Numerical Study of Lander Engine Plume Impingement on the Surface of Europa

JANNAF Meeting

June 2019

Rebekah Lam, Elham Maghsoudi, William Hoey

Jet Propulsion Laboratory
California Institute of Technology

Distribution Statement A: Approved for public release; distribution is unlimited.
The decision to implement the Europa Lander mission will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

Team

- Simulation of Spacecraft engine's exhaust plume is a multidisciplinary problem with applications in propulsion, thermal, and contamination control

- Team Members
  - Rebekah Lam, Propulsion Engineer
    - DSMC analyst
  - Elham Maghsoudi, AeroThermo Engineer
    - CFD analyst
  - William Hoey, Contamination Control Engineer
    - DSMC and Contamination Control Consultant

Distribution Statement A: Approved for public release; distribution is unlimited.
Pre-Decisional Information – For Planning and Discussion Purposes Only

Agenda

- Plume Concerns
- Landing Architecture
- Methodology
- CFD Domain
  - Overview
  - Code Validation
  - CFD/DSMC Interface
- DSMC Domain
  - Overview
  - Methodology
  - Code Validation
  - Results
- Summary and Conclusions

Distribution Statement A: Approved for public release; distribution is unlimited.
Pre-Decisional Information – For Planning and Discussion Purposes Only

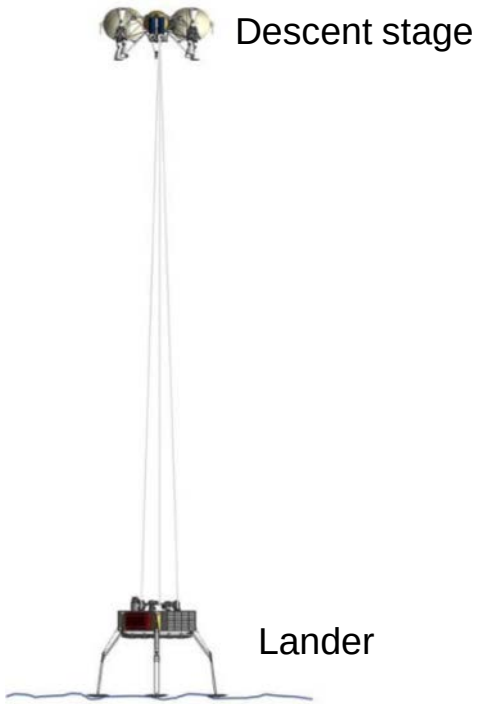
Plume Concerns for a Potential Europa Lander

- Impingement on the surface
  - Particle entrainment
  - Contamination of surface where science will be conducted
  - Heating → erosion or surface where science will be conducted
- On the lander vehicle
  - Direct impingement → vehicle torques
  - Direct heating
  - Contamination of vehicle surfaces

Distribution Statement A: Approved for public release; distribution is unlimited.
Pre-Decisional Information – For Planning and Discussion Purposes Only

Landing Architecture Assumptions

- Four pairs of hydrazine monopropellant engines on descent stage
  - 30° and 5° canted engine in each pair
- All descent stage engines used above 30 m altitude
- Only 30° canted engines used during final Sky Crane stage used to lower lander onto Europa surface below 30 m altitude
- Descent stage at 12 m altitude when lander touches down



Artist's Concept

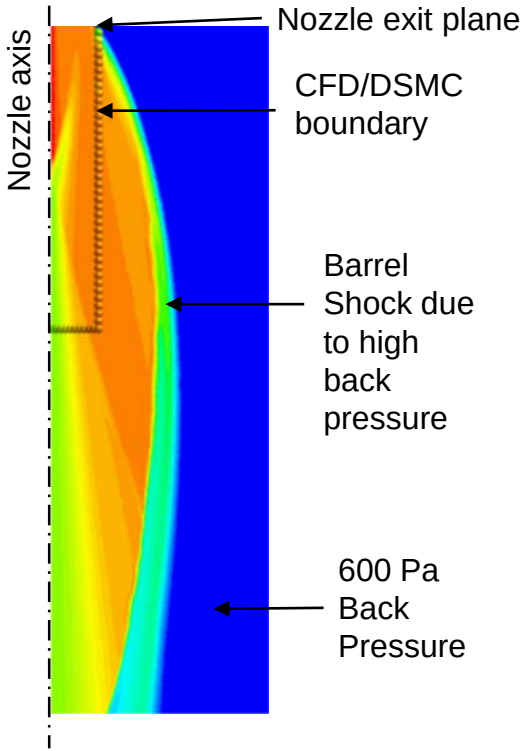
Hand, K.P. et al. ***Report of the Europa Lander Science Definition Team***, (Posted February, 2017).

Distribution Statement A: Approved for public release; distribution is unlimited.
Pre-Decisional Information – For Planning and Discussion Purposes Only

Methodology for Plume Simulations

- One-way coupled CFD/DSMC approach
  - CFD alone cannot be used to solve plume in rarefied environment
- Build single nozzle in CFD
  - Solve flow with high background pressure in 2D axisymmetric simulation
- Establish boundary to transition to DSMC (Direct Simulation Monte Carlo) before continuum breaks down
- Transition to DSMC at boundary
- Validate using lunar lander engine simulation

CFD Plume



Distribution Statement A: Approved for public release; distribution is unlimited.
Pre-Decisional Information – For Planning and Discussion Purposes Only

CFD Overview

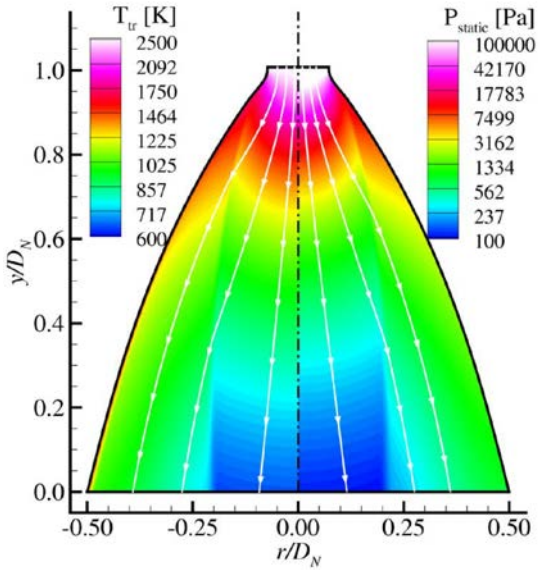
- STAR-CCM+ commercial package used
  - 2D axisymmetric model
  - Non-reacting Eulerian multi-component gas model with real gas assumption
  - Specific heat (c_p) as a function of temperature for each constituent
  - K-omega turbulence model
  - Mesh refined to achieve T+ of 1 at nozzle walls
- Monopropellant hydrazine products (NH_3, H_2, N_2)
- 3D wedge model used to validate axisymmetric results
- Back pressure of 600 Pa
  - No back pressure sensitivity between 1000 Pa and 50 Pa (lowest achievable)
- Validated with lunar lander engine model

Distribution Statement A: Approved for public release; distribution is unlimited.
Pre-Decisional Information – For Planning and Discussion Purposes Only

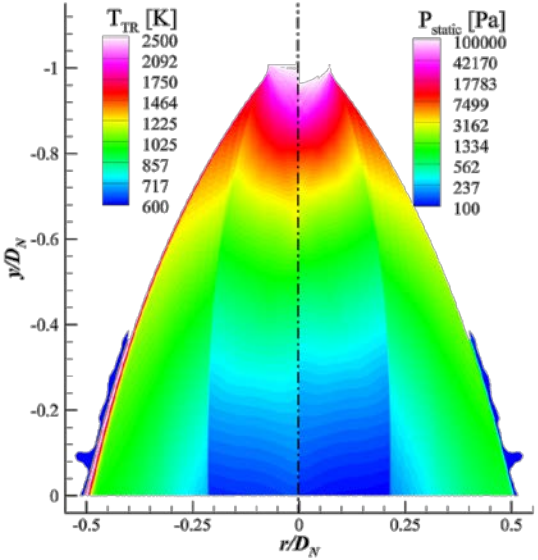
STAR-CCM+ Model Validation – Inside Nozzle

- Good agreement inside nozzle with LMDE (Lunar Module Descent Engine) simulation by Aaron Morris

Morris



STAR-CCM+



- Uses $c_p(T)$
- Single species H_2O Vapor

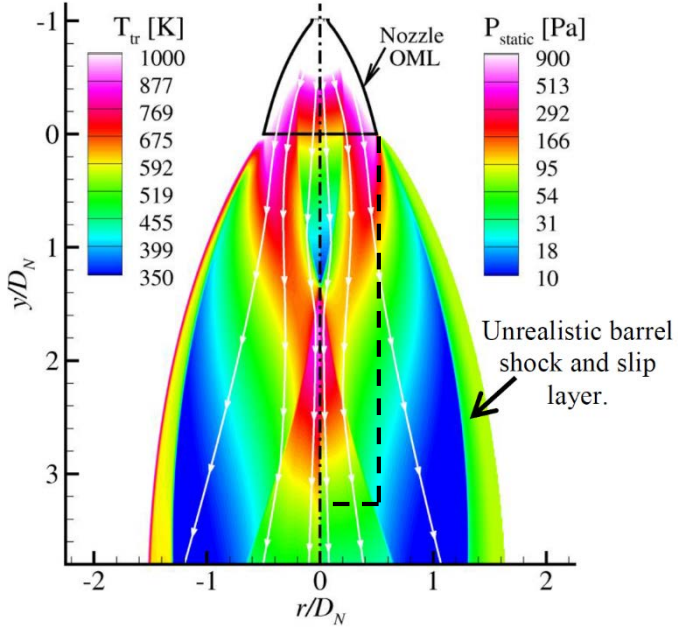
Morris, A., ***Simulation of Plume Impingement and Dust Dispersal on the Lunar Surface***, Ph.D. Dissertation, Aerospace Engineering Dept., Univ. of Texas at Austin, Austin, TX (2012). Solved using NASA DPLR Code.

Distribution Statement A: Approved for public release; distribution is unlimited.
Pre-Decisional Information – For Planning and Discussion Purposes Only

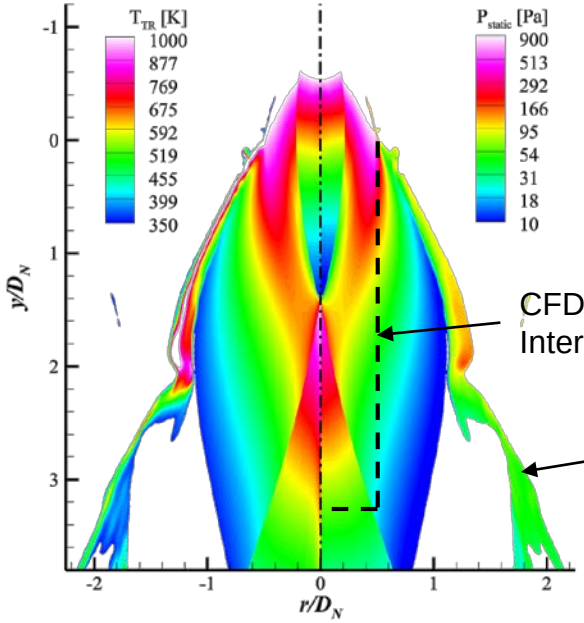
STAR-CCM+ Model Validation – Downstream of Nozzle

- Good agreement just downstream nozzle with LMDE simulation

Morris



STAR-CCM+

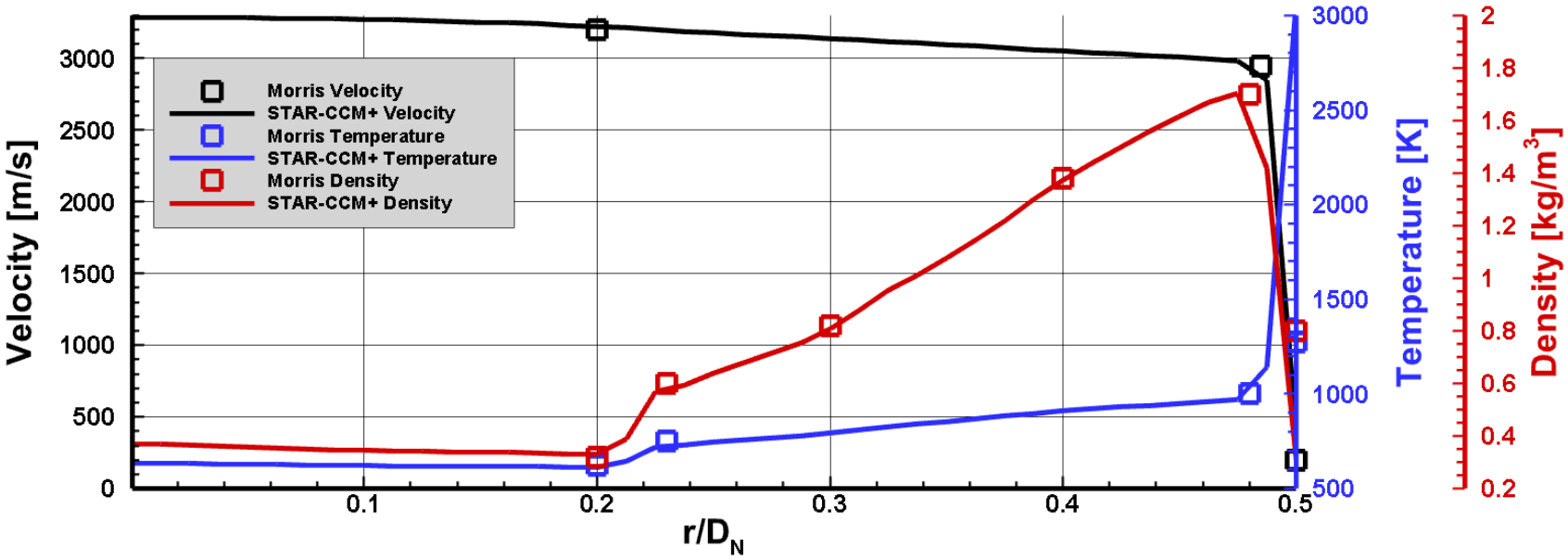


Morris, A., ***Simulation of Plume Impingement and Dust Dispersal on the Lunar Surface***, Ph.D. Dissertation, Aerospace Engineering Dept., Univ. of Texas at Austin, Austin, TX (2012). Solved using NASA DPLR Code.

Distribution Statement A: Approved for public release; distribution is unlimited.
Pre-Decisional Information – For Planning and Discussion Purposes Only

STAR-CCM+ Model Validation

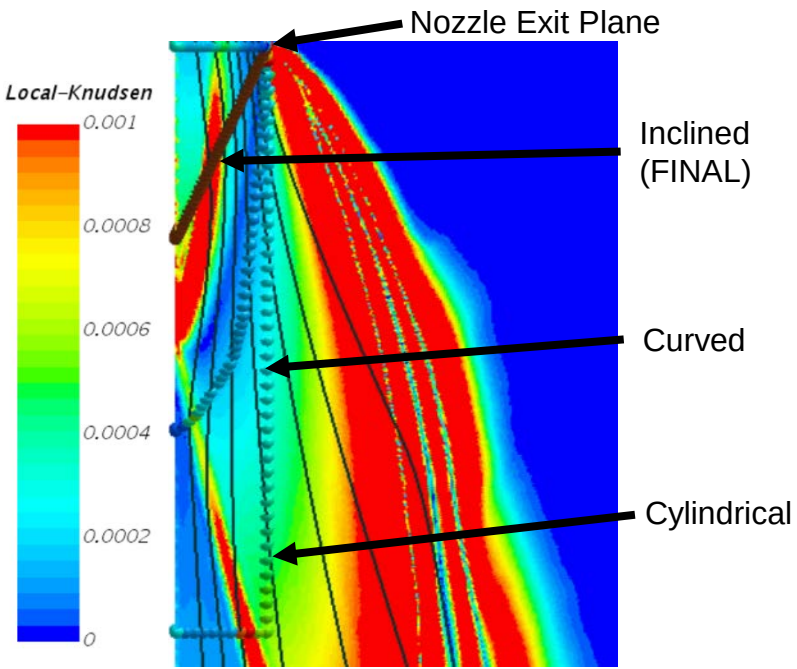
- Very good agreement with LMDE simulation at exit plane



Morris, A., ***Simulation of Plume Impingement and Dust Dispersal on the Lunar Surface***, Ph.D. Dissertation, Aerospace Engineering Dept., Univ. of Texas at Austin, Austin, TX (2012).

CFD/DSMC Interface Definition

- Requirements for CFD/DSMC Interface:
  - Within continuum regime, i.e. Kn < 0.001
    - Density gradient length scale based Kn
  - Interface-normal flow is supersonic
  - As far out from nozzle as possible to minimize DSMC computation size
- Iterated to satisfy all requirements – boundary sketched, then interface-normal Mach numbers computed
- Interface ends up as straight line extending 0.1 m downstream of nozzle exit



DSMC Plume Simulation Overview

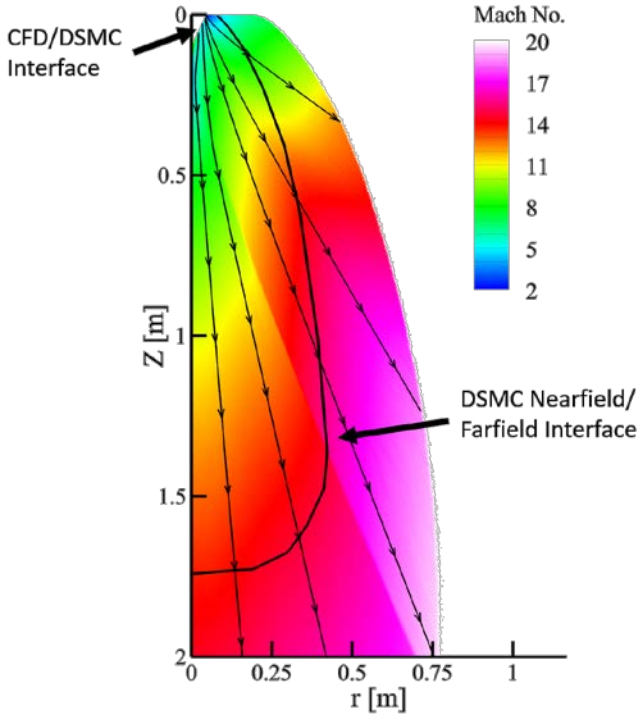
- CFD is not valid at near-vacuum Europa conditions so a kinetic solver is required
- NASA's DAC (DSMC Analysis Code) used
- Inflow Boundary Condition at CFD/DSMC Interface using macroscopic flow properties from CFD
- Single engines simulated at altitudes spanning final stages of landing
  - 5° cant at 25 m
  - 30° cant at 25 m, 20 m, 15 m, 10 m altitudes

Distribution Statement A: Approved for public release; distribution is unlimited.
Pre-Decisional Information – For Planning and Discussion Purposes Only

DSMC Plume Simulation Method

- Staged approach allows for cell size to be increased manually
  - Layer of smaller cells always used along surfaces
- DSMC domain broken into 2-3 stages:
  - Nearfield 2D axisymmetric simulation
    - No Europa surface
    - Second interface defined to transition to 3D
  - Farfield 3D simulation
    - Half-symmetry with cant
    - Inflow boundary condition uses Nearfield flow data
    - Domain extends to Europa surface
      - For altitudes greater than 10 m, second Farfield stage used before extending to surface

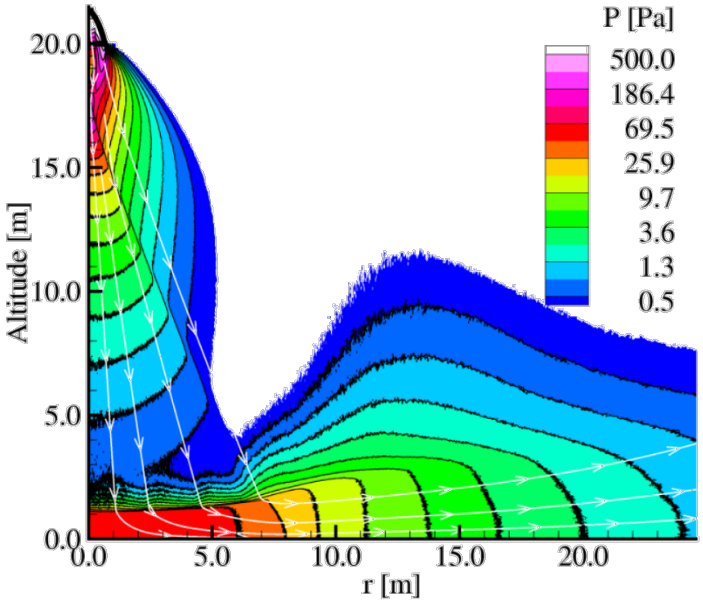
Nearfield DSMC Stage



DAC Validation – 2D, 0° Cant, 20 m Altitude

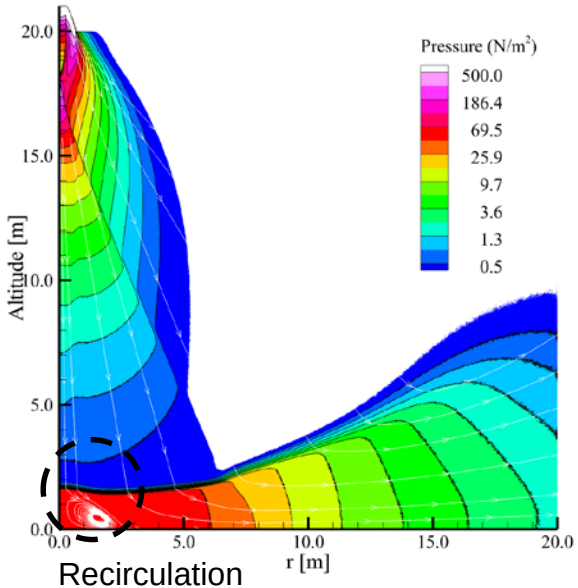
- Good agreement but DAC has recirculation zone and better resolved shock

MORRIS



Morris, A., ***Simulation of Plume Impingement and Dust Dispersal on the Lunar Surface***, Ph.D. Dissertation, Aerospace Engineering Dept., Univ. of Texas at Austin, Austin, TX (2012). Solved using University of Texas at Austin in-house code.

DAC

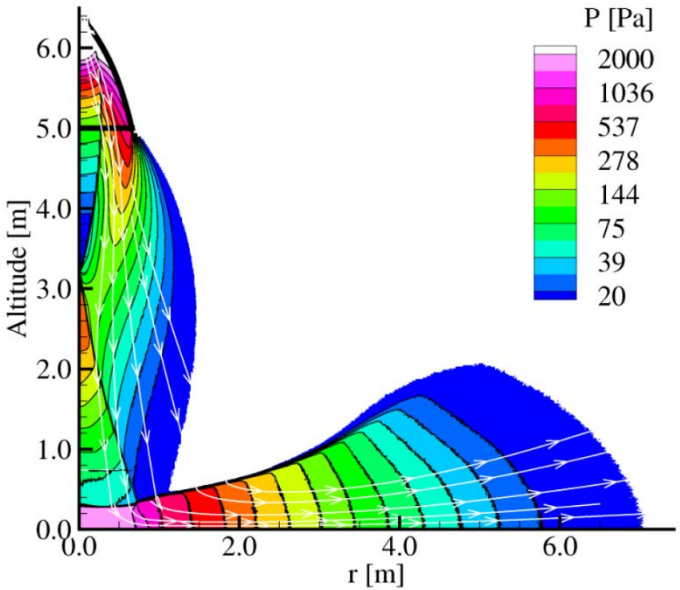


Recirculation zone

DAC Validation – 2D, 0° Cant, 5 m Altitude

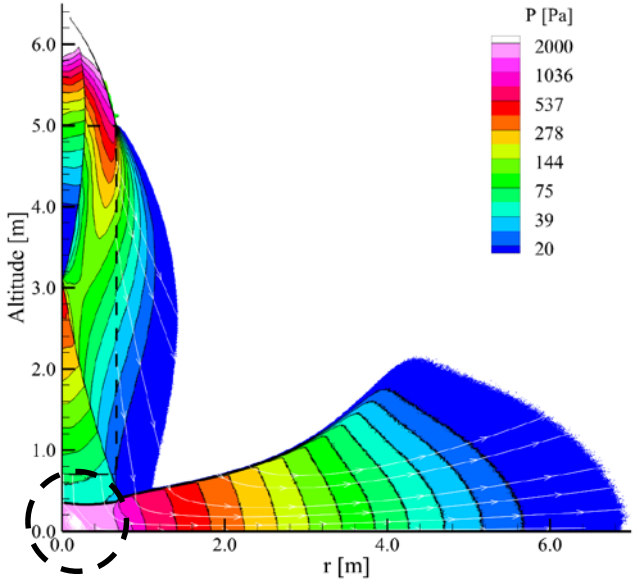
- Good agreement but DAC has recirculation zone

MORRIS



Morris, A., ***Simulation of Plume Impingement and Dust Dispersal on the Lunar Surface***, Ph.D. Dissertation, Aerospace Engineering Dept., Univ. of Texas at Austin, Austin, TX (2012). Solved using University of Texas at Austin in-house code.

DAC

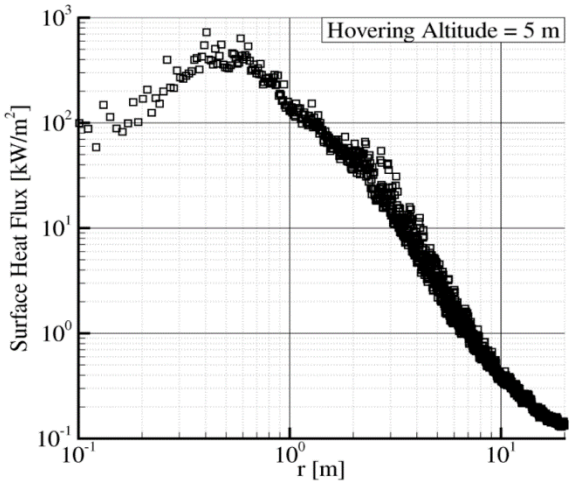


Recirculation zone

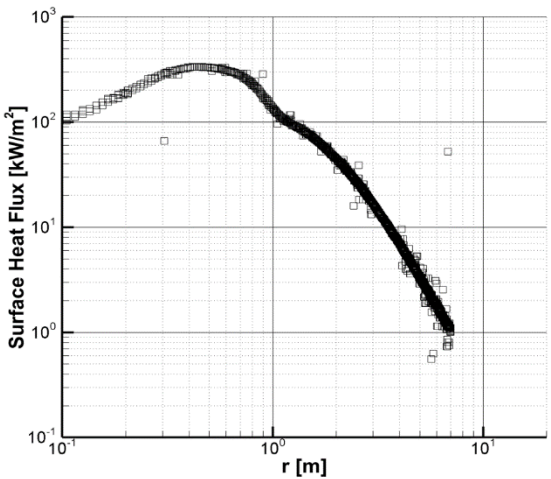
DAC Validation – 2D Surface Heat Flux

- At 5 m altitude, heat flux at surface agrees very well with Morris
  - Peak Heat rate ~300-400 kW/m^2 at r= ~0.5 m

MORRIS



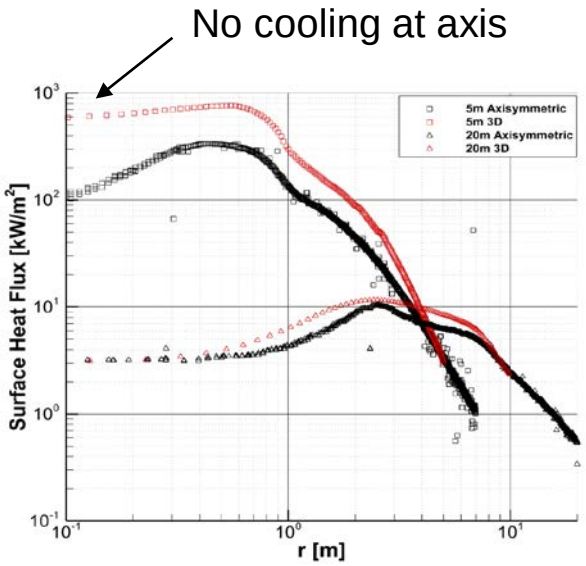
DAC



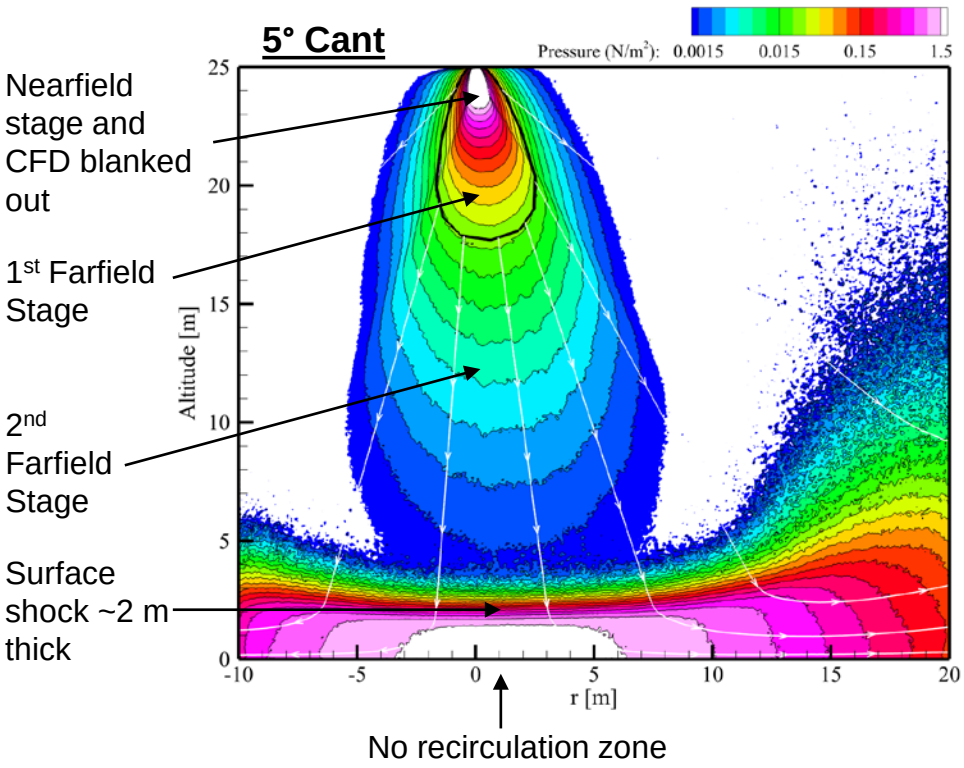
Morris, A., ***Simulation of Plume Impingement and Dust Dispersal on the Lunar Surface***, Ph.D. Dissertation, Aerospace Engineering Dept., Univ. of Texas at Austin, Austin, TX (2012).

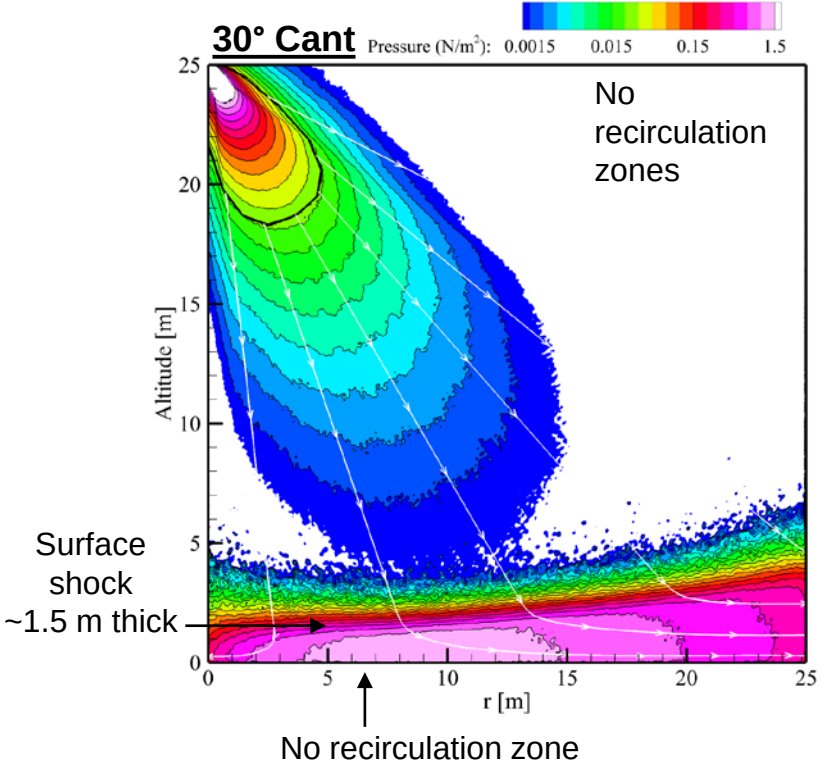
DAC Validation – 3D vs. 2D

- Europa simulations need to be in 3D due to cant, so 3D DAC must also be validated
- DAC simulations repeated in 3D using staged approach and compared to 2D solution
  - Pressure contours at both 20 m and 5 m altitude agreed well with 2D (and Morris)
    - At 5 m altitude, no recirculation zone seen in 3D
  - At 20 m altitude, 3D surface heat flux profile for 3D matches 2D well
  - At 5 m altitude, 3D surface heating is higher near axis due to lack of recirculation zone cooling
- Canted Europa lander engine simulations do not have recirculation zones



DAC Pressure Contours – 25 m Altitude

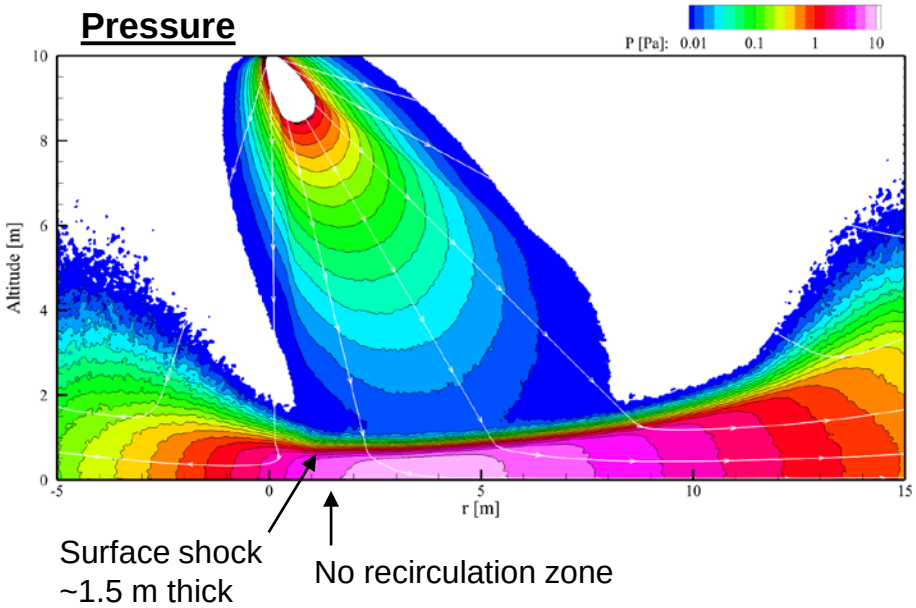


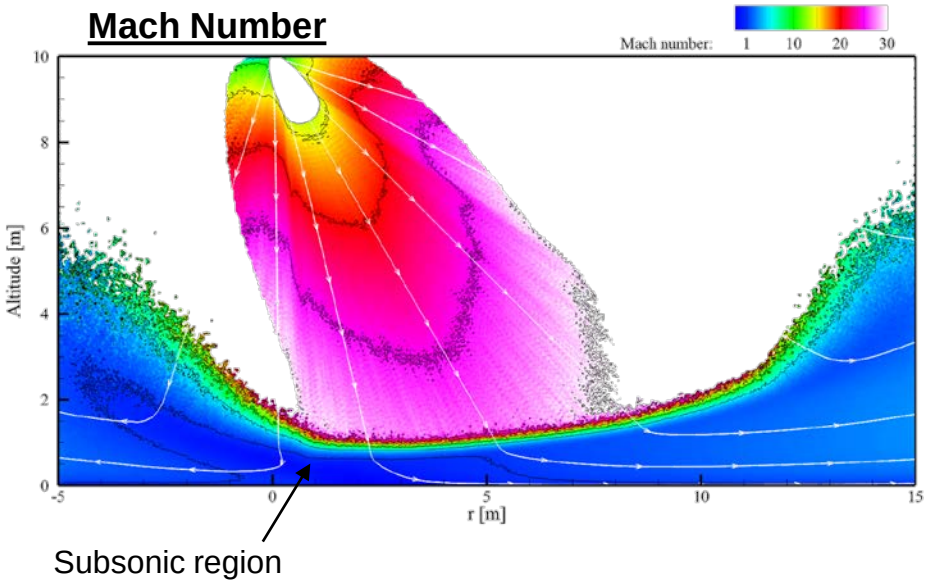


Distribution Statement A: Approved for public release; distribution is unlimited.
Pre-Decisional Information – For Planning and Discussion Purposes Only

DAC Pressure & Mach – 10 m Altitude, 30° Cant

- Lowest altitude – worst case

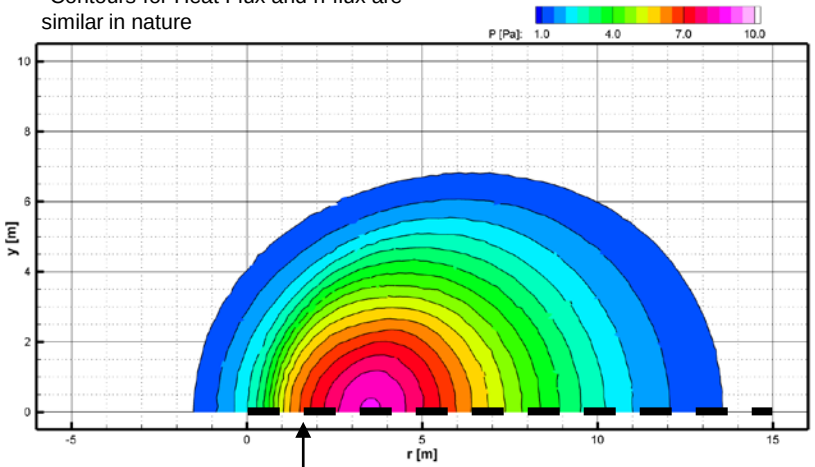




DAC Surface Impingement Results

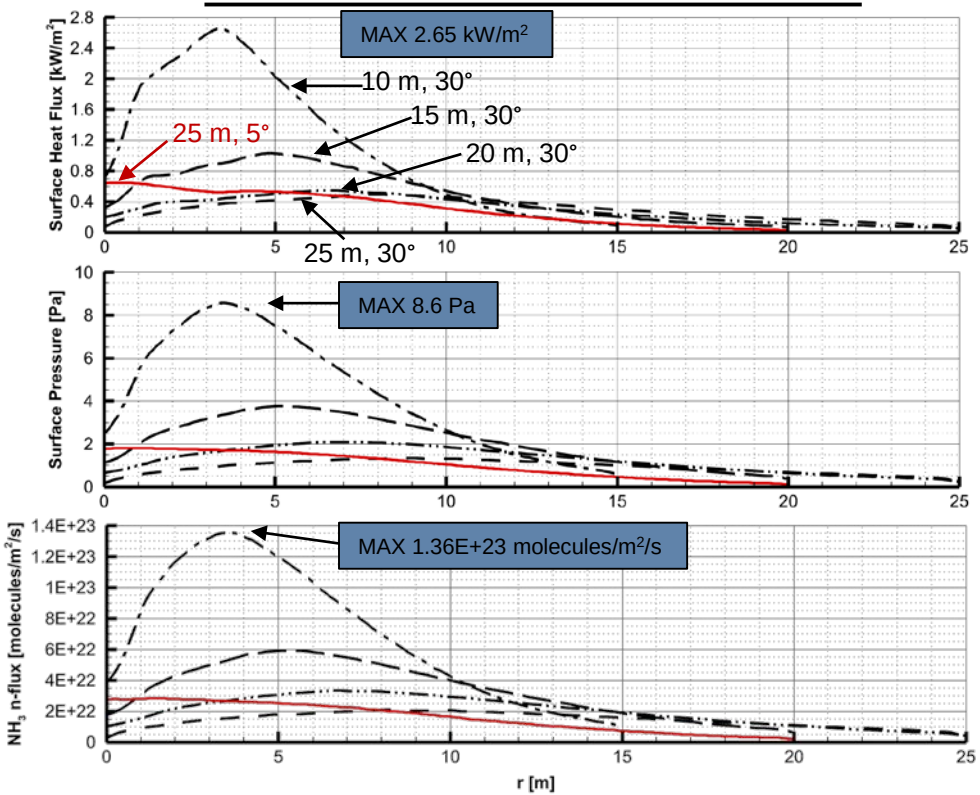
Surface Pressure - 10 m Altitude, 30° Cant

*Contours for Heat Flux and n-flux are similar in nature



Profiles along symmetry axis on plots to right

Surface Profiles – All altitudes & cants



Summary & Conclusions

- Potential Europa Lander engine plume was modelled using validated combination of CFD and DSMC with interface between the two defined within continuum region
- STAR-CCM+ and DAC well-validated with lunar lander engine simulation
  - $c_p(T)$ is important
  - Recirculation zones exist in DAC but irrelevant for canted Europa cases
- Plume impingement with Europa surface results in slightly angled surface shocks < 2 m from surface during final stages of landing (25 m to 10 m altitude)
- Worst plume impingement occurs 3.3 m out from cant axis at 10 m altitude

Distribution Statement A: Approved for public release; distribution is unlimited.
Pre-Decisional Information – For Planning and Discussion Purposes Only

Summary & Conclusions

- Current results are meant to get a general idea of what plume environment is from single engine
- Results can be used to study plume effects in detail:
  - NH_3 accumulation and erosion of landing area
  - Particle entrainment and effects on lander and descent stage
  - Direct impingement/heating/contamination of lander and descent stage
  - Plume-plume interaction between engine pairs

Distribution Statement A: Approved for public release; distribution is unlimited.
Pre-Decisional Information – For Planning and Discussion Purposes Only

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov