National Aeronautics and Space Administration

Supersonic Retropropulsion Technology Development in NASA's Entry, Descent, and Landing Project

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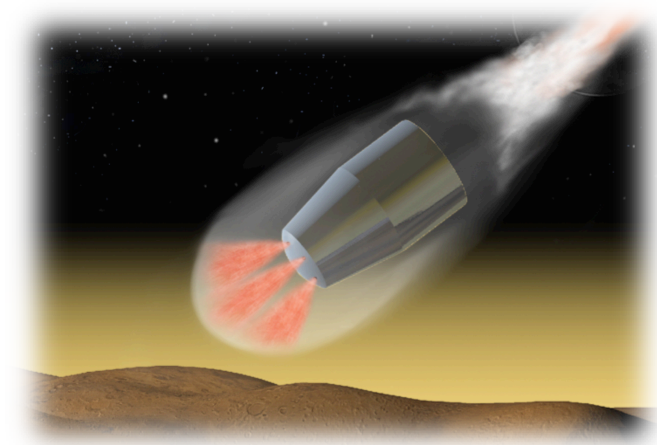

9th International Planetary Probe Workshop

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EDL Project
SRP Team, 2009-2011

- **Langley Research Center**
  - Karl Edquist (Lead)
  - Scott Berry
  - Artem Dyakonov
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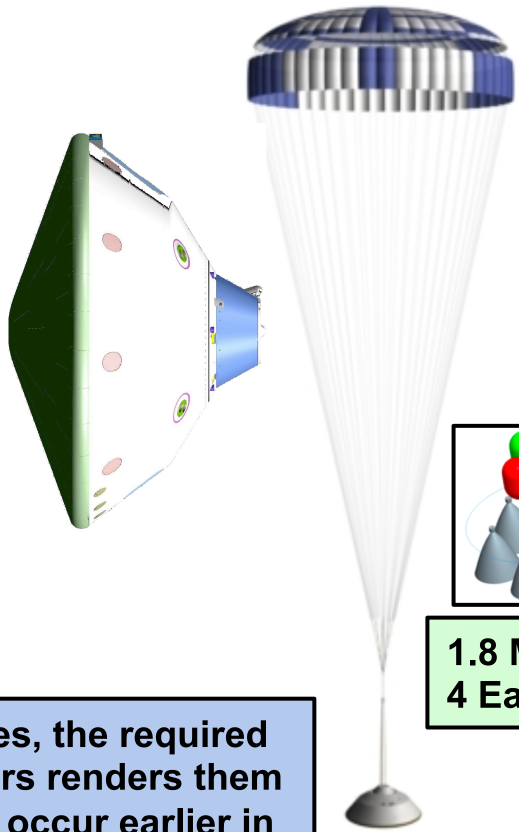
  - Jan-Renee Carlson
  - Pieter Buning
  - Chris Laws
  - Jeremy Shidner
  - Joseph Smith
  - Ashley Korzun (GT)
  - Chris Cordell (GT)
  - Bill Oberkampf (Contractor)
  - Juan Cruz Ayoroa (GT)
  - Josh Codoni (UVa)
  - Patrick Schultz (UNCC)
- **Ames Research Center**
  - Kerry Zarchi
  - Emre Sozer
  - Ian Dupzyk
  - Noel Bakhtian
- **Jet Propulsion Laboratory**
  - Ethan Post
  - Art Casillas
  - Rebekah Tanimoto
- **Johnson Space Center**
  - Guy Schauerhamer
  - Bill Studak
  - Mike Tigges
- **Glenn Research Center**
  - Tim Smith
  - Bill Marshall

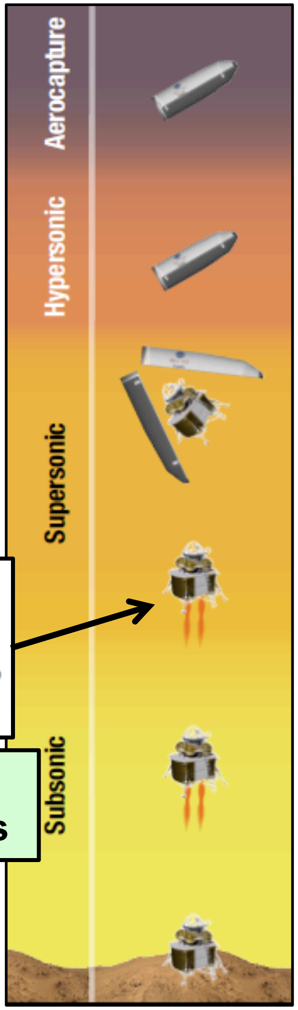
Motivation

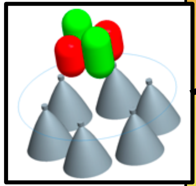
- **Problem: Mars EDL technologies are nearing their payload limit**
  - Mars Science Laboratory → 4.5 m aeroshell + 21.5 m parachute = 1 metric ton (t) payload within ~10 km of target
  - ~1.1 t max. to 0 km using MSL system (AIAA 2011-7294)
- **Goals beyond MSL:**
  - Order of magnitude more mass (10s of t)
  - Four orders of magnitude better accuracy (meters)
  - Higher landing elevation
- **Candidate enabling technologies includes Supersonic Retropropulsion (SRP)**

MSL Aerodynamic Decelerators



EDL-SA Architecture with SRP (NASA/TM-2010-216720)





1.8 MN
4 Earth g's

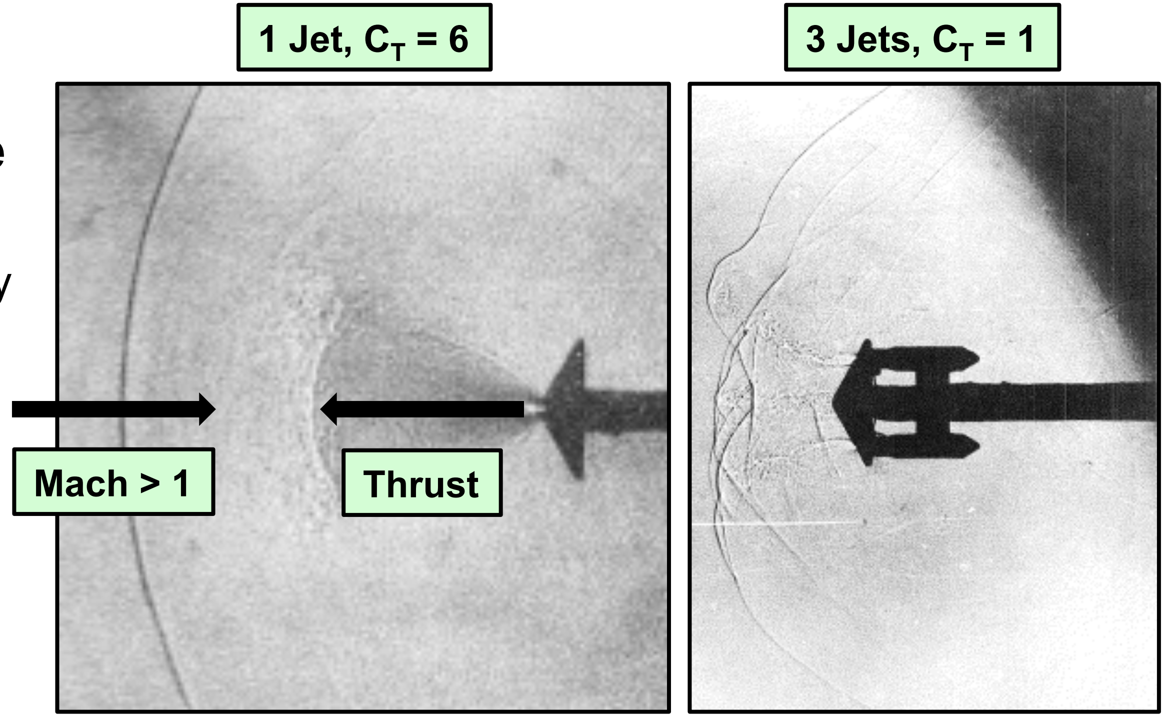
40 t payload

"As Mars missions approach human class entry masses, the required size of supersonic deployable aerodynamic decelerators renders them impractical…initiation of propulsive deceleration must occur earlier in the descent phase…SRP becomes an enabling technology for human class Mars missions."
- NASA EDL Space Technology Roadmap (TA09), November 2010.

Supersonic Retropropulsion

- **SRP uses retro-rockets to increase total drag**
  - Total drag, $C_{D,Total} = C_{D,Aero}$ (aerodynamic drag) + C_T
  - C_T (= $T/q_\infty S_{ref}$) known from engine thrust and trajectory conditions
  - $C_{D,Aero}$ depends on vehicle geometry, jet configuration & thrust magnitude
- **Wind tunnel tests from 1950s to 1970s showed general aerodynamic trends, but no development beyond the laboratory**
  - Data have limited applicability for modern CFD validation
- **For human scale, $C_T >> C_{D,Aero}$**
- **SRP for EDL provides:**
  - Additional timeline
  - Higher altitude
  - Better precision

Jarvinen, NASA CR NAS 7-576, 1970



SRP in NASA's EDL Project, 2009-2011

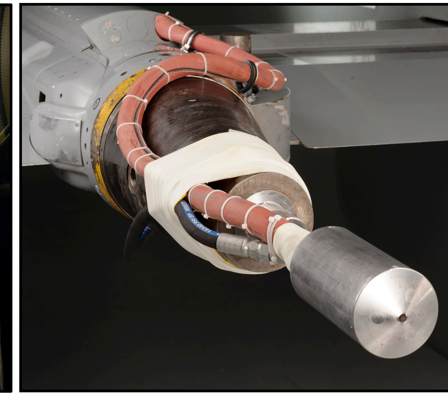
- **Renewed interest in SRP due to anticipated Mars EDL technology needs in the 2020s and 2030s**

- **SRP Objectives within EDL Project:**
  - Assess the technical maturity of SRP and define a roadmap for advancement
  - Conduct SRP wind tunnel tests to provide:
    - Better understanding of SRP fluid dynamics for range of thrust levels and Mach numbers
    - Data to validate computational fluid dynamics (CFD) codes
  - Compare existing CFD codes to wind tunnel data
    - Quantitative (surface pressure) and qualitative (flow structure)
  - Investigate concepts for an Earth-based flight test

Wind Tunnel Testing

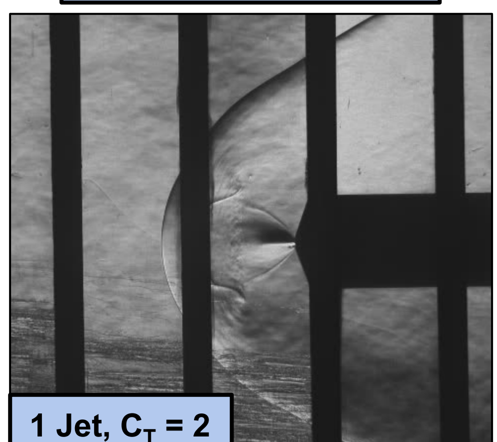
- **Objective:**
  - Conduct wind tunnel tests on a SRP configuration and provide data for validation of computational fluid dynamics (CFD) models
- **Accomplishments:**
  - Completed tests in two NASA wind tunnels
    - ➢ 6-in diameter model with 0-4 air jets
    - ➢ Mach 1.8 to 4.6, AoA = -8 to +20 deg
    - ➢ $C_T = T/q_\infty S_{ref}$ = 0 to 10
  - Collected surface pressure (167 ports) and high-speed video (up to 20,000 fps)
- **Open Issues:**
  - Scaling, chemical propellants, Mars geometries, aerothermal effects, force & moment measurement, "optimal" jet configurations

Model in Langley 4x4 and Ames 9x7 Wind Tunnels



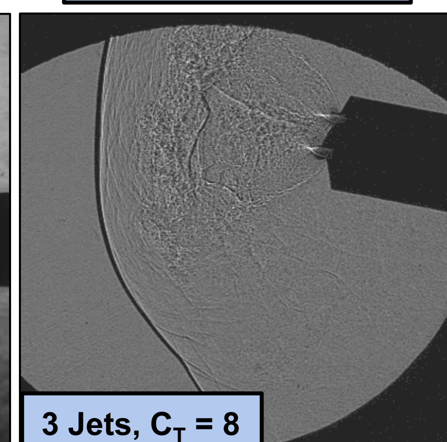
Scott Berry, IEEEAC 1499
Scott Berry, AIAA 2011-3489
Scott Berry, AIAA 2012-XXXX
Matt Rhode, AIAA 2012-XXXX

Langley 4x4, Mach 4.6



1 Jet, C_T = 2

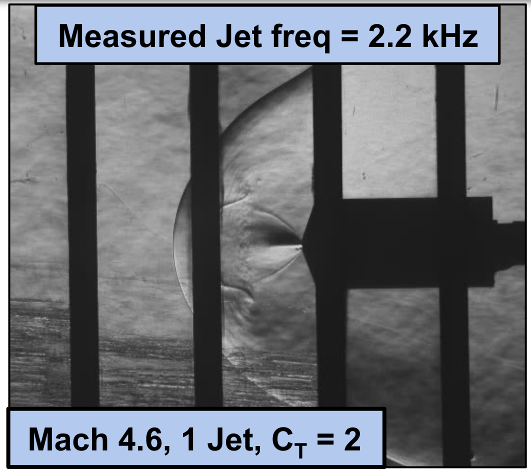
Ames 9x7, Mach 2.4

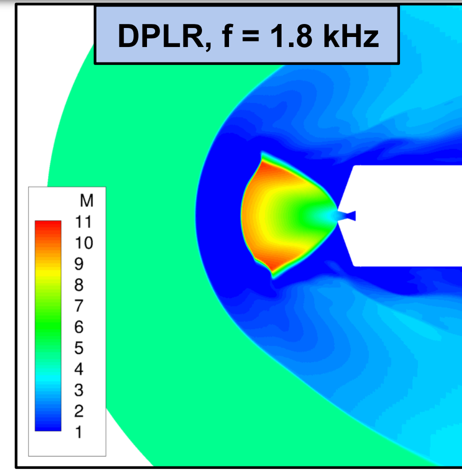


3 Jets, C_T = 8

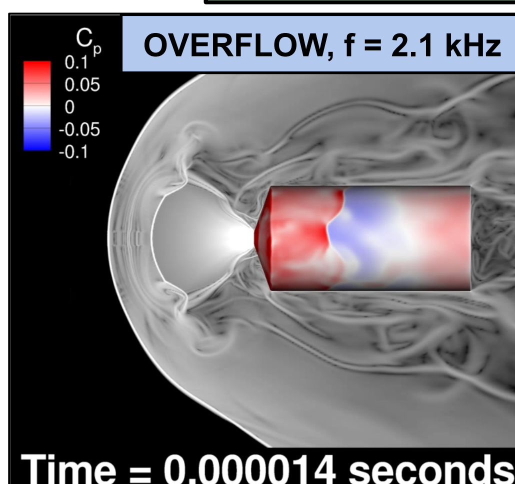
Computational Fluid Dynamics Modeling

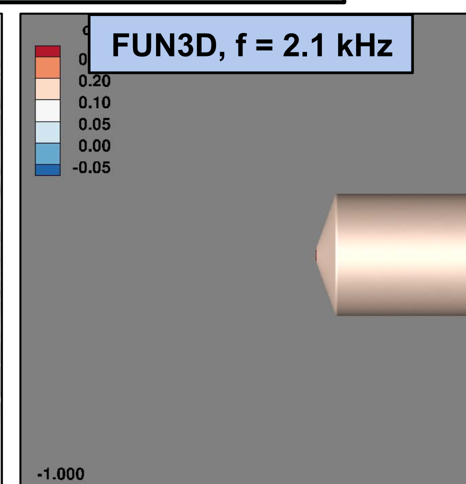
- **Objective:**
  - Begin to validate CFD codes for SRP applications using wind tunnel data
- **Accomplishments:**
  - Obtained 0-4 jet solutions using 3 NASA codes
  - Showed promising qualitative & quantitative agreement with data
  - Identified lessons learned for turbulence modeling, grid generation, time advancement
- **Open Issues:**
  - Scaling, flowfield unsteadiness & turbulence, vehicle stability/ controllability, aerothermal effects, time-accuracy requirements





Kerry Trumble, AIAA 2010-504
Kerry Trumble, IEEEAC 1471
Bil Kleb, AIAA 2011-3490
Guy Schauerhamer, AIAA 2012-864
Kerry Zarchi, AIAA 2012-XXXX

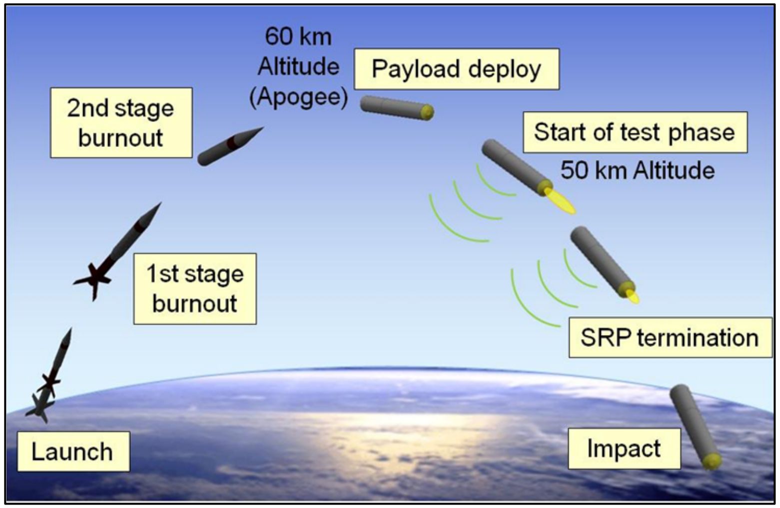




Earth Flight Test Concept

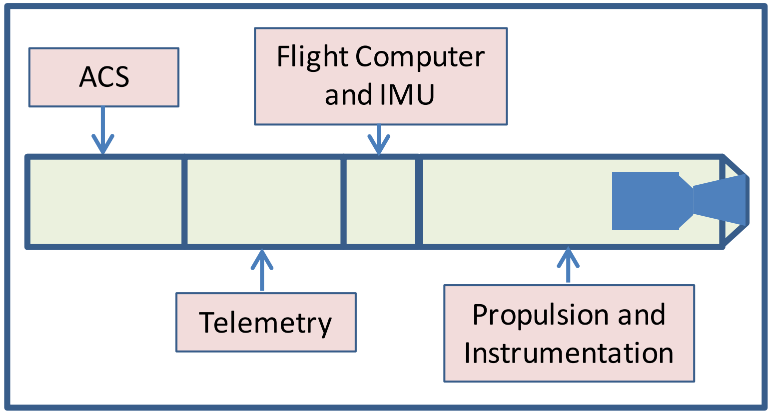
- **Objective:**
  - Identify platforms and begin conceptual design of a "proof-of-concept" Earth flight test article
- **Accomplishments:**
  - Started conceptual analysis of sounding rocket test payload (17 in. diameter)
  - Identified engine options (solid & liquid)
  - Completed conceptual mass/ packaging & fuel requirements vs. test duration (15 to 35 sec.)
- **Open Issues:**
  - Requirements & constraints, trajectory design, scaling, vehicle stability, GN&C, TPS, instrumentation, telemetry

Concept of Operations



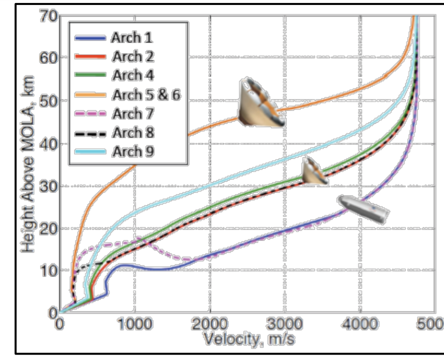
Ethan Post, "Supersonic Retropropulsion Flight Test Concepts," IPPW-8

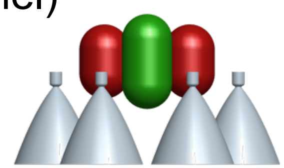
Test Article Layout

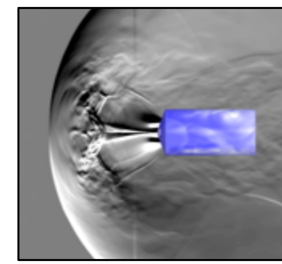


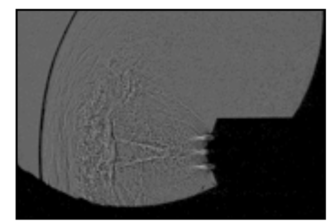
Near-Term Recommendations

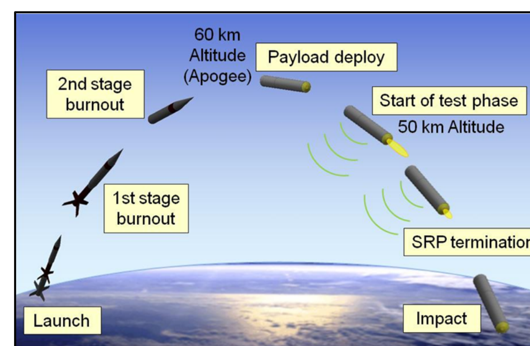
- **Verify/revise existing SRP performance and mature configurations**
  - Develop higher-fidelity models for performance, mass & packaging
  - Develop algorithms/strategies for vehicle control & stabilization
  - Test a model representative of flight-relevant SRP configurations at conditions of interest (supersonic wind tunnel)
  - Reduce computational effort until configurations mature
- **Demonstrate start-up and nominal operation of SRP engine**
  - Initiate development of a throttle-able engine or establish relationships with existing development programs
  - Demonstrate operation of a prototype engine in relevant environment (ground and/or Earth-based flight test)
- **Development for robotic precursor directly feeds forward to human-scale mission applications**
- **Well-positioned to continue SRP development for a robotic precursor mission at Mars (2020+)**











Summary and Conclusions

- **SRP is a potentially enabling technology for human-scale Mars EDL (10s of metric tons payload)**
- **NASA investment in SRP motivated by EDL-SA studies and carried out by the EDL Project**
- **EDL Project Accomplishments:**
  - Completed two wind tunnel tests (0-4 jets, Mach 1.8-4.6, $C_T < 10$)
  - Showed promising qualititative & quantitative agreement of 3 CFD codes with wind tunnel data
  - Started conceptual design of sounding rocket “proof-of-concept” Earth flight test
- **Investments in SRP must continue now to support Mars missions starting in the 2020s (robotic precursors)**
  - Develop mission requirements and constraints
  - Mature EDL performance models
  - Initiate engine development (throttling capability)

SRP References

Conference	Lead Author	Title	Paper No.
2010 AIAA/ASME Joint Thermophysics & Heat Transfer	K. Edquist	Development of Supersonic Retro-Propulsion for Future Mars Entry, Descent, and Landing Systems	AIAA 2010-5046
	K. Trumble	An Initial Assessment of Navier-Stokes Codes Applied to Supersonic Retro-Propulsion	AIAA 2010-5047
2011 IEEE Aerospace	S. Berry	Supersonic Retro-Propulsion Experimental Design for Computational Fluid Dynamics Model Validation	IEEEAC 1499
	K. Trumble	Analysis of Navier-Stokes Codes Applied to Supersonic Retro-Propulsion Wind Tunnel Test	IEEEAC 1471
2011 International Planetary Probe Workshop	G. Schauerhamer	Ongoing Validation of Computational Fluid Dynamics for Supersonic Retropropulsion (Poster)	
	E. Post	Supersonic Retropropulsion Flight Test Concepts	
2011 AIAA Thermophysics	B. Kleb	Toward Supersonic Retropropulsion CFD Validation	AIAA 2011-3490
	S. Berry	Supersonic Retropropulsion Experimental Results from the NASA Langley Unitary Plan Wind Tunnel	AIAA 2011-3489
2012 AIAA Aerospace Science Meeting & Exhibit	G. Schauerhamer	Continuing Validation of Computational Fluid Dynamics for Supersonic Retropropulsion	AIAA 2012-864
2012 AIAA Fluid Dynamics	S. Berry	Supersonic Retropropulsion Experimental Results from the NASA Ames 9- x 7-Foot Supersonic Wind Tunnel	To be presented
	M. Rhode	Estimation of Uncertainties for a Supersonic Retro-Propulsion Model Validation Experiment in a Wind Tunnel	
	K. Trumble	Computational Fluid Dynamics Validation and Post-test Analysis of Supersonic Retropropulsion in the Ames 9x7 Unitary Tunnel	
	J. Codoni	Analysis of High Frequency Data from Supersonic Retropropulsion Experiments in the NASA Langley Unitary Plan Wind Tunnel	

Acknowledgement

- **This work was supported by the Entry, Descent, and Landing Technology Development Project (EDL-TDP) in the Enabling Technology Development and Demonstration (ETDD) Program**

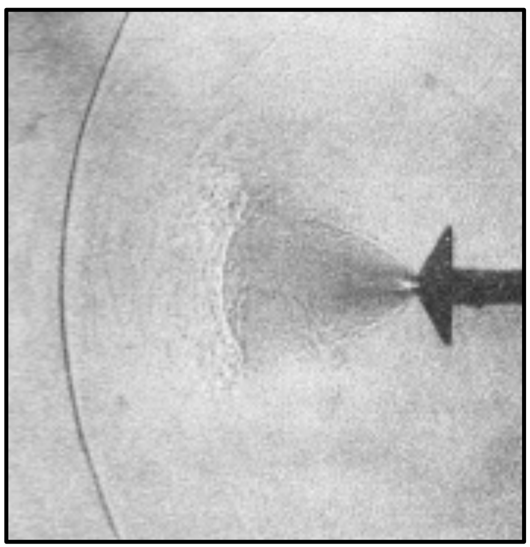
Backup

Supersonic Retropropulsion (SRP)

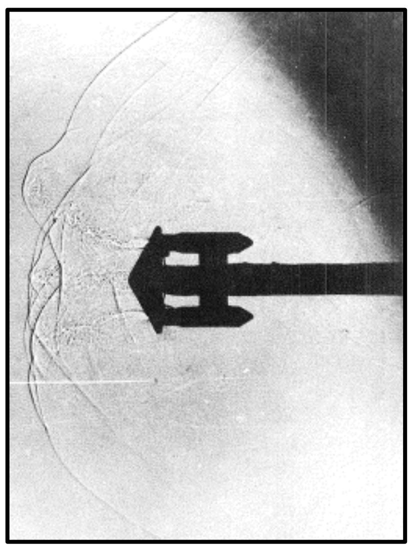
- **SRP uses retro-rockets to increase deceleration**
  - Total drag, $C_{D,Total} = C_{D,Aero}$ (aerodynamic drag) + C_T (thrust coeff. = $T/q_\infty S_{ref}$)
  - C_T known, $C_{D,Aero}$ depends on jet configuration and C_T magnitude
- **Wind tunnel tests from 1950s to 1970s showed general aerodynamic trends, but no development beyond the laboratory**
- **For human scale, $C_T > C_{D,Aero}$**

Jarvinen, NASA CR NAS 7-576

1 Jet, $C_T = 6$



3 Jets, $C_T = 1$



Jarvinen, NASA CR NAS 7-576
McGhee, NASA TN D-6002