

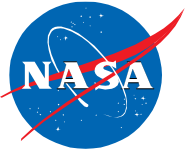
Optimization of Plug Nozzles Using CFD Informed Design Space Querying

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Motivation and Objective



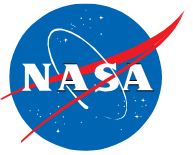
- Plug Nozzles Overview:
 - Gaining attention for supersonic transport
 - Possible acoustic advantages in crucial landing and takeoff (LTO) scenarios
- Computational Challenges:
 - Acoustic analysis is computationally expensive
 - Lower fidelity tools needed for efficient aerodynamic performance assessment

Approach

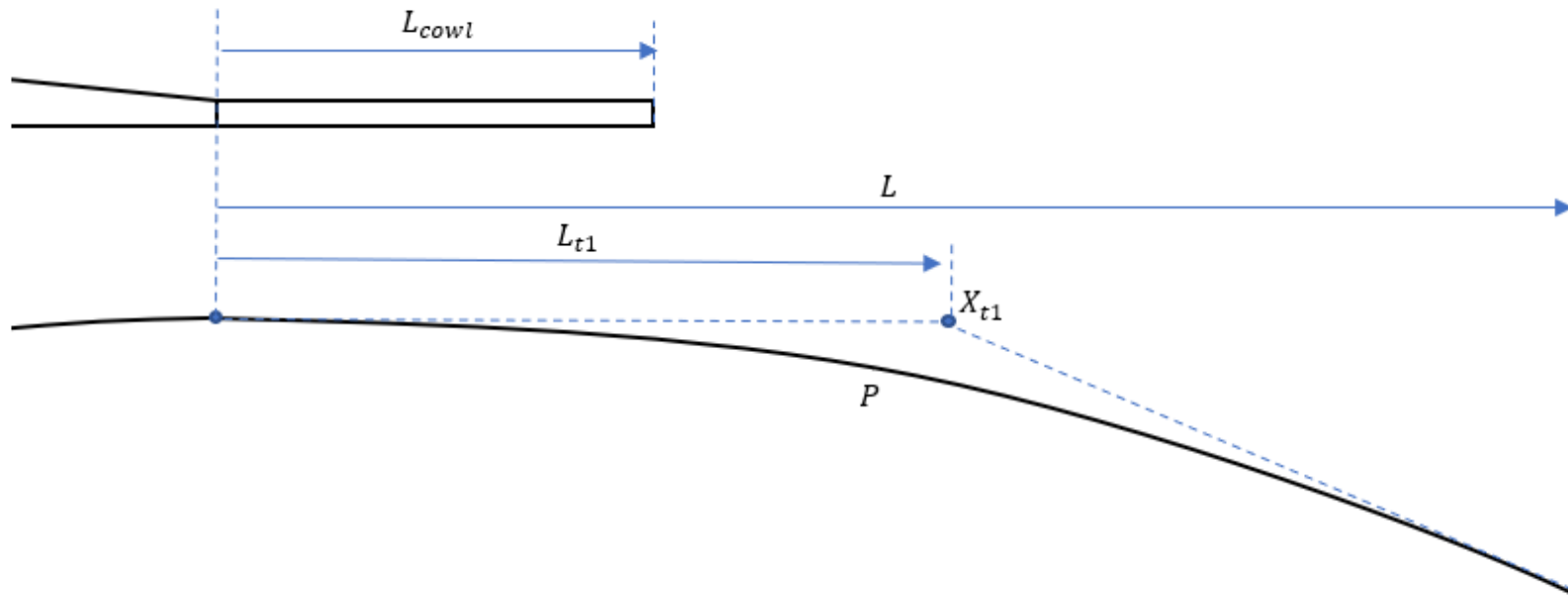


- Approach:
 - Using RANS-based CFD for shape optimization
 - Independent variables: Three geometric plug parameters
 - Dependent variables: Thrust coefficient (C_{fg}) and discharge coefficient (C_d)
- Analysis Conditions:
 - Cruise: NPR ~ 5.9 , Mach 1.4
 - LTO: NPR 2.0, Mach 0.01
 - Additional cases: NPR 7.57, Mach 0.01

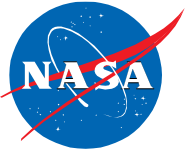
Geometry



- Simplified Plug Nozzle Conic Section Plug Parameters
 - Tangency control point location (X_{t1})
 - Plug length (L)
 - Conic parameter (P)

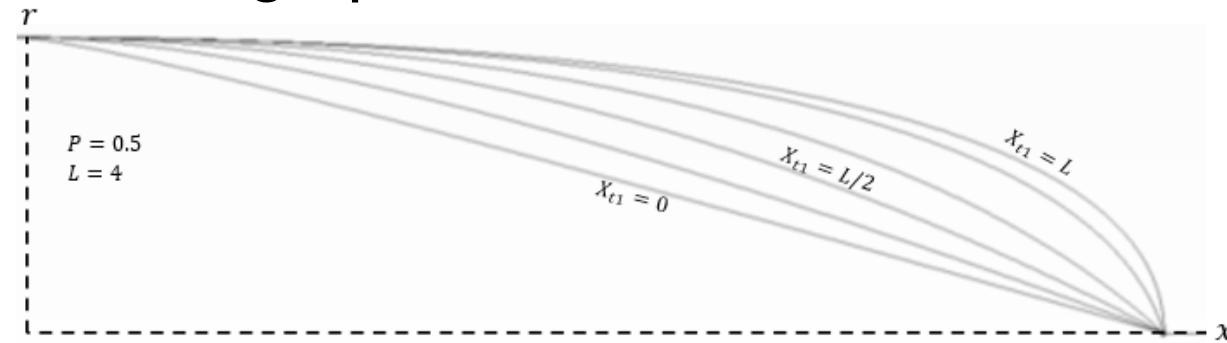


Geometry, etc.

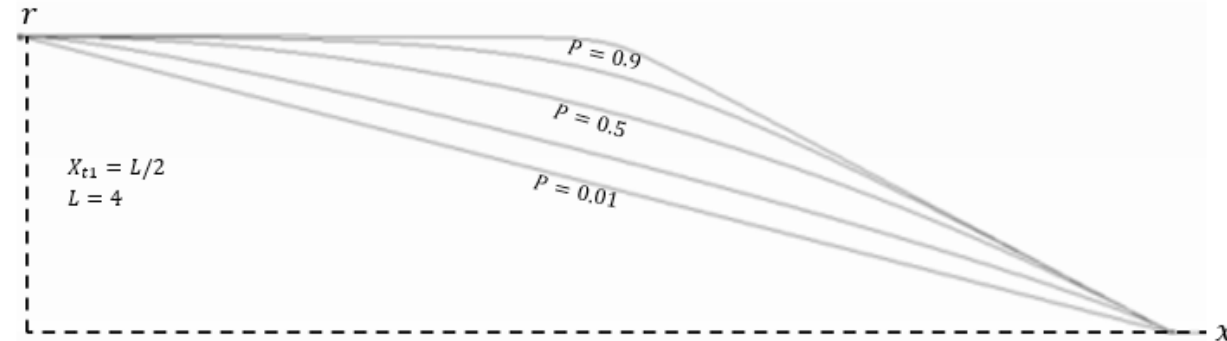


➤ Example variation of design parameters

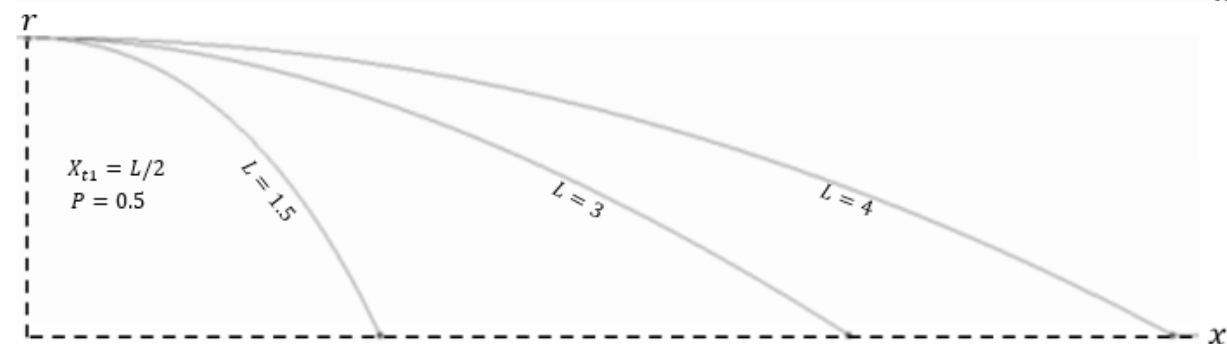
➤ Varying X_{t1}



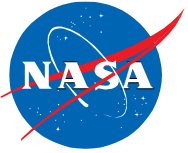
➤ Varying P



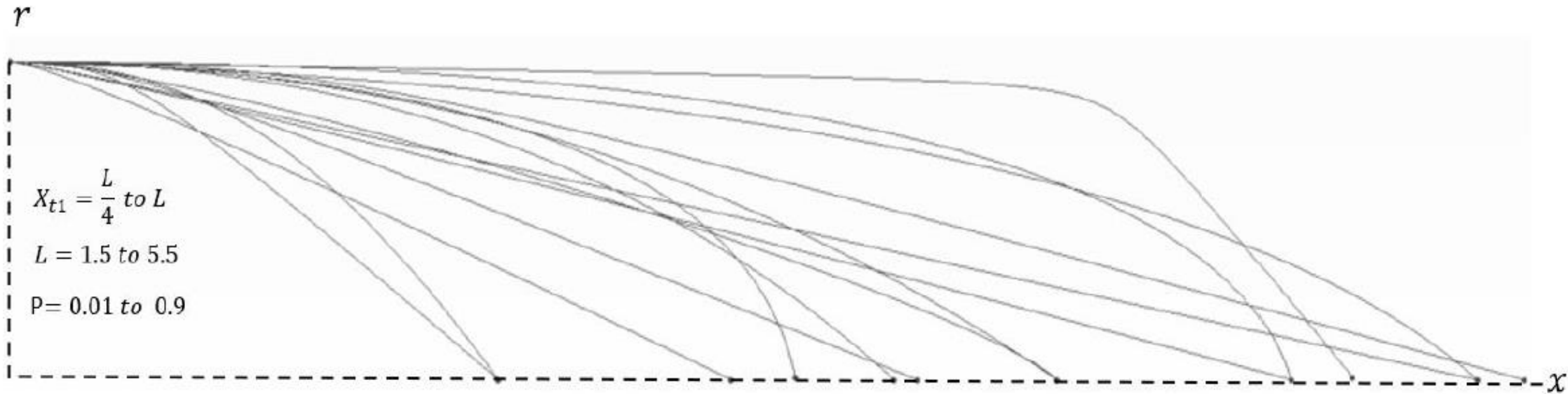
➤ Varying L



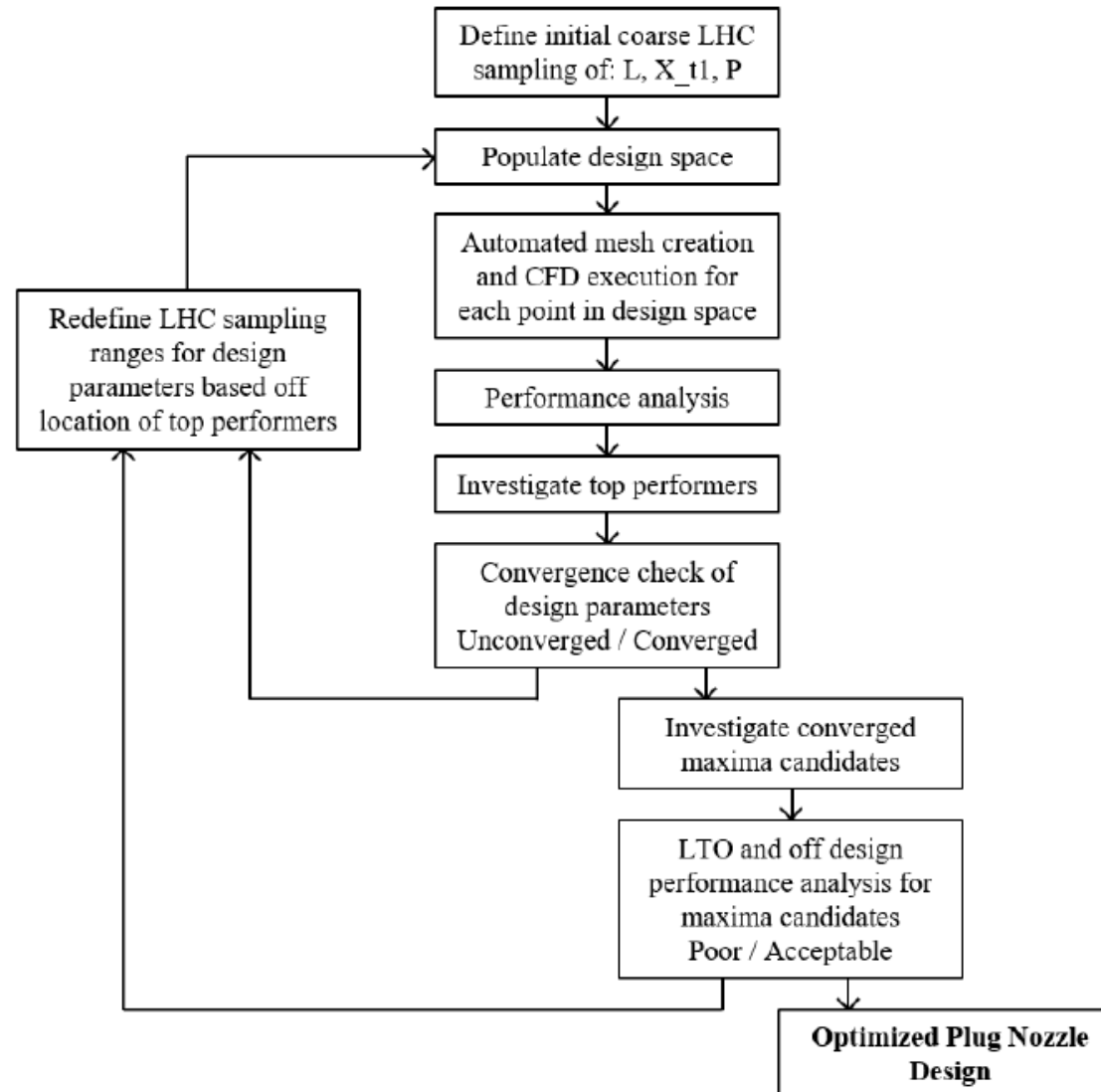
Geometry, etc.



- Random variation of design parameters



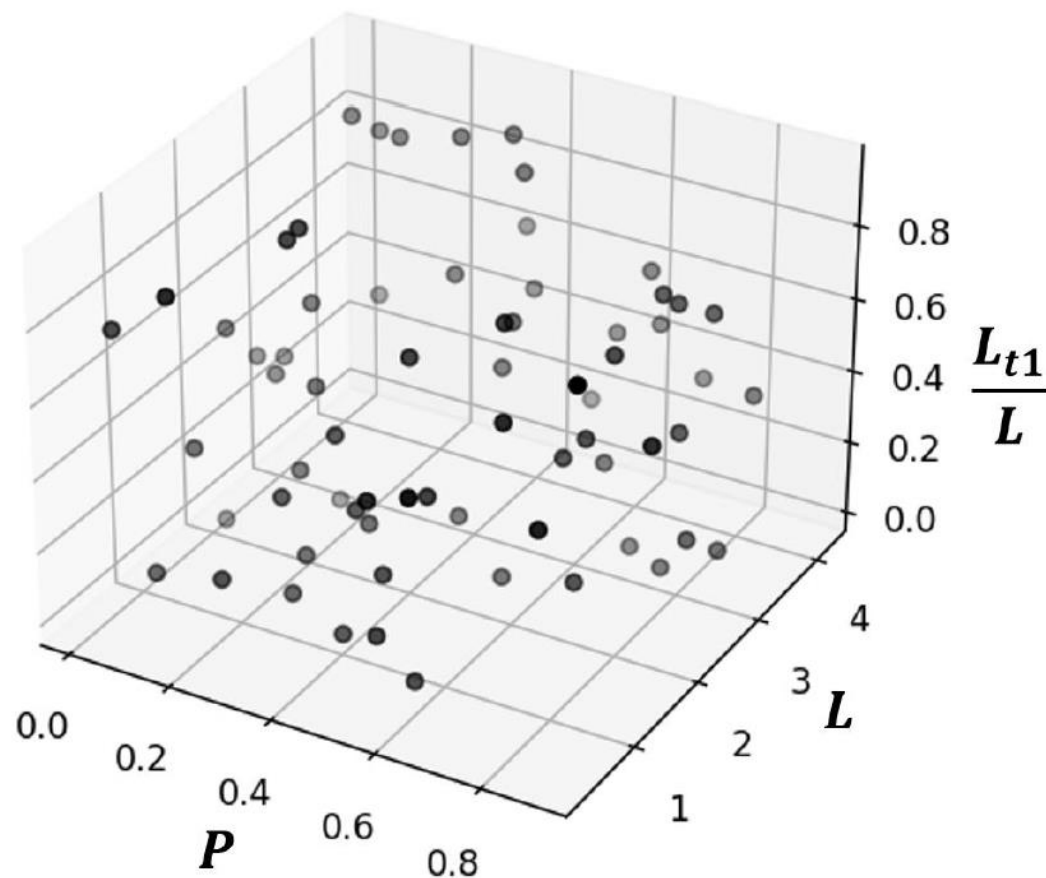
Solution Process



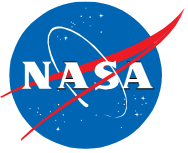
The Software Toolchain, Design Space Seeding



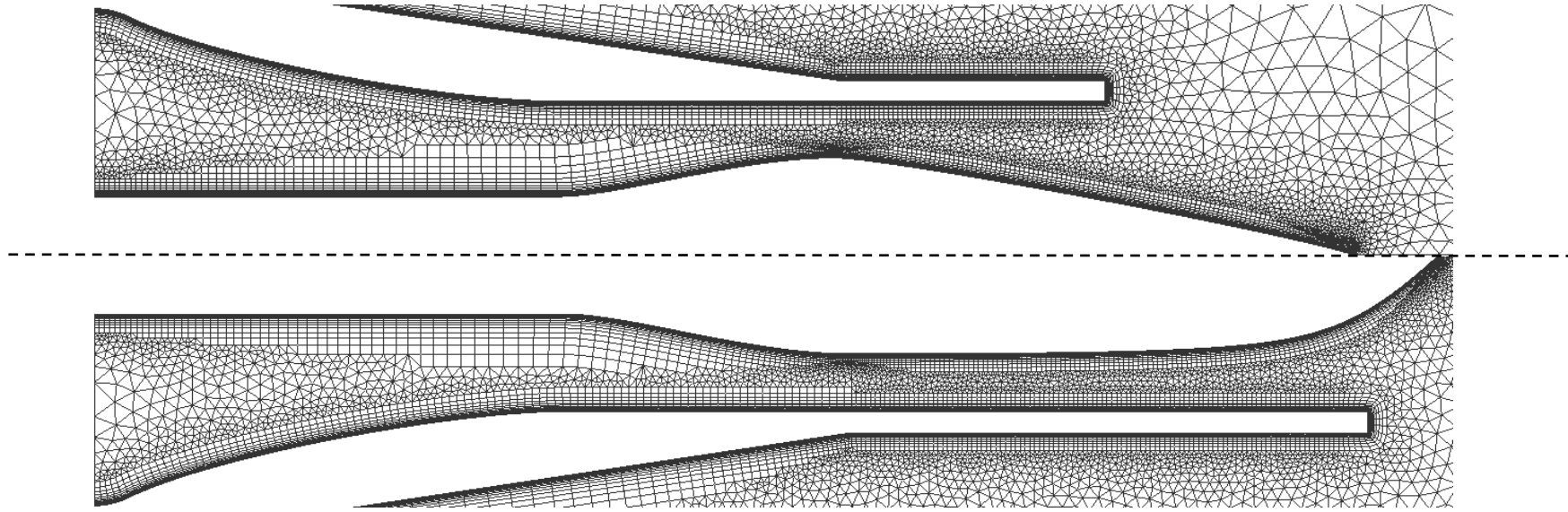
- Geometric Variable Exploration:
 - Latin Hypercube seeding all three conic section parameters



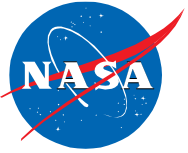
The Software Toolchain, Meshing



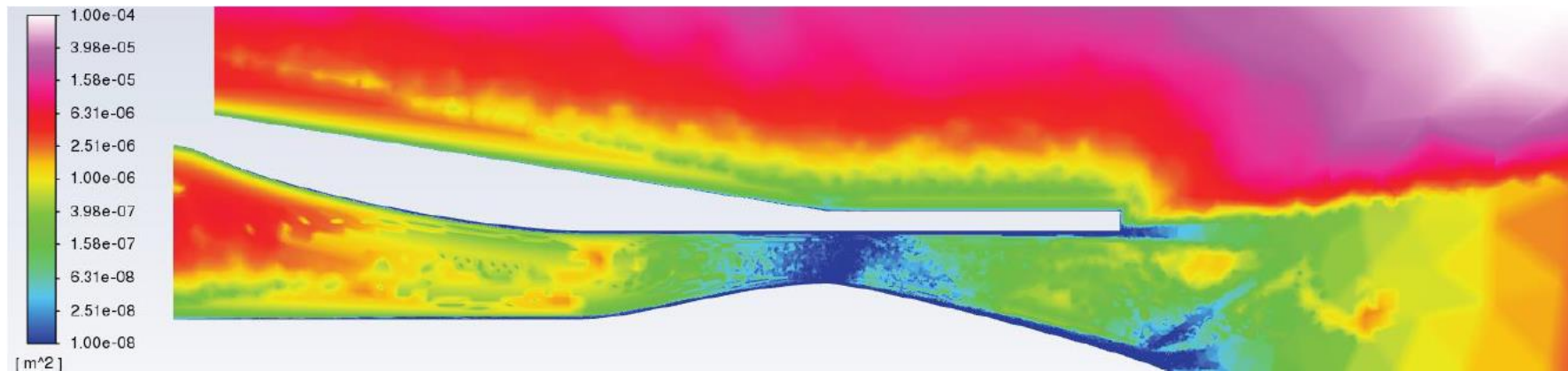
- Mesh Generation:
 - Initial unstructured meshes in Pointwise (18,000 to 22,000 cells)
- Automation Method:
 - Pointwise pilot mesh with Python matrix input, Glyph script, and bash wrapper



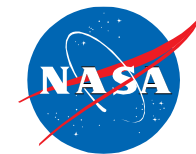
The Software Toolchain, CFD



- ANSYS Fluent CFD Simulation Details:
 - Axisymmetric, calorically perfect gas models, k- Ω SST turbulence
 - “Cold flow” subscale test rig conditions: 273 K, 101,325 Pa
- Convergence and Refinement:
 - Density-based adaptive mesh refinement (7 cycles per run)
 - ~20k cell count pre refinement — 500k post refinement (BL, Shocks, shear layers)



The Software Toolchain, Performance Analysis



- Dependent Quantities:
 - Gross thrust coefficient (left) and discharge coefficient (right)
- CFD Postprocessing Processes of Note:
 - Velocity Quantities: Mass flow-weighted averages
 - Pressure Quantities: Area-weighted averages

$$C_{fg} = F/F_{ideal}$$

$$F = \dot{m}V_i + A_i(p_i - p_{Plenum}) - F_{Pressure} - F_{Visc}$$

$$F_{ideal} = \dot{m} \sqrt{2C_p T_{oi} \left(1 - \left(\frac{1}{NPR}\right)\right)^{\frac{\gamma-1}{\gamma}}}$$

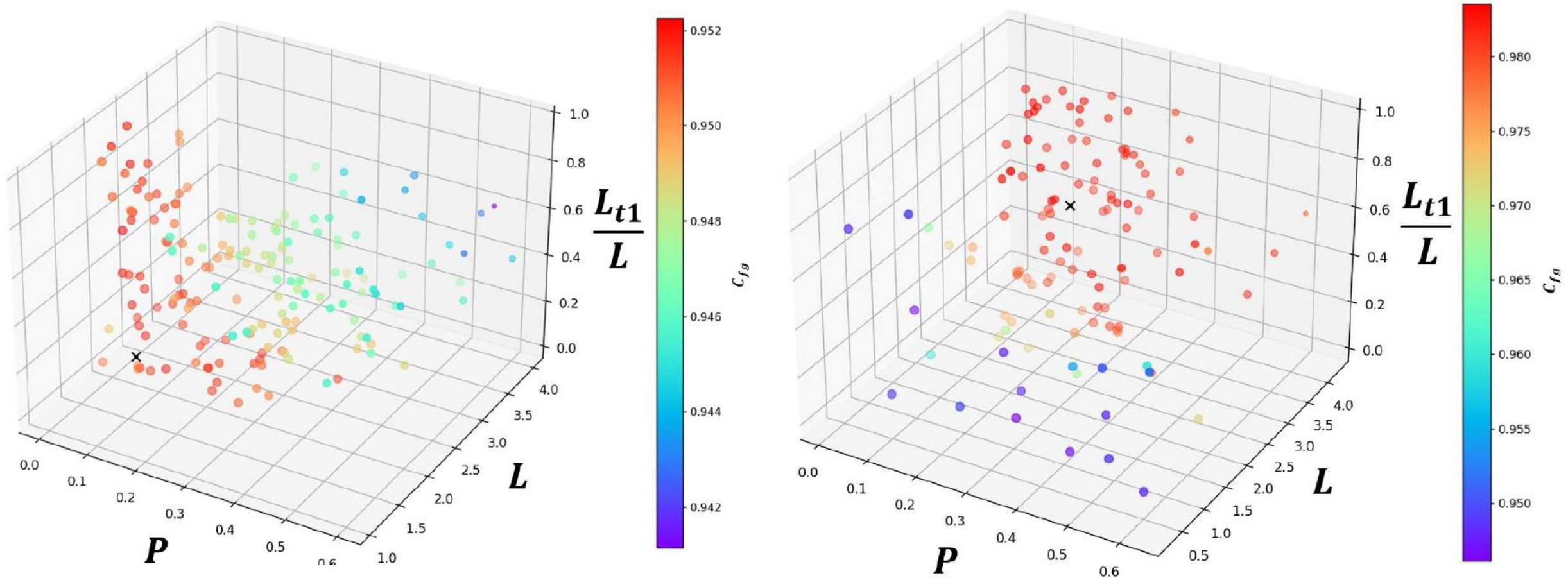
$$C_d = \dot{m}/\dot{m}_{ideal}$$

$$\dot{m}_{ideal} = A_e P_{Plenum} NPR \sqrt{\frac{\gamma}{C_p T_{oi}} \left(1 + \left(\frac{\gamma-1}{2}\right)\right)^{-\left(\frac{\gamma+1}{2(\gamma-1)}\right)}}$$

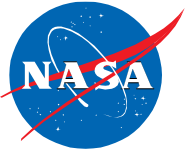
- Efficiency and Convergence:
 - Optimized plug nozzle achieved with geometric parameters converged to 1 part in 1000 ($1e-3$)
 - A few days of wall time on a single CPU for hundreds of candidates
- Optimized Profiles:
 - Profiles K1b (LTO) and K7 (Cruise) obtained
 - Additionally, LTO-cruise compromise profile K9

Results, Ctd.

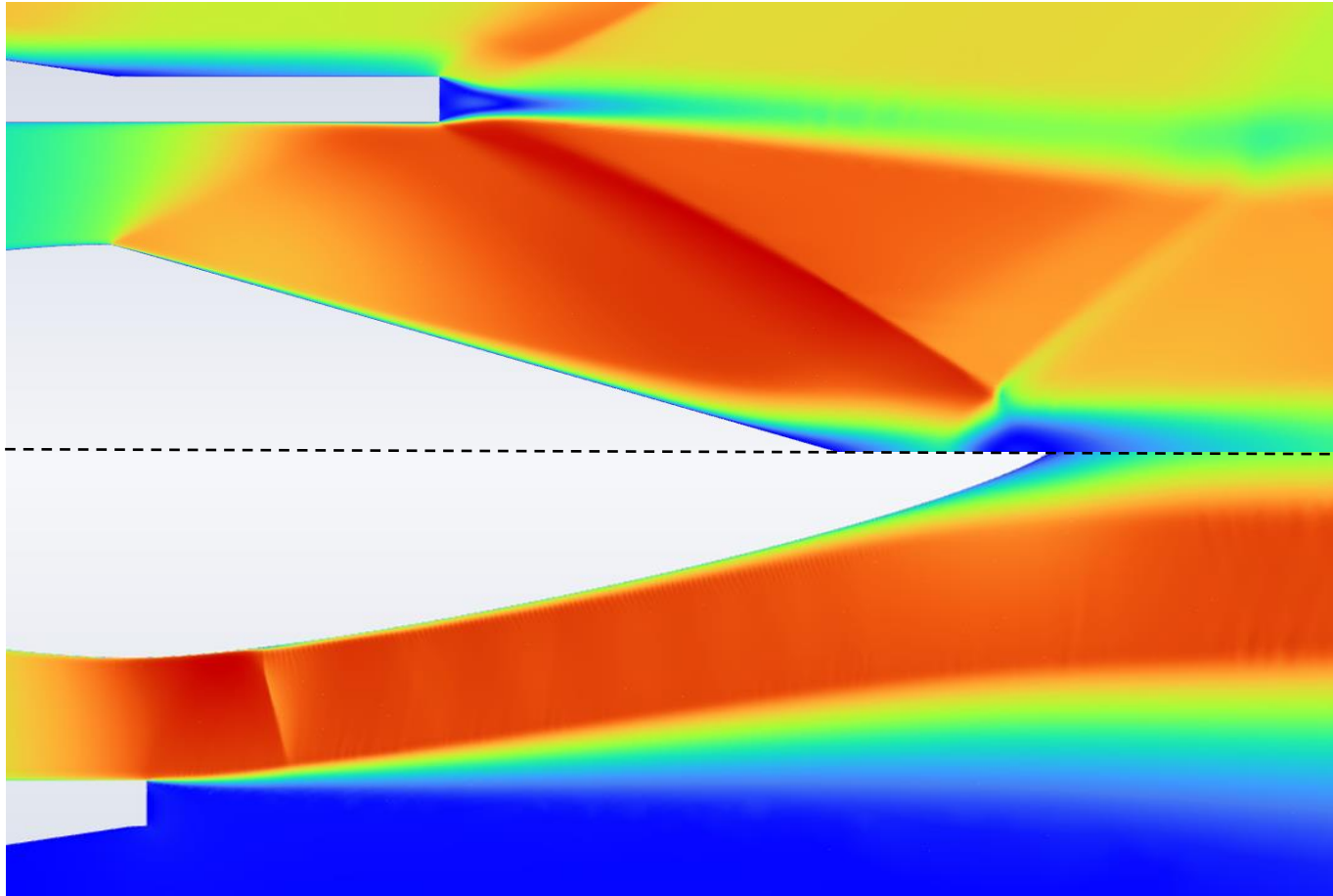
- Example results for Cruise (left) and LTO (right)



Results, Ctd.



- Example flowfields for optimal Cruise (top) and LTO (bottom)



$$L = 2.087 \text{ [in]}$$

$$\frac{L_{t1}}{L} = 0.046$$

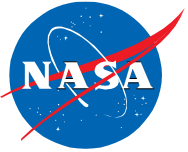
$$P = 0.041$$

$$L = 2.763 \text{ [in]}$$

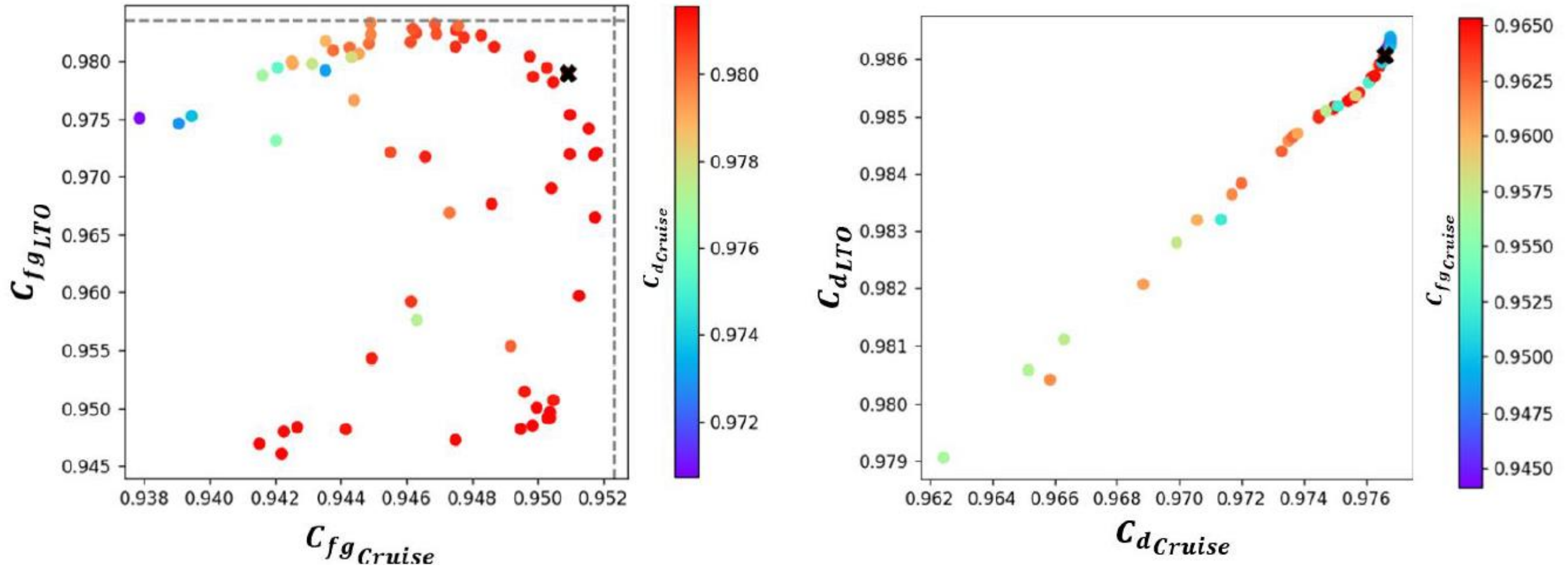
$$\frac{L_{t1}}{L} = 0.659$$

$$P = 0.267$$

Results, Ctd.

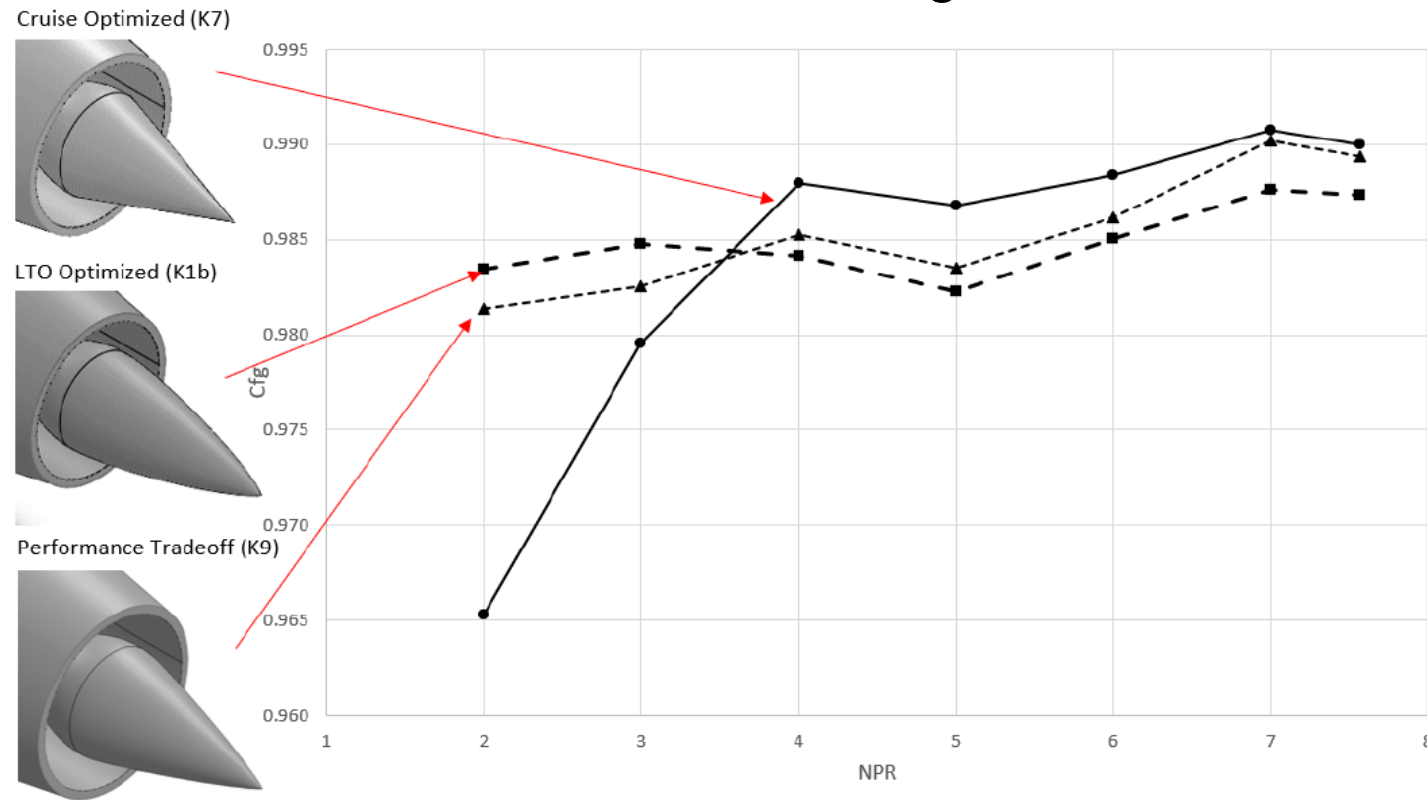


➤ Pareto-front for Cruise-LTO compromise design “K9”

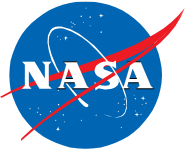


Results, Ctd.

- Final plug nozzles to be investigated with higher fidelity tools
 - Computational: LES and Acoustic analysis
 - Experimental: NASA GRC, CW-17 test rig



Acknowledgements



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 - Provided by the NASA Commercial Supersonic Technology project (CST)
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 - James Bridges: Leadership and contributions to nozzle design
 - Khairul Zaman: Experimental nozzle work
 - William Banks: Contributions to Python tools and assistance with CFD