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*

UK Space Agency Contract No:
UKSAG23A_00100

Milestone 2 Deliverable (D4)
TN-04 Future research programme plan

15 December 2024

Prepared by

Minkwan Kim, University of Southampton, UK
Alexander Wittig, University of Southampton, UK
Bharathram Ganapathisubramani, University of Southampton, UK
Ian Williams, University of Southampton, UK
Arunkumar Chinnappan, University of Southampton, UK
Ian Williams, University of Southampton, UK
Rachael Craufurd Smith, University of Edinburgh, UK
Ian Christensen, Secure World Foundation
Michael Picard, University of Edinburgh, UK
Rania Djojosugito, University of Edinburgh, UK
Eswar Theagaragan, University of Edinburgh, UK
Hercules Wessels, University of Edinburgh, UK

Reference	**G23A.00100.TN.04**
Issue/Revision	**1001**
Date of Issue	**15/12/2024**
Status	**Initiated**

Approval

Title: TN-04 Future research programmeme plan	
Issue Number: 1	**Revision Number: 1**
Author(s): **Minkwan Kim** (University of Southampton), **Alexander Wittig** (University of Southampton), **Bharathram Ganapathisubramani** (University of Southampton), **Ian Williams** (University of Southampton), **Arunkumar Chrinnanppan** (University of Southampton), **Michael Picard** (University of Edinburgh), **Rachael Craufurd-Smith** (University of Edinburgh), **Andrew Bacon** (Space Forge), **Ian Christensen** (Secure World Foundation)	**Date:** 15/12/2024
Approved by:	**Date of Approval:**
	15/12/2024

Change Log

Reason for change	Issue	Revision	Date
N/A	N/A	N/A	N/A

Change Record

Issue Number: N/A	Revision Number: N/A		
Reason for change	**Date**	**Pages**	**Paragraph(s)**
N/A	N/A	N/A	N/A

Distribution

Name/Organisational Unit:
Leire Parla (Leire.Parla@ukspaceagency.gov.uk, UK Space Agency)
Jodie Howlett (Jodie.Howlett@ukspaceagency.gov.uk, UK Space Agency)
Ray Fielding (Ray.Fielding@ukspaceagency.gov.uk, UK Space Agency)

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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 programme 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-04, successfully meets the requirements outlined in Milestone 2 (MS3) by establishing a prioritized research plan with clear rationale, mapping ongoing efforts by UK Space Agency, ESA and NASA. TN-04, therefore, will lay the foundation for a robust future research programme focused on the sustainable use of space in the context of atmospheric ablation.

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
[AD3]	G23A.00100.TN.01	A research strategy for evidence-based space policy development	1001
[AD4]	G23A.00100.TN.02	Literature review document	1001
[AD5]	G23A.00100.TN.03	Report on critical landscape analysis	1001

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 capacity-building and challenges.	1	June/2024

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 Research Roadmap

Scientific and technical gaps can be categorised as '**Prediction**', '**Prevention/Mitigation**' and '**Implementation**'.

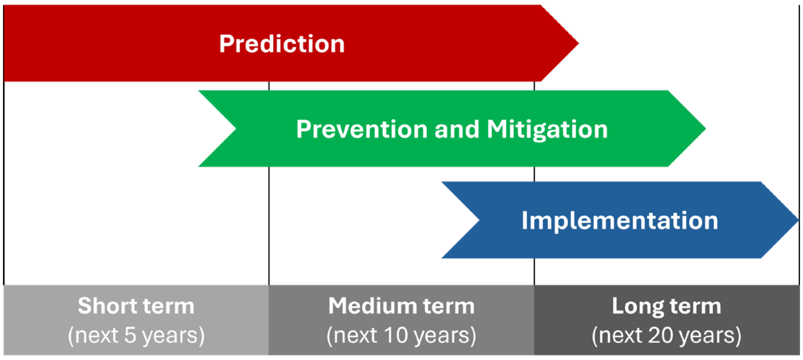

Figure 1. Technical research roadmap overview.

Prediction primarily involves modelling and data collection capabilities for assessing the global impact of ablating spacecraft in Earth's upper atmosphere, as well as evaluating the validity and credibility of these models. Since predictive capabilities can provide essential scientific evidence for regulators and policymakers, they should be a core focus of short- and medium-term technical research programmes.

The **Prevention & Mitigation Research Programme** focuses on developing technologies to prevent harmful environmental impacts in the upper atmosphere and remediate contamination caused by material ablation from re-entering spacecraft and launch vehicles. This programme will encompass:

- Developing low-cost controlled re-entry technologies.
- Establishing *Design for Demise (D4D)* practices to reduce or prevent material ablation in the upper atmosphere.
- Creating new spacecraft materials that minimize the release of harmful byproducts during atmospheric re-entry.
- Developing technologies to reduce the atmospheric residence time of byproducts generated from ablated materials.

By offering technical solutions aligned with emerging regulations and guidelines, prevention and mitigation capabilities should be a core focus of medium- and long-term technical research programmes.

The **Implementation Research Programme** will serve as the final phase in establishing regulations and guidelines for atmospheric re-entry. This programme will focus on:

- Identifying key mitigation and prevention principles.
- Developing specific mitigation measures and regulatory guidelines.
- Defining technical implementation strategies.

As the core activity of a long-term research initiative, this programme will ensure the sustainable use of space environments. Additionally, it will involve developing technologies for monitoring re-entry emissions, enabling regulators to assess compliance with established regulations and guidelines.

Figure 2 illustrates the proposed research programme, encompassing all three categories. Detailed descriptions of each research programme are provided in the following sections.

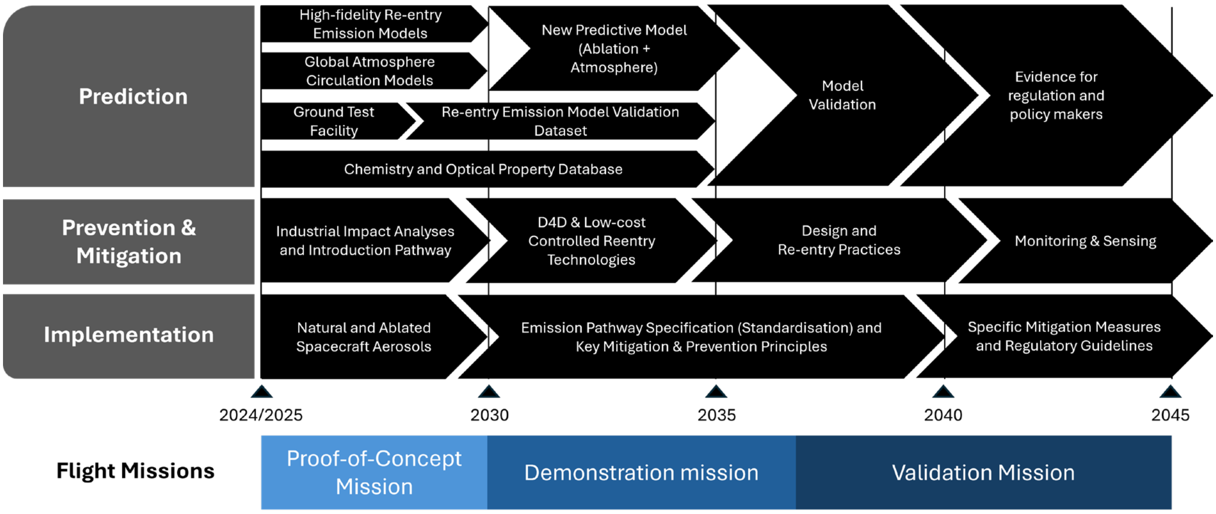

Figure 2. Suggested Technical Research Roadmap Diagram

2.1 Prediction Programme (short- and medium-term)

This research programme will be the core of short-term technical research, enhancing our understanding and predictive capabilities regarding the global impact of re-entry emissions. Running until 2045, its outcomes will provide critical scientific evidence supporting future regulations and mitigation guidelines.

The **Prediction Programme** aims to address key gaps in scientific understanding by advancing modelling techniques and data collection capabilities. By enabling comprehensive impact assessments aligned with the projected growth of the space industry, it will serve as the central pillar of the entire research initiative.

To strengthen its foundation, the Prediction Programme will be integrated with a small proof-of-concept mission using nano-satellites to validate both models and measurement capabilities. This approach will support the development of robust and scalable predictive tools for long-term environmental sustainability.

The Prediction Programme will have two core sub-divisions: **Modelling** and **Testing.**

- **Modelling:** This sub-division will focus on enhancing our ability to model key processes such as material ablation, re-entry dynamics, gas and aerosol production during re-entry, impacts on the upper atmosphere, and global re-entry effects.
- **Testing:** This sub-division will focus on building ground-based testing and flight data collection capabilities essential for assessing the validity and establishing the credibility of the developed scientific models.

By integrating these two components, the programme will ensure that prediction methods are accurate, reliable, and applicable for regulatory and policy development.

2.1.1 Modelling

The **Modelling Programme** aims to develop a new Predictive Model for spacecraft re-entry and its long-term atmospheric effects. This effort will involve the development and integration of several advanced modelling capabilities, including

- **High-Fidelity Re-entry Emissions Model:** This model will incorporate an atmospheric re-entry trajectory simulator coupled with Direct Simulation Monte Carlo (DSMC) and Computational Fluid Dynamics (CFD) models. These will simulate interactions between spacecraft components and the atmosphere to obtain accurate lift and drag values for trajectory calculations during hypersonic re-entry in the upper atmosphere. It will include a high-fidelity thermal non-equilibrium model based on multi-vibrational models, allowing species-based vibrational temperatures to better predict material ablation, where electron and vibrational temperatures play key roles in ionisation and dissociation. Vibrational-electronic modes can be modelled with a single temperature for each species, assuming rapid energy transfer between electronic and vibrational modes. This will enable the developing model to account for thermal non-equilibrium by considering translational, rotational, species-specific vibrational-electronic, and free-electron temperatures.
- **Material Response and Chemical Models:** These models will simulate material ablation and the production of gases and aerosols from high-temperature reactions between ablated materials and atmospheric constituents during re-entry. It will model atomic interactions by accounting for interatomic potentials and external forces. The chemical bond breakage and formation during the ablation process will be modelled using the Reactive Force Field (ReaxFF).
- **Global Circulation Models:** These models will simulate the spread of reaction products throughout the upper atmosphere, enabling global environmental impact assessments. Based on Community Atmospheric Model (CAM), it will the expecting impact of chemical byproducts from ablating spacecraft materials on ozone layer and Earth's radiative balance.

Currently, existing physical models lack the required fidelity to accurately predict key parameters such as ablation rate and occurring altitude. Many rely on oversimplifications, such as using constant average drag coefficients in re-entry trajectory simulations, which overlook complex local heating and chemical reactions essential for comprehensive ablation modelling during atmospheric re-entry.

The **characterisation of material behaviour** under re-entry conditions, both physical and chemical, is a crucial aspect of ablation modelling. During re-entry, a portion of the heat generated by atmospheric friction is transferred to the spacecraft's surface, causing a gradual increase in material temperature. As the temperature rises, the spacecraft material undergoes progressive transformation and removal through two key processes: **pyrolysis** and **ablation**.

Depending on the specific re-entry conditions, ablation can result from several mechanisms, including:

- **Heterogeneous Chemical Reactions:** Such as oxidation and nitridation, where reactive species in the atmosphere interact with the spacecraft material.
- **Phase Change:** Including sublimation, where the material transitions directly from a solid to a gas.
- **Mechanical Erosion:** Such as spallation, where surface layers break off due to thermal stress or aerodynamic forces.

To accurately estimate the amount of re-entry emissions and their by-products, precise prediction of both the ablation rate and the peak surface temperature of the re-entering spacecraft is essential.

2.1.2 Testing

Having the ability to test and validate spacecraft and re-entry vehicle designs in controlled and realistic environment is required in the context of validating and assessing the physical models to predict the global environmental impact of re-entry emissions. Due to the high cost and difficulty of conducting in-situ measurements, this will be accomplished through extensive ground-based testing in specialised facilities such as high-enthalpy plasma wind tunnels. The resulting data will contribute to the development of a **Re-entry Emissions Model Validation Dataset** and a **Re-entry Chemistry and Optical Properties Database**, which will directly inform high-fidelity trajectory simulations. These datasets will also support the design of monitoring and sensing solutions and the validation of predictive models.

A ground test facility capable of realistically simulating and measuring the flow and vehicle design parameters of atmospheric re-entry/entry is crucial to adequately support the implementation of mitigation measures in the spacecraft design and its operation. Without a ground test capability, it would be difficult to manufacture and design spacecraft complying with specific mitigation measures and regulatory guidelines for reducing and preventing the environmental impacts of re-entering spacecraft. Moreover, the ground testing capability will improve the demisability and survivability of spacecraft during their post-mission disposal atmospheric re-entry at their end-of-life. The state-of-the-art ground test facility, therefore, serves as a critical infrastructure that contributes to the growth, competitiveness, and long-term sustainability of the global space industry.

A ground test facility requires following capabilities at least:

- **Reproducing atmospheric re-entry/entry environments**: The capability of a ground test facility should span from initial descent to final landing, enabling scientists, engineers, and researchers to gain deeper insights into spacecraft performance and behaviour under realistic conditions. By simulating the complex aerodynamic forces, extreme temperatures, and pressures, it should be able to facilitate rigorous testing of spacecraft designs and material response. This will enhance understanding, improves design parameters, and fosters technological advancements in environmentally friendly disposal of spacecraft at the end of their mission.
- **Dynamic re-entry/entry trajectory testing**: For assessing the by-product of atmospheric ablation during re-entry, a ground test facility should have an ability to dynamically vary flow conditions during testing; replicating the complex and ever-changing conditions encountered during atmospheric re-entry. This capability will allow

simulating the diverse flow conditions experienced throughout the entire trajectory. This level of dynamic flow control capability will be a game-changer in the field of re-entry and ablation testing.

- **In-situ material/sample analysis**: In addition to its re-entry flow testing capability, it is important to have in-situ testing capabilities for material evaluation. In-situ material and sample analysis capability will enable scientists and engineers to gain real-time insights into the behaviour, integrity, and performance of materials under extreme thermal and structural conditions. This integrated capability will facilitate a comprehensive understanding of material response and aids in the development of materials for spacecraft reducing the emission of harmful by-products during re-entry.
- **Digital twin wind tunnel**: The digital twin is a virtual replica of the physical wind tunnel, faithfully capturing its characteristics, behaviour, and capabilities using the state-of-art computational thermo-chemical non-equilibrium flow model. The digital twin will enable scientists and engineers to perform virtual experiments, optimising test setups, and parameters in the digital realm before conducting costly physical experiments using a physical ground testing facility. The digital twin, therefore, provides a cost-effective and time-saving avenue for exploring various scenarios, validating designs, and fine-tuning experimental protocols. This seamless synergy between the physical facility and its digital counterpart accelerates the research and development process, significantly reducing costs and enhancing overall efficiency.

2.1.3 Flight Mission (Proof-of-concept)

In this programme, a proof-of-concept flight mission will be planned using a 6-12U CubeSat. The primary objective of this mission is to evaluate the feasibility of the monitoring and measurement technologies proposed in the Prediction Programme and to gather preliminary flight data to validate the developed physical and computational models. Additionally, the mission will test the capabilities of the proposed ground monitoring facilities, ensuring their readiness for future operations.

2.1.3.1 Mission objective

The planned mission will serve as a proof-of-concept to validate key components and technologies developed as part of the Prediction Programme. The CubeSat will be equipped with a suite of monitoring and measurement instruments designed to test the feasibility of the proposed technologies in a real space environment. This will include collecting flight data necessary to refine and validate physical and computational models related to spacecraft dynamics, performance, and environmental interactions during re-entry.

2.1.3.2 Mission Overview

- **CubeSat Configuration**: A 6-12U CubeSat will be selected, based on size and payload accommodation requirements.
- **Mission Duration:** The planned mission will span a minimum of 6 months, from launch to data collection and initial analysis.
- **Orbit:** The CubeSat will be placed in a low Earth orbit (LEO), with a suitable altitude (250 - 300 km) to quickly re-enter atmosphere with minimum propulsive capability.

- **Primary Payload:** The CubeSat will carry payloads including advanced sensors for monitoring physical data such as atmosphere density, temperature and UV/VIS spectrum, alongside communication and telemetry systems to record and transmit data back to ground stations.

2.1.3.3 Mission Requirements:

- **Payload Capacity:** The CubeSat must accommodate payloads including measurement instruments for monitoring physical parameters critical to the mission's goals.
- **Power:** Adequate power generation and storage will be required to support the continuous operation of onboard sensors and communication systems.
- **Communication:** A reliable communication link is necessary for transmitting data from spacecraft to ground stations, ensuring real-time data exchange and the ability to receive commands from mission control.
- **Ground Support:** Ground monitoring facilities must be capable of tracking the CubeSat in orbit, managing data flow, and conducting system diagnostics to support mission operations.
- **Data Storage and Analysis:** Sufficient onboard data storage must be provisioned for the communication interruption during atmospheric re-entry, along with a robust plan for data analysis post-flight, to support the validation of the physical and computational models.

2.2 Prevention and Mitigation Programme (medium- and long-term)

This research programme will be the cornerstone of medium-term technical research, focusing on developing technical and engineering practices to reduce or minimize the environmental impacts of re-entry emissions. Its outcomes will inform mitigation measures and prevention strategies, providing essential support for the implementation of future regulations.

Based on the critical landscape analysis conducted in WP3 (G23A.00100.TN.03), the **Prevention and Mitigation Programme** is expected to:

- Adapt *Design for Demise (D4D)* practices to reduce the presence of re-entry emission by-products in the upper atmosphere.
- Develop low-cost controlled re-entry technologies to manage the altitude at which ablation occurs during re-entry.
- Create new spacecraft materials that minimize the emission of harmful by-products during atmospheric re-entry.
- Establish technologies for monitoring and measuring re-entry emissions.
- Develop in-orbit material recycling technologies, including docking and collection systems for spacecraft at the end of their operational life.

In the long term, spacecraft manufacturers and operators could adopt sustainable post-mission disposal methods to prevent environmental impacts in the upper atmosphere. This approach would also drive the emergence of a new space industry focused on in-orbit recycling of spacecraft materials, reducing the need for disposal through atmospheric re-entry.

2.2.1 Overview

The **Prevention and Mitigation Programme** focuses on developing technical and engineering practices to reduce the environmental impacts of spacecraft re-entry emissions. This programme is designed as a medium- to long-term research initiative, addressing key technological gaps through a phased development approach. The roadmap will be executed in three stages: Research & Development (R&D), Technology Demonstration, and Operational Deployment

2.2.1.1 Research & Development (2025 ~ 2030)

The initial phase will centre on advancing required technologies, including material development, D4D practice, and monitoring. Key activities include:

- **Material Development:** Designing and testing new spacecraft materials with reduced harmful by-product emissions during re-entry.
- **Design for Demise (D4D) Guidelines:** Establishing D4D engineering standards to minimise upper atmospheric contamination.
- **Monitoring Technologies:** Designing sensors and payloads for tracking re-entry by-products in the upper atmosphere.

2.2.1.2 Technology Demonstration (2030 ~ 2035)

This phase will involve TRL of the required technologies and conducting proof-of-concept demonstrations in relevant operational environments. Activities include:

- **Flight Demonstration Mission (FDM):** Conducting a dedicated flight mission to test new materials, D4D techniques, and monitoring sensors.
- **Sub-Orbital and Orbital Testing:** Conducting sub-orbital tests followed by orbital re-entry missions to validate system performance.
- **Emission Monitoring Network:** Establishing a preliminary ground- and space-based monitoring network.

2.2.1.3 Operational and Deployment (2035 ~ 2045)

The final phase will focus on integrating developed technologies into commercial and governmental missions. Activities include:

- **Policy Integration:** Collaborating with regulatory bodies to adopt proposed guidelines and standards.
- **Industry Adoption:** Supporting spacecraft manufacturers in implementing sustainable post-mission disposal strategies.

2.2.2 Flight Demonstration Mission

The **Flight Demonstration Mission** will be the pivotal experimental mission of the Prevention and Mitigation Programme. The mission will validate core technologies in a real-world setting, ensuring readiness for large-scale implementation. By following this roadmap and executing the Flight Demonstration Mission, the Prevention and Mitigation Programme will bridge the gap between scientific research, technological development, and policy implementation, driving sustainable space operations for future generations.

2.2.2.1 Mission Objectives

- **Validate New Materials:** Test spacecraft components made from low-emission materials in a controlled atmospheric re-entry.
- **Demonstrate D4D Compliance:** Evaluate spacecraft designed with D4D principles, ensuring controlled disintegration and minimal environmental impact.
- **Monitor Emissions:** Deploy advanced sensors to measure emissions in situ, characterising chemical by-products and atmospheric interactions.

2.2.2.2 Mission Requirements

- **Spacecraft Configuration:** The spacecraft will feature modular panels made from newly developed materials. It will be equipped with atmospheric sensors, spectrometers, and imaging systems.
- **Re-entry Profile:** The spacecraft will re-enter from low Earth orbit (LEO) at a controlled trajectory, ensuring data collection during critical re-entry phases.
- **Data Collection Strategy:** Ground-based and space-based assets will track the spacecraft's descent, enabling comprehensive analysis of emission dynamics.

2.2.2.3 Mission Outcomes

- **Data Validation:** Creation of a validated emissions database to refine atmospheric models.
- **Guideline Development:** Establishment of industry-wide D4D and emissions monitoring standards.
- **Policy Support:** Provision of critical scientific evidence supporting environmental regulations and mitigation policies.

2.3 Implementation Programme (long-term)

The **Implementation Programme** will represent the final stage in addressing the environmental impact of spacecraft disposal through atmospheric re-entry. This will involve introducing specific mitigation measures and regulatory guidelines aimed at either limiting the total amount of re-entry emissions or reducing the atmospheric residence time of harmful ablated by-products. The programme could encompass three key activities:

- **Estimating the Threshold for Atmospheric Tolerance:** Determining the maximum amount of re-entry emissions that Earth's upper atmosphere can sustain without adversely affecting the global climate.

- **Standardising Emission Pathways:** Establishing key mitigation and prevention principles by defining standard emission pathways.
- **Specifying Mitigation Measures and Regulatory Guidelines:** Developing measures and regulatory frameworks to ensure sustainable post-mission spacecraft disposal, which will be based on WP1 outcome (G23A.00100.TN.01).

This approach will lay the groundwork for a comprehensive regulatory and guidance framework that supports environmental sustainability in space operations.

2.3.1 Overview

The Implementation Programme will represent the final stage in addressing the environmental impact of spacecraft disposal through atmospheric re-entry. This programme involves introducing specific mitigation measures and regulatory guidelines aimed at either limiting the total amount of re-entry emissions or reducing the atmospheric residence time of harmful ablated by-products. The programme is divided into three key stages: **Exploring Natural and Ablated Spacecraft Aerosols** (2025 ~ 2030), **Emission Pathway Specification and Mitigation Principles** (2030 ~ 2040), and **Mitigation Measures and Regulatory Guidelines** (2040 ~ 2045).

2.3.1.1 Exploring Natural and Ablated Spacecraft Aerosols (2025 ~ 2030)

- Conduct studies on aerosol production during spacecraft re-entry, focusing on chemical compositions and atmospheric dynamics.
- Develop models to estimate aerosol accumulation thresholds in the upper atmosphere.
- Establish baseline environmental tolerance limits for re-entry emissions.

2.3.1.2 Emission Pathway Specification and Mitigation Principle (2030 ~ 2040)

- Define standard emission pathways to minimise harmful by-product dispersal.
- Establish key mitigation principles based on empirical and simulated data.
- Specify best practices for spacecraft design and operational procedures to reduce atmospheric contamination.

2.3.1.3 Mitigation Measures and Regulatory Guidelines (2040 ~ 2045)

- Develop mitigation measures and regulatory frameworks for post-mission spacecraft disposal based on WP1 outcomes (G23A.00100.TN.01).
- Collaborate with international space agencies and organisations to create unified global emission regulations.
- Establish long-term monitoring networks for continuous emission assessment.

2.3.2 Validation Mission

The **Validation Mission** will be a dedicated flight experiment to evaluate the effectiveness of mitigation measures and emission monitoring technologies. Through this flight mission, the Implementation Programme will build a robust framework for sustainable spacecraft disposal and environmental protection in space operation

2.3.2.1 Mission Objectives

- **Validate Mitigation Measures:** Test and verify specific regulatory guidelines under real re-entry conditions.
- **Monitor Compliance:** Use advanced sensing technologies to measure emissions in real-time.
- **Policy Support:** Collect critical data supporting the introduction of global environmental standards.

2.3.2.2 Mission Requirements

- **Spacecraft Configuration:** A test spacecraft with integrated mitigation and prevention technologies and sensing payloads.
- **Re-entry Profile:** Controlled re-entry with precision targeting for emission measurement.
- **Data Collection Strategy:** Comprehensive ground-based and orbital tracking systems to monitor atmospheric impacts.

2.3.2.3 Mission Outcomes

- **Database Development:** Establish a validated emissions and mitigation dataset.
- **Global Standards Integration:** Support for international mitigation measures and regulation guidelines related to post-mission disposals and their emissions at upper atmosphere.
- **Long-term Monitoring Framework:** Blueprint for a global monitoring and compliance system.

3 Geopolitical and Regulation Roadmap

As outlined in TN01 (G23A.00100.TN.01), developing a policy and regulatory framework to manage the environmental impact of spacecraft re-entry ablation necessitates a structured and evidence-based approach grounded in scientific and technical research. With the continued expansion of the space industry, regulatory frameworks must evolve to address emerging environmental challenges, particularly those related to material ablation and atmospheric contamination caused by spacecraft disposal at the end of their operational lifetimes. Consequently, a robust policy development roadmap must balance technical feasibility, legal obligations, and international collaboration to ensure effective and comprehensive environmental governance.

3.1 Scientific and Regulatory Needs

3.1.1 Short- to Medium-Term

The short- to medium-term roadmap for addressing scientific and regulatory needs focuses on establishing a knowledge-driven regulatory foundation by creating an inventory of existing scientific data on material ablation and spacecraft components. It explores options for enhancing current national, regional, and international databases or developing new repositories for reporting relevant data. Additionally, the roadmap highlights the need for legal and procedural assessments concerning data sharing, export controls, and intellectual property management.

By aligning with established international agreements such as the Espoo Convention on Environmental Impact Assessment in a Transboundary Context and the Aarhus Convention on Access to Information, Public Participation in Decision-Making, and Access to Justice in Environmental Matters, this roadmap seeks to promote transparency, foster industry collaboration, and ensure compliance with global environmental standards.

Therefore, core activities of the short- to medium-term roadmap are listed in the following sections. The proposed structured approach will create a strong regulatory framework that balances scientific evidence, legal considerations, and international cooperation, supporting the sustainable development of the global space industry.

3.1.1.1 Development of an Inventory of Scientific and Technical Data

Establish a comprehensive inventory of existing scientific and technical information related to material ablation and spacecraft components. Identify knowledge gaps and assess further data requirements to build a robust evidence base for regulatory development.

3.1.1.2 Evaluation of Data Repositories and Reporting Frameworks

Assess the feasibility of expanding existing national, regional, or international registries/databases to include mandatory reporting of ablation-related information. Consider the potential roles of UN-level space object registries (in capturing, reporting, and sharing information relevant to spacecraft ablation) and explore options for their evolution. Alternatively, evaluate the creation of new centralised or decentralised databases managed by domestic agencies, following standardised protocols

3.1.1.3 Legal and Procedural Mapping Exercise

Identify legal constraints such as export controls, intellectual property rights, data protection laws, and other barriers that could limit access to and sharing of ablation-related information, particularly regarding spacecraft components and materials.

3.1.1.4 Information Transparency and Data Sharing Frameworks

Develop strategies to ensure continuous data updating, transparency, and data sharing. Address industry concerns while meeting legal obligations under international conventions. Establish clear duties for sharing environmental risk information based on existing conventional obligations, such as the Espoo Convention on Environmental Impact Assessment in a Transboundary Context and the Aarhus on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters, to which the UK is a party.

3.1.2 Medium- to Long-Term

As the space industry advances, the need for comprehensive data management frameworks becomes increasingly critical to assess and mitigate the environmental impacts of spacecraft re-entry ablation. The medium- to long-term roadmap focuses on operationalising data repositories, addressing legal and commercial barriers, and ensuring transparent and accountable information exchange. By building on the foundational work established in the short- to medium-term roadmap, this phase will transition from data collection and evaluation to the design, implementation, and management of integrated data systems.

Key efforts, therefore, will include developing tailored database structures that facilitate the systematic collation of relevant ablation data while ensuring transparency and accessibility through clear data-sharing protocols. Additionally, proposals for addressing legal and commercial challenges, such as intellectual property restrictions, export controls, and commercial confidentiality, will be explored, including potential legislative modifications and industry incentive mechanisms. This approach will support long-term international cooperation, enabling more effective environmental governance and accountability in the global space sector.

3.1.2.1 Database Design and Modification

Provide recommendations on modifying or designing databases to ensure the systematic collation of data required for assessing ablation impacts, while establishing appropriate data management, transparency, and access protocols.

3.1.2.2 Addressing Legal and Commercial Barriers

Develop proposals to address identified legal and commercial barriers to information exchange, including legal modifications and industry-driven incentive measures.

3.1.2.3 Operationalising Data Repositories

Support the implementation and operationalisation of databases by ensuring efficient information exchange, clear accountability mechanisms, and compliance with international environmental standards such as ISO14000 and IES 60068.

3.2 Clarification and amendment to regulatory and legal frameworks

As the space industry continues to expand, the regulatory and legal frameworks governing spacecraft re-entry must adapt to address emerging challenges related to environmental sustainability. The complex legal landscape includes questions of jurisdiction, international treaty obligations, and the applicability of environmental principles such as the precautionary approach. Clarifying these legal frameworks is critical to ensuring the responsible use of outer space while maintaining compliance with international environmental standards.

This roadmap outlines a phased approach for reviewing and amending relevant legal and regulatory frameworks. The short- to medium-term phase will focus on clarifying jurisdictional issues, assessing legal obligations related to human rights and the environment, and reviewing environmental impact assessment (EIA) practices. In the medium- to long-term phase, the emphasis will shift toward developing international guidelines, supporting the evolution of licensing frameworks, and exploring the applicability of multilateral environmental agreements (MEAs) to spacecraft re-entry.

3.2.1 Short- to Medium-Term

In the short- to medium-term, the focus will be on clarifying legal ambiguities and establishing foundational principles for spacecraft re-entry regulation. This includes defining jurisdiction over atmospheric re-entry, assessing state obligations related to environmental protection and human rights, and reviewing current EIA practices globally. Addressing these core legal questions will provide a strong basis for future international cooperation and policy development.

3.2.1.1 Jurisdiction and Legal Authority

Clarification of jurisdiction in relation to ablating materials, whether in the airspace over a state or areas beyond national jurisdiction, such as the high seas. In particular, the status of a '**right of overflight**' and whether, if this exists, it is subject to a requirement of prior notice and consent. A systematic review of whether States have already adopted relevant regulations regarding transit in the upper atmosphere and their approach to this issue.

3.2.1.2 Environmental and Human Rights Obligation

Review of the implications for state practice, in particular the licensing of space activities, of the evolving field of human rights and the environment, notably the right to a safe and sustainable environment. It needs to evaluate potential legal risks for states stemming from inaction and explore required legislative measures.

3.2.1.3 Precautionary Approach in Space Law

Given the '**access and benefit for all**' principle enshrined in the Outer Space Treaty (OST), it is essential to explore how the **precautionary approach** can be applied to limit the amount of materials re-entering the stratosphere. This includes assessing potential mechanisms for implementing and enforcing the precautionary approach, while ensuring an equitable distribution of regulatory costs under the principle of common but differentiated responsibilities for environmental risks associated with spacecraft re-entry.

The Ozone Treaty provides a relevant precedent through its use of advanced technologies, such as computer models incorporating 'trend uncertainties,' to address emerging environmental risks.[1] Integrating such uncertainties into environmental risk modelling aligns closely with the precautionary principle.[2] Although emissions from spacecraft ablation are currently excluded from Ozone Treaty modelling, rocket emissions have been frequently referenced in the Quadrennial Reports, demonstrating the treaty's flexibility and adaptability in identifying emerging threats to atmospheric protection.[3]

Therefore, the roadmap will explore methodologies from Multilateral Environmental Agreements (MEAs), such as the Ozone Treaty's advanced modelling techniques, including trend uncertainty analysis, as a basis for integrating the precautionary approach into spacecraft re-entry regulation frameworks.

3.2.1.4 Application of MEA to Ablation

Building on activities described in Section 3.2.1.1 to 3.2.1.3, TN2 (G23A.00100.TN.02) and TN3 (G23A.00100.TN.03), it will conduct a comprehensive review of relevant MEAs to ablation, and in particular, the scope for conceptualising re-entering spacecraft as 'waste'. Then, it will assess the legal implications and possible regulatory frameworks for such a classification.

3.2.1.5 Comparative Environmental Impact Assessments

It will review the environmental impact assessment (EIA) practices of major space-faring nations as well as major market which satellite constellation operators wish to serve, and covering Asia and South America in addition to UK, Europe, and US (for which initial review was performed in TN01 (G23A.00100.TN.01) and TN02 (G23A.00100.TN.02)), to evaluate how emerging risks such as mega-constellations are assessed thus ensuring that national practices align with international environmental standards.

3.2.2 Medium- to Long-term

The medium- to long-term roadmap focuses on operationalising legal reforms, harmonising international licensing standards, and developing advanced regulatory mechanisms to monitor and limit the environmental impact of spacecraft re-entry. The objective, therefore, is to create a consistent and enforceable international legal framework.

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[1] The United States National Oceanic and Atmospheric Administration (NOAA) Chemical Sciences Laboratory (CSL), 'How is ozone measured in the atmosphere?' Q.13, online: https://csl.noaa.gov/assessments/ozone/2010/twentyquestions/Q5.pdf: 'Remote sensing techniques use quantitative molecular spectroscopy to convert the strength of an absorption or emission feature in an atmospheric spectrum into abundances or concentrations, in line with the Beer-Lambert law.' p. 62; 69.

[2] The United States National Oceanic and Atmospheric Administration (NOAA) Chemical Sciences Laboratory (CSL), 'How is ozone measured in the atmosphere?' Q.13, online: <https://csl.noaa.gov/assessments/ozone/2010/twentyquestions/Q5.pdf>.

[3] Though these reports have mostly qualified the effect of rocket emissions on stratospheric ozone as 'small', the 2022 Assessment recognises that emissions from novel propellants such as methane could become significant in the future. World Meteorological Organization, 'Scientific Assessment of Ozone Depletion' 2022: < https://ozone.unep.org/sites/default/files/2023-02/Scientific-Assessment-of-Ozone-Depletion-2022.pdf >, p 395.

3.2.2.1 Modification of Licensing Practices

It requires to support updates to national and international licensing practices to ensure compliance with international environmental and legal obligations. Therefore, it aims to develop clear guidelines for licensing environmental assessments related to spacecraft re-entry.

3.2.2.2 International EIA and Licensing Guidelines

It will develop global best practice guidelines for conducting EIAs and licensing mega-constellations, taking into account industry-specific factors such as commercial viability. This will promote greater consistency among national regulatory frameworks, ensuring a more level '**regulatory playing field**'.

3.2.2.3 Application of MEAs to Spacecraft Re-entry

It will aim to develop guidance on the application of MEAs in addressing the environmental impacts of re-entry emissions in the upper atmosphere, along with outlining the necessary procedures required for their effective implementation. In addition, it will provide advice as to whether the scope of specific MEAs could be extended, and the processes involved, where action is considered desirable to ensure greater consistency in national approaches.

3.2.2.4 Critical Load Mapping for Re-entry Emissions

One regulatory design employed under the Convention on Long Range Transboundary Atmospheric Pollution is the concept of the '**critical load**', defined as the highest annual deposition level at which adverse effects on natural ecosystems are unlikely to result in the long term. Critical load maps served an important role in supporting the negotiations of the 1994 Sulphur Protocol and the 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone. In the medium to long term, a '**critical load map**' could also be designed to determine the maximum number of deposition levels for materials such as aluminium (Al), lithium (Li), and silicon (Si) emitted during re-entry. In addition, it will require to consider appropriate compliance mechanisms, including monitoring protocols and emission limits, to enforce regulatory standards effectively.

3.3 Improving articulation and coordination between technical information and regulatory and policy implementation

While the environmental impacts of spacecraft re-entry ablation remain an emerging area within space sustainability policy and regulatory frameworks, current research efforts are fragmented, with limited coordination between scientific communities, space agencies, regulatory bodies, and industry stakeholders. This lack of systematic exchange has led to critical policy gaps, including insufficient awareness of environmental risks, limited access to data on satellite materials, and minimal regulatory oversight of spacecraft re-entry emissions, which are already highlighted in TN1 (G23A.00100.TN.01) and TN2 (G23A.00100.TN.02)

For addressing these challenges, a more structured policy dialogue is required, supported by outreach efforts and standard-setting initiatives. This roadmap proposes establishing a Technical-to-Regulator Dialogue on Atmospheric Impacts of Spaceflight Activities and a complementary Outreach Campaign to engage industry stakeholders, policymakers, and regulatory bodies. Additionally, it highlights the need for active participation in international standard-setting processes and the evaluation of relevant administrative capacities.

3.3.1 Short- to Medium-Term

The short- to medium-term roadmap focuses on fostering communication, raising awareness, and initiating industry standards development. It aims to bridge gaps between research, policy development, and regulatory action by creating dedicated forums and outreach initiatives.

3.3.1.1 Establishing a Technical-to-Regulator Dialogue

While scientific and technical research is ongoing to assess the sources, magnitude, and potential adverse impacts of spaceflight activities on the atmosphere, analysis conducted earlier in this project (G23A.00100.TN.01) has identified that this research is being conducted in a dispersed, uncoordinated manner. There is not – either at the national level or at the international level – a strategy for coordination and sharing of findings, other than through the standard academic and agency publication process. Research is underway in various space agencies and national scientific bodies (e.g. NASA, ESA, JAXA, NSF, NOAA). These bodies are interfacing ad-hoc with their national regulators, but are not systematically exchanging with each other, and with the broader regulatory community. Other regulatory, policymaking, and industry stakeholders who will need to take mitigation steps may not be accessing or tracking research findings in this way.

It has also been noted in prior analysis under this project that political leadership will be required to encourage policy and or regulatory action. With the political leanings of the incoming U.S. administration and Congress, it is unlikely that this leadership will come from the U.S. (a leading market for the large constellations which are driving increased re-entry activity). These findings suggest the need for a focused effort to convene the regulatory, spacecraft industry, and research communities on a regular basis.

To promote structured policy leadership, the UK Space Agency (UKSA) is well-positioned to establish a regular, invitation-only **Technical-to-Regulator Dialogue on Atmospheric Impacts of Spaceflight Activities.** This annual two-day event should (ideally) rotate between the UK, the US, and Asia and aim to:

- **Facilitate Scientific Exchange:** Enable space agencies, their funded researchers, and regulatory bodies to share technical and scientific knowledge.
- **Enhance Policy Capacity:** Build regulators' and policymakers' understanding of the environmental impact of re-entry emissions and access to scientific data.
- **Integrate Mitigation Strategies:** Discuss embedding mitigation strategies into existing space debris guidelines and industry best practices.
- **Engage Industry Stakeholders:** Promote data-sharing, including materials used in spacecraft manufacturing, and explore voluntary compliance measures such as Life Cycle Assessments (LCAs).
- **Coordinate with International Bodies:** Explore roles for international organisations such as COSPAR and IADC as well as governance fora such as the ITU and COPUOS to foster data-sharing and prepare the issue for multilateral consideration.

The first day would focus on government-to-government interaction, including government-funded researchers, while the second day would expand to include satellite operators and other industry stakeholders. Discussions on launch emissions, environmental risks, and spectrum management would also be essential.

3.3.1.2 Developing an Industry Outreach Campaign

To build broader awareness of environmental risks associated with spacecraft re-entry, a dedicated **Outreach Campaign** would complement the Technical-to-Regulator Dialogue. Prior analysis under this project has identified that space activities currently fall into a regulatory and policy gap regarding their potential environmental impact (G23A.00100.TN.03) and that space sustainability policy has only considered this topic at a relatively cursory level (G23A.00100.TN.02). A future strategy, therefore, should include a line of effort to build awareness of the potential impacts of atmospheric ablation of spacecraft and associated mitigation strategies. This outreach campaign would involve:

- **Event Engagement:** Delivering targeted presentations and interactive sessions at major industry events such as the International Astronautical Congress, Satellite Conference, and COSPAR Assembly.
- **Targeted Publications:** Publishing non-academic materials tailored to industry and policymaker audiences.
- **Strategic Engagement Planning:** Establishing a timeline of relevant international and regional meetings to ensure sustained attention to environmental concerns.

The goal of this Outreach Campaign would be to build industry confidence that mitigation is important to the continued development of the space economy and future sustainability; and also to prepare the policy system for action. In the medium and longer term this awareness campaign would also link into objectives of developing circular economy concepts in the space environment and into rationalizing the number of spacecrafts launched.

3.3.1.3 Advancing Industry Standard-Setting

Engagement with standard-setting bodies such as ISO and BSI should be prioritised to explore the development of relevant ablation-related standards. Proposed actions include:

- **Initial Engagement:** Opening discussions with working groups to assess the appetite for ablation-specific standards.
- **Standards Assessment:** Identifying existing standards that could be adapted to include ablation concerns.
- **Sponsor Identification:** Evaluating potential sponsors and technical partners for standard development projects.

This would also involve engagement with entities developing voluntary best practice for space sustainability (e.g. GSOA, ESSI) to review alignment between these initiatives and the formal standards development process; as these voluntary initiatives are in particular a pathway in which industry engagement is prevalent.

3.3.1.4 Evaluating Administrative and Technical Capacities

A systematic evaluation of administrative and technical capacities within environmental and space-related bodies is essential. This evaluation would:

- **Institutional Mapping:** Identify institutions best suited to address satellite material sustainability, spacecraft numbers, and operational guidelines.
- **Capacity Analysis:** Assess administrative and technical strengths and weaknesses in both environmental and space policy sectors.
- **Implementation Framework:** Recommend the most suitable international and national regulatory bodies for implementing identified measures

3.3.2 Medium- to Long-Term

The medium- to long-term roadmap will focus on institutionalising policy dialogues, formalising industry standards, and ensuring that regulatory frameworks evolve with scientific and technical advancements.

3.3.2.1 Institutionalising Policy Dialogues and Industry Standards

- **Standard Development Support:** Collaborate with international standard-setting bodies to formalise industry guidance and regulations.
- **Regulatory Integration:** Support the integration of environmental impact assessments (EIAs) and licensing requirements for mega-constellations.
- **Compliance Mechanisms:** Establish mechanisms for monitoring compliance with environmental standards.

3.3.2.2 Strengthening International Legal Frameworks

- **Policy Framework Development:** Work with international space and environmental bodies to develop consistent licensing and regulatory practices.
- **Expanded MEA Scope:** Explore expanding the scope of multilateral environmental agreements (MEAs) to include spacecraft re-entry emissions.
- **Global Coordination:** Promote a coordinated global regulatory framework through international organisations such as COPUOS, ITU.,

3.4 Building Industry Confidence and Exchange

Efforts to mitigate the potential impacts of atmospheric ablation of spacecraft will require significant industry participation. These efforts will be most effective if they foster a participatory, collaborative approach between industry stakeholders and the scientific community, rather than relying exclusively on regulatory or legal measures. Industry engagement, underpinned by trust and transparency, will be key to advancing data-sharing efforts and implementing viable mitigation strategies that consider both environmental and economic factors.

As part of a forward-looking research strategy, it is essential to explore and develop frameworks that enable cooperation between industry and the scientific community. This includes mechanisms to facilitate data sharing, particularly with respect to spacecraft materials and re-entry observations, to better assess environmental impacts. Equally important is the establishment of mitigation strategies that align with business and economic priorities, ensuring their practicality and widespread adoption.

Efforts to mitigate the potential impacts of atmospheric ablation of spacecraft will require industry participation and will be most successful if industry is proactively engaged in a participatory process, rather than relying solely on regulatory and/or legal measures.

3.4.1 Short Term

In the immediate future, the research strategy should prioritize evaluating existing models of collaboration between industry and the scientific community in related areas. These evaluations will provide valuable insights into designing effective frameworks for addressing atmospheric impacts of spaceflight activities. For example, the International Astronomical Union (IAU) Center for the Protection of Dark and Quiet Skies offers a useful case study, as discussed in TN2 (G23A.00100.TN.02).

The primary objectives of this evaluation would be to:

- **Identify and map collaboration models** used to address adjacent environmental and technical challenges;
- **Extract lessons learned** from these models to inform the design of engagement strategies for spaceflight-related issues;
- **Document institutional frameworks** that support effective cooperation, enabling knowledge transfer and implementation.

By identifying best practices, this research can help shape a model for industry and scientific collaboration, tailored to the unique challenges posed by atmospheric impacts of spaceflight.

3.4.2 Short- to Medium-Term

Building on this evaluation, the findings could be used to propose the creation of a structured cooperation model. This model would aim to establish a platform where industry and scientific stakeholders can work together to develop voluntary mitigation strategies while informing future governance and regulatory approaches. Such a structure could also serve as a foundation for building trust and encouraging data-sharing between stakeholders, thereby accelerating progress toward shared goals

3.5 Addressing the Impact of -Very Large Constellations

The proliferation of very large constellations such as Starlink, which was listed in TN1 (G23A.00100.TN.01) represents a major driver of spacecraft launches and re-entries, which, in turn, contribute to potential atmospheric impacts such as material ablation. These constellations are propelled by a combination of societal, economic, national, and commercial imperatives. However, they also introduce externalities, such as their effects on the environment and other societal interests, including the protection of dark and quiet skies.

For achieving sustainable growth in the space industry, future research must focus on balancing the benefits of these systems with their potential costs. A well-informed understanding of the economic trade-offs and environmental consequences associated with very large constellations will be critical for shaping regulatory frameworks, optimizing system designs, and guiding policy decisions.

3.5.1 Short- to Medium-Term

In the near term, research efforts should prioritize enhancing our understanding of the economic costs and benefits associated with large satellite constellations. Building on the analyses presented in TN3 (G23A.00100.TN.03), a dedicated line of research should be established to:

- **Develop robust economic models** to quantify the societal, commercial, and national benefits of these constellations, as well as pros/cons of developing dedicated national systems vs. cooperation and shared systems;
- **Assess the externalities associated with their deployment**, particularly their environmental impacts and their interference with other societal priorities (e.g., astronomical observation and atmospheric quality);
- **Explore how better data and analysis can inform regulatory frameworks**, helping to rationalize the number of spacecraft launched and reduce speculative filings.

Such efforts will provide a clearer picture of the trade-offs involved in the deployment of very large constellations, enabling policymakers and operators to make informed decisions that maximise benefits while mitigating negative impacts. This work could also help industry players optimise the scale and configuration of their systems, fostering a more sustainable approach to satellite design and deployment.

3.5.2 Medium- to Long-Term

Over the longer term, the insights gained from this research can help build a compelling economic and business case for mitigation strategies based on life cycle analyses and circular economy principles. For example, operators could be encouraged to adopt practices that minimize waste, enhance material recovery, and reduce the overall environmental footprint of their activities.

In addition, these analyses could guide the development of innovative policy and regulatory approaches that incentivize sustainable practices. By linking economic imperatives with environmental considerations, this research would lay the groundwork for a holistic strategy to address the atmospheric impacts of satellite constellations, ensuring the long-term sustainability of the space sector.