Contradictory Design Requirements and Linchpin Technology in Aerospace Engineering

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In order to be up in the air

In order to be up in the air

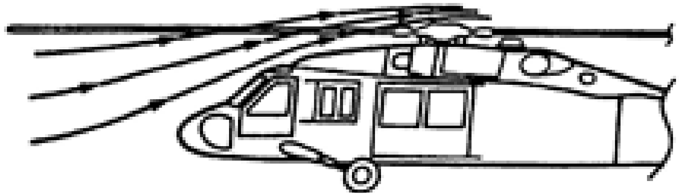
Beyond the Earth: Saturn & Cassini (1997-2017)

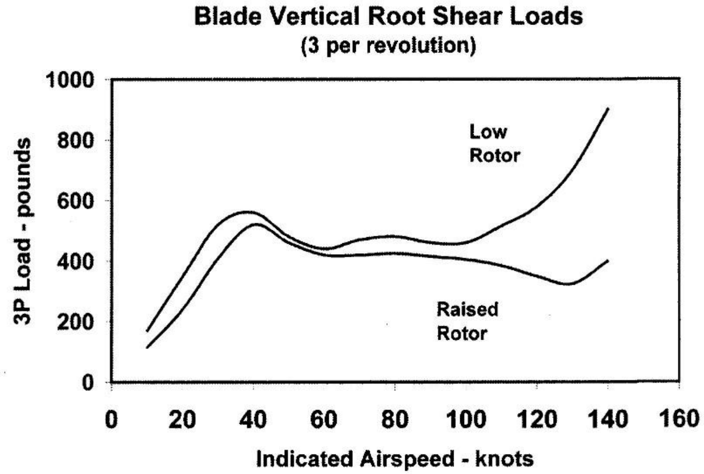
Background (UH-60 main rotor)

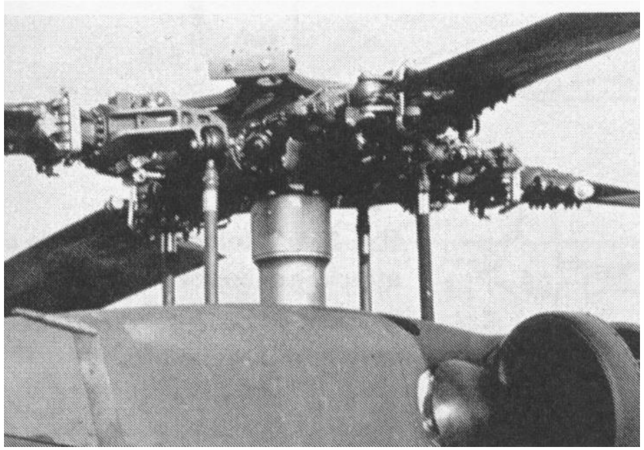
- The design requirements in the development of complicated system are often **contradictory**.
- In case of the Black Hawk (UH-60), the US army's high-priority requirement: **air transport capability** (using a C-130 cargo aircraft) demanding the main rotor close to the fuselage
- However, the **low rotor position created severe interference** flow conditions that could increase **required power** in forward flight significantly. What can you do?

Background (UH-60 main rotor)

- In order to resolve this contradictory requirement, the Sikorsky rotor designers invented an ingenious solution; a **two-position rotor system** based on a removal new part.
- The rotor shaft extender enabled the rotor location **15 inch higher during flight**, while it permitted the rotor to be **lowered for air transport**.

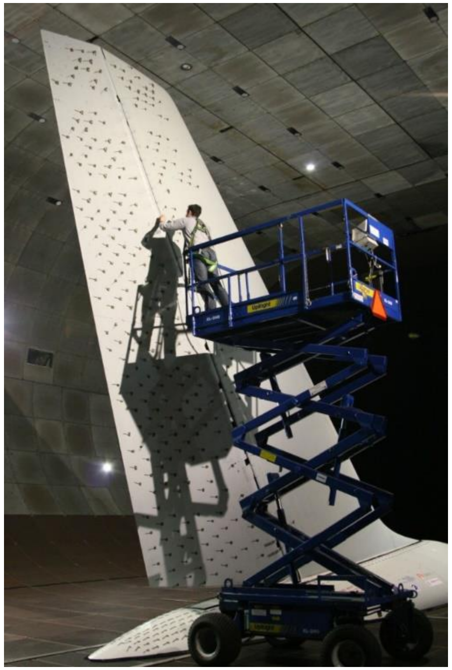


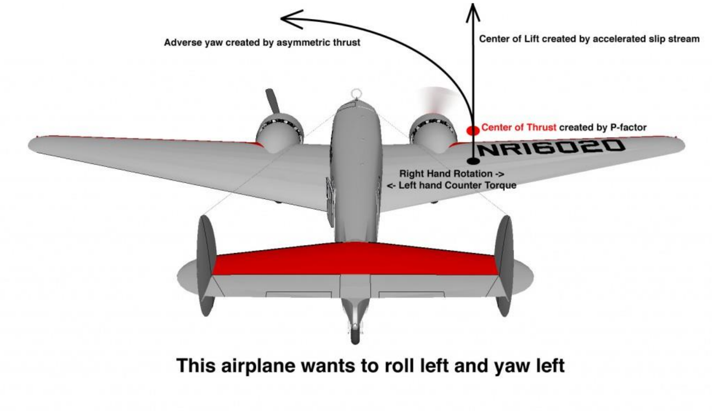




Background (size of vertical tail)

- In **one engine-out scenario** at take-off, the pilots need enough rudder power to counter the yaw moment. Thus, rudders are **designed oversized**.
- But if we can maintain laminar airflow over the rudder through tiny **sweeping jet actuators**, we make the rudder more effective, **making it smaller**.
- A smaller rudder creates **less drag and weighs less**, which increases fuel efficiency.





Background (winglet and bird's formation flight)

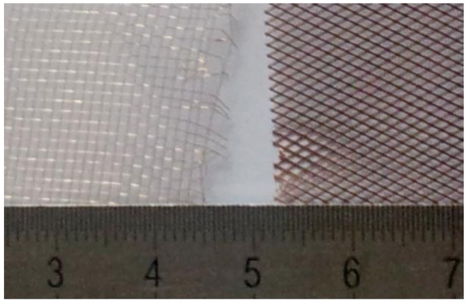
- It is possible to **decrease the induced drag by using winglets** to redistribute the strength of the trailing vortex sheet.
- A carefully designed winglet can produce **a gain in induced efficiency (and root bending moment as well as marketing)** at a **small cost in viscous drag and weight**.

Understanding of contradictory requirements

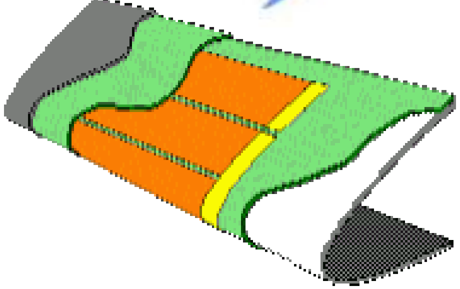
- Contradictory design requirements arise from the nature of **multi-function, multi-disciplinary, multi-objective** problem in complex system.
- The **mindset of the conductor** of an orchestra is required.

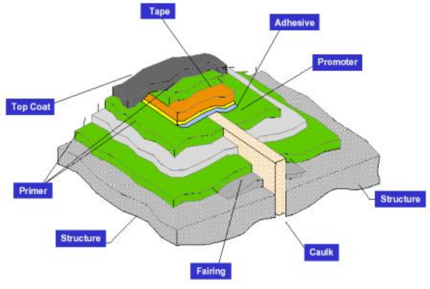
Multi-function in composite skin structure

- Multi-function in composite skin structure: **lightning** (copper foil), **icing** (electro-thermal pad), **RF stealth** (low-observable structure)



Left: bronze mesh (BM), right: expanded copper foil (ECF)





Gap Treatment

Pitot-type air intake vs anti-icing system

- The **Pitot-type air intake** (with good total pressure recovery) **requires** an (electro-thermal) **anti-icing** system.

EC 725 Super Puma: Pitot intake

Bell 430: side mounted intake

Agusta A109: flush side intake

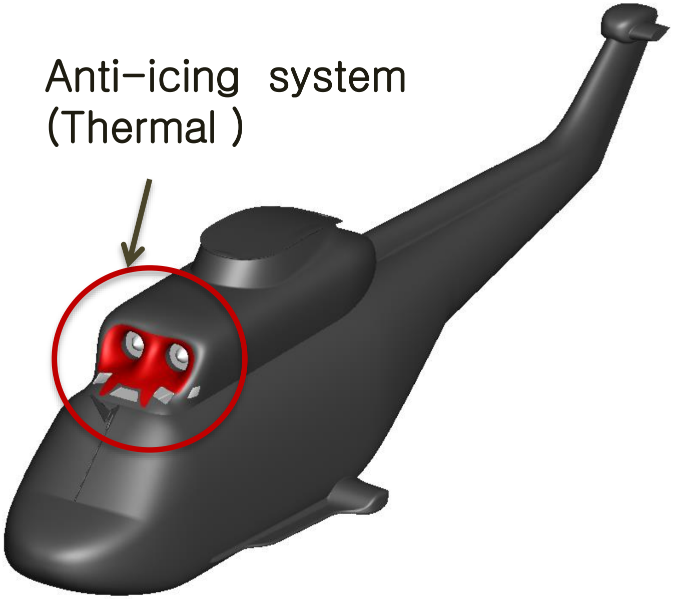
Mill Mi 24: radial inflow intake

Total pressure recovery
Distortion
Foreign object impact

Icing (ice ingestion
130 g for 2 minutes)

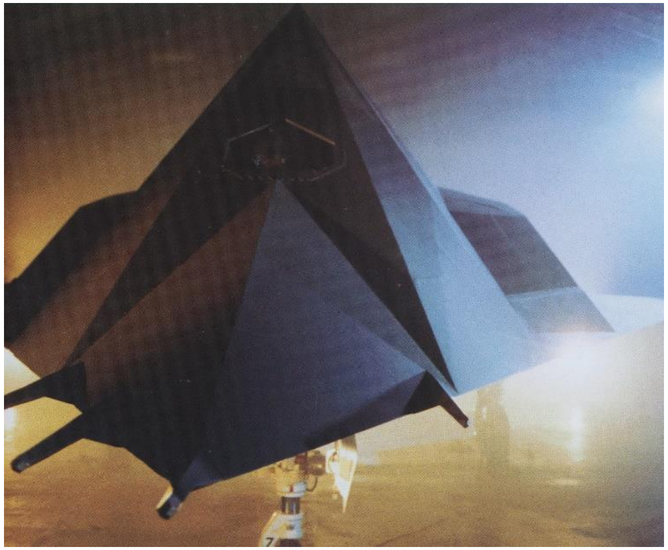
Pitot-type air intake vs anti-icing system

- Korean Surion helicopter with Pitot-type dynamic intake

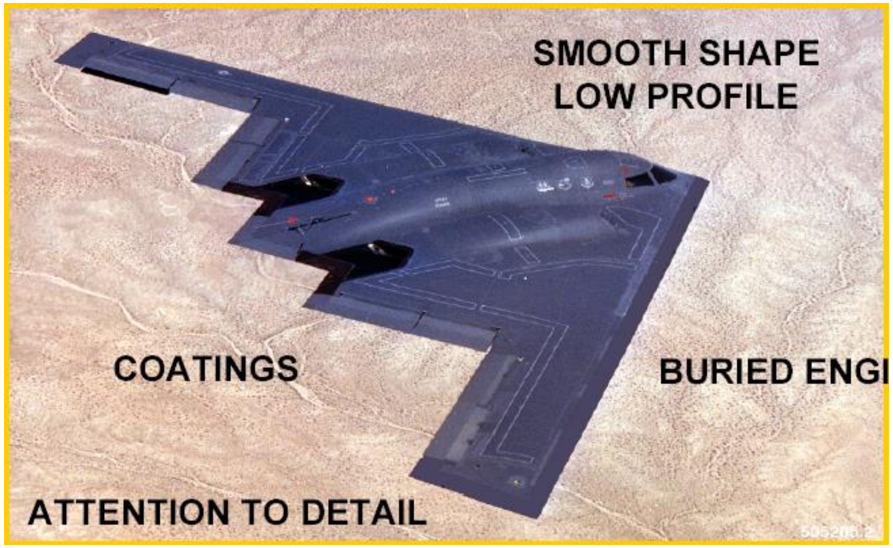


RF low observability vs aerodynamic performance

- The requirements for radar stealth with **low radar cross section (RCS)** and aerodynamics with **low drag** are contradictory; **faceted** and **streamlined smooth** shapes.



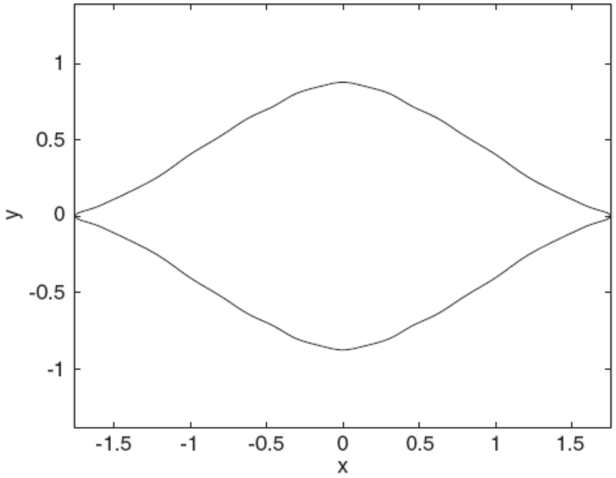
F-117



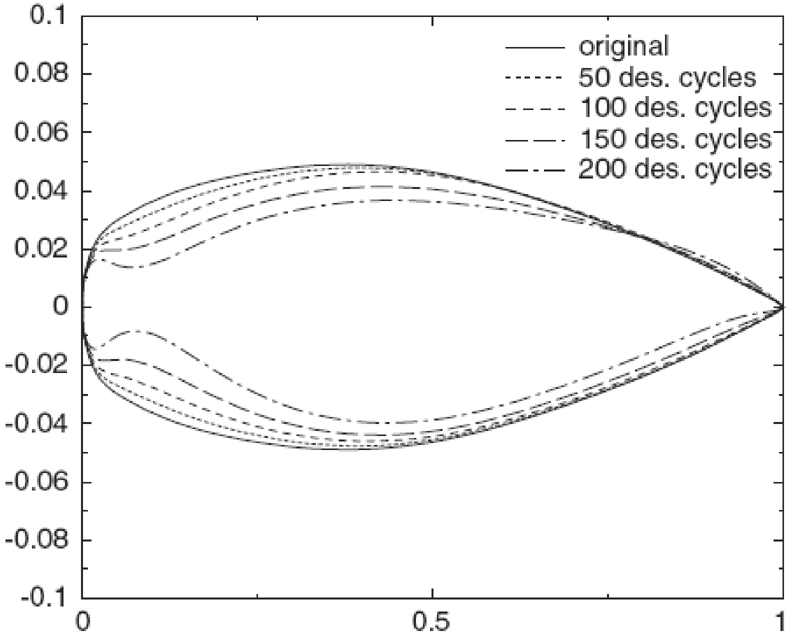
B-2

Simple RCS and drag optimization

- Simple combined (RCS and drag) shape optimization yields **unrealistic airfoil**.



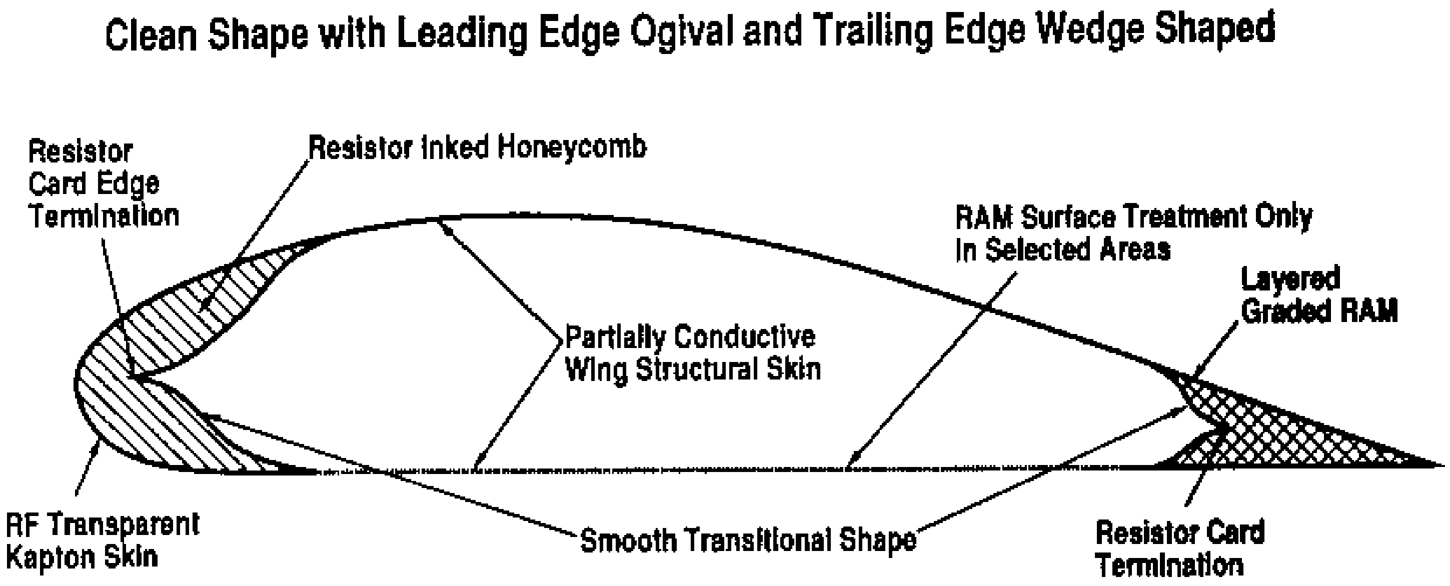
Shape optimized for TE and TM polarization with a penalty



Wing profile from the combined RCS and drag optimization with $\beta = 0.8$

Radar absorbing structure

- An ingenious solution to meet both requirements for radar stealth and aerodynamics is the **radar absorbing structure** (RAS).

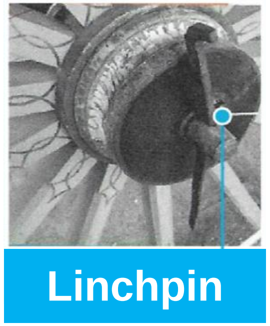


Typical RCS edge treatments

Linchpin technology and computational modeling

Linchpin technology

Linchpin (the pin going through the axle of a wheel to keep it in place) means a small piece, but everything collapses without it.

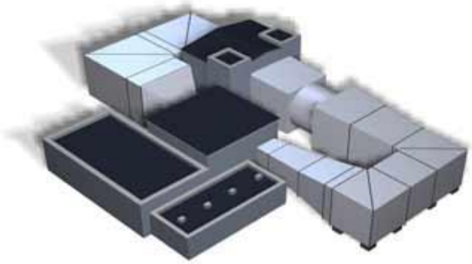


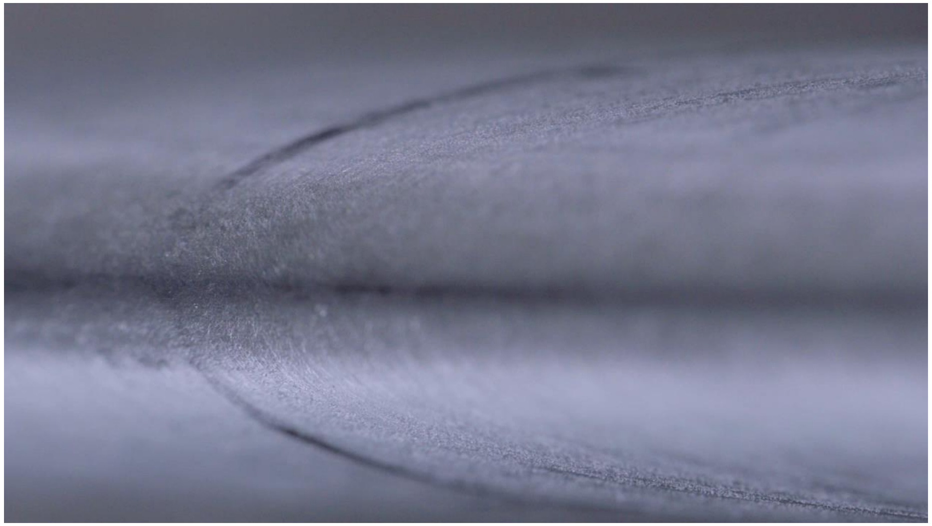
Rotorcraft icing on Earth and planetary landings in outer space are characterized by the **two-phase flow** of compressible air-droplet and gas-particle, respectively.

Computational modeling of these flows is challenging due to large variations in temperature, particle concentration, including the near-zero limit, and flow velocity, as well as the complexities and nonlinearities of the flow involved in rotorcraft with rotor blades and planetary landers with rocket motors.

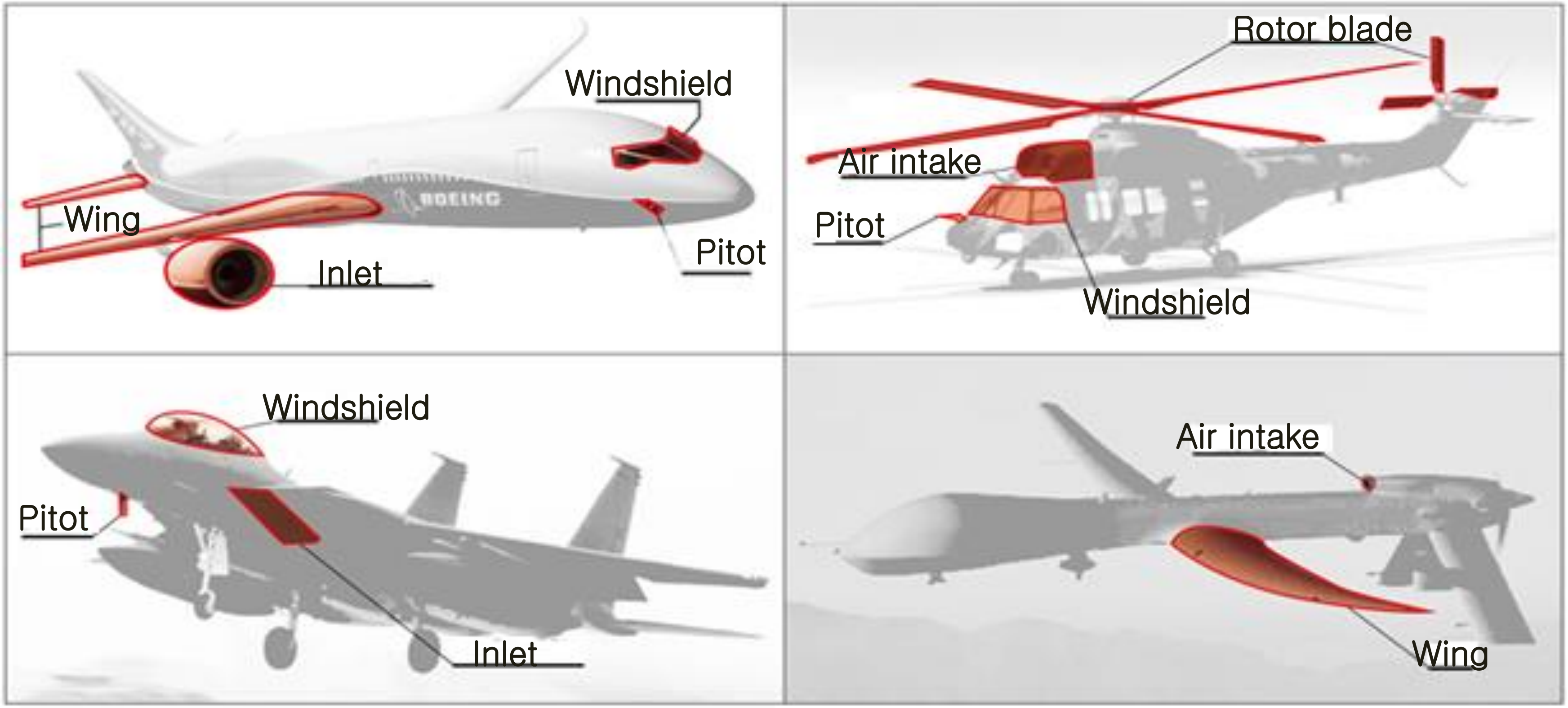
In-flight icing: a critical safety issue

- Icing is an atmospheric phenomenon which deserves adequate protection of aircraft.
- Icing is a **key certification issue** related to **aircraft safety.**
- Need to predict **most critical icing conditions** and the resulting ice shapes within the flight and certification envelopes.
- **Anti-icing** systems: **Prevent** the ice from forming/adhering
- **De-icing** systems: **Remove** the accumulated ice before incurring significant aerodynamic penalties

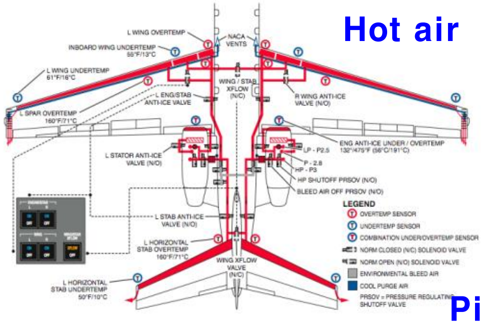


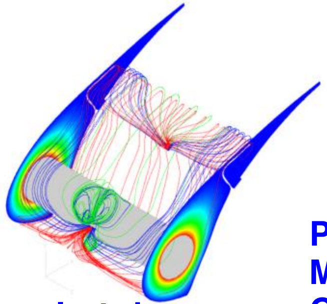


Aircraft in-flight icing: IPS (Ice Protection System)



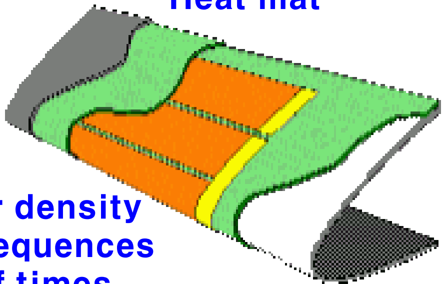
Hot air





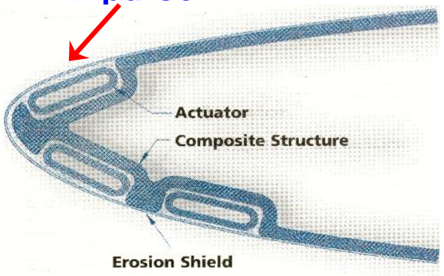
Piccolo tube

Heat mat



Power density
Mat sequences
On/off times

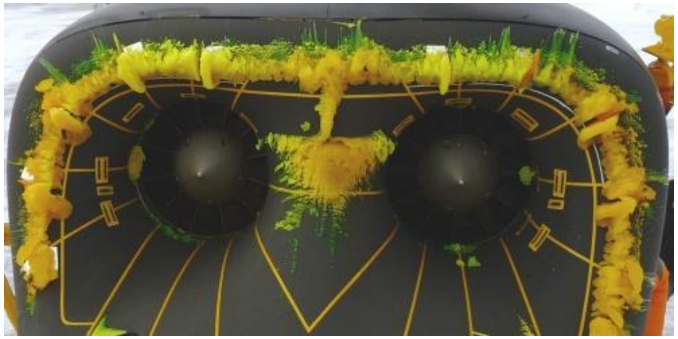
Impulse



Icing certification campaign: failure & 2nd full effort

A critical redesign of IPS

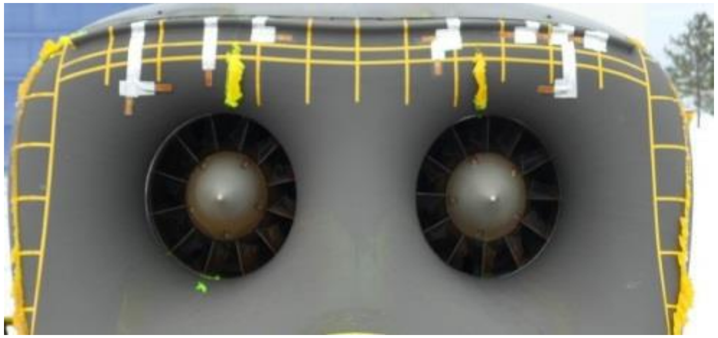
More than 130g for 2 minutes



Season 2015-16

Removing runback ice

Higher surface temperature
More time for evaporation
Longer distance for evaporation



Season 2017-18

Clearance of ice shedding of windshield & wiper

Season 2017-18

Courtesy of Korea Aerospace Industries LTD (KAI) (2018)

CFD-FVM methods base on multi-disciplinary physics

Equations for clean air

$$\begin{bmatrix} \rho_g \\ \rho_g \mathbf{u}_g \\ E \end{bmatrix}_t + \nabla \cdot \begin{bmatrix} \rho_g \mathbf{u}_g \\ \rho_g \mathbf{u}_g \mathbf{u}_g + p\mathbf{I} \\ (E+p)\mathbf{u}_g \end{bmatrix} = \nabla \cdot \begin{bmatrix} 0 \\ \boldsymbol{\tau} \\ \boldsymbol{\tau} \cdot \mathbf{u}_g + \mathbf{Q} \end{bmatrix}, \quad \begin{aligned} \boldsymbol{\tau} &= 2\mu \left[\nabla \mathbf{u}_g \right]^{(2)} \\ \mathbf{Q} &= k \nabla T \end{aligned}$$

Shear stress
Heat flux

Equations for droplets

$$\begin{bmatrix} \rho \\ \rho \mathbf{u} \end{bmatrix}_t + \nabla \cdot \begin{bmatrix} \rho \mathbf{u} \\ \rho \mathbf{u}\mathbf{u} + \rho \mathbf{g} d\mathbf{I} \end{bmatrix} = \begin{bmatrix} 0 \\ \mathbf{S}_D + \mathbf{S}_G + \mathbf{S}_S \end{bmatrix}$$

Droplet impact velocity
Collection efficiency

Equations for ice accretion

$$\begin{bmatrix} h_f \\ h_f T_{equi} \end{bmatrix}_t + \nabla \cdot \begin{bmatrix} \dfrac{h_f^2}{2\mu_w} \tau_{wall} \\ \dfrac{h_f^2 T_{equi}}{2\mu_w} \tau_{wall} \end{bmatrix} = \begin{bmatrix} \dfrac{S_M}{\rho_w} \\ \dfrac{S_E}{\rho_w C p_{,w}} + \dfrac{T_c S_M}{\rho_w} \end{bmatrix}$$

$$S_M = U_\infty LWC_\infty \beta - \dot{m}_{evap} - \dot{m}_{ice}$$

$$S_E = \left[Cp_{,w} \tilde{T}_{d,\infty} + \frac{\left\| \vec{u}_d \right\|^2}{2} \right] \times U_\infty LWC_\infty \beta - L_{evap} \dot{m}_{evap}$$

$$+ \dot{m}_{ice} \left[L_{fus} - Cp_{,ice} T_{equi} \right] + h_c \left(T_{equi} - T_\infty \right)$$

$$+ \sigma_o \varepsilon \left[T_{equi}^4 - T_\infty{}^4 \right]$$

$$h_f \geq 0, \dot{m}_{ice} \geq 0, h_f T_{equi} \geq h_f T_C, \dot{m}_{ice} T_{equi} \leq \dot{m}_{ice} T_C$$

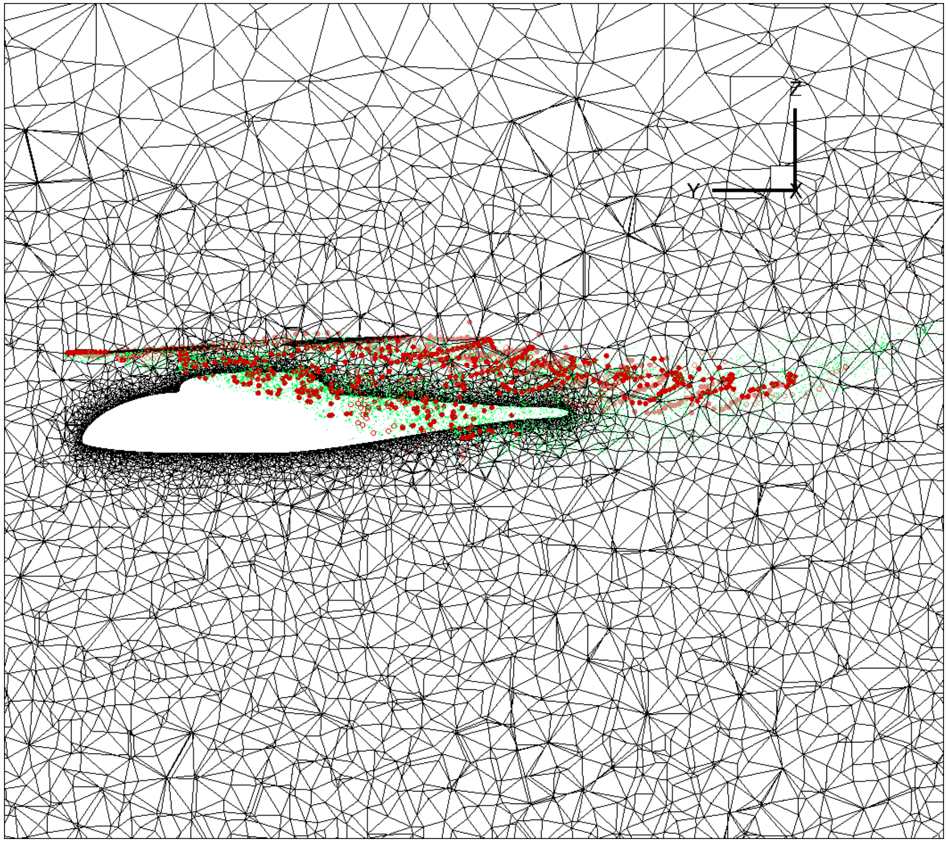
Conjugate (convection-conduction-convection) heat transfer

Equations for conductive heat transfer

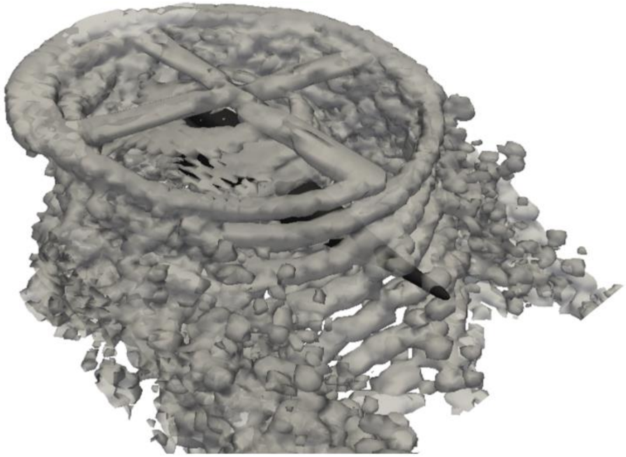
$$\rho_s C_p (\Delta T)_t = \nabla \cdot \mathbf{Q} - \rho_s (\Delta H / \Delta T), \quad \mathbf{Q} = k_s \nabla (\Delta T)$$

Poor rotor wake capturing: CFD suffers from excessive numerical dissipation on coarse grids; hence, wake structure and vorticity tend to dissipate rapidly after shedding from rotating blades.

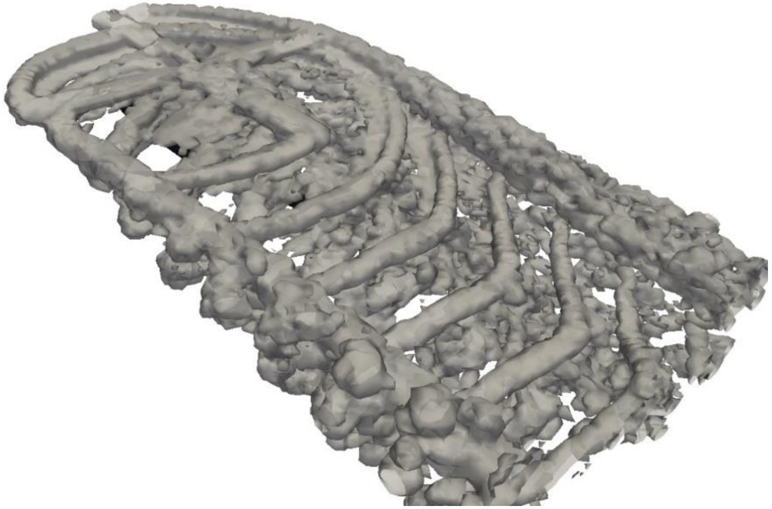
Visualization of the flow structure (Q-criterion)



$$Q = \frac{1}{2}\left(\Omega_{ij}\Omega_{ij} - S_{ij}S_{ij}\right)$$

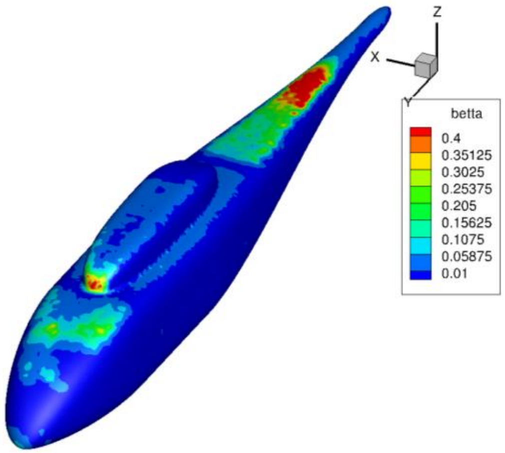


Advance ratio 0.051

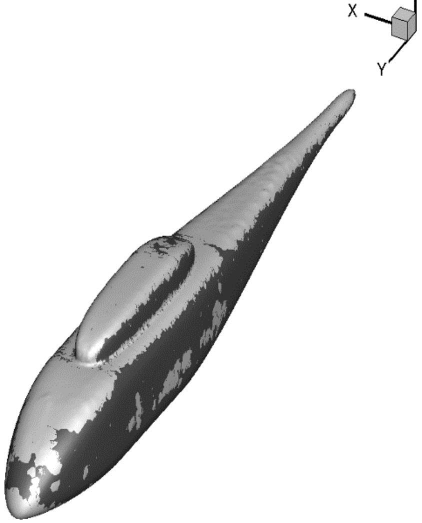


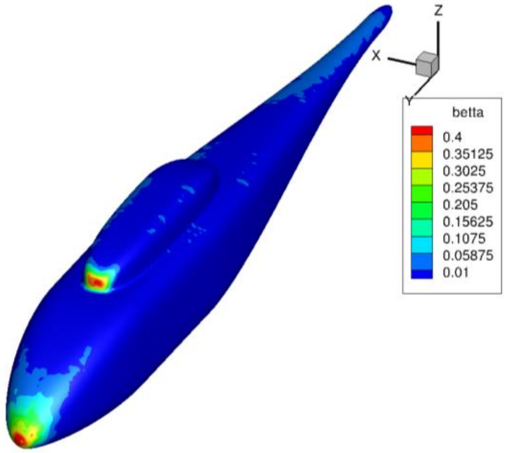
Advance ratio 0.232

Collection efficiency and ice accretion (C_T=0.008)



Advance ratio 0.051





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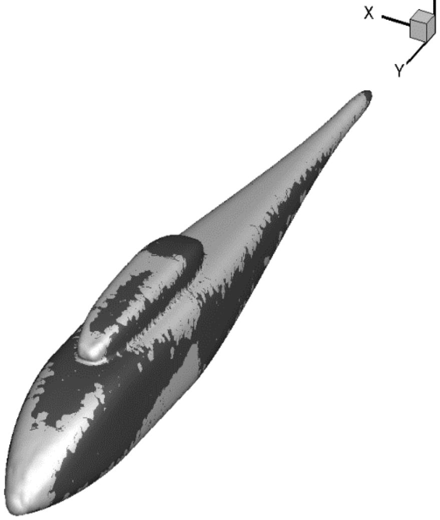


Another critical issue: planetary landings

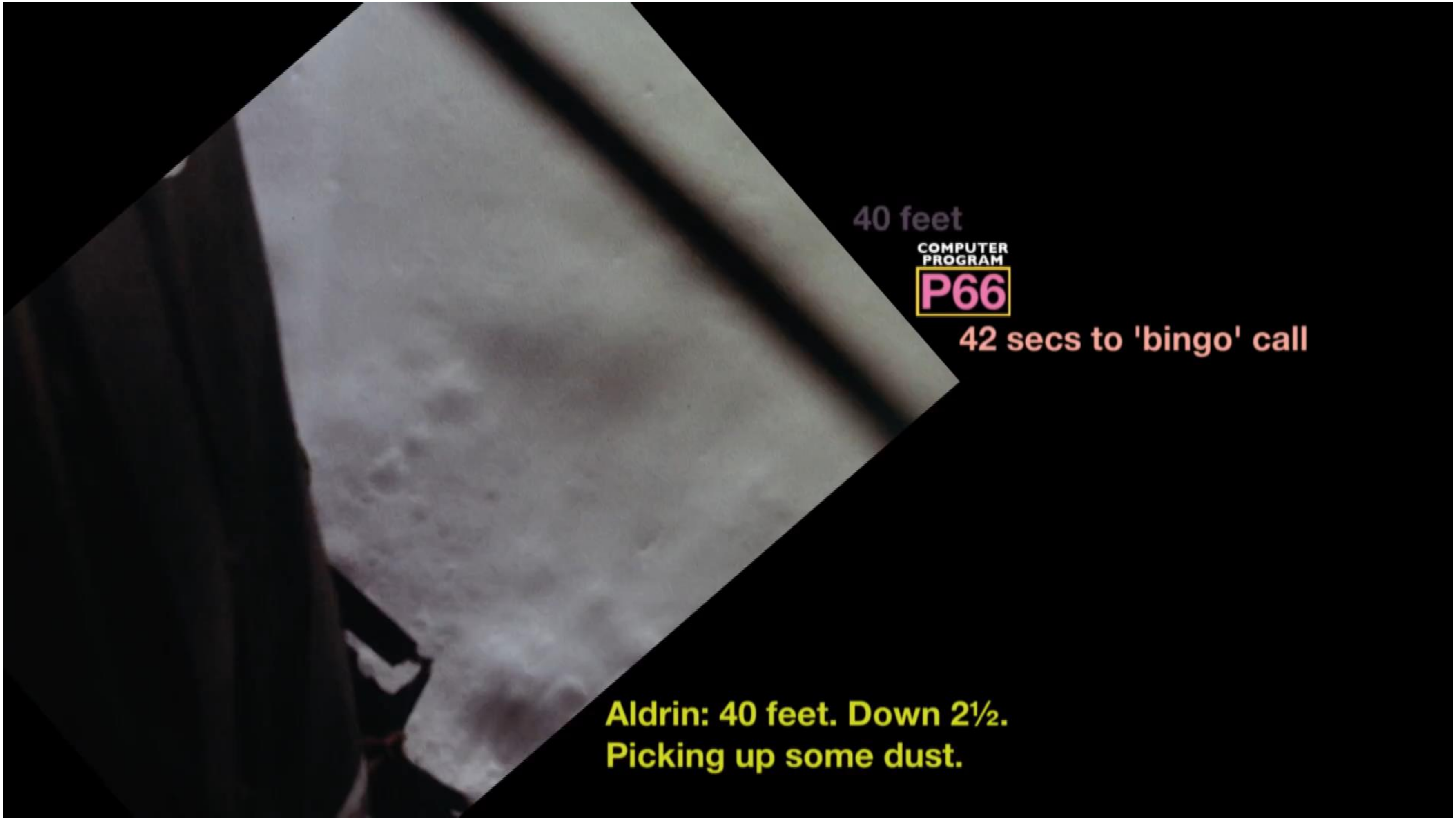
Planetary landings in outer space is characterized by the **two-phase flow** of compressible gas-particle.

Challenging due to large variations in temperature, particle concentration, including the near-zero limit, and flow velocity, as well as the complexities and nonlinearities of the flow involved in planetary landers with rocket motors.

In a planetary landing, compressible gas-particle flow is formed when the rocket plume of the lander impinges on a dusty surface and causes erosion and dispersal of solid particles into the flow field.

Micro-gravity, vacuum, extreme dryness, unique properties of regolith, multi-scale (m to hundred km) in dispersal

Lunar landing: Apollo 11



40 feet

COMPUTER PROGRAM P66

42 secs to 'bingo' call

Aldrin: 40 feet. Down 2½.
Picking up some dust.

Dust is the number one concern!

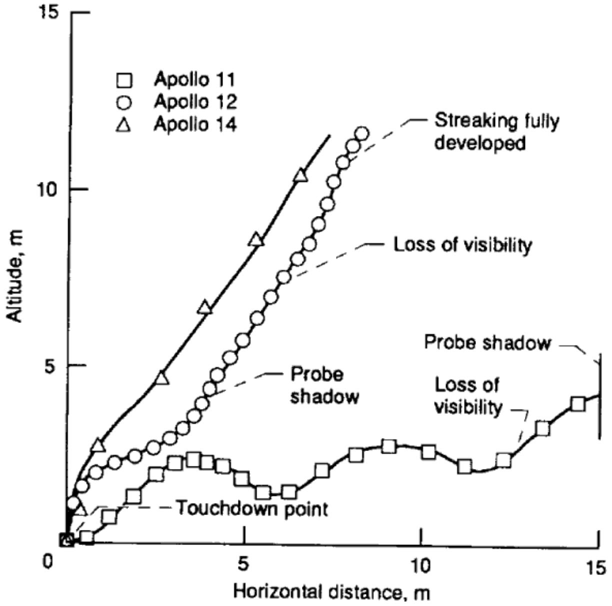
Physical damage to lander and sensors

Blocking vision, mal-function of tracking sensor of landing velocity and camera

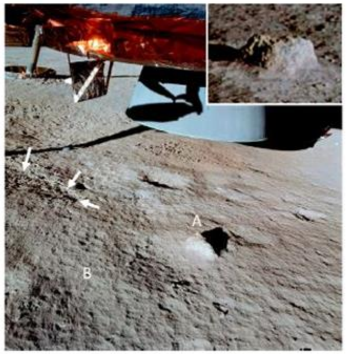
Trouble in exploration (degradation in thermal-control, dust contamination)

Apollo Astronaut John Young

“Dust is the number one concern in returning to the moon!”



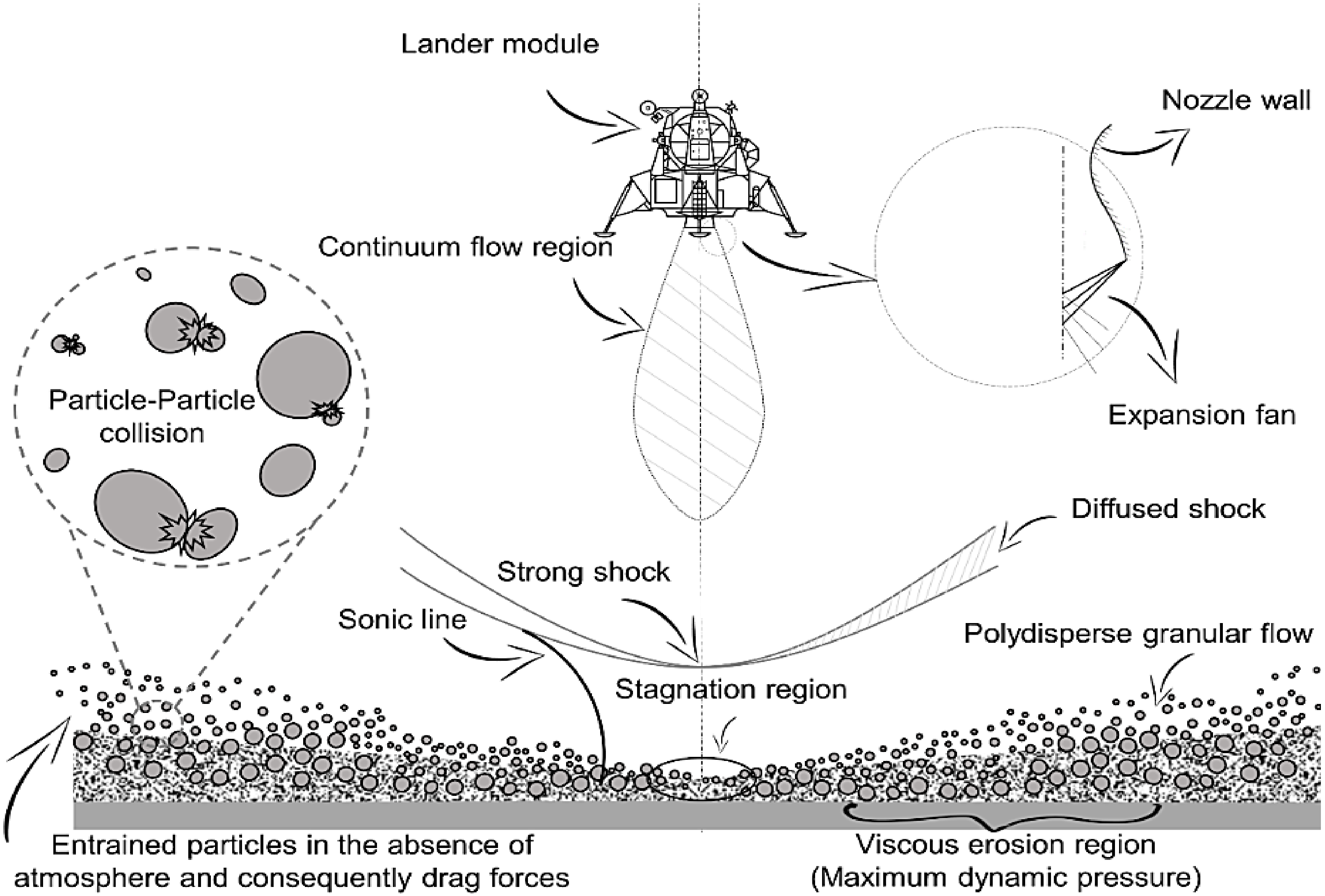
First Lunar landing
(Apollo 11)



Apollo 14 surface
(NASA photograph AS14-66-9261HR)

Lunar surface

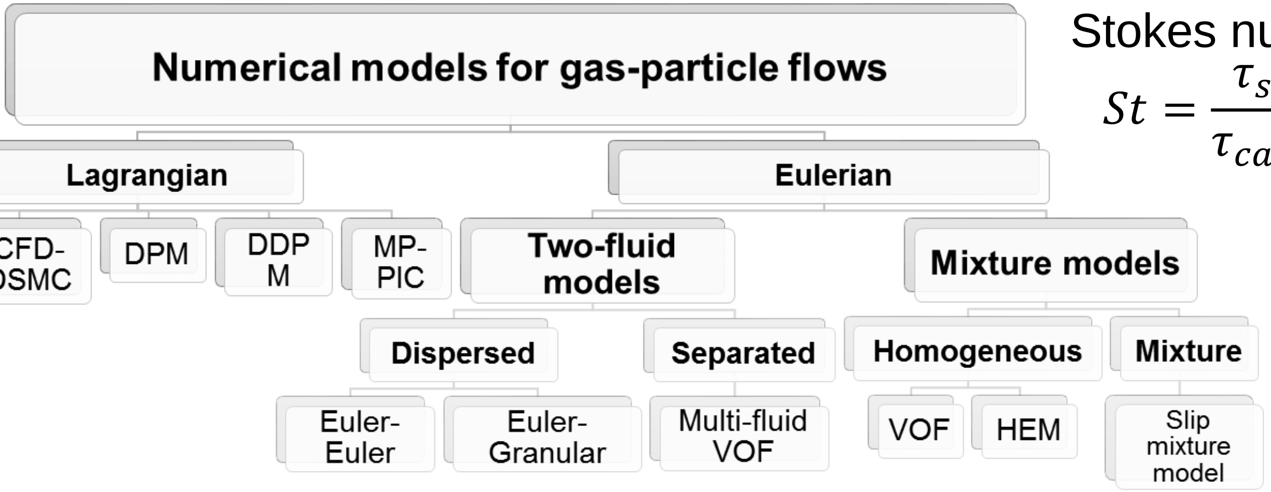
Lunar landing problem



Computational models

Particulate loading

$$\beta = \frac{\alpha_s\rho_s}{\alpha_g\rho_g}$$



Numerical models for gas-particle flows

Lagrangian

CFD-DEM

CFD-DSMC

DPM

DDPM

MP-PIC

Eulerian

Two-fluid models

Dispersed

Euler-Euler

Euler-Granular

Separated

Multi-fluid VOF

Mixture models

Homogeneous

VOF

HEM

Mixture

Slip mixture model

Stokes number

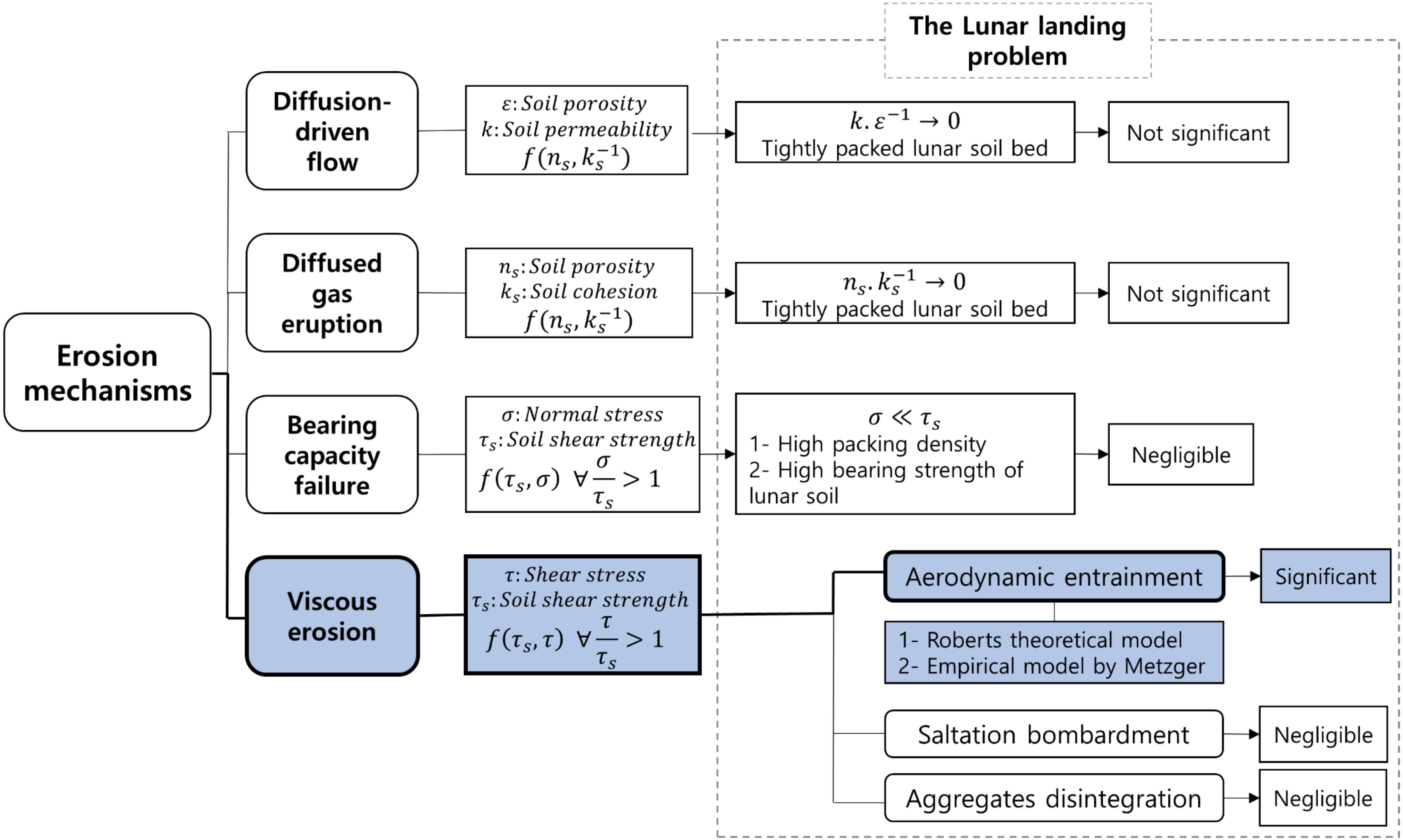
$$St = \frac{\tau_{solid}}{\tau_{carrier}}$$

$$\begin{bmatrix}\alpha_g\rho_g\\ \alpha_g\rho_g\mathbf{u}_g\\ \alpha_g\rho_g E_g\end{bmatrix}_t + \nabla\cdot\begin{bmatrix}\alpha_g\rho_g\mathbf{u}_g\\ \alpha_g\rho_g\mathbf{u}_g\mathbf{u}_g + p_g\mathbf{I}+\mathbf{\Pi}_g\\ (\alpha_g\rho_g E_g + p_g)\mathbf{u}_g + \mathbf{\Pi}_g\cdot\mathbf{u}_g + \mathbf{Q}_g\end{bmatrix} = \nabla\cdot\begin{bmatrix}0\\ D_{g,s}(\mathbf{u}_s-\mathbf{u}_g)\\ D_{g,s}(\mathbf{u}_s-\mathbf{u}_g)\cdot\mathbf{u}_s + Q_{g,s}(T_s-T_g)\end{bmatrix},$$

$$\begin{bmatrix}\alpha_s\rho_s\\ \alpha_s\rho_s\mathbf{u}_s\\ \alpha_s\rho_s E_s\\ \alpha_s\rho_s e_s\end{bmatrix}_t + \nabla\cdot\begin{bmatrix}\alpha_s\rho_s\mathbf{u}_s\\ \alpha_s\rho_s\mathbf{u}_s\mathbf{u}_s + p_s\mathbf{I}+\mathbf{\Pi}_s\\ (\alpha_s\rho_s E_s + p_s)\mathbf{u}_s + \mathbf{\Pi}_s\cdot\mathbf{u}_s + \mathbf{Q}_s\\ \alpha_s\rho_s e_s\mathbf{u}_s\end{bmatrix} = \nabla\cdot\begin{bmatrix}0\\ D_{g,s}(\mathbf{u}_s-\mathbf{u}_g)\\ D_{g,s}(\mathbf{u}_s-\mathbf{u}_g)\cdot\mathbf{u}_s + Q_{g,s}(T_s-T_g)\\ \dot{\gamma}\end{bmatrix},$$

e_s grandular temp., $\dot{\gamma}$ the dissipation of pseudo-thermal energy owing to the inelastic particle collisions

Surface erosion model (Roberts' model)



Erosion mechanisms

The Lunar landing problem

Diffusion-driven flow

ε: *Soil porosity*
k: *Soil permeability*
$f(n_s, k_s^{-1})$

$k.\varepsilon^{-1} \to 0$
Tightly packed lunar soil bed

Not significant

Diffused gas eruption

n_s: *Soil porosity*
k_s: *Soil cohesion*
$f(n_s, k_s^{-1})$

$n_s . k_s^{-1} \to 0$
Tightly packed lunar soil bed

Not significant

Bearing capacity failure

σ: *Normal stress*
τ_s: *Soil shear strength*
$f(\tau_s, \sigma)\ \forall \frac{\sigma}{\tau_s} > 1$

$\sigma \ll \tau_s$
1- High packing density
2- High bearing strength of lunar soil

Negligible

Viscous erosion

τ: *Shear stress*
τ_s: *Soil shear strength*
$f(\tau_s, \tau)\ \forall \frac{\tau}{\tau_s} > 1$

Aerodynamic entrainment

Significant

1- Roberts theoretical model
2- Empirical model by Metzger

Saltation bombardment

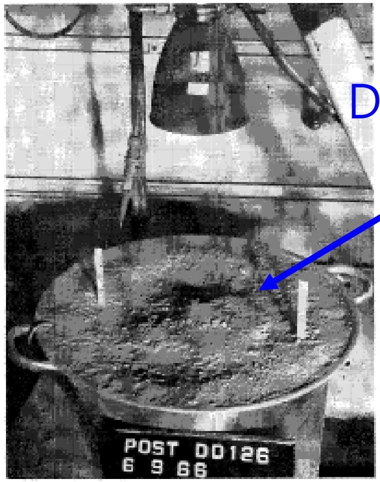
Negligible

Aggregates disintegration

Negligible

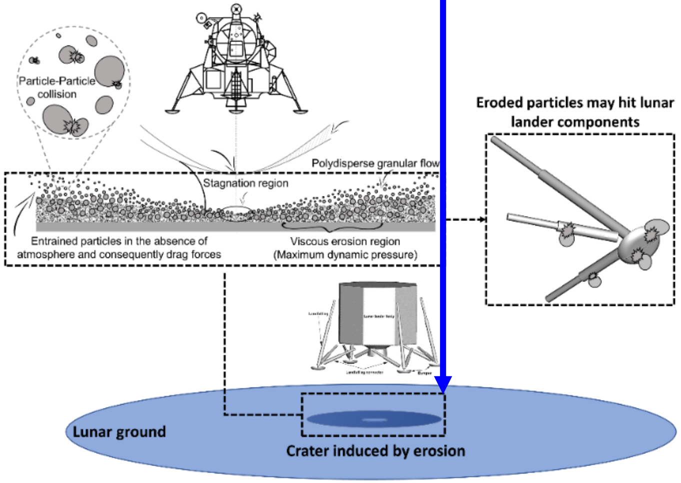
Dispersal simulation from the induced crater

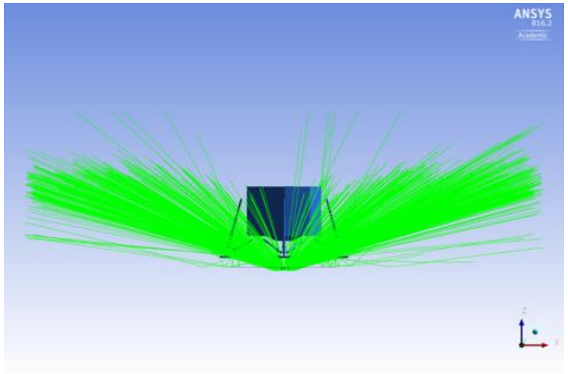
Rahimi, A., Ejtehadi, O., Lee, K. H., Myong, R. S., “Near-field Plume-surface Interaction and Regolith Erosion and Dispersal During the Lunar Landing,” *Acta Astronautica*, Vol. 175, pp. 308-326, 2020.



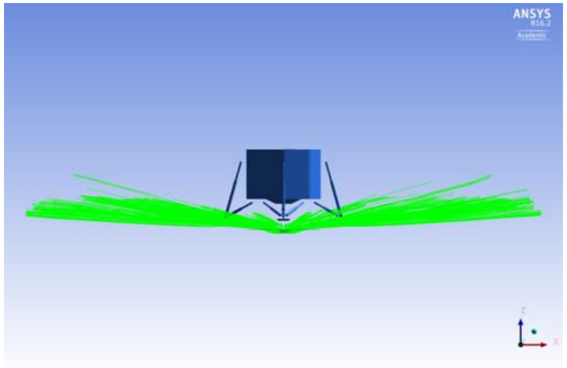
Depth & width

Surface erosion experiment courtesy of Ronald F. Scott 1966

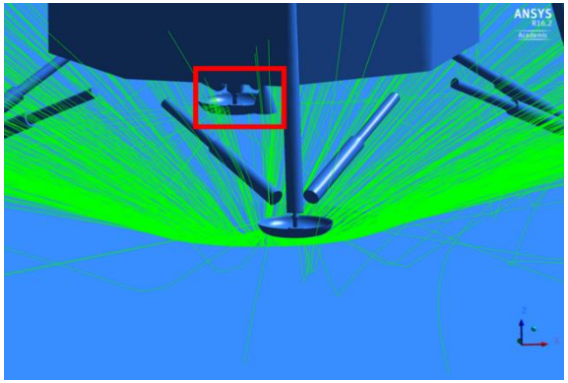




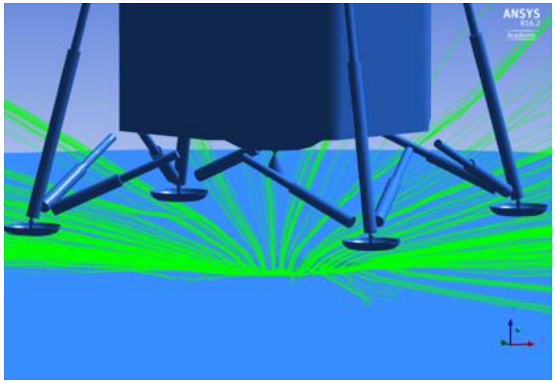
Injected particles with diameter $100\mu m$ and $St = 757$



Injected particles with diameter $1\mu m$ and $St = 0.0757$

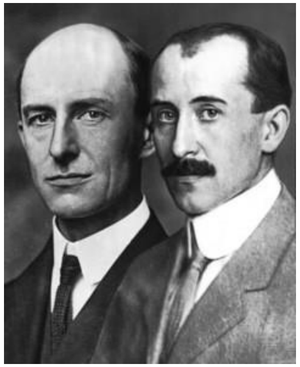


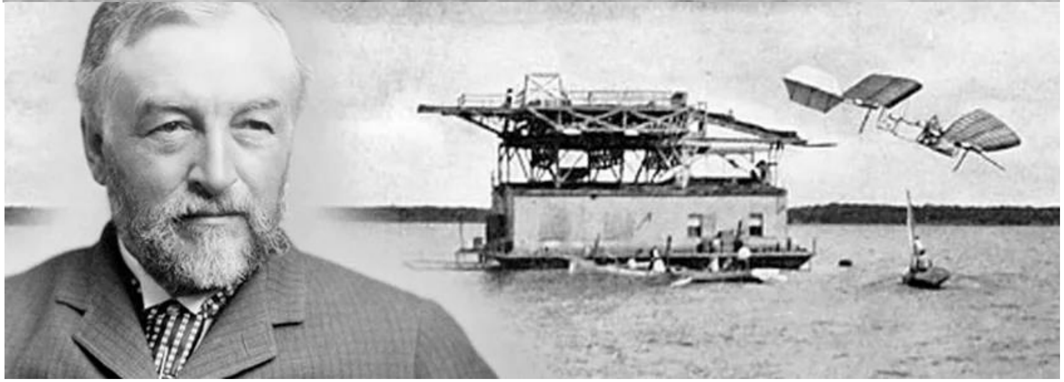
Impingement of particles to the bumper $(100\mu m)$



No impingement of particles to the bumper $(1\mu m)$

Wright Brothers vs Samuel Langley

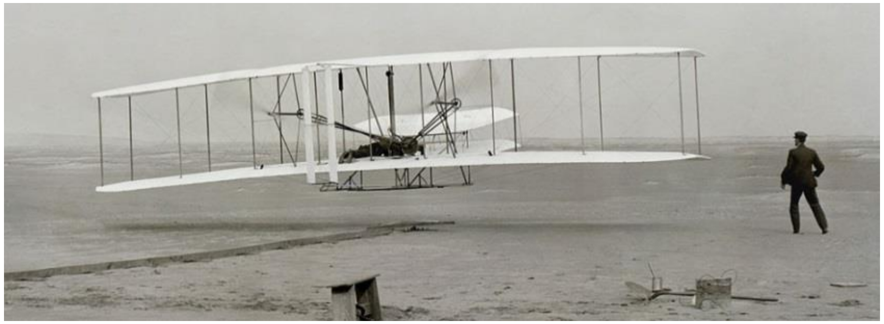




David vs Goliath

Attitude for learning in aerospace engineering 1

Learning by doing (and acting)



- Wright brothers (1903; Flyer)
  Learning by doing (and acting)

- Riding on bicycle

  (Cf. Implicit knowledge)

- Learning mathematics by solving

  problems

- The proof of the pudding is in the eating.

Attitude for learning in aerospace engineering 2

Question the question!

- One of the biggest questions in science:
  What is the origin of living things?

- Instead, one should ask
  What is a “living thing”?

- Freedom to seek truth
  Freedom of conscience
  Freedom of expression

⟺

Peer pressure
Excessive emotion/anxiety

Attitude for learning in aerospace engineering 3

There is nothing new under the sun!?

- No harm in asking

- Standing on the shoulders of giants

- If you believe too much you'll never notice the flaws.
  If you doubt too much you won't get started.
  It requires a lovely balance.