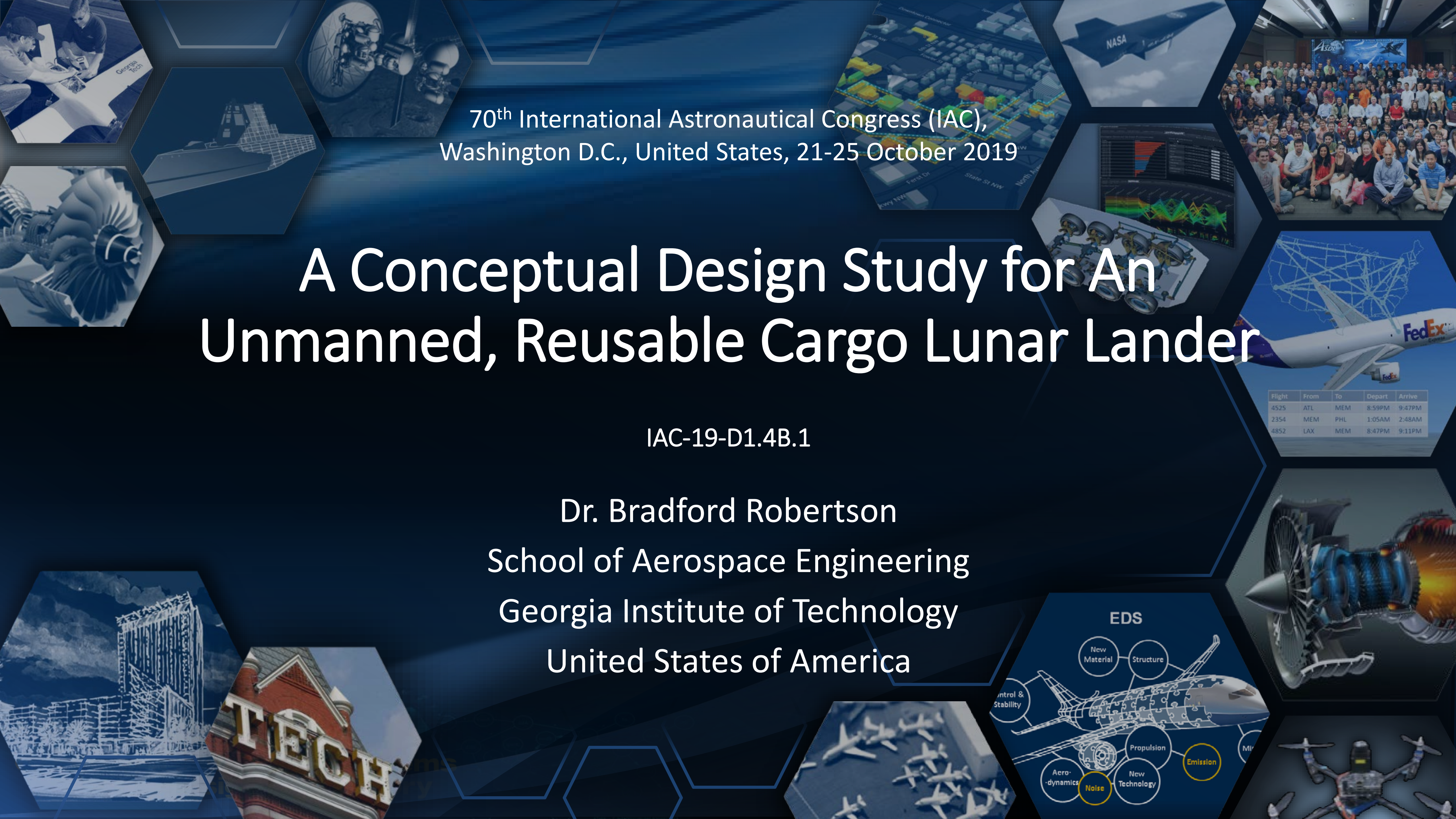

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A Conceptual Design Study for An Unmanned, Reusable Cargo Lunar Lander

IAC-19-D1.4B.1

Dr. Bradford Robertson
School of Aerospace Engineering
Georgia Institute of Technology
United States of America

Background/Motivation

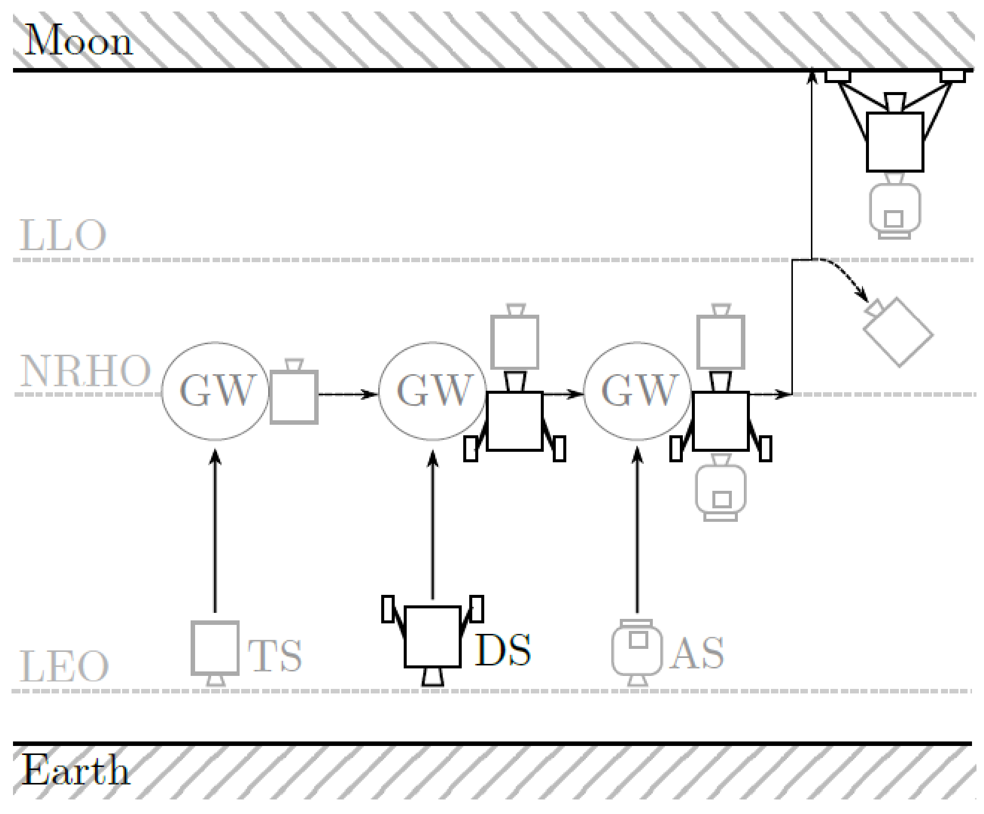
- NASA’s Artemis program targets a manned lunar mission by 2024 and sustainable missions by 2028

- As part of the overall program, roles for different classes of lunar lander have been identified
  - Small landers (~10 kg) land small scientific and demonstration payloads
  - Mid-sized landers (500 – 1000 kg) land larger payloads and act as technology demonstrators
  - Human landers (9000 – 12000 kg) land 4 astronauts and an ascent stage

- NASA has also identified several technological goals
  - Reusability, cryogenic fluid management, cryogenic refueling
  - Need to be demonstrated on unmanned missions

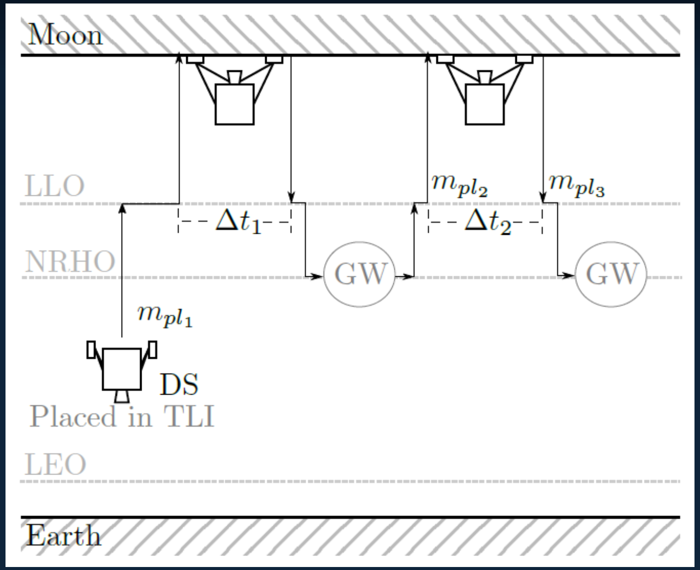
Multi-Mission Lunar Lander

- Artemis proposes using a three stage lunar lander
  - Transfer stage: NRHO → LLO
  - Descent stage: LLO → Surface
  - Ascent stage: Surface → NRHO
- All elements can be launched on commercial vehicles and are staged at Gateway
- This study examines utilizing the Artemis descent stage as a multi-mission lander
  - Operate as a mid-sized reusable cargo lander with a useful payload capacity
  - Enable technology demonstration flights and evolution of descent stage
    - Cryogenic fluid management (CFM) as a key technology

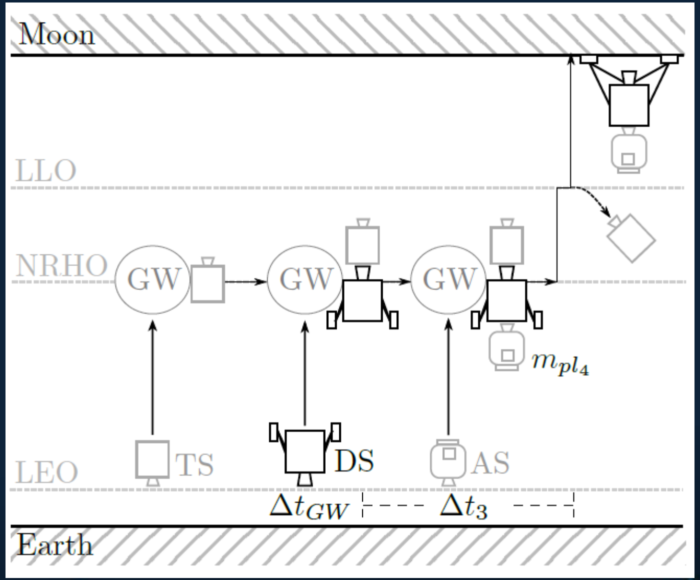


Sizing Missions

- Mid-sized lunar lander cargo mission
  - Deployment Mission
    - Launch Vehicle places lander in TLI
    - Lander delivers a deployment payload
    - After delivery lander returns to gateway
  - Reuse Cycle
    - Lander departs from gateway
    - Delivers reuse payload
    - Lander returns to gateway with a return payload
- Human Landing Mission
  - Launch vehicle places lander in TLI
    - Fast or slow transfer to Gateway
  - Lander inserts into NRHO
  - Lander waits for ascent stage and crew
  - Lander performs descent and landing maneuvers with ascent stage as payload



Cargo Mission



Human Landing Mission

Vehicle and Mission Trade Space

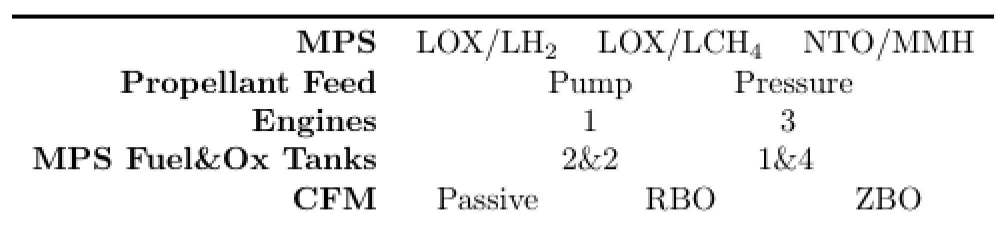
- Discrete and Continuous Trade space

- 28 Vehicle Architecture options
  - Only considering pressure fed NTO/MMH
  - NTO/MMH not eligible for active CFM
  - LOX/LCH4 only allowed ZBO

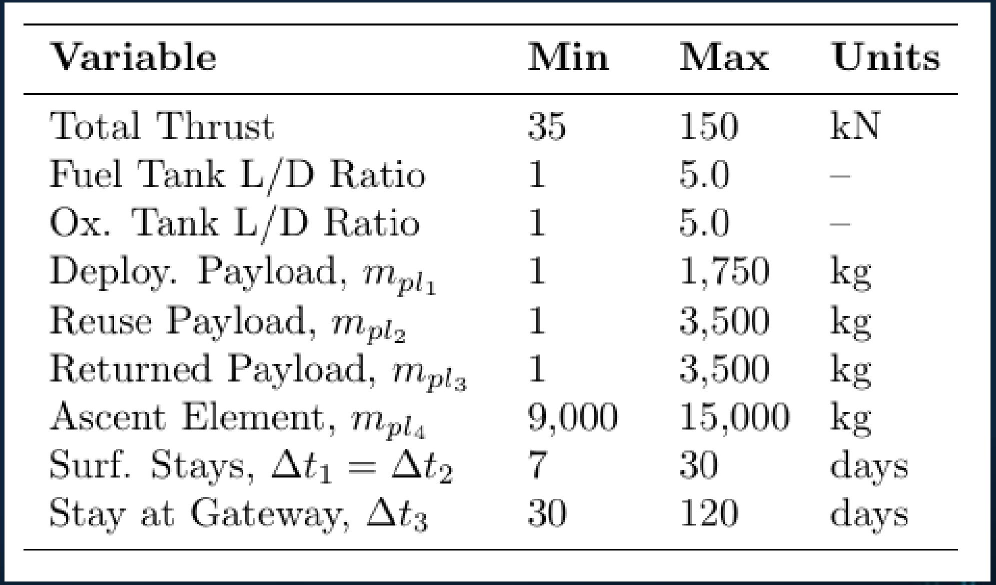
- Two mission architecture options
  - Fast or slow transfer to Gateway

- 56 total discrete vehicle/mission combinations

- For each architecture, 9 continuous variables
  - 3 vehicle design parameters
  - 4 payload parameters
  - 2 mission parameters



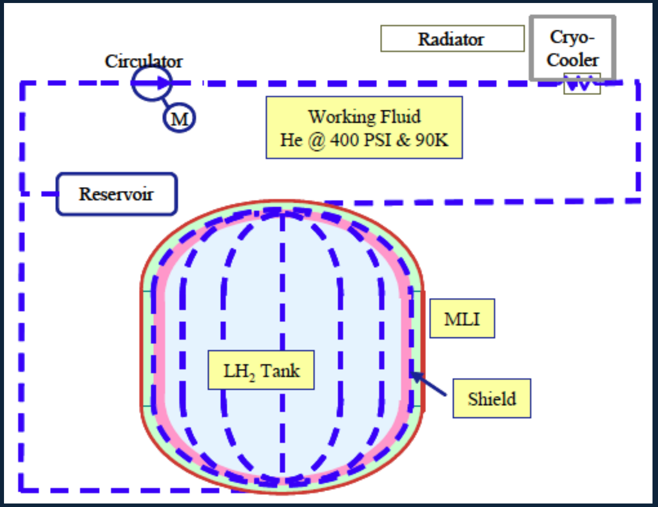
MPS	LOX/LH_2	LOX/LCH_4	NTO/MMH
Propellant Feed	Pump	Pressure	
Engines	1	3	
MPS Fuel&Ox Tanks	2&2	1&4	
CFM	Passive	RBO	ZBO



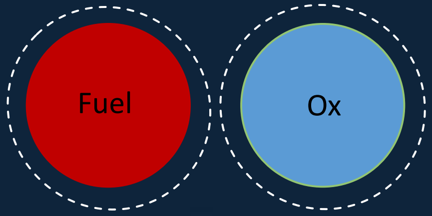
Variable	Min	Max	Units
Total Thrust	35	150	kN
Fuel Tank L/D Ratio	1	5.0	–
Ox. Tank L/D Ratio	1	5.0	–
Deploy. Payload, m_{pl_1}	1	1,750	kg
Reuse Payload, m_{pl_2}	1	3,500	kg
Returned Payload, m_{pl_3}	1	3,500	kg
Ascent Element, m_{pl_4}	9,000	15,000	kg
Surf. Stays, $\Delta t_1 = \Delta t_2$	7	30	days
Stay at Gateway, Δt_3	30	120	days

Cryogenic Fluid Management

- ➢ LOX/LCH4 ZBO: 90 K cryocooler LOX + dedicated shield (@ 90 K)
  + 90 K cryocooler LCH4 + dedicated shield (@ 90 K)
- ➢ LOX/LH2 RBO: 90 K cryocooler LOX + dedicated shield (@ 90 K)
  + 90 K cryocooler LCH4 + dedicated shield (@ 90 K)
- ➢ LOX/LH2 ZBO: 90 K cryocooler LOX + dedicated shield (@ 90 K)
  + 90 K cryocooler LCH4 + dedicated shield (@ 90 K)

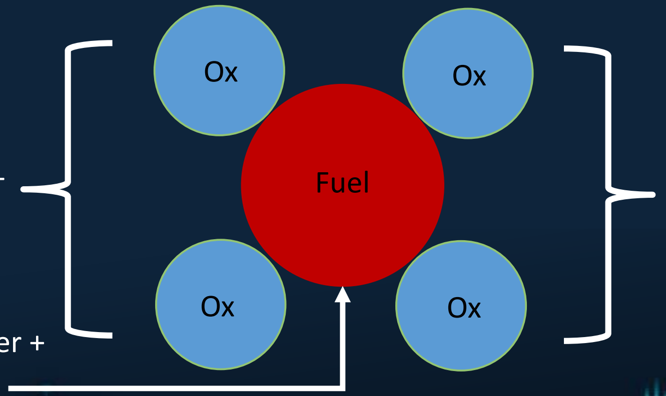


[1] Plachta, D. W., et al. "Cryogenic Propellant Boil-Off Reduction System." *AIP Conference Proceedings*. Vol. 985. No. 1. AIP 2008.



One cryocooler + shield

One cryocooler + shield



Another cryocooler + 2 shields

One cryocooler + 2 shields

Single cryocooler + 1 shield

Analysis Framework and Methodology

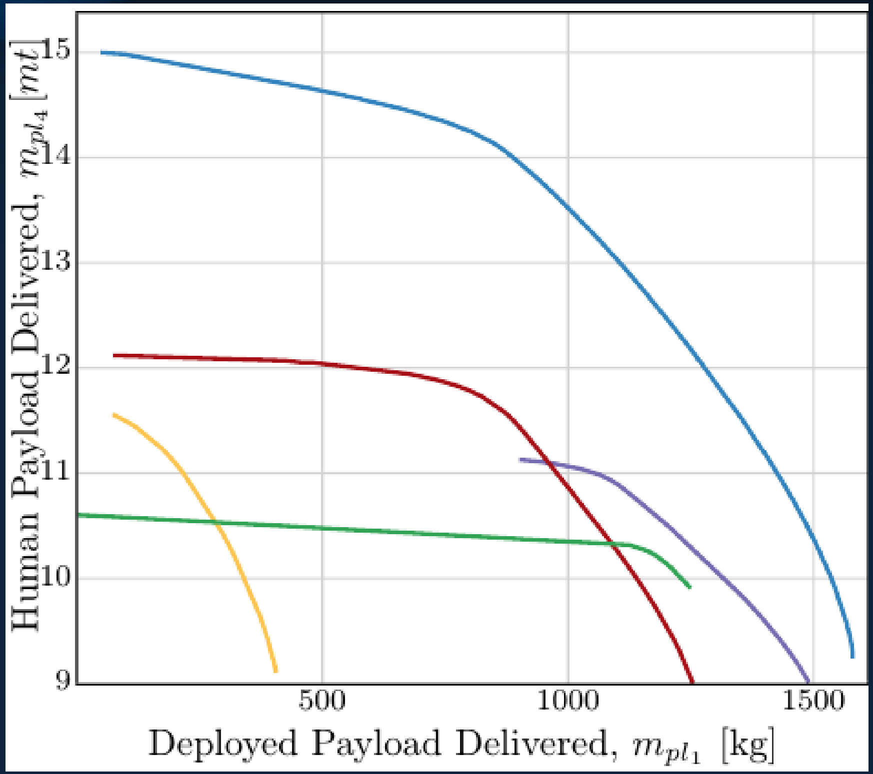
- Study performed utilizing the Dynamics Rocket EQuation Tool (DyREQT)
  - Specialization of OpenMDAO for space transportation systems
- 6 Contributing Analyses

Avionics	Structures	Power
Propellant Tanks	Engine	Thermal Control

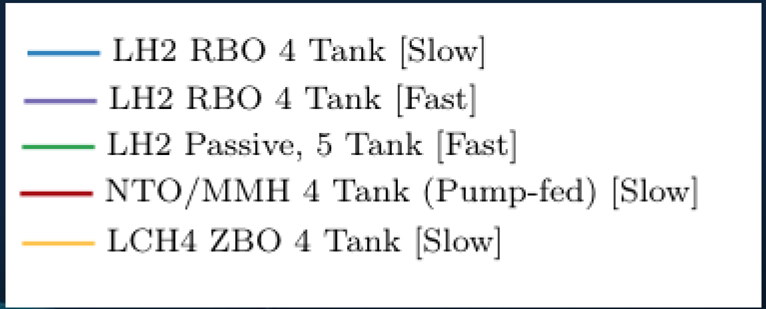
- Thermal control based on NASA’s CryoSIM
  - Passive boiloff calculations
  - Cryocooler power and mass relations
- Ran Design of Experiments (DoE) for each architecture
  - Over 560,000 cases
  - ~48 hours to run on a high end workstation
- Trained Neural Networks
  - Two fully connected layers of 45 nodes each
- Neural networks needed because of the multi-modal complex design space
  - Different payloads size lander
  - Lander can launch partially fueled

Results

- NSGA-II produced the best of breed architecture for each propulsion system
  - Minimum in-space loiter times
- For Launch Vehicle 1
  - Pump-fed NTO/MMH provides excellent performance, exceeding the payload requirements outlined in NextSTEP-2
  - RBO LH2 greatly exceeds NextSTEP-2's payload requirements
  - With a fast transit to Gateway, LH2 Passive also exceeds NextSTEP-2's payload requirements
  - ZBO CH4 architecture does meet the cargo payload requirements.
  - Neither ZBO LH2 nor Pressure-Fed NTO/MMH meet payload requirements

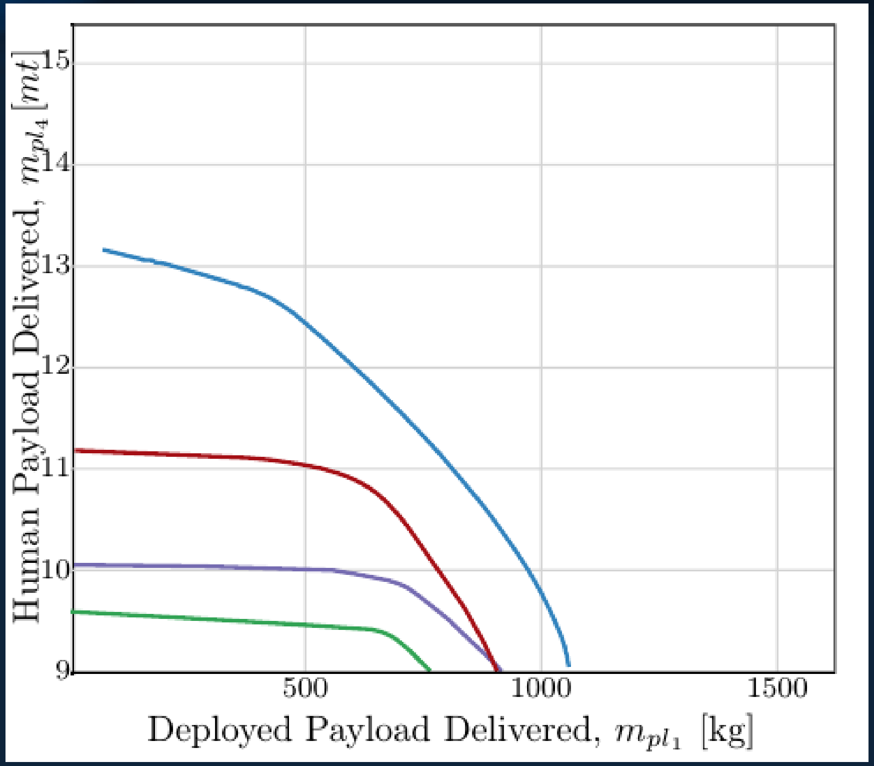


Launch Vehicle 1

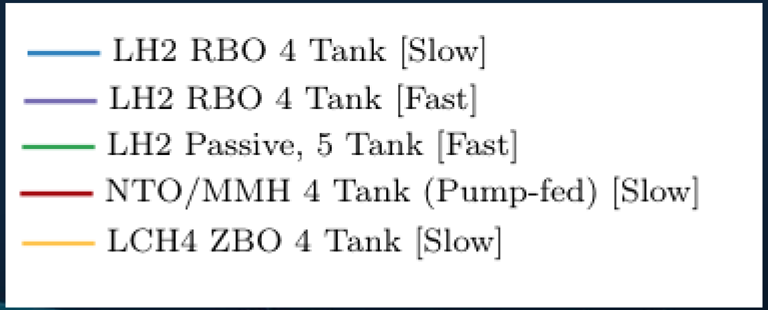


Results

- NSGA-II produced the best of breed architecture for each propulsion system
- Changes due to using a less capable launch vehicle
  - Fewer architectures are feasible vs. LV1.
  - Pump-fed NTO/MMH and RBO LH2 architectures are feasible among both LVs
    - slightly reduced performances on LV2.
- Key tradeoff: pump fed NTO/MMH

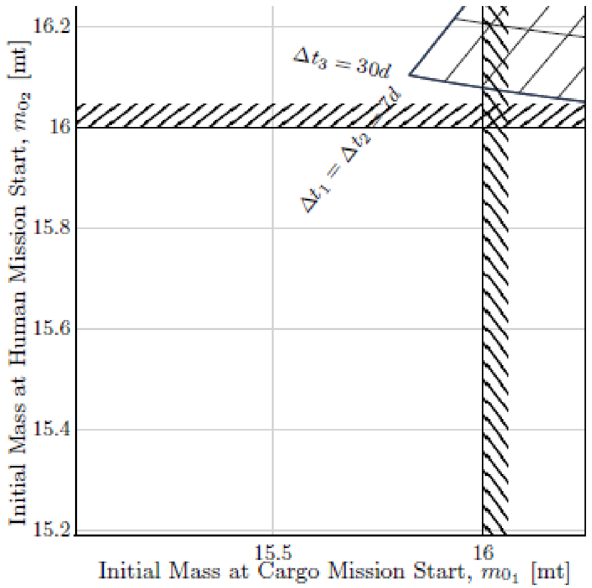


Launch Vehicle 2

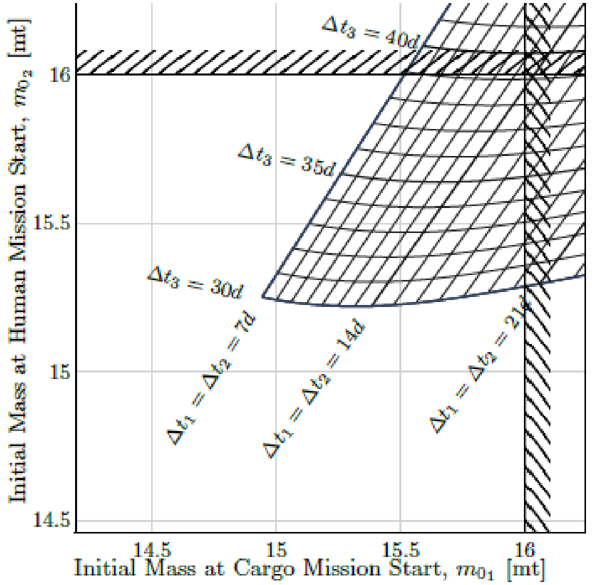


Hydrogen Landers

- Best-of-breed analysis shows that RBO LH2 landers outperform NTO/MMH systems
  - Difficult to baseline a cryocooler for a 2024 flight
  - Need a demonstration mission
- Passive LH2 systems can meet minimum NextSTEP-2 requirements
  - 5 tank system can meet
  - 4 tank system needs additional technology infusion to reduce boiloff
- 4-tank RBO LH2 beats 5-tank RBO LH2
  - Additional cryocooler mass penalizes 5-tank RBO
- **Possible evolutionary path exists**



(a) 2 Fuel & 2 Ox Tanks



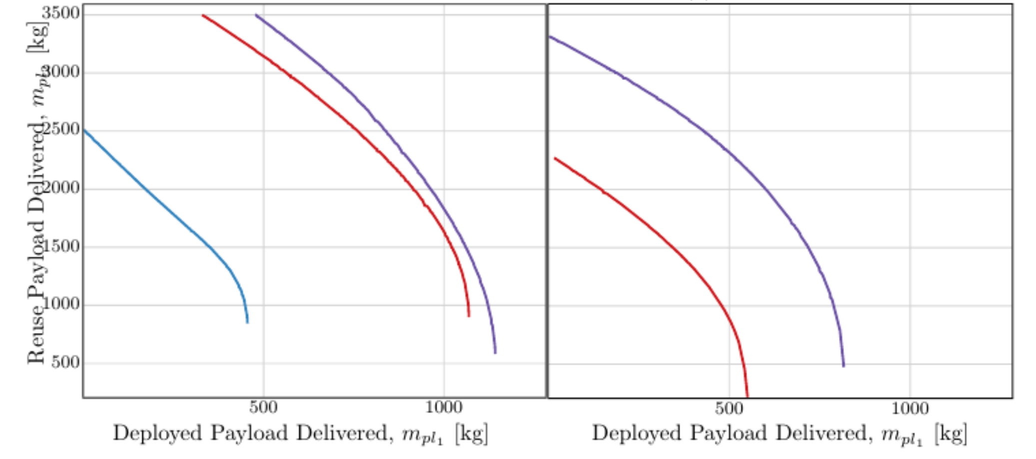
(b) 1 Fuel & 4 Ox Tanks

Utilizing Off-the Shelf Engines

- Examined off-the-shelf engines to support 2024 landing date
  - 1 RL10C-1 for hydrogen landers
  - 1 RS-72 for NTO/MMH landers
- Observations
  - 4-tank LH2 RBO provides superior crewed mission performance
  - NTO/MMH provides superior cargo performance
  - Performance difference due to additional mass of cryocoolers needed for RBO system

(a) Launch Vehicle 1

(b) Launch Vehicle 2



Conclusion

- Exercised DYREQT to perform a multi-mission analysis of alternatives
- Showed the ability of the descent stage of the human landing system to be used as a stand-along mid-sized lander
- Key trade: RBO LH2/LOX vs Pump-Fed NTO/MMH
  - Passive LH2/LOX can be used for 2024 mission
  - Evolvable to RBO system
  - Utilize capability as a cargo lander to fly technology demonstration missions

References

[1] Plachta, D. W., et al. “Cryogenic Propellant Boil-Off Reduction System." *AIP Conference Proceedings.* Vol. 985. No. 1. AIP 2008.