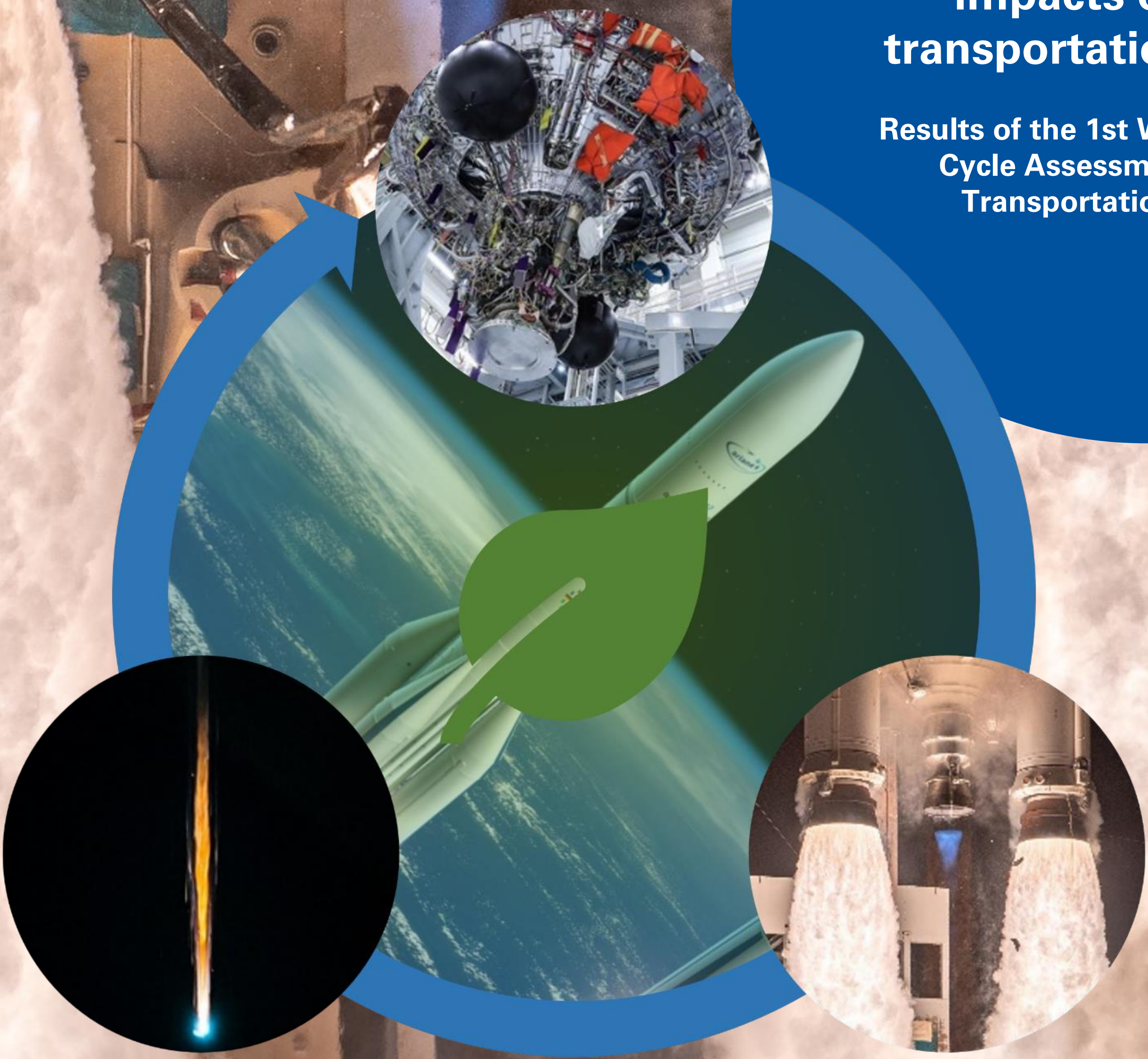
University of Stuttgart
Institute of Space Systems

Measures for an improved understanding of the environmental impacts of space transportation systems

Results of the 1st Workshop on Life Cycle Assessment of Space Transportation Systems



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Executive Summary of the results of the Workshop on Life Cycle Assessment of Space Transportation Systems

In a two-day workshop, a group of 22 experts from academia, agencies and industry came together to assess the current status of research in order to identify necessary measures for a better understanding of "Life Cycle Assessment of Space Transportation Systems".
In two working groups, the participants focused on the following topics:
• How can we assess the environmental impacts of space transportation systems?
• What knowledge gaps exist in the assessment of environmental impacts?
• What measures and tools are necessary to close these knowledge gaps in joint research projects?
The main conclusions of the two working groups are the following measures:

Working group on "Design and production of (more environmentally friendly) space transportation systems" (Pages 7 & 8)

- LCA as a mandatory step during process development resulting in the establishment of a common database platform
- The need to define requirements for consideration of environmental aspects in development
- Further development of LCA methodology regarding launcher systems, requirements for uncertainty assessment and regionalization
- Development of a predictive database with common baseline scenarios

Working group on "Measuring, simulating and calculating the impacts of emissions during launch" (Pages 10 & 11)

- Database on and measurement of launch emissions
- Soot (black carbon) size distribution and amount measurement
- THEMIS emission measurement campaign
- Remote measuring with satellites
- Simulation of interaction with atmosphere
- Climate and ozone modelling of launch emissions
- Implementation of environmental impacts of launch emissions into LCA

Workshop on Life Cycle Assessment of Space Transportation Systems

This whitepaper is intended to give an overview of the results from the 1st workshop on Life Cycle Assessment of Space Transportation Systems. During a two-day workshop (06 and 07 October 2022), a group of 22 experts from academia, agencies and industry came together at the Space Center 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, the identification of knowledge gaps using pre-defined Key Questions was targeted. This was followed by a discussion about the key questions and already known answers from other departments as well as possible solutions. At the end of the workshop, measures for dedicated implementation concepts were defined. These conclusions are summarized in the following.

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Why do we need to look at the environmental impacts of launchers ?

The increase in space activities over the past two decades culminated with 146 orbital launches into a new annual record in 2021. This growth is expected to continue and accelerate in the coming years due to the various upcoming satellite constellations put in operation. In addition, an unprecedented increase of suborbital launches is also expected in the next years due to the growing space tourism activities. Spaceflight is obviously at a turning point, entering maybe a new era. Thus, it is mandatory to understand and mitigate potential environmental impacts of space activities in general and of space transportation systems in particular, in a best-case scenario hopefully before increasing the activities by at least one order of magnitude and risking irreversible damages [1]. The environmental impacts of ships, cars and aircraft were not recognized until decades later, after they had become commonplace. With space transportation systems, the understanding of potential impacts in a timely manner seems achievable, opening opportunities to then counteract them with more environmentally friendly technical solutions.

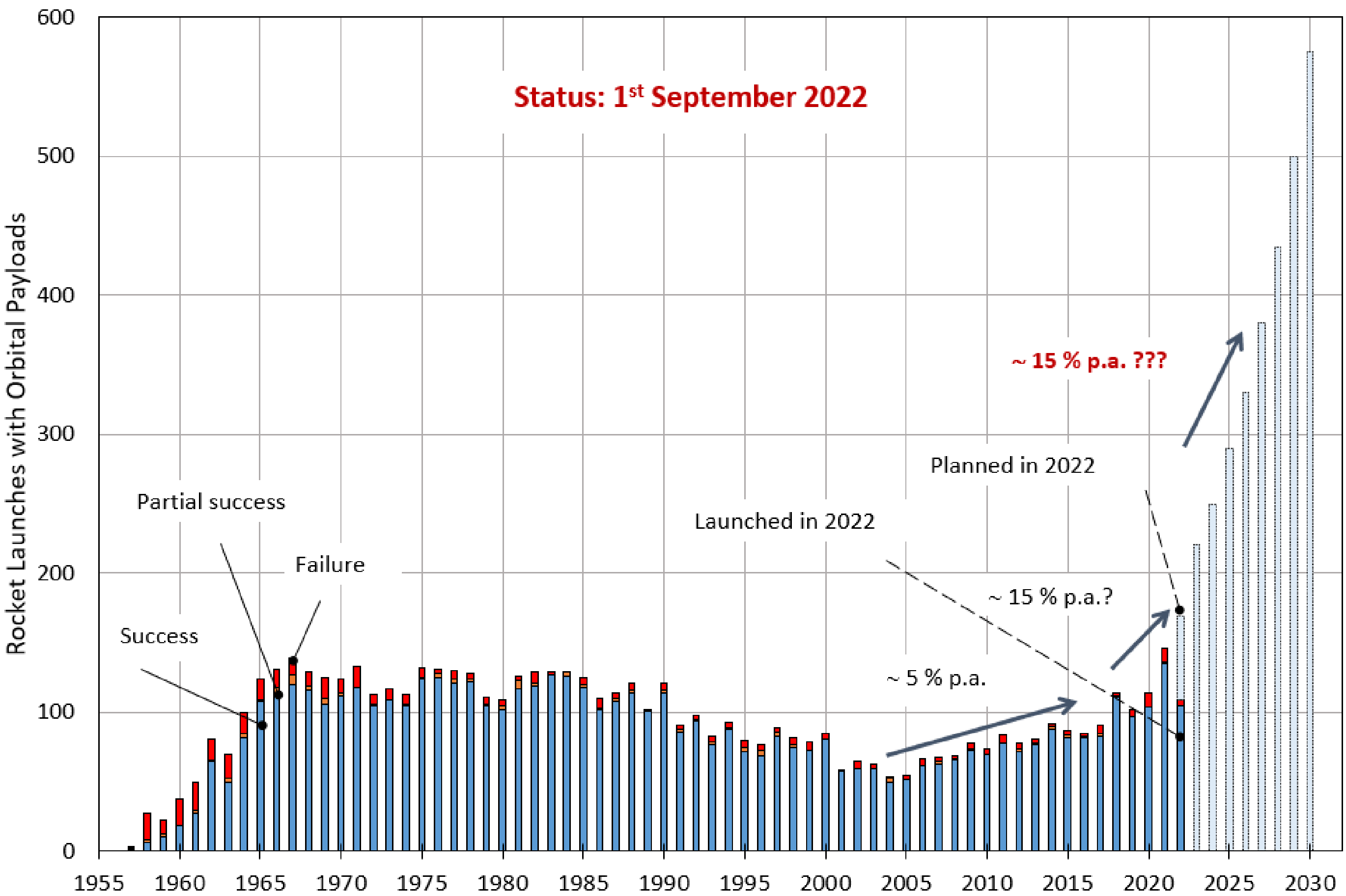
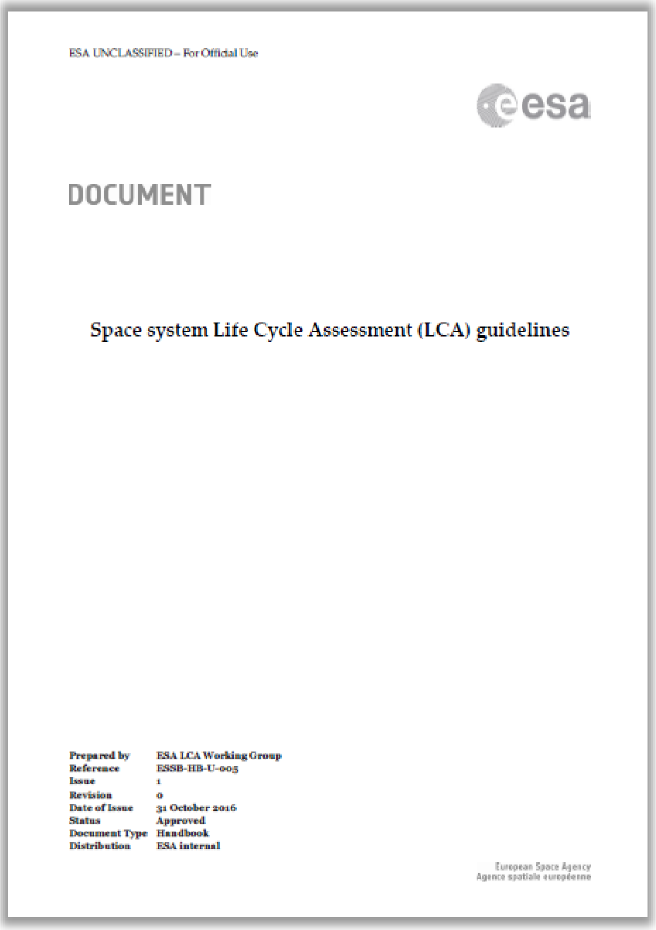


Fig. 1: Historical and expected number of orbital launches

How can the environmental impact of launchers be assessed ?

For some decades now, we have begun to understand the impacts our actions have on us and the environment, and that the Earth's resources are not inexhaustible. There are different approaches to calculating the environmental impact of products in general. International standards are given for example in ISO 14040 and 14044, on the basis of which ESA has been developing a life cycle assessment (LCA) methodology since 2012. This is specific for space projects due to unique requirements, low production rates, specific materials and intensive testing. In view of the development of the Product Environmental Footprint regulations at European level ((EU)2021/2279), the guidelines are currently being revised.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DOCUMENT

Space system Life Cycle Assessment (LCA) guidelines

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Fig. 2: Life Cycle Assessment Guidelines of ESA [2]

Although life cycle assessment already covers production, the effects of launch or re-entry events, which occur in every atmospheric layer are not sufficiently implemented. In order to be able to take these effects into account in life cycle assessment, further measures are therefore necessary.

Fig. 3: Life Cycle Assessment of Space Systems [ESA]

The impacts of ~~the~~ production of space transportation systems

So far, there are only two known LCA studies [3,4] on the production of European rockets, as the production of launch vehicles is a sensitive and very confidential area. Furthermore, the ESA LCI-Database includes generic data on propellant production, specific materials and production processes. In these studies, the influences of stage production, launch campaign, transport, fuel production and launch event were considered. The development phase, testing and infrastructure were not considered. The results show a remarkably high influence of the stage and fuel production. Therefore, design choices, selection of materials and propellants have a significant impact on the overall environmental effects of space transportation systems. However, absolute values are not available from the studies themselves. Against this background, discussions regarding the implementation and methodology of life cycle assessment in the design and production, as well as the data base, are necessary.

Results of the working group on "Design and production of (more environmentally friendly) space transportation systems"

The working group focused on questions regarding implementation and consideration of life cycle assessment during the design and production processes of launcher structure and propellants. The existing ESA guidelines on LCA and the database already provide a good base for this, but need further development. We defined the following measures:

LCA as a mandatory step during process development resulting in the establishment of a common database platform

The informative value of life cycle assessment can only be as good as the accuracy of the database. Since process chains in industry are usually complex and involve many partners and processes, it is difficult to obtain detailed data for all materials, processes and systems. In addition, there are barriers due to confidentiality and data exchange issues. For this reason, we have identified as a necessary step, that development of new materials, processes and systems must always be accompanied by a life cycle assessment in the future. This measure will be significantly simplified by increasing digitalisation and the eventual implementation of a 'digital twin' in production and development. Furthermore, companies can benefit in regard to cost reduction by analysing their production and implementing e.g. energy reducing measures. The data should be collected by a central agency and made available to all participants. This would also significantly improve the data situation for academic institutions in particular, which is currently difficult due to confidentiality, and would also enable better scientific evaluation. As the problem does not only concern the space sector and such a task requires a reliable and trusting partner, we recommend the inclusion of this measure in the framework of the European Green Deal at the European level to the European Commission.

The need to define requirements for consideration of environmental aspects in development

Eco-design is currently being carried out on a system level by first conducting life cycle assessment to accompany developments in order to identify hot spots and subsequently mitigate the impact of certain phases, components or processes through alternative solutions. However, there is a lack of clear targets for the technical development of future systems with a lower environmental impact. For example, an alternative solution with a lower impact on global warming but higher toxicity to human health or a significantly higher impact in another life cycle phase (burden shifting) is difficult to evaluate overall. Furthermore, it becomes more complicated, if a trade-off between cost, performance and environmental impact has to be conducted during development. There is a lack of appropriate requirements that provide a framework for the design of systems regarding their impacts on the environment and their consideration in the development process. A standard from the European Cooperation for Space Standardisation (ECSS) could provide a possible framework for this.

Further development of LCA methodology regarding launcher systems, requirements for uncertainty assessment and regionalization

The existing ESA LCA methodology is a good baseline, unique for the space industry and an important measure to calculate and mitigate the environmental impacts of this sector. With regard to the European product environmental footprint regulation, the methodology needs to be aligned to a single common European method in order to be able to compare the results of studies made on similar products or systems. Furthermore, it needs to be improved in some aspects which were identified during the usage of this methodology on launch system development and analysis.

First of all, the current version of the LCA methodology, which already considers launch systems separately, needs to be developed further to a standard approach for implementation of development phases, infrastructure and functional unit. At the moment, the impacts of the design and development phase, as well as the infrastructure, is not considered in an LCA, as these impacts are difficult to assign to one single launch. Furthermore, a standardised functional unit needs to be defined. This becomes very important in view of the ongoing developments towards reusable launch systems. A single standardised European methodology is therefore needed for comparison between different studies and systems.

Secondly, the implementation of an uncertainty standard for data quality is required for the methodology. Also here, the first solution is given in the guidelines, which need to be specified even more, as the data quality of the LCI is highly dependent on the implementation of uncertainty values from partners or existing background data. This requires a detailed internal consultation and a standard approach for data collection and uncertainties. Moreover, the usage of proxy/background data in a dataset delivered from a partner is not always clearly stated at the moment and should be reported in a standardised way. Furthermore, the environmental indicators themselves contain uncertainties. Therefore, the methodology requires a specification on uncertainty implementation in data sets and a requirement to access the final uncertainty of the study.

Another question is about regionalization as the basic databases often implement market group data. A specific process can have a significantly different impact when it is conducted in another country. Therefore, a standardised approach to regionalisation needs to be implemented.

Development of a predictive database with common baseline scenarios

The development process in space industry currently takes a very long time compared to other industries. Therefore, life cycle assessment based on current data is not sufficiently meaningful for the analysis of future launcher systems. For this reason, in consideration of existing political targets, such as the implementation of renewable energies, common baseline scenarios for life cycle assessment should be carried out for the analysis of systems in the coming decades. Furthermore, for the future, novel production processes, e.g. electrolysis or bio-based propellants, should be implemented into the database as soon as possible, in line with our first identified measure.

The impacts of launch emissions of space transportation systems

Rockets are the only human built engineering systems that emit into all layers of the atmosphere. The effects are not well understood despite the fact, that up to now most studies on rocket emissions have been focused on the impacts on stratospheric ozone depletion from solid rocket motors. However, many questions on the impact of other propellant systems, as well as climate and ozone impact remain unanswered. Emissions depend on the propellant system used and on the extent of interaction with the surrounding atmosphere (e.g. afterburning and shock systems), in which thermal NOx is also formed. However, the prediction of emissions is based on approximate calculations and models and only allows for an estimation with high uncertainty remaining. Even though CO2 emissions of rockets have often been discussed in public, they are not relevant in absolute terms regarding the impact on global warming. Soot in particular (e.g., from kerosene rockets) is thought to contribute to a significant increase in radiative forcing as it accumulates in the stratosphere, absorbs sunlight, and heats the environment. According to recent studies, rockets contributed 0.7% of the annual change in radiative forcing in 2019 [5]. This would lead to a significant impact with a tenfold increase of launches. However, these numbers are highly uncertain and require extensive research. Furthermore, the contribution of alumina particles and cloud formation in the stratosphere and mesosphere, as well as re-entry effects of space debris and expendable stages, is unclear at the moment. Another effect is the impact on the ozone layer, as rockets emit directly into it. Particularly noteworthy are chlorine compounds, NOx and heterogeneous reactions on the surface of alumina. The ozone-depleting effect was proven in several measurement campaigns. Simulations showed that the annual ozone depletion caused by rockets is less than 0.1% today [6]. However, significantly increased launch rates could undo the measures of the Montreal Protocol. Against the background of possible emerging discussions about regulations, a scientifically well-founded understanding is necessary. Furthermore, in LCA studies, the non-CO2 emissions during launch and re-entry are therefore not considered and ozone depletion is only reported as a relative value.

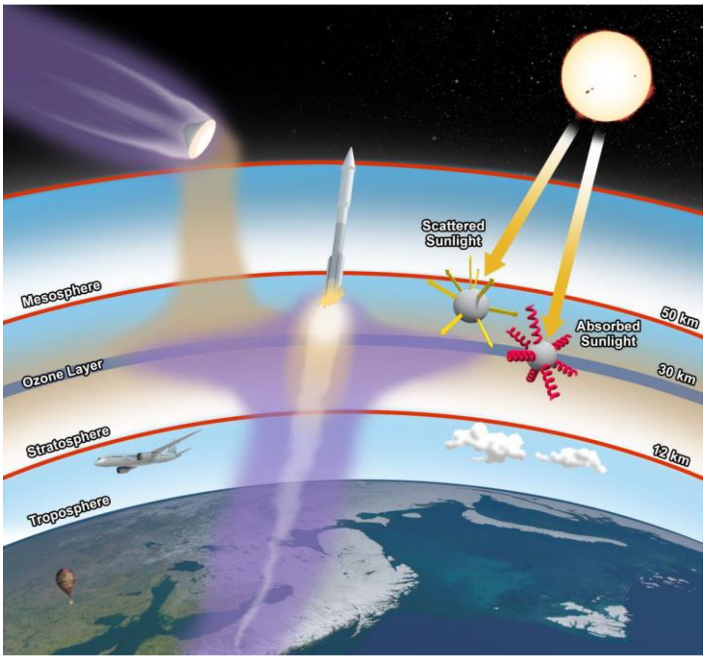

Fig. 4: Impacts of launch emissions on atmosphere [7]

Results of the working group on "Measuring, simulating and calculating the impacts of emissions during launch"

The working group focused on measuring, simulating and calculating the impacts of emissions during launch. We identified a three-step process of first measuring/simulating the emissions to feed climate and ozone models for calculating the impact, and finally implementing this data into LCA. We have therefore identified the following measures:

Database on and measurement of launch emissions

Since rocket emissions are highly dependent on the chosen propellant and operating point, as well as atmospheric conditions, and furthermore differ for each engine, a database containing the emission indices must first be developed. For this the emission of CO2, aerosols, water vapour, chlorine, NOx, soot and trace gases must be taken into account, as the production ratio is currently highly uncertain. In particular, the mass as well as the particle size distribution and aggregate state must be considered. This database should be available to all stakeholders and should also be expanded by all interested parties. To feed the database, many measurements are necessary, which can be taken on the ground during engine tests (gas chromatography or spectroscopy), in the air from aircraft, with on-board instruments on rockets and from satellites. Existing measuring facilities (e.g. Kiruna or airborne platforms) should be included in this regard. For the measurement of soot and other emissions, established airborne measurement systems already exist, which have been successfully used for the measurement of aircraft exhaust and have contributed to an improved understanding of the impacts of aviation on radiative forcing. Therefore, measurements of launch vehicle emissions and a database is the basis for a better understanding of their impact on climate, ozone and the environment.

Soot (black carbon) size distribution and amount measurement

Studies on the impacts of rocket emissions are particularly concerned about soot. In addition, current launch systems with high launch rates and a significant number of future systems, currently under development are based on soot-producing hydrocarbons (kerosene/methane). To better understand the effects, measurements of the amount and size distribution of soot particles are necessary. These can be carried out on the ground at engine test facilities, as well as in the air via airborne measurements. It is very important to carry out both measurements, as it is expected that the emission index changes with altitude, as the interaction with the atmosphere changes (afterburning).

THEMIS emission measurement campaign

The workshop explored the idea of using such a measurement system to perform measurements in the air during a THEMIS test launch. The THEMIS launch lends itself to this for several reasons. Firstly, it is an ESA development project and is therefore subject to fewer constraints than a commercial launch with higher safety requirements. Secondly, THEMIS will use a methane-based fuel system, so the characterisation of emissions and soot is very interesting in view of the broad use expected in the future.

Remote measuring with satellites

In addition to measurements on the ground and in the air, satellite data can help gaining a better understanding of launch vehicle emissions. For this purpose, existing data, which are collected on a large scale within the Copernicus programme, for example, are to be evaluated with regard to rocket emissions during launch events. Further, airborne and remote measurements should be combined to better understand cloud formation. However, the feasibility of this research methodology must first be investigated in more detail in a study.

Simulation of interaction with atmosphere

Simulation tools are already available for calculating emissions. Common CFD tools can represent the emission of gaseous species and their interaction with the atmosphere. However, the current implementation of solid/liquid particles and cloud interactions, especially at high altitudes, remains highly uncertain. The development of suitable numerical techniques to model these is therefore fundamental and could also benefit the climate science community. In addition, the simulations must be verified against the targeted measurements, therefore a close interaction between experiments and measurements/simulation is necessary. In a first step, the existing results are to be evaluated. Later, simplified emission models are to be verified in order to minimise the computational effort.

Climate and ozone modelling of launch emissions

The preceding measures serve to feed climate and ozone models with significant data. For this purpose, the existing modelling tools needs to be analysed with regard to their capabilities, in order to see where aerosol and chemistry schemes in models need to be developed for conditions representative of launch emission problems, such as higher altitude chemistry and heterogeneous chemistry. The existing campaigns for meteorite surveillance might be helpful for this.

Implementation of launch emissions into LCA

The final step is the implementation of the launch emissions into the LCA methodology. For this purpose, the implementation of the launch emissions for different propellant systems, flight trajectories and their effects on the existing impact categories must be considered in more detail. Climate and stratospheric ozone metrics, which capture the impacts from launch emissions and are suitable for comparison against other life cycle phases, must be developed. Uncertainties in emission calculations and climate/ozone modelling must also be taken into account.

Outlook

The participants work on the next steps regarding the feasibility and implementation of the identified measures. Follow-up and progress meetings are planned to further promote exchange. The next workshop is planned to take place in summer 2023. In addition to the existing working groups, the environmental impacts of re-entry will also be considered.

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Sources

Pictures on cover page: ESA/ArianeGroup/John Kraus

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