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Modeling of Lunar Dust Contamination Due to Plume Impingement

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2009 Contamination, Coatings, & Materials Workshop

22 July 2009

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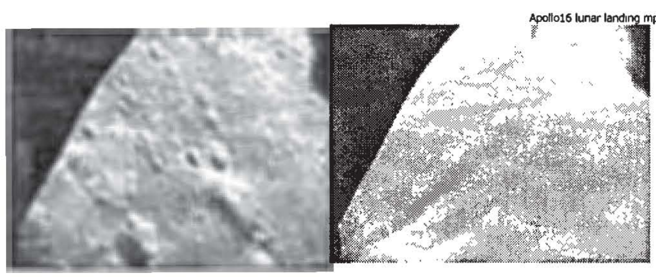
Introduction (1 of 3)

- 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*

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Introduction (2 of 3)

- 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)

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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

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Problem Description

- Analyze dust contamination environment generated during first Altair 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

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Approach

- Model consists of three standalone elements
  - Model main engine plume
    - Transient decay after shutdown
  - Calculate regolith removal rate due to plume impingement
    - Discussion of Roberts "viscous erosion" model
  - Determine electrostatic work necessary to overcome kinetic energy of mobile dust particles
- Must keep open mind
  - Each model element has approximations that could be replaced with elements containing greater sophistication
    - with better knowledge of physical inputs

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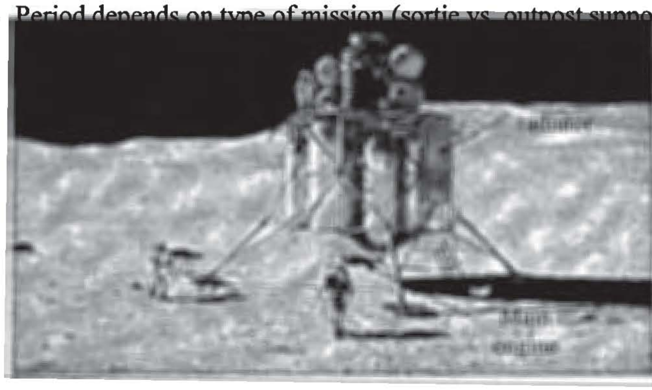
Altair Lunar Lander

- 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)



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Descent Engine Comparisons

- Altair RL-10 vs. Apollo LM Descent Stage (DS)
  - Fuel
    - LOX/LH_2 vs. N_2O_4/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

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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, frozen flow)
    - 22 H_2O + 10 H_2
    - $V_e = 4.3$ km/s, $T_0 = 2600$ K, $T_e = 870$ K, $M_e = 5.0$
    - Decided flat exit profile adequate for current application
      - Neglect boundary-layer development and its high-angle influence
      - Altair geometry inhibits backflow development

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Engine Model Observations

- Period of highest plume impingement not same as period of worst dust attraction
  - Particle drag will overwhelm charge effects during operation
- Attraction may occur during, after engine shutdown
  - Only for disturbed, charged dust within Debye radius from Lander
  - Intersection with lunar surface produces disk of influence
    - Simplify to radial problem
- No engine unstart in vacuum during shutdown
  - Reason for failure of Falcon 1, Flight 3 (3 August 2008)
  - Assume transient decay in mass flow rate, based on loss of driving pressure that forces propellant into combustion chamber

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Plume Model Formulation

- Initial modeling uses FM plume formulation
  - Can use rapidly to approximate incident fluxes (impingement stresses)
- Can substitute results from different approaches
  - DSMC simulations
  - CFD computations

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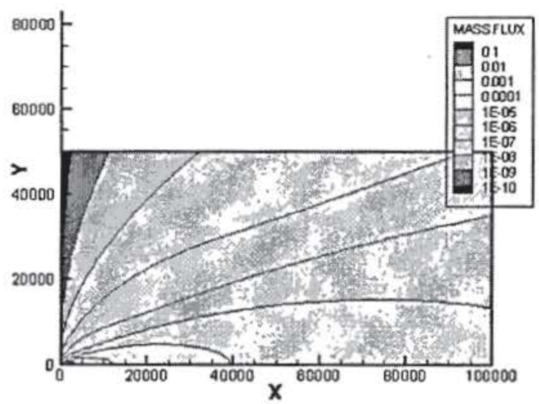
FM Model—Free Expansion

- Logarithmic mass flux contour map (steady-state)



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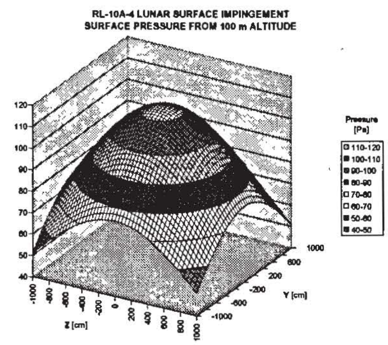
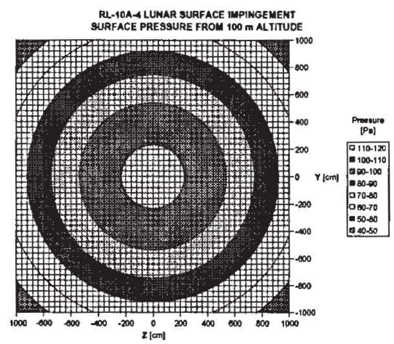
FM Model—Surface Impingement

- Pressure contours (incident + reflected, $T_{surf} = 300$ K)
  - Not for current study conditions





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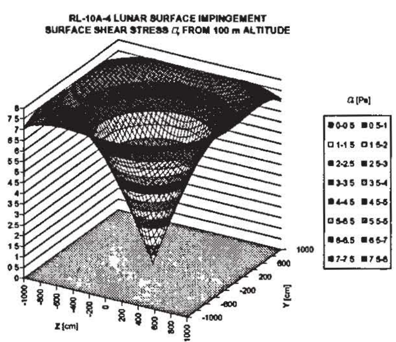
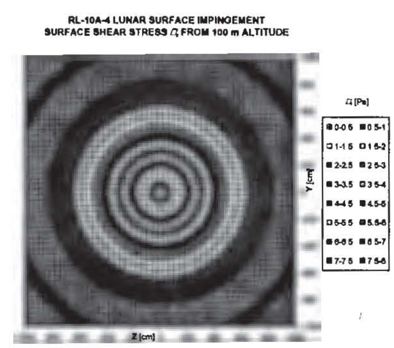
FM Model—Surface Impingement (cont.)

- Radial shear stress contours (not for current study conditions)
  - Max of 7.5 Pa @ $r = 11.3$ m





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Plume Model Procedure

- Create time-varying gas properties across starting surface
- Inputs at each timestep affects solution domain over long subsequent period
  - 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

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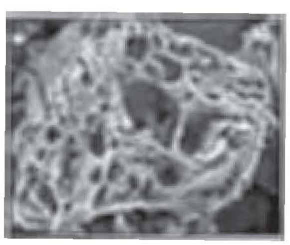
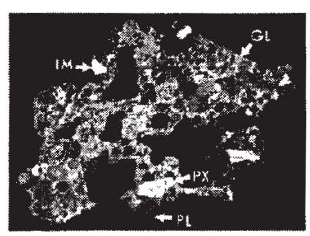
Lunar Dust Attributes





(Frame width ≈ 0.66 microns)

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Lunar Dust Attributes

- Typical sample described as a basaltic ash
- Density ≈ 2.9 g/cm^3
- Avg. grain radius ≈ 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

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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
  - Recent tests show multiple mechanisms responsible, much more complicated than viscous erosion model assumptions
    - KSC, Mars Phoenix, various NASA-academia partnerships

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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

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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

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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.

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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

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