University of Stuttgart
Institute of Space Systems

A Pathway for Closing the Knowledge Gaps for a Comprehensive Life Cycle Assessment and Ecodesign of Space Transportation Systems

Results of the 3rd Workshop on Life Cycle Assessment of Space Transportation Systems

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Executive Summary

The aim of this document is to summarize the state of knowledge on the environmental impacts of space transportation systems and to propose measures to close the identified knowledge gaps. It is intended to provide a basis for discussions in the context of the further development of the ESA Handbook, the development of the PEFCR for Space by the European Commission, the upcoming discussions in the context of CM25 and in the scientific and industrial community. The following open action points have been identified:

- **Early Implementation of Ecodesign Principles**: Embed Ecodesign principles in the initial stages of STS development, ensuring environmental impacts influence design decisions.
- **Set Quantitative Ecodesign Targets:** Establish KPIs to assess reduced resource depletion, emissions, and efficiency improvements in design and operations.
- **Centralize Ecodesign Knowledge:** Develop a centralized repository to consolidate ecodesign guidelines, best practices, and lessons learned across the sector.
- **Expand Data Access and Quality:** Enhance LCA databases for aerospace applications, including atmospheric emissions, by fostering data sharing and filling data gaps.
- **Develop and Fund Emission Impact Research:** The impacts of emitted species from rockets on radiative forcing and ozone especially in the upper atmospheric layers must be better understood; this requires experimental investigations.
- **Validate Rocket Engine Emission Models with Experimental Data:** Conduct ground tests on multiple engine configurations to validate models and ensure accurate prediction of emissions.
- **Enhance Black Carbon Modelling:** Develop refined black carbon (BC) models tailored to space systems, as current models adapted from aviation do not fully capture rocket-specific conditions.
- **Develop and Fund Emission Measurement Campaigns:** Support studies to measure emissions at varied altitudes using both direct and remote sensing, emphasizing cost-effective methods and standardization**.**
- **Create Comprehensive Emissions Databases:** Develop accessible emissions databases following FAIR principles, enabling global collaboration for policy and research.
- **Expand Modelling Tools for Re-Entry Demise:** Advance existing re-entry tools to analyze atmospheric impact and disintegration patterns for safety and environmental assessment.
- **Obtain Comprehensive Material Data:** Improve access to material composition data for rocket bodies to predict disintegration behaviour, possibly through legal requirements for data disclosure to regulatory bodies.
- **Establish and Standardize Atmospheric Modelling Approaches**: Further develop CCM and CTM to understand the atmospheric impact of launch and re-entry emissions, with a focus on ozone depletion, radiative forcing, and cloud formation.
- **Expand Particle Transport and Deposition Models:** Model the atmospheric lifespan and deposition of particles to understand their dispersion and long-term environmental impact, focusing on sedimentation rates and stratospheric circulation patterns.

Workshop on Life Cycle Assessment of Space Transportation Systems

This whitepaper gives an overview of the results from the 3rd workshop on Life Cycle Assessment of Space Transportation Systems. During a three-day workshop from 17th – 19th September 2024 a group of 35 experts from academia, agencies, industry and politics came together at the Space Centre Baden Württemberg to access the status of research on "Life Cycle Assessment of Space Transportation Systems" in order to identify necessary measures for a better understanding of the environmental impacts.

Based on a series of presentations where the participants presented their expertise and status of research, three working groups discussed the status of knowledge and further measures. These working groups were: Ecodesign of STS, Operational Impact (launch and propulsive re-entry emissions) and Demise Impact. In these groups, a discussion about the knowledge gaps, key questions and already known answers from other departments as well as possible solutions was conducted. At the end of the workshop, measures for dedicated implementation concepts were defined. These conclusions are summarized in the following.

List of acronyms

CSG	Guiana Space Centre
BC	Black Carbon
CCM	Chemistry Climate Model
CFD	Computational Fluid Dynamics
CTM	Chemistry Transport Model
ESA	European Space Agency
GWP	Global Warming Potential
IAM	Integrated Assessment Models
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MBSE	Model-Based Systems Engineering
MDAO	Multidisciplinary Design Analysis and Optimisation
ODP	Ozone Depletion Potential
PB	Planetary Boundaries
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
SSSD	Strathclyde Space Systems Database
STS	Space Transportation System
TPS	Thermal Protection System
WMO	World Meteorological Organization

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1. What Is a Sustainable Space Transportation System ?

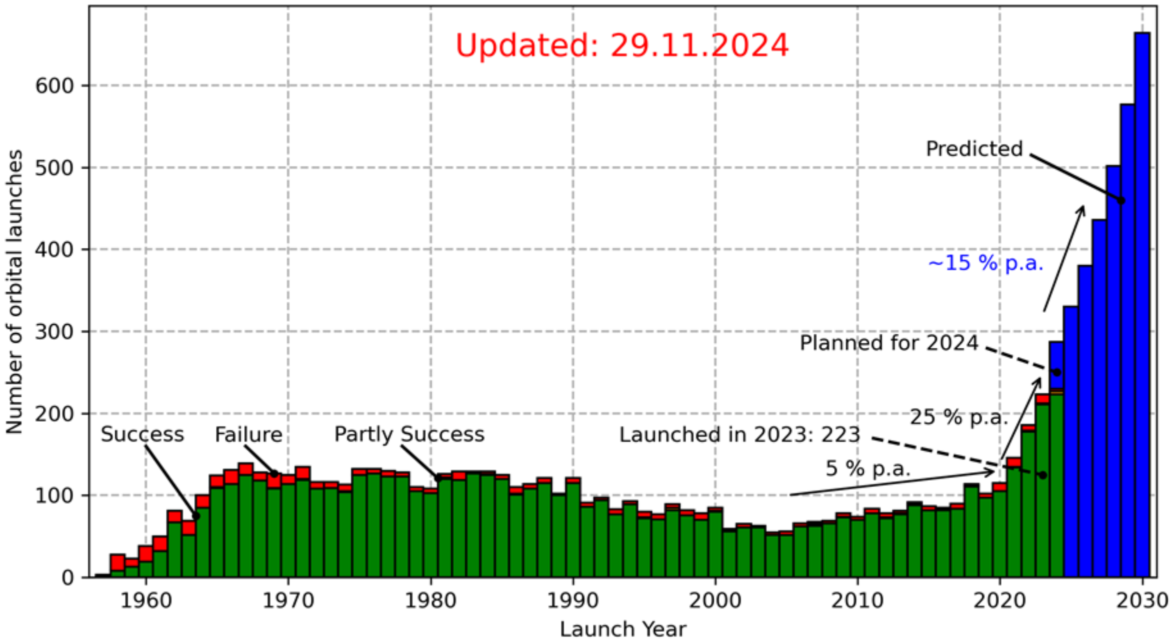

Figure 1: Historical and expected future orbital rocket launches (data from [1])

In recent years, there has been a significant increase of ~25% p.y. in orbital rocket launches. This is expected to continue in the coming years at around 15% p.y. The significant increase in activities and the associated environmental impact raises the question of what impact rockets have on the environment. Although the impact is very small at around 100 launches per year, there are concerns at other scales. The World Meteorological Organization (WMO) mentions “heightened concerns about influences on 21st century ozone include impacts of: ... increased frequency of civilian rocket launches ... ." [2]. Against this background, the development of sustainable rockets is desirable.

When talking about the environmental impact of space transport systems, however, the question inevitably arises as to what a sustainable space transport system looks like. There are different definitions of sustainability for this. “Meeting the needs of the present without compromising the ability of future generations to meet their own needs.” [3] is the common definition of the United Nations. In the area of spaceflight, sustainability can be divided into "to space", "from space" and "in space". The aspects covered here are the impact on the environment and atmosphere including climate and ozone, the influence of earth observation on sustainable action and the situation in orbits with regard to space debris [4]. Against this background, we developed a definition of a sustainable space transport system in the workshop to:

“A sustainable space transportation system should minimize emissions and ablation, produce no space debris while minimizing environmental and societal impacts.”

Based on this, we talked about the different aspects of developing sustainable space transportation systems in the three working groups. The first one on **Ecodesign**, dealing with implementation of environmental criteria into STS design. The second one talking about the **Operational Impact** during launch and re-entry of reusable systems. The third one covering the **Demise Impact** after the end of mission. Furthermore, we talked about the implementation of those effects into atmospheric modelling and developed a pathway for the required research efforts.

2. Ecodesign

2.1. Establishing Ecodesign in STS design

Ecodesign is an important aspect in order to make launcher systems more sustainable. By taking environmental criteria into account in the design processes, the environmental impact of launchers can be reduced. However, data and knowledge gaps exist and need to be addressed and closed. The recent workshop on Ecodesign in STS emphasized the importance of incorporating environmental sustainability at the earliest stages of system development. The sessions highlighted the state-of-the-art and future practices in Ecodesign, focusing on actionable recommendations for enhancing the sustainability of space systems while balancing environmental and economic objectives.

Early Implementation of Ecodesign Principles

A primary takeaway from the workshop was the importance of embedding Ecodesign principles at the earliest stages of STS development. By initiating exchanges between LCA experts and systems engineers early in the design process, we can ensure that environmental considerations influence critical design decisions before they are finalized. Early-stage Ecodesign allows us to optimize resource consumption and reduce emissions throughout the system's lifecycle, from material sourcing to disposal. For satellite projects, we propose presenting at least one “ecodesigned” option at the Preliminary Design Review (PDR), while for launch vehicles, critical design decisions such as the staging, reusability option, and propellant type, should be made even earlier.

Balancing Environmental and Economic Objectives

Implementing Ecodesign often requires upfront investments, which can pose challenges for budget-constrained organizations. Balancing environmental benefits with associated costs is a significant consideration for broader industry adoption. We discussed how simplified tools could support SMEs, complemented by e.g. Model-Based Systems Engineering (MBSE) which could help bridge some gaps by enabling cost-effective design optimizations. This facilitates integration across complex systems, making it easier to adopt sustainable practices.

Setting Quantitative Targets for Ecodesign

To ensure Ecodesign efforts are measurable, we discussed quantitative targets. Key Performance Indicators (KPIs) such as environmental indicators, reduced system mass, power efficiency, and lower emissions were recommended as tangible objectives. We also highlighted the importance of setting subsystem-specific targets to ensure that all teams contribute to overarching Ecodesign goals. A final system-level assessment shall be conducted to prevent burden-shifting, ensuring that improvements in one area don’t inadvertently increase impacts elsewhere, thus supporting holistic sustainability goals.

Setting Tailored Ecodesign Goals

We recommend establishing Ecodesign goals tailored to the specific characteristics of different STS types. For example, reusable systems designed for multiple missions have different environmental and durability needs compared to expendable systems used only once. Ecodesign goals for reusable systems should focus on the sustainability of launch and operational phases, whereas expendable systems should prioritize minimizing the environmental impact of material production, manufacturing and disposal. This targeted approach ensures that Ecodesign addresses the environmental "hotspots" of each system type.

Identifying and Prioritizing Key Environmental Hotspots

An essential strategy discussed is identifying and prioritizing critical "hotspots", areas where environmental impacts are most concentrated. Attempting to mitigate impacts across all lifecycle phases can be costly and inefficient. Instead, we should start by focusing on the top three to five most impactful areas. For example, propellant production, energy consumption during production and operation, and surface treatments involving hazardous chemicals were identified as potential hotspots. The impacts of launch and re-entry might also have a significant impact but are not yet well enough researched. Focusing our efforts on these areas allows us to achieve meaningful environmental gains efficiently.

Establishing a Centralized Ecodesign Repository

We also see the value in creating a centralized repository of Ecodesign guidelines, shared lessons learned, and best practices. This resource would allow the industry to standardize Ecodesign practices and create a collective knowledge base for guiding future projects. We envision this repository being secure, with proprietary data protected or possibly only used for non-confidential data (lessons learnt from studies but not data used in the studies), for secure data exchange, thereby promoting transparency and collaboration across the industry.

Integrating Ecodesign into Existing Design Processes

Integrating Ecodesign principles into current design workflows is essential for smooth adoption by engineers. We considered whether new tools are necessary or if existing design tools can be adapted. To avoid disruptions, we recommend ensuring that Ecodesign tools, whether new or adapted, are compatible with traditional design processes used in the space industry. Furthermore, we identified the need for practical and actionable Ecodesign guidelines that engineers can easily incorporate into traditional design processes. Concurrent Design Facilities (CDF) provide ideal opportunities for integrating Ecodesign adjustments, allowing teams to make sustainable design choices early without needing costly redesigns later. Digitizing the design and production chain, along with standardizing data formats, could streamline Ecodesign implementation, facilitating collaboration across departments and organizations. Selecting supply chains based on environmental criteria is integral to Ecodesign, requiring a holistic view of system architecture for key decisions, followed by localized optimizations.

Evaluating Ecodesign Effectiveness Through Holistic Approaches

We explored methodologies for evaluating the effectiveness of Ecodesign, questioning the adequacy of single-score formulas for capturing the multidimensional aspects of environmental impact. A more holistic approach, using multi-criteria analysis to assess trade-offs between impact categories like carbon footprint and resource use, is recommended.

Advancing Ecodesign Methodologies Beyond LCA

Further development of Ecodesign methodologies is necessary to move beyond descriptive LCA assessments and provide actionable insights for design decisions. We believe LCA should be the baseline for the transition from merely measuring impacts to actively informing design choices. We suggest defining data flows within these tools to clarify their role in the design process. Additionally, the use of Multidisciplinary Design Analysis and Optimization (MDAO) could support system-level Ecodesign optimizations during early design stages, with simplified parameters to reduce complexity.

2.2. Data gaps and availability

Existing Life Cycle Assessment (LCA) databases, such as ecoinvent, the Strathclyde Space Systems Database (SSSD) and ESA's LCA database, provide foundational resources for environmental analysis. However, these databases do not yet fully address the unique needs of space systems today and tomorrow. We recognize the potential value of developing a further customized space industry database or to capture more space-specific impacts, such as atmospheric emissions and production processes unique to aerospace. Additionally, we see a need to update LCIA indicators to better reflect the atmospheric impacts. Characterization factors at least for climate change and ozone depletion for every altitude and species would be the goal to achieve to close this gap. A way to achieve this is discussed in the following chapters. Comparing allocation methods like cut-off, that takes environmental benefits only from input recycled materials, with other methods that includes benefits of recycling wastes, could improve the accuracy of environmental impact assessments in space applications.

Strategies for Facilitating Data Sharing in Ecodesign

Data sharing emerged as a critical issue, given the challenges in obtaining proprietary data from private companies. To address this, we explored several strategies, including compensating companies for data sharing or creating legal frameworks that mandate data sharing through an independent, trusted organisation. Note that a legal framework for LCA of space systems in Europe is currently being developed with the European Commission (PEFCR4Space). For effective early-stage analysis, we propose aggregating data for Ecodesign purposes but limiting insight into company specific data to protect proprietary information. A “black box” system was suggested as a potential solution, allowing review without full dataset access, thereby balancing transparency with confidentiality.

Essential Data Types for Ecodesign Assessment

We identified the types of data that are essential for effective Ecodesign. Here we have different viewpoints. Academia needs insight into technical system specifications, process flows, material composition, energy consumption, propellant details, and trajectory information. For industry the challenges lie more on include raw material inputs and wastes, energy consumption and origin, transport data distances and means, manufacturing techniques, auxiliary processes and product such as surface treatment, packaging and recycling data. Additionally, data on each component's dimension and mass is crucial for an early assessment with generic datasets. Furthermore, data quality information is essential. The project's phase influences data requirements, with data quality evolving as the project advances. We see heritage data, or insights from past projects, as valuable in supporting Ecodesign without requiring a full LCA for every new initiative.

Identifying and Addressing Data Gaps in LCA for Aerospace

During the workshop, we pinpointed areas where current datasets fall short for aerospace applications. Limited information exists on the percentage of recycled materials, raw material origins, and specific by-products used now or expected in the future in aerospace production, such as surface treatments, glue and paint. We propose addressing these gaps through frameworks comparable to REACH for environmentally critical processes and trace material inputs, and initiating data collection campaigns led by ESA or industry authorities.

Development of Prospective LCA Methodologies

Prospective LCA for space transportation systems is crucial when looking into the ecodesign of future STS. Based on Shared Socioeconomic Pathways (SSPs) the environmental impacts of future launch systems under varying global scenarios could be explored. These scenarios allow prospective LCA to evaluate the environmental performance of rockets in the context of broader societal trends, helping industry stakeholders anticipate challenges and design systems that align with future global priorities while addressing environmental sustainability.

Managing Uncertainties in Ecodesign Data

Handling uncertainties and variability in data quality is crucial for effective Ecodesign. One suggested approach was to introduce confidence levels or margins to account for uncertainties, albeit without full quantification. Uncertainties in Ecodesign data can arise from multiple sources, such as variability, model uncertainty, data gaps, and scenario assumptions. Variability refers to natural fluctuations in data, such as resource availability or energy efficiency variations in manufacturing processes. Model uncertainty stems from limitations in the underlying mathematical models used to predict environmental impacts, which might oversimplify complex systems. Data gaps, including incomplete datasets or missing information about material sourcing or supply chains, can lead to assumptions that reduce reliability. Scenario uncertainty arises when future developments, such as technological innovations or policy changes, deviate from anticipated trajectories. To manage these types of uncertainty, integrating probabilistic methods, sensitivity analysis, and scenario-based modelling can enhance the robustness of Ecodesign strategies, providing a more comprehensive framework for decision-making.

2.3. Potential Ecodesign implementation approaches

We identified specific application areas for Ecodesign within STS, focusing on material selection and mass reduction in vehicle structures, which directly influence production impacts. Designing reusable components emerged as an essential strategy to extend component lifespans and minimize waste , while we must acknowledge that the relative climate impact (absolute impact per kg of payload sent) might be worse for a reusable launch system compared to an expendable one, especially when looking at the yet uncertain launch event effects. We emphasized the importance of evaluating environmental trade-offs in design decisions, such as balancing the initial cost of reusable components against their long-term sustainability benefits. Additionally, end-of-life considerations, including reusability and refurbishment or recyclability of components, are crucial to minimizing the overall environmental footprint of STS.

Global and Local Optimization Strategies

Balancing global and local optimization emerged as essential for Ecodesign in STS. A global approach ensures sustainable practices across the entire lifecycle and design elements, while local optimization addresses specific subsystems or processes with high environmental impact. Transitioning from traditional Ecodesign to a circular economy model - emphasizing resource reuse, repair, and recycling - can significantly reduce resource depletion across the lifecycle of space technologies.

Assessing LCAs to Identify Ecodesign Potential

We reviewed existing LCAs to determine where Ecodesign could be most impactful. Major contributors to environmental impacts, like the core structure and propellant mass, were identified due to their energy demands. Specific stages, including assembly and the launch campaign (particularly the water deluge cooling system), were highlighted for optimization to reduce environmental impacts.

High Level Design Choices

The environmental impact of a STS is heavily influenced by early high-level design decisions, such as the selection of engine cycle, propellants and reuse strategies. However, the presence of substantial uncertainties in LCIA, particularly regarding the atmospheric effects of launch events, prevents the establishment of universally applicable design guidelines.

A key question is identifying the primary hotspots: Are the main impacts driven by the dry mass (e.g. manufacturing or logistics) or by the wet mass (e.g. propellant production or the launch event itself). This analysis is further complicated by the fact that the dominant hotspot may vary depending on factors like the propellant type and, if applicable, the recovery mode. Additionally, optimizing engine cycles (fuel rich versus oxidizer rich precombustion, mixture ratio) can reduce emissions and enhance STS sustainability. Careful evaluation of these variables is critical to understanding the trade-offs and optimizing the environmental performance of STS designs.

Opportunities in Dry Mass Production

Dry mass production, which includes structural and material components, presents significant Ecodesign opportunities while also bringing performance benefits. We focused on selecting materials with lower environmental impacts and optimizing structures to reduce weight. Reusing structural components, as demonstrated by SpaceX’s Falcon rockets, can further minimize some but not every environmental impact. Strategies such as optimizing the geographical sourcing of materials, reducing waste in manufacturing, and enhancing recyclability are essential steps for sustainable production over multiple launches and lifecycles.

The materials and structure of a spacecraft influence its ablation products. Therefore, design choices can directly impact the type and quantity of pollutants released upon re-entry. We suggested exploring design strategies that minimize pollution, including using non-demisable materials. Effective prevention strategies could help reduce the atmospheric and environmental impacts of re-entry. However, more research is needed to fill this important methodological gap and be able to suggest effective prevention strategies.

Addressing Environmental Impact of Propellant Production

Propellant production is a major environmental concern due to its high energy demands, emissions, and leakage risks. Especially for reusable systems they have a significant impact. We discussed developing new propellants with lower greenhouse gas emissions, like bio-propane, though these require additional testing. Reducing propellant mass, and addressing leakage during production and storage were identified as practical steps for lowering emissions.

Optimizing Launch and Re-entry Trajectory

Launch events present unique Ecodesign challenges due to high emissions and atmospheric impacts. We suggested optimizing trajectories to minimize time in sensitive atmospheric layers (e.g. ozone layer), which could reduce rocket emissions' impact. Considering timing (day versus night, seasonal factors) may further mitigate environmental impact, though more research is needed. While alternative launch methods, like spin launch or airplane launched rockets, were discussed, we concluded that optimizing conventional launches and re-entry paths offers more immediate and realistic sustainability benefits.

Adopting a Circular Economy Model in STS

Transitioning to a circular economy is a promising approach to increase sustainability in STS. We discussed implementing practices like refurbishment, reuse, and recycling to extend the lifecycle of STS parts. The "Nine R's" framework supports a circular economy and aligns with long-term sustainability goals. We also explored repurposing upper rocket stages in space and extending the usability of components like computers to minimize waste and environmental impact. For stages or parts that cannot be returned to Earth, in-orbit refurbishment or repurposing was suggested. Such initiatives align with a "blue economy" mindset, where resources are managed for sustainably in space. However, a significant regulatory challenge is ensuring that reused materials or components do not compromise safety standards. Collaboration with international regulatory organisations, such as the United Nations, would be essential to ensure adherence to safety and sustainability protocols for in-orbit resource use.

Leveraging Advanced Technologies in Ecodesign

Advanced technologies, such as artificial intelligence (AI), can enhance data analysis and potentially support Ecodesign processes in STS in the future. AI can streamline LCA data management, interpret complex environmental information, and optimize design parameters in real-time. While AI has limitations, such as requiring large data sets that currently do not exist and the risk of overly optimized, non-sustainable designs, integrating it potentially with Ecodesign tools can improve decision-making and help achieve environmental goals efficiently in the future.

Reducing Infrastructure Environmental Impact

Ground infrastructure, particularly cleanrooms and testing facilities, contributes to STS's overall environmental footprint. We discussed minimizing cleanroom emissions and reducing nitrogen use in thermal testing as practical steps to lower the environmental impact of ground operations. Optimizing infrastructure design is an essential part of an integrated approach to Ecodesign in STS.

2.4. Implementation of atmospheric impacts into LCA

One focus of the workshop was on the integration of atmospheric impact assessments in the LCA process for space technologies, highlighting both the challenges and necessary steps to achieve reliable and actionable insights. Discussions centred on understanding global warming potential (GWP) and ozone depletion potential (ODP) metrics, improving data for atmospheric impact assessment, addressing current data gaps, and fostering international collaboration. These elements are critical for implementing effective Ecodesign in space transportation systems and mitigating the environmental impact of aerospace operations. A joint session with the three working groups was held to understand the interfaces and the work to be done with this objective in line.

Implementing Atmospheric Impacts into LCA

To integrate atmospheric impacts effectively, an ideal LCA approach that characterizes emissions by species, altitude, and other relevant factors is needed. We also discussed about the required developments of atmospheric models, which is addressed in Chapter 5. A key question was whether to introduce new indicators or integrate these impacts within existing GWP and ODP metrics. Some participants argued for a new indicator, while others questioned the need, considering there are already 16 primary environmental indicators in use. There was general agreement that research should focus on aligning atmospheric impacts with existing metrics to avoid overcomplicating the LCA framework. However, this is not always possible, especially when it comes to basic research of atmospheric impacts and effects. Therefore, the uncertainties need to be addressed sufficiently. Additionally, understanding short-lived atmospheric effects, such as contrails in aviation, was discussed as these have large, albeit temporary, impacts. Addressing timescales - from hours to centuries - is critical for a comprehensive atmospheric impact assessment. We noted that the current trend focuses on emissions per altitude, represented simply as a flow. However, for a more precise assessment, specific characterization factors should be defined, accounting for different altitudes and atmospheric conditions. Another question arises regarding the limit of the atmospheric impacts. Although the Homopause seems to be a sufficient boundary, emissions from higher altitudes might fall back to earth and integrate into the atmosphere.

Understanding GWP and ODP Metrics

A significant part of the workshop was dedicated to discussing GWP and ODP derivation and their relevance to space missions. Participants emphasized the complexity in calculating these metrics due to variations in altitude, seasonal factors, and chemical interactions in the atmosphere. For GWP, there are several calculation methods, each with distinct time frames (e.g., GWP20, GWP100), sources, and assumptions, which can lead to variations in results. These discrepancies underscore the need for standardized approaches tailored to specific atmospheric conditions encountered during launches.

There is also the challenge of calculating GWP for pollutants like e.g. aluminium oxides and nitrogen oxides (NOx), which are not greenhouse gases but potentially significantly impact the atmosphere chemistry and radiative forcing. To establish more accurate metrics, GWP confidence for those emissions must be improved by considering altitude, season, and background chemistry, although GWP itself is traditionally tailored for greenhouse gases, not aerosols. For ODP, similar issues arise, and there is a call for better-defined derivations, potentially through climate models or faster parametric approaches. The consensus was that using established sources like the Intergovernmental Panel on Climate Change (IPCC) reports is advisable, as these provide reliable data on greenhouse gas impacts across different scenarios.

Identifying Current Data Gaps

A substantial barrier to effective atmospheric impact assessment in LCA is the lack of comprehensive data on emissions and their effects across different atmospheric layers. Participants highlighted that while there is knowledge of propellant loading, launch numbers and basic trajectory information, gaps remain in data regarding emitted species (primary and secondary), black carbon production, particle size, and their distribution and lifespan across atmospheric layers.

These data gaps hinder accurate impact assessment, as understanding both the size and lifetime of emissions is crucial for predicting their atmospheric effects. To address these, the workshop recommended focusing on collecting data on emitted species, especially from the afterburning phase, and on understanding their behaviour across different atmospheric layers.

Closing Data Gaps: Approaches and Collaboration

To bridge these gaps, the workshop proposed several strategies, including conducting ground tests on engine test benches under controlled conditions, where emissions can be measured across a variety of propellants, altitudes, and times (e.g. day vs. night). These tests could be carried out at facilities like Lampoldshausen or Vernon, where specific campaigns could be designed to simulate real launch conditions.

A collaborative approach with international organizations such as NASA and JAXA was recommended to unify measurement standards and data-sharing protocols. An existing working group by the European Science Foundation on spacecraft reentry could serve as a model or foundation for broader international cooperation on atmospheric impact assessment. Such collaboration would facilitate knowledge-sharing and potentially streamline regulatory requirements across agencies.

Design Impact of Atmospheric Considerations

The incorporation of atmospheric impact can have direct implications for spacecraft design. One primary design factor influenced by atmospheric impacts is the final mass of the STS, as lower mass can lead to reduced emissions. Furthermore, optimizing propellant choice and developing engines that produce fewer high-impact emissions can limit negative impacts. Optimizing the combustion cycle and adjusting launch timing were proposed as further measures. Optimizing the trajectory is also essential; designers may need to consider trade-offs between trajectory performance and emissions reduction. For instance, selecting trajectories that minimize time spent in sensitive atmospheric layers could lower the ecological footprint, albeit potentially at the cost of reduced propulsion performance.

Reusable systems face particular challenges, as they generally require heavier designs and greater propellant use, which exacerbates the environmental impact of their launch event. Additionally, there is a risk of future regulations - such as those stemming from REACH standards - that could restrict the use of certain materials or propellants if they are deemed too impactful. Such potential regulations should motivate designers to prioritize low-impact materials and configurations.

Timeline for Achieving Confidence in Atmospheric Impact Values

Estimating the time frame needed to attain reliable atmospheric impact data revealed varied opinions. While some participants optimistically suggested that high-confidence values could be obtained within a year, others anticipated a timeline of one to three decades, noting that the aviation sector took over 20 years to achieve similar milestones. To expedite this process, participants advocated for substantial resource allocation and targeted PhD research initiatives, as well as structured measurement campaigns.

In an effort to outperform the aviation sector's timeline, we are emphasizing the necessity for better-organized and well-funded research efforts. The goal is to establish robust data sets and reliable metrics, providing the aerospace sector with clear guidelines to minimize atmospheric impacts within a reasonable timeframe.

2.5. Collaboration for Ecodesign

Collaboration is essential for implementing Ecodesign as a standard approach. Data sharing between OEM and contractors as well as academia and agencies is required.

Common standardized data format

A central recommendation is to establish a standardized format for data collection that can be reused across different tools and studies. Compatibility of database file formats within LCA tools is crucial to ensure interoperability and streamline the data exchange process. The management of database updates also poses challenges, as outdated or incomplete information could compromise the accuracy of LCA assessments.

To facilitate data sharing, there is a need for simple data retrieval tools for collaborators and suppliers. A digital product passport was proposed as one potential solution, where relevant product information could be stored and accessed as needed. However, questions of willingness to share data and the need for incentives remain pressing concerns. Organizations like the European Space Agency (ESA) have developed templates and online tools, yet these are not binding to the space industry.

A common suggestion was the establishment of a standardized approach, such as an ISO or ECSS (European Cooperation for Space Standardization) standard, which would define consistent protocols for data sharing and quality validation. A standardized list of data gaps, which organizations like ESA could address, would further enhance the effectiveness of these collaborative efforts. Additionally, collaborative projects between suppliers and prime contractors could target specific subsystem improvements, allowing for incremental enhancements in Ecodesign practices.

Benefits of collaboration

The workshop emphasized several benefits of collaboration, including cost-sharing and a targeted focus on Ecodesign hotspots affecting multiple systems or companies. By addressing shared challenges, organizations could reduce duplication of effort and streamline the LCA and Ecodesign processes. Furthermore, collaboration can foster a deeper understanding of Ecodesign and LCA methodologies, paving the way for the establishment of common standards across the industry. The sharing of ideas and lessons learned was also highlighted as a key benefit, with the potential to enhance the reduction potential of Ecodesign solutions and drive industry-wide improvements.

Pain points of collaboration

Despite the recognized benefits, participants noted significant pain points associated with collaboration in Ecodesign. Intellectual property (IP) concerns were frequently mentioned, as companies are often hesitant to share data that might reveal proprietary methods or competitive advantages. Limited time and resources further complicate collaboration, as many organizations prioritize short-term objectives that conflict with the long-term sustainability goals of Ecodesign. Additionally, there is a lack of training opportunities, particularly for professionals non LCA experts, which inhibits the broader adoption of Ecodesign practices. While some training programs exist, such as ESA's Clean Space Webinars, ESA Academy, EPFL Sustainability Course and specialized courses within master's programs, there remains a demand for more targeted and accessible educational resources.

Support of Ecodesign collaboration efforts

Workshops similar to the current one were proposed as an effective means for stakeholders to engage in open dialogue. Establishing a “sharing mentality” within the industry was emphasized as a critical step for advancing sustainability goals, with participants urging each other to be open to collaboration on Ecodesign hotspots. Moreover, regular touchpoints, such as remote networking events, were proposed as a means of maintaining communication and engagement within the Ecodesign community. Events like the Clean Space Days could provide valuable opportunities for industry members to share progress and challenges, reinforcing collective commitment to sustainability. A panel discussion at European conferences is further recommended to raise awareness about the need for advanced atmospheric models and encourage cross-institutional collaboration.

3. Operational Impact

3.1. Engine emission calculation and modelling

The workshop underscored the importance of a collaborative framework among academia, industry, and space agencies to facilitate data sharing and standardization regarding emissions. Shared databases managed by a trusted third party, possibly under ESA's or EC guidance, could help pool critical data while protecting proprietary information.

Modelling complex propulsion emissions remains a substantial challenge due to the diversity of engines and the need for high-fidelity data. For systems with pre-combustion stages, the workshop recommended using modular modelling techniques that allow for flexibility in adjusting to different configurations. Participants highlighted the utility of coupling object-oriented modelling with ecodesign tools to simulate complex interactions and facilitate comprehensive impact assessments.

Validation of these models against experimental data is essential. Participants recommended ground tests with different engine configurations to gather empirical data that could inform model adjustments. Collaborative research efforts across agencies and universities could help streamline this process, ensuring that validated BC models are available for broader industry adoption.

Tools for Emissions and Impact Assessment

The workshop evaluated several existing tools for assessing emissions and impacts from space systems, noting both their strengths and limitations.

Among them are chemical equilibrium solvers like NASA's CEA, Cantera, and the Rocket Propulsion Analysis (RPA) software. Those tools are fast and potentially useful for initial emission predictions, but they lack accuracy. Computational Fluid Dynamics (CFD) tools, such as RANS, LES, and DNS, allow for detailed analysis of fluid flow, combustion, and emissions in propulsion systems. High-fidelity CFD models provide greater accuracy and can account for complex multi-physics interactions but are computationally expensive and time-consuming. However, both modelling approaches are limited by their high computational demands and the lack of comprehensive validation data, especially for minor species emissions.

For complex propulsion systems involving multiple pre-combustion stages, similar methodologies as for simpler systems were suggested, though with modifications. Open-source models and shared data are necessary to create generic models applicable to various engine configurations. Additionally, coupling these models with object-oriented codes such as Modelica or Ecosim can enable flexible modelling of complex systems.

The workshop highlighted furthermore the current limitations in modelling the interaction between a rocket's exhaust plume and the atmosphere. Due to data limitations, especially regarding post-combustion thermodynamics, simple models are often insufficient for accurately simulating the dissipation of exhaust gases at high altitudes. While basic approaches can approximate shock lines in the atmosphere, achieving a nuanced understanding of pollutant dissipation and interaction with atmospheric layers requires empirical data.

Black carbon modelling

Regarding black carbon (BC) emissions, the workshop considered methods from James et al. [5] for BC estimation, which offer a first-order approximation but require further refinement. One recommendation is the development of more precise BC models, as current options adapted from aviation (e.g., the DLR-VT BC model) and CFD models for internal combustion engines, although adaptation for rocket-specific conditions remains a challenge. Establishing programs to develop a dedicated model for black carbon emissions in the space context, like the MaiaSpace collaboration on BC measurements, was suggested

Improvement of modelling

The need for data of empirical measurement was underscored, as theoretical models are currently constrained by insufficient validation. Therefore, advancing measurement campaigns to collect empirical data on nozzle exit emissions and exhaust plume behaviour in the upper atmosphere is essential. This data would enable more sophisticated modelling approaches and more accurately predict the environmental impact of engine emissions. Participants emphasized the need for a new or adapted model that can simulate the unique conditions of rocket combustion, potentially incorporating high-temperature and pressure data from test benches. Enhanced validation techniques, such as combining experimental data with simulations, were also encouraged to ensure more reliable predictions of black carbon emissions. However, given the unique combustion conditions in rocket engines, these models are currently inadequate.

Emissions database

To improve the understanding of the environmental impact of rocket propulsion, participants emphasized the need for a comprehensive emissions database (including emissions for different engines and operating conditions as well as emissions after interaction with the atmosphere for different altitudes), which would require collaboration between academia, industry, and legislative institutions. The need for accessible data-sharing platforms was discussed, as well as the importance of aligning efforts on international standards, potentially under frameworks like ISO or ECSS.

Recommendations for the database included ensuring data accessibility, adherence to FAIR data principles (Findable, Accessible, Interoperable, Reusable), and fostering synergy with existing propulsion databases. The workshop emphasized the potential of a shared database to guide policy and support research aimed at reducing environmental impacts of rocket emissions.

3.2. Reusable systems re-entry modelling and impact

During the re-entry of reusable systems different emissions occur. For STS, the currently most used technology is propulsive re-entry, which sets challenges regarding modelling atmospheric interaction of the plume during the supersonic and transonic phases along the return trajectory.

Emission Types and Their Characteristics

Emissions during re-entry include engine exhausts (primarily during retro burns), thermal NOx due to high temperatures, and particulate emissions from the ablation of thermal shielding materials. Thermal NOx generation is a direct result of high-temperature interactions, either in the plume – air interaction or where shock waves occur. This complex interaction necessitates sophisticated modelling to predict how re-entry trajectories affect emission profiles, especially under varying conditions.

For atmospheric decelerating (ballistic or lift supported) re-entries, emissions stem from surface friction and thermal shield ablation. Thermal protection systems protect re-entering vehicles either by ablating or oxidation, a process that results in emissions of particulate matter and volatile compounds. It was noted that while there is a wealth of experimental data on TPS ablation, the focus on environmental emissions has been limited. We recommend the further analysis of the aerosols generated during TPS ablation, including characterizing the types and amounts of emissions.

Cork, identified as a potential alternative material, was discussed for its sustainability and effectiveness in reducing emissions during thermal evaporation. However, emissions through thermal evaporation need quantification, as understanding the layer-wise contribution of resins, fibres, and coolants could inform eco-design improvements in TPS materials.

Tools and Models for Atmospheric Interaction and Emissions

We examined various empirical and numerical models for predicting atmospheric impacts, especially NOx emissions, associated with re-entry. While analytical models like the one from Park [6] are straightforward and provide a starting point, they lack the precision needed for complex simulations, particularly for high-altitude, high-speed re-entries. Numerical models, on the other hand, offer greater accuracy and are more adept at capturing chemical interactions, though they require more computational resources and specific data inputs.

Recommendations for Future Improvements in Modelling and Data Collection

We have a need for both experimental and theoretical quantification methods, especially since different re-entry scenarios (e.g., altitude-specific burns) could result in varied environmental impacts. There is currently a knowledge gap regarding NOx generation at high altitudes, especially where free molecular flow is not accounted for in existing models. Additionally, we suggest that further research focus on altitude-specific pollutant behaviour, as different re-entry trajectories and reusability profiles impact pollutant levels differently. We need more ground testing to verify NOx generation models and to conduct empirical studies of exhaust plumes under controlled conditions. The suggestion to use re-entry vehicles as a baseline for environmental impact assessments was also made, given their routine exposure to extreme atmospheric conditions.

3.3. Measurement of emissions

To get a better understanding of the occurring impacts and a validation of models, we recommend targeted studies should focus on specific pollutants at varied altitudes, examining how emission levels change with altitude and whether emissions from launch, re-entry and landing burns are more significant at lower or higher altitudes.

Measurement Needs and Challenges

We identified the importance of precise measurements both at the nozzle exit and after the interaction with the atmosphere to better understand and mitigate emissions from rocket propulsion systems. Accurate measurements of principal species, minor species, pollutants, and black carbon are necessary for building reliable emission models. However, the high cost of measurement systems and the technical challenges associated with in-flight measurements limit current capabilities. The use of subscale experiments was discussed as a possible approach to cost-effectively gather data that can be extrapolated to full-scale systems. Remote diagnostics from the ground and indirect measurements were identified as potential methods to complement direct measurements, especially when in-flight measurement is impractical for higher altitudes. A recurring point was the need for European initiatives to fund a public database for measurement data from emissions campaigns.

Tools and Techniques for Emission Measurement

The workshop explored various intrusive and non-intrusive methods for emissions measurement. Intrusive methods include gas probes, in-flight measurements and mass spectrometry, while non-intrusive options include satellite observations, and spectroscopy of plumes. Ground-based measurements at rocket engine test facilities can provide useful data, with possibilities for altitude simulation in controlled environments. Intrusive methods provide detailed data on specific gases but may interfere with the engine’s operation. Non-intrusive methods allow for more remote data gathering without direct impact on the propulsion system but may lack resolution or face challenges in measuring specific species or particles in a complex exhaust plume.

Practical Applications and Future Directions

To develop a measurement-based database on European launcher emissions, it is estimated that 3-5 years will be required to adapt instrumentation and establish a robust ground measurement technique. This timeline is inversely proportional to the level of funding available. The development of flight-ready instrumentation packages for in-flight testing is currently uncertain but is a critical next step. Projects like FIREWALL are a good example of this. Cross-propulsion synergies were identified as an area to streamline development, allowing shared instrumentation across various propellant and engine types.

High-Altitude Emissions and Measurement Techniques

The impact of emissions at high altitudes was another focal point. Participants discussed the use of remote sensing platforms such as drones, balloons, and satellites for high-altitude data collection. High-altitude emissions, such as NOx production at mesospheric levels, were considered particularly significant due to the limited understanding of their atmospheric interactions. To advance high-altitude measurements, we recommend developing specialized instruments capable of operating in these environments, including lightweight spectrometers and remote gas analyses. Additionally, using aircrafts and sounding rockets for in-situ measurements within the plume were proposed as means to gather more detailed data on high-altitude interactions.

Local Environmental Impacts of Launch Emissions

The environmental consequences of rocket emissions need to be examined on both local and global scales. Immediate local impacts, such as air quality degradation, water contamination, and acoustic disturbances, are normally not assessed as well as the global effects. The deposition of unburned hydrocarbons, chlorine and other chemical residues around launch sites was noted as a particular concern for soil and water quality.

We therefore recommend more comprehensive environmental assessments around spaceports, including regular monitoring of soil, water, and air quality. Additionally, we need more environmental protection measures at launch site operations, including spill containment strategies and soundproofing initiatives to mitigate acoustic impact.

4. Demise impact

4.1. Re-entry debris development and data availability

Data Sources for Re-entry Events

Identifying and analysing existing data sources is critical for gaining a comprehensive understanding of the atmospheric impacts of spacecraft re-entry. Databases such as the McDowell Database, NORAD (space-track.org) and ESA’s DISCOS provide data, including re-entry parameters for upper-stage components. They offer time, location, and mass information. These resources are useful for understanding the distribution and behaviour of objects prior to re-entry. However, these data do not cover all re-entries and upper stages leaving data gaps in the assessment of the impact. Additionally, we suggest that demise reports become mandatory to improve transparency in space operations.

Tools for Modelling Re-entry Demise

Various tools are available to model the demise of space transportation vehicles, each with specific strengths and weaknesses: Tools like TITAN, DRAMA, SCARAB, and ORSAT allow researchers to simulate different impact scenarios, taking into account ground and atmospheric effects. These tools enable analyses of where and how components might reach the ground, as well as the mass loss due to re-entry in the atmosphere. However, they are conservative regarding the ground impact and might therefore underestimate the atmospheric impact. Traditional impact assessments focus on ground impact results, but expanding these tools' scopes to include atmospheric impact and partial disintegration could yield more realistic outcomes. The demise of objects depends significantly on fragment size, with larger objects potentially posing more considerable safety risks. Understanding the fragmentation limits, such as the smallest stable size in the atmosphere, informs models on what particles will remain or burn up.

Improvement of Tools for Ablation Modelling During Re-entry Demise

A model for heat input and output during re-entry is critical to understanding how materials fragment and ablate. Accurate modelling of radiative heating and cooling could help predict fragmentation patterns.

Understanding the ablation process and the emissions produced during re-entry is crucial. Ablation, which involves the gradual erosion of material from spacecraft surfaces due to intense heat and friction, leads to the release of emissions. This process needs thorough investigation to predict re-entry outcomes accurately. Data on re-entry events for upper rocket stages are limited. Access to this information could improve modelling and help predict the behaviour of various materials and structures upon re-entry. This area remains relatively unexplored but is essential for environmental assessments. Determining in which segments of the re-entry trajectory ablation is most likely to occur helps refine models and predict when and where materials will disintegrate. There is a balance between designing spacecraft for high demisebility (to minimize debris risk) and mitigating atmospheric impact. Zero-debris designs are challenging, but efforts must focus on minimizing the risk to the atmosphere and ground impact areas.

Material Data for Rocket Bodies

Obtaining material data for rocket bodies is crucial for predicting how objects disintegrate upon re-entry. However, this data is often proprietary or incomplete. We discussed possible approaches to improving access to material data: Environmental reports provide some information, but they involve approximations. Requesting data from manufacturers may occasionally yield useful material data, but there is no guarantee. Scientific literature, such as aerospace studies, can serve as a secondary resource for material information on launch vehicles. However, these are often indirect sources and might not reflect the exact materials used in all space vehicles.

Suggestions were made to impose legal requirements for disclosing material information to regulatory bodies or international organizations, such as the United Nations.

Learnings from Meteoroids

Understanding the ablation of meteoroids can provide insights into the disintegration processes of spacecraft materials during re-entry, though the entry parameters of meteoroids largely differ from spacecraft. Micrometeoroids, which do not melt and are typically micron-sized, offer a natural comparison for understanding the limits of re-entry fragmentation. This insight suggests a similar behaviour for small fragments from artificial objects, potentially persisting without ablation.

4.2. Modelling Emissions and Impacts from atmospheric demise

After discussing the data sources for the estimation of mass of emissions, we identified the various by-products of atmospheric demise, including particles and gases released as spacecraft materials burn up upon re-entry. The release of certain emissions, such as different metals and metal oxides , occurs rapidly as materials combust at high altitudes. There might also be secondary emissions due to yet unknown chemical reactions. Furthermore, carbon dioxide (CO_2), carbon monoxide (CO), and various hydrocarbon residues as well as black carbon (BC) could result from incomplete combustion formation from CFRP structures. These compounds could have environmental impacts, including possible increased cloud formation, destruction of ozone and radiative forcing. One point of concern is the nitrous oxide formation due to heating during re-entry.

Atmospheric Interaction of Re-entry Vehicles and NOx Emissions

A significant area of discussion involved the interaction of re-entry vehicles with the atmosphere, especially regarding the production of nitrogen oxides (NOx), Re-entry plasma and wavefields produce high temperatures that lead to the formation of nitrogen oxides. These emissions are concerning due to their role in ozone depletion and air pollution. Larger objects and those with high ballistic coefficients produce more NOx, as they have greater mass and heat generation potential during re-entry.

Tools for Modelling Ablation Emissions

To analyse emissions, multiple computational tools and approaches exist, each with unique capabilities and limitations. The NASA CEA (Chemical Equilibrium with Applications) solver was identified as a useful tool for simulating combustion and ablation chemistry during re-entry. However, participants noted its limited ability to handle dynamic, non-equilibrium conditions typical of re-entry.

Tools like SAMj, PAMPERO, TITAN, and SCARAB allow for ablation and thermochemistry simulations providing initial estimates of mass loss and pollutant distribution based on the height and speed of re-entry. However, there is a consensus that these tools require improvements in fidelity and observational validation, to accurately simulate complex re-entry processes. Current research into advancing thermochemistry models aims to increase the fidelity of re-entry simulations. Accurately modelling the chemical processes in the re-entry plume is crucial for understanding the pollutant profile released during ablation.

Recommendations for Enhancing Models

Models need to account for more complex physical interactions, including atmospheric dissociation, turbulence, and changes in flow characteristics during breakup. Adding wave chemistry would also help refine predictions for how materials behave and degrade during re-entry. Comparing existing models with observed data is essential to validate and refine predictions.

Particle Size and Circulation and Deposition Cycles modelling

There is a need for parameter studies to understand how particles of different sizes are transported in the atmosphere. Sedimentation is a crucial factor, as particles eventually settle based on their size and density. Larger particles sediment faster, reducing their atmospheric lifetime, while finer particles may persist longer, particularly in the stratosphere. Global atmospheric circulation, such as the Brewer-Dobson cycle, move particles across atmospheric layers, influencing their deposition.

In assessing how long particles and emissions persist in the atmosphere and potentially can interact chemically and radiatively, the size distribution of particles is therefore a fundamental factor in understanding atmospheric and environmental impacts.

Post-Re-entry Particle Atmospheric Interactions

High-altitude emissions undergo complex interactions with the atmosphere. Key processes include mesospheric chemistry, transport to stratosphere heights, coating and catalytic reactions. Particles transported into the stratosphere may be coated with sulfuric acid in the Junge layer, altering their chemical impact. This process probably slows deposition, extending the atmospheric lifetime and altering the particles' optical and radiative properties. Certain particles may catalyse chemical reactions in the atmosphere, potentially affecting ozone or other essential components of atmospheric chemistry. Understanding these catalytic effects is crucial for assessing long-term environmental impacts. As particles from re-entry accumulate, they may shift atmospheric equilibrium. Long-term studies are needed to evaluate how continuous re-entry activities might alter chemical balances in these layers.

Recommendations for Model Enhancement

There is a need to improve models at high altitudes where free molecular flow dominates. This knowledge gap limits the accuracy of existing models, as high-altitude conditions are not fully considered. Many tools require additional data inputs and computational resources to handle the full range of re-entry conditions. There is also a need to integrate ablation models with atmospheric chemistry and dispersion models, which is challenging given current limitations in data and model fidelity. Developing methods for quantifying the uncertainty in predictions is vital for risk assessments. This would involve evaluating potential errors in numerical models and improving their robustness across different re-entry scenarios.

We emphasized the importance of validation through code-to-code comparisons, experimental tests, cross-referencing models, and most importantly observational validation. Verification ensures that models reliably replicate observed phenomena and can be trusted for policy and design decisions. Obtaining accurate measurement data is essential for validating and refining models. Data from laboratory experiments, flight tests, and remote sensing of re-entry events can provide ground truth for model calibration.

4.3. Measurement of emissions from re-entry

Evaluating past re-entry events using models can highlight discrepancies and suggest areas for improvement. We suggest new methods for gathering data on re-entry processes, including LIDAR, balloon observations, sounding rockets, and satellite-based measurements. Remote sensing technologies, such as those installed on aircraft, could also offer data on re-entry particles and emissions [7]. Observing the characteristics of decaying plumes from re-entering objects could enhance understanding of emission impacts in the upper atmosphere.

Measurement Approaches

Accurate assessment of emission species requires both qualification (identifying pollutant types) and quantification (measuring pollutant concentrations). Measurements of emissions from re-entry tackle a challenge due to timely and spatial restrictions. In the following, three different timely approaches are discussed.

Event-Based Approach

This method involves planning measurements around specific re-entry events, allowing for detailed knowledge of the object and expected emissions. Advantages include a large, identifiable signal and comprehensive data collection opportunities. However, it requires significant planning, and uncertainties remain regarding the exact re-entry time and location.

Coincidental Approach

This approach involves analysing existing data that might have captured re-entry events by chance. It is less resource-intensive and leverages large data sets, but instruments may not be tuned specifically for re-entry detection, reducing data accuracy and specificity.

Surveillance Approach

This method involves continuous monitoring and collecting data over time. While it can generate vast amounts of data, it requires substantial resources and time to analyse, posing challenges for real-time application.

Furthermore, we examined different measurement methods regarding special approaches.

Ground based measurements

Techniques like LIDAR, radar, emission spectroscopy, test facilities and camera-based observations as well as particle detection on ground were proposed. These methods can measure aerosols and certain elements or compounds from a distance, making them useful for observing high-altitude emissions over broad areas.

LIDAR technology is effective for detecting particle sizes and concentrations, which is crucial for understanding the radiative and transport properties of re-entry aerosols. It can detect aerosol clouds formed post-ablation, offering insight into the dispersion and size distribution of particles. LIDAR is valuable for high-altitude monitoring but is limited by spatial coverage.

Measuring elements and particles that eventually settle in the Arctic regions due to atmospheric circulations can provide indirect data on high-altitude emissions (Murphy et al. 2023 [7]). This technique can help track long-term environmental impacts and pollutant dispersion patterns.

Simulating ablation in controlled settings, such as plasma wind tunnels, can provide data on particle formation and distribution. These experiments help create predictive models for in-flight ablation processes. Emission spectroscopy can detect and analyse gases released during re-entry. This technique is valuable for identifying the composition of volatile emissions and assessing their potential environmental impact.

Space-Based Measurements

Instruments mounted on satellites, such as spectral sensors, can directly detect and analyse emissions from re-entering objects. Additionally, recovered space hardware can offer valuable insights into material composition post-re-entry.

In-situ Techniques

This category includes the use of stratospheric balloons, sounding rockets, and satellite dipping or re-entry experiments. These methods allow for the direct collection and analysis of emissions and particles at specific altitudes, providing high-fidelity data on the composition and concentration of re-entry pollutants.

Launching balloons up to 40 km altitude to capture emissions was proposed. These balloons can gather data in the upper stratosphere, providing insight into emissions in near-space conditions.

Sounding rockets can capture direct particle samples in the atmosphere shortly after re-entry events. These samples help assess background vs. event-specific emissions and understand particle size and composition. However, shock waves could affect the accuracy of particle size detection, introducing challenges to direct applications in re-entry studies. Additionally, the timing and spatial accuracy needed might be an insurmountable technical challenge.

Missions where satellites briefly dip into lower altitudes to take in-situ measurements could be valuable. These missions could allow for direct measurement of re-entry emissions and plume behaviour at altitudes closer to the re-entry trajectory. However, very low dipping (such as 80 km) might be technically infeasible.

Developing sensors capable of surviving and measuring emissions within a re-entry plume (e.g., Draco-type mission) was suggested. These sensors would need to withstand extreme temperatures and pressures, capturing data in real-time as objects break up.

Observational methods used for meteoroid entry, which share similarities with space object re-entry, are noted as potential approaches. These methods could provide baseline data and techniques for observing high-velocity atmospheric entries.

Establishing a Measurement-Based Database

The final step would be to create a database for re-entry emissions. Developing a database requires a clear understanding of the available data as well as the types of measurements necessary to build a comprehensive emission profile. Creating a complete database immediately might be infeasible due to the diverse measurement types and conditions. A phased approach could start with simpler measurements and gradually incorporate more complex data as technology and methodologies advance. Initially, the database could focus on major pollutants, such as metal oxides, to capture primary emission types. As more data becomes available, additional pollutants and environmental factors could be included.

4.4. Further Impact from demise

Although our main focus lies on the atmospheric impact of demise, we would like to also address other impacts from spacecraft demise currently posing a knowledge gap.

Impact on light pollution

Another concern raised was the potential for re-entry events to contribute to light pollution. The rising number of re-entering reflectivity of satellite components and the release of aerosols could impact nocturnal light levels and disrupt astronomical observations.

Impact on aviation

An example of an airspace closure due to a potential Chinese upper stage re-entry over Spain and the continuous rising number of launches also raises the question on the impact of launchers on aviation. Both re-entry events, which are not always predictable in a sufficient manner, and a rapid unscheduled disassembly during launch pose a risk. Closing airspaces might lead to longer flight routes and therefore a higher impact of aviation.

Toxic Elements

Emissions of toxic substances, such as beryllium oxide (BeO) and hydrazine (N_2H_4) and potentially further unknown ones, are of particular concern due to their harmful effects on human health and the environment. These chemicals are often components of space system fuel systems or structural elements and pose a unique hazard upon demise. Examining the toxicity of materials commonly used in space vehicles provides baseline data for assessing environmental risks. Understanding the potential for toxicity, especially when materials interact with land or marine ecosystems, supports policy and design recommendations.

Impact of Demise at Land

Fuel residues, such as hydrazine, or combustion residues can be hazardous and pose significant environmental risks if they survive re-entry and land on populated areas. Though the probability of land impact is low, the toxicity of such substances calls for effective mitigation measures.

Physical Impacts

One of the most addressed hazards in the past, the potential for harm increases with a rise in launch attempts if larger fragments reach the ground intact. Although most materials ablate in the atmosphere, the sheer volume of re-entries increases the likelihood of terrestrial impacts over time.

Radioactive material

Certain spacecraft include radioactive sources, which, if they survive re-entry, could pose severe environmental and health risks. Policies to address these risks are necessary, especially for future satellite designs.

Impact of Demise in Oceans

Demise over oceans poses different challenges than land impacts, but it is significant due to the potential scale of impact:

Dilution in Oceans

Pollutants such as metals and combustion products might be diluted by oceanic water, reducing their immediate toxicity. However, repeated inputs could accumulate, impacting marine ecosystems over time.

Floating Debris

Components like fuel tanks or carbon fibre-reinforced polymers (CFRPs) may float, potentially interfering with marine traffic and ecosystems. Persistent debris poses a long-term hazard, as it resists breakdown in oceanic conditions.

Combustion Products

The environmental effects of combustion products on ocean chemistry were noted, particularly regarding dissolved toxic compounds. Monitoring these impacts requires understanding the chemical transformations these materials undergo in marine environments.

Quantifying the Environmental Impact

Calculating the mass and location of impacts, along with comparisons to natural or anthropogenic emissions, helps contextualize the environmental influence. By understanding the scale of mass input, researchers can better predict long-term effects.

5. Implementation of Launch and Re-entry Emissions in Atmospheric Modelling

Implementing launch and re-entry emissions into atmospheric modelling is currently facing significant challenges that we would like to highlight here.

Desired Outputs of Atmospheric Models

When talking about the simulation of atmospheric effects of space transportation systems emissions we need to look at different desired outputs. We have to keep in mind that not all of them can currently be fulfilled by state-of-the-art models.

Local Atmospheric Composition Changes

Understanding how launch and re-entry events alter local atmospheric composition, particularly in the higher layers of the atmosphere as well as the ozone layer, should have a primary focus. This includes tracking emitted metals and gases and their potential to alter atmospheric chemistry.

Radiative Forcing and Climate Impact

In light of the challenging climate crisis, we would like to highlight the importance of calculating radiative forcing from launch and re-entry emissions, including how these effects vary by altitude and over time. This information would help in assessing the broader climate implications of spaceflight activities. We suggest to integrate this emission into existing IPCC Representative Concentration Pathways (RCP) scenarios as well as IPCC reports to gauge their climate impact

Ozone Depletion

Assessing the potential for launch and re-entry emissions to deplete stratospheric ozone was highlighted as a critical concern, not only by the WMO. If no further understanding of these effects is targeted, we could potentially destroy the efforts we achieved with the Montreal protocol. Emission species like metal oxides, black carbon and further potentially yet unknown compounds could catalyse reactions that degrade ozone, also leading to increased UV radiation at the surface.

Particle Residence Time and Deposition

Knowing how long particles remain in the atmosphere and where they eventually settle is essential for modelling the transport and environmental fate of emissions. For this, detailed information on the type and size of particles is needed first.

Cloud Formation and Precipitation Effects

The influence of launch and re-entry emissions, particularly descending metals, on cloud formation and precipitation patterns was noted as a significant area of inquiry. Studies highlighted a potential link between Shuttle launches and mesospheric cloud formation. Stratospheric clouds, playing a significant role in ozone depletion are currently also not well understood.

State of the art atmospheric model types

Chemistry-Climate Models (CCM)

Models like EMAC (ECHAM/MESSy), NASA GEOS, and the Whole Atmosphere Community Climate Model (WACCM) are capable of simulating climate-relevant chemistry processes across different atmospheric layers. These models handle conservation equations, grid cells, wind calculations, and atmospheric composition. Chemistry-climate models offer high-resolution ability to resolve complex atmospheric processes, and capacity for comprehensive simulations across large spatial and temporal scales detailed simulations but are computationally demanding, have a lower spatial resolution (100 km horizontal), and regarding sensitivity to small perturbations, chaotic to small changes which requires averaging across multiple simulations to derive stable results.

Chemistry Transport Models (CTM)
Models like GEOS-Chem, CLAMS, and SlimCat simulate the transport of pollutants based on wind patterns, with less computational complexity than CCMs. CTMs are suitable for simulating pollutant dispersion, although they may lack detailed chemical interactions. CTMs are less computationally expensive, and are suitable for small perturbations like those from individual launches, and can provide quick estimations of pollutant transport. However, they have limited applicability for modelling cloud formation or detailed coupling mechanisms, and lower precision for intricate chemical interactions and are less precise for small-scale perturbations.

Simplified climate models
In addition to the two presented large atmospheric models, also simplified models exist. They offer mostly linear dependencies or are based on the results of multiple CCM or CTM calculations.

Multi model approach

Utilizing multi-model comparisons to improve confidence in environmental impact estimations was proposed. Such comparisons could help validate results and improve the robustness of sector-specific impact estimations.

Development of Emission Inventories

For a sufficient implementation and simulation of launch and re-entry emissions and their impacts we need to comprehensive real data-based emission inventories including uncertainties from launch and re-entry events, as these inventories would support more accurate modelling efforts and facilitate the tracking of cumulative impacts. Information on the spread, altitude, and timing of emission plumes is essential to accurately simulate the behaviour of emissions in atmospheric models. Furthermore, particle size distribution is required for aerosols. Developing 4D emission (Latitude, Longitude, Altitude, Time) inventories has now started and first databases were released. However, these mostly rely on assumptions and do not represent a complete real data model. Establishing best practices for incorporating launch and re-entry emission databases and their implementation into atmospheric models could enhance the reliability of simulations and facilitate collaborative research efforts.

Required Developments for Modelling High-Altitude Emissions

Most atmospheric models are sufficient for calculating the impact up to the lower stratosphere where aviation emissions occur. However, as launchers are the only human designed objects that emit to every atmospheric layer, the extension of the models is required. Numerical models for high-altitude emissions further are challenging to validate due to limited observational data. We therefore suggest developing experimental facilities to test and validate specific aspects of these models, potentially using scaled-down simulations. Participants suggested agencies like the European Research Council (ERC) and Horizon Europe (HEur) as potential funders.

Atmospheric Chemistry of New Elements

The introduction of new elements and compounds into the atmosphere from launch and re-entry necessitates refined models that can account for new reactions and catalytic effects in atmospheric chemistry. For instance, metal oxides and other potentially unknown compounds could alter ozone chemistry, which must be integrated into model assumptions. Understanding how metals and other particles from launch and re-entry interact with atmospheric layers, including potential catalytic effects on atmospheric chemistry, was identified as a priority. Furthermore, impacts that change the atmospheric conditions like season, day/night, solar cycle phase, and magnetic conditions affect atmospheric reactivity and transport and thus should be factored into emission simulations. Expanding aerosol models to include particles like aluminium oxide and black carbon is essential.

Temporal and Spatial Scales

Either when capable of simulating the local and global emissions of space transportation systems we need to develop models that can simulate the transition effectively between near-field (local launch/re-entry events) and far-field (global atmospheric changes) that are essential to capturing the impact of launch and re-entry events accurately. Factors such as buoyancy, ambient air entrainment, wind shear, and solar radiation absorption were discussed as critical influences on plume behaviour. Models need to account for both short-term local effects (e.g., within days of launch or re-entry event) and long-term global dispersion. However, current models may struggle with spatial scales between 200 meters and 10 kilometres, as well as temporal spaces between a few minutes and days, which are relevant to tracking the spread of re-entry plumes.

6. Conclusions

The whitepaper summarises the outcomes of the workshop held at the University of Stuttgart. The integration of Ecodesign into STS presents a promising pathway toward minimizing the environmental footprint of aerospace activities. Central to Ecodesign is the concept of embedding sustainability at the earliest stages of system design. This early-stage integration allows designers to influence decisions that affect the entire lifecycle, leading to optimizations in material selection, mass reduction, and waste management. Crucially, developing “ecodesigned” system options by Preliminary Design Review (PDR) helps to ensure that sustainability objectives are deeply embedded into the design phase.

Implementing quantitative targets in Ecodesign, such as specific KPIs around emissions, mass, and efficiency, will provide measurable benchmarks that drive continuous improvement across the lifecycle of STS components. Tailoring these targets to different system types - expendable vs. reusable - ensures that design choices are relevant to each system’s environmental impact profile. For instance, reusable systems demand durable materials and minimise in-flight emissions, while expendable systems benefit more from a reduction in disposable mass and eco-friendlier disposal.

A centralised repository that aggregates Ecodesign knowledge would empower designers across organisations with a standardized knowledge base. This collaboration would reduce redundancy, accelerate the adoption of best practices, and support incremental improvements in Ecodesign across the space industry. Given the proprietary nature of much aerospace data, balancing transparency with confidentiality through “black box” systems or compensated data-sharing could incentivize broader participation while protecting competitive advantages.

In addressing data gaps, enhancing LCA databases with space-specific environmental indicators will provide a stronger foundation for Ecodesign efforts. Particularly, expanding metrics around atmospheric impact will aid in aligning space missions with broader environmental policies. Collaboration across academia, industry, and regulatory bodies will further facilitate improvements in model accuracy, especially around emissions, by providing more empirical data.

The workshop's findings reveal significant advancements to the earlier workshops in developing a pathway in understanding the environmental impact of space transportation systems. To fully assess the operational impact of rocket engines and re-entry activities, a multi-tiered approach that integrates robust modelling, comprehensive databases, and precise measurement techniques is essential. Collaborative frameworks play a foundational role by encouraging data sharing across academia, industry, and agencies. Establishing shared public databases under the guidance of organisations like ESA or European Commission fosters a cooperative environment, supporting standardised methodologies while safeguarding proprietary data. This cooperative model, following FAIR data principles, not only aligns industry practices but also accelerates emission-reduction initiatives.

Black carbon emissions, a significant impact by-product of combustion, present unique modelling challenges due to the distinct combustion environment within rocket engines. While methods adapted from aviation offer a preliminary framework, dedicated space-focused models are necessary for accurate BC estimations. Experimental validation, such as ground tests of various engine configurations, provides critical data to refine these models. By simulating exhaust plume interactions in controlled environments, the industry can achieve more reliable predictions of BC emissions across different propulsion stages.

For those multiple techniques are possible, on the one side propulsive re-entry techniques, which involve retro burns or, on the other side, aerodynamic re-entries relying on lift generation and high-temperature thermal protection systems (TPS). Both of them produce thermal NOx and possibly particulate emissions. This underlines the need for specialised models that can capture emissions from both high-speed re-entry and surface ablation. Materials like cork offer promising alternatives for TPS design due to their potential for lower emissions; however, further research is required to quantify their environmental benefits, especially at the particulate level.

Measurement techniques are crucial for validating these models, and the workshop highlights the need for in-situ and remote sensing methods to capture data at varied altitudes. High-altitude emissions, such as those from mesospheric NOx production, pose particular challenges due to limited in-flight data. Using a combination of ground-based measurements, drones, and sounding rockets for in-situ measurements would provide high-fidelity data essential for calibrating models and improving emission estimations. A Europe-led initiative to establish a public database on emissions would enhance transparency and serve as a foundation for future research.

Modelling re-entry events requires advanced demise tools which offer insights into how spacecraft materials fragment and release emissions upon re-entry. However, these tools currently focus more on ground impacts than on atmospheric interactions, suggesting a need to broaden their scope to enhance the incorporated atmospheric chemical-physical interaction and partial disintegration patterns. Refining models to predict fragmentation by particle size would support more accurate assessments of the atmospheric and environmental impacts. Material composition data is another critical area for improved modelling. Currently, access to material properties is limited, often due to proprietary constraints, but transparent data sharing could enable more accurate simulations. Meteoroid ablation provides useful analogies, as meteoroids exhibit similar high-velocity, high-temperature interactions with the atmosphere. Studying meteoroid behaviour could inform models for re-entry fragmentation, particularly for smaller debris that may persist in the atmosphere without fully disintegrating.

Modelling emissions from re-entry also requires a comprehensive understanding of the by-products released during atmospheric demise. Aluminium oxides, titanium oxides, black carbon, and nitrogen oxides (NOx) are notable pollutants produced through combustion and ablation. These compounds pose environmental risks, particularly through ozone depletion and greenhouse effects. NOx formation during re-entry is particularly concerning, as its role in air pollution and ozone layer degradation calls for high-altitude-specific emission models that account for temperature and trajectory-specific chemical interactions.

Measurement approaches play an instrumental role in validating these models. Event-based, coincidental, and continuous surveillance methods provide diverse pathways for gathering emissions data across different scenarios. Tools like LIDAR and satellite-mounted spectrometers can capture high-altitude emissions, but expanding in-situ techniques, such as balloon launches or sounding rockets, would provide targeted data for validating re-entry models. Data-driven insights gathered from remote sensing and in-situ measurements help refine existing models and validate predictions, guiding policy and regulatory frameworks aimed at minimising atmospheric impacts.

To facilitate the integration of space system emissions into broader atmospheric models, Chemistry-Climate Models (CCM) and Chemistry Transport Models (CTM) should be used in tandem. These models can simulate long-term atmospheric effects of launch and re-entry events, including radiative forcing, ozone depletion, and particle transport. Developing emission inventories that include latitude, longitude, altitude, and time parameters would further refine these models, supporting accurate simulations of pollutant dispersion and deposition cycles.

In sum, the pathway to improved understanding involves strengthening data collection, gaining an improved understanding of chemical and physical processes, refining ablation and emission models, and validating predictions with empirical measurements. Ultimately, advancing Ecodesign in STS requires an ongoing investment in research, international collaboration, and resource allocation. A unified effort to establish standards, share data, and continuously update methodologies will enable a more profound understanding of aerospace's environmental impact. This approach ensures a more comprehensive assessment of the environmental impacts associated with spacecraft re-entry and demise, providing a foundation for sustainable policy and regulatory action. Building on these foundations, the space industry can progressively transition toward a circular economy model, ultimately transforming aerospace design and operations into sustainable practices that harmonise technological advancement with ecological responsibility.

References

[1] J.C. McDowell, General Catalog of Artificial Space Objects Release 1.5.4, (2024). https://planet4589.org/space/gcat.

[2] World Meteorological Organization (WMO), National Oceanic and Atmospheric Administration (NOAA), United Nations Environment Programme (UNEP), National Aeronautics and Space Administration (NASA), European Commission, Scientific Assessment of Ozone Depletion: 2022, https://library.wmo.int/records/item/58360-scientific-assessment-of-ozone-depletion-2022.

[3] Commission on Environment and Development, Our Common Future, Oxford University Press, 1987. https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf.

[4] A.R. Wilson, M. Vasile, The space sustainability paradox, J. Clean. Prod. 423 (2023) 138869. https://doi.org/10.1016/j.jclepro.2023.138869.

[5] M.M. James, S.V. Lympany, A.R. Salton, Matthew F. Calton, R.C. Miake-Lye, R.L. Wayson, Commercial Space Vehicle Emissions Modelling, Transportation Research Board, Washington, D.C., 2021. https://doi.org/10.17226/26142.

[6] C. Park, Estimates of nitric oxide production for lifting spacecraft reentry, Atmospheric Environ. 1967 10 (1976) 309–313. https://doi.org/10.1016/0004-6981(76)90171-2.

[7] D.M. Murphy, M. Abou-Ghanem, D.J. Cziczo, K.D. Froyd, J. Jacquot, M.J. Lawler, C. Maloney, J.M.C. Plane, M.N. Ross, G.P. Schill, X. Shen, Metals from spacecraft reentry in stratospheric aerosol particles, Proc. Natl. Acad. Sci. 120 (2023) e2313374120. https://doi.org/10.1073/pnas.2313374120.