Overview of DLR Initiative S3D: Space Sustainability and Sustainable Development

Clean Space Days 2024

Moritz Herberhold – German Aerospace Center (DLR) – Institute of Space Systems

Overview:

- S3D-Initiative Overview
- Impact of Launch Emissions
  - Importance
  - Challenges
  - Current Results
- 2025 Goals of S3D

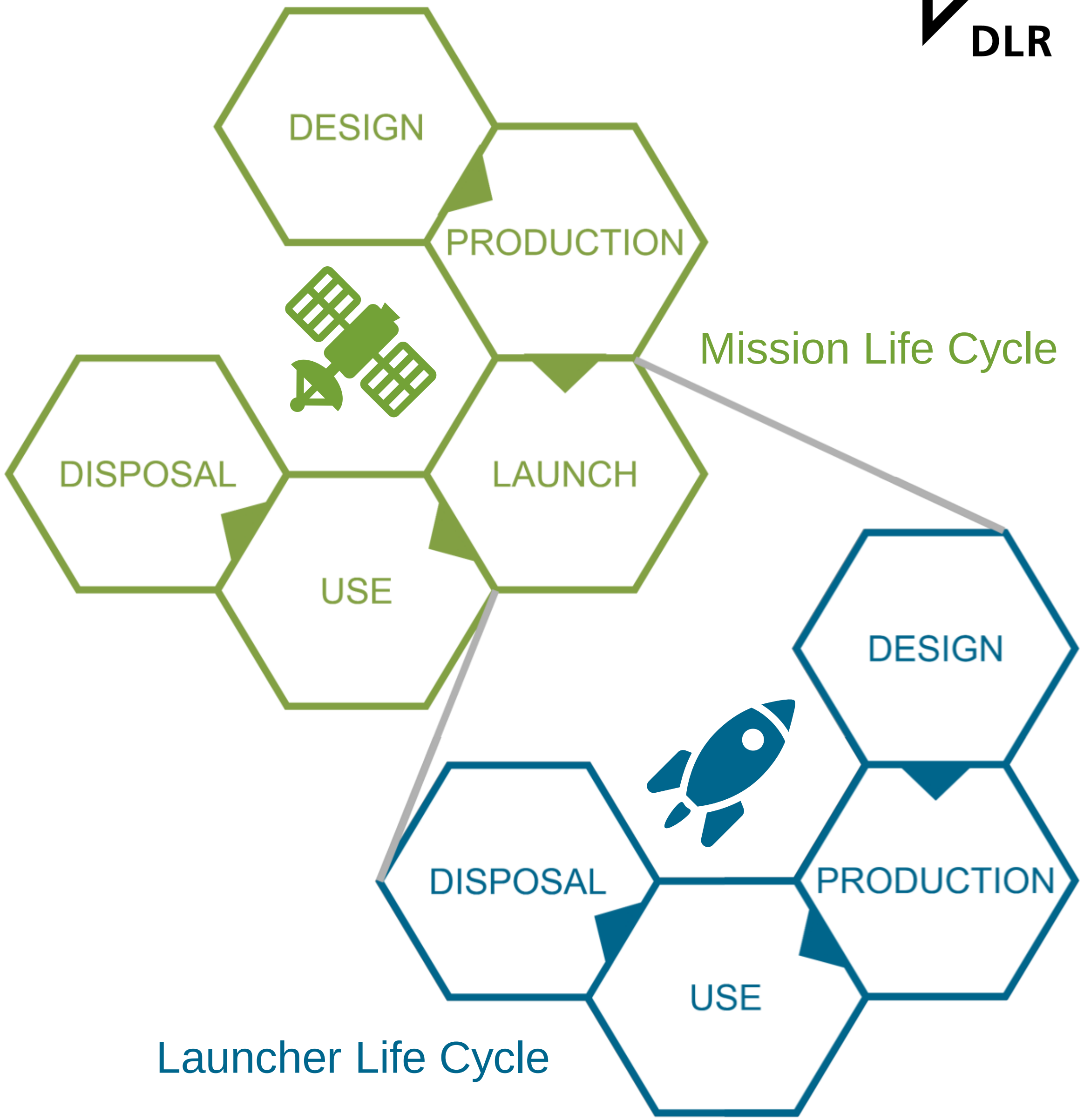
S3D-Initiative Overview:

Goal

- Build the ability to assess space missions, programs and systems in terms of ecological, social and economical sustainability
- Two sectors:
  - Mission Life Cycle
  - Launcher Life Cycle

Participants

- DLR-Institutes:
  - Space Systems (RY)
  - Networked Energy Systems (VE)
  - Structures and Design (BT)
  - Software Technology (SC)
  - Aerodynamics and Flow Technology (AS)
  - Space Propulsion (RA)
  - Atmospheric Physics (PA)



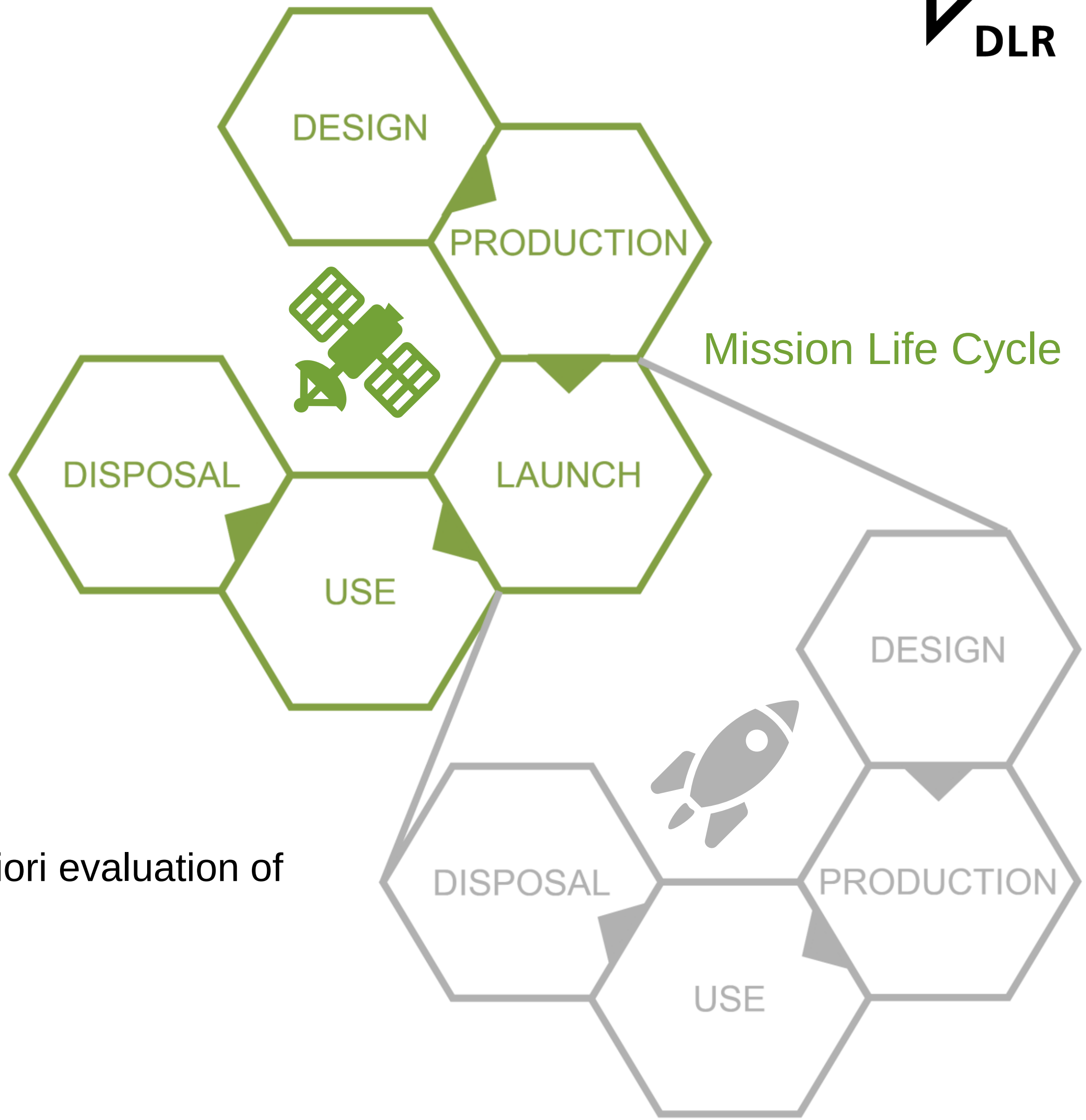
S3D-Initiative Overview: Mission Life Cycle

Problem

- No established processes for assessing space projects in all sustainability dimensions (Life-Cycle-Sustainability-Assessment)
  - Ecological
  - Social
  - Economical
- Lack of data

Contribution

- Identification of suitable sustainability metrics (RY, VE)
- Establishment of a process in DLR (and the industry) for a priori evaluation of **missions**, **launchers** and **technologies** (RY, VE, BT, SC)
  - Integration into digital spacecraft tools (VirSat)



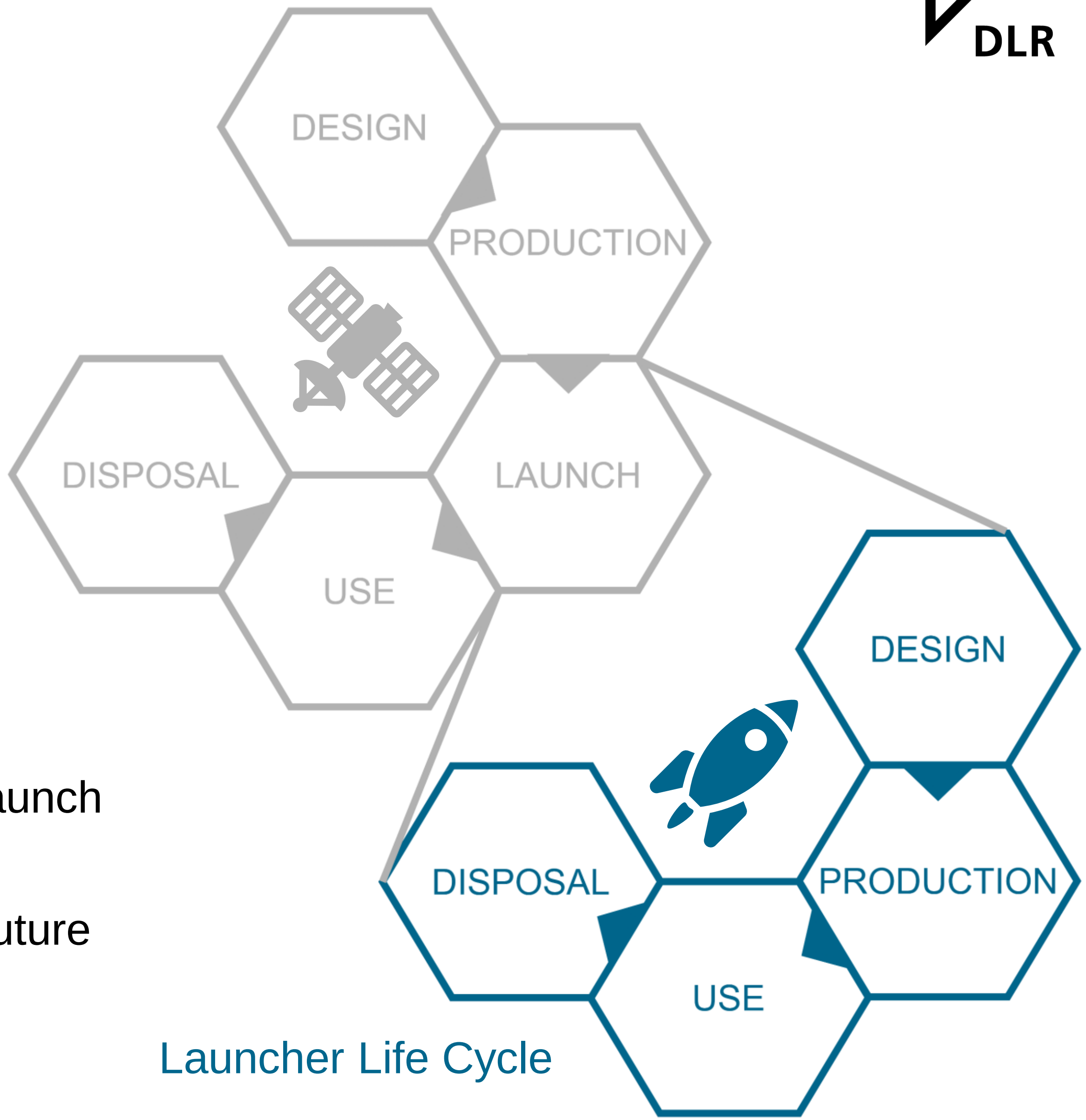
S3D-Initiative Overview: Launcher Life Cycle

Problem

- Similar problems for design and production phases
  - Lack of data and additional secrecy
  - No established processes
- Unique problems for use and disposal phases
  - Impact of launch and demise emissions remains largely unknown

Contribution

- Combined, multidisciplinary effort to evaluate impact launch emissions (RY,RA,AS,PA)
- Consolidation and application in LCSA, evaluation of future launchers (RY)

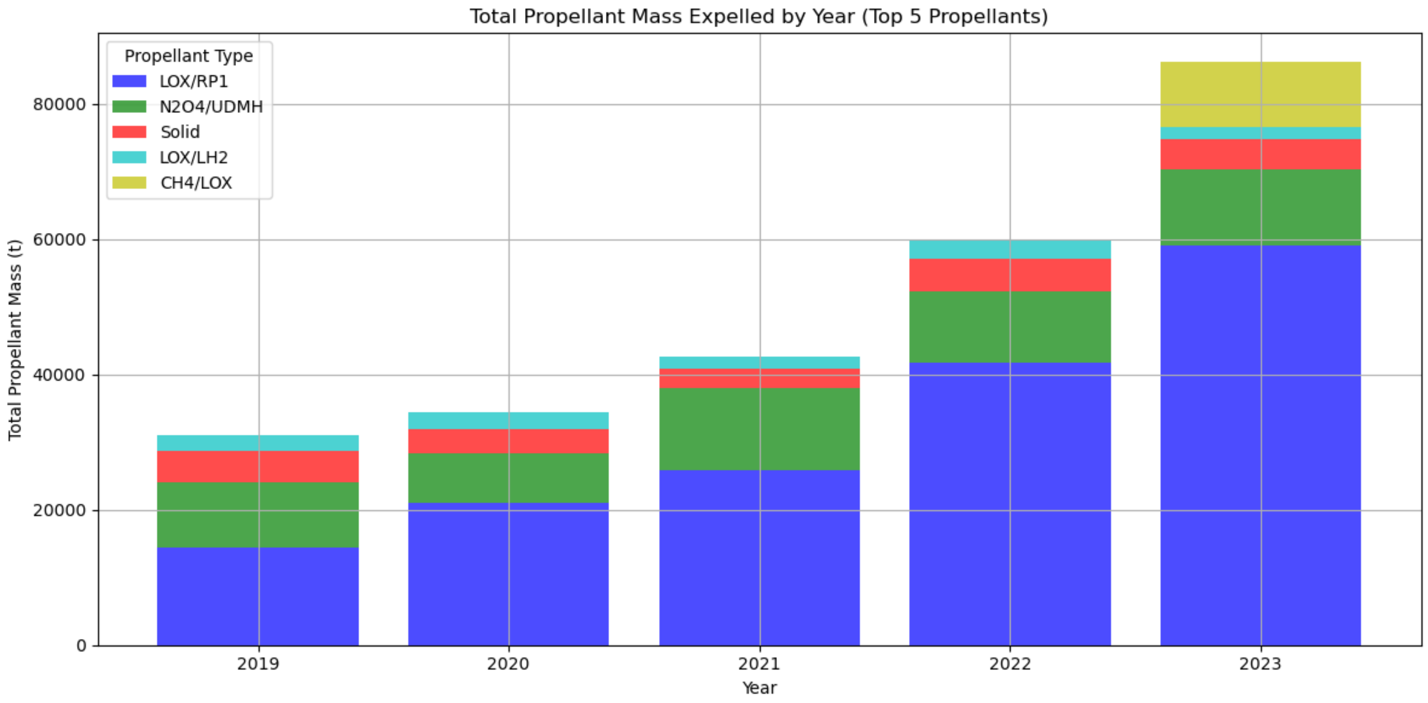


Launcher Life Cycle

Impact of Launch Emissions: **Significance**

Significance:

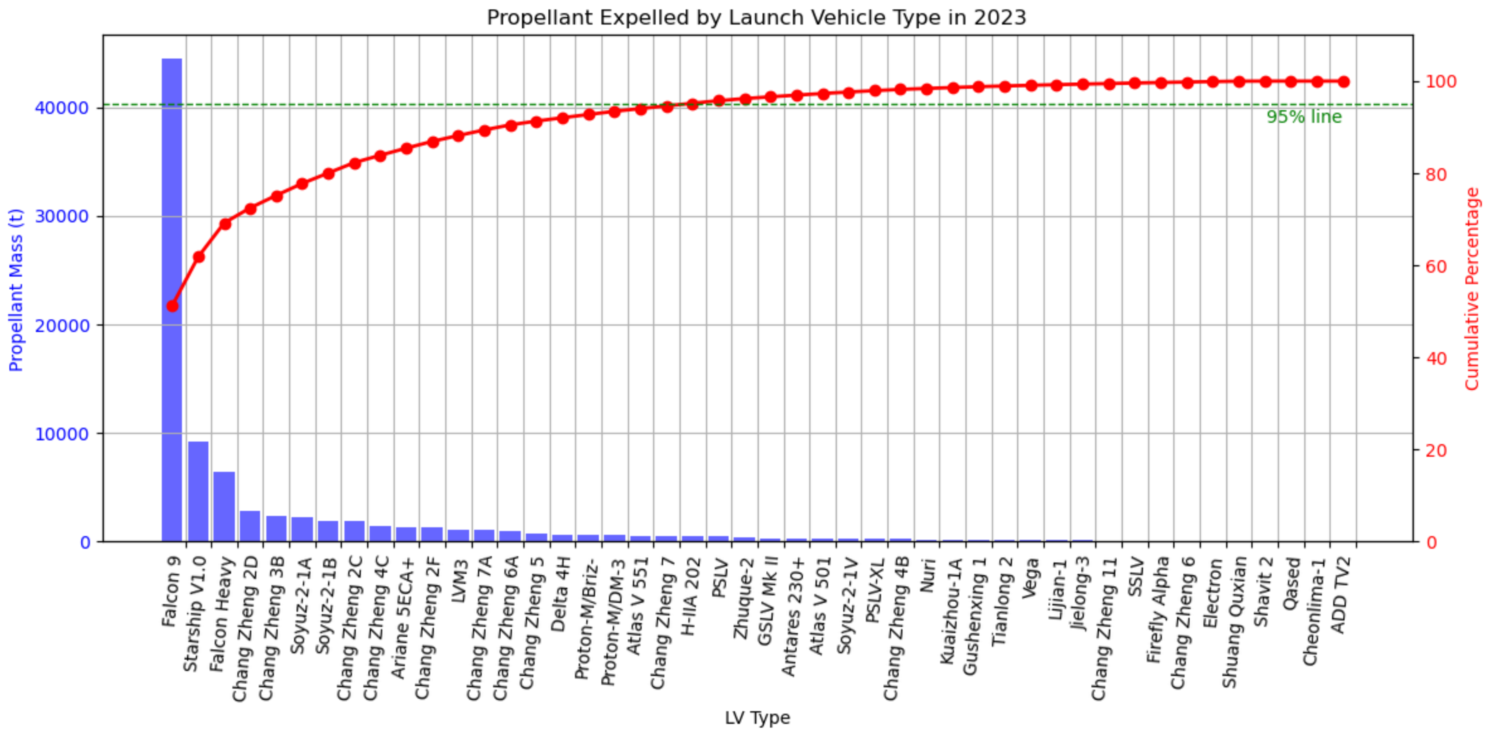
- Total propellant mass burned almost tripled since 2019 and continues to grow
- Direct emission into all atmospheric layers of potentially relevant gases and particles (CO2, H2O, Soot, Al2O3, Al, NOx…)
- Large uncertainty in the impact of exhaust gases in the stratosphere, mesosphere and beginning of the thermosphere
- Studies for super- and subsonic aviation show large dependence of impact on emission altitude [1,2]
- Evaluation or optimization of current and future space transport systems with regard to ecological impact is only possible if launch emission impact is known



Impact of Launch Emissions: **Challenges**

1. Challenge: Launchers

- Large variety of launchers, propellants, engines and trajectories
- Limited data about individual launchers
- Future development difficult to predict



➢ Remodeling of current and future launchers and their trajectories (RY)

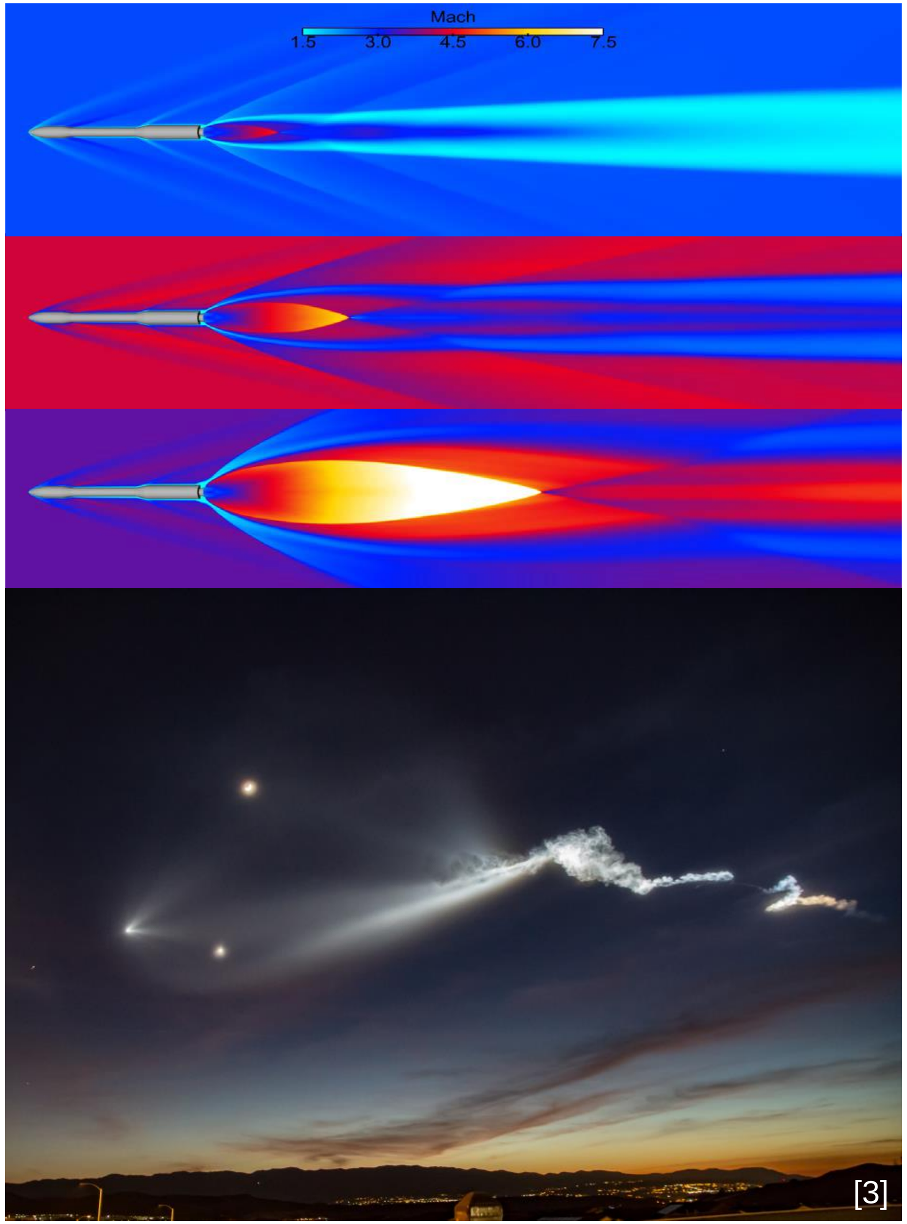
Impact of Launch Emissions: **Challenges**

1. Challenge: Launchers

2. Challenge: Engine Exhaust + Early & Intermediate Plume

- Large variety of propellants and engine cycles with enormous variety of chemical products
- In the early plume highly energetic flow post-combusts and mixes and reacts with the atmosphere
- Intermediate plume spreads in the atmosphere due to concentration gradient and further reacts with ambient air
- Realistic modeling needs multiple sequenced models that represent many dependencies

➢ Numerical (AS) and experimental (RA, AS) investigation of the exhaust plume



[3]

Impact of Launch Emissions: **Challenges**

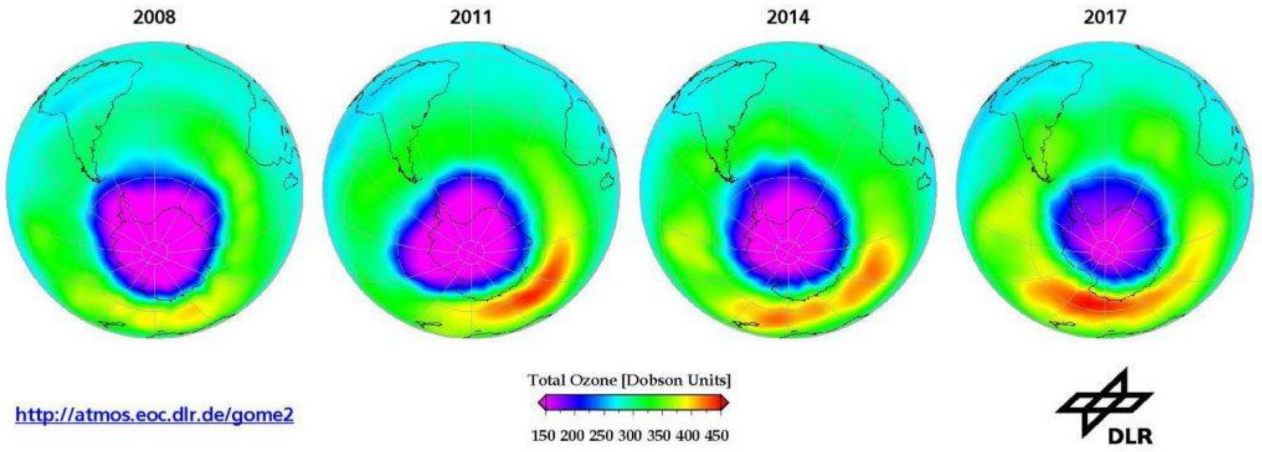
1. Challenge: Launchers

2. Challenge: Engine Exhaust + Early & Intermediate Plume

3. Challenge: Atmospheric impact

- Multitude of potential effects (radiative forcing, ozone depletion e.g. through catalytic reactions, cloud effects,...)
- Complex effects dependent on species, concentration, altitude, location…
- Climate models are complex and often end between 50-80km

➢ Simulation of influence of gases/particles in high atmospheric layers, also from re-entries with chemistry climate model (PA)



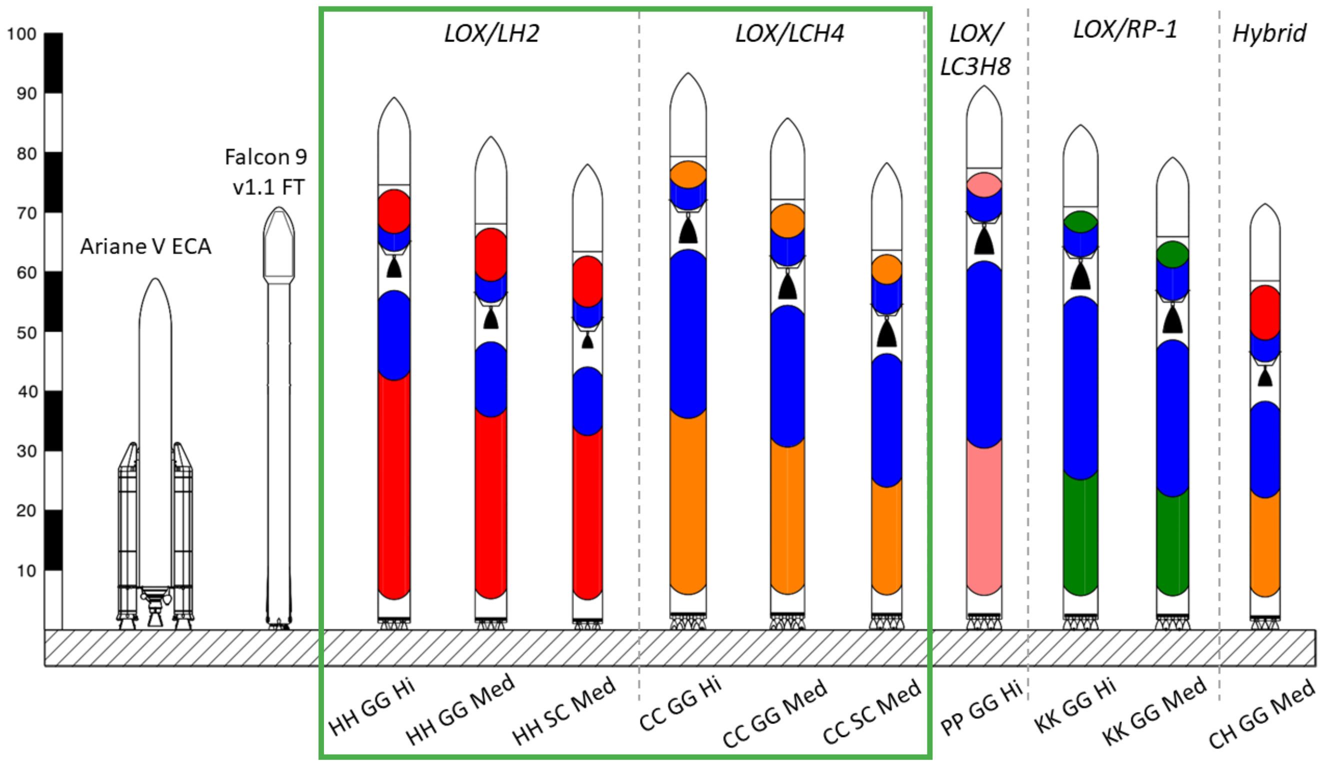
Impact of Launch Emissions: **Current State**

Exhaust Inventories for ENTRAIN

- ENTRAIN provides a library of generic launchers
- designed for identical mission (7.5t to GTO)
- different fuel combinations, engine types, and reuse methods

So far investigated:

- **Expendable** vs. **Vertical Landing** vs. Horizontal Landing (IAC)
- **LOX/LH2** vs. **LOX/LCH4**
- Gas Generator Engine vs. Staged Combustion Engine



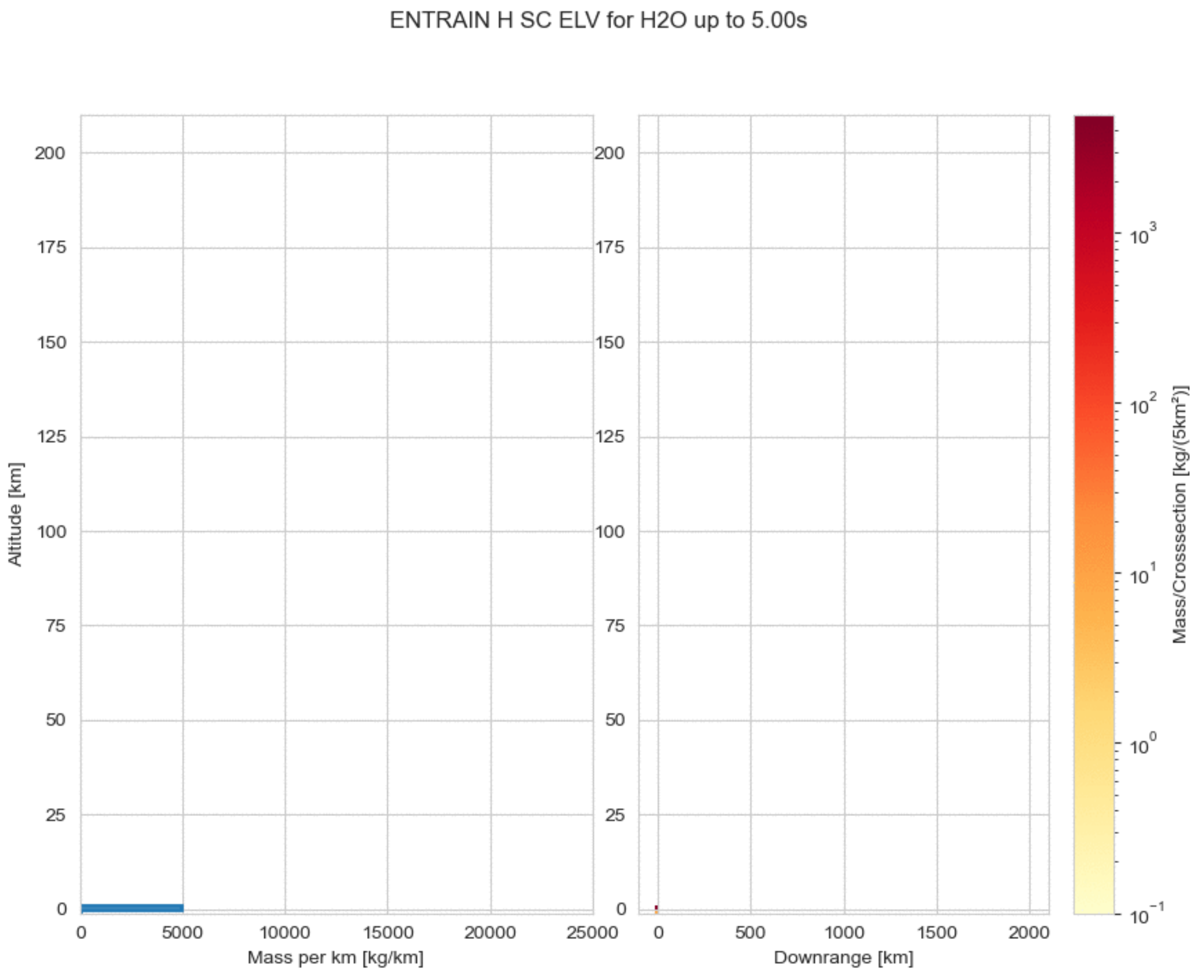
Impact of Launch Emissions: **Current State**

Exhaust Inventories for ENTRAIN

- Ascent trajectory is simulated and exhaust is calculated from engine mass flow
- Only representation of reactions in combustion chamber
- No nozzle, no post-combustion, no reactions with air, no independent movement of exhaust

Result for H2 ELV:

Species	Total Mass [kg]	Share
H20	219422	95.8%
H2	4848	2.1%
OH	3973	1.7%
O2	561	0.2%
H	156	<0.1%
O	138	<0.1%
HO2	2	<0.1%
H2O2	1	<0.1%
Total	229101	



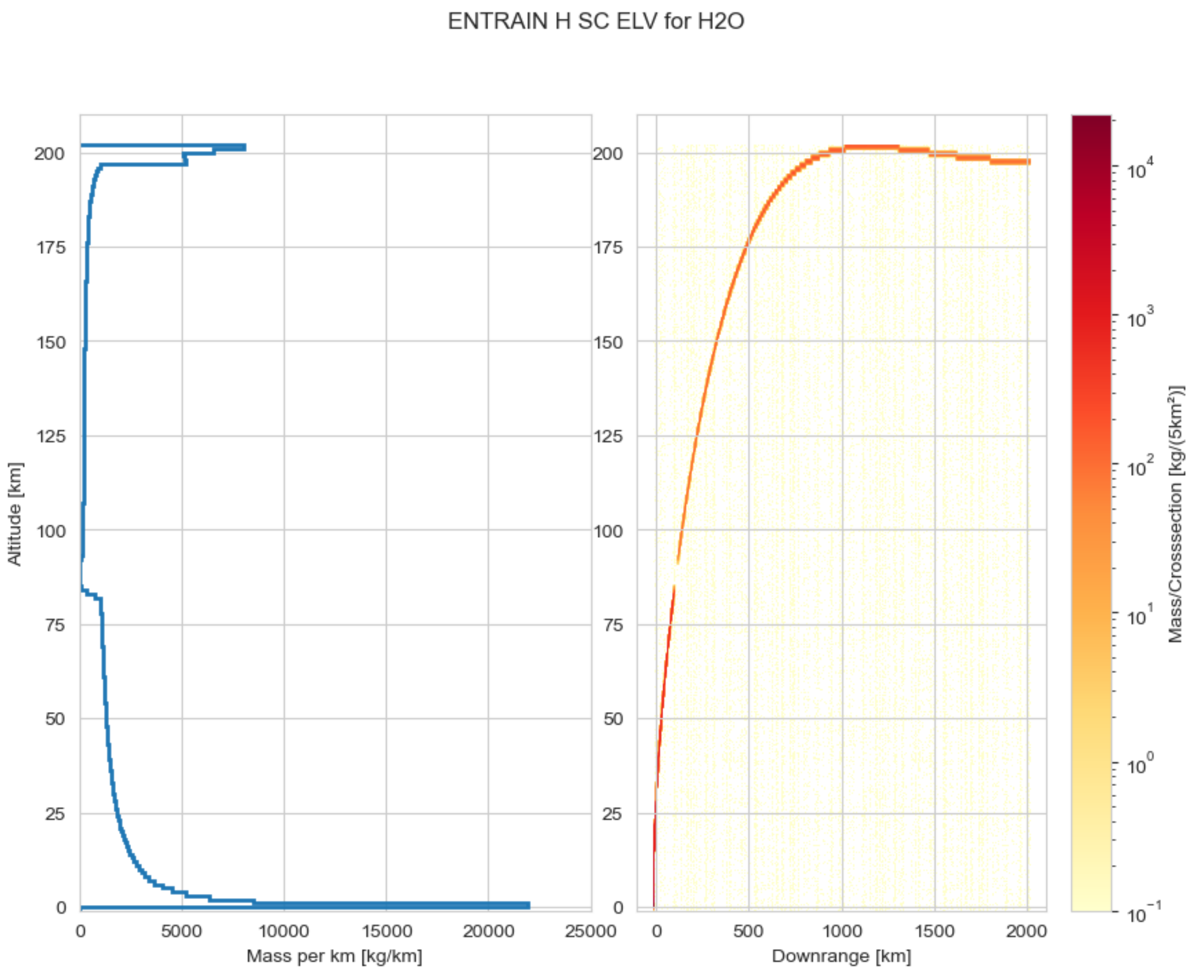
Impact of Launch Emissions: **Current State**

Exhaust Inventories for ENTRAIN

- Ascent trajectory is simulated and exhaust is calculated from engine mass flow
- Only representation of reactions in combustion chamber
- No nozzle, no post-combustion, no reactions with air, no independent movement of exhaust

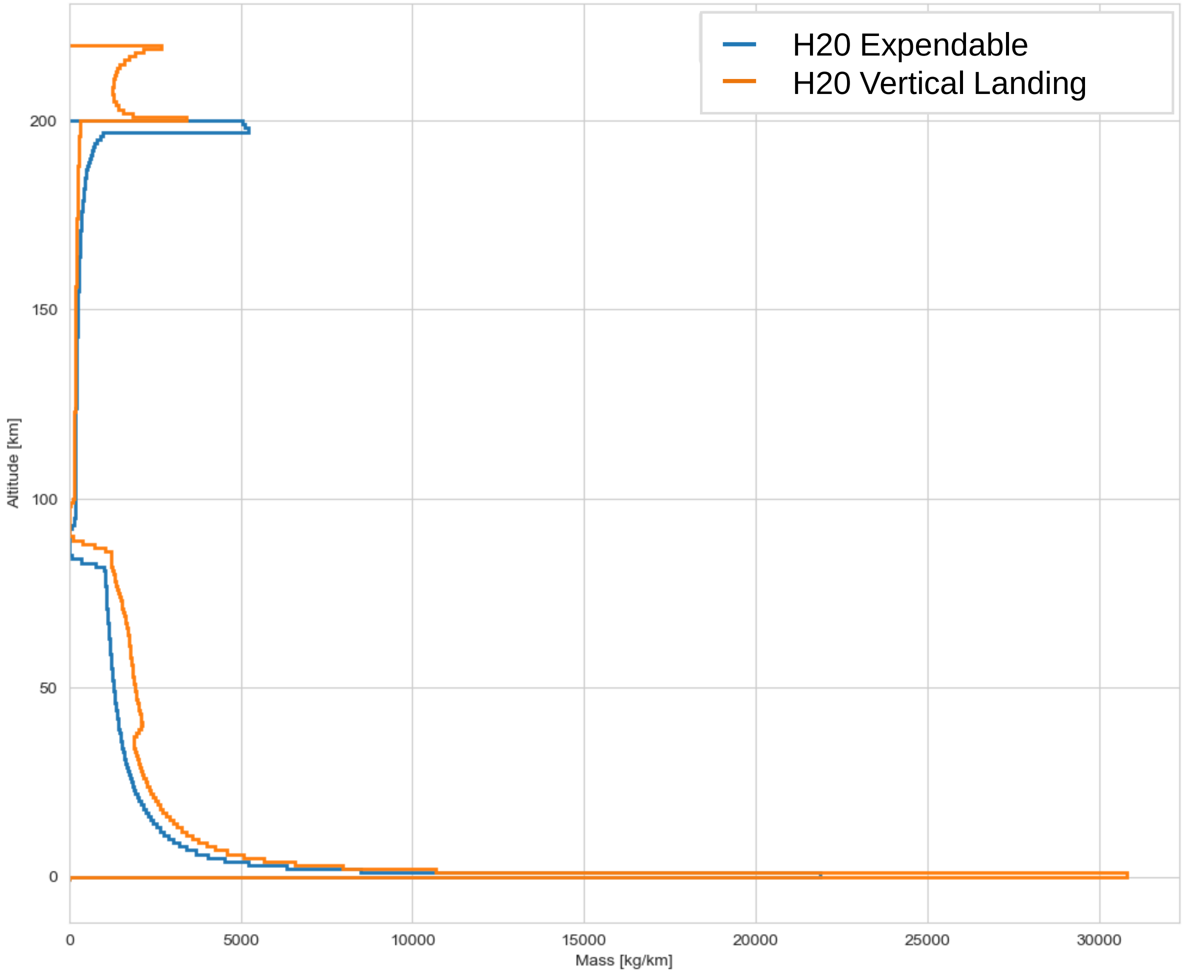
Result for H2 ELV:

Species	Total Mass [kg]	Share
H20	219422	95.8%
H2	4848	2.1%
OH	3973	1.7%
O2	561	0.2%
H	156	<0.1%
O	138	<0.1%
HO2	2	<0.1%
H2O2	1	<0.1%
Total	229101	



Impact of Launch Emissions: **Current State**

ELV vs. VTVL vs. VTHL: H20 Exhaust



Expendable

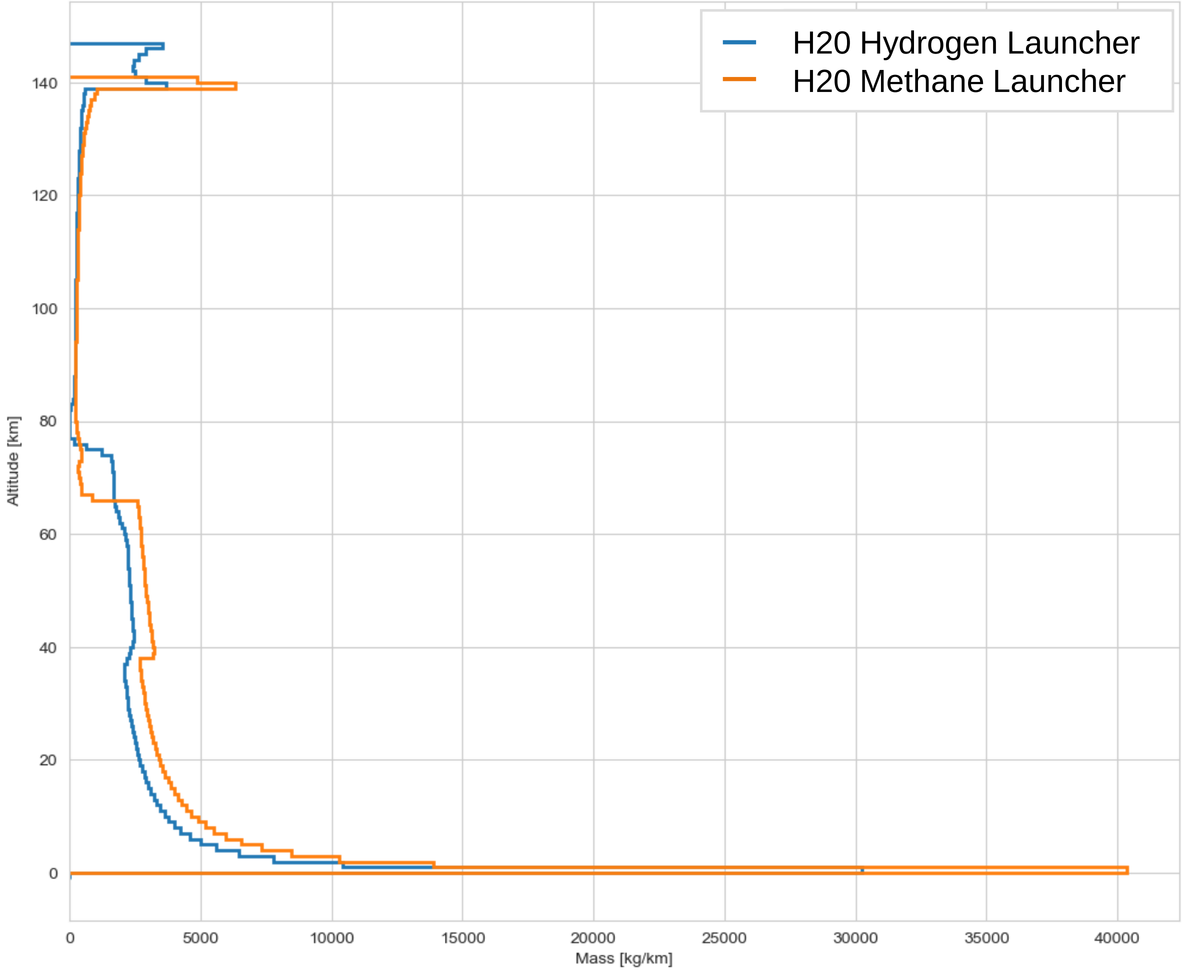
Total Exhaust 229 t

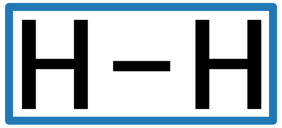
Vertical Landing

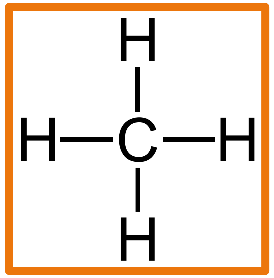
Total Exhaust 301 t +31%

Impact of Launch Emissions: **Current State**

LOX/LH2 vs LOX/LCH4: H20 Exhaust







Species	**LH2/LOX Total Mass [kg]**	**CH4/LOX Total Mass [kg]**
H20	288134	+12% 322976
CO2	-	221383
CO	-	154371
…	…	..
Total	300840	+139% 718751

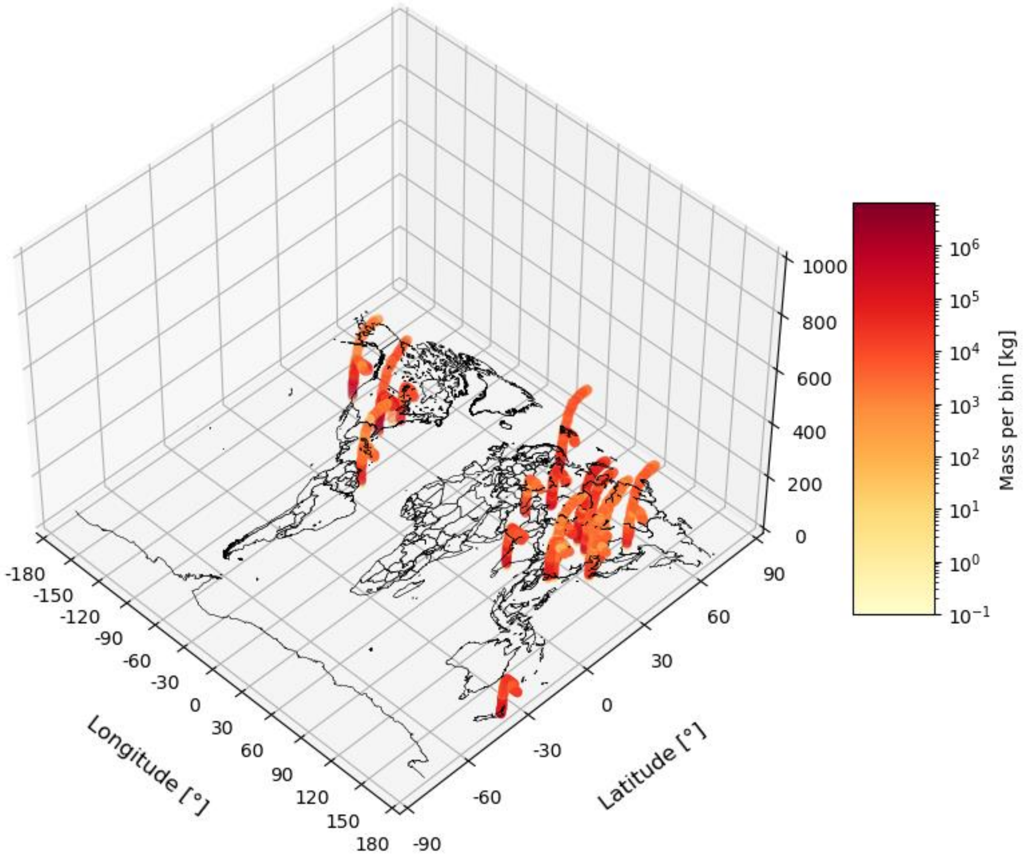
2025 Goals of S3D:

Impact of launch emissions:

- Creation of exhaust inventories of relevant, current launchers
- Analysis of climate impact for the created exhaust inventories
- Numerical analysis of typical flight conditions during ascent and re-entry
- Spectrographic measurements on engines

Mission life cycle:

- Implementation of LCSA with approx. 10 indicators
- Stakeholder involvement via exchange
- Identification of drivers for sustainability impacts
- Identify/ evaluate alternative technologies

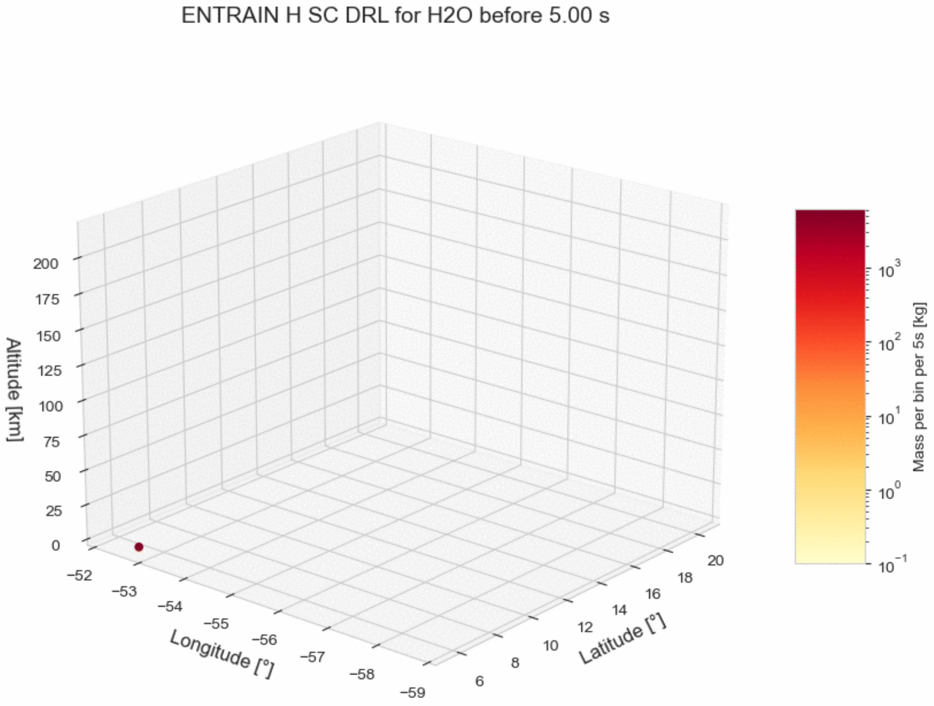


Thank you for listening!

Contact:

Moritz Herberhold - Presenter
Mail: Moritz.Herberhold@dlr.de
Telephone: +49 421 24420-1339

Volker Maiwald – Initiative Leader
Mail: Volker.Maiwald@dlr.de
Telephone: +49 421 24420-1251

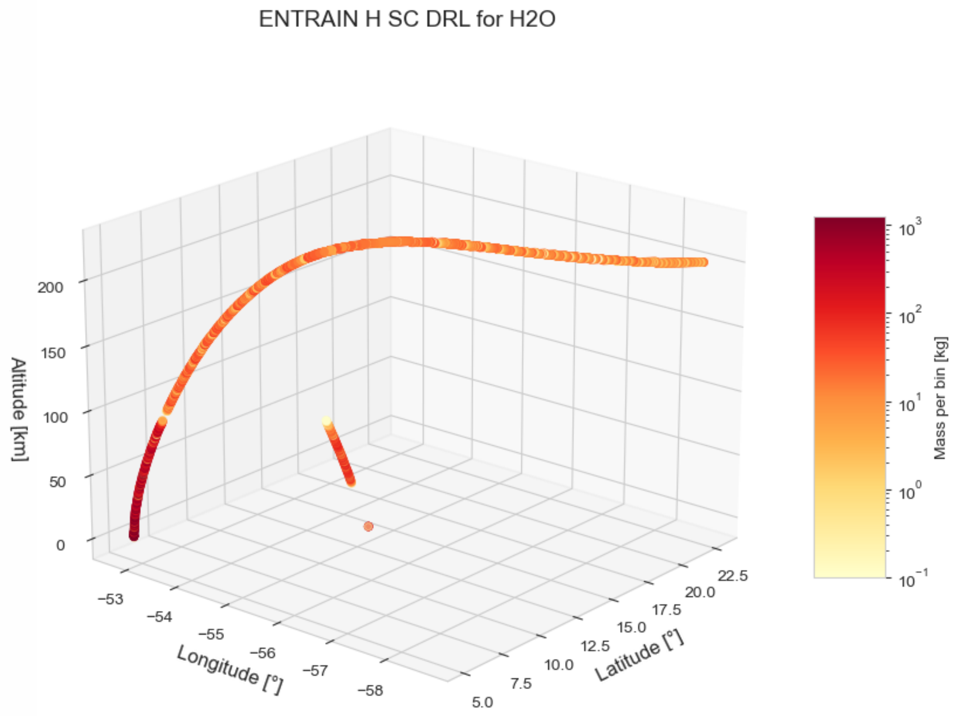


Thank you for listening!

Contact:

Moritz Herberhold - Presenter
Mail: Moritz.Herberhold@dlr.de
Telephone: +49 421 24420-1339

Volker Maiwald – Initiative Leader
Mail: Volker.Maiwald@dlr.de
Telephone: +49 421 24420-1251



Sources:

[1] Impacts of a near-future supersonic aircraft fleet on atmospheric composition and climate, Sebastian D. Eastham, Thibaud Fritz, Inés Sanz-Morère, Prakash Prashanth, Florian Allroggen, Ronald G. Prinn, Raymond L. Speth, Steven R.H. Barrett ; Laboratory for Aviation and the Environment, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[2] Review: The Effects of Supersonic Aviation on Ozone and Climate, Sigrun Matthes, , David S. Lee, Ruben Rodriguez De Leon, Ling Lim, Bethan Owen, Agnieszka Skowron,Robin N. Thor and Etienne Terrenoire

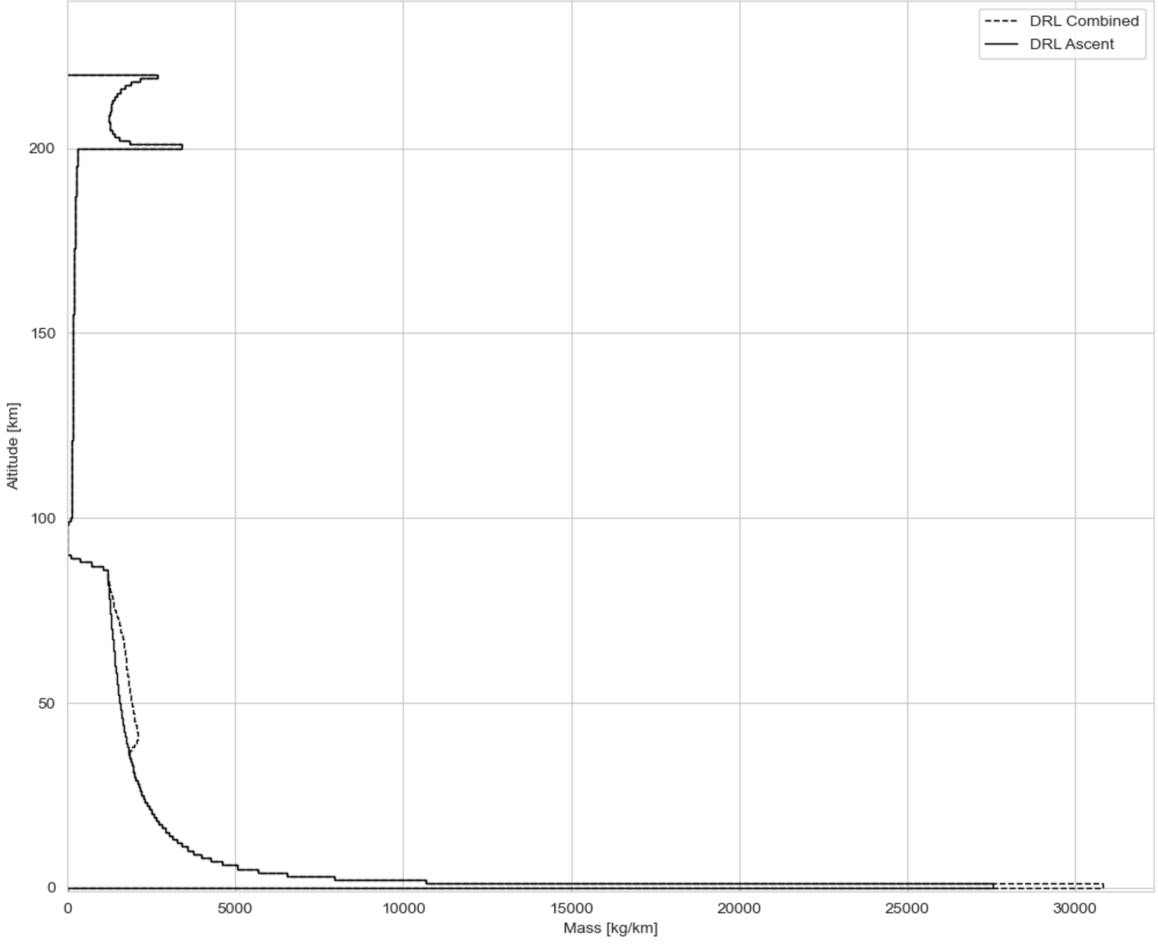
[3] Plume from SpaceX Launch of Iridium-4 Falcon 9 Flight 46,Wikimedia , Available: https://upload.wikimedia.org/wikipedia/commons/d/d4/Plume_from_SpaceX_Launch_of_Iridium-4_Falcon_9_Flight_46.jpg [Accessed 7 10 2024].

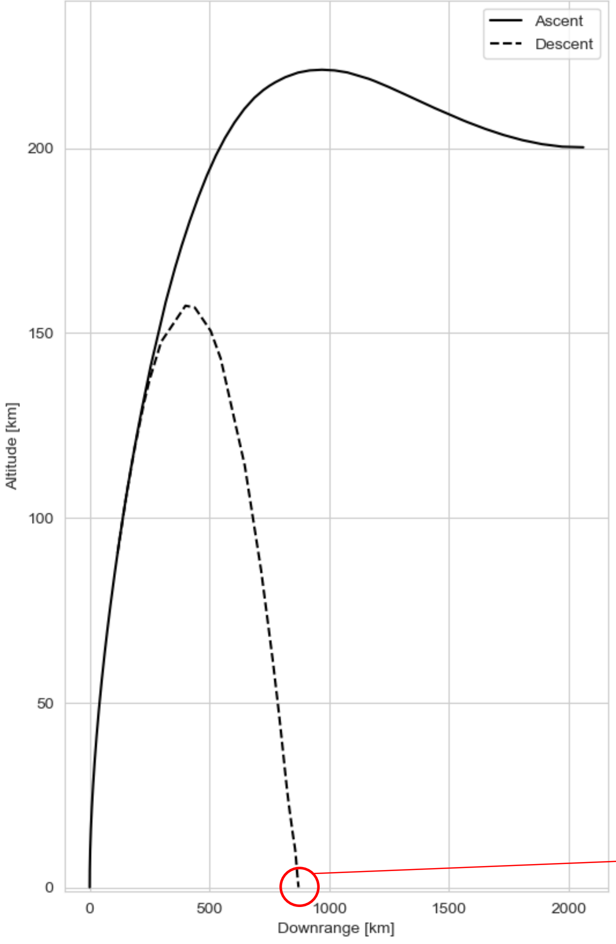
[4] SpaceX, X.com, 2021-2024, URL: https://x.com/spacex Available: https://forum.nasaspaceflight.com/index.php?topic=47352.520 [Accessed 25 9 2024].

[5] Stoke Space Successfully Completes Hotfire Test of Full-Flow Staged-Combustion Engine, SATNow, Available: https://www.satnow.com/news/details/2058-stoke-space-successfully-completes-hotfire-test-of-full-flow-staged-combustion-engine [Accessed 6 10 2024].

Impact of Launch Emissions: **Current State**

LOX/LH2 Staged Combustion Down Range Landing:

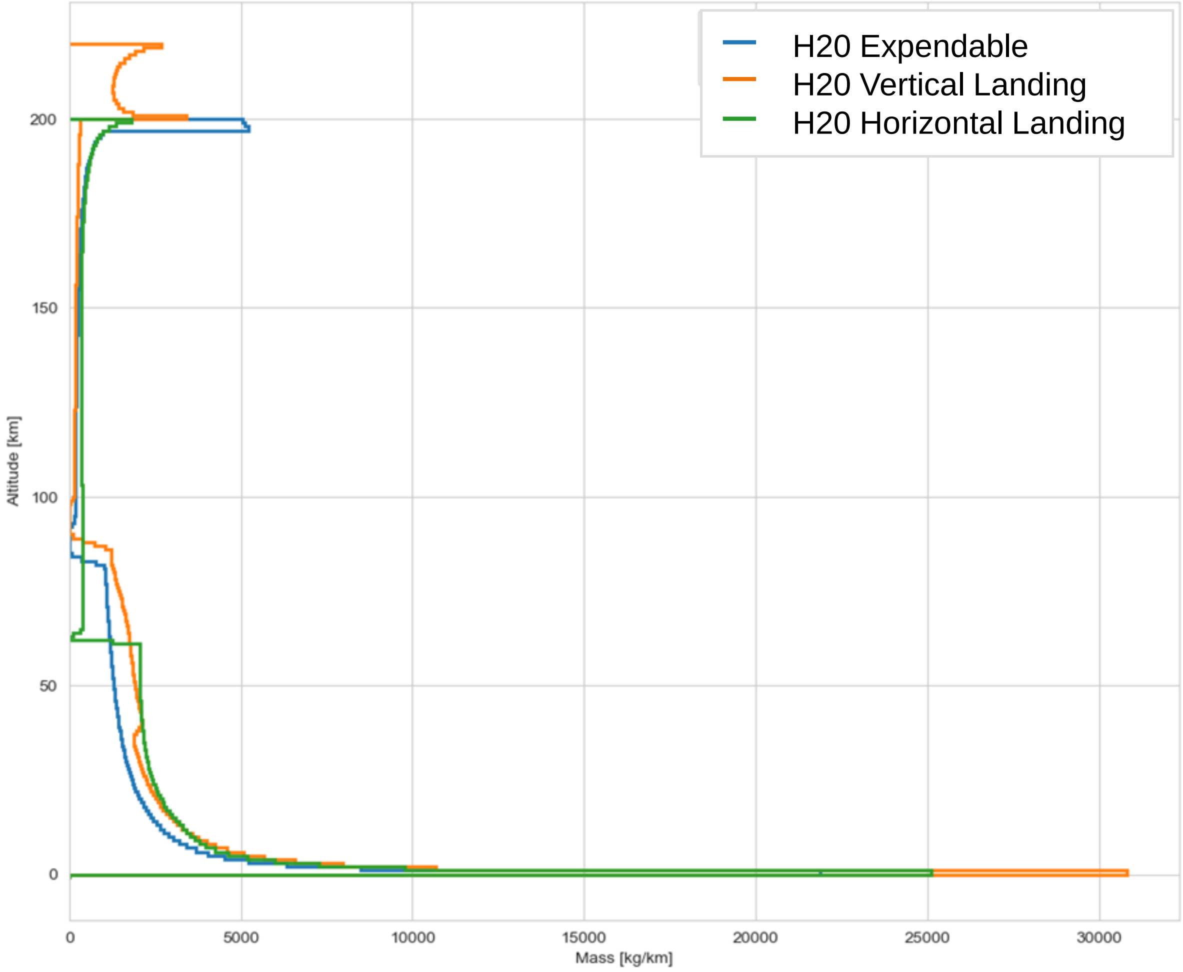




Species	Total Mass [kg]
H20	288134
H2	6366
OH	5216
O2	736
H	204
O	181
HO2	2
H2O2	1
Total	300840

Impact of Launch Emissions: **Current State**

ELV vs. VTVL vs. VTHL: H20 Exhaust



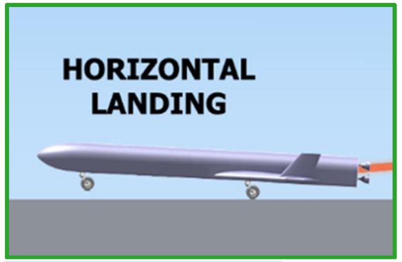
Expendable

Total Exhaust	229 t

Vertical Landing

Total Exhaust	301 t

+31%



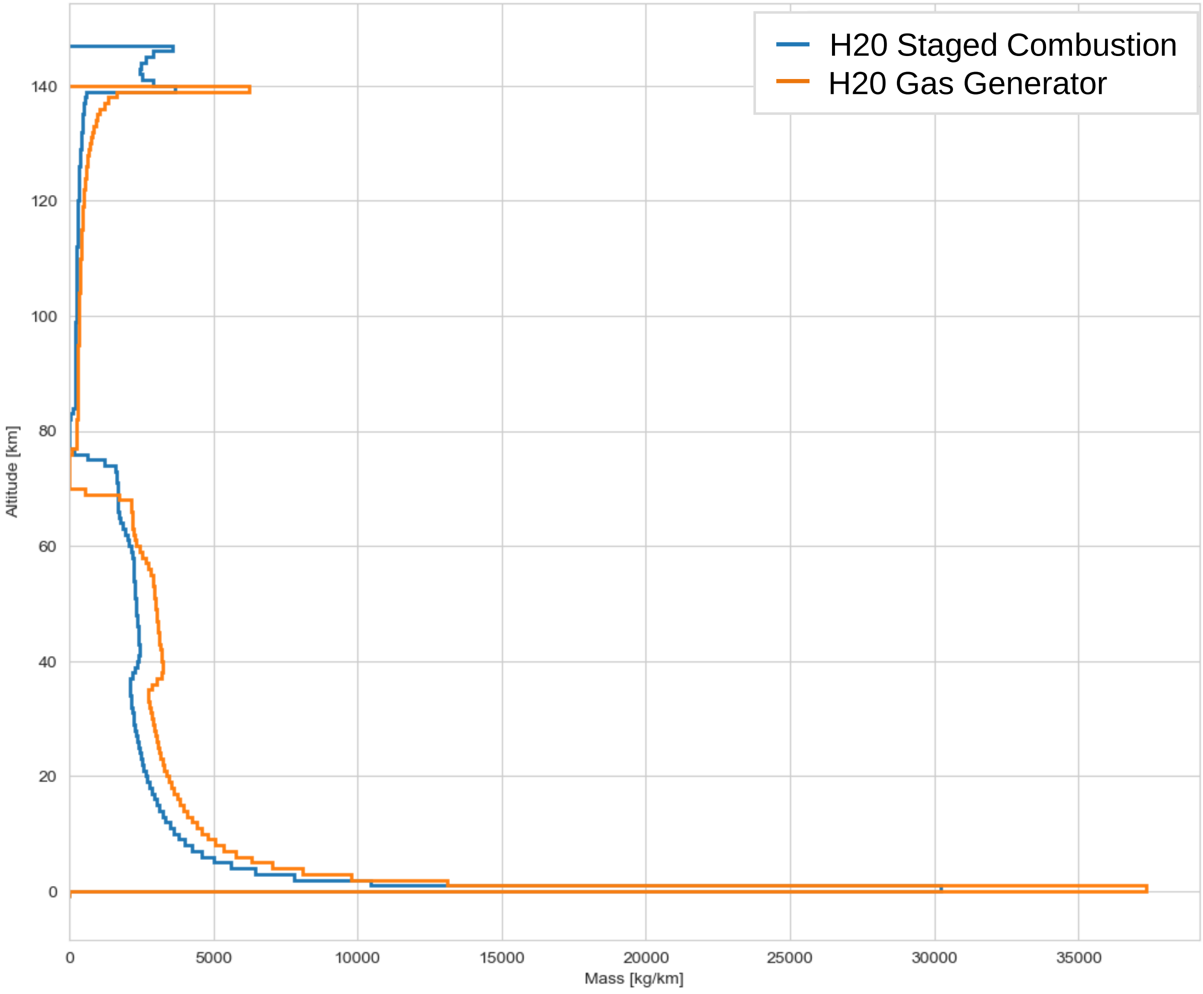
Horizontal Landing

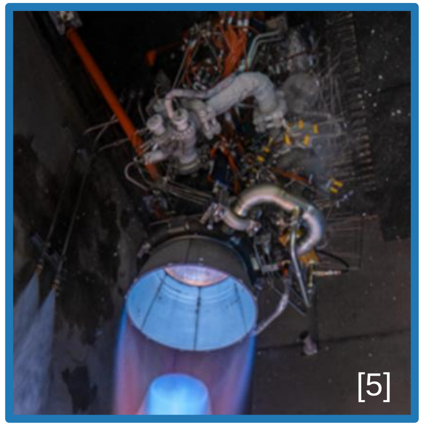
Total Exhaust	264 t

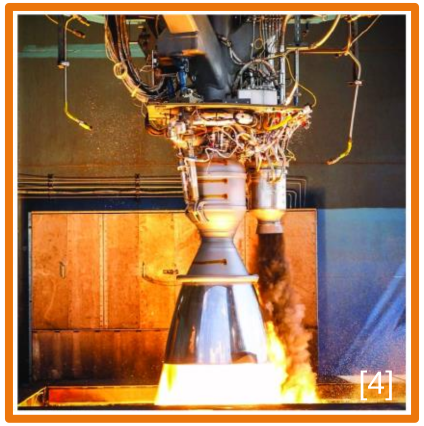
+15%

Impact of Launch Emissions: **Current State**

LOX/LH2 Engine Type Comparison: H20 Exhaust







Staged Combustion

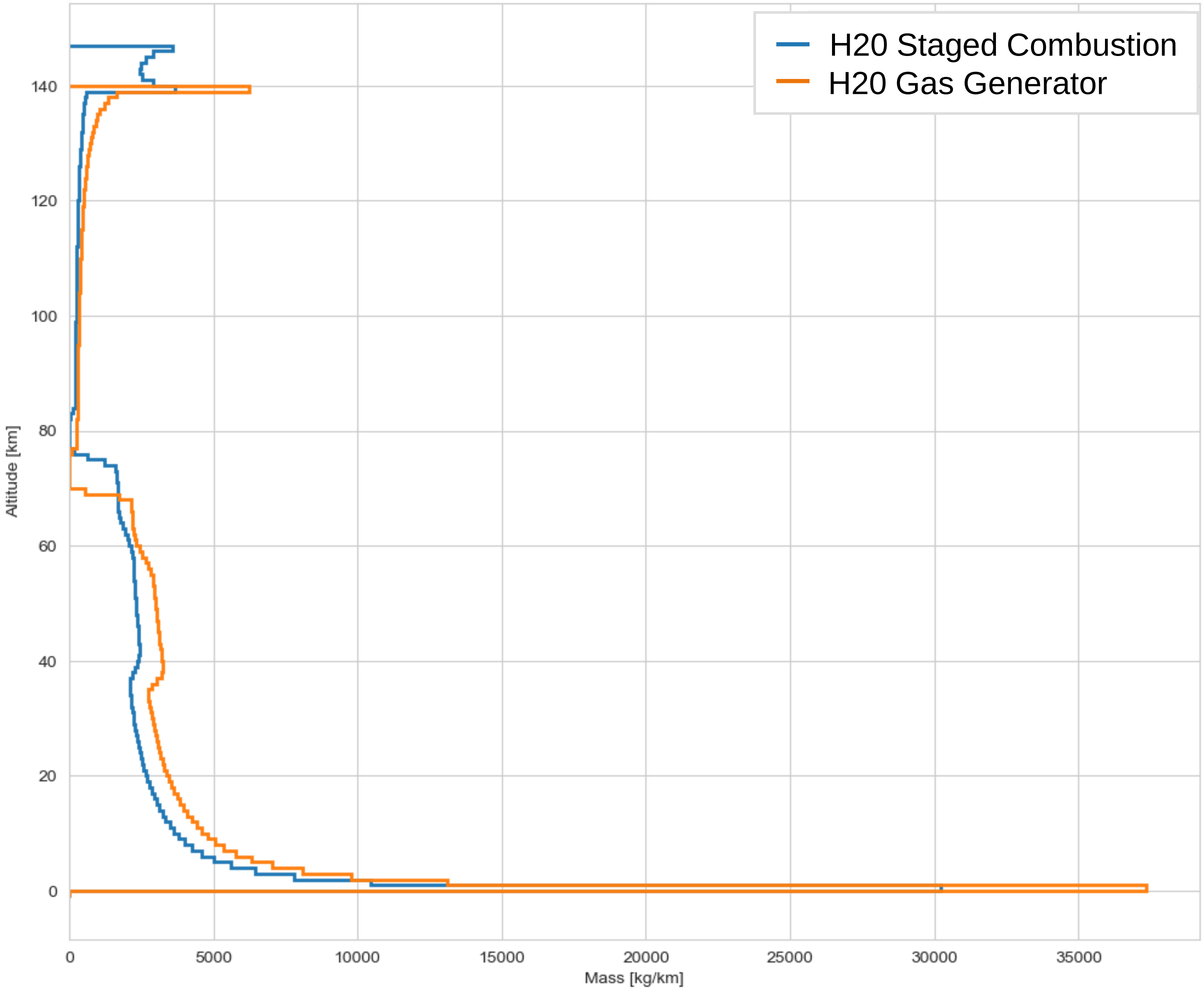
- Higher specific impulse
- Higher complexity
- All fuel flows through main combustion chamber

Gas Generator

- Higher Thrust-to-Weight ratio
- Fuel-rich, incompletely combusted exhaust gases from gas generator

Impact of Launch Emissions: **Current State**

LOX/LH2 Engine Type Comparison: H20 Exhaust



Species	Staged Combustion Total Mass [kg]	Gas Generator Total Mass [kg]
H20	272885	318841
H2	6029	17060
OH	4940	5747
O2	697	811
H	194	225
O	172	200
HO2	2	2
H2O2	1	1
Total	284920 +20%	342887