University of Stuttgart
Institute of Space Systems

A Comprehensive Approach to Life Cycle Assessment of Space Transport Systems

Clean Space Industry Days
ESTEC, Noordwijk
12. October 2022

J.-S. Fischer, S. Fasoulas

Supported by:
Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

Motivation

Development of orbital launches

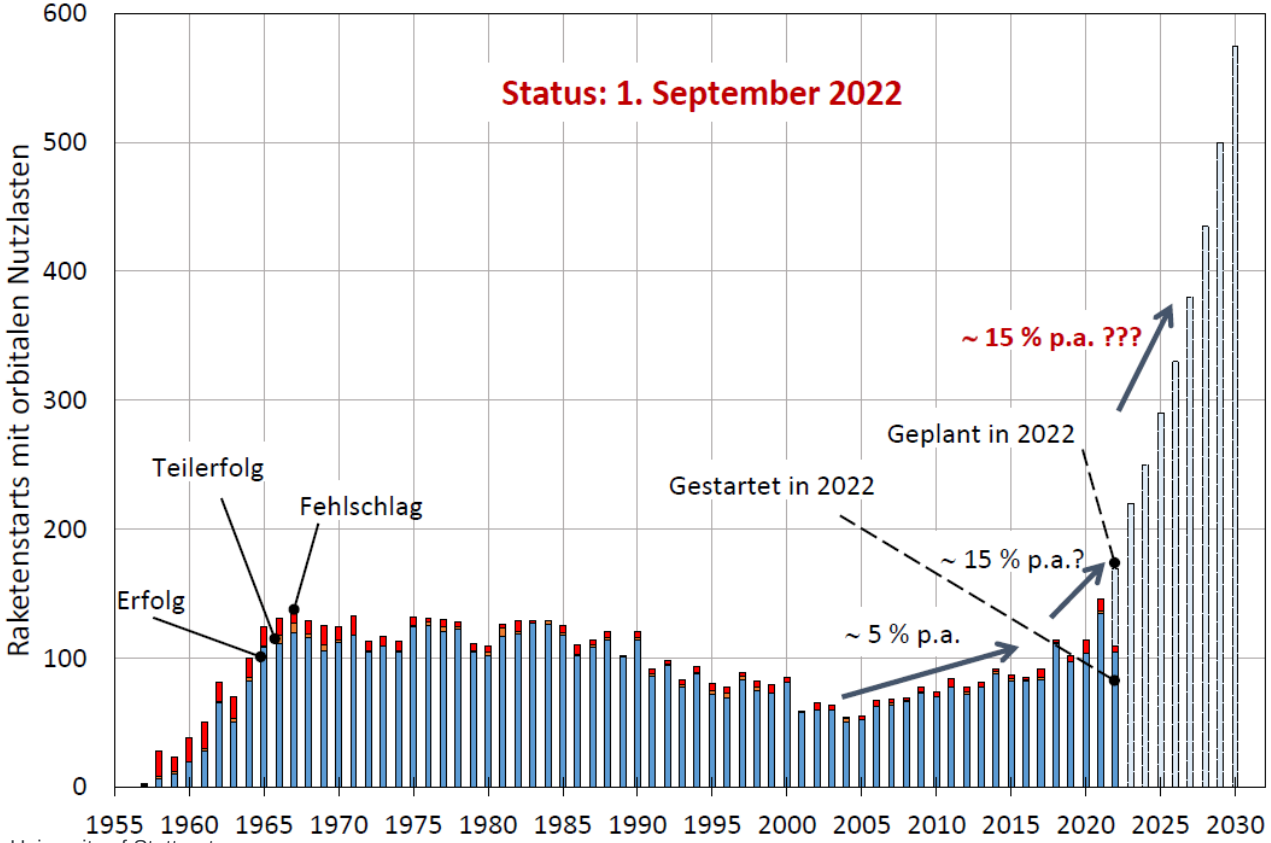
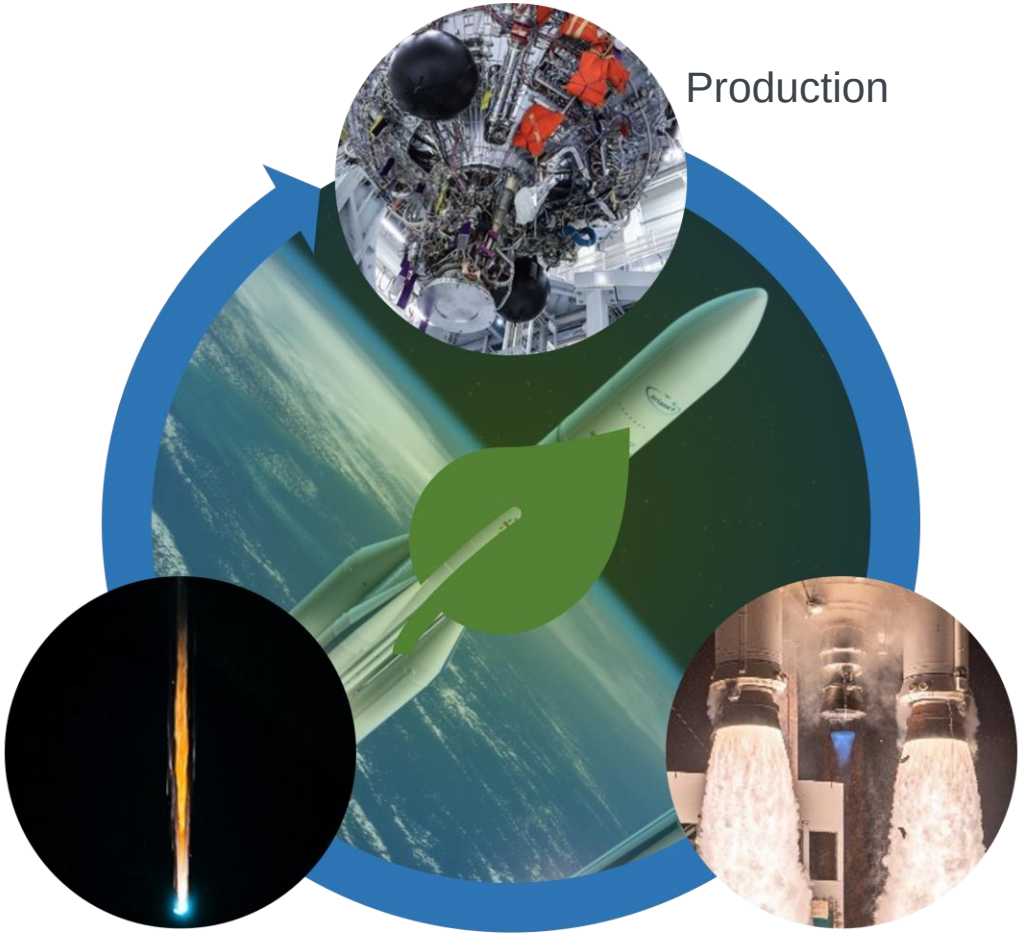


Fig. 1: Historical and expected orbital launches

Project „Life Cycle Assessment of Space Transportation Systems

Research Goals



Project „Life Cycle Assessment of Space Transportation Systems“

Life Cycle Assessment Methodology

Resource Depletion

Energy Consumption

Global Warming

Ozone Depletion

Human Health

Environmental Damage

Space System Life Cycle Assessment (LCA) Guidelines [1]
→ 20 Environmental Indicators

Production

Production

LCA Study on Ariane 5 & 6

PRELIMINARY RESULTS

Environmental profile of A64

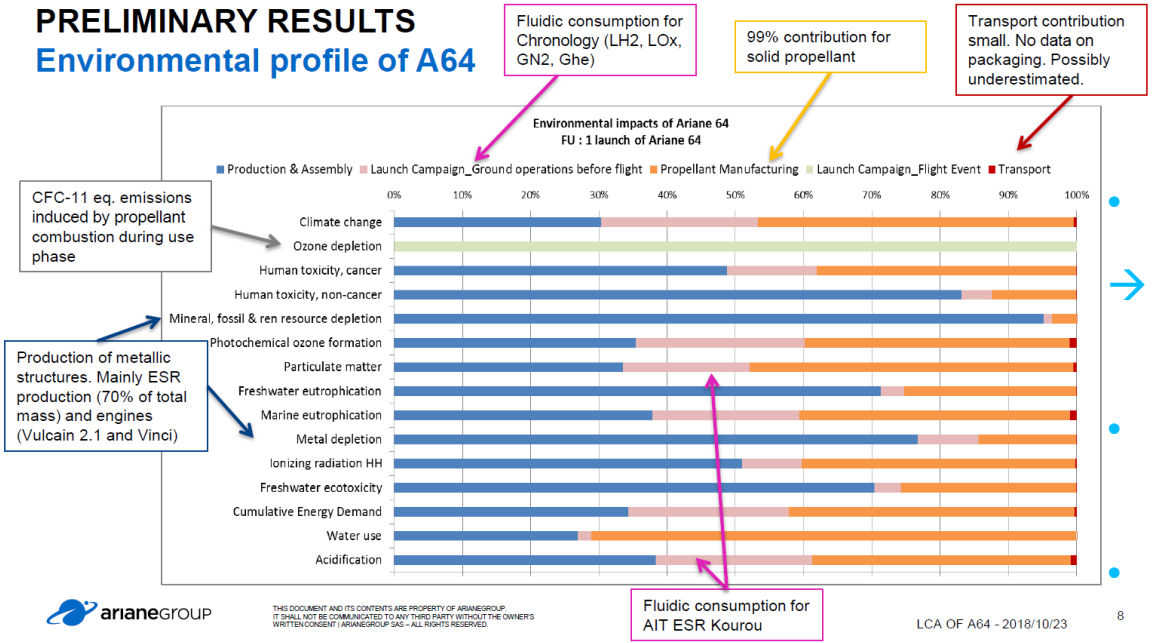


Fig. 2: Results of Ariane 6 LCA [2]

- High Impact of production

→ Launch ready system has already 98% of its GWP

- Booster and core stage have the higest impact (85 – 90%)
- No absolute values published

Production

Measures in the Project

- Cooperation with ArianeGroup to close knowledge gaps
  - Project „Analysis of the Production of Launcher Systems Using the Example of Ariane 6 “
  - Development of a generic dataset for analysis
- Life cycle assessment studies
  - Identification of Hot-Spots
  - Comparison of different launch system architectures
  - Comparison of different materials
  - Comparison of different propellant systems
  - Analysis of alternative processes

Launch Emissions

Emissions of the propellants

Stoichiometric calculation

Name	Reaction equation	Mass equation
LOX/LH2	$H_2 + 0.5\ O_2 \rightarrow H_2O$	$1\ kg\ \ H_2 + 7.94\ kg\ O_2 \rightarrow 8.94\ kg\ H_2O$
LOX/CH4	$CH_4 + 2\ O_2 \rightarrow CO_2 + H_2O$	$1\ kg\ CH_4 + 3.99\ kg\ O_2$ $\rightarrow 2.74\ kg\ CO_2 + 2.25\ kg\ H_2O$
LOX/RP-1	$C_{12}H_{23.4} + 17.9\ O_2 \rightarrow 12\ CO_2 + 11.7\ H_2O$	$1\ kg\ C_{12}H_{23.4} + 3.41\ kg\ O_2$ $\rightarrow 3.15\ kg\ CO_2 + 1.26\ kg\ H_2O$
NTO/MMH	$CH_6N_2 + 1.25\ N_2O_4 \rightarrow CO_2 + 3\ H_2O + 2.25\ N_2$	$1\ kg\ CH_6N_2 + 2.50\ kg\ N_2O_4$ $\rightarrow 0.96\ kg\ CO_2 + 1.17\ kg\ H_2O + 1.37\ kg\ N_2$
NTO/UDMH	$C_2H_8N_2 + 2\ N_2O_4 \rightarrow 2\ CO_2 + 4\ H_2O + 3\ N_2$	$1\ kg\ C_2H_8N_2 + 3.06\ kg\ N_2O_4$ $\rightarrow 1.46\ kg\ CO_2 + 1.20\ kg\ H_2O + 1.40\ kg\ N_2$
AP+Al+HTPB	$NH_4ClO_4 \rightarrow 0.5\ N_2 + HCl + 1.5\ H_2O + 1.3\ O_2$ $1\ Al + 0.8\ O_2 \rightarrow 0.5\ Al_2O_3$ $(C_4H_6)_{50}(OH)_2 + 274.5\ O_2$ $\rightarrow 200\ CO_2 + 151\ H_2O$	$1\ kg\ NH_4ClO_4$ $\rightarrow 0.12\ kg\ N_2 + 0.31\ kg\ HCl + 0.23\ kg\ H_2O$ $+ 0.34\ kg\ O_2$ $1\ kg\ Al + 0.89\ kg\ O_2 \rightarrow 1.89\ kg\ Al_2O_3$ $1\ kg\ (C_4H_6)_{50}(OH)_2 + 3.21\ kgO_2$ $\rightarrow 3.21\ kg\ CO_2 + 1.0\ kg\ H_2O$

Emissions of the propellants

Analytic calculation (CEA)

Species	LOX/LH_2 (6.2:1)	LOX/CH_4 (3.8:1)	LOX/RP−1(2.6:1)
CO	-	8.43	30.10
CO_2	-	43.90	40.17
H	0.25	0.02	0.02
HO_2	0.01	<0.01	-
H_2	3.36	0.24	0.66
H_2O	88.5	43.74	28.79
H_2O_2	<0.01	-	-
O	0.48	0.12	0.01
OH	6.26	1.45	0.24
O_2	1.09	2.09	0.03

	N_2O_4/ CH_6N_2 (MMH) (2.05:1)	$N_2O_4/C_2H_8N_2$ (UDMH) (2.67:1)
CO	8.46	8.33
CO_2	18.02	26.81
H	<0.01	<0.01
H_2	0.67	0.34
H_2O	32.44	29.62
NO	-	0.01
N_2	40.40	34.85
OH	0.01	0.04
O_2	-	<0.01

Tab. 2a: Analytic calculation of emissions

→ Simple stoichiometric calculation is not sufficient

→ Analysis of trace gases is necessary

Emissions of the propellants

Analytic calculation (CEA)

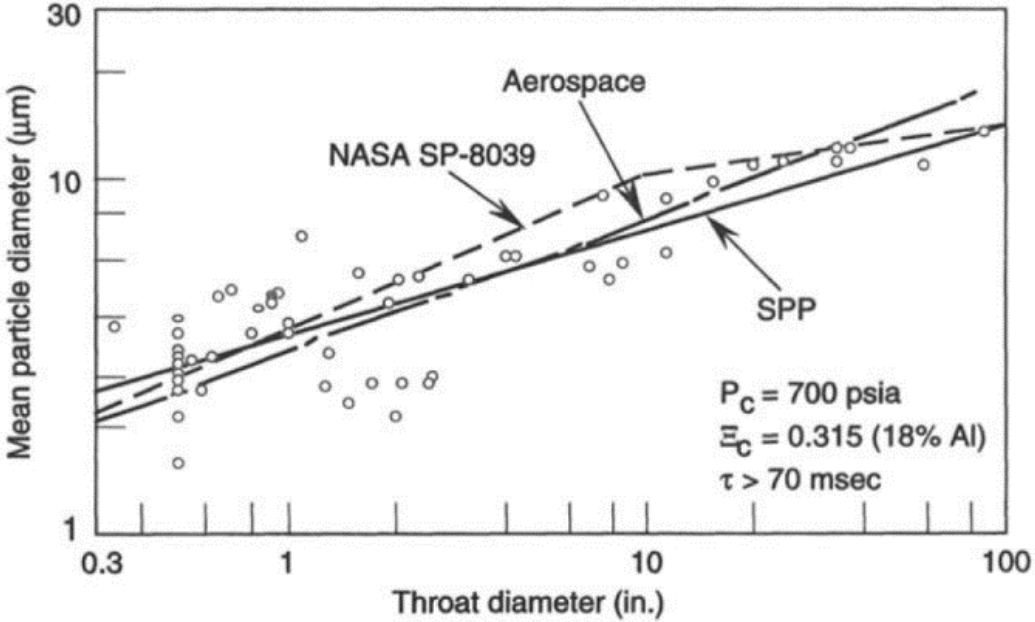


Fig. 3: Particle size distribution dependent on engine dimensions [3]

	NH_4ClO_4/ Al/HTPB (69:19:12)	N_2O/HTPB (5.2:1)
$AlCl$	0.01	-
$AlCl_2$	<0.01	-
$AlCl_3$	<0.01	-
$AlOH$	<0.01	-
$AlOHCl_2$	<0.01	-
$Al(OH)_2Cl$	<0.01	-
CO	21.89	20.13
CO_2	1.48	8.76
Cl	0.22	-
H	0.58	<0.01
HCl	16.00	-
H_2	30.22	10.15
H_2O	11.58	11.82
NO	<0.01	-
N_2	8.26	49.00
OH	0.04	-
$Al_2O_3(s)$	4.98	-
$Al_2O_3(l)$	4.74	-

Tab. 2b: Analytic calculation of the emissions

Emissions of the propellants

Afterburning

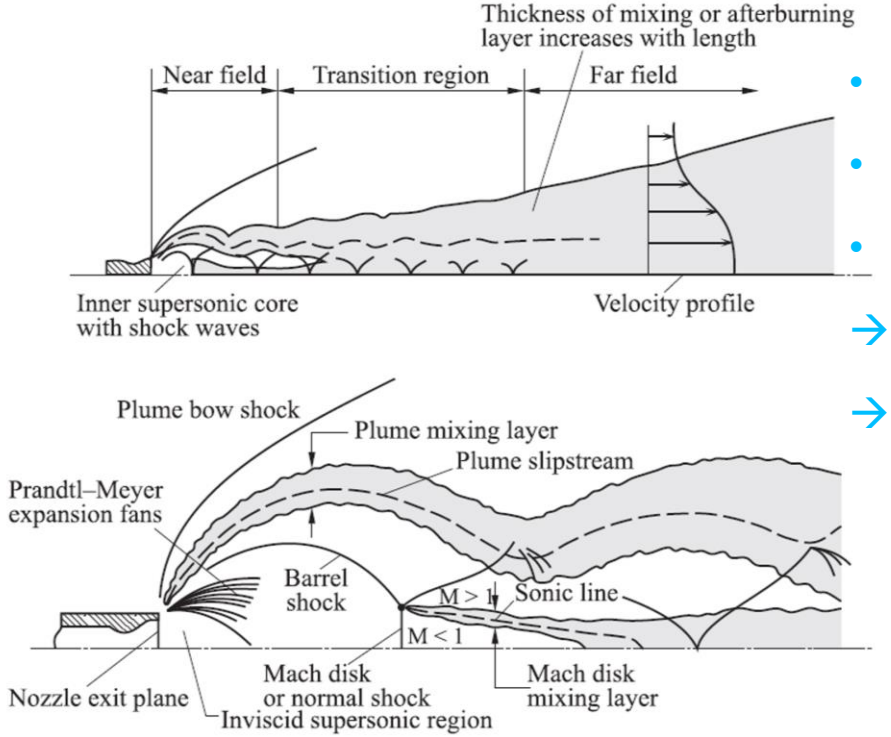


Fig. 4: Scheme of a rocket plume [3]

- Conversion of kinetic in thermal energy
- Complex gasdynamic processes
- Mixture with ambient air

→ Burning of propellant residues

→ Formation of thermal NOx

Impacts of emissions

Impacts on climate

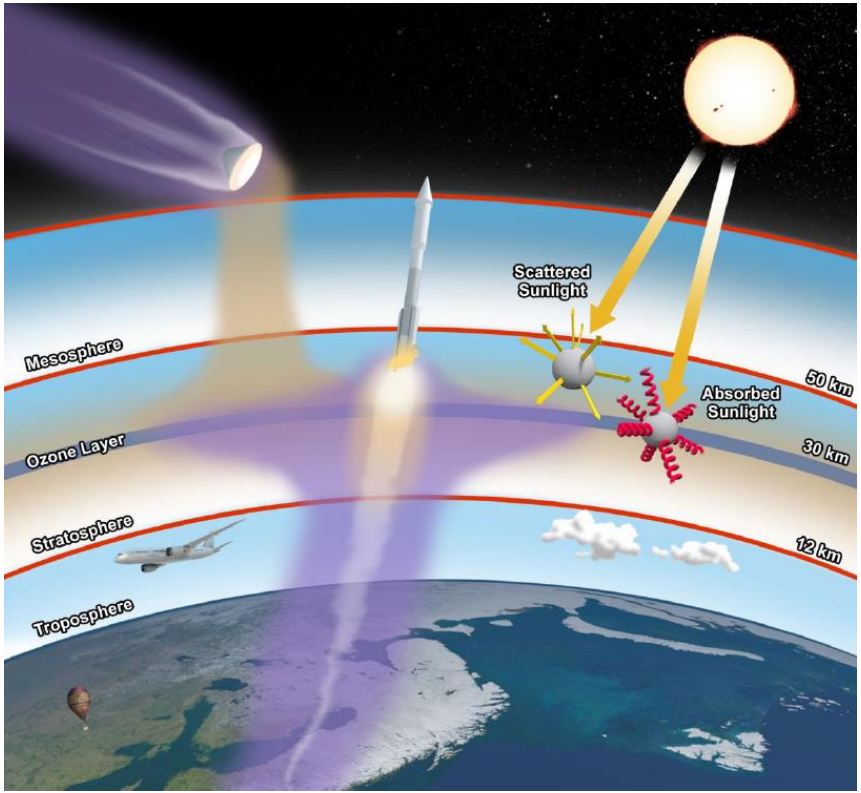


Fig. 5: Scheme of the impacts [4]

- CO2
- CO
- Ruß

→ Kerosene rocket GWP factor 10^5

- Al2O3

→ Great uncertainty

Impacts of emissions

Impacts on ozone

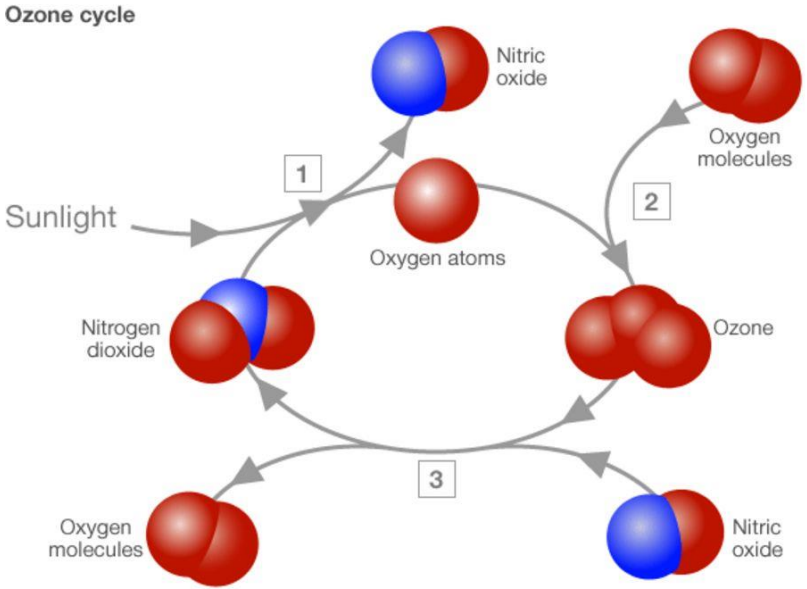


Fig. 6: Natural ozone cycle [5]

- NOx
- Chlorine
- Hydroxyl-radicals
- Iron
- Aluminia (heterogenous)
- PSC (heterogenous)
- Soot (heterogenous + temperature increase)

Impacts of emissions

Further effects

Fig. 7: Polaric Mesospheric Clouds [6]

- Increased formation of PMC after launches

→ uncertain impact on RF

- Impacts on Ionosphere

Impacts of emissions

Human Health

Fig. 8: Dropped and disposed rocket stage [7]

- Fuel residues e.g. hydrazine
- $7.7 \cdot 10^6$ km^2 in Kazakhstan "zone of ecological disaster"
- carcinogenic, mutagenic, convulsive, teratogenic and embryotoxic effects

Impacts of emissions

Environmental damage

Fig. 9: Impact on vegetation [8]

- Acid formation due to HCl

→ Fish kill

- Deposition on vegetation
- Reduction in quantity & diversity of plants

→ Normalisation after cessation of launch activities

Measurement of Emissions

Airborne Measurements

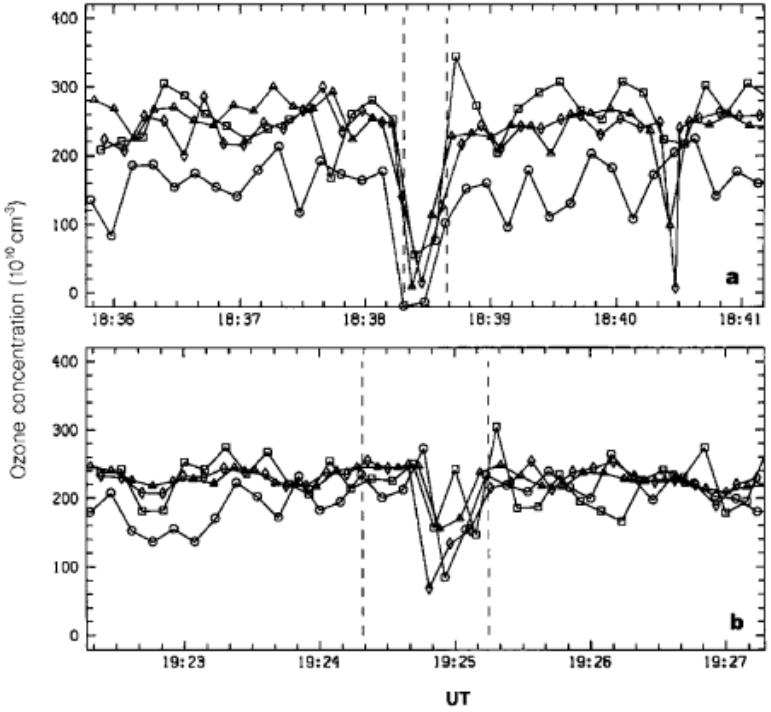


Fig. 10: Measured ozone depletion [9]

- Passage through exhaust plume

→ Measurement of temporary ozone depletion

→ Measurement of exhaust gas composition

- No ozone depletion during night

Fig. 11: Measurment aircraft of NASA [10]

Simulation of emissions

Local effects

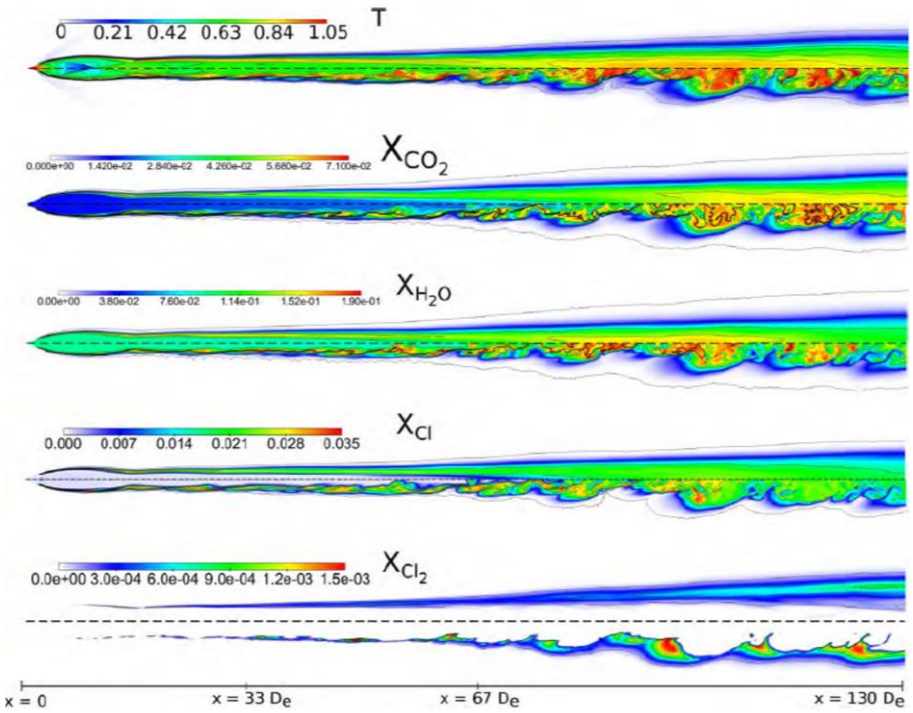


Fig. 12: CFD-simulation of rocket plumes [11]

- Chemical reaction models
- CFD calculations

→ missing verification

Simulation of emissions

Global effects on climate

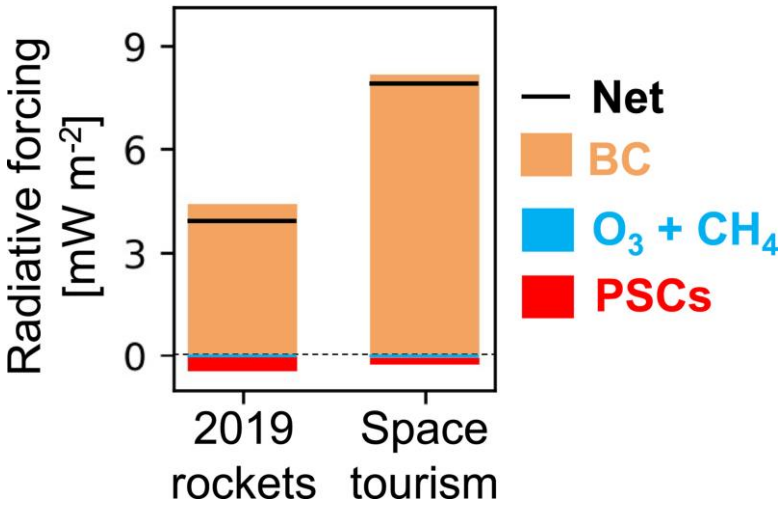


Fig. 13: Share of RF [12]

Author	Method	Scenario	RF [mW/m^2]
Bekki	3D	6 Ariane 5	0.06
DeSain	Analytic	Launches 1985-2013	2.1
Larson	NOCAR/ WACCM	10^5 LOX/LH2	30
Ross	WACCM3	1000 Hybrid	100
Ross	Analytic	Launches 2013	16±8
Ryan	GEOS-Chem + RRTMG	Launches 2019 +5,4%/y for 10 years	3.9
Ryan	GEOS-Chem + RRTMG	Space Tourism 3-Years	7.9

Tab. 3: Simulationen zu den Klimaauswirkungen

- Total anthropogenic RF 2.72 W/m2 (+0.43 W/m2 2014 - 2021)
  → Space launches 2019: 0.3 mW/m2 → 0.56% annually
  → Tourism scenario: 2.6 mW/m2 → 4.9% annually
- Aviation RF 2018: 100.9 mW/ m2 ()

Emissions of propellants

Global impact on ozone

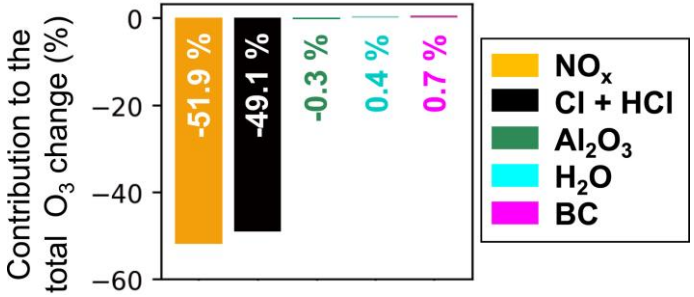


Fig. 14: Share of ozone depletion [12]

- Ozone recovery due to Montreal Protocol ~+81 ppbv
  → 10 years impact -8,5 ppbv (10%)
- Global ozone depletion ~2,2% to 1964-1980

Autor	Method	Scenario	Ozone local [%]	Ozone global [%]
Bekki	3D	6 Ariane 5	-0.1	-0.011
Bennett	Analytic	9 Space Shuttle, 6 Titan IV	-	-0.012
Danilin	3D	9 Space Shuttle, 4 Titan IV	-0.07	-0.034
DeSain	Analytic	Launches 1985-2013	-	-0.189
Jackman	2D	Space Shuttle, Titan III/IV Launches 1975-1997	-	-0.025
Jackman	2D	9 Space Shuttle, 3 Titan IV	-	-0.099
Jackman	2D	9 Space Shuttle, 3 Titan IV	-0.14	-0.05
Jones	2D	10 Ariane 5	-	-0.08
Potter	?	60 Space Shuttle	-0.3	-
Prather	AEF, GSFC, GISS	9 Space Shuttle, 6 Titan IV	-0.25	<-0.1
Ross	2D	10 Proton Launches	-	-0.00012
Ross	WAACCM3	1000 Hybrid	-6	-1
Ryan	GEOS-Chem + RRTMG	Launches 2019	-0.15	-0.01

Tab. 4: Simulations regarding ozone depletion

Launch emissions

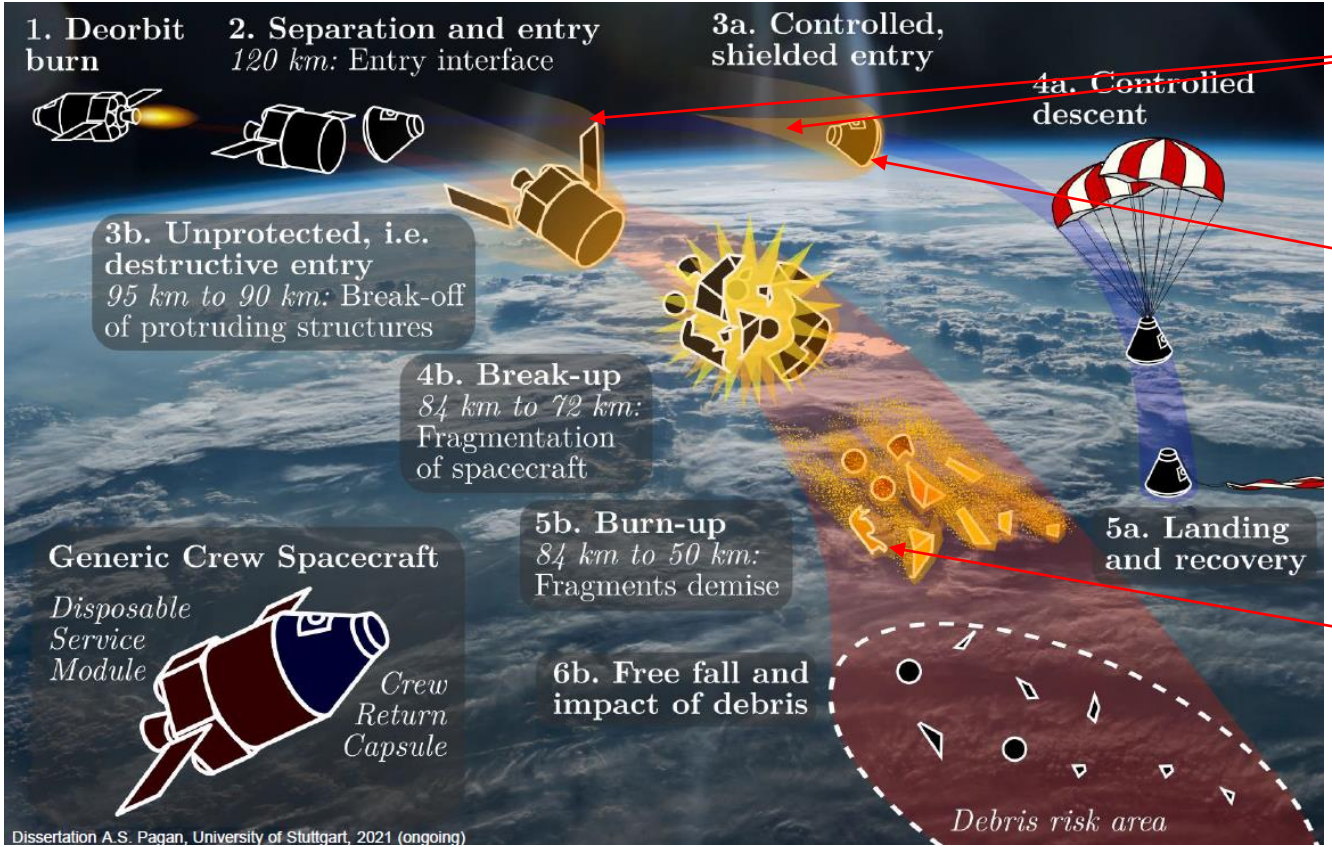
Measures in the project

- Simulation of rocket plume emissions and afterburning
  - Approximate calculation using CEA
  - CFD calculation of emissions
- Simulation of emissions using common atmospheric models
  - Open-source models (WAACM, GEOS-Chem)
- Possible measurement campaign scenarios
  - Ground-based measurements (emission spectroscopy, gas chromatography)
  - Aircraft-based measurements (aerosols, gas composition)
  - Satellite-based measurements (emission and ozone data)

Re-Entry

Emissions during re-entry

Characterisation



Thermal NOx

Ablative: Combustion

Radiative: Oxidation

Combustion products of structural materials

Fig. 15: Sheme of re-entry emissions [13]

Emissions during re-entry

Comparison to natural sources

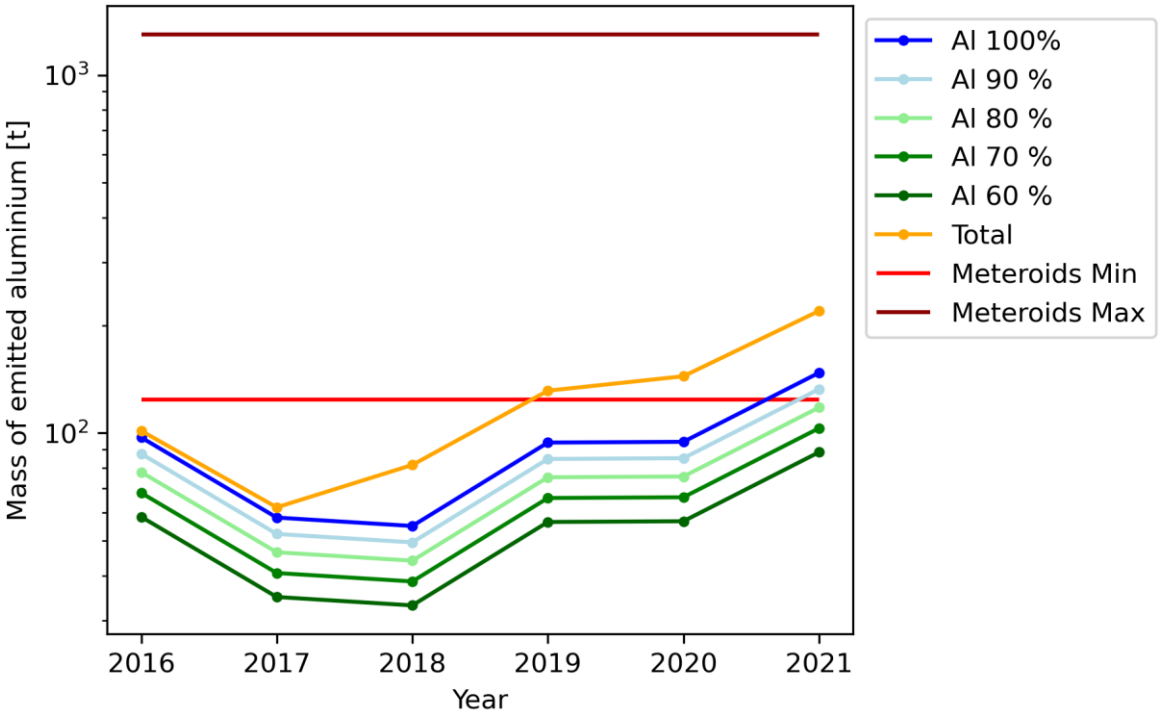


Fig. 16: Masses of aluminium emitted into the earth's atmosphere

Emissions during re-entry

Measures in the project

- Simulation of emissions
- Measurement campaigns
  - Emission spectroscopy
  - Particle distribution analysis

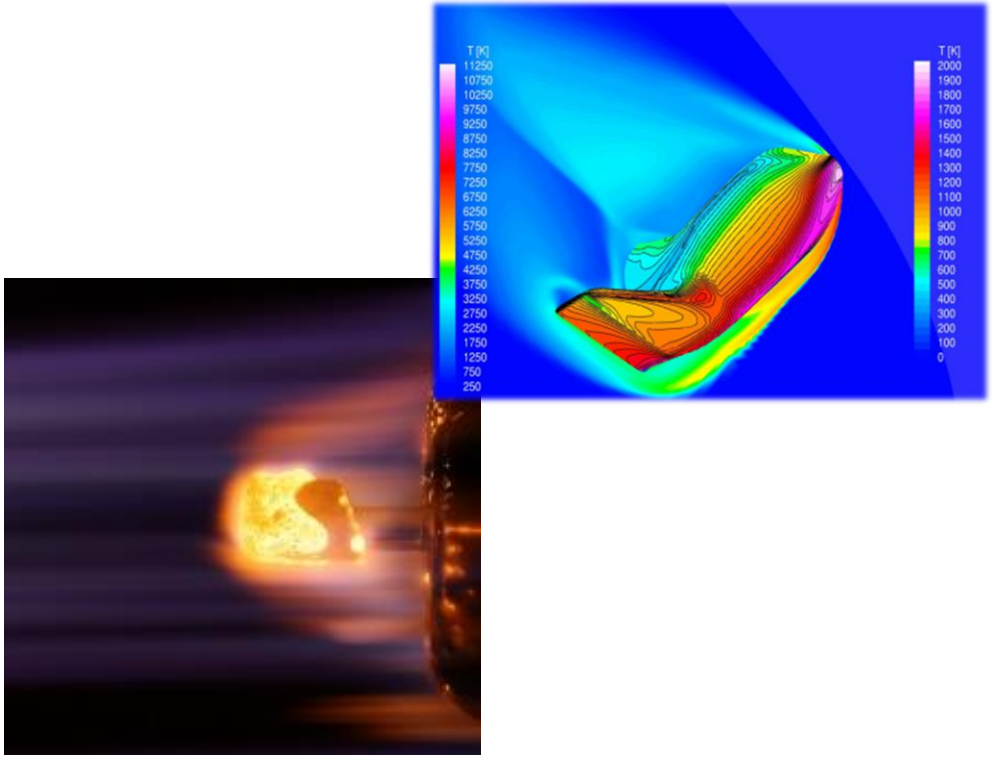


Fig. 17: IRS activities

Conclusion

- Production
  - Significant contribution but limited insight
  - LCA and ecodesign to reduce
- Start emissions
  - no significant impact at the moment
  - at other scales, however, critical in terms of ozone depletion
- Re-entry emissions
  - Only little researched
  - Aluminium emissions in the same order of magnitude as natural sources

→ Further research activites necessary

Supported by:

Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

Acknowledgements

German Space Agency, funding reference 50RL2180

Sources

[1] ESA LCA Working Group, Space system Life Cycle Assessment (LCA) guidelines: ESSB-HB-U-005, 1st ed., 2016.
[2] A. Gallice, T. Maury, E. del Olmo, Environmental Impact of the Exploitation of the Ariane 6 Launcher System, in: Clean Space Industrial Days, Noordwijk, Netherlands, 2018.
[3] F. Simmons, Rocket Exhaust Plume Phenomenology, American Institute of Aeronautics and Astronautics, Inc, Washington, DC, 2000.
[4] M.N. Ross, K.L. Jones, Implications of a growing spaceflight industry: Climate change, Journal of Space Safety Engineering (2022).
[5] BBC
[6] NASA
[7] Jonas Bendiksen/Magnum
[8] C.R. Hall, P.A. Schmalzer, D.R. Breininger, B.W. Duncan, J.H. Drese, D.A. Scheidt et al., Ecological impacts of the space Shuttle Program at John F. Kennedy Space Center, Florida, 2014.
[9] M.N. Ross, J.R. Benbrook, W.R. Sheldon, P.F. Zittel, D.L. McKenzie, Observation of stratospheric ozone depletion in rocket exhaust plumes, Nature 390 (1997) 62–64.
[10] NASA
[11] R. Paoli, A. Poubeau, D. Cariolle, Large-Eddy Simulations of a Reactive Solid Rocket Motor Plume, AIAA Journal 58 (2020) 1639–1656.
[12] R.G. Ryan, E.A. Marais, C.J. Balhatchet, S.D. Eastham, Impact of Rocket Launch and Space Debris Air Pollutant Emissions on Stratospheric Ozone and Global Climate, Earth's Future 10 (2022) e2021EF002612.
[13] A.S. Pagan, Dissertation, University of Stuttgart, 2021 (ongoing)

University of Stuttgart
Institute of Space Systems

Thank you!

Jan-Steffen Fischer, M.Sc.

e-mail fischerj@irs.uni-stuttgart.de
phone +49 (0) 711 685- 69628
www.irs.uni-stuttgart.de

University of Stuttgart
Institute of Space Systems
Pfaffenwaldring 29
70569 Stuttgart