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:
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Milestone 2 Deliverable (D5)
TN-05 Outline research business case

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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.

The TN-05 outlines a proposed 3-year research programme aimed at addressing the environmental impacts of ablating re-entry spacecraft. The program focuses on two integrated research approaches:

- **Modelling, Policy, and Regulatory Research (approx. budget of £1.5M)**
- **Testing and Measurement Research (approx. budget of £4.5M)**

Particularly, the centrepiece of the testing program is the establishment of the UK's first plasma wind tunnel, a unique and pioneering facility globally for dynamically simulating spacecraft re-entry conditions. This facility will enable precise assessment of environmental emissions and ablation impacts, bridging critical knowledge gaps. Alongside, multidisciplinary PhD programme will nurture future leaders in space sustainability to ensure sustained growth in future UK and global space industry.

By harmonising cutting-edge **testing**, robust **modelling**, and **policy-driven frameworks**, the programme will position the UK as a global leader in space environmental research. The outcomes will deliver critical scientific advancements, policy recommendations, and significant social and economic benefits.

1.1 Scope

This document, TN-05, successfully meets the requirements outlined in Milestone 2 (MS2) by delivering a robust roadmap for UK Space Agency investment in economically viable research options with achievable delivery timelines within 1-5 years. TN-05, therefore, will bridge the gap between research and reality, creating a compelling business case for short-term research priorities identified in TN-04.

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
[AD6]	G23A.00100.TN.04	Future research programme plan	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 Research Programme Overview and Objective

2.1 Overview of the 3-year Research Programme

The proposed short-term research plan outlined in WP4 (G23A.00100.TN.04) seeks to advance capabilities in **modelling**, **testing**, and **policy development** related to the environmental impact of spacecraft re-entry on Earth's upper atmosphere. Recognising that this challenge is inherently multidisciplinary, the programme adopts a fully **harmonised approach**, integrating engineering and scientific research with regulatory and policy frameworks. This integration ensures that technological innovations align with legal and policy measures, fostering effective environmental governance.

As highlighted in TN-01 (G23A.00100.TN.01) and TN-02 (G23A.00100.TN.02), the environmental consequences of atmospheric ablation from re-entering spacecraft represent a pressing concern as space operations continue to grow. This **3-year research initiative** aims to bridge critical scientific, regulatory, and technological gaps by establishing a comprehensive programme that connects advanced modelling, experimental testing, and policy development. This integrated research structure ensures a robust response to the environmental risks posed by spacecraft re-entry emissions.

2.1.1 Research Streams

The research programme is organised into two complementary streams:

1. **Prediction Stream (Modelling, Regulation, and Policy Development):**
    - Focuses on developing **predictive computational models** to simulate spacecraft material ablation, atmospheric chemical reactions, and emission pathways.
    - Evaluates potential environmental impacts, including upper atmospheric contamination and global climate change.
    - Supports regulatory development by assessing legal compliance mechanisms and proposing sustainable spacecraft disposal frameworks.

2. **Validation Stream (Experimental Testing):**
    - Establishes the **UK's first plasma wind tunnel facility**, providing a controlled environment to test spacecraft material ablation and validate model predictions.
    - Generates **validated datasets** through ground-based testing, ensuring the scientific credibility of computational models.
    - Delivers critical data to inform emerging environmental policies and strengthen regulatory compliance.

These interconnected streams reinforce one another: the Prediction stream provides scientifically grounded estimates of environmental impacts, while the Validation stream verifies these predictions through real-world testing. This dual approach enables **data-driven regulatory recommendations** that balance environmental sustainability with technological feasibility.

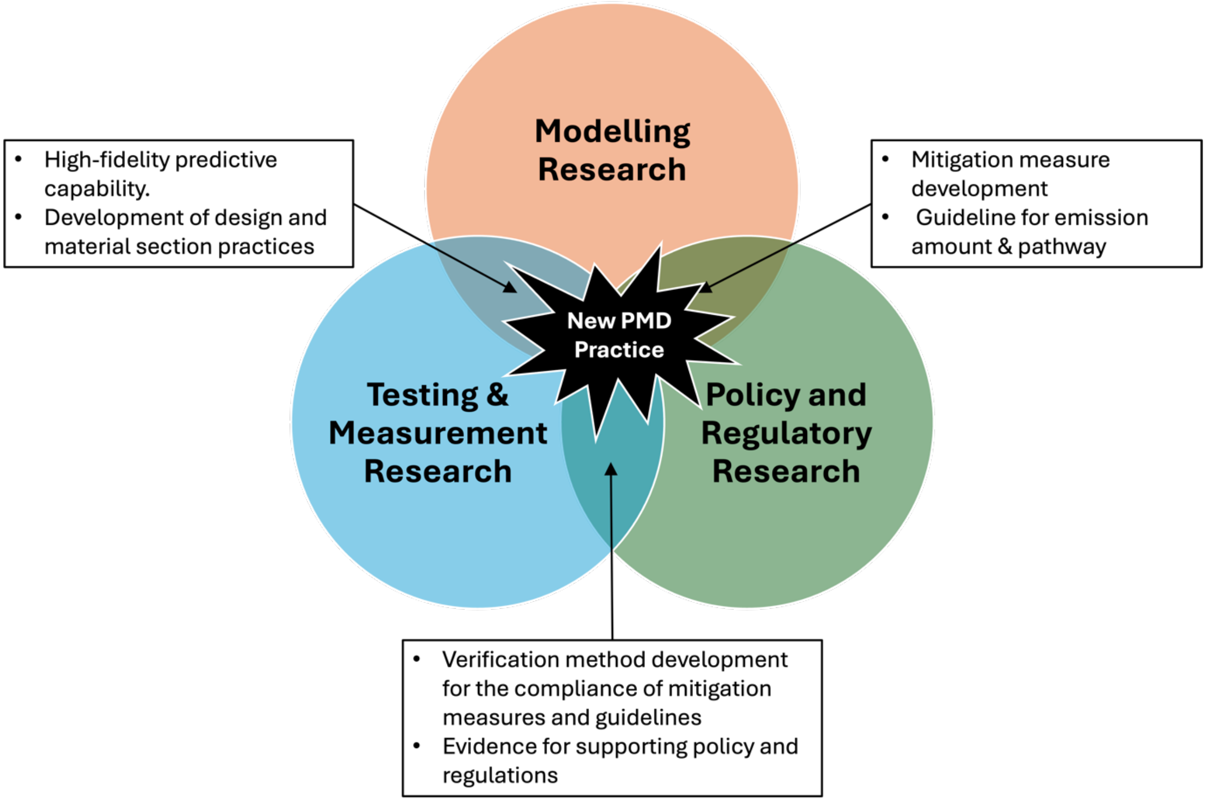

Figure 1. In*terdisciplinary Approach Overview:* *The interdisciplinary nature of this programme integrates cutting-edge engineering research with legal and policy frameworks, creating a foundation for sustainable space operations***.**

2.1.2 PhD Programme for Capacity-Building

To strengthen interdisciplinary collaboration, the programme will establish a specialised **PhD initiative** focusing on the integration of **engineering, law, and policy studies**. This initiative will support **three PhD students**, including:

- **Two PhDs in Engineering** with a focus on space law and policy integration.
- **One PhD in Law** with a focus on regulatory frameworks for emerging space technologies.

The PhD programme will feature a **six-month exchange component**, fostering cross-disciplinary learning and enabling collaboration between technical and policy-focused institutions. This will ensure a pipeline of experts equipped to address environmental sustainability in the space industry.

2.2 Objectives

The primary objectives of the 3-year research programme are organised across five core areas:

1. **Scientific Advancement**
   - Develop **high-fidelity computational models** for spacecraft re-entry, including material ablation dynamics, emission pathways, and atmospheric chemical interactions.
   - Validate these models through **experimental data** obtained from ground-based facilities and potential flight missions.

2. **Technical Innovation**
   - Build the **UK's first plasma wind tunnel**, a globally unique facility dedicated to studying atmospheric ablation under simulated re-entry conditions.
   - Use cutting-edge measurement tools to analyse spacecraft materials' behaviour and environmental emissions during testing.

3. **Regulatory Framework Development**
   - Establish **data-sharing standards** and create **policy guidelines** to mitigate environmental risks through international cooperation.
   - Develop **legislative frameworks** and **regulatory policies** grounded in experimental and modelling data, ensuring that proposed regulations are feasible and enforceable.

4. **Policy Integration and Industry Engagement**
   - Facilitate regular **industry-science-policy dialogues** to translate research findings into actionable industry standards.
   - Promote **transparency and data-sharing agreements**, enabling best-practice adoption in collaboration with international regulatory bodies and the private sector

5. **Educational and Capacity-Building Initiatives**
   - Launch a **multidisciplinary PhD programme** producing experts capable of working across technical, legal, and policy domains in space sustainability.
   - Encourage **academic-industry partnerships**, fostering innovation and strengthening international research collaboration.

These objectives will be realised through the following integrated efforts:

- **Advancing Modelling Capabilities:**
  - Develop **high-fidelity models** combining material ablation physics, atmospheric dynamics, and chemical reactions.
  - Use these models to **predict environmental impacts** and inform space policy frameworks.
- **Establishing Testing Infrastructure:**
  - Commission the **UK's first plasma wind tunnel**, offering a world-class experimental facility.
  - Conduct **experimental studies** simulating real-world re-entry scenarios, ensuring accurate environmental risk assessments.
- **Supporting Regulatory Frameworks:**
  - Use **validated datasets** and **scientific evidence** to guide international regulatory development and policy recommendations.
  - Propose **sustainability-driven legal frameworks** that balance technological feasibility with environmental responsibility.
- **Enhancing Research Capacity:**
  - Launch an interdisciplinary **PhD programme** that bridges engineering, policy, and law.
  - Support **structured exchanges** between research institutions and regulatory agencies, fostering innovation and policy integration

By harmonising these research efforts, the programme aims to position the UK as a global leader in **space environmental research**, driving policy development and technical innovation while creating a robust foundation for **long-term environmental sustainability** in space operations

3 Detailed Research Approach

The proposed 3-year research programme addresses spacecraft re-entry emissions through a harmonised, multidisciplinary approach integrating **Modelling**, **Testing**, and **Policy Development**. By combining technical advancements with environmental governance, the programme ensures that scientific findings are translated into actionable policies and regulatory frameworks.

The programme's core structure involves two interconnected research streams:

1. **Prediction Stream (Modelling, Regulation, and Policy Development):** This stream develops high-fidelity computational models, assesses regulatory frameworks, and proposes international standards.
2. **Validation Stream (Experimental Testing):** This stream conducts material testing, emissions measurements, and model validation using experimental facilities, including the UK's first plasma wind tunnel.

The **planned workshops** play a central role by providing a platform to synthesise research findings, engage policymakers, and refine legal frameworks through multi-stakeholder dialogues.

3.1 Prediction Stream (Modelling, Regulation, and Policy Development)

The Prediction Stream focuses on developing computational models and regulatory frameworks that align scientific advances with environmental governance. This stream builds predictive tools, conducts policy analysis, and proposes standards for spacecraft design, manufacturing, and disposal practices.

3.1.1 Modelling Research Activities

Modelling forms the scientific foundation of the research programme, enabling detailed predictive analyses of spacecraft re-entry processes. The stream uses advanced computational methods, such as **Direct Simulation Monte Carlo (DSMC)**and **Computational Fluid Dynamics (CFD)**, to simulate spacecraft-environment interactions during re-entry.

3.1.1.1 Research Areas

- **Re-entry Dynamics Simulation**
  - Simulate spacecraft re-entry conditions, including drag, heat transfer, and aerodynamic forces.
  - Model dynamic interactions between spacecraft materials and the atmosphere.

- **Material Ablation Models**
  - Develop detailed models of thermal degradation, sublimation, pyrolysis, and mechanical erosion of spacecraft components.

    - Use physics-based algorithms to simulate material behaviour under extreme temperatures and pressures.

- **Chemical Reaction Modelling**
    - Simulate chemical reactions between ablation by-products and atmospheric gases.
    - Assess the formation of greenhouse gases, ozone-depleting chemicals, and aerosol particles.

- **Global Atmospheric Impact Assessments**
    - Apply global circulation models (GCMs) to evaluate long-term dispersion and accumulation of re-entry emissions.
    - Study atmospheric transport processes and potential impacts on climate and weather patterns.

3.1.1.2 Expected Deliverables

- Advanced simulation tools for industry and research use.
- Data-driven environmental impact assessments

3.1.2 Policy and Regulatory Development Activities

Policy development ensures that scientific findings are effectively integrated into legal and regulatory frameworks. This component bridges the gap between **technical advancements** and **environmental governance**, supporting the development of sustainable spacecraft disposal policies.

3.1.2.1 Research Areas

- **Policy Analysis**
    - Conduct policy and regulatory analysis to adapt existing frameworks for mitigating spacecraft re-entry emissions.
    - Review environmental impact assessment (EIA) frameworks and propose improvements for international standards.

- **Standards Mapping and Engagement**
    - Assess existing industry and regulatory standards for spacecraft design, testing, and disposal.
    - Identify gaps and propose revisions informed by validated scientific findings.

- **International Collaboration**
    - Establish a Technical-to-Regulator Dialogue on Atmospheric Impacts of Spaceflight Activities.

- Launch an Outreach Campaign targeting industry stakeholders and policymakers, fostering transparency and international collaboration.

3.1.2.2 Expected Deliverables

- Policy briefs and regulatory proposals.
- Reports on standard-setting initiatives and engagement strategies.
- Policy frameworks integrating the precautionary principle, EIAs, and multilateral environmental agreements (MEAs).

3.2 **Validation Stream** (Experimental Testing)

The Validation Stream ensures that predictive models are **scientifically validated** through real-world testing. Establishing the **UK's first plasma wind tunnel** will enable spacecraft re-entry conditions to be replicated, providing experimental data for model refinement. An inductively coupled plasma wind tunnel is the core facility of the validation stream for simulating atmospheric re-entry/entry environment at the ground. As shown its overall configuration in Figure 2, it consists of pressure control system, heat exchanger, test chamber, plasma heater, power supply and control console.

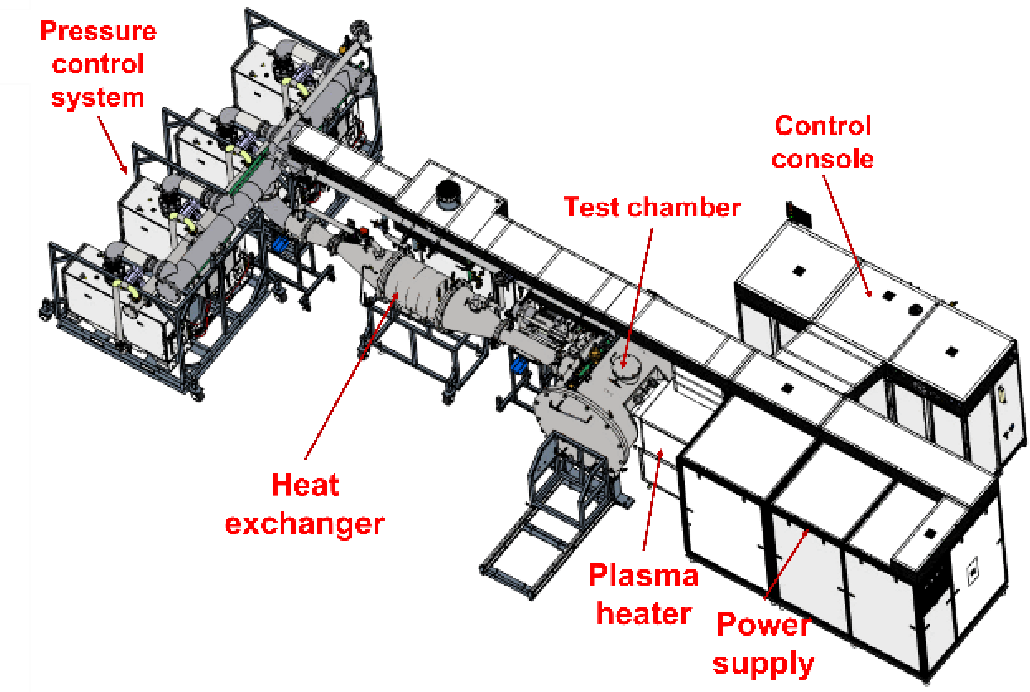

Figure 2. Designed configuration of a plasma wind tunnel for space sustainability assessment

3.2.1 Research Activities

- **Material Characterisation Testing:** Conduct laboratory tests on spacecraft materials to measure thermal, chemical, and mechanical properties under extreme re-entry conditions.

- **Re-entry Simulation Facility Development**: Design, build, and operate the plasma wind tunnel, enabling controlled material ablation experiments.
- **Aerosol and Gas Emission Measurements:** Use advanced diagnostics to measure gas and aerosol emissions produced during re-entry simulations.
- **Model Validation Testing:** Perform comprehensive experiments to compare theoretical model predictions with empirical results.

3.2.2 Expecting deliverables

- Commissioned plasma wind tunnel facility.
- Validated datasets for spacecraft re-entry emissions.
- Reports linking experimental data to computational model improvements

3.3 Planned Workshop

The **three annual workshops** will synthesise research findings and facilitate policy engagement through expert consultations. Each workshop builds on technical, legal, and policy insights gathered through the Prediction and Validation streams.

3.3.1 Workshop 1: Legal and Standards Development

3.3.1.1 Objective

Investigate existing legal frameworks and identify regulatory gaps related to upper atmospheric contamination.

3.3.1.2 Expected Outcomes

- Recommendations for engaging with the International Standard Organisation (ISO).
- Proposals for international standards governing spacecraft re-entry emissions.

3.3.2 Workshop 2: Precautionary Approach and Transboundary Harm

3.3.2.1 Objective

Adopt a precautionary approach to address transboundary harm by establishing global atmospheric impact assessment protocols.

3.3.2.2 Expected Outcomes

- Functional models for integrating the precautionary principle into space sustainability policy.
- Recommendations for including spacecraft re-entry emissions in multilateral environmental agreements (e.g., Montreal Protocol)

3.3.3 Workshop 3: Legal Competence and Jurisdiction

3.3.3.1 Objective

Clarify legal responsibilities concerning spacecraft re-entry emissions across different jurisdictions, including international waters and high seas.

3.3.3.2 Expected Outcomes

- Recommendations on jurisdictional authority and legal responsibilities.
- Compliance guidelines for commercial operators based on prior workshop findings.

4 Key Milestones and Deliverables

The research programme follows a structured timeline with clearly defined milestones linked to technical, policy, and regulatory development goals. The planned tasks are designed to ensure continuous progress and integration across **Modelling**, **Testing**, and **Policy Development**, culminating in scientific, regulatory, and industry-facing deliverables.

Year	Prediction Stream (Modelling + Policy Development)	Validation Stream (Experimental Testing)	Workshops and Policy Engagement
1	Framework design and computational model development Initial regulatory review and policy analysis	Plasma wind tunnel design and facility specifications	**Workshop 1:** Legal and Standards Development – Exploring international legal constraints and standards for spacecraft re-entry
2	Model integration for atmospheric impact simulations Standards mapping and international engagement begins	Facility construction completed; commissioning begins	**Workshop 2:** Precautionary Approach & Transboundary Harm – Developing a functional MEA-based regulatory framework
3	Policy briefs and regulatory proposals delivered Final predictive models and policy recommendations	Experimental testing starts; data collection for validation	**Workshop 3:** Legal Competence & Jurisdiction – Defining roles of states, agencies, and industry in environmental responsibility

4.1 Year 1: Foundational Research and Design Phase

- **Modelling Deliverables:** Initial spacecraft ablation models, trajectory simulations, and chemical reaction modules.
- **Testing Deliverables:** Wind tunnel design completed; facility procurement and construction plan initiated.
- **Policy Deliverables**: Policy gap analysis report, initial legal review of existing regulatory frameworks.
- **Workshop Deliverable:** Legal and standards development roadmap.

4.2 Year 2: Development and Validation Phase

- **Modelling Deliverables:** Integrated global atmospheric impact models; preliminary results shared with international regulatory bodies.
- **Testing Deliverables:** Plasma wind tunnel construction completed and operational; initial lab-scale validation tests conducted.
- **Policy Deliverables:** Policy development strategy based on MEAs, including draft recommendations on regulatory improvements.

- Workshop Deliverable: Recommendations for international frameworks integrating the precautionary approach and transboundary responsibility.

4.3 Year 3: Final Integration and Policy Engagement

- **Modelling Deliverables:** Final predictive models validated through experimental data.
- **Testing Deliverables:** Comprehensive emissions and ablation datasets; validation reports.
- **Policy Deliverables:** Final policy recommendations and regulatory proposals submitted to national and international agencies.
- **Workshop Deliverable:** International policy guidance and standards proposals defining national and global responsibilities.

5 Social and Economic Impacts

The research programme's integrated approach delivers substantial **social** and **economic** benefits through technological innovation, regulatory development, and industry engagement. These impacts extend across scientific, industrial, environmental, and policy-making domain.

The 3-year research program combines **innovative testing**, advanced modelling, and policy alignment to deliver actionable solutions for mitigating the environmental impacts of spacecraft re-entry. The establishment of the **plasma wind tunnel** solidifies the UK's leadership in space sustainability, offering global benefits through cutting-edge research, policy advancements, and significant economic contributions.

5.1 Social Impact

5.1.1 Environmental Stewardship and Sustainability

- **Improved Environmental Governance:** The programme directly addresses environmental concerns by developing new spacecraft disposal standards that mitigate atmospheric contamination.
- **Global Environmental Responsibility:** Through international collaboration, the project promotes global environmental governance, helping to shape MEA-based policy frameworks.

5.1.2 Scientific Leadership and Knowledge Sharing

- **Academic Excellence:** Establishing the UK's first plasma wind tunnel will make the UK a global centre for spacecraft re-entry environmental research.
- **International Collaboration:** Workshops, conferences, and policy dialogues will create a global knowledge-sharing network, fostering cooperation between governments, industry, and academia.

5.1.3 Skill Development and Education

- **PhD and Research Training:** Supporting three multidisciplinary PhD students will create highly skilled professionals equipped to address future space policy, environmental science, and space engineering challenges.
- **Knowledge Transfer:** Regular research exchanges will strengthen collaboration between universities, regulatory bodies, and industry partners.

5.2 Economic Impact

5.2.1 Technology and Infrastructure Development

- **Innovation Hub:** Establishing the UK's first plasma wind tunnel will position the UK as a global hub for spacecraft environmental impact research.
- **Industrial Advancement:** The programme will attract international industry investment by offering unique testing and validation capabilities.

5.2.2 Market Competitiveness and Cost Savings

- **Competitive Edge:** By supporting international space sustainability standards, UK-based companies will gain a competitive advantage in the rapidly expanding space industry.
- **Operational Cost Reduction:** Accurate environmental risk assessments will reduce future compliance costs for spacecraft operators.

5.2.3 Job Creation and Economic Growth

- **Research and Development Jobs: The** programme will create new jobs in engineering, environmental science, regulatory policy, and data analysis.
- **Industry Partnerships:** Collaboration with UK-based aerospace and environmental technology firms will drive innovation, economic growth, and job creation

5.3 Long-term Impact

The integrated approach ensures that technical, scientific, and policy advancements feed directly into environmental governance, fostering **sustainable space operations**. This research programme will not only provide the UK with cutting-edge capabilities but also shape global policy, driving environmental, technological, and economic progress.

6 Risk of VLEO Constellation

Very Low Earth Orbit (VLEO), situated at altitudes between 100 and approximately 450 km, is gaining increasing attention for both commercial and scientific applications, offering a range of potentially market-disruptive mission opportunities. It benefits from a relatively low risk of space debris accumulation, as objects naturally decay and re-enter the Earth's atmosphere more rapidly due to residual atmospheric drag. Additionally, the more benign radiation environment allows the use of terrestrial-grade, general-purpose electronic components, reducing costs and complexity.

Operating in VLEO also enables significant improvements in observational resolution, creates opportunities for ultra-high-speed telecommunication applications, and offers new avenues for scientific investigations of the upper atmosphere and Earth's gravitational field. These advantages make VLEO constellations particularly attractive for a variety of low-cost systems or constellations, facilitated by reduced launch costs and greater flexibility in launch options, such as micro-launchers and in-orbit transfer vehicles.

Despite these advantages, spacecraft operating at such low altitudes face significant challenges, primarily atmospheric drag and surface erosion caused by atomic oxygen. Below 250 km, drag requires continuous compensation to prevent rapid orbital decay. Furthermore, atomic oxygen, the predominant gas species in VLEO, is highly reactive with many materials, leading to shrinkage, cracking, and surface erosion. While these factors present critical design and operational challenges for sustained missions in this orbital regime, drag compensation poses the greatest challenge for VLEO constellations due to the substantial amount of propellant required throughout the mission.

6.1 Air-Breathing Electric Propulsion

The concept of air-breathing electric propulsion, known as RAM-EP, offers a transformative approach to addressing the challenge of drag compensation for VLEO constellations. Instead of relying on onboard propellants, RAM-EP utilises the surrounding atmosphere to produce thrust. The system consists of an intake and an electric thruster [1], where the intake collects atmospheric gas molecules and directs them to the thruster or accelerator. The collected atmospheric gas is then ionised and accelerated to generate thrust, functioning similarly to electric propulsion systems such as ion thrusters or Hall effect thrusters. A power system, typically a combination of solar arrays and batteries, supplies the necessary electrical power [2]. By adopting RAM-EP technology, thrust can be generated in VLEO without the need for onboard propellant, effectively mitigating the limitations on spacecraft lifetime caused by atmospheric drag while simultaneously reducing the total wet mass of the spacecraft.

The thrust produced by an electrostatic accelerator in the RAM-EP concept can be estimated as:

$$T = \gamma \cdot \frac{M}{e} I_b \cdot \sqrt{\frac{2e\eta_v V_{as}}{M}} \tag{6.1}$$

where γ is a collection factor accounting double ionisation and beam divergence, M is the molecular mass of propellant (atmosphere molecules), e is the electron charge, η_v is the voltage utilisation efficiency, I_b is the ion beam current, and V_{as} is the applied discharge voltage. With considering the momentum of incoming air flow, Equation (6.1) can be modified as:

$$T = \gamma \cdot \frac{M}{e} I_b \cdot \sqrt{\frac{2e\eta_v V_{as}}{M}} - \dot{m}V_\infty \tag{6.2}$$

where $\dot{m}$ is the mass flow rate accepted into the thruster, and V_∞ is the orbital velocity.

The mass utilisation efficiency, η_m, can be defined as:

$$\eta_m = \frac{ionised\ mass\ flow\ rate}{inlet\ mass\ flow\ rate} = \frac{\frac{MI_b}{e}}{\dot{m}} \tag{6.3}$$

From neutral continuity, the achievable mass utilisation efficiency can be calculated as:

$$\eta_m = 1 - \exp\left(-\frac{L}{\frac{V_{n,th}}{n_e < \sigma_i V_{e,th} >}}\right) \tag{6.4}$$

where L is a reference ionisation length, $V_{n,th}$ is the injection velocity of neutral particles, σ_i is an ionisation cross-section, and $V_{e,th}$ is electron thermal velocity.

From Equations (6.4) and (6.5), Equation (6.2) can be rewritten as [3]:

$$T = \dot{m}\left[\gamma \cdot \left\{1 - \exp\left(-\frac{L}{\frac{V_{n,th}}{n_e < \sigma_i V_{e,th} >}}\right)\right\} \cdot \sqrt{\frac{2e\eta_v V_{as}}{M}} - V_\infty\right] \tag{6.5}$$

6.2 Atmospheric Drag Estimation

In VLEO, atmospheric drag inevitably reduces the orbital energy, leading to the decay of the orbit and eventual re-entry of spacecraft. During the operation of VELO satellites, it requires to compensate its atmospheric drag using propulsion system. The amount of atmospheric drag can be estimated as:

$$D = \frac{1}{2}\rho V^2 C_D A_{ref} \tag{6.6}$$

where ρ is the atmospheric density, V is the relative velocity of spacecraft with respect to the atmosphere, C_D is the drag coefficient, and A_{ref} is the frontal area of spacecraft. As can be seen from Equation (6.6), three key parameters are associated with atmospheric drag, the atmospheric density, the velocity of the spacecraft with respect to the atmosphere, and the drag coefficient. The atmospheric density, ρ, and spacecraft velocity, V, are mainly determined by the operation altitude of VELO satellite. The drag coefficient, C_D, is determined by the shape of satellite.

In VELO, the atmospheric density is sufficiently low enough to be considered as a rarefied gas thus the flow around spacecraft should be considered as the free molecular flow. Satellites with complex shapes can be combination of elementary shaped, including flat plates, cylinders and spheres. In the free molecular flow regime, the theoretical drag coefficient of the flat plat, cylinder, and sphere can be estimated as [4]:

For a plat plate:

$$C_D = \frac{1}{S^2}\left\{\frac{S}{\sqrt{\pi}}[4\sin^2\alpha + 2\sigma\cos(2\alpha)]\cdot e^{-(S\sin\alpha)^2} + \sin\alpha\left[1 + 2S^2 + (1-\sigma)(1-2S^2\cos(2\alpha))\cdot \mathrm{erf}(S\sin\alpha) + \sigma\sqrt{\pi}\frac{S^2}{S_r}\sin^2\alpha\right]\right\} \tag{6.7}$$

$$S = \frac{v_m}{\sqrt{2R_{sp}T}} \tag{6.8}$$

$$S_r = \frac{v_m}{\sqrt{2R_sT_r}} \tag{6.9}$$

where α is an angle of attack, S is the modular speed ratio defined as the ratio of the gas macroscopic velocity, v_m, and the most probable molecular thermal velocity, v_t, R_s is the specific gas constant, T is the temperature of the incident stream, and Tr is the temperature of diffusely reflected particles of the reflected stream. σ is an accommodation coefficient to characterise the degree of adaptation of molecule to the wall, which is in between 0 and 1.

For a cylinder:

$$C_D = \frac{4-\sigma}{3}\frac{\sqrt{\pi}e^{-\frac{S^2}{2}}}{S}\cdot\left\{\left(S^2+\frac{3}{2}\right)I_0\frac{S^2}{2} + \left(S^2+\frac{1}{2}\right)I_1\frac{S^2}{2}\right\} + \frac{\sigma\pi^{\frac{3}{2}}}{4S_r} \tag{6.10}$$

where I_0 and I_1 are the zeroth-order and first-order modified Bessel function, respectively.

For a sphere:

$$C_D = \frac{e^{-S^2}}{\sqrt{\pi}S^3}(1+2S^2) + \frac{4S^4+4S^2-1}{2S^4}\mathrm{erf}(S) + \frac{2\sigma\sqrt{\pi}}{3S_r} \tag{6.11}$$

As can be seen from Equations (6.7) – (6.11), the key parameters affect the drag coefficient are the angle of attack, α, accommodation coefficient, σ, and the molecular speed ratio. Using the atmospheric parameter listed in Table 1, the drag coefficients for elementary shapes can be estimated in terms of altitude. At 200 km altitude, CD for flat plate, cylinder and sphere with zero angle of attack are about 2.12 2.10 and 2.09, respectively. For a typical VLEO satellite having 0.18 m^2 frontal area with the length of 1.5 m, which is similar to ESA's GOCE satellite, the estimated drag at 200 km is about 5 mN, and it will be increased to 10 mN at 180 km operation. Therefore, VLEO satellite should be able to generate consistent thrust about 10 mN during its operation for compensating its atmospheric drag.

Table 1. Atmospheric parameters predicted using US Standard Atmosphere model.

Altitude (km)	Velocity (m/s)	Number density (m^{-3})	Temperature (K)	Composition (N2/O2/O)	Speed ratio
200	7782	7.18×10^{15}	855	0.408/0.027/0.565	9.53
220	7770	4.04×10^{15}	899	0.341/0.020/0.639	9.07
240	7758	2.42×10^{15}	930	0.281/0.015/0.704	8.73
260	7747	1.52×10^{15}	951	0.230/0.011/0.759	8.46
280	7734	9.81×10^{14}	966	0.186/0.008/0.806	8.24
300	7723	6.51×10^{14}	976	0.149/0.006/0.945	8.07

6.3 Environmental Risk of RAM-EP

During the operation of RAM-EP, the atmospheric gas has been ionised to generate thrust. Therefore, mono-nitrogen oxides, such as nitric oxide (NO) and nitrogen dioxide (NO_2), will be produced during the RAM-EP operation. When NO is present in the stratosphere, it can react with ozone to form nitrogen dioxide and oxygen. Then, nitrogen dioxide can react with a single oxygen atom to reform NO and O2. The NO_x-O_3 reaction can be summarised as:

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$NO_2 + O_3 \rightarrow NO_3 + O_2$$

$$NO_2 + NO_3 \rightarrow NO_2O_5$$

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$2NO_2 + O_3 \rightarrow N_2O_5 + O_2$$

$$N_2O_5 + H2O \rightarrow 2HNO_3$$

As demonstrated, each NO molecule has the potential to destroy multiple ozone molecules. Notably, nitrogen dioxide (NO_2) shares several characteristics with chlorofluorocarbons (CFCs) [5]. Both NO_2 and CFCs are highly stable in the atmosphere and contribute to the destruction of stratospheric ozone.

Table 2 presents the ionisation cross-sections of major atmospheric species at an altitude of 200 km. Using these ionisation cross-sections and Equations (6.6) and (6.10), we can estimate the drag experienced by a VLEO satellite with a design similar to that of the GOCE satellite. GOCE's slim, symmetrical shape is specifically designed to minimise drag. Assuming a cross-sectional area of 1.1 m^2 and a cylindrical shape with a length of 5.3 m [6], the estimated drag is approximately 21 mN. For a RAM-EP system delivering performance comparable to a Hall thruster operating on pure nitrogen, a mass flow rate of approximately 3 mg/s would be required to be operated at 200 km.

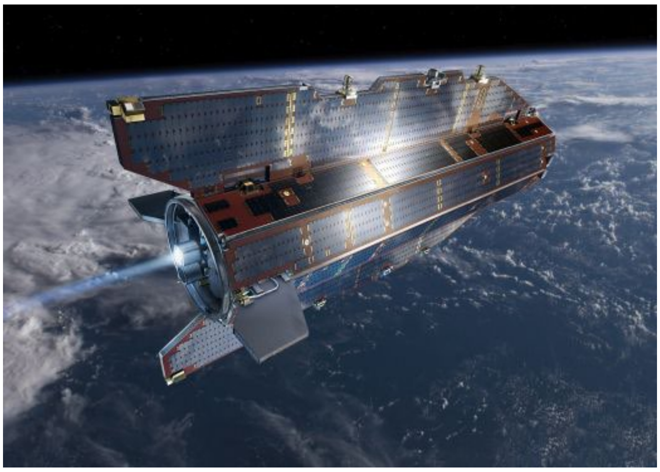

Figure 3. GOCE (Gravity field and steady-state Ocean Circulation Explorer) VLEO Satellite

Table 2. Ionisation cross section of main atmospheric species at 200 km.

Species	**σ_i, 10^{-20} m^2**
O	0.49

N_2	0.64
O_2	0.54

A VLEO satellite operating at 200 km for one year can produce approximately 94 kg of nitrogen oxides (NOx). Due to the reduced coverage area at VLEO compared to LEO, a VLEO constellation requires a significantly higher number of satellites than a comparable LEO constellation. For instance, considering a VLEO mega-constellation of similar scale to Starlink's planned 42,000 satellites[7], such a system could generate over 3,900 tonnes of nitrogen oxides annually to maintain their orbits.

By comparison, CFC emissions peaked in the late 1980s at around 12,000 tonnes per year and have since been reduced to approximately 1,100 tonnes per year since 2010, due to international regulatory efforts [8][9]. The production of 3,900 tonnes of NOx per year by a VLEO mega-constellation is, therefore, a substantial contribution to atmospheric pollution. As nitrogen oxides are highly stable in the atmosphere and significantly contribute to the destruction of stratospheric ozone [5], this level of emission could pose a notable environmental risk, particularly with respect to ozone layer depletion.

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