Modeling of Lunar Dust Contamination Due to Plume Impingement

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Introduction (1 of 3)

• Apollo 16 Lunar Module landing sequence

• “I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome physiological or physical or mechanical problems except dust.”
  – Gene Cernan, Apollo 17 Technical Debrief
• During the Apollo missions it became apparent that lunar dust was a significant hazard. Problems included
  – Surface obscuration during landing sequence
  – Abrasion damage to gauge faces and helmet visors
  – Mechanism clogging
  – Development of space suit pressurization leaks
  – Loss of radiator heat rejection capabilities to the point where vulnerable equipment exceeded maximum survival temperature ratings
  – Temporary vision and respiratory problems within the Apollo Lunar Module (LM)
Introduction (3 of 3)

• NASA Constellation Program features many system-level components
  – including the Altair Lunar Lander

• Altair to endure longer periods at lunar surface conditions
  – Apollo LM, about three days
  – Altair, over seven months

• Program managers interested in plume-generated dust transport onto thermal control surface radiators of the first Altair created by its own landing operations
Problem Description

• Analyze dust contamination environment generated during first Lunar Lander landing
  – Self-contamination of critical thermal control radiators
  – Non-LOS

• Virtually no lunar atmosphere
  – No atmospheric mixing of gases

• Concern that electrostatically-charged particles, freed from lunar regolith by lander engine operations, may find their way to critical lander surfaces
Approach

- Model main engine plume
- Calculate surface stresses on lunar regolith
- Calculate regolith removal rate
  - Fluid acceleration against particle inertia, short-range forces
- Determine electrostatic work necessary to overcome kinetic energy of mobile dust particles
- Current modeling efforts still underway
Altair Lunar Lander

• Much larger than Apollo Lunar Lander
  – 46,000 kg vs. 16,400 kg

• Meant to remain on lunar surface for weeks
  – Period depends on type of mission (sortie vs. outpost support modes)
Pratt & Whitney RL-10 Engine Description

- Created RL-10 model
  - Hard to pin down unspecified Altair parameters
    - Range of O/F ratios
    - Various $I_{sp}$’s, nozzle geometries
    - Versatile engine, designed in 1957, has used vast array of fuels under test conditions, throttled down to 1% full thrust in testing
  - Used RL-10A-4 info
    - $I_{sp} = 449$ s, O/F = 5.5, $p_0 = 39$ bar, $\dot{m} = 21$ kg/s, $A_e/A^* = 84$
  - Nozzle exit properties (simplistic)
    - 22 H$_2$O + 10 H$_2$
    - $V_e = 4.3$ km/s, $T_0 = 2600$ K, $T_e = 550$ K, $M_e = 6.37$
    - Decided flat exit profile adequate for current application
      - Neglect boundary-layer development and its high-angle influence
      - Altair geometry inhibits backflow development
Descent Engine Comparisons

• Altair RL-10 vs. Apollo LM Descent Stage (DS)
  – Fuel
    • LOX/LH₂ vs. N₂O₄/Aerozine-50
  – Thrust
    • 99.1 kN vs. 44.0 kN
  – Specific Impulse \( I_{sp} \)
    • 449 s vs. 311 s
  – Exit velocity
    • 4.3 km/s vs. 3.1 km/s

• Altair DS engine parameters much more energetic than Apollo
  – Apollo-related models may not be suitable for Altair investigations
Observations

• Period of highest plume impingement not same as period of worst dust attraction

• Particle drag will overwhelm charge effects
  – Neglect dust attraction during firing periods
    • Drag force and attraction both fall with square of distance

• Attraction occurs during, after engine shutdown
  – Only for disturbed, charged dust within Debye radius from Lander
  – Intersection with lunar surface produces disk of influence
    – Varies with particle size, relative potential
Plume Model Formulation

• Initial modeling uses FM plume formulation
  – Can use rapidly to approximate incident fluxes (impingement stresses)
  – Try correcting for Knudsen layer using bridging technique
    • DLR
    • Potter
      – Reynolds analogy for high density shear (Legge)

• Can substitute results from different approaches
  – DSMC simulations
  – CFD computations
FM Model—Free Expansion

- Logarithmic mass flux contour map

- Mass flow rate verified from mass flux map
FM Model—Surface Impingement

- Pressure contours (incident + reflected, $T_{surf} = 300$ K)
• Radial shear stress contours
  – Max of 7.5 Pa @ \( r = 11.3 \) m
Plume Model Procedure

- Create time-varying gas properties across starting surface
- Inputs at each timestep affects solution domain over long subsequent period
  - May identify arbitrary response periods to individual input timestep conditions beyond which influences decay to negligible values
  - Build up overall FM solution from summation of transient responses to inputs at each single timestep
- Look for opportunities to revise with solutions using higher-fidelity techniques
  - DSMC, CFD, hybrids
Lunar Dust Attributes

(Frame width ≈ 0.66 microns)
Lunar Dust Attributes

• Typical sample described as a basaltic ash
• Density $\approx 2.9 \text{ g/cm}^3$
• Avg. grain radius $\approx 70$ microns
  – Size distribution ranges from sub-micron to hundreds of microns
• Jagged features
  – Oxidation removes roughness for terrestrial dust
  – Exposure to high-energy solar wind
• Low electrical conductivity
• Surface adhesion facilitated by
  – Burr-like geometry
  – Electrostatic effects
Dust Production Mechanism

• “Viscous erosion” model developed for Apollo program
  – Issue concerned obscuration of landing site, not charged particle attraction
• Particle expected to remain at rest until local plume shear stress
  overcomes static friction, cohesive stress, component of gravity
  – Does this process produce triboelectric charging?
• Plume shear stress in excess of the critical value converted into
  accelerating particles to their final velocities
• Some subsequent testing found model erosion rates match to
  within an order of magnitude
  – Verification of particle velocities not mentioned
Observations

• Viscous erosion model
  – assumes instantaneous acceleration to final velocity
  – Neglects persistent influence of plume environment
    • Model assumes dust trajectories determined by surface ejection angle
    • Recent photogrammetric analyses indicate actual trajectories lie 1-3° off horizontal
    • Effects on dust velocity

• Current studies identify at least three other mechanisms
  – “Bearing Capacity Failure”
  – “Diffused Gas Eruption”
  – “Diffusion-Driven Shearing”

• Erosion model modifications currently under development
Electrostatic Attraction to Altair

• Compute Debye radius
  – Representative distance over which significant charge separation can occur and still exert influence
  – Outside this distance, charges are considered screened

• Time lag determines whether generated particles remain within influence disk (intersection of Debye sphere and lunar surface) at instant engine firing ceases
  – Sorta like “musical chairs” once music stops

• Electrostatic attraction model
  – Electrostatic work performed to overcome K.E. for Altair surface attraction
  – Translate these effects to a incident dust mass flux
Final Results--Dust Mass Flux

- Dust return flux will be particle size dependent
  - Must use binning to create return fractions
  - Summation provides estimate for Percent Area Coverage (PAC)
    - Assume no overlap of particles (simple, conservative for high PAC’s)
- Relate PAC to radiator degradation
  - Changes in absorptivity, emissivity
- Others could use mass flux to determine effects on mechanisms, visors, etc.
Concluding Remarks

- Relatively unique investigation requires at least three models
  - Transient plume impingement problem
  - Dust generation rates
  - Non-line-of-sight electrostatic attraction
- Must remain responsive to possibility of incorporating
  - high-fidelity RL-10 lunar plume impingement computational results
  - updates to dust generation models from current studies
    - Including newly-defined generation mechanisms
  - Estimates of charging of lunar surface, Altair due to various mechanisms