Mars Sample Retrieval Lander: Aerothermal feasibility analysis and shape optimization on the use of ADEPT

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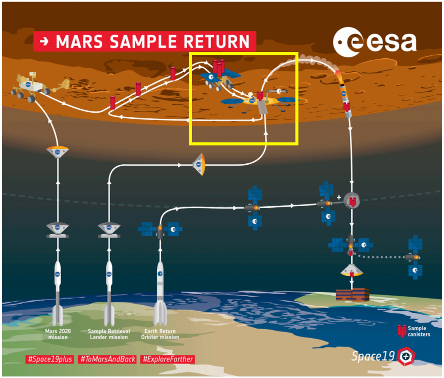
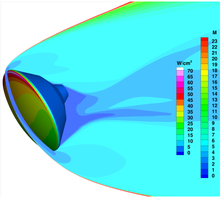
Mars Sample Retrieval Lander (SRL)

- **Mars Sample Return** (MSR) is a planned sequence of (3) missions to bring samples from Mars to Earth
- The concept includes a **Sample Retrieval Lander** (SRL) to land a fetch rover and an ascent vehicle on Mars
- Compared to MSL and M2020, the payload is required to be heavier
- All previous Mars missions used 70° Sphere-Cone sections; **SRL** will be the first one using Spherical section (for increasing the payload volume)
- **Challenge**: how do we land an additional $500\,kg$ of mass with only slight changes to entry capsule (compared to M2020)?
- One option being considered is the use of **Adaptable, Deployable Entry Placement Technology** (ADEPT) to increase drag during entry, and increase the payload capability



Source: overview infographic from www.esa.int

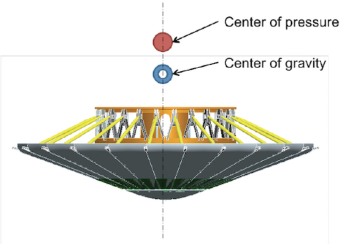


Sample Retrieval Lander (Courtesy of David Saunders)

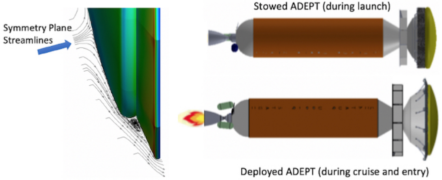
- **ADEPT** is an innovative, semi-rigid, mechanically deployable drag skirt system conceptualized at NASA Ames

  VENKATAPATHY, ARNOLD, FERNANDEZ, ..., PRABHU, ET AL., "Adaptive deployable entry and placement technology (ADEPT): a feasibility study for human missions to Mars", (AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, 2011)

- The added aerosurface is a thin skin draped over high-strength ribs
- Preliminary analysis of SRL with ADEPT shows increased payload capability
- SRL-ADEPT flowfield is characterized by flow separation at the heatshield-ADEPT interface
- **Objective**: use CFD to optimize the heatshield shape, ADEPT skirt length and SRL-ADEPT interface



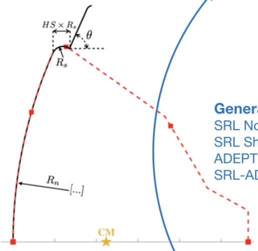
Source: Adaptive deployable entry and placement technology (ADEPT): a feasibility study for human missions to Mars



Courtesy of Suman Muppidi

Objective:

increase Drag
decrease heat flux peak at the reattachment on ADEPT
decrease flow recirculation region

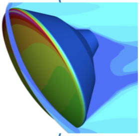


DPLR
Data Parallel Line Relaxation Code

Solve the Flowfield

Generate Geometry:
SRL Nose radius (R_n)
SRL Shoulder radius (R_s)
ADEPT angle (θ)
SRL-ADEPT connection (HS)

Extract QoI:
Drag, Drag Coefficient
Heat Flux Peak
Recirculation Region
Blockage Area



Minimize Weighted Cost Function

$$\mathcal{S}(\theta,\, HS,\, R_n,\, R_s)$$

Constraints:

weights for the cost function
position of Center of Mass (CM)
maximum diameter of SRL fore-body
min-max bounds for the geometric variables

Physical and Numerical Modeling

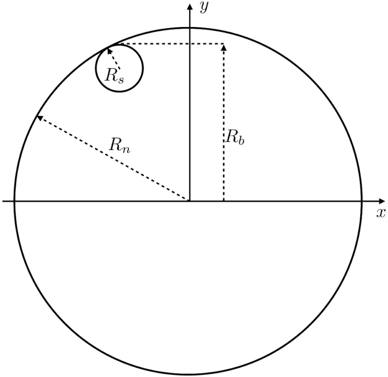
- **Hydrodynamics**: chemically reactive Naver-Stokes equations
  - 2T Non-Local Thermodynamic Equilibrium (NLTE)
  - 2D-axisymmetric
- **Thermodynamics**:
  - vibrational non-equilibrium (single T_v)
  - rotational equilibrium (statistical mechanics)
  - electronic energy (statistical mechanics $T_{el} = T$)
- **Transport**:
  - transport coefficients: Yos mixing rule
  - diffusion coefficients: self-consistent effective binary diffusion
- **Chemistry**: $CO_2 - N_2$ mechanism (10 species, 20 reactions)

Johnston and Brandis, "Features of Afterbody Radiative Heating for Earth Entry", (Journal of Spacecraft and Rockets, 2014)

- **Numerics**: DPLR CFD solver
  - Fully implicit time integration
  - Steger-Warming 3^{rd} order upwind-biased flux extrapolation
  - MinMod flux limiter

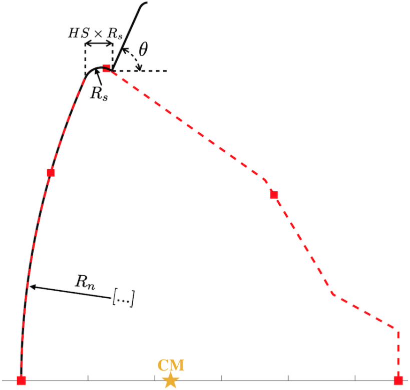
SRL and SRL-ADEPT: Baselines

- **SRL fore-body**: two circles



- **Control Variables**
  - Nose Radius (R_n)
  - Shoulder Radius (R_s)
  - Base Radius (R_b)

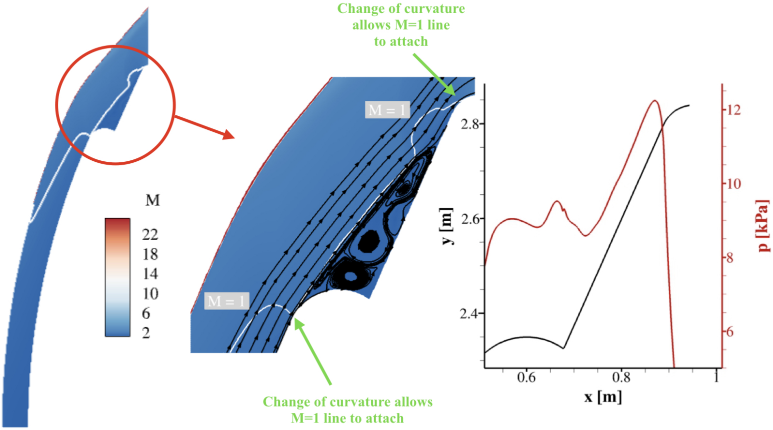
- **ADEPT**: straight rib with curved tip



- **Control Variables**
  - ADEPT angle (θ)
  - SRL-ADEPT connection (HS)
  - ADEPT length (L)

ADEPT length and shape

- Large flow separation region at SRL-ADEPT interface
  - $L = 180\,cm$ ensures flow reattachment for ADEPT modeled as straight rib
  - $L = 58\,cm$ ensures flow reattachment for ADEPT modeled as straight rib with curved tip

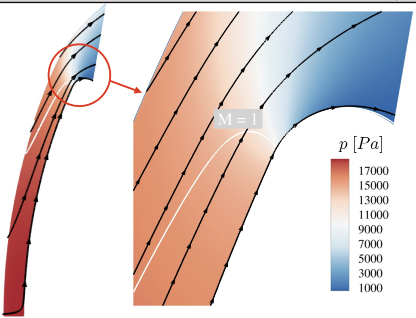


Large part of ADEPT experiences flow separation; the additional area is not fully efficient

SRL and SRL-ADEPT: Converged Solutions

SRL

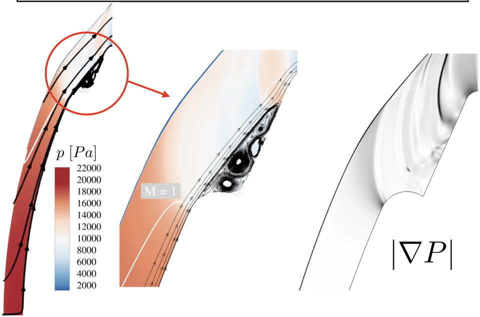
$V_\infty = 5216\,m/s$ $T_\infty = 159.545\,K$ $\rho_\infty = 0.7243\,g/m^3$



- Wall tangential min spacing: $5.0\,mm$
- Wall normal min spacing: $3.0\,\mu m$
- Number of grid points: 600×400
- Number of alignments: 4

SRL-ADEPT

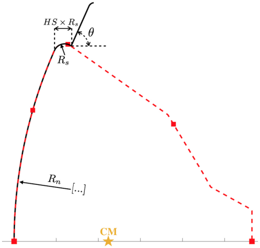
$V_\infty = 5216\,m/s$ $T_\infty = 159.545\,K$ $\rho_\infty = 0.7243\,g/m^3$



- Wall tangential min spacing: $4.0\,mm$
- Wall normal min spacing: $1.5\,\mu m$
- Number of grid points: 800×400
- Number of alignments: 7

Drag increased 30%, but the recirculation region makes C_x drop 14%

Fore-Body Shape Optimization



- Geometrical control variables:
  - ADEPT angle: θ
  - ADEPT connection point with the TPS: HS
  - Fore-body Nose radius: R_n
  - Fore-body Shoulder radius: R_s
- The QoI are:
  - Drag (D) and drag coefficient (C_x)
  - skirt pressure and heat flux peaks (at the reattachment point) (p_w, q_w)
  - length of the recirculation region in ADEPT (L_{rec})
- The Cost Function is:

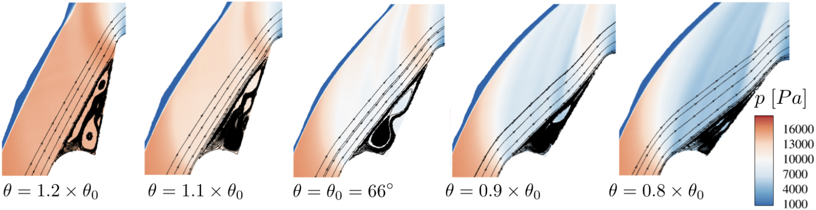
$$\mathcal{S}(\theta, HS, R_n, R_s) = w_1 f_D + w_2 g_{p_w} + w_3 h_{q_w} + w_4 l_{rec}$$

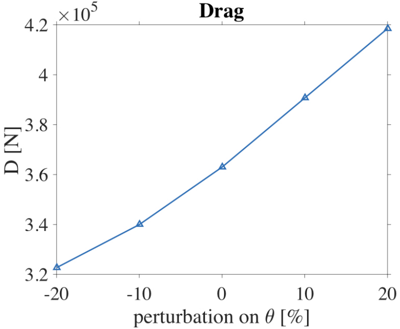
$$w_1 f_D = \frac{0.6 \times D_{baseline}}{D(\theta, HS, R_n, R_s)} \qquad w_2 g_{p_w} = \frac{0.1 \times p_w(\theta, HS, R_n, R_s)}{p_{w,baseline}}$$

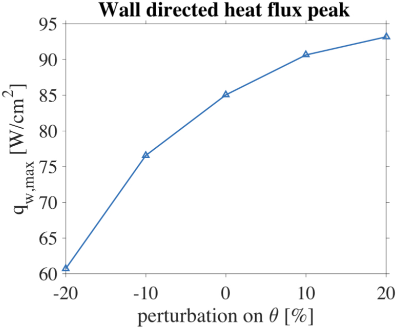
$$w_3 h_{q_w} = \frac{0.1 \times q_w(\theta, HS, R_n, R_s)}{q_{w,baseline}} \qquad w_4 l_{rec} = \frac{0.2 \times L_{rec}(\theta, HS, R_n, R_s)}{L_{rec,baseline}}$$

Fore-Body Shape Optimization

- The functional dependence of f_D, g_{p_w}, h_{q_w}, l_{rec} on θ, HS, R_n, R_s has been assessed by perturbing the variables $\pm10\%$ and $\pm20\%$

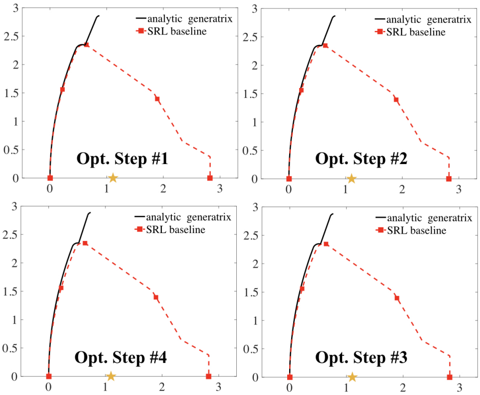


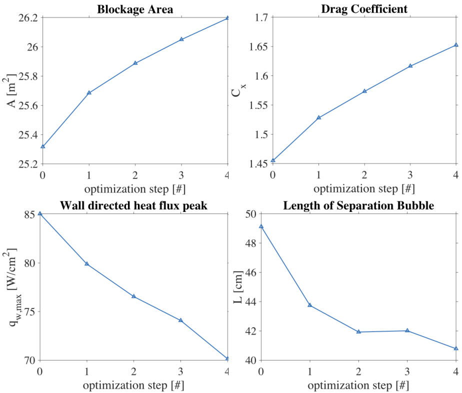




Fore-Body Shape Optimization: Results

- Results are shown for the following set of constraints:
  - $L_{ADEPT} = 57.5\,cm, \;\; \theta < 72°$
  - $R_b = 4.7/2\,m, \; 4.77\,m < R_n < 6.46\,m, \;\; 7.5\,cm < R_s < 15\,cm$
  - $CM_0 - 2.5\,cm < CM < CM_0 + 2.5\,cm$



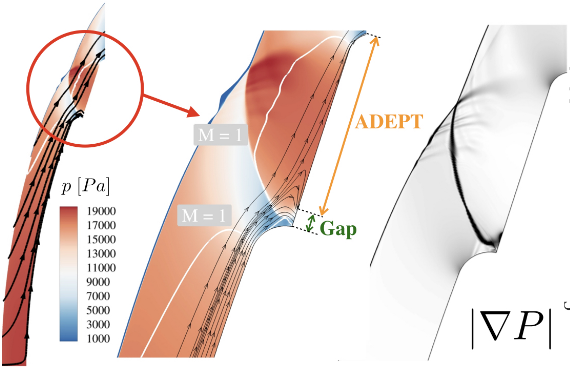


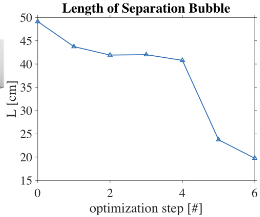
- Automated optimization (with scripts) from parametric meshing to post-processing
- Given a set of constraints and weights, the optimization takes $\approx 4\,hr$ (96 procs)

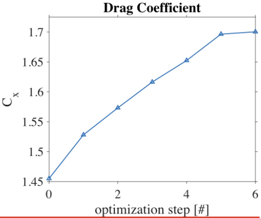
Fore-Body Shape Optimization: Results

- The recirculation region is still large ($\approx 60\%$ of L)
- Gap at SRL-ADEPT interface might bleed the separation zone [D. Prabhu]

$V_\infty = 5216\, m/s$	$T_\infty = 159.545\, K$	$\rho_\infty = 0.7243\, g/m^3$





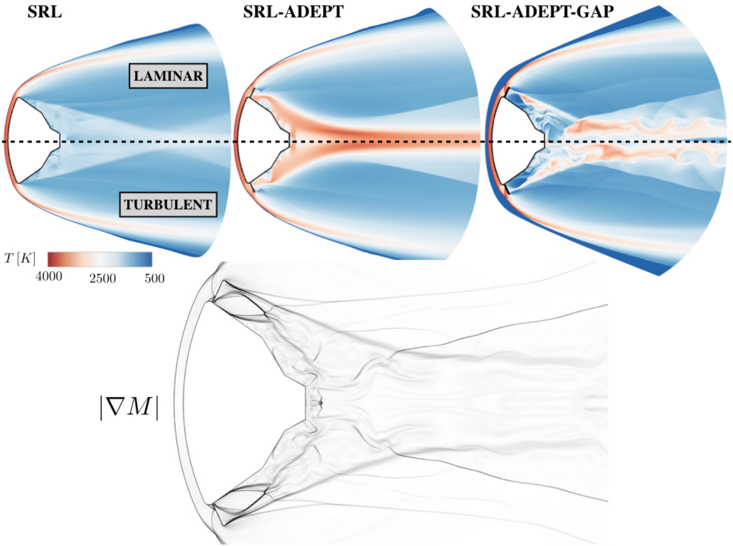


Opt. Step #5 = Opt. Step #4 w/ GAP 10% of ADEPT
Opt. Step #6 = Opt. Step #4 w/ GAP 5% of ADEPT

C_x **for a** 70° **sphere cone is** 1.67

Effects on Aft-Body

- ADEPT has been observed to generate a high temperature wake
- The gap works as an over-expanded nozzle and provides kinetic cooling to the aft



Conclusion and Future Work

Conclusion

- Drag increased 55% with respect to SRL without ADEPT
- Drag coefficient increased up to 1.65 (1.7 when using the gap)
- Heat flux peak in ADEPT dropped 20% wrt SRL-ADEPT baseline
- ADEPT appears to be a viable solution for delivering larger payload
  - benefit of spherical section: increased payload volume wrt 70° sphere-cone section
  - benefit of ADEPT: C_x comparable with 70° sphere-cone section
- Optimization framework is general and automated

Future Work

- Shape optimization considering the full-body
- Consider other geometrical shapes not limited to spheres
- Include radiative heating for the aft body (expensive)
- Extend the framework to 3D at an Angle-of-Attack (also expensive)

Acknowledgments

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- the fellow interns for the good times and the inspiring stories

National Aeronautics and Space Administration

Ames Research Center
Entry Systems and Technology Division

BACK-UP

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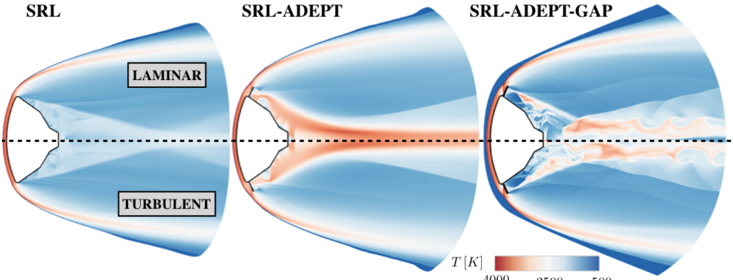

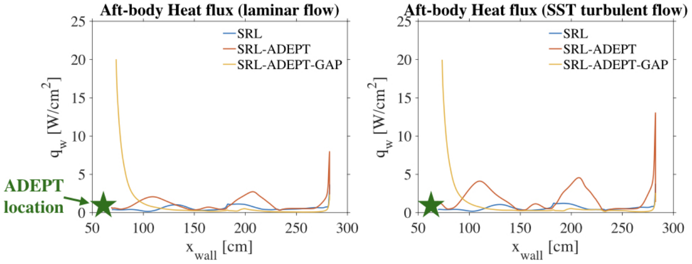

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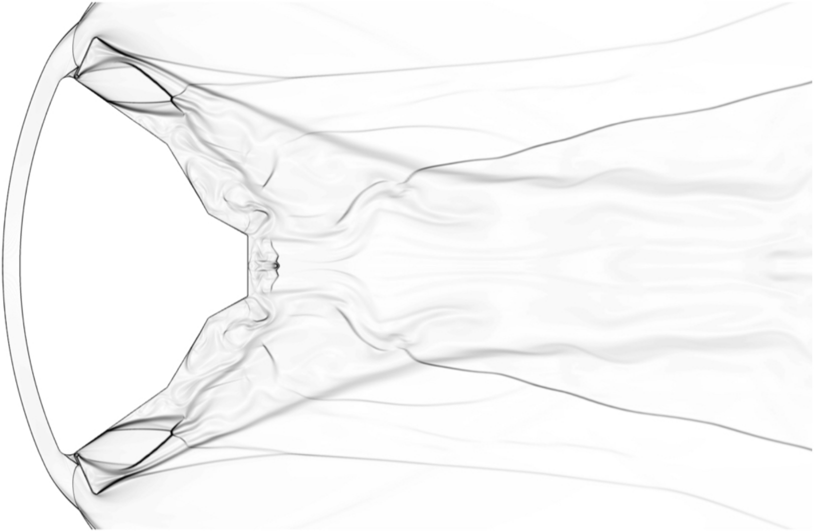

Effects on Aft-Body