISO Technical Committee. Standards can be initiated through a bottom-up process originating from national level standards bodies. In some jurisdiction (e.g.) France ISO standards, once published, become binding by default.

3.1.3 Application of Environmental Life Cycle Assessment (LCA)

Efforts to introduce changes in materials or design practices in satellite manufacturing to reduce or mitigate harmful particles or emissions released during ablation would benefit from a more holistic approach to assessment of the potential environmental impacts during the design and manufacturing process. One method to potentially do this is through increased adoption and application of Life Cycle Assessment (LCA) methodologies to spacecraft design, production, and operations. LCA is “an internationally standardised methodology that takes a holistic approach in determining and evaluating the environmental impacts of a product or process over its entire life cycle - from raw materials extraction through to end of life."[47] LCAs have been defined through a set of ISO standards, including ISO 14040 and ISO 14044. LCAs are a process to compile, review and evaluate "the inputs, outputs and potential environmental impacts of a product system throughout its life cycle."[48] LCAs seek to identify the categories and types of potential environmental impacts in different stages of a product's lifecycle and seek to identify ways to lesson or shift the burden of those impacts.[49]. In Figure 4, below, Aerospace Corporation researchers Karen Jones and Asha Jain provide an overview of the satellite life cycle.[50]

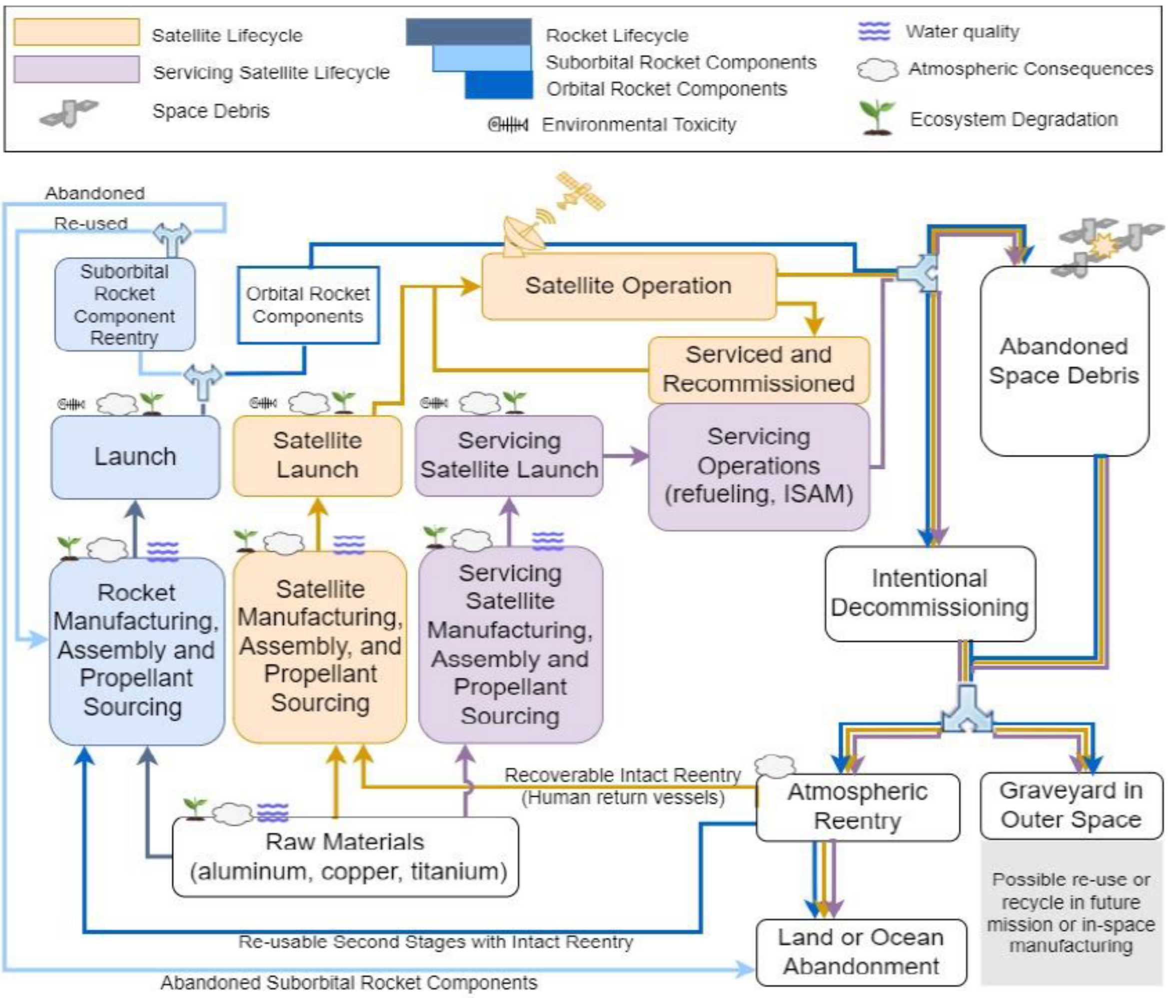

Figure 4. The Satellite Life Cycle, as Described by Jones and Jain[32]

A number of researchers and analysts have argued that application of LCAs offers one of the more holistic ways to assess and mitigate the environmental footprint of space activities as well as compare to the footprint of other types of technology.[51]

Within the space sector implementation of LCAs is most advanced within Europe, lead by work withing ESA and put into practice by ESA contractors in the launch and spacecraft manufacturing segments (e.g. Ariane, Airbus, Thales).[52] ESA began work in 2012 to develop an LCA methodology that could be applied across all space activities and facilitate comparability. This work began with an analysis of ISO 14040 and 14044, which concluded that the space industry had both unique characteristics and operating environment which limited the applicability of the existing standards. ESA then published its Space System Life Cycle Assessment (LCA) Guidelines in 2016 to extend ISO 14040 and 14044's relevance to the space sector. This framework "includes five impact categories which ESA expects E-LCAs to specifically address: Ozone depletion, Climate change, Metal and mineral resource depletion, Human toxicity, and Freshwater aquatic ecotoxicity."[53] ESA has included LCA requirements in procurement specifics for projects such as Copernicus and Ariane 6. For a more complete review of LCA development and implementation within ESA (and its implementation in contracts), see Fischer and Udriot, et. Al., 2024; Jones and Jain, 2023; and Koffler, 2024.

ESA has also developed an LCA Handbook – giving guidance on how to perform LCA for space-specific products including ground, launch, and space segment – and an accompanying database to capture results.[54] These products are only accessible to organizations from ESA Member States.[55] LCA development within in ESA is also thematically aligned to broader policy approaches withing Europe. The European Commission (EC) has developed the Product Environmental Footprint (PEF) methodology to provide a standardized approach to integration of LCAs into product development withing the European market, and the Commission is implementing this framework in requirements for its own space sector projects including the IRIS[2] constellation.[56] The EC is also in the midst of a broader consultative project to develop Product Environmental Footprint Category Rules (PEFCR) for the space sector. This effort seeks to "provide a standardised method to assess environmental impacts" in response to space sustainability needs.[57]

The under-development European Space Law is currently considering a requirement for performing LCAs in the development of space systems.[58]

Applying LCA methodologies in the space sector offer a number of potential advantages to both understanding and mitigating potential environmental impacts and to incentivizing or encouraging adoption of more sustainable practices in industry. These include:

- Ideally LCAs allow for the estimate of environmental impacts of all phases of a product life cycle during the design phase, and thus allow designers to identify means to minimize those impacts or offset them in other areas.[59] Essentially LCA and ecodesign can be used to help identify and understand potential alternative design options that could lead to improved or optimized technologies
- Doing so can also help producers reduce costs in production. Literature reviews of experience from LCAs and ecodesign in other sectors shows that "typical savings of 10-20% are consistently reported based on LCA, with the average profit margin of ecodesigned products being around above the margin of conventional products."[60]
- LCA methodologies can also be linked to financial and corporate reporting requirements, both voluntary and those required by financial or environmental regulation. The quantitative science-based data developed during LCAs can contributed to corporate sustainability reporting.[61]

However, there are a number of notable challenges to increased adoption of LCAs withing the space sector, and to applying the methodology to better understand and mitigation potential atmospheric impacts of spacecraft ablations. These include;

- Most implementation of LCA approaches in the space sector has been focused on launch segment, and in general the research and development phase has been currently excluded from LCA practice in the space sector.[62] These factors may limit the transferrable of current experience to the informing or changing satellite design and materials.
- The experience with LCAs in the launch segment to date indicates that the "climate and ozone metrics have not yet been determined" to assess launch emissions potential during a LCA. This is in large part because the "given characterization factors, including CO2 emitted at the stratosphere or mesosphere, are provided with large uncertainty ranges, since the current state of climate research does not have a high confidence level for many emissions"[63] This limitation likely extends to emissions from ablation during re-entry.
- Several reviews of the applicability of LCAs note that environmental impact categories and metrics specific to the space sector and it's design, manufacturing and operations practices need to be developed. Existing commercial database used to inform professional LCA analysis do not capture specific metrics or attributes for the space industry. The lack of these space-specific categories limits the outcomes and robust of LCA results for space systems.[64]
- Ideally LCAs would be based on "only primary data from the manufacturer itself and its supply chain."[65] However supply chain issues and concerns about proprietary and commercial sensitivity concerns in the space sector limit the willingness of space industry stakeholders to share these primary source input and output data. Based on a literature view of experience with LCAs Maury and colleagues report that "the quality of and access to the inventory data remain the major issue regarding these studies. This is mainly due to the complex supply chain for the large-scale systems as well as the inherent confidential nature of the space sector."[66] Jones and Jain write that "LCAs are still relatively new in the space sector and concerns about sharing potentially sensitive information play a role in hesitancy to implement."[67]

Implementation of LCAs can be required in regulatory provisions or procurement requirements. As review conducted by Wilson and Nuemann notes: "within the European space sector, the application and perceived importance of LCA has exponentially increased in recent years to the point that it is beginning to become entwined with the procurement process."[68] Adoption of LCAs has not been as prevalent in the U.S as it has in Europe. Opportunity exists for large government agencies (such as NASA and the Department of Defense) who seek to reduce their own environmental footprint to begin to increase use of LCA (or related methodologies) in procurements. This would begin to increase uptake of LCAs in the U.S. space sector.[69]

Market forces may provide also incentive or mechanism for increasing uptake of LCAs in the U.S. space sector, even as regulatory or procurement requirements for them lags Europe. The space supply chain is a global one, and if significant markets in Europe required LCAs process, standardization and market preference may force U.S suppliers to keep pace. As Wilson and Nuemann write non-compliance or adoption of LCAs in U.S. suppliers who wish to work with European manufacturer "could become a serious problem for United States (U.S.) original equipment manufacturers (OEMs) and suppliers in the near-term future due to misalignment or non-compliance with European procurement policies, with the potential to cause widespread supply chain disruption."[70]

Lastly LCAs relate to other policy mitigation tools discussed in this section. The data collection challenges and opportunities involved in applying LCAs to the space sector, also apply to further use of environmental impact assessments as a regulatory tool. Therefore, efforts to address these challenges will contributed to effectiveness of both tools. In addition, further uptake of LCAs is likely to be an important contributory step towards advancing circular economy concepts in space.

3.1.4 Revision / Application of Environmental Impact Assessments

Section 4.2.5 of TN01 and Section 3.2.5 of TN02 provide detailed discussion of the current application of national-level environmental impact assessments (EIAs) as an element of space sector regulation and licensing. In general (and with some national exceptions) impact of re-entering space objects on the terrestrial atmosphere is not being considered or reviewed through current EIAs applied to the space sector. Expansion of the application of EIAs to more directly consider atmospheric impacts from ablation, or to use them as a tool to implement mitigation strategies, face a number of technical and political challenges.

First, as noted in TN02, is the issue of fragmentation in regulatory authorities. In some national jurisdictions, space licensing is spread across multiple offices or administrations. While national level environmental law applies, the scope of particular licensing administrations may not clearly capture spacecraft re-entry emissions. An EIA applied to the launch segment will likely not included the properties of entering spacecraft in its evaluation. A licensing authority that is concerned with space debris mitigation and post mission disposal may consider the terrestrial atmosphere to be outside of the scope of its authority. It is easy for atmospheric ablation of spacecraft during re-entry to fall into a gap in authorise or applicability.[71]

The applicability of EIAs also limited by the lack of available and reputable scientific reference data. For example, in the United States, EIAs are conducted under procedural requirements set by the National Environmental Policy Act (NEPA). Former NASA Senior Climate Advisor Gavin Schmidt was quoted in a 2023 article describing the challenge of applying NEPA provisions to evaluation of satellite constellations as follows: " 'One of the key principles of NEPA is that you have to use the best available science,' said Schmidt. "In a situation like this, the best available science is not very good.'"[72] Lack of quality science data to underpin EIAs threatens their viability and puts outcomes at risk to court challenge. The applicability of EIAs to re-entering space objects is also challenged by similar questions of identifying the appropriate metrics and impact categories that is an uncertainty in the applications of LCAs to spacecraft demise (as described in the previous).

Expansion of EIAs to address the potential impacts of satellite re-entries also face political headwinds and challenges, in particular in the United States. There is a perception of a tension between policy goals of enabling and expanding the space industry (as the associated economy and industry competitiveness benefits) with environmental obligations and responsibilities. Existing EIA's are often described by space industry actors as burdensome and inefficient and expansion of EIAs cover additional space activities is often challenged as regulatory overreach. Instead of regulation approaches to mitigation of environmental impact, market and liability-based approaches are proposed.[73] In a political context where *laissez-*

faire approaches and regulatory streamlining are dominant goals, expansion of environmental reviews are likely to be challenging to implement.

3.1.5 Application / Revision of Environmental Law

Tools and approaches from environmental law and environmental policy might also apply. These are discussed in context of a broader analysis of environmental law in a subsequent section of this document.

3.1.6 Development of Circular Economy Approaches in Space

In recent years – in part in response to the increasing activity in the space environment and the growing public awareness of the space industry – a growing number of editorials and voluntary commitments are arguing for the development and application of circular economy principles and practices in the space sector. Broadly speaking circular economy may defined as in Kirchherr et al: “An economic system that replaces the ‘end of life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes.”[74]

Withing the space sector this perspective argues for a shift away from operating space objects as single use, disposal assets and towards reuse and waste minimization principles as drivers of space operations. It is argued that this is essential mitigating the risks associated with space debris, addressing impacts to the terrestrial environment from space activities and for ensuring the long-term viability of space exploration. In terms of atmospheric ablation of space objectives, a shift towards circular economy concepts in space operations would reduce the use of atmospheric re-entry as a method of post mission disposal. It could also reduce the total number of space objects launched – by encouraging or developing in-space manufacturing capabilities.[75]

While research[76] indicates that circular economy approaches in space may be economical viable in the medium to long term, it is still is a nascent topic and faces a number of policy, economic, and technical challenges (a full analysis of which is outside the scope of this study). A whitepaper resulting from ESA’s 2023 Clean Space Industrial Days lists some key examples of these challenges:[77]

- “The business justification needs to be matured.
- Regulatory framework needs to be defined.
- Availability of funding and willingness to support from stakeholders.
- Customers involvement is fundamental in defining future service needs.
- A significant step in the state-of-the-art for the enabling technologies is required (e.g., standardized interfaces, verification approaches, long-term reliability of complex mechanisms).
- Space Circular Economy demands innovative mission concepts and architectures.
- Complexity of operations for circular economy.”

Governments have a pivotal role in this transformation – ESA has set a goal of enabling a circular space economy by 2050, and efforts under the ESA Zero Debris charter are considering linkages to circular economy approaches. Government R&D funding, technology development support, and willingness to use market power as an adopter of circular economy practices will be key in moving this transition forward.[78]

However current developments related to circular economy are largely represented by the In-Space Servicing, Assembly, and Manufacturing (ISAM) segment of the space sector. Capabilities here are being developed for satellite life extension, active debris removal, and abilities to inspect and assess anomalies in satellites. For the most part the space activities that are driving the increase in space objects launching and re-entering are not designed to benefit from life extension – large LEO constellation business plans are partially depending on regular constellation replacement and replenishment to take advantage of technology advancements. They are not designed to benefit from long on-orbit lifetimes (as in the case of traditional geostationary communications satellites). Concepts for in-space recycling and reuse or materials to enable in-space manufacturing of spacecraft and components are primarily at concept stage and low-TRL levels. This possess a note of caution for reliance on circular economy development to address mitigation of atmospheric impacts of re-entering objects. It is likely a medium to long term development prospect before circular economy in space concepts are sufficiently mature from an economic and technical standpoint to be a viable option in shifting large amounts of activity away from atmospheric disposal.

3.1.7 Rationalize Number of Satellites to be Launched

An intuitive way to reduce the amount of ablation from spacecraft re-entry is to reduce the number of satellites being launched in the first place (which would also have the effect of some reduction in launch activity). However, this is easier said than done. Rationalizing or reducing the amounts of satellites launched would require national governments to set aside national interest motivations (economic, national security, and diplomatic) which are driving investments in satellite infrastructure and constellations; in the interests of collective action and cooperation.

Space systems are also becoming interwoven into society's infrastructure. Research reported in an OECD compendium "identified the dependency rate of satcom and GNSS on the information and communication industry in Europe as 85% and 15% respectively."[79] Other researches have suggested that governments are beginning to treat satellite broadband as a public utility.[80]

These themes are evident in the trends towards deployment of large constellations of satellites in LEO to provide satellite broadband is being driven by both commercial and sovereign interest factors. As the OECD notes this trend "reflects the growing strategic and economic importance of satellite broadband and the ongoing race between companies and countries to exploit orbital space and radio spectrum."[81] National governments are investing in, provide infrastructure for, and acting as anchor customers for satellite broadband constellations, contributing to an increase in the number of these constellations, and some case driving toward duplicative capabilities. The very nature of LEO constellations means that the constellations can offer global service; but sovereign interest in independent capabilities and the national security and economic benefits of those capabilities drives redundancy.

If a strategy of reducing the number of large constellations to be deployed (or the number of satellites in those constellations) would be successful it would require the governments supporting those constellations to act counter to these trends and perceived sovereign interests. Sovereign interests and obligations in other domains (e.g environmental and climate) may provide some of the incentive or motivation to do so. But economic and policy evidence would also be benefit. Analysis of the cost / benefit of space activities has been a long-running challenge.[82] The increasing reliance on satellite infrastructure coupled with potential negative impacts of that increased activity complicates this existing challenge. Policymakers may be faced with a trade-off between the economic and societal benefits of satellite-based connectivity and the potential environmental impacts of those systems; but lack the evidence to evaluate that trade-off in a evidence-based fashions. Some in the academic community have argued that this created "an urgent need for studies that quantify and compare the life-cycle impacts of mega-constellations of small satellites and the associated terrestrial infrastructure with those of functionally equivalent cabled and mobile networks."[83]

"This unprecedented growth in space activity is now prompting greater scrutiny of the space industry's environmental impacts and potential to improve sustainability. On balance, the space sector contributes enormously to environmental and humanitarian concerns. Should the space sector continue to get a "free pass" to ignore its environmental footprint and sustainability opportunities?" [32]

3.2 Information Sharing Barriers

This review of potential policy approaches towards supporting technical strategies has identified several information sharing barriers or challenges. These are:

1. <u>Concerns About Sharing Materials Data</u>

   Work related to both EIAs and LCAs in the space sector has faced challenges in accessing data on materials used in spacecraft design. Spacecraft manufactures and operators often consider supply chain and materials data to be proprietary or commercially sensitive. This is complicated by some aspects of the space supply chain which remain highly bespoke and customized.[84] Stakeholders may also have concern about reputational impact if sharing material data leads to them being perceived as environmentally unresponsible.[85] Jones and Jain suggested that this "could be mitigated by an E-LCA process orchestrated by a trusted body with a data management protocol which provides both sufficient information to conduct E-LCAs and protection of confidential and competitive information."[86]

2. <u>Lack of Systematic Exchange Between Agencies</u>

   Research into the atmospheric impacts of spaceflight activity is being conduced in space agencies, atmospheric agencies, and general science foundations in several countries and regions, but there is little formal coordination of these research programs; or formal sharing of experience, outside of the formal academic publication process and at conferences. This lack of coordination extends to involvement of industry partners. It has been suggested that agencies, such as NASA, should establish a more structed funding and information sharing regime to provide strategic direction to research efforts in this area. However political leadership and will would be required for this to occur.[87]

3. Export Controls

   Exchange of data is further limited by export control limitations and concerns. The space industry remains highly involved with the defense sector, and space technology and facilities are often subject to national export control limitations. For example in the United States all available hypersonic or ablation test facilities are under ITAR control regulations are therefore generally not accessible to non-US persons. Researchers often have to prepare two versions of data or model based on use of ablation facilities: one which meets export control requirements and one which is under export control restriction. Conferences often have restricted sessions due to export control.

4. Speculative Fillings

   Efforts to accurately forecast future potential impacts are made more complicated by a market externality in the satellite and spectrum licensing process: speculative and 'paper' satellite filings. As the OECD writes "The number of planned satellites is exaggerated by duplicative and speculative filing applications and multiple projects are likely to fail due to technological problems and lack of finance."[88] It is difficult to realistically estimate the range in the number of satellites likely to launch (and re-enter) in the coming decade, which can make evidence-based assessment of the potential atmospheric impacts more challenging. Discussions are underway within the International Telecommunications Union, and associated processes, to address the problem of speculative filings, but any changes will take considerable time and the result is uncertain.

3.3 Conclusion: Public Perceptions and a Tipping Point?

The environmental impact of spaceflight emissions remains in a policy and regulatory gap, as far it's place in the space-specific governance systems. This may change, and from a political perspective the question to be asked is what factors might cause a tipping point or shift in political and policy attention to this issue. As leading spaceflight emissions research Martin Ross, and his colleague Karen Jones, write "…as the space industry grows and becomes commercialized, it is increasingly perceived as a normal part of the economy, no longer a special case. The long-held protection from regulation afforded to spaceflight may not survive a change in perception."[89]

The increasing visibility and role of space applications in the economy, coupled with the increasing visibility of climate change as a public, political, and economic issue, may create conditions in which a tipping point for regulatory action on spaceflight emissions is created. Shifting in public perceptions of space, and it's potential environmental impacts, may create pressure on political decision-makers to act.[90] Space sector stakeholders can prepare for this possibility by increasing the systematic attention to data-collection, increasing understanding of spaceflight emissions, and facilitating exchange of discussion on potential mitigation strategies. It is in the interests of both regulators and industry operators to engage in this process as can support effective regulation and protect against regulatory overreaction.[91] Tools discussed previously in this section are likely to aid in this process.

4 Environmental and Social Dimension

In addressing the environmental problems posed by satellite re-entry there is a tendency to see law and regulation as tools that come into play only *after* the full nature of the challenge has been scientifically explored and clarified. If there is found to be strong evidence of a causal link between ablation and various forms of significant environmental damage then consideration should turn to the appropriate legal and regulatory response and venue, or alternative mechanisms most likely to realise change in practice. But as discussed in TN02, space activities must be exercised in accordance with states' obligations created by rules, or principles, of customary international law (CIL) and the international space, environmental and human rights treaties to which they are a party.[92] Initial consideration should thus be given to those laws or principles that currently apply, which should inform state action now, not in the future.

In relation to international space law, we have noted the obligation to explore and use space for the benefit, and with due regard for, the interests of all countries (articles I and IX), and to be guided by the principle of co-operation and mutual assistance (article IX). In relation to international environmental law, key obligations that have the status of CIL and that are germane to space activities, include:

- the obligation to prevent transboundary harm,
- the due diligence obligation, and
- the obligation to cooperate.[93]

Peel refers to the duties of co-operation and to prevent transboundary harm as 'principles' but notes that in the context of the general principles of international environmental law these 'are sufficiently well established' and 'reflect an international customary legal obligation, the violation of which would give rise to a free-standing legal remedy'.[94] Other general principles of international environmental law are important in that they should guide states' space activities in so far as they have an impact on the Earth's environment.[95] These principles 'may influence the interpretation and application' of CIL, as well as treaties, pursuant to Article 31(3) of the Vienna Convention. [96] These general principles include, amongst others, the precautionary principle.[97]

State parties or members of regional or bilateral agreements are required to implement the relevant treaty or measure in domestic law, which they may supplement with self-standing domestic space-related or generic environmental or sustainability requirements. A range of non-binding international and regional guidelines, such as the COPUOS Guidelines on the Long-Term Sustainability of Outer Space Activities,[98] the ESA Zero Debris Charter,[99] and, in particular, the International Law Commission Guidelines on Protection of the Atmosphere,[100] can inform how these obligations are interpreted and applied in practice either by States or private actors.

Private actors are not only subject to domestic legal requirements in the space and environmental fields, they frequently adhere, on a voluntary basis, to certain of the management, design and performance standards identified in TNO2, or seek accreditation under ESG reviews, such as the Space Sustainability Rating.

Embedded within many of these international and domestic requirements, as well as industry standards, are complex hazard evaluations and environmental and sustainability risk assessments. Indeed, environmental impact assessments ("EIAs") have been described as a requirement of general international law, [101] and the *Pulp Mills Case* confirmed that undertaking an environmental impact assessment forms part of exercising the 'due diligence' obligation.[102] It is also accepted that in scrutinising states' adherence to their due diligence obligations through implementation of EIAs, the further adoption of decision-making tools such as multi-criteria decision making (MCDM) analysis should be positively noted. Especially in the face of complex scientific uncertainty (as in the case of ablation) and a wide variety of stakeholders, potentially involving trade-offs, MCDM analysis enables better environmental decision-making and governance by states through "bringing together criteria and performance scores, usually in matrix form, to provide a basis for integrating risk and uncertainty levels".[103].

These evaluations and assessments, which form the focus of this work-package, have been subject to considerable theoretical and practical analysis, both at a general level and in relation to specific forms of atmospheric pollution. It is thus important to consider how these could apply to satellite ablation. Three questions underpin this paper:

(i) what processes have been developed at international and national levels to assist in the identification of environmental hazards, ensuing risks, and the adoption of well-grounded regulatory responses;

(ii) by what process or processes are other social and economic objectives incorporated into these decision-making processes; and

(iii) which substantive or procedural measures enhance the likelihood that any ultimate accommodation or 'trade-off' among competing objectives or interests will be considered legitimate, even by those negatively affected.

The report begins by briefly outlining, in section **Section 4.1**,, the range of space activities that are beneficial for society and that could be affected by future regulation of satellite ablation. Questions (i)–(iii) are explored in **Section 4.2**, with reference to risk evaluations, notably environmental impact assessments. This part also considers when and how social and economic objectives are incorporated into these assessments and the procedural requirements that have been adopted to enhance legitimacy.

The second part of this report considers whether Multilateral Environmental Agreements (MEAs) could apply to the ablation of specific satellite materials, and how well suited these measures are to address questions (i)-(iii) above. In particular, **Section 4.3** focuses on the potential application of five key environmental treaties to ablation and their relevance in developing a regulatory framework in this field in the future.

4.1 Competing Objectives and Interests Arising in the Context of Satellite Ablation.

Satellite deployment in line with current developments can be expected to stimulate economic growth and continued access to the benefits of space technology, up until the point where congestion and collision risks impose constraints.[104] In this report (at 5 below) we consider two main approaches to mitigating the potentially damaging effects of re-entry ablation: (A) limiting the mass of ablated material introduced into the Earth's upper atmosphere by limiting satellite launches, optimising materials ,and enhancing design for demise practices; and (B) reducing the presence of ablated materials in the upper atmosphere by altering re-entry practices and other design features to ensure that the spacecraft burn up at lower temperatures. A and B are not mutually exclusive.

Imposing a limit on the number of new satellites gaining access to space (A), would be an effective mechanism to reduce environmental damage but it could also lead to a drop in **economic growth** in the space sector, potential redundancies and/or business failure. It would have implications for those **communities that depend economically on the production, transportation or marketing of constituent products, potentially affecting developing countries and some of the world's poorest workers.**

Not only would such action constrain the **freedom to explore, use and gain access to space**, recognised in recital 2 to the Outer Space Treaty as being in the 'common interest', it could also impact certain socially and economically valuable space-related services and activities.[105] These include: **core civil services that underpin many of today's social and economic relations**, including communications (internet, mobile, television broadcasting, e-learning), earth observation (agriculture, mining, infrastructure planning), meteorology (weather and disaster forecasting), and navigation services (international maritime trade and mobile geolocation services); **scientific research activities** (relating to e.g. outer space, the Earth, and its environments); and **safety, security and defence applications**. Given that the majority of space assets fall under the jurisdiction of a handful of developed states, any such restriction could also entrench existing inequalities if new players were limited in terms of access.

On the other hand, the need to quickly establish the scale of the risks posed by re-entry ablation and develop sustainable solutions, should incentivise technological innovation and investment, ultimately supporting a new era of space activities.

Although option B would not have the same negative impacts on space-based essential services or prevent in theory the entry of new space players, it would increase the cost of space activities, requiring modifications in satellite design and composition and enhancement to existing modelling and tracking systems. This could negatively impact established supply chains, affecting dependent communities and create additional risks to human safety from component survivability. The additional costs could suppress growth in the space sector and exclude potential new players; the sector continuing to be dominated by a few countries, regional organisations and large private corporations.

A failure to address atmospheric degradation caused by ablation could also deter **technological innovation** otherwise spurred on by regulation, potentially leading to **a loss or re-direction of economic development**, employment and trade. As noted in WP320, a failure to address the Earth-based implications of the space sector could negatively affect public perceptions of space activities and public support for further investment and development.

More importantly, recent scientific research indicates that, with untrammelled growth or even a steady-state scenario, satellite ablation could have negative **environmental effects** on the Earth's atmosphere, notably the ozone layer, and climate system; as well as terrestrial and marine environments.[106] Were global atmospheric or marine systems to be significantly disrupted this would have serious implications for **human health, safety, and food security**.

The right to a healthy environment is explicitly set out in regional treaties including the African Charter on Human and Peoples' Rights, the San Salvador Protocol, the Escazú Agreement, and the Arab Charter on Human Rights. In 2021, a non-binding UN Human Rights Council resolution took a first step towards filling a significant gap in international law, by recognising the human right to a safe, clean, healthy and sustainable environment.[107] On the basis of this resolution, the UN General Assembly adopted in 2022 resolution 76/300, which unanimously recognized the right to a clean, healthy, and sustainable environment as a human right.[108]

The right to a clean, healthy, and sustainable environment is further recognized in the Aarhus Convention, which is considered a key instrument for environmental protection in Europe and the UK. Whilst not explicitly protecting a substantive right to a healthy environment, the Aarhus Convention guarantees procedural rights, namely the right to have access to information, the right to public participation, and access to justice in environmental matters.[109] The **Protocol on Pollutant Release and Transfer Registers** to the Aarhus Convention is an international agreement that establishes legally binding standards for making pollutant data available to the public.[110] States are mandated to establish inventories of pollution from industrial sites and other sources. However, Annexes I to III listing activities to be reported do not include space activities.

Compliance mechanisms for the right to a clean, healthy, and sustainable environment are further detailed by the Special Rapporteur in a 2023 report. Key strategies to protect the right to a healthy environment include:

- States must guarantee to the public the right to information about hazardous waste, its management, and disposal methods;
- Action to strengthen global efforts through treaties and collaborations to ensure sustainable, human-rights-compliant waste management practices;
- Development of infrastructure for safe waste disposal and recycling, minimizing harmful practices of waste dumping;
- Encouragement of Corporate Accountability of the private sector involved in waste generation.[111]

With regard to space objects, the international community of States are thus required to inform the public about ablation, determine global rules to mitigate its impact on the environment, including the atmosphere, and review their liability regime to share responsibility for waste management with the private sector.

However, States have unevenly complied with and implemented these measures. The Special Rapporteur's most recent assessment reveals **shortcomings of pollution prevention mandates, the limited scope of the pollutants and activities covered, voluntary instead of mandatory reporting, and a lack of integration between environmental information systems**.[112] With regards to the public right to information and participation, **Pollution Information Portals** focus on major industrial sources, while significant sources of emissions and wastes are not covered.[113] We might add that there is no such Pollution Information Portal on space activities to date.

The 2024 Special Rapporteur Report observes that Portals mostly capture data from point sources, such as industrial facilities, whereas the assessment of more diffuse sources of pollution, such as transportation, is limited.[114] Emissions from companies that are relevant for such sources of pollutant releases, which are not considered as an industrial point source, could be added to the list of pollutants under annex II to the Aarhus Protocol and include, for example, operators and owners of companies in the transport sector.[115] This requirement already exists under the European Union Emissions Trading System, with aircraft operator reporting obligations. All airlines operating in Europe are required to monitor, report and verify their emissions. This example illustrates how reporting obligations could be assigned to space companies not currently included in the Protocol. This could be done by finding synergy between international instruments and compiling the substances listed under Basel, Aarhus, Stockholm and other Environmental Conventions, discussed further at section 4 below, into **a single database** to account for all the activities generating chemical harm to the environment.[116] This single database would relate emerging evidence indicating risks to human health and the environment, including chemicals used in the space industry, such as lead.[117]

4.2 Addressing Environmental Risks in the Context of Scientific Uncertainty

Environmental risk assessments (ERAs) are a well-established part of the 'regulatory toolbox' at national, regional, and international levels, explored further in WP320. They can be self-standing, or operate as part of a broader life-cycle assessment that considers all stages of a product's manufacture, operation, and disposal. ERAs are based on the understanding that environmental damage and related harms can stem from complex chemical reactions and transmission processes that occur over variable time periods. By ensuring that the most appropriate expertise is employed to answer specific questions; by systematically identifying, prioritising and evaluating risks; and by working through the implications of modified practices for interested parties, ERAs can enhance effectiveness, reduce costs, and encourage public and stakeholder confidence in regulatory outcomes and difficult trade-offs.

At the national level, the UK has provided generic guidance ('Green Leaves III') on the structure and processes that can be adopted when undertaking an environmental risk assessment.[118] In terms of specific legislation, environmental and related risk assessments are required in various contexts, notably when granting particular licences or permits, and specialised guidance is for these areas. These include certain planning decisions,[119] and the grant of permissions to handle specific dangerous, notably explosive or radioactive, materials.[120] As previously discussed in TN02, the CAA is required to take into account an environmental impact assessment (EIA) when considering whether to grant a spaceport or launch operator licence under section 11 of the 2018 Space Industry Act, as well as international space debris mitigation guidelines when carrying out its functions more generally under section 2(2)(h) of that Act. Government guidance on EIAs lists, among those documents that the CAA should 'take into account', the COPUOS Guidelines on Space Debris Mitigation and the Long-term Sustainability of Outer Space Activities (LTSG), as well as the European Code of Conduct for Space Debris Mitigation (ECCSDM), which contain various provisions relating to hazard identification; consideration of social, economic and environmental concerns; minimisation of environmental impact;[121] as well as mitigation and management plans, extending to 'potential harm at the Earth's surface or damage to the environment caused by the re-entry of its product'[122].

UK government guidance is stated to be 'complementary' to the existing approach of the regulator, which seeks to 'minimise' and 'mitigate' the environmental impact of space flight activities 'as much as it is practicable and reasonable to do'.[123] As further discussed in TN02, however, an EIA is not required for an operator licence, and to date the focus of EIAs for spaceport or launch operations has been on the impact of these operations on domestic/local environments, a context falling clearly within UK jurisdiction, rather than transboundary pollution.

At the international and regional levels, we have noted the existence of treaties, declarations, decisions and guidelines that establish State responsibilities 'to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction',[124] and to take 'all appropriate and effective measures to prevent, reduce and control significant adverse transboundary environmental impact from proposed activities'[125]. These measures are the foundation on which the International Law Commission (ILC) includes within its voluntary Guidelines on the Protection of the Atmosphere, an obligation to exercise 'due diligence in taking appropriate measures, in accordance with applicable rules of international law, to *prevent, reduce or control atmospheric pollution and atmospheric degradation*', and to engage in an environmental impact assessment of activities 'under their jurisdiction or control which are *likely to cause significant adverse impact on the atmosphere* in terms of atmospheric pollution or atmospheric degradation'. [126]

The Espoo Convention on transboundary environmental impacts, widely adopted across Europe,[127] including by the UK, establishes a framework of questions and procedures to be adopted regarding environmental impact assessments for activities that fall within its scope. In particular, Annex II identifies what information, as a minimum, should be collected in order to assess environmental risks within the terms of the Convention:

(a) A description of the proposed activity and its purpose;

(b) A description, where appropriate, of reasonable alternatives (for example, locational or technological) to the proposed activity and also the no-action alternative;

(c) A description of the environment likely to be significantly affected by the proposed activity and its alternatives;

(d) A description of the potential environmental impact of the proposed activity and its alternatives and an estimation of its significance;

(e) A description of mitigation measures to keep adverse environmental impact to a minimum;

(f) An explicit indication of predictive methods and underlying assumptions as well as the relevant environmental data used;

(g) An identification of gaps in knowledge and uncertainties encountered in compiling the required information;

(h) Where appropriate, an outline for monitoring and management programmes and any plans for post-project analysis; and

(i) A non-technical summary including a visual presentation as appropriate (maps, graphs, etc.).

Though satellite ablation would appear to be covered by the Convention's reference to impacts on the air, water, and climate (art. 1(vii)), and even 'transboundary impact' (art.1(viii)), the Convention does not apply to transboundary impacts 'of an exclusively global nature', nor do satellite activities fall within the list of activities in Annex 1 that bring into play an EIA, though activities beyond this may be addressed through the procedure in article 2.5.[128] The limited purchase of the major international environmental agreements dealing with specific aspects of transboundary air pollution, or movement of hazardous wastes, on ablation is discussed in more detail at sections 4 and 5 below, but it relevant to note here the fact that they include a number of tailored risk assessment procedures and guidance.

At the private level, ISO and BSI standards establish various methodologies and procedures for life cycle assessments, environmental impact and management assessments, such as ISO 14040 and ISO 14044, while jointly defined space debris and sustainability guidelines increasingly make reference to environmental concerns, such as the Zero Debris Charter, which calls for the adverse effects of space debris when re-entering the atmosphere on the Earth's environment to be 'anticipated and mitigated to the greatest possible extent'.[129]

Risk assessments involve consideration of the likelihood of a particular hazard arising in a given set of circumstances. By establishing the **probability of a hazard arising** (eg low/medium/high) and **its potential negative consequences** (low/medium/high) such assessments help to clarify the need for, and urgency of, action. A low risk of limited negative environmental effects will not require, for example, the same degree of attention as a high, medium, or even a low risk of serious environmental consequences. The information gathered by risk assessments can further feed into MCDM analysis tools, as "the level of risk determined in the risk assessment process can be used to parameterise the decision matrix".[130]

When designing a risk assessment, it is necessary to consider how the various processes of data collection, consultation, analysis, evaluation, and implementation, interact and build on each other over time. Environmental risk assessments typically involve four phases: an initial framing of the problem; the risk assessment itself; identification and evaluation of potential risk management options; and implementation of the selected risk management strategy. The stages are not hermetically sealed, and findings at one stage can feed into the analysis at other stages. Key stages and considerations are identified in Figure 5 below.

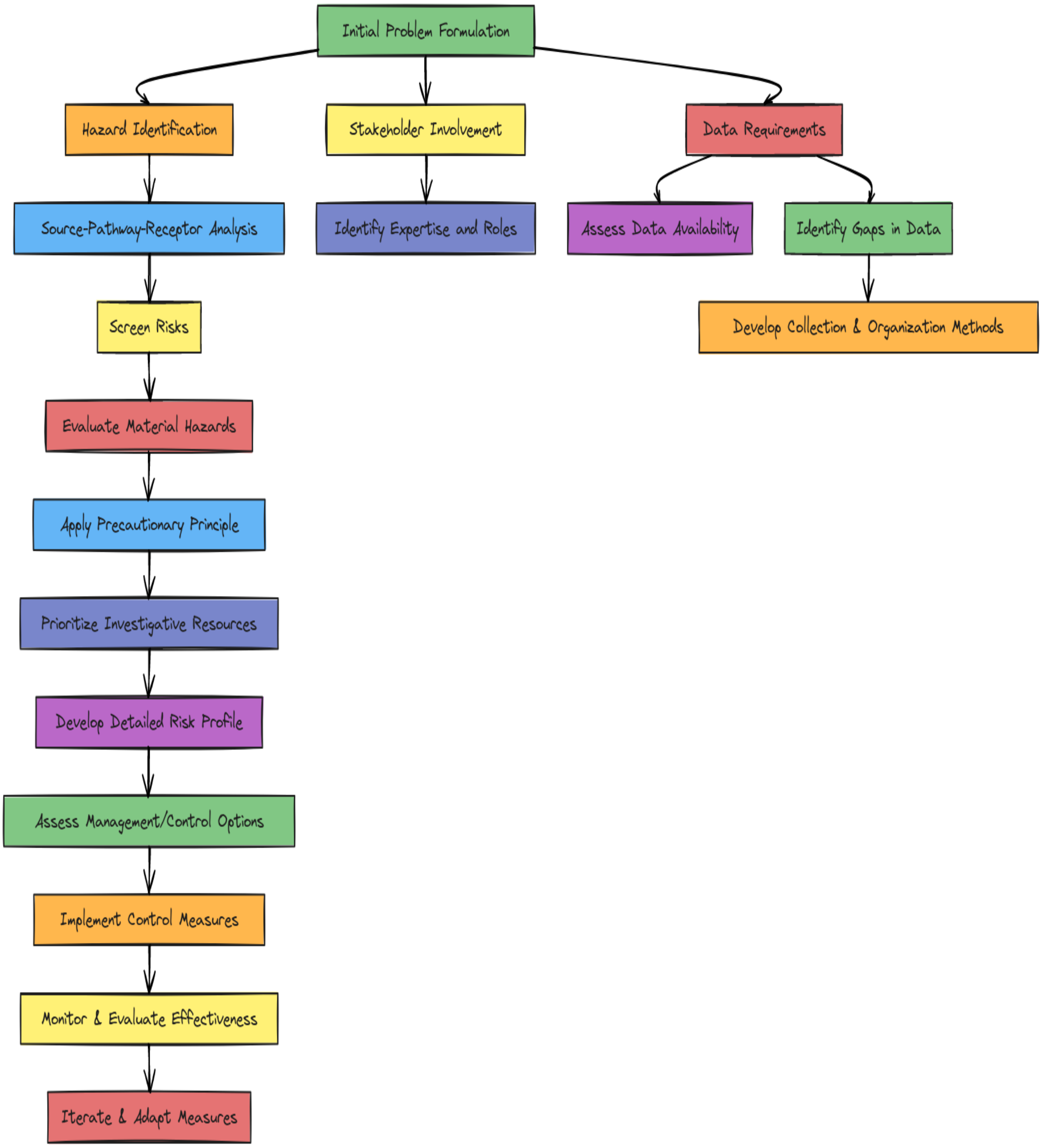

Figure 5. Diagram of key stages and considerations of designing a risk assessment

In Sections 4.2.1 ~ 4.2.4 below, we discuss these stages in more detail, with reference to the generic UK 'Green Leaves III' guidance and, by way of a concrete example, the 2001 Stockholm Convention on Persistent Organic Pollutants (POPs), which the UK has ratified.[131] Although there is limited evidence of POPs being at issue in the context of this study, the Convention addresses many parallel concerns, including unintended transboundary atmospheric pollution, the need to address complex chemical interactions, waste management, and the screening of potentially problematic chemicals for control. The Convention underlines the existence of mature international systems for evaluating and controlling transboundary atmospheric pollution that can act as a reference point when addressing the potential environmental, social, and economic considerations in play in the management of satellite ablation.

4.2.1 Framing the Problem

The **initial formulation of the problem** should establish clear boundaries for the assessment, identifying the nature of the hazard and its operation, through, for instance, a 'source-pathway-receptor' analysis.[132] Consideration should be given to where and when the risk arises, related jurisdictional issues, such as jurisdiction in relation to airspace and the atmosphere, and the existence of relevant regulatory and legislative provisions. This encompasses, not only to the application of international law in this field – space, environmental, human rights – but also domestic jurisdiction. Such a review can indicate substantive or procedural actions that are currently required or precluded.

Initial planning should consider future stakeholder involvement and expertise. In this context, the relevance of the 1998 Aarhus Convention on Access to Information, to which the UK is a party, should be noted.[133] The Convention provides the public with certain rights to access environmental information (art.4); to participate in decisions on proposed activities that may have 'significant effects on the environment' (art.6); and to participate in relation to plans, programmes and policies (art.7), as well as in the preparation of regulations and binding laws, relating to the environment (art.8). Although the grant of a licence for the operation of a single satellite may not be though likely to have 'significant effects on the environment', it is arguable that approval of a mega-constellation 'may' have such an effect.

An important aspect of this initial review is the identification of the nature and extent of data that is required; methods of data collection, including from future experimentation; and how data is to be stored, organised, and accessed/shared. Consideration should here be given to currently available data - its source, potential reliability and weight (expertise/interests/funding/purpose/audience etc.), as well as gaps. The guidance on information sources linked to the Stockholm Convention refers to the use of national or targeted surveys and literature reviews, including international literature, databases, government sources and legislation, as well as industry sources and expertise.[134] In relation to ablation, UN data sources, satellite production handbooks and product guidance, information published by regional and national agencies, and life cycle assessments, notably the ESA Database and LCA Handbook,[135] can provide valuable information in this regard.

As indicated in section 2 of WP 320, access to the granular data required to assess the impact of ablation is, however, currently problematic owing to commercial sensitivities; limits to the scope and currency of the centralised UN and national registers; lack of systematic exchange between agencies; export controls; difficulties in evaluating future development pathways stemming from speculative filings at the ITU; and the financial and logistical challenges of identifying and collating this fragmented information. **Further consideration should thus be given to clarifying what data is required to carry out risk assessments regarding the ablation of specific satellite components and materials. We also suggest that any initiatives to enhance and co-ordinate information at the international level, for instance in connection with congestion and space traffic management, include within their remit reporting of data relevant to environmental concerns, including component materials and weights.** This would not only facilitate consideration of ablation but also wider LCA analyses now being undertaken.

Initial review also enables an element of screening of risks so that investigative resources are prioritised and targeted effectively on, for instance, those materials most likely to be hazardous or to address significant uncertainties in chemical interactions. In relation to ablation, the main material of concern is aluminium, because of its significance in satellite construction and potential links with ozone depletion. There are, however, a wide range of other materials employed, discussed in TN01, that could have negative environmental effects. In our assessment at Table 2 below of the application of the key international environmental treaties to ablation we examine aluminium, lithium and silicon.

Under the Stockholm Convention, proposals for inclusion of a new chemical must first be screened through a preliminary assessment that considers: chemical composition, evidence of persistence, bio-accumulation, long-range transport, and adverse effects. Only if the chemical passes the initial screening process is it subjected to a more detailed and extensive risk profile assessment, designed 'to evaluate whether the chemical is likely, as a result of its long-range environmental transport, to lead to significant adverse human health and/or environmental effects, such that global action is warranted'.[136]

Limited evidence of environmental effects is not, however, a sufficient basis for screening out a chemical or activity at this initial stage, where serious environmental harm could ensue if no action is taken. The precautionary principle, which 'endorses action for the protection of the environment, even when there is no conclusive proof that environmental harm will occur' is relevant in this context, operating as 'a pre-prevention principle that dictates the application of measures earlier in the time-scale applicable to prevention measures, when science cannot prove that harm will occur, but there are risks that it will'.[137]

As indicated above, whilst the precautionary principle is not a rule of customary international law, it should be understood as a general principle of international environmental law, endorsed both by the international community and judiciary, and is thus a guiding principle that can be used to scrutinise states' fulfilment of other international environmental law obligations.[138] The precautionary principle as understood in international environmental law has various interpretations but the definition of the related 'precautionary approach' in Principle 15 of the Rio Declarations ('Principle 15') is widely accepted.[139] This reads:

'In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.[140]

Jaekel identifies three interdependent considerations that can be used to create an assessment matrix to determine the extent to which the precautionary principle should be applied in a specific context.[141] These are: the degree of risk posed by the threat of environmental harm; uncertainty in relation to the probability of harm; and the effectiveness and proportionality of proposed remedial action in response to the potential harm.[142] In relation to the first and third of these we can see that the Principle 15 formulation, for example, requires there to be a threat of *serious or irreversible damage* and for the measures taken to be *cost-effective*. Whilst noting these three elements, Jaekel states 'there is no default way of applying the precautionary [principle] as a rule but rather it serves as a guiding principle for the development of more specific rules or their subsequent interpretation and application'.[143]

In addition, three distinct dimensions of the precautionary principle have been identified. Firstly, a **procedural dimension**, which relates to how the precautionary principle can be implemented through procedural means, for instance, listing harmful activities, or conducting risk assessment procedures and EIAs.[144] Secondly, implementing a precautionary approach could take the form of **protective measures** regarding the environment, which may include 'banning certain activities' and, potentially highly important in the ablation context, commissioning 'scientific and economic research to enhance knowledge of long-term options'.[145] Thirdly, an **institutional dimension,** which relates to the composition, capacity, and procedures by which, an institution, such as a competent local authority or international body, can administer and make decisions in respect of the first two dimensions.[146] This final dimension thus brings into play questions of representation, effective consultation, transparency and accountability.

The Green Leaves III Guidance identifies as relevant considerations when undertaking a precautionary analysis: 'the acknowledgement of ignorance; the requirement of long-term monitoring; ensuring that real-world conditions are accounted for in regulatory appraisal; consideration of benefits as well as risks; ensuring the use of lay and local knowledge as well as specialist expertise; and avoiding 'paralysis by analysis' … where there are reasonable grounds for concern'.[147] We can thus see how the precautionary principle can operate as an integral part in certain environmental risk assessments and how its implementation itself incorporates aspects of such risk assessments.

4.2.2 The risk assessment.

Stage two involves the main risk assessment, **designed to establish the likelihood of the risk and its significance**. The Green Leaves III Guidance suggests that such assessments typically have four distinct stages: i) identification of the hazard/s; ii) assessment of the potential consequences; iii) assessment of the probability of those consequences; and iv) characterisation of the risk and uncertainty.[148] Following through with the example of the Stockholm Convention, after the initial screening of a potential pollutant, it is necessary to engage in a 'risk profile', which considers, in relation to a specific chemical: its sources, including production data, uses and releases; a hazard assessment, including consideration of interactions involving multiple chemicals; assessment of environmental fate, transportation and dispersal, including long-range; degradation and persistence; monitoring data, including its quality/reliability etc; exposure in local areas; national and international risk evaluations, classifications or labels; and the status of the chemical under international conventions.[149] In relation to satellite emissions, a risk assessment can be expected to entail not only complex investigations into the impact of ablation on specific materials, but also the processes by which ensuing gases or particles interact with each other and with the atmosphere or other terrestrial environments over various time periods.

The implications of these findings will need to be assessed in the context of models that explore how satellite modification (composition and operation) and numbers affect the nature and quantity of ablating materials in the short and longer term. Careful attention will need to be given to the strength, weight, and currency, of available information and the role of expert judgment.[150] A clear understanding of the different skill sets required to undertake these assessments and the potential for collaboration across institutions and jurisdictions will be essential.

4.2.3 Management and Control Options

The third stage involves an **evaluation of the management/control options** that can be implemented to address the particular risk or risks identified at stage two. As discussed further in Section 3.1, a wide range of incentive-based measures, command and control regulations, and voluntary approaches can be employed. These include measures designed to terminate the source of an established risk (activity, use etc.) or to reduce or mitigate its negative effects and to pre-empt or diminish the risk of future contamination. More indirect strategies involve transferring potential liability for the risk, for instance, through insurance, or encouraging its removal/reduction through technological innovation or recourse to alternative means of providing a good or service by means of financial or other incentives. In certain situations, there may be a decision simply to accept the risk and take no action, or accept the risk on the basis that the polluter adopts offset or compensatory measures, such as carbon sequestration, to reflect the negative environmental effect.[151] Where there is considerable uncertainty regarding causal processes and effects, an offset may take the form of funding for further research.

The Stockholm Convention identifies a range of potential control measures including: the elimination or restriction of the production, use, export and/or import, of specific chemicals; control of discharges and emissions; replacement of chemicals; clean-up of contaminated sites; and the establishment of exposure limits.[152]

In relation specifically to ablation, control options include measures designed to limit either the total amount of specific materials subject to ablation or emissions therefrom; or the total amount of specific materials ablating in the upper atmosphere or specific emissions at this level (WP320 p.6). The former could entail imposing limits on the number or type of satellites launched (immediate/phased); prohibiting or imposing limits (immediate/phased) on the use of certain materials; tradable emission permits calculated with reference to a total acceptable load; supporting innovation in the development of replacement materials/components or use of alternative (e.g. land based) means of delivery; promoting satellite longevity through re-use and repair capabilities, encouraging component standardisation and interoperability; and consideration of alternative means of disposal such as relocation to another orbit. Technical guidance/rules relating to re-entry trajectories and location could be developed at national, regional, and international levels to address the latter, with support for related safety and tracking requirements.

Given these options it is necessary to develop a management plan outlining which measure or measures should be applied in light of the prior risk assessment. To avoid discrimination and limit the scope for subjective assessment, the criteria for selection should be clarified in advance; follow appropriate notice and consultation procedures in line with the Aarhus Convention;[153] and be published. Four (clusters of) considerations are of particular relevance in this context:

i) The importance afforded by society to avoiding the particular damage in question, reflected, inter alia, by the recognition at international, regional, or national levels of certain rights or interests; the probability of that harm arising under the various scenarios explored in the risk assessment; and the likely severity of the harm.

ii) The technical difficulty of implementing a specific control option and the likely efficacy of a control in achieving the desired risk reduction.

iii) The existence of competing rights and interests and the degree of recognition and prioritisation afforded these at international, regional and national levels.

iv) The degree of discretion to be accommodated at the implementation stage and who should exercise this.

International, regional, or domestic rules and principles may indicate that a high level of importance should be afforded to the avoidance of certain forms of damage. In relation to environmental protection, the UN General Assembly has, as noted at 2 above, unanimously recognised that there is a human right to a clean, healthy and sustainable environment.[154] At the European level, the Grand Chamber of the European Court of Human Rights recently decided that Article 8 of the European Convention on Human Rights, which establishes a right to private and family life, imposes on State authorities an obligation to provide individuals *with effective protection from the serious adverse effects of climate change on their lives, health, well-being and quality of life*.[155] More specifically in relation to ablation, it is now firmly accepted that customary international law imposes on States an obligation to prevent significant adverse effects from transboundary atmospheric pollution, though it remains ‘rather unsettled’ whether a similar obligation exists in relation to ‘global atmospheric degradation’.[156]

These developments indicate that where there is a relatively low likelihood of serious environmental consequences, those control options should be preferred that minimise the likelihood of those consequences actually occurring. Measures designed to **terminate** the hazardous activity, or to reduce the activity to a point where the risk is no longer thought to arise, will in principle be preferable to measures that merely **mitigate**, but do not prevent, its negative effects. In such a context, reliance simply on ‘offset’ measures is unlikely to be acceptable.

This preference is also reflected in the ‘waste hierarchy’: prevention, reuse, recycle, and dispose.[157] Waste prevention is the *preferred option* under the Waste Framework Directive, which is a legal framework for waste management in the EU transposed into UK law.[158] Waste prevention is the first pillar of the circular economy model, which has gained traction recently and is presented in more depth in TN-03 WP230 Section 1.1.6. If material restriction is socio-ecologically desirable, TN-03 WP230 highlights the political and economic difficulties this would entail for the space sector. **Reuse** (an operation by which satellites or satellite components that are not waste are used again for the same purpose for which they were conceived) and **recycling** (satellites converted for another purpose) are technically difficult to achieve at scale. A disintegrating solar panel, for instance, would fall under the category of Wastes in Electrical and Electronic Equipment (including printed circuit boards, electronic components and wires) which cannot be reused again as fully functional equipment, or recycled and therefore must be categorised as hazardous waste **to be disposed of** in an environmentally sound manner.[159] If preventing or re-using or recycling satellite waste is neither feasible nor practical, then it follows that **disposal** must conform to best practices (D4D) and international standards, such as those of the European Cooperation for Space Standardization (ECSS), in which case ESM would define re-entry procedures that determine 1) angle of re-entry; 2) altitude boundaries for re-entry; 3) heating limits, etc. Such standards apply to hazardous chemicals/materials of very high concern once they re-enter the earth’s atmosphere, such as aluminium (structure), lithium (battery) and silicon (panel).

This illustrates the potential importance of considerations such as technical feasibility, efficacy and efficiency, when evaluating control options, criteria also identified in Annex VII of the Stockholm Convention. Specific measures that appear superficially most suited to terminate problematic activities can be difficult to formulate with sufficient precision in practice or present significant technical challenges by way of implementation, for example, where there is limited access to replacement materials or an alternative is still at the trial stage. There are as yet, for example, no viable and tested replacements for aluminium in the satellite chassis. Implementation may also be rendered more difficult by insufficient organisational capacity within industry or at state or international levels to monitor and ensure application of the rules.

One approach that reflects the importance of the risk but which also factors in other costs, is the 'as low as reasonably possible' approach (ALARP).[160] On this basis, measures are adopted to reduce the risk as low as possible up to the point where the costs of intervention outweigh any benefits. A formulation that is rather more modulated in protecting environmental interests can be seen in Article 5 of the Stockholm Convention, which concerns unintended emissions. This requires State Parties to 'Promote the application of *available, feasible and practical measures* that can *expeditiously achieve* a *realistic and meaningful level of release reduction or source elimination'*. Terms such as 'reasonably possible', 'realistic and meaningful', and 'cost effective' all involve difficult judgements, potentially subject to special interest capture or subjective assessment. To minimise these risks, it is necessary to clarify in advance the basis on which they are to be reached and to establish open and accountable procedures. Engagement with industry, professional and regulatory organisations, and those with expertise in independent regulation more generally, will thus be necessary when considering the criteria to be applied, and their respective weights, in developing a management plan.

It will be apparent that the 'decision matrix' is rendered increasingly complex where there are a number of competing interests. In the UK, a distinction is sometimes drawn between environmental impact assessments, where the primary concern is to evaluate environmental risks, and 'sustainability evaluations', which consider the impact of an activity on a range of sustainability related interests, including the environment.[161] But even within most environmental impact assessments, consideration is given to the positive or negative impact of intervention on other economic and social interests, discussed at 2 above, when exploring control options.

The Stockholm Convention, for example, requires socio- economic factors to be taken into account including the positive or negative impacts on human health; agriculture, including aquaculture and forestry; biodiversity; the economy; sustainable development goals; and social costs.[162] How can tensions between incommensurate interests be addressed to minimise or legitimise consequent trade-offs?

Techniques designed to assist in such complex multi-criteria decision making are MCDM analysis tools that have evolved over time in environmental sciences and governance.[163] MCDM models support the development of a structured approach to considering the impact of alternative action lines on specific objectives, evaluated with reference to pre-determined criteria. As mentioned, data or information collected through risk assessments or EIAs, and specifically information gathered from stakeholders about competing interests and rights, can set the parameters for pre-determined criteria of MCDM models.[164] MCDM techniques are particularly helpful in clarifying choices and identifying where trade-offs may need to be addressed. Deciding on trade-offs may involve policy evaluations that are better suited to deliberation by democratically accountable representatives, for instance in a meeting of state parties, rather than in a technical scientific committee and attention should be given to the role that different skill sets play at different stages of the evaluation process.

Whilst a full exposition of MCDM techniques goes beyond the scope of this report, evaluation of the available techniques should take place at an early stage to determine how best they can support the development of a robust management plan. Using the template provided in Green Leaves III Guidance, in Table 2 we provide an example of how a basic version of MCDM could apply to aspects of the 2 scenarios described in TN03, namely Limiting the Total Number of Satellites Launched (Scenario 1) and Limiting the Time Satellites Ablate in the Upper Atmosphere (Scenario 2). Table 2 explores how different approaches to each scenario –do nothing/mitigate the activity/terminate the activity – would impact, positively or negatively, on specific dimensions - environmental and safety/social equity/economic – and their technological feasibility. For present purposes, despite the limited scientific evidence, we have assumed that there will be a significant environmental effect on a) climate change, and b) ozone depletion if a steady state approach is followed. We also note that without more granular social, economic, and technical information, the comparison is inevitably 'broad brush'. Even this basic form of MCDM, however, can help to highlight what information is needed as well as some of the potential outcomes for decision makers. For instance, it is apparent that the environmental dimension is well-suited by option 3 (termination) in 1.2.1, has negative outcomes for all the other dimensions, including technological feasibility. The two charts also enable the decision maker to contrast the impact that each scenario has on the different dimensions.

Table 3. Summary of impact of Scenario 1 (Limiting Total Amount of Ablated Materials in Upper Atmosphere)

Dimension	Option 1: Do Nothing	Option 2: Mitigate	Option 3: Terminate
Environmental Impact and Safety Concerns	Unchecked satellite launches increase ablating material deposition, further damaging the ozone layer, atmospheric balance, climate change, ground risk of debris strikes, etc.	Partial reduction in satellite launches lowers ablation flux and improves atmospheric stability. Reduces risk of ground strikes.	Complete cessation of satellite deployment eliminates debris generation. It only leaves existing debris unaddressed along with the ablation impacts. Reduces risk of ground strikes.
Social Equity	Poorer nations, particularly in the Southern Hemisphere, will disproportionately bear the brunt of atmospheric changes caused by ablation of space debris. This increases the economic divide, as the spacefaring nations responsible for most space debris may escape the immediate consequences.	Can promote equity where move to shared regional satellite networks. This would improve access while balancing environmental goals. Impacts felt in both developing and underdeveloped countries especially where co-ordinated access to space assets or data not agreed.	Severe inequity as developing nations lose potential access to orbital resources entirely. Developed countries may be better placed to develop alternative means of terrestrial provision.
Economic Implications	Strong growth in commercial satellite industries at the cost of environmental sustainability.	Balanced economic benefits with some restrictions; compliance costs may increase but are offset by shared systems. May stimulate sustainable space technologies.	Revenue losses for satellite operators, particularly in broadband and IoT industries, with disproportionate effects on startups. Strong stimulus to develop sustainable space technologies.
Technological Feasibility	No effort required.	Moderate technological challenges; but requires coordination and ITU-like frameworks, with significant political challenges in implementing any quota system.	High development demands for new materials, predictive models, and alternative ground-based infrastructure globally.

Table 4. Table 5. Summary of impact of Scenario 2 (Limiting Residence Time of Ablated Materials in Upper Atmosphere)

Dimension	Option 1: Do Nothing	Option 2: Mitigate	Option 3: Terminate
Environmental Impact and Safety Concerns	Ablated materials persist in the atmosphere, disrupting radiation balance and accelerating ozone depletion.	Reduced residence time of harmful particles mitigates long-term atmospheric disruption and ecological risks. Operational change could increase risk of component survivability and ground strikes.	Total elimination of harmful materials during re-entry minimizes environmental risks but requires universal design overhaul. Operational change could increase risk of component survivability and ground strikes.
Social Equity	Vulnerable populations suffer from climate impacts driven by prolonged atmospheric perturbations.	Equitable access to affordable compliance technologies required to ensure participation from developing nations. Some developing countries could benefit from new production and material requirements, while other lose current position.	High equity risks as developing nations may lack resources to adopt required technologies, further marginalizing them. Wealthier nations could dominate sustainable practices Some developing countries could benefit/lose from new production requirements.
Economic Implications	Lower upfront costs for operators but long-term economic harm due to climate impacts and policy backlash.	Initial R&D investments required, balanced by sustainability incentives and reduced environmental liabilities over time. New material demands would advantage producer countries and disadvantage those that lose existing demand. Investment in tracking and monitoring could be significant.	Extremely high costs to redesign all spacecraft systems, with prohibitive barriers for smaller companies. New material demands would advantage producer countries and disadvantage those losing prior demand. Investment in tracking and monitoring could be significant. Potential domination of the sector by a few countries/commercial operators.

Dimension	Option 1: Do Nothing	Option 2: Mitigate	Option 3: Terminate
Technological Feasibility	No effort required.	Technologically demanding but feasible with coordinated R&D and international standards. Green propulsion techniques to lower orbit, Thermite for Demise (T4D) Concept etc. are underway.	See mitigate. Extremely difficult, as it requires complete global compliance and technological innovation on a massive scale.

One obvious, but nevertheless important, observation is that the (possibly limited) purpose behind a risk assessment must be kept in mind. A risk assessment relating to satellite congestion, for example, which focuses on the risks posed by mega-constellations to continuing access to certain orbits, could lead to the adoption of satellite launch restrictions that are suited to congestion/collision concerns but which would be inappropriate as the outcome of a risk assessment focusing on Earth-based environmental harms from satellite re-entry. Engagement among bodies undertaking risk assessments for diverse purposes is thus essential to prevent cross-cutting policy development.

4.2.4 Implementation of the Management Plan

The final stage involves **implementation of the selected control measures**, in particular, the putting into place, evaluation, monitoring, and reporting on, the operation of the management plan. The Multilateral Environmental Agreements (MEAs) discussed in Section 4.3 incorporate a range of regular reporting and oversight mechanisms, including the development of centralised data bases and the creation of inventories. States may be afforded a degree of latitude when complying with a particular requirement, and it will be important to establish, if trust in the system is to be maintained, that this latitude has not been abused. Dispute resolution procedures, for instance arbitration, may be provided and regular review should be undertaken to ensure that control or incentive measures remain effective and adequate as new information comes to light and technology, or economic circumstances, evolve.

4.2.5 The Relevance of Human Rights

At various points in this report, we have noted the relevance of human rights. Essentially, two aspects are in play. Firstly, where an interest can be framed in terms of an internationally recognised human right it should be afforded enhanced priority when balancing competing interests as part of a risk assessment exercise, and enhanced weight within a MCDM process. Secondly, human rights can be used to challenge the substantive outcome of a risk/environmental impact assessment or the procedures followed, and it is thus desirable to consider how a given risk assessment process and its outcome would be approached from a human rights dimension.

We have previously noted, at 2 above, that there has been international and regional recognition of a right to a clean, healthy, and sustainable environment, which could support curtailment of satellite activity, even at considerable cost to other interests. Other rights, or generally recognised interests, are, however, also relevant and could be relied on to question the legitimacy of such curtailment. For example, although states are generally afforded considerable scope to restrict economic interests, the EU Charter of Fundamental Rights recognises in Article 16 the ‘freedom’ to conduct a business, and such restrictions must be justifiable.[165] In addition, Article 15(1)(b) of the International Covenant on Economic, Social, and Cultural Rights recognises a right to enjoy the benefits of scientific progress and its applications;[166] with freedom of scientific exploration in outer space recognised in Article 1 of the OST. Market intervention could lead to a reduction in quality or even termination of key services, essential for communications (freedom to express and to receive information under article 19 of the International Convention on Civil and Political Rights (ICCPR)); [167] for emergency, disaster warning and navigation (human health and safety, inherent right to life under article 6 ICCPR);[168] as well as national defence.

A challenge to the outcome of a risk assessment on human rights grounds brings into play distinct legal criteria. Broadly speaking, it will be necessary to establish that there is a recognised and legitimate basis for the intervention; that any measure adopted is clear; and that the restriction is proportionate. Although proportionality has different emphases in different courts and jurisdictions, key criteria are whether the measure is capable of attaining the desired result; whether it goes beyond what is required to achieve that result; and whether it strikes a 'fair balance' between competing interests. [169] Curtailing satellite launches designed to offer 'space tourism' may thus be evaluated differently to measures that restrict essential communication and earth observation satellites.

4.3 Do Multilateral Environmental Agreements Provide a (Suitable) Framework for Addressing Ablation?

Although a state may wish to lead by example in the environmental field, the nature of satellite ablation, a transboundary phenomenon with multiple contributors and potentially global consequences, renders independent action unattractive. Firstly, unless the state is a major space-faring nation, independent action is unlikely to have much impact on the problem, and, secondly, additional domestic regulation could lead to forum shopping and reduced growth in the home space related market. The costs are likely to outweigh any environmental benefit and a co-ordinated effort to investigate and understand the complex chemical and physical processes is thus required.

Action at international or regional levels could involve amendment to the existing space-related sustainability and debris guidelines, such as the COPUOS Long Term Sustainability Guidelines or Space Debris Mitigation Guidelines, but these are purely voluntary and states may be unwilling to impose costs on domestic operators that are not uniformly applied abroad. In terms of binding international law, the Outer Space and Liability Conventions do not clearly address this problem, contain significant ambiguities, and do not provide effective mechanisms for treaty clarification and enforcement (see further TN02). A new international space treaty with an environmental focus would be difficult to negotiate in the current political climate, and would take time to draft and implement.

In this context, an alternative avenue for investigation, previously identified in TN02, is the applicability of Multilateral Environmental Agreements (MEAs). In particular, a number of MEAs address transboundary pollution affecting the atmosphere, or are concerned, as discussed previously, with the control of transboundary waste, two fields potentially relevant in this context. And although we are dealing with satellites or their component parts, ablation occurs primarily in the airspace below what would generally be considered 'outer space', it thus relates to the Earth's environment and not that of outer space, the focus of MEAs

A further reason for considering MEAs is that they have been adopted, together with related protocols and guidance, on a fairly regular basis from as far back as the seventies. They have thus acted as a test bed within which to explore how international agreement on transboundary pollution and waste can best be secured, as well as the effectiveness in practice of various assessment, control and oversight mechanisms.

We have focused our attention on five conventions that appear most relevant from the perspective of satellite ablation. These are:

- The Montreal Protocol on Substances that Deplete the Ozone Layer (signed September 16, 1987; entered into force January 1, 1989)
- The Convention on Long-Range Transboundary Air Pollution (CLRTAP)(signed November 13, 1979; entered into force March 16, 1983)
- The Kyoto Protocol to the UN Framework Convention on Climate Change (UNFCCCC) (adopted 11 December 1997; entered into force 16 February 2005)
- The Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (Basel Convention) (signed 22 March 1989; entered into force 5 May 1992)
- The Stockholm Convention on Persistent Organic Pollutants (adopted 22 May 2001; entered into force 17 May 2004)

Below we identify specific substantive and procedural characteristics of some or all of these conventions that are designed to enhance their effectiveness and legitimacy in addressing environmental damage. These characteristics should thus be considered when examining the potential for international or regional co-ordination in the ablation field, whether of a binding or advisory nature, and what form this might take.

i) The relatively **high levels of state adherence** (with exceptions for certain conventions/states), enhancing overall environmental gains and limiting free riding. The Montreal Protocol, for example, has 198 parties, Stockholm 186, and Basel and Kyoto 191 and 192 respectively.

ii) Models of **governance that combine specialist expertise with ultimate political oversight** by the Committee of Parties (COP). Specialist committees and panels can enhance objectivity and acceptance of outcomes. The Montreal Protocol, for example, is supported by three panels: a Scientific Assessment Panel, which assesses the status of the depletion of the ozone layer and related atmospheric scientific issues, reports from panel inform decisions regarding new substance inclusions; a Technology and Economic Assessment Panel, which advises on the feasibility of alternatives to ozone depleting substances (ODS) and the practicalities of phasing out and transition; and the European Monitoring and Evaluation Panel, which provides data and advice on the public health impacts of any ODS. The Kyoto Protocol does not maintain a scientific panel and relies instead on the work of the Intergovernmental Panel on Climate Change with its three working groups.

iii) **Clarity in terms of scope**, through use of defined terms and the listing of specific materials or activities in annexes or schedules. A variety of guidance documents and handbooks are generally provided. The precise nature of specific definitions can exclude the application of these measures to (unanticipated) space related hazards, even though the environmental concerns may be in point.

iv) A **co-operative approach** to addressing problems and implementation. This can take the form of the technical and practical guidance noted above, as well as support for public-private partnership programmes to develop such advice regarding developing or problematic areas, as under the Basel Convention where guidance has been developed in relation to the management of end-of-life mobile phones and computing equipment. Co-operation can also be seen to underpin the **prior informed consent mechanism** in, for example, the Basel Treaty. This restricts the export of hazardous waste from one party to another where the 'receiving' country has not been properly informed or given consent.

v) **Flexibility and scope for adaptation** through protocols or annexes, with reference to well-developed risk assessment procedures. The Montreal Protocol has been amended five times and enables adjustment of those substances considered to have an ozone depleting or global warming potential without formal amendment of the treaty itself (Article 2(9). As noted above, the Stockholm Convention establishes a detailed risk assessment procedure for reviewing new chemicals, which **takes into account the economic and social costs and benefits of specific control options**.

vi) A **tiered approach to intervention that takes into account both the benefits and costs of specific controls**. The Stockholm Convention establishes outright bans on the use, import and export of the most harmful chemicals, but allows for reduction and a phased withdrawal in other contexts.

vii) **Accommodation of different national economic and social contexts,** reflecting the application of the principle of subsidiarity in determining how best to realise specific targets. The Kyoto Protocol, for example, establishes three mechanisms that provide states with a degree of flexibility in contributing to the reduction of green-house gasses: international emissions trading; joint implementation (where countries earn emission reduction credits by investing in projects in other countries); and the Clean Development Mechanism that allows countries to receive credits towards their targets by investing in emission reduction projects in developing countries.

viii) **Redistributive mechanisms**, such as Trust Funds (eg the Stockholm Trust Fund, to which the UK made a substantial pledge and payment in 2024), to facilitate technological change and compensate for losses derived from adaptation;

ix) **Compliance mechanisms**, combining, for example, international customs co-ordination with national fines;

x) **Monitoring and oversight mechanisms** in the form of regular national reports, inventories etc.

Although treaties rarely explicitly codify decision-making methodologies, we can see that operational mechanisms in, for example, the Kyoto Protocol and Stockholm Convention, entail the application of MCDM principles by balancing competing objectives such as equity, cost-efficiency, and environmental sustainability. The Kytoto Protocol, for example, includes a suite of flexibility mechanisms, such as a cap-and-trade mechanism, and calls for consideration of factors such as environmental friendliness; cost-effectiveness; socio-economic co-benefits; and equity as reflected in the 'Common but Differentiated Responsibilities' principle, which seeks to acknowledge both the scale of historical emissions and current developmental needs.

With these considerations in mind, we examined whether the ablation of a satellite containing either **aluminium, lithium or silicon**, substances present in the composition of many satellites, would fall within the scope of these five treaties.

Our main finding is that it is unlikely that emissions produced by the ablation of these substances, or the ablation process itself, would currently be covered by any of these treaties.

This is because such emissions or activities do not fall within the relatively tightly defined lists of substances/activities that reflect the focus of each convention (as with the focus on POPs in Stockholm, for example), or there is not as yet sufficient evidence that ablation of these materials has the required level of impact (as with the Montreal Protocol). In other contexts, the scope of the treaties appears to exclude application to waste originating from outer space (as with the Basel Convention, which applies to the import-export of commodified wastes).

In all instances, there is scope to include additional substances or activities, but these would still need to fall within the scope of the particular Treaty. The position is made more difficult by the fact that in relation to three of these treaties, the USA, a key space faring state, is either not a party or has yet to implement the treaty in domestic law.

It nevertheless remains possible that additional evidence as to the effects of ablation could render one or other of these conventions applicable. Alternatively, future modification in the understanding of, or amendment to, particular definitions (eg waste) could broaden their scope. Moreover, although these appear the most relevant MEAs regarding atmospheric pollution, other MEAs could be applicable, including those concerned with maritime and terrestrial pollution.

Our findings are summarised in the table below.

Table 6. ***MEAs, their present and prospective ablation applicability***

Dimension	Montreal Protocol	CLRTAP	Kyoto Protocol	Basel Convention	Stockholm
Primary Objective	Global protection of the ozone layer by phasing out ozone-depleting substances (ODS) and addressing high-global warming potential (GWP) substances.	Addressing long-range transboundary air pollution.	Reducing anthropogenic greenhouse gas emissions.	Protect human health and the environment from the adverse effects of hazardous wastes and prohibit the import/export of hazardous wastes to countries with less-rigorous waste management measures (disposal and storage).	Protection of human health and the environment from persistent organic pollutants (POPs).
Membership	Universally ratified (198 parties, including all UN member states and the EU). Ensures universal applicability and participation.	Limited scope with 51 parties. Notable absences include major emitters like India and China.	192 parties. Absence of Canada and USA, a significant space debris contributor.	191 Parties. USA has signed the convention but has yet to ratify and put enter into force. Ban Amendment has 104 Parties.	186 State Parties. USA has neither ratified nor entered the Convention into force.
Targeted Substances	• CFCs, HCFCs, and halons. • Carbon tetrachloride and methyl chloroform • Methyl bromide • HFCs, (added by Kigali Amendment).	• Acidifying compounds (e.g., SO_2, NOx). • Persistent organic pollutants (e.g., PCBs, dioxins). • Heavy metals (e.g., lead,	• Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), HFCs, PFCs, and SF_6.	• Annexes 1 nominally lists medical waste, paints & varnish, list of chemicals, mercury, lead compounds, as inherently hazardous; • Annex 3 lists any waste that may have the following qualities: flammable, explosive,	• focus on POPS: organic chemical substances (carbon-based) • grouped into to be eliminated, restricted, and minimized • Pesticides: Aldrin, Chlordane, Linane, etc.

		cadmium, mercury).		oxidizing, corrosive, or toxic.	• Industrial chemicals: UV-328, HCB, HBCDD, SCCPs Unintentional Production: PCB, PCDF, PCDD, etc. – Certain chemicals used in aerospace and space and defense applications exempt (eg. Dechlorane Plus found in Part XI)
Why Excluded?	Focused on stratospheric catalysts (chlorine, bromine) that deplete ozone directly. Space ablation products lack sufficient evidence of comparable atmospheric impacts.	Al, Li, and Si are not acidifying agents, bioaccumulators, or POPs. Lack proven harm or persistence across national borders	Current focus is on direct greenhouse gases with known impacts on radiative forcing. Space-origin pollutants lack sufficient data for inclusion.	Scope of the convention restricted to the transboundary movement of wastes between areas under national jurisdiction	Materials covered are organic in nature (carbon-based) whereas materials ablated are predominantly inorganic
Potential for Inclusion	Possible under Article 6. Would require more evidence linking these materials to ozone layer degradation or high-GWP impacts. (Research studies	Traditionally applies to terrestrial emissions. Global Commons originating pollutants from high altitudes fall outside its	Possible if IPCC assessments evolve to address high-altitude particles and their indirect climate effects. However, the absence of the USA	The E-waste amendment (effective as of 1 January 2025) has the possibility of broadening the scope of wastes including materials that are present in space objects.	Consideration of other (carbon-based) chemical outputs from ablation. The Persistent Organic Pollutants Review Committee reviews chemicals proposed for the Annexes, review of new chemicals and those in Annex D, E, and F are handled under Article 8.

	have started to come in)	jurisdictional scope. Inclusion might become possible if space debris by-products are shown to have adverse cross-border impacts. Existing scientific thresholds must be revised to accommodate these materials.	significantly limits its applicability.		
Flexibility for Expansion	High flexibility for adding substances via amendments (e.g., Kigali for HFCs). Article 6 enables frequent scientific review to inform inclusion decisions.	Protocol-specific revision process allows for new substances to be added. Requires robust scientific proof and consensus to justify amendments (assessed by the WGE/EMEP). EMEP also considers the socio-economic factors.	Articles 2.9 and 9 allow adjustments to targets. Periodic reviews ensure alignment with scientific advances.	Amendments can be proposed with relevant scientific and technical considerations (Art 17). These are to be communicated 6 months prior and adopted at the meeting of the COP. A ¾ majority vote or a 2/3 majority who are present and voting at the meeting, is undertaken where consensus cannot be reached. Entry into force occurs on the 19th day after receipt by the Depositary	Parties may submit a proposal to include chemicals under the Annexes A, B, and C to the Secretariat (Art 8) Amendments can be proposed by any Party to the Convention (Art 21) which are adopted during the meeting of the COP and communicated 6 months prior. Amendments to the annexes of the convention are restricted to procedural, scientific, technical or administrative areas. The proposal and adoption of new annexes follows the procedure of Article 21. The new annex

					becomes binding unless Parties give notify their inability to accept the new annex in the time given timeframe.
Challenges to Inclusion	Materials must demonstrate significant impacts comparable to ODS or HFCs. Space-origin pollutants currently lack explicit inclusion under the Protocol's scope.	Article 1 excludes non-terrestrial sources. Amendments require evidence that these materials meet the transboundary pollution criteria (persistence, harm, transportability). Requires broad reinterpretation of existing definitions and thresholds.	Limited by the Protocol's reliance on known GHGs with direct climate impacts. Data gaps and lack of USA participation further hinder applicability to space-origin pollutants.	Scope of the convention restricted to the movement of wastes between areas under national jurisdiction. Need to determine whether the movement of debris from orbit into the atmosphere constitutes a for of import/export trade off.	Ablated materials of concern such as aluminum, lithium (except. Lithium perfluoro octane sulfonate) and silicone, are not covered in the scope of the convention.

4.4 Concluding remarks

The regulation of satellite ablation and its environmental impacts is a complex and pressing issue requiring coordinated international action. There already exist, however, well established substantive and procedural requirements and principles that can guide future study in this field. These include:

- the precautionary principle,
- environmental audits, and
- sustainability and risk assessments incorporating relevant MCDM methodologies.

When considering how to balance social, economic and environmental interests, the human rights framework should also be taken into account, not only to inform how particular interests are prioritised but also because significant regulatory decisions that curb space activities could be the focus of legal challenge.

Environmental audits and risk assessments systematically gather and evaluate information enabling policy choices to well-informed and rational, minimising subjective choice. In considering and ranking control options, MCDM techniques can establish structured decision-making processes that assign weights to criteria, prioritize alternatives, and resolve trade-offs transparently. This capability is crucial for addressing complex global challenges where multiple stakeholders and objectives converge, as seen in the ablation context. We applied a MCDM methodology to the two specific ablation-related scenarios in this report, albeit in the context of very restricted information. The first scenario, Option A, focused on limiting the ablated material introduced into Earth's atmosphere by restricting satellite launches, optimizing materials, and enhancing satellite design to reduce debris. However, we found this could hinder economic growth in the space sector, affect dependent communities, and restrict equitable access to space-related services, such as communication, navigation, and earth observation. Conversely, Option B proposes modifications to satellite design and re-entry practices to ensure lower atmospheric degradation. Although this approach preserves space sector access, it would raise costs, disrupt supply chains, and exclude new players, potentially entrenching existing inequalities.

In resolving complex problems, there is no perfect solution. When assessing steps that should be taken now, and in the future, to address the environmental risks posed by ablation, a large net should be cast to involve international standardisation bodies, the participation and information of the public, environmental audit agencies and social scientists involved in structured risk assessments.

The report also underscores the broader environmental implications of unregulated satellite ablation, including potential harm to the ozone layer, climate systems, and human health. Existing international legal frameworks recognize the right to a healthy environment, but these often exclude space activities from their mandates. The report calls for integrating space industry emissions into global pollutant tracking systems, enhancing corporate accountability, and strengthening treaties to address gaps in reporting and mitigation efforts. Developing a unified database for pollutants, including space-related chemicals, is proposed to support better regulation and public participation, ensuring sustainable and equitable practices in the space sector.

Current Multilateral Environmental Agreements provide limited applicability to satellite ablation due to narrow definitions and insufficient inclusion of relevant chemicals, materials or activities. Nonetheless, they offer valuable frameworks for addressing transboundary environmental hazards, especially through their risk assessment methodologies, compliance mechanisms, and adaptability to emerging scientific evidence. Policy makers have at their disposal a variety of risk assessment models, (e.g., the ‘as low as reasonably possible’ approach or ALARP), and governance structures, such as the complex MCDM, to tackle the issue.

Future steps should prioritize filling data gaps on the environmental effects of ablation, fostering collaboration among nations to develop targeted policies, and leveraging existing MEA structures for inclusion of space-related hazards in their annexes and additional protocols. While independent state actions may be insufficient, advancing treaties or guidelines with binding standards is essential for mitigating the atmospheric and environmental risks posed by satellite ablation, while balancing economic and societal interests in space activities.

5 Scenarios for Sustainable Space Utilisation

In this section, we have considered two distinct scenarios encompassing viable mitigation strategies and actionable recommendations for non-binding or regulatory solutions, which are

- **Scenario A:** focusing on limiting the total mass of ablated material introduced into Earth's upper atmosphere by implementing strategies such as using alternative materials, D4D enhancements, and stricter post-mission disposal practices. The aim is to minimize the overall environmental footprint of spacecraft re-entry.
- **Scenario B:** focusing on reducing the residence time of ablated particles in Earth's upper atmosphere by altering re-entry practices and optimizing spacecraft design to ensure material demise occurs at lower altitudes. The goal is to accelerate the removal of particles from the atmosphere, minimizing their long-term environmental impact.

Table 7 shows the summary of comparative analysis on these two scenarios.

Table 7. Comparative Analysis of two scenarios

	Scenario A Limiting total material flux	Scenario B Reducing presence time
Focus	Limiting total mass introduced into the atmosphere	Reducing time particles remain in the atmosphere
Key strategy	Material substitution, D4D enhancements, controlled re-entry.	Optimized re-entry trajectories, component recovery.
Implementation costs	High due to material development and manufacturing changes	Moderate to high depending on trajectory and recovery requirements
Implementation feasibility	Requires global agreements and technological development.	Requires advanced modeling and tracking, with higher operational complexity,
Environmental impact	Direct reduction in material deposited in the atmosphere	Faster removal of ablated particles, minimising long-term effects
Safety concerns	Minimal ground risk but potential impact on spacecraft reliability	Elevated ground risk from surviving debris
Industry feasibility	Challenging for small operators due to cost	Requires advanced modelling and coordination, but scalable

5.1 Scenario A: Limiting the material flux

The first scenario focuses on limiting the total amount of material introduced into Earth's atmosphere during spacecraft re-entry by limiting satellite launches, optimising materials, and enhancing Design for Demise (D4D) practices. This approach addresses the growing concern over the environmental impact of metallic oxides, such as aluminium and titanium, ablated during re-entry. By capping the number of active satellites. particularly from mega-constellations like Starlink and Kuiper, this strategy directly reduces the mass of materials that will eventually enter the atmosphere. Additionally, employing D4D principles ensures that materials used in spacecraft are optimised for complete burn-up, minimising harmful residuals such as metal oxides in the atmosphere.

While this scenario has significant environmental benefits, such as reducing the deposition of persistent metals in the mesosphere and stratosphere, it also raises challenges. Restricting satellite launches may slow the expansion of space-based services like broadband internet, particularly in underserved regions. This could exacerbate the digital divide and reduce opportunities for SMEs to compete in the space sector. Furthermore, redesigning spacecraft materials to meet D4D standards requires significant research and development, which could increase manufacturing costs, placing additional burdens on smaller operators.

From a sustainability perspective, limiting total flux offers a straightforward way to mitigate environmental harm. However, it requires international cooperation to enforce launch limits and ensure compliance with material efficiency standards. This scenario could encourage innovation in spacecraft design and materials but may also constrain the rapid growth of the space industry, posing economic and technological trade-offs.

Table 8. Summary of strengths and weaknesses of limiting total material flux.

Strengths	Weakness
• Directly reduces total material flux. • Encourages adoption of environmentally friendly designs. • Promotes a global focus on space sustainability.	• Caps on satellite launches could stifle innovation and market growth. • High costs of redesign and D4D compliance for smaller operators. • International consensus on launch limits may be challenging.

5.1.1 Mitigation Strategies

Following three mitigation strategies can be implemented on Scenario A:

1. Restrict the Number of Satellite Launches
   - Set launch limits on mega-constellations, such as Starlink and Kuiper, which significantly contribute to re-entry flux due to the high frequency of satellite replacements.
   - Promote international agreements to cap the number of satellites in operation within Low Earth Orbit (LEO), focusing on balancing utility and environmental sustainability.

2. Material Optimisation for Satellites
   - Adopt high-demisability materials that fully burn up upon re-entry, reducing the deposition of persistent metals like aluminium and titanium in the upper atmosphere

- Redesign critical components, such as propellant tanks, using composite materials with improved demise characteristics.

3. Controlled Re-Entry Mandates
   - Require controlled re-entries for large satellites or those with high-risk materials, targeting unpopulated areas for safe material deposition.

5.1.2 Evaluation for Space Sustainability

5.1.2.1 Environmental Impact

- Reducing the number of satellites launched directly limits the volume of ablated material, lessening the environmental burden on Earth's atmosphere.
- Enhanced D4D practices ensure that any launched satellites contribute minimally to atmospheric deposition upon re-entry.

5.1.2.2 Economic and Industrial Impact

- Capping satellite launches may hinder the growth of space-based services like broadband internet and Earth observation, potentially impacting global connectivity and data services.
- Smaller operators and startups may struggle with higher costs associated with D4D compliance and controlled re-entry requirements.

5.1.2.3 Feasibility and Implementation

- International agreements are necessary to enforce launch limits, but achieving consensus may be difficult due to competing national and commercial interests.
- Material redesign and controlled re-entry systems require significant upfront investment and technological development.

5.2 Scenario B: Reducing the presence time

The scenario B focuses on reducing the residence time of ablated material particles in the upper atmosphere by altering re-entry practices and implementing D4D approach. By optimising re-entry trajectories, spacecraft can be designed to burn up at lower altitudes, where atmospheric density accelerates the removal of ablated particles. Components with high survivability can be intentionally designed to withstand re-entry and be recovered on the ground, preventing their dispersion in the atmosphere. This strategy ensures that harmful materials, such as metallic oxides, are either burned up completely at lower altitudes or removed from the environment through targeted recovery.

However, this can introduce new challenges related to the safety of ground. Increasing the survivability of spacecraft components raises the risk of ground impact, particularly in populated areas, creating safety and liability concerns for operators. Effective implementation requires precise trajectory modelling, monitoring systems, and robust international coordination to establish designated recovery zones, such as remote oceanic regions. Additionally, optimising re-entry practices increases the operational complexity and costs of satellite missions, particularly for operators lacking advanced propulsion and tracking systems.

From a sustainability standpoint, limiting presence time directly addresses the long-term environmental impact of ablated metal particles, reducing their potential to damage the ozone layer or alter the radiation balance of the Earth. It will allow for continued growth in satellite launches without imposing strict caps, supporting the industry's expansion while mitigating environmental risks. However, balancing ground safety with atmospheric sustainability remains a critical challenge that requires further research and international collaboration.

Table 9. Summary of strengths and weaknesses of reducing the presence time.

Strengths	Weakness
• Reduces long-term environmental impact by minimizing presence time. • Does not impose direct limitations on satellite launches. • Scale and adaptable to varying mission profiles.	• Increased risk of ground impact from surviving spacecraft components. • Required significant investment in tracking and recovery systems. • Complexity of modelling in atmosphere and re-entry.

5.2.1 Mitigation Strategies

Following three mitigation strategies can be implemented on Scenario B:

5.2.1.1 Optimise Re-Entry Trajectories:

- Controlling re-entry angles to ensure materials burn up at lower altitudes where atmospheric density accelerates their removal from the mesosphere and stratosphere
- Design re-entry profiles to target areas with minimal atmospheric circulation, reducing the spread of ablated particles.

5.2.1.2 Controlled Ground Recovery for Durable Components

- Enhance the survivability of select components, such as reaction wheels and payload housings, for targeted recovery post-re-entry.
- Develop infrastructure to track and retrieve surviving debris, minimizing its long-term impact on the environment.

5.2.1.3 D4D Implementation

- Use sacrificial coatings on spacecraft components to control ablation rates, ensuring that harmful materials fully burn up at lower altitudes.
- Use self-destructing structures that trigger at a certain altitude to expose internal components

5.2.2 Evaluation for Space Sustainability

5.2.2.1 Environmental Impact

- Reduces the persistence of harmful particles in the upper atmosphere, where they could catalyse ozone depletion or alter radiative forcing
- May increase risks associated with ground impact of surviving debris if not managed carefully.

5.2.2.2 Economic and Industrial Impact:

- Requires investment in trajectory planning and ground recovery systems, which could raise mission costs, particularly for small operators.
- Offers a scalable solution that does not directly restrict satellite launches, preserving industry growth.

5.2.2.3 Feasibility and Implementation:

- Advanced atmospheric modelling tools and tracking infrastructure are required for effective implementation, adding technical complexity.

5.3 Recommendations

To achieve a sustainable balance between environmental protection and the continued growth of the space industry, a hybrid approach combining elements from both scenarios is recommended. By integrating strategies to limit the total material flux while also reducing the atmospheric residence time of ablated particles, we can address the environmental challenges posed by spacecraft re-entry more comprehensively.

An implementation strategy could begin with voluntary adoption of mitigation measures, gradually transitioning to regulatory frameworks as technologies and practices mature. For example, encouraging the use of high-demisability materials through industry recognition programs or subsidies can promote early compliance without imposing immediate financial burdens. Over time, these practices can be formalised into international agreements under the leadership of organizations such as the United Nations Office for Outer Space Affairs (UNOOSA) or the European Space Agency (ESA), ensuring uniform adoption across operators.

Moreover, international collaboration is essential for the success of these strategies. Global coordination can standardise guidelines for D4D and optimise re-entry trajectories and methods, creating a level playing field for all stakeholders. By pooling resources for shared R&D efforts, such as advanced materials testing or trajectory modelling tools, spacefaring nations and private operators can collectively reduce costs while improving environmental outcomes.

In parallel, technological innovation must also be prioritised to address the unique challenges of each scenario. Developing materials that both enhance spacecraft performance and burn up completely during re-entry at low altitude will reduce total material flux at the upper atmosphere, while advanced tracking and trajectory control systems can minimise atmospheric residence times. Investments in infrastructure, such as recovery zones for surviving debris, can further mitigate risks to both the environment and human safety.

Ultimately, a flexible and inclusive approach that fosters collaboration, incentivises innovation, and gradually implements regulations will support the long-term sustainability of space operations. This hybrid strategy ensures that the benefits of space exploration and commercialisation can be realised while safeguarding Earth's atmospheric and orbital environments for future generations.

Table 10. Summary of Recommending Strategies.

Hybrid Approach	**Phased Implementation**	**Collaborative Frameworks**	**Technological Investment**
Combine elements of both scenarios by encouraging material-efficient D4D practices (Scenario A) while optimising re-entry trajectories to reduce atmospheric persistence (Scenario B).	Introduce voluntary adoption of these strategies, transitioning to regulatory measures as technologies mature	Develop international guidelines under bodies like the UN or ESA to balance environmental sustainability with industry needs	Fund research into advanced materials and trajectory modelling to support widespread adoption of mitigation practices

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[109] Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters 2161 UNTS 447 (opened for signature 22 March 1989, entered into force 25 June 1998, entered into force 30 October 2001), art 4, 5, 9(3).

[110] Kyiv Protocol on Pollutant Release and Transfer Registers 2629 UNTS 119 (opened for signature from 21 May 2003, entered into force 8 October 2009).

[111] Report of the Special Rapporteur Marcos Orellana on the implications for human rights of the environmentally sound management and disposal of hazardous substances and wastes, 'Shipping, toxics and human rights: Implications for human rights of the environmentally sound management and disposal of hazardous substances and wastes', 13 July 2023, A/78/169.

[112] Report of the Special Rapporteur Marcos Orellana, 'Pollution information portals: strengthening access to information on releases of hazardous substances Report of the Special Rapporteur on the implications for human rights of the environmentally sound management and disposal of hazardous substances and wastes', A/HRC/57/52, 15 July 2024.

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[125] Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention) 2017 (ECE/MP.EIA/21/Amend.1), article 2

[126] ILC Guidelines (n.9) Guidelines 3 and 4, emphasis added.

[127] The Russian Federation and the USA have signed but not further ratified the Convention.

[128] Espoo (n.125).

[129] Zero Debris Charter (n.99) para 1.2.

[130] Green Leaves III (n. 118) p 46.

[131] Stockholm Convention on Persistent Organic Pollutants (adopted 22 May 2001; entered into force 17 May 2004).

[132] Green Leaves III (n.118) at pp.10-20.

[133] Aarhus Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters (signed 25 June 1998, entered into force 30 October 2001), United Nations Treaty Series, vol. 2161, p. 447. The Convention has been widely adopted across Europe, including by the EU and UK. Decisions relating to national defence may be excluded from the scope of art.6.

[134] Stockholm (n.131), Annex VII, E. Guidance for Information Collection.

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[137] Sage-Fuller Bénédicte Sage-Fuller, *The Precautionary Principle in Marine Environmental Law: With Special Reference to High-Risk Vessels* (Taylor & Francis Group 2013) 68; James Harrison, Saving the Oceans Through Law: The International Legal Framework for the Protection of the Marine Environment (Oxford University Press, 2017) 14.

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[142] Jaeckel (n. 138) 37-43.

[143] Jaeckel (n. 138) 43-48; Implementing the precautionary approach to activities in the Area, ISBA/25/C/8 (9 January 2019) ('Secretariat's note') 4. A view shared by Harrison (n 137) 233.

[144] Jaeckel (n. 138) 44-46.

[145] Jaeckel (n. 138) 47.

[146] Jaeckel (n. 138) 44.

[147] Green Leaves III (n.118) at p.44.

[148] Ibid, p.22.

[149] Stockhom Convention (n. 131) Annex E.

[150] Green Leaves III (n.118) pp.32-35.

[151] Green Leaves III (n.118) p.41.

[152] Stockholm (n.131) p.

[153] Aarhus Convention (n.133).

[154] See further discussion at section 4.

[155] *Verein Klima Seniorinnen Schweiz and Others v. Switzerland*, application no. 53600/20, judgment of the 9 April 2024, available at: https://hudoc.echr.coe.int/eng/#{%22itemid%22:[%22001-233206%22]}.

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[157] EU Recital 8 of Directive 2009/98/EC.

[158] EU Framework Directive EC/2008/98 on Waste, 19 November 2008: waste prevention programmes (Article 29); UK Waste and Environmental Permitting etc. (Legislative Functions and Amendments etc.) (EU Exit) Regulations 2020.

[159] See Basel Convention (n 1) Annex IX B1110; Technical guidelines on transboundary movements of electrical and electronic waste and used electrical and electronic equipment, in particular regarding the distinction between waste and non-waste under the Basel Convention, UNEP/CHW.14/7/Add.6/Rev.1, Paragraph 32(a) p 10.

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[161] See Ministry of Defence, Sustainability and Environmental Appraisal Tools Handbook, version 8.2 October 2019, Section 2: Sustainability Appraisal, at: https://assets.publishing.service.gov.uk/media/5db81b52e5274a4aa29e3c28/20190930-Section_2-Sustainability_Appraisal-O.pdf.

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