Transient Plume Model Testing Using LADEE Spacecraft Attitude Control System Operations

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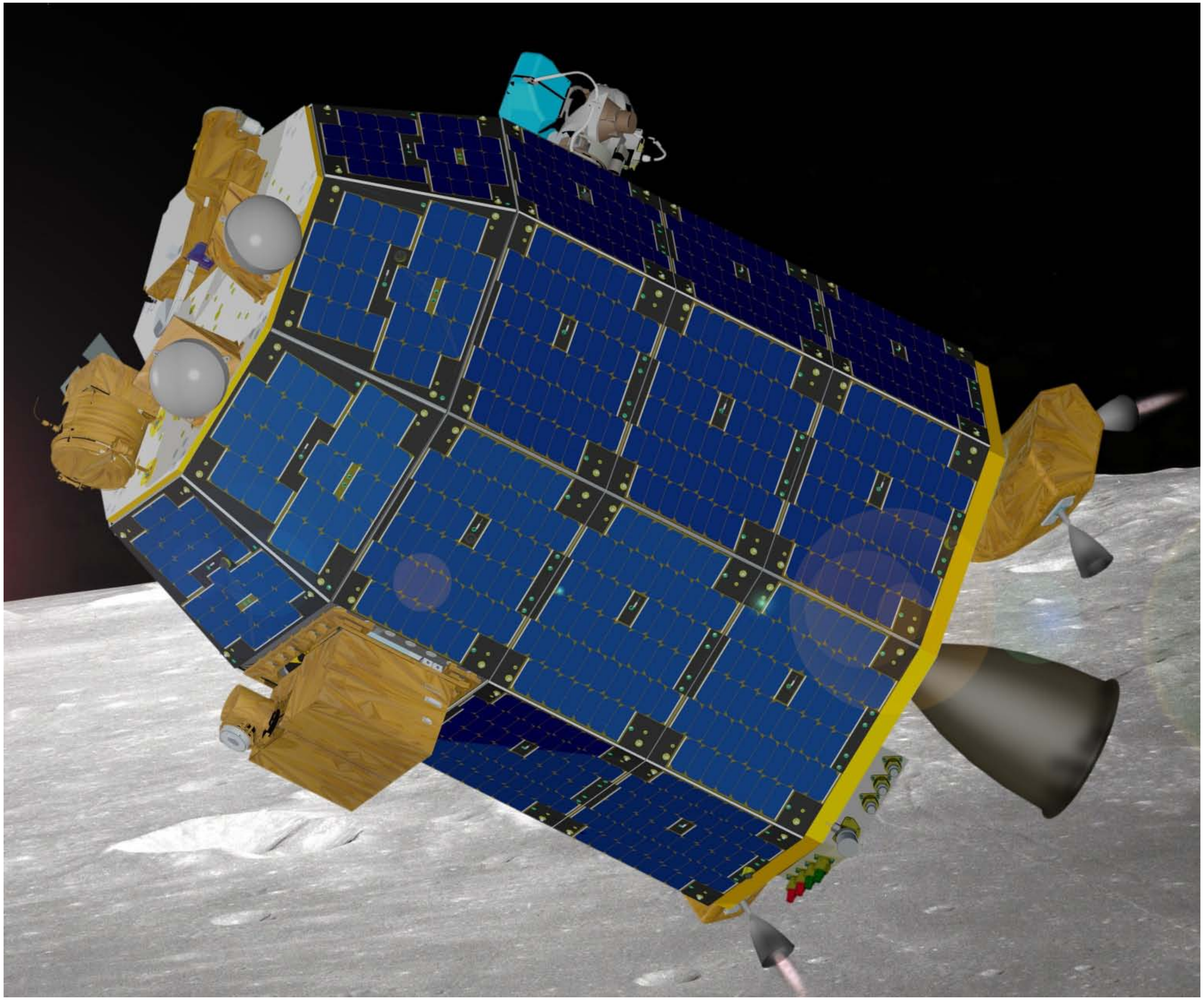
LADEE Spacecraft



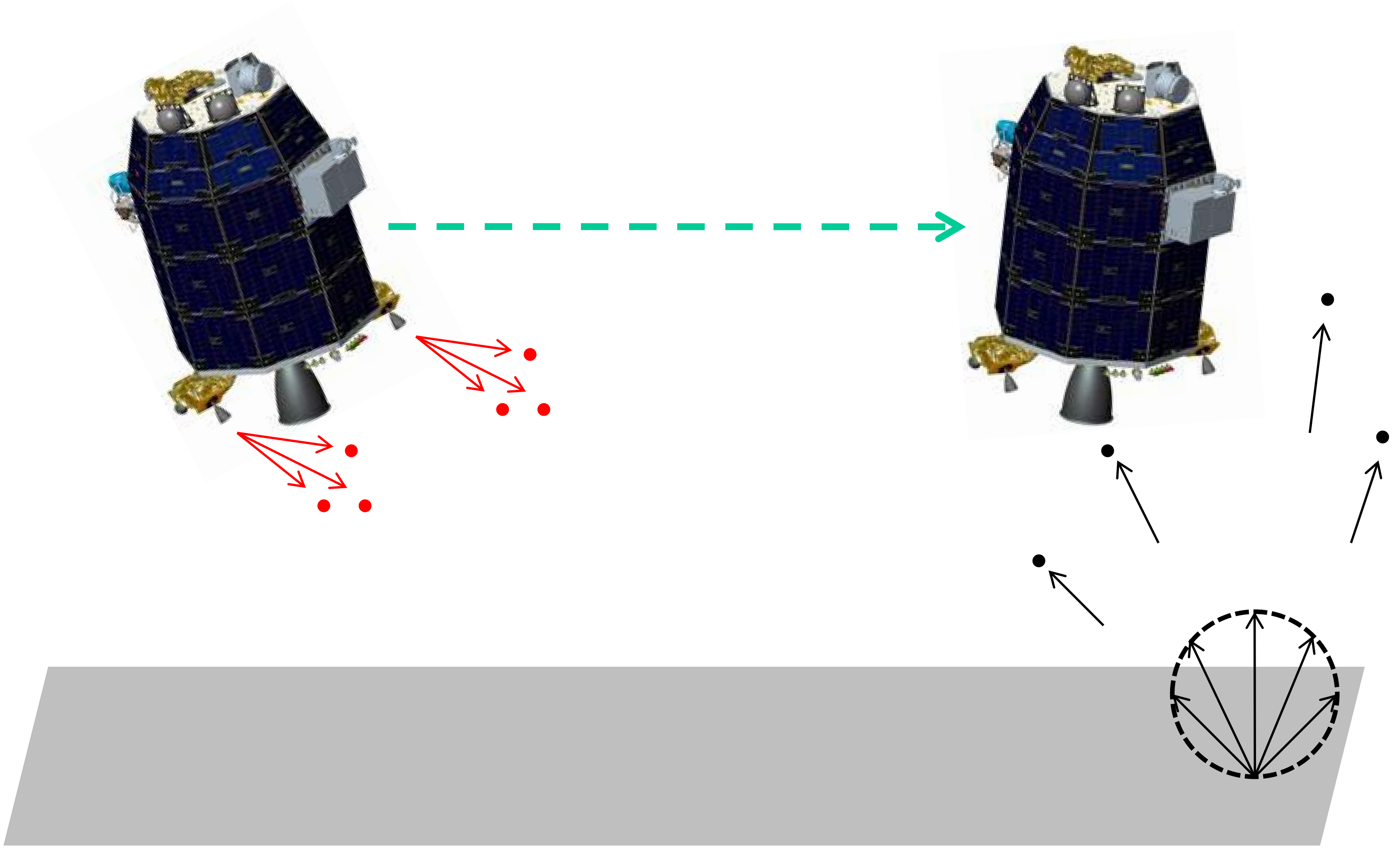
Introduction (2 of 3)

- Lunar Atmosphere Dust Environment Explorer (LADEE)
  – Collect data regarding lunar atmosphere (gases, dust) before alteration due to future exploration activities
- Features include
  – Operational period ~ 100 days
  – Variety of orbits (elliptical, circular)
    - Nominal = 50 km, circular
    - As low as 20 km, circular
  – Variety of orientations used for making measurements, communicating with Earth
- Lunar atmosphere is so rarefied it's referred to as an "exosphere"
  – Essentially free-molecule conditions

Introduction (3 of 3)

- Instruments include Neutral Mass Spectrometer (NMS)
  - Designed to measure concentration levels of species up to 150 amu
  - Design is sensitive enough to detect ~100 molecules/cm^3
- NMS measurement sensitivity drives many LADEE contamination control requirements
  - Causes consideration of unusual scenarios
    - Outgassing
    - Attitude Control System (ACS) thruster plume influence

Schematic Diagram



Objective

- Learned it is conceivable NMS could measure gases from surface-reflected ACS plume
  - At minimum altitude
    - Measurement would be maximized
    - Gravitational influence minimized (“short” time-of-flight situation)
  - Could use to verify aspects of thruster plume modeling
- Model the transient disturbance to NMS measurements due to ACS gases reflected from lunar surface
- Observe evolution of various model characteristics as measured by NMS
  - Species magnitudes, TOF measurements, angular distribution, species separation effects

Test Case Conditions (1 of 2)

- Minimum altitude (20 km, circular)
- NMS faces ram direction
- Orbital velocity = 1.67 km/s
  - Lunar Radius = 1737 km
  - Lunar Gravitational Acceleration g = 1.62 m/s^2
- Featureless, impermeable, daylight lunar surface
  - $T_s \approx 380$ K
- Forward-facing ACS thruster pair
  - Operates for 1 s
  - Orientation = 20° below horizontal
  - Ignore changes in spacecraft altitude
- Particularly interested in water vapor influence

Test Case Conditions (2 of 2)

- ACS Thrusters consist of 5 lb_f bipropellant units
  - Monomethylhydrazine (MMH) fuel
  - MON-3 (mixed oxides of nitrogen, 3% nitric oxide in N_2O_4)
  - Exit conditions include $V_e \approx 3.0$ km/s, $T_e \approx 550$ K
  - Approximate dominant species:

Species	Mass Fraction
N_2	0.43
H_2O	0.29
CO	0.18
CO_2	0.086
H_2	0.016

Gravitational Effect

- Time to reach lunar surface based on V_e
  - 19.2 s, ballistic
  - 19.5 s, radial
- Time for water vapor normally-reflected from lunar surface at T_s to reach 20 km
  - 31.1 s, ballistic
  - 29.9 s, radial
- For the purposes of this study, can ignore influence of lunar gravity if period under consideration is limited to approximately one minute

Model Formulation

- Find particular solution to collisionless Boltzmann equation for source Q_1:

$$\frac{\partial f}{\partial \boldsymbol{t}} + \boldsymbol{v} \cdot \frac{\partial f}{\partial \boldsymbol{x}} + \boldsymbol{g} \cdot \frac{\partial f}{\partial \boldsymbol{v}} = Q_1$$

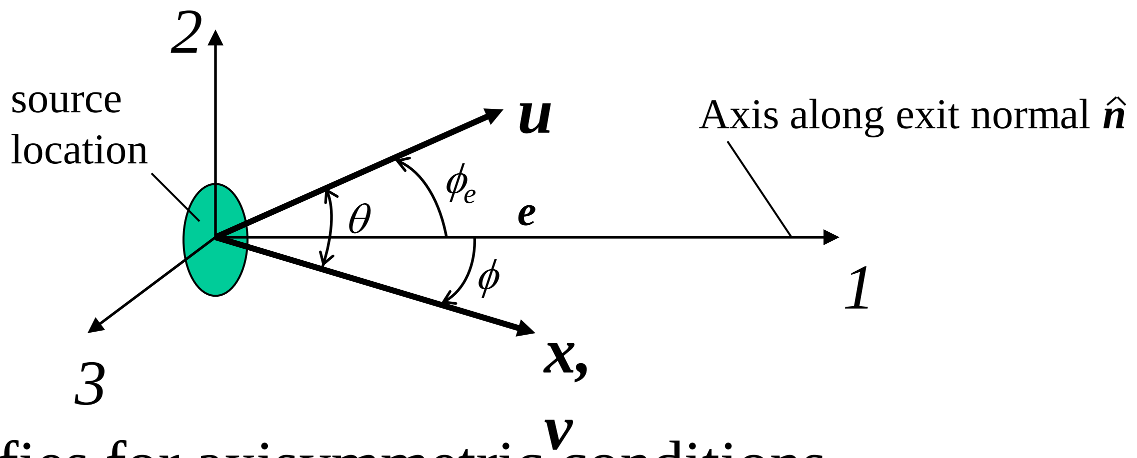
where

$$Q_1 \equiv \frac{2\beta^4}{A_1 \pi} \delta(\boldsymbol{x}) \dot{m}(t) |\boldsymbol{v} \cdot \hat{\boldsymbol{n}}| \exp\left(-\beta^2 (\boldsymbol{v} - \boldsymbol{u}_{\mathrm{e}})^2\right)$$

and

$$A_1 \equiv e^{-s^2 \cos^2 \phi_{\mathrm{e}}} + \sqrt{\pi}\, s \cos\phi_{\mathrm{e}} \left(1 + \mathrm{erf}\left(s \cos\phi_{\mathrm{e}}\right)\right)$$

Model Development

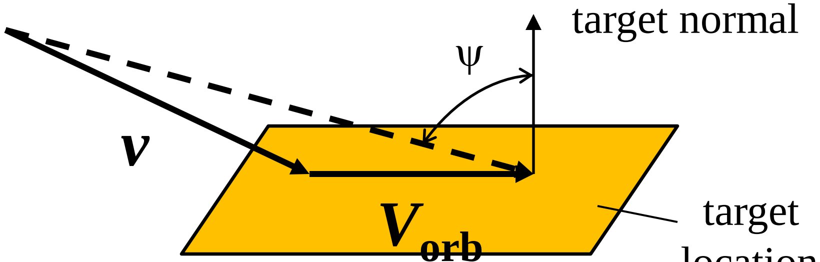


- Simplifies for axisymmetric conditions
  - $\phi_e = 0$
  - $\phi = \theta$
- other definitions:

$$s \equiv \beta u_e = \frac{u_e}{\sqrt{2RT_e}}; \quad z \equiv \alpha - w; \quad \alpha \equiv \beta r/t; \quad w \equiv s\cos\theta$$

Model Development—Pulse

- Plume equations when mass flow rate is described by $\dot{m} = \Delta m \delta(t)$
  - Angle between incident plume and impinged surface given by ψ



$$\rho(\boldsymbol{x},t) = \frac{2\Delta m \alpha^4 \cos\phi}{A_1 \pi r^3} e^{-(w-s)^2} e^{-z^2}; \qquad \dot{\Phi}(\boldsymbol{x},t) = \frac{\rho r}{t} \cos\psi$$

Model Development—Unconstrained

- Earlier, Narasimha developed model describing unconstrained expansion:

$$Q_{\mathrm{N}} \equiv \frac{\beta^3}{\pi\sqrt{\pi}}\delta(\boldsymbol{x})\dot{m}(t)\exp\left(-\beta^2(\boldsymbol{v}-\boldsymbol{u}_{\mathrm{e}})^2\right)$$

- Density response, pulse mode:

$$\rho(\boldsymbol{x},t)=\frac{\Delta m\alpha^3}{\pi\sqrt{\pi}r^3}e^{-(w-s)^2}e^{-z^2};$$

- Format of other expressions similar to constrained case

$$\dot{\Phi}(\boldsymbol{x},t)=\frac{\rho r}{t}\cos\psi;$$

Approach

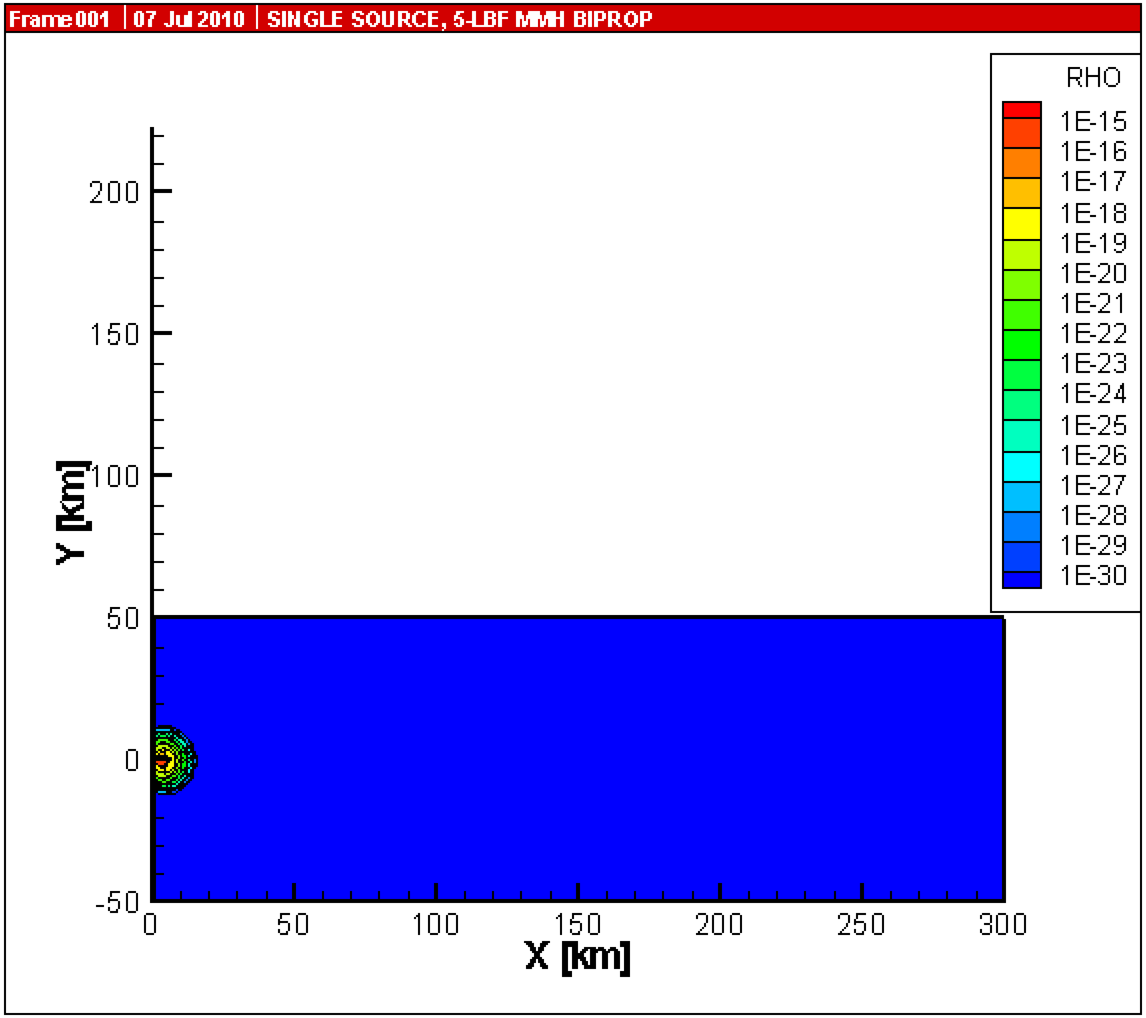
- ACS thruster firings modeled using single sources
- Determine subsequent transient density and species mass fluxes across representative lunar surface for each timestep
- Use mass conservation
  - assume flux in = flux out for each species
  - Each surface node becomes source for diffusely-reflected material at T_s for times beyond current timestep ("complementary timesteps" out to 1 min.)
  - Fluxes reaching NMS along its path come from surface nodes ahead of LADEE
    - Spacecraft body blocks influence at ram-facing NMS sensor head
- Possible to create more sophisticated mass conservation statements
  - Effects of lunar regolith permeability, gas-surface interactions

Results

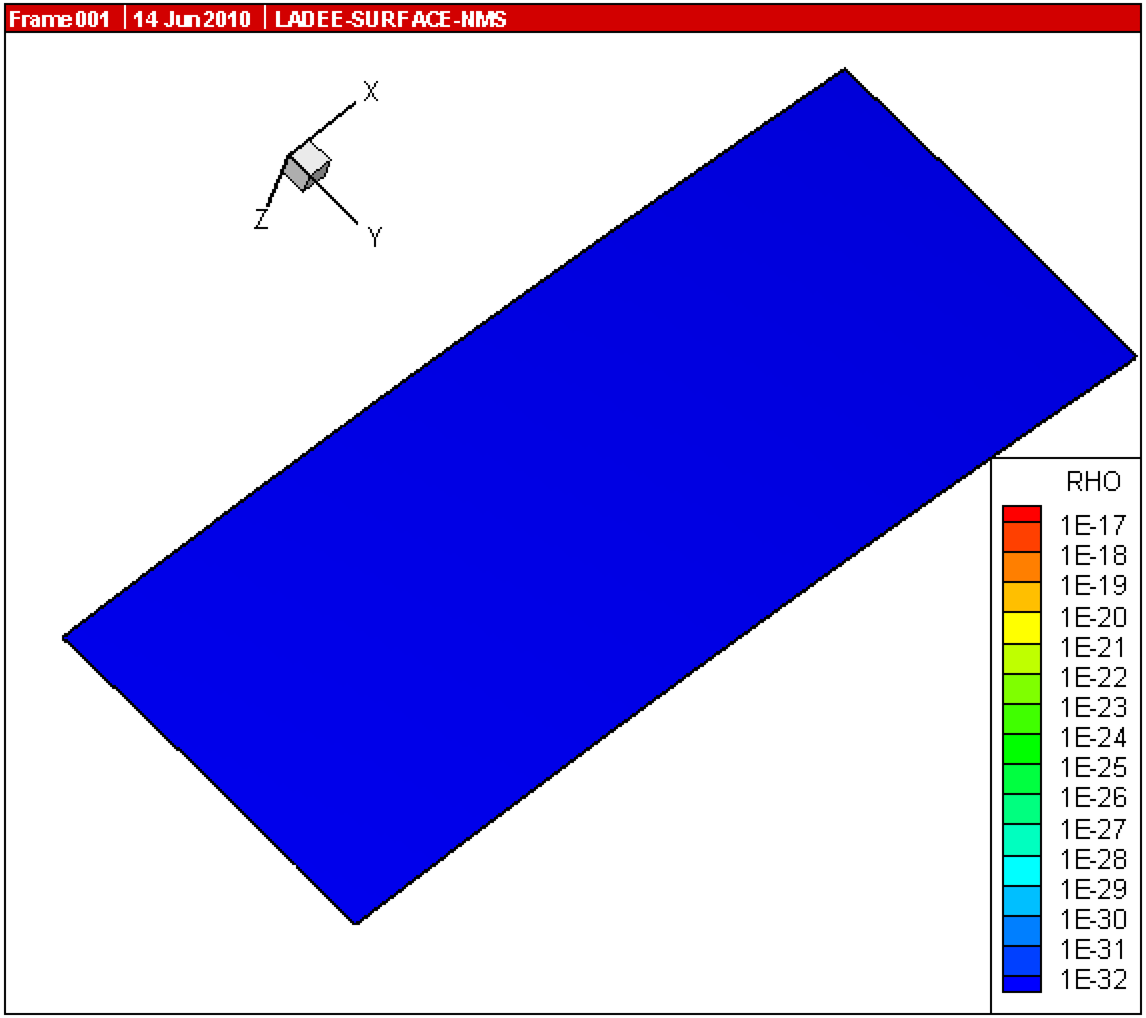
- Observe free expansion development
- Logarithmic density contour maps for surface impingement
  - Compare Q_1 vs. Q_N
  - Effect of T_e
- Estimates for transient species concentrations along NMS path
  - Similar comparisons

Free Expansion

Click on Picture



Surface Interaction Development



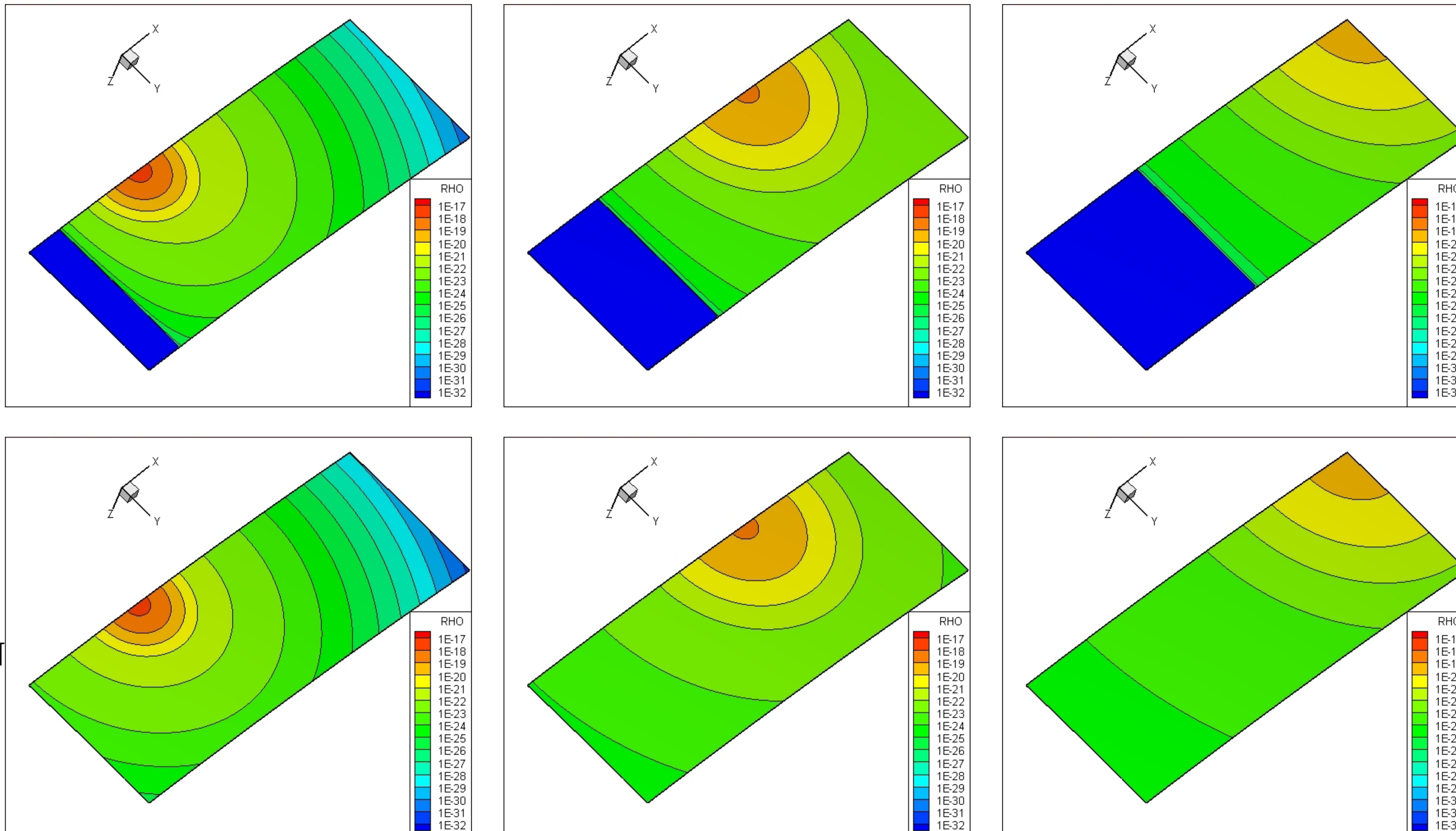
Click on Picture

Results—Surface Density, Source Model Effects

20 s | **40 s** | **60 s**

Q_1

Q_N



Nozzle Exit Temperature T_e Influence

- Elapsed time for peak species mass fluxes to reach lunar surface occurred quicker than expected based on $V_e \sin 20°$
- Time derivative of mass flux equations ($\Phi \propto t^{-D}$) indicates

$$t_{\max\,\text{flux}} = \frac{2\beta r}{w\left(1+\sqrt{1+\dfrac{2D}{w^2}}\right)}$$

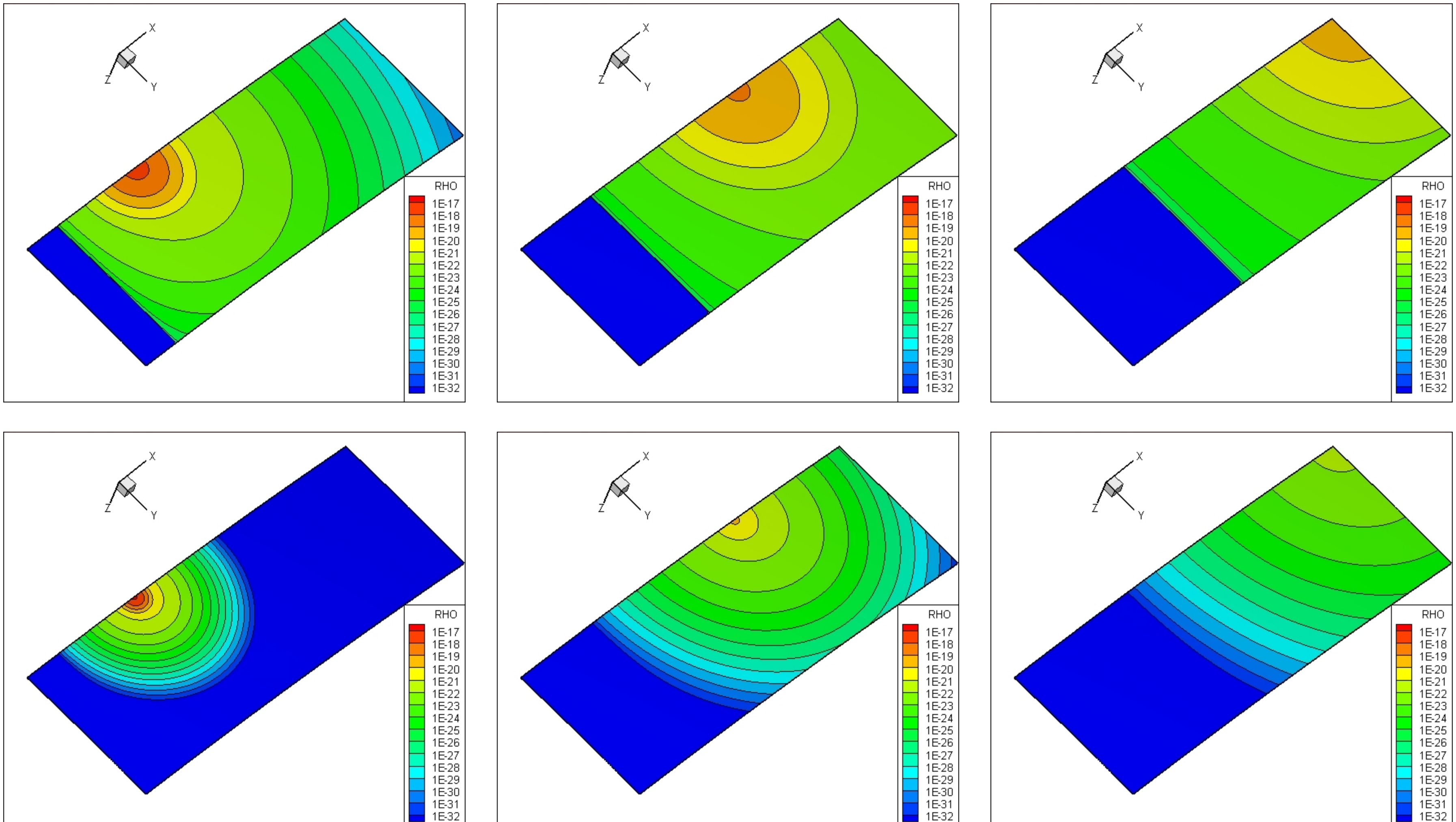
- For $w = s$ on the plume centerline, $t_{\text{max flux}} \rightarrow r/V_e$ as $s \rightarrow \infty$
- For finite s, this period is always shorter
  - Consequence of thermal energy component
- Create new Q_1 case using arbitrarily low temperature (55 K vs. 550 K)

Results—Surface Density, Q_1 Exit Temperature Effects

20 s | 40 s | 60 s

~550 K

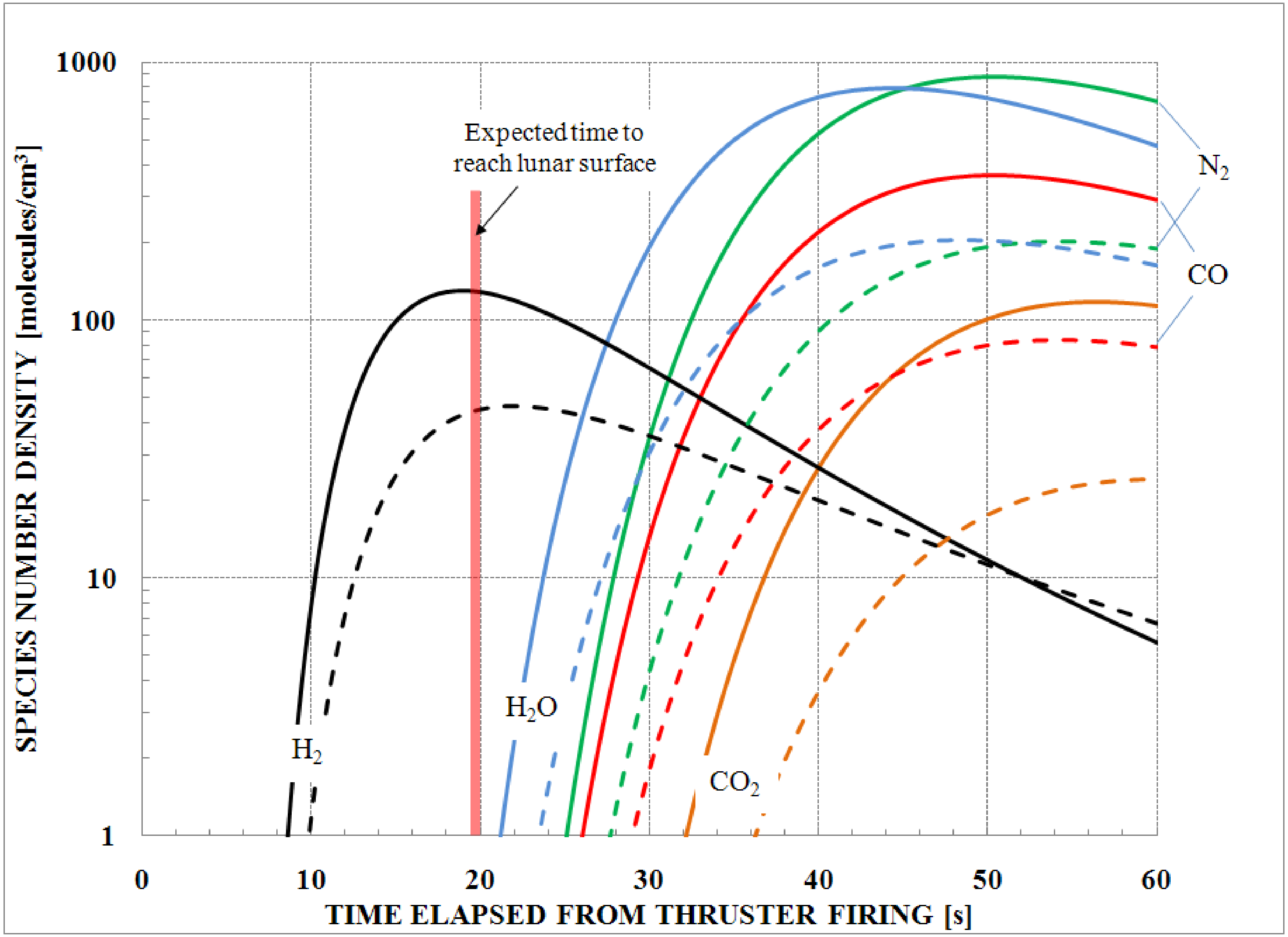
~55.0 K



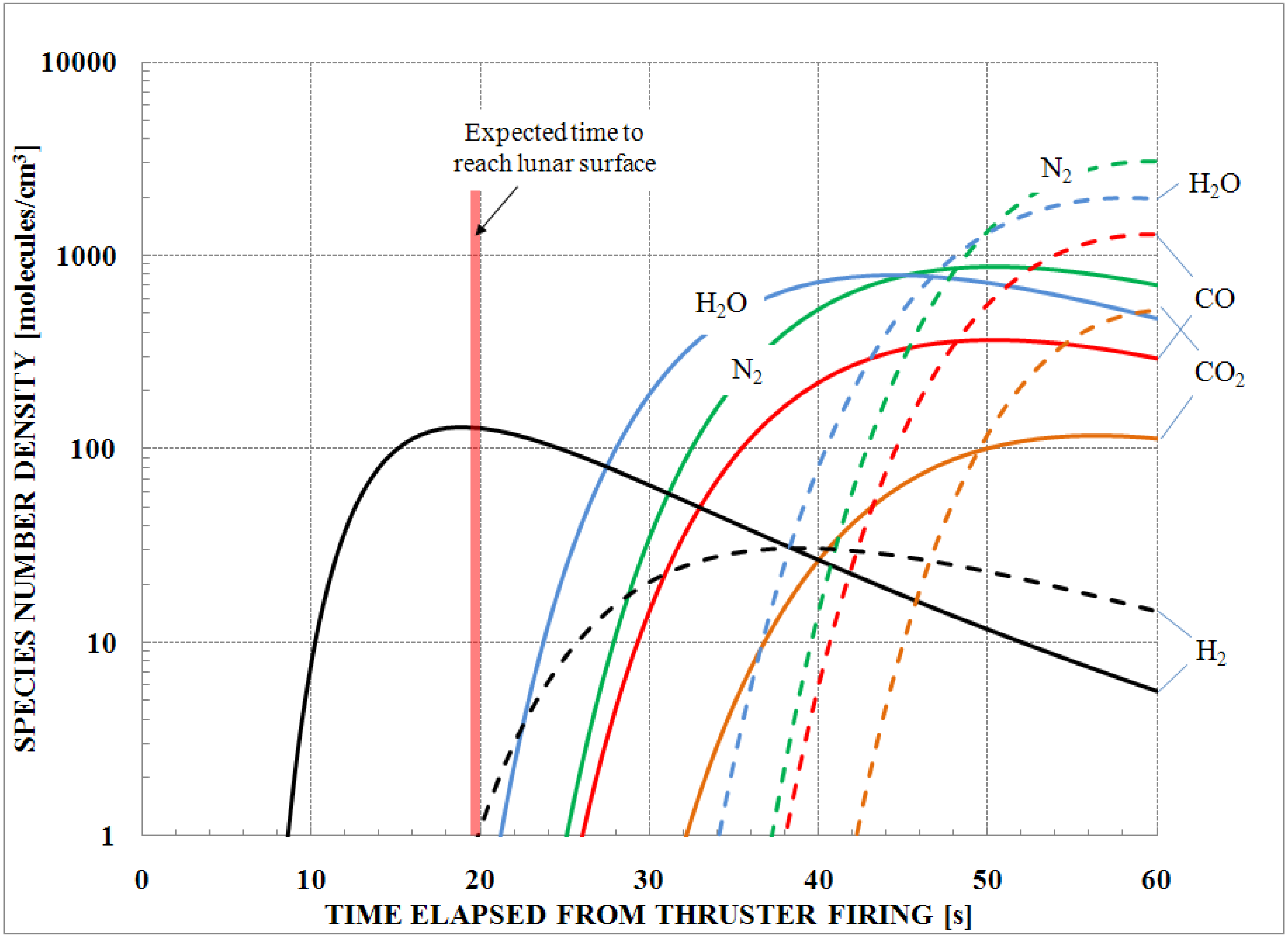
Results—Peak Surface Fluxes

Item [cgs units]	Peak Flux, Q_1	Elapsed Time	Peak Flux, Q_N	Elapsed Time	Peak Flux, Q_1, low-T_e	Elapsed Time
ρ [g/cm^3]	2.7e-18	15	2.6e-18	15	1.3e-17	20
N_2 [g/cm^2/s]	1.7e-13	14	1.6e-13	14	5.8e-13	19
H_2O	8.6e-14	12	7.9e-14	12	2.2e-13	19
CO	7.1e-14	14	6.7e-14	14	2.4e-13	19
CO_2	5.1e-14	15	4.9e-14	15	2.2e-13	20
H_2	2.5e-15	6	1.9e-15	6	1.3e-15	13

NMS Species Density Estimates, Source Model Effects



NMS Species Density Estimates, Exit Temperature Effects



Concluding Remarks

- Appears possible NMS could measure surface-reflected gases from ACS operations
- Comparing Q_1 and Q_N solutions
  - Plume interactions with surface largely similar
  - Differences more pronounced for surface-reflected molecular distribution
  - Ability to distinguish levels of fidelity depend on possibly subtle distinctions
- Strong dependence on speed ratio (effective nozzle exit temperature)
  - Peak values of species fluxes
  - Time to reach max flux values
- Possible to revisit scenario to include effects of permeable lunar regolith, surface interaction
- Related scenario, relevant for ONIMS instrument on OSIRIS-REx asteroid mission