Feasibility Study of a Carbon Dioxide Breathing, Solid-Fueled Ramjet for Martian Descent and Landing of Human Class Payloads

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Agenda

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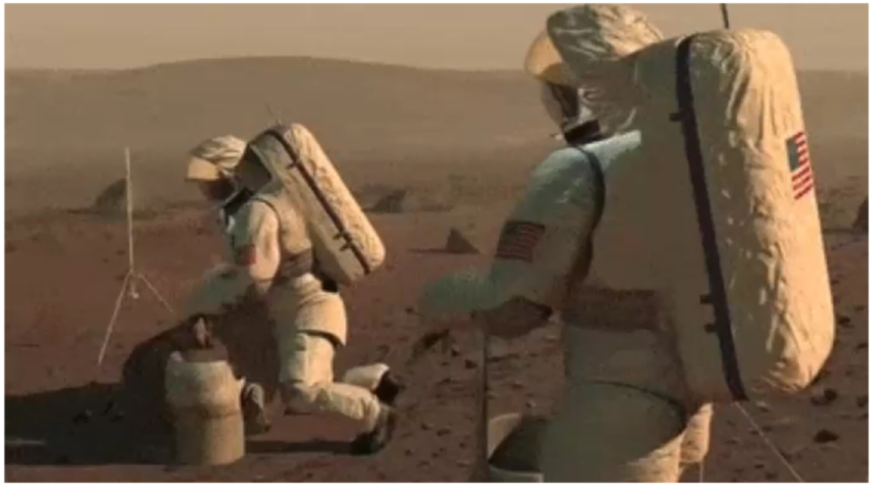


[1]

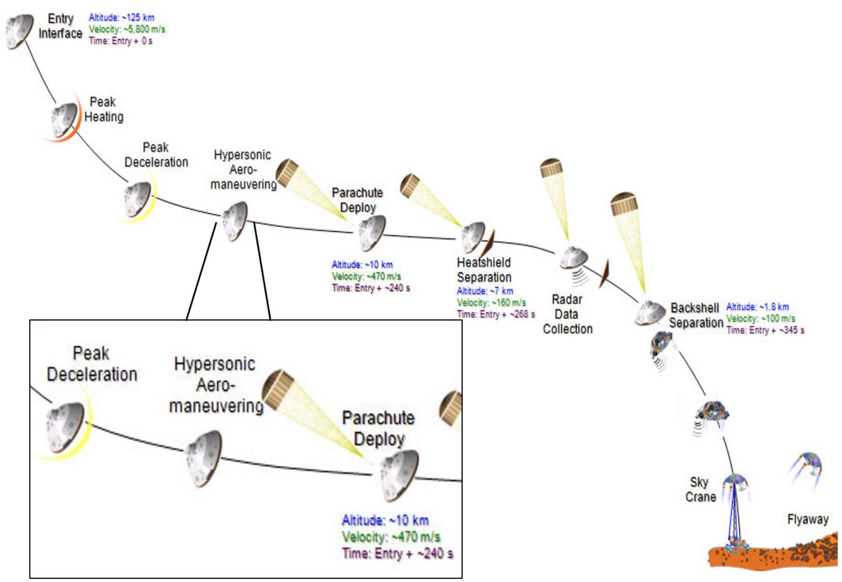
[1] https://nasa.tumblr.com/post/132022872799/where-will-we-land-on-mars

Introduction

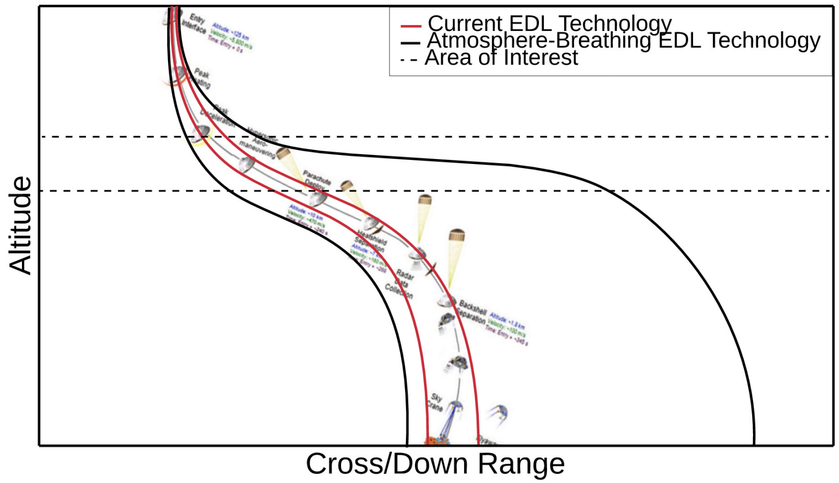
Background

- Current Entry, Descent, and Landing (EDL): deceleration with parachutes and rocket-assisted landing
  - Scalability difficulties for human-class missions with large payloads
  - Cross-range capability limited
  - Orbital plane changes required for latitudinal access

- Conventional air-breathing (Turbojet)
  - No on-board oxidizer required
  - Turbomachinery incompatible with metallic fuels
- Atmosphere-breathing (Ramjet)
  - No on-board oxidizer required
  - Compatible with most fuels, including metallic fuels
  - Scalable



Mars Science Laboratory EDL concept of operations [2]

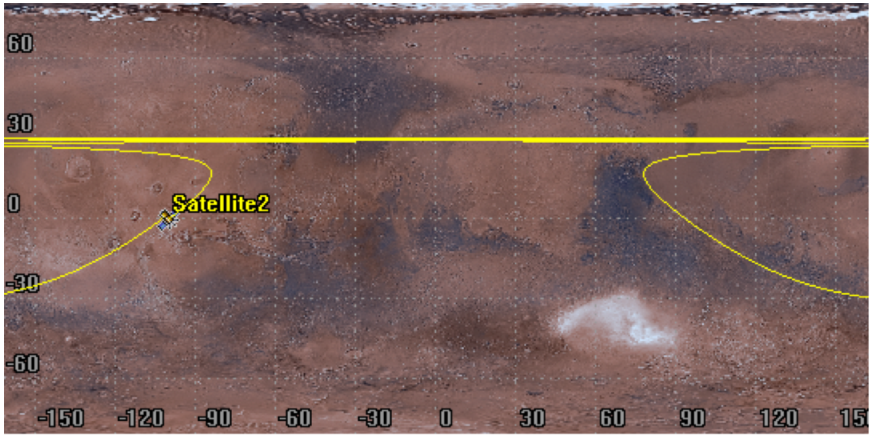


Conceptual Cross/Down Range Gains for Atmosphere-Breathing EDL Technology over Current State-of-the-Art EDL Technology

Mission

Mission Statement

Assess feasibility of solid (metal) fueled pre-burner and/or combustor for a ramjet in a carbon dioxide atmosphere using physics-based modeling and simulation to provide enhanced capability for scientific exploration of planets with carbon dioxide atmospheres



Ground track of 5-sol elliptical orbit at inclination of 30 degrees

Purpose

- Show that vehicle-integrated ramjet propulsion can provide enhanced capability over conventional EDL, particularly for human class missions
  - Maximize payload-to-ground
  - Maximize latitudinal access (cross-range) to reach landing sites which would otherwise require costly orbital plane changes
- Determine conditions under which atmosphere-breathing (A/B) propulsion provides capability over current EDL
  - Ground path
  - Vehicle size
  - Payload mass/volume
  - Flight envelopes
- Develop analysis tools that are limited or do not exist

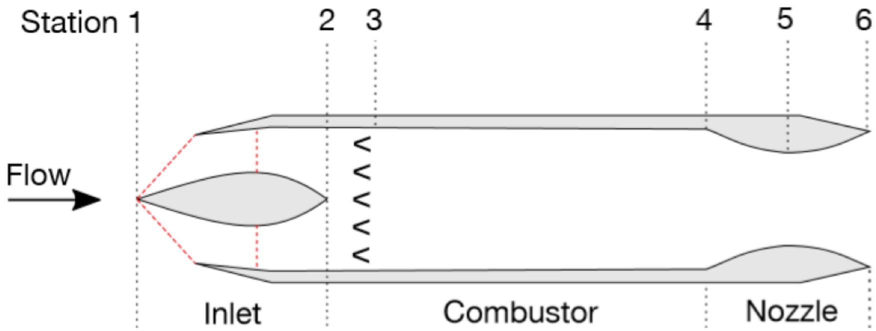
Ramjet Overview

Solid Fueled Ramjet (SFRJ) propulsion

- Inlet captures & compresses freestream flow (supersonic to subsonic)
- Fuel introduced into the compressed flow
- Combustor provides ignition source for fuel/oxidizer chemical reactions
- Nozzle produces thrust by expanding the subsonic flow back to supersonic

Potential high impact variables on overall performance

- Freestream conditions
  - ~95% CO_2 by volume
  - ~1% of Earth atmosphere pressure
- Inlet geometry
- Combustor
  - Fuel introduction method
    - Injector
    - Solid regression
  - Geometry
  - Efficiency (solid particle production)
- Nozzle geometry

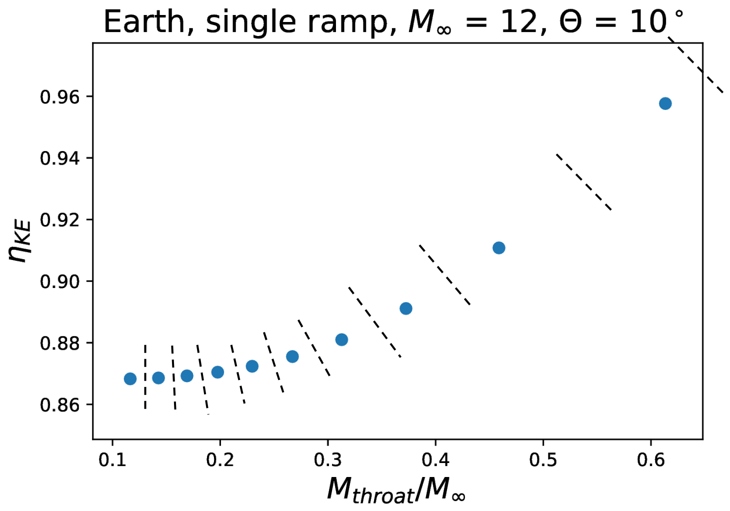


Uninstalled ramjet engine

Inlet

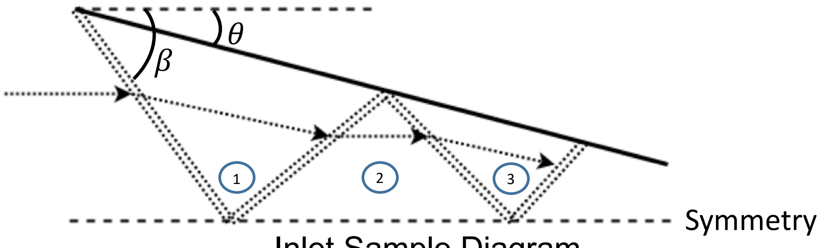
Methodology

- Integrated design environment (IDE) for inlet
  - Mixed compression
  - Alligator
- Shock-induced compression of inflow
  - Oblique shocks (real gas)
  - Constant area throat for scaling
- Function-based architecture
  - *In*: Atmosphere, M, q, throat area, Θ/β definition (no. of ramps)
  - *Out*: η_{KE}, $P_{t,rec}$, $M_{throat}/M_{freestream}$

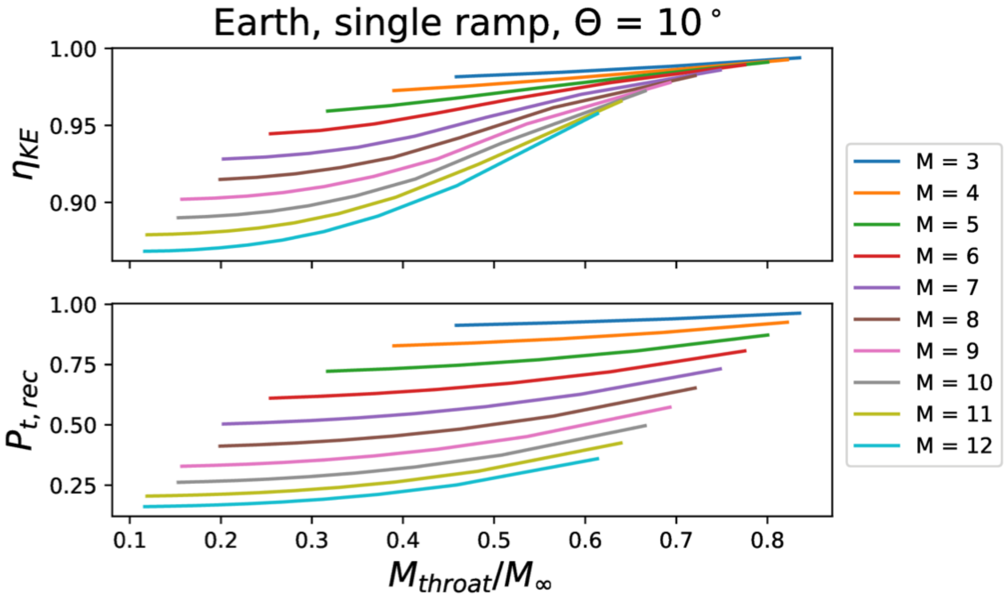


Preliminary Results

- Properties at various points of flow
  - Validation against historical data and benchmarking against known CFD cases
  - Geometry generation



Inlet Sample Diagram



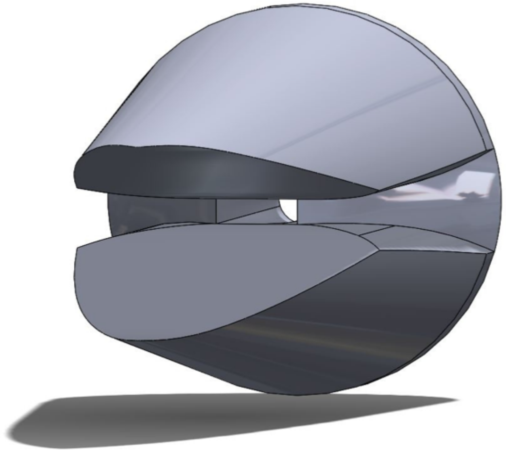
Inlet

Future Work

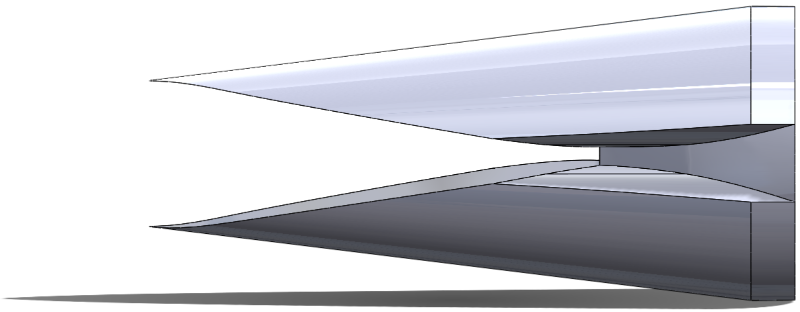
- Additional design tool capability
  - η_{KE}*(L0D-inlet)*
  - CO_2 atmosphere
  - Geometry generation
- Analysis of different inlet classes
  - Continued development of IDE
- Geometric design of other modules

Expected Results

- Novel design tool for carbon dioxide atmospheres
  - Ability to optimize inlet for atmosphere composition and desired performance
- IDE/parametric modeling combo will expedite inlet design time
- Integrated atmosphere-breathing engine development



Notional Alligator Inlet (a)

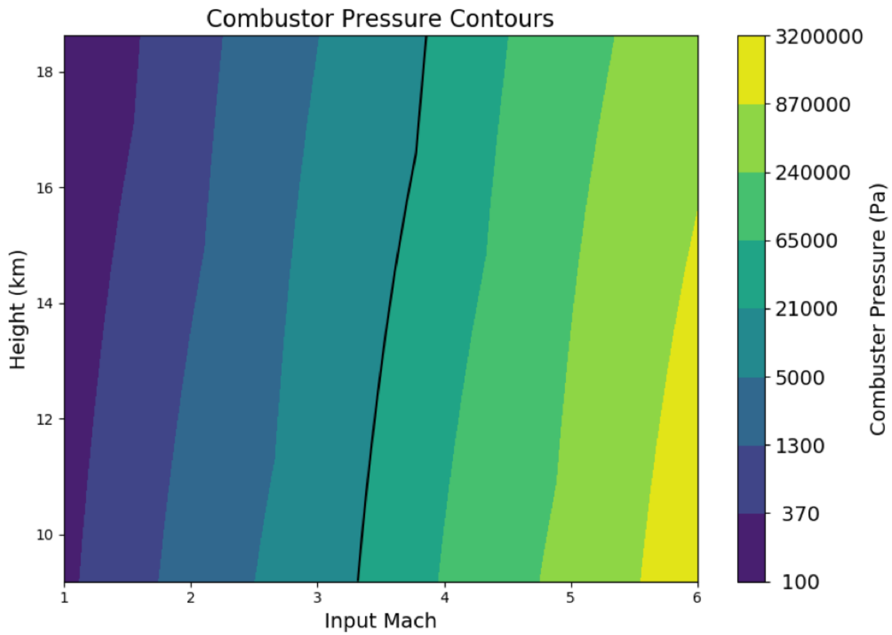


Notional Alligator Inlet (b)

Combustor

Methodology

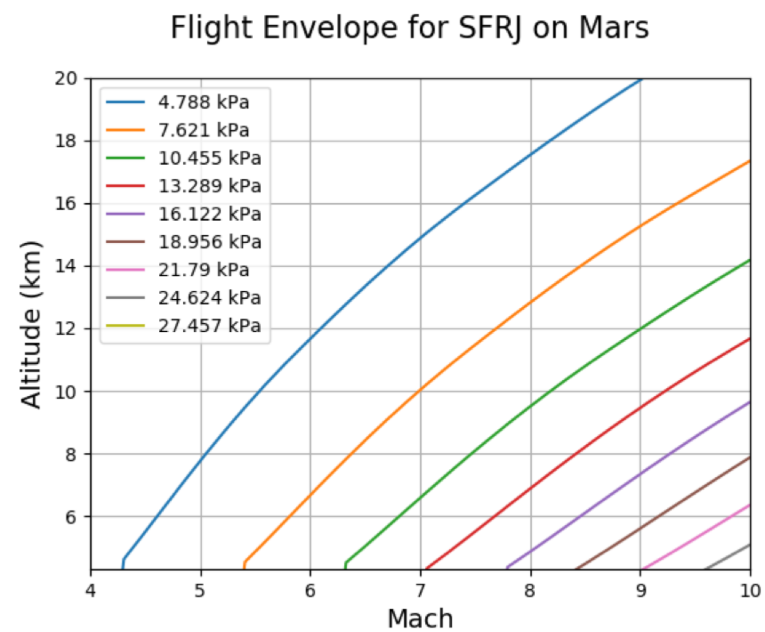
- Developed allowable Mach-q, atmosphere-breathing window
  - Based on minimum Mg-CO_2 ignition pressure
  - Combustor entrance pressure was calculated from simulating a converging-diverging ramjet inlet



Preliminary Results

- Ignition pressure of 0.2 atm (achievable with normal shock placed in diffuser of inlet)

$$Mg_{(s)} + CO_2 \rightarrow MgO_{(s)} + CO$$



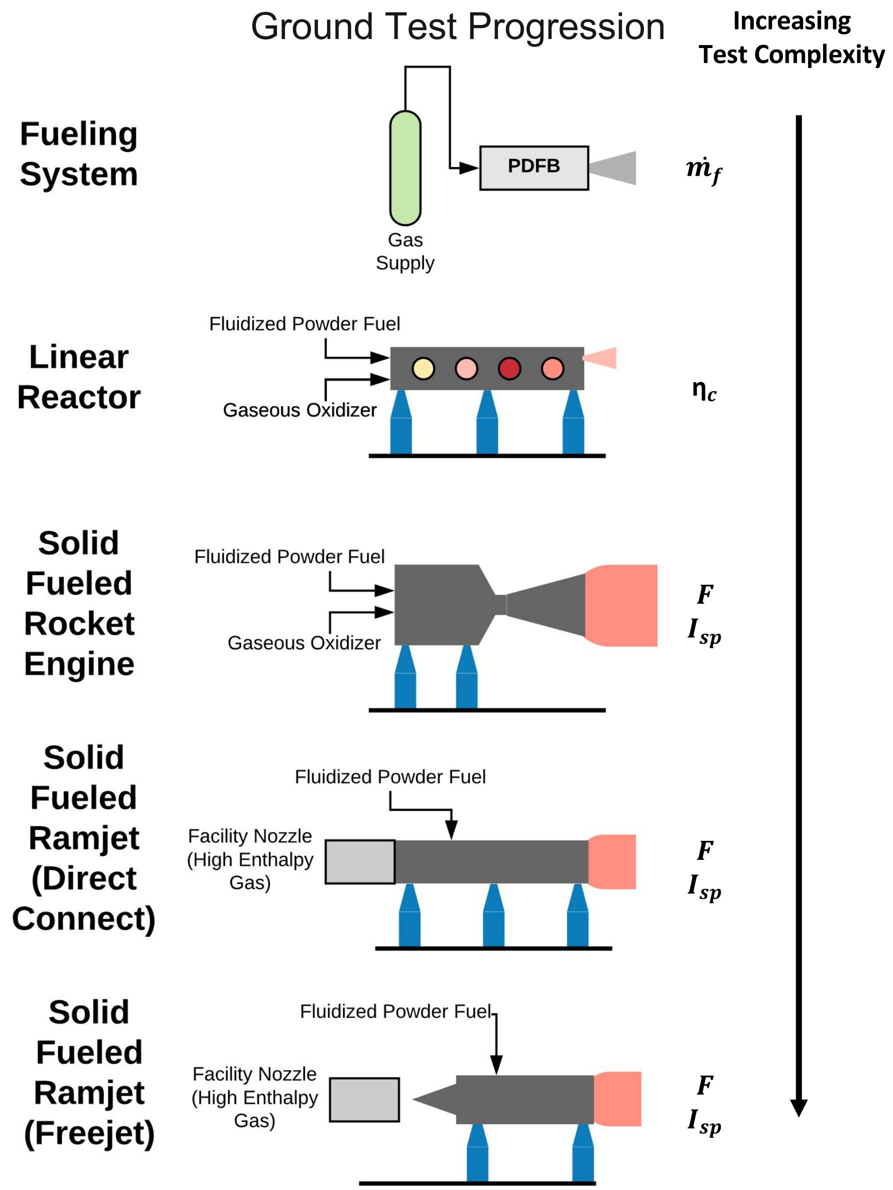
Ground Testing

Purpose

- Proof of concept and new technology validation
  - Project return on investment increased with spinoff technologies
- Develop ground test validation database for ground-to-flight performance mapping
- Implement modular system to iterate on design concepts

Prerequisites

- Define module connection method
- Enhance test cells for CO_2 operation
  - Safety
  - Operating environment



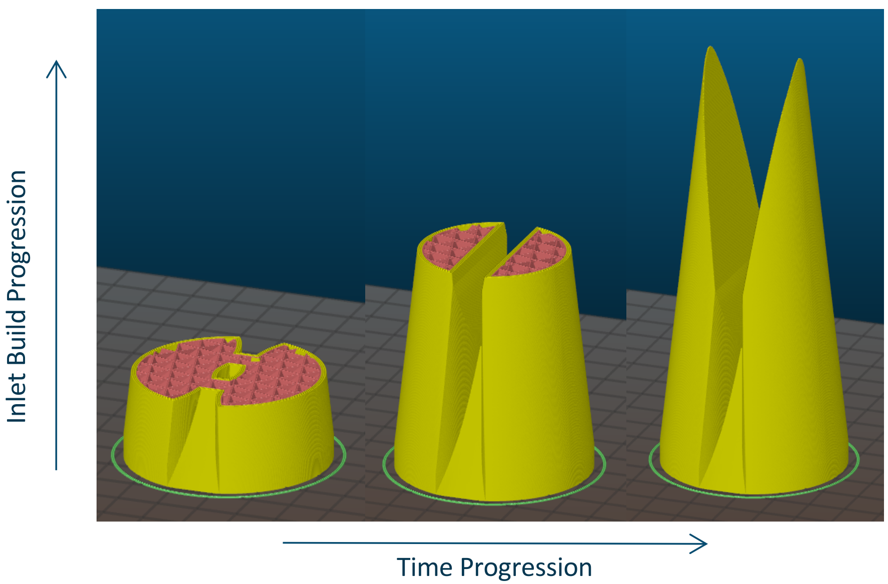
Additive Manufacturing

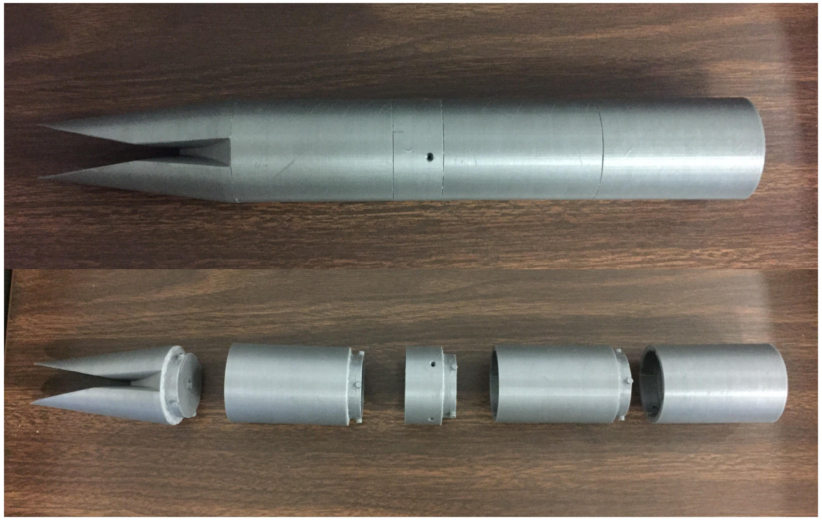
Approach

- Challenging geometries
- Efficient and affordable iteration of design concepts
- 3D printed with Fused Deposition Modeling (extrusion based printers)
- New additive design techniques and standard practices

Prototype

- Modular prototype
  - When damaged (abrasion, clogging, slagging etc.)
  - New design ideas
- Module fastener designs
- Complex geometries possible





Notional ground test articles and connectors

System Analysis

Methodology

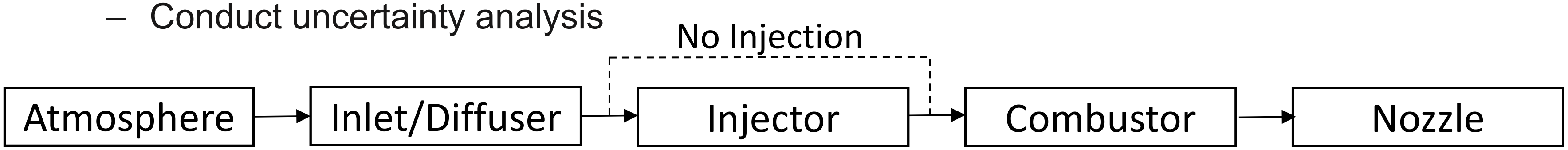
- Analyze system through model-based system analyses
  - In-house codebase
    - General purpose supersonic code
    - Metal-CO_2 combustion code
    - Planned: powder injection & solid regression
  - Complete integration of new modeling and simulation framework into existing analyses
- Conduct sensitivity study, in-depth studies, and further system analysis
  - Potential high impact variables on overall performance
  - Vary to test sensitivity
    - Non thermal equilibrium of solid particles post combustion
    - Accelerated/non-accelerated solid particles
    - Frozen/equilibrium nozzle
    - Fuel-to-atmosphere ratio
  - Conduct uncertainty analysis

Preliminary Results

- Individual analyses addressed on previous slides
- Three major areas likely to have high impact on overall performance
  - Inlet geometry
  - Combustor efficiency
  - Solid particle production

Expected Results

- Trades required for maximum cross-range capabilities
  - L/D vs. volume
  - Payload-to-ground mass vs. cross/down range distance
  - Conditions under which atmosphere-breathing propulsion provides capability over orbital plane changes



Flow of Information [3]

[3] Erik L. Axdahl and Lin Li, Uninstalled Performance Predictions of a Magnesium-Fueled Ramjet Cycle in Carbon Dioxide Atmospheres (Preliminary Paper)

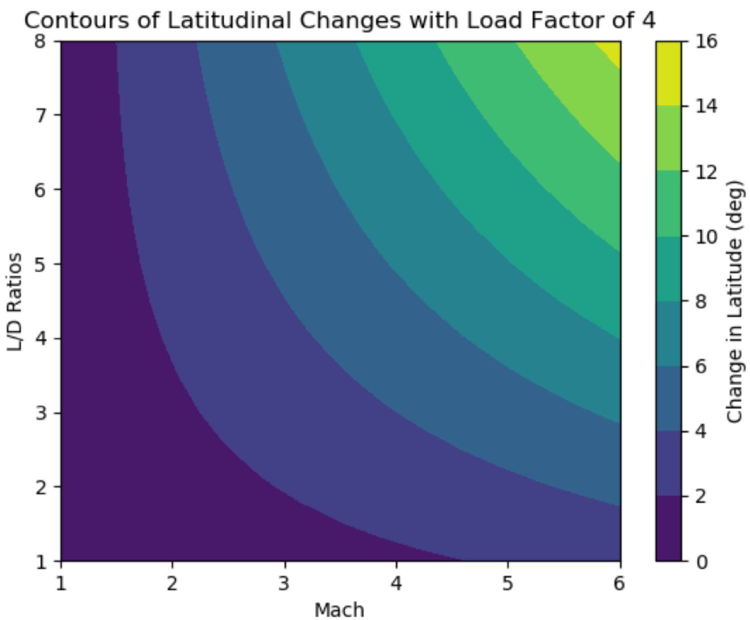
Key Takeaways

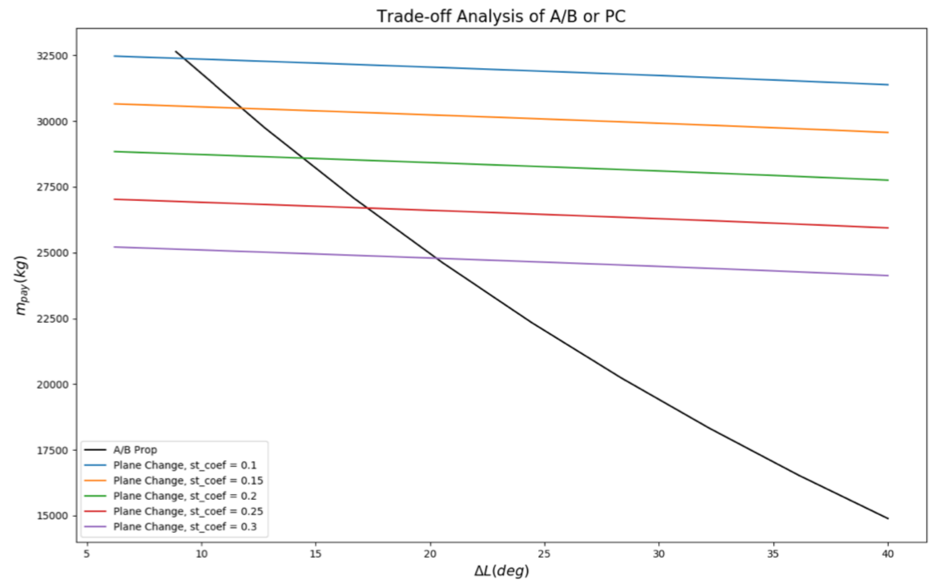
Cross-Range of A/B Engine

- Cross-Range most significantly affected by L/D of body, structural efficiency, and flight speed
- Maximum attainable latitude varies from 10-40 deg (depending on parameters)

Trade-Off Analysis

- Primary interest is comparing payload capability at varying latitude changes.
- Selection of plane change vs. atmosphere-breathing vehicle dependent on latitude and multiple flight/spacecraft parameters





Conclusion

Due to their potential for increased propulsion efficiency and reduced on-board propellant, atmosphere-breathing propulsion systems may have the potential to provide increased payload and cross-range capabilities for human class Mars missions

Summary

- Trade-off analysis suggests A/B propulsion yields higher cross-range than conventional EDL and some PC maneuvers
- Inlet model capable of estimating preliminary loss and performance metrics for CO_2 operation
- Increasingly complex geometries now possible for ground testing with additive manufacturing

Ongoing Work

- Optimizing a model to simulate the Martian inlet/combustor environment and to determine a feasible operating range
- Establishing preliminary ground test procedures
- Developing potential entry trajectories using optimal control

Future presentations on this subject:

AIAA Propulsion and Energy 2018: Uninstalled Performance Predictions of a Magnesium-Fueled Ramjet Cycle in Carbon Dioxide Atmosphere

AIAA Space 2018: Mars Entry, Descent, and Landing Capability Enhancement using a Carbon Dioxide Breathing Ramjet Propulsion Cycle

Questions

POC for follow up questions:

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