

National Aeronautics and Space Administration

SPACE LAUNCH SYSTEM

A Computational Study of Plume Modeling for Space Launch System Abort Scenarios

AIAA SciTech, SLS Aerodynamics IV, January 24th, 2023

Jonathan Boustani*, Michael P. Applebaum*, William M. Eppard*, Thomas Steva*, Leslie Hall*,

*Mclaurin Aerospace, Jacobs ESSCA Group, Huntsville, AL

*NASA Marshall Space Flight Center, Huntsville, AL

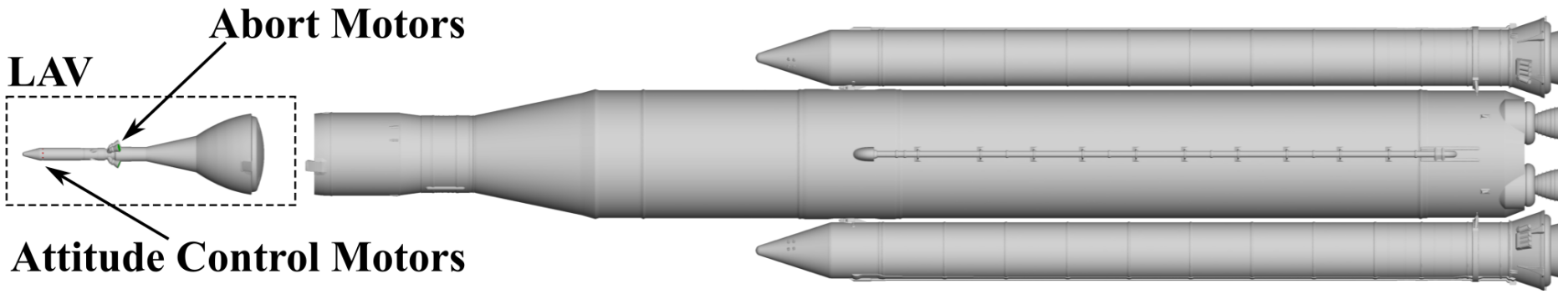
www.nasa.gov/sls

Contents

- **Motivation and Introduction**
- **Methodology**
  - Multispecies, equivalent species, and perfect gas modeling
- **Results**
  - Core stage CA comparison
  - Line/Sectional loads analysis
  - Cost comparison
- **Conclusions**

Motivation and Introduction

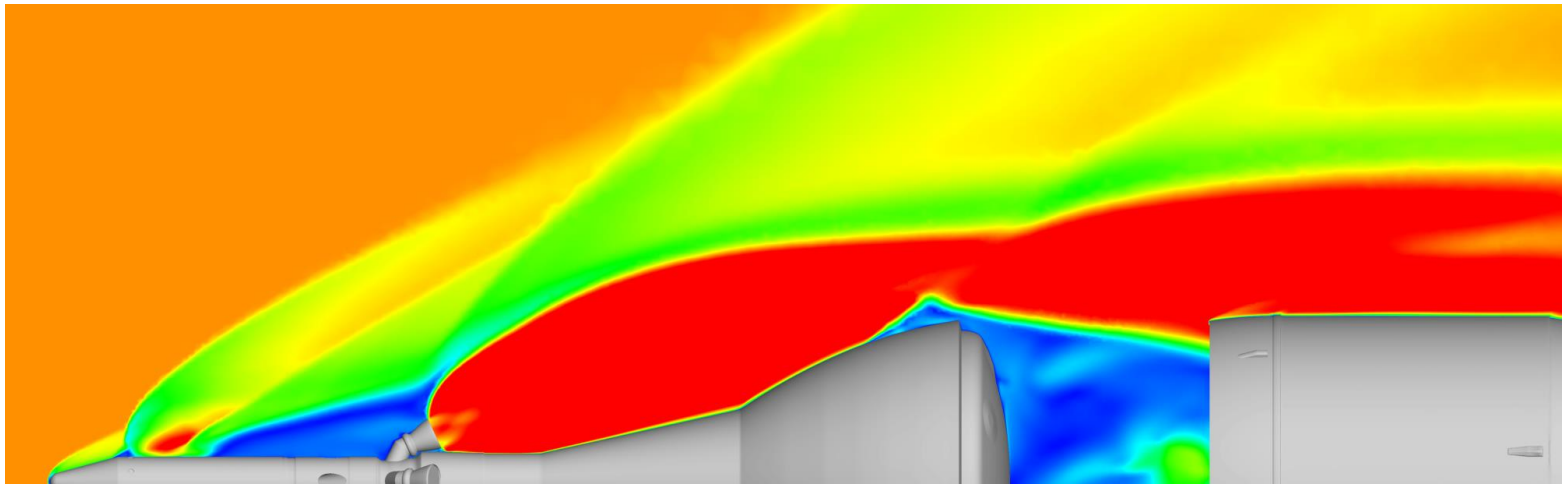
- **Due to complications during flight, a launch abort may be required**
- **During a Mode-1 abort, abort motors (AM) and attitude controls motors (ACM) fire**
  - This maneuvers the Orion capsule and its crew away from the core stage
  - The motors, the Orion vehicle, and the tower are collectively referred to as the launch abort vehicle (LAV)



- **One primary concern during this scenario is if the core stage can recontact the LAV**
- **The result is a function of: (1) M, q, α, β, (2) distance from LAV to core stage, (3) AM and ACM thrust level *(e.g.,* off, low, high*)***

Motivation and Introduction

- **The authors were tasked with the generation of a database to answer this**
  - The core stage axial force coefficient, CA, was computed as a function of the aforementioned factors
- **The present work stems from determining uncertainty bounds in the database**
  - *e.g.,* given perturbations from a ‘nominal’ state, how much did the core stage CA change
- **The database was constructed without the AMs and ACMs firing** *(see paper for details)*
  - The present work considers a selection of database cases with the engines firing



- **The ignition of the solid rocket propellent in the AMs and ACMS yields a multispecies and reacting exhaust gas mixture**
  - Different exhaust gas models are studied here

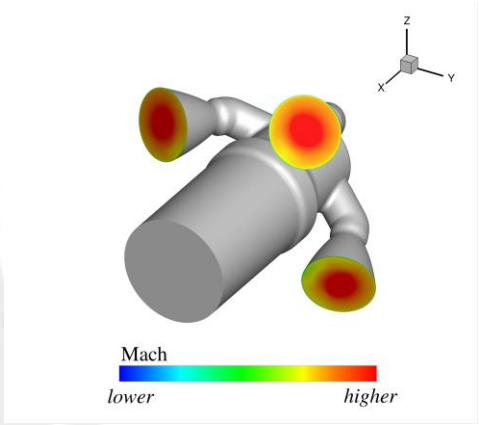
Methodology – Overview of Exhaust Gas Modeling

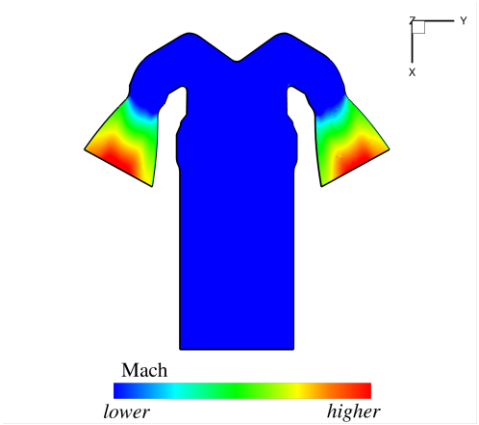
- **The 'true' exhaust gas mixture is multispecies and chemically reacting in nature**
  - This is represented in the current work by a 15-species, 30-reaction model identified by Niu *et al*. 2017*
- **Chemically reacting models tend to be very computationally expensive**
  - One additional continuity equation per species (more memory and arithmetic)
  - Reactions tend to increase linear system stiffness (may require stronger/slower solver)
- **Assuming most of the reactions have already occurred in the combustion chamber, the exhaust gas mixture can also be modeled as a single "equivalent" species**
  - This model matches the mass-averaged quantities of the multispecies mixture
- **Finally, the exhaust gas model can be modeled as calorically perfect air**
- **The topic of the present work is the comparison of these three models**

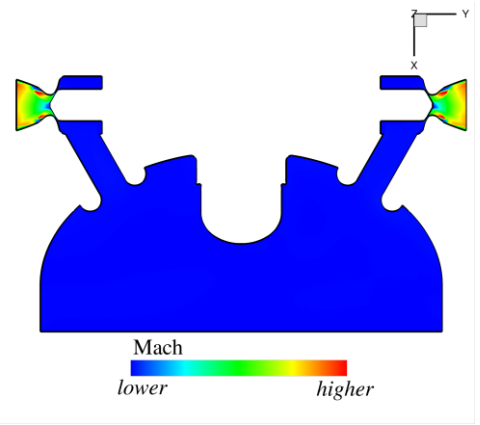
*Niu, Q., HE, Z., Dong, S. "IR radiation characteristics of rocket exhaust plumes under varying motor operating conditions", *Chinese Journal of Aeronautics* (2017)

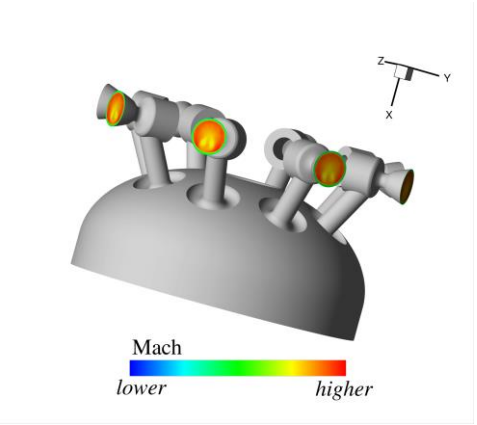
Methodology – Overview of CFD Simulation Setup

- **First, the combustion chambers are simulated using provided stagnation conditions**
  - Corresponding to a low- and high-thrust level in the AMs; the ACM thrust is constant









- **The state at the nozzle outflow planes is used to define a single equivalent specie**
  - The primitive state variables are matched exactly
  - Caloric imperfections are represented by McBride-Gordon curve fits*
  - Typical mass-averaging is used obtain the species gas constant, molecular weight, and specific heats

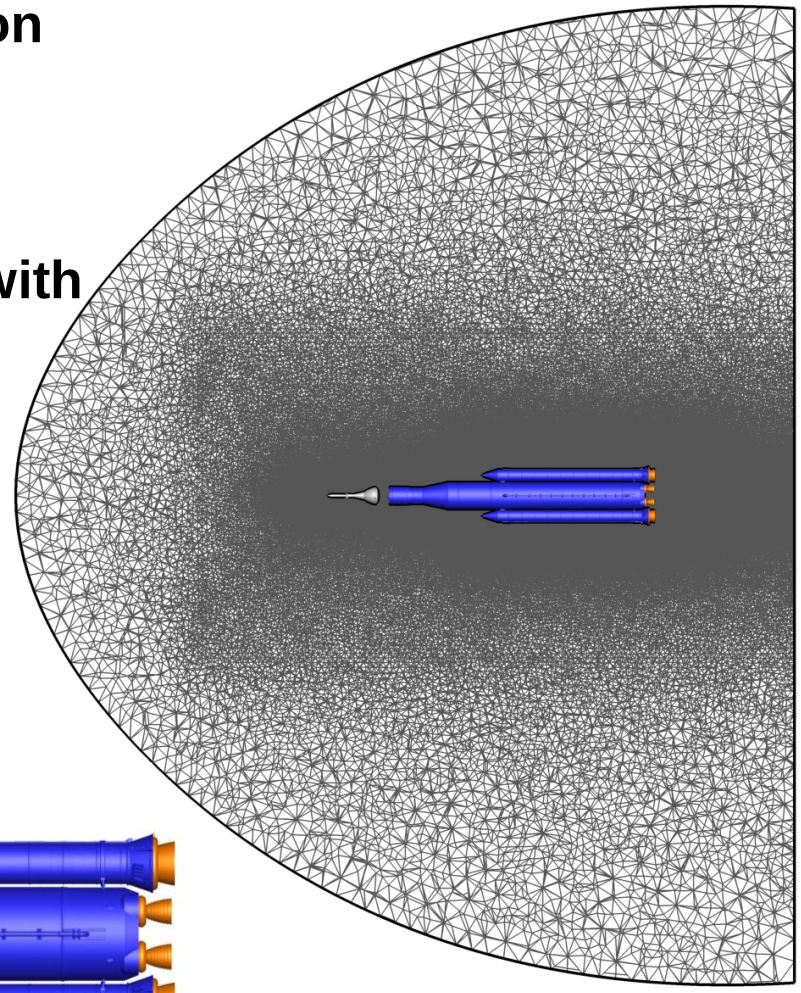
- **For perfect air, the primitive state cannot be matched**
  - To match thrust, pressure and velocity are matched
  - Since, $R_{air} = const.$, however, temperature must "float"

*McBride, B. J., Gordon, S., Reno, M. A. "Coefficients for calculating thermodynamic and transport properties of individual species," *NASA Technical Memorandum* (1993)

Model	Species Present	Considers Reactions
Niu Multi-species	CO_2, CO, Cl_2, Cl, H_2O, H_2, HCl, HO_2, H, N_2, NO, N, O_2, OH, O	Yes
Equivalent species	Equiv. ACM Gas, Equiv. AM Gas, Equiv. Air	No
Perfect Air	Equiv. Air	No

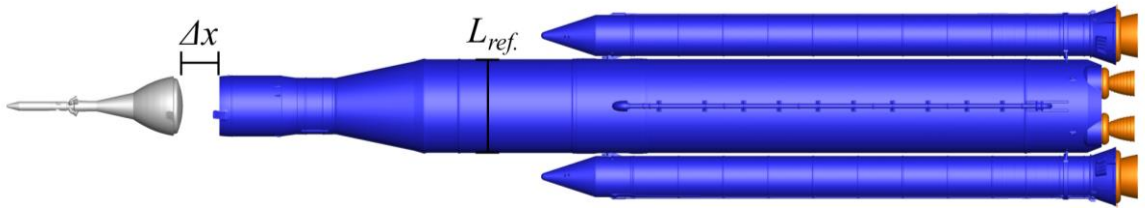
Methodology – Overview of CFD Simulation Setup

- **The primitive state and corresponding mass fractions at the AM and ACM nozzle exit plans are used as inlet boundary conditions for a full-scale simulation**
- **An unstructured volume domain is generated with AFLR3**
- **loci/CHEM solves the compressible Navier-Stokes equations with formally second-order accuracy**
- **Turbulence is modeled with Wilcox's 2008 $k-\omega$ model**
  - Wilcox's compressibility correction is also employed
- **All surfaces are no-slip, adiabatic walls**



Run Matrix

$\Delta x/L_{ref.}$	Mach Number	AM Thrust Level
0.5	0.7, 3.0	Low, High
1.5	3.0	Low, High
2.5	3.0	Low, High

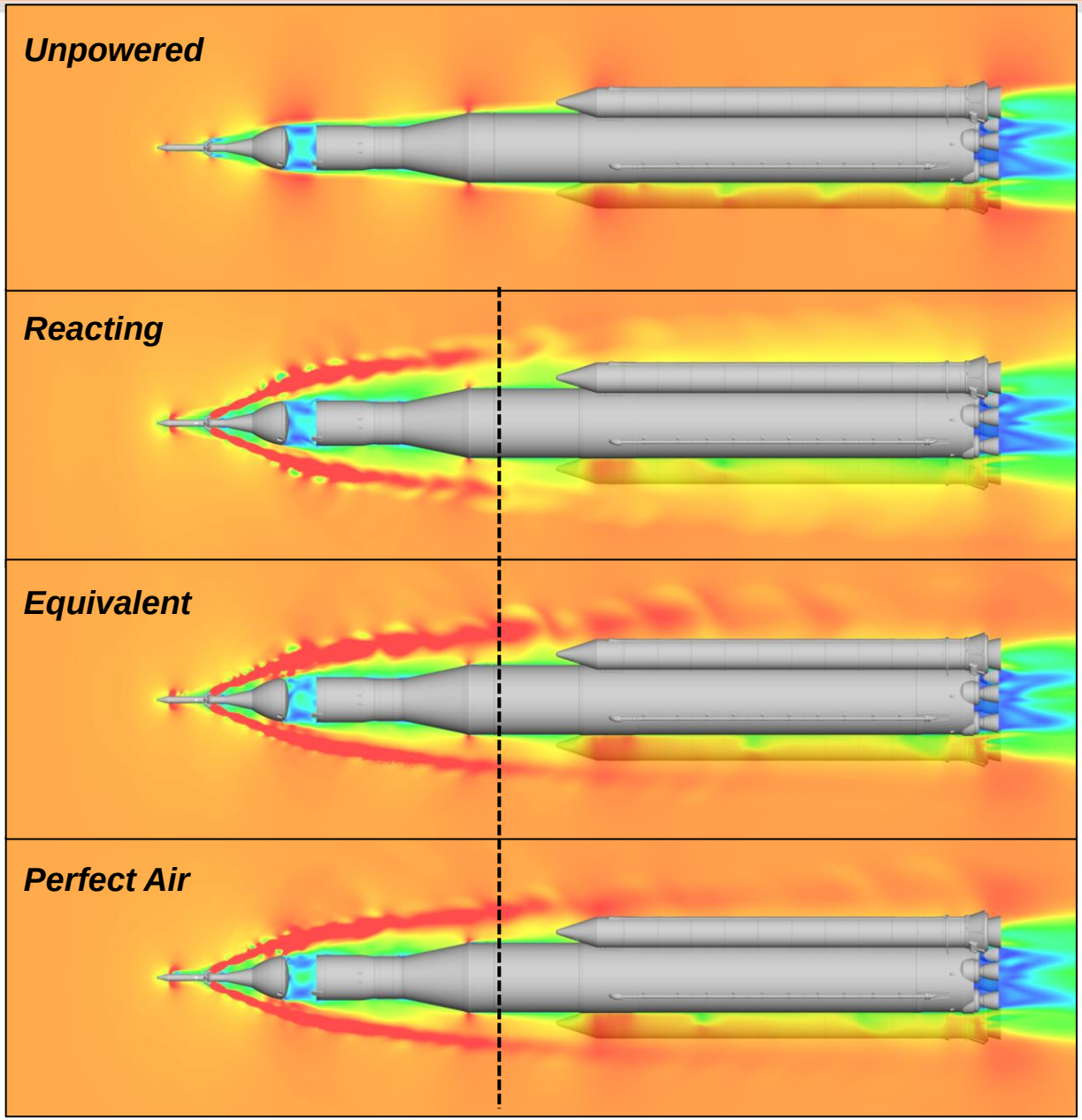


Blue surfaces are drag-producing surfaces used in subsequent computations of CA

Results – M = 0.7, $\Delta x/L_{ref.}$= 0.5, LT

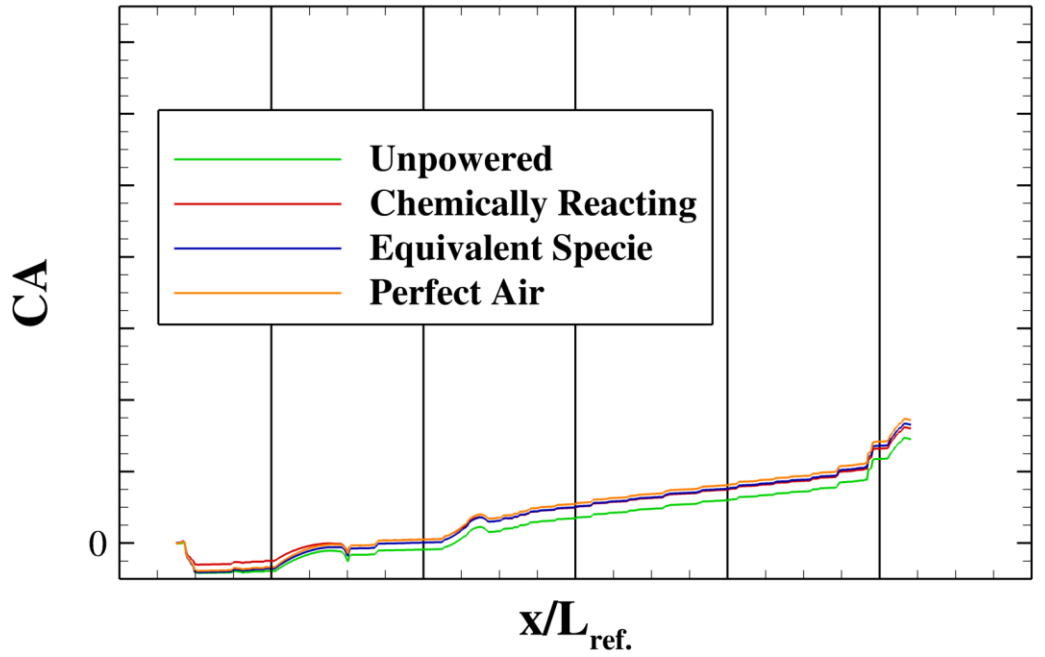
- Color contours of Mach number show qualitatively similar predictions
- In the equivalent and perfect air cases, high speed exhaust gas travels further downstream
- Core stage CA increases with decreasing exhaust gas modeling fidelity

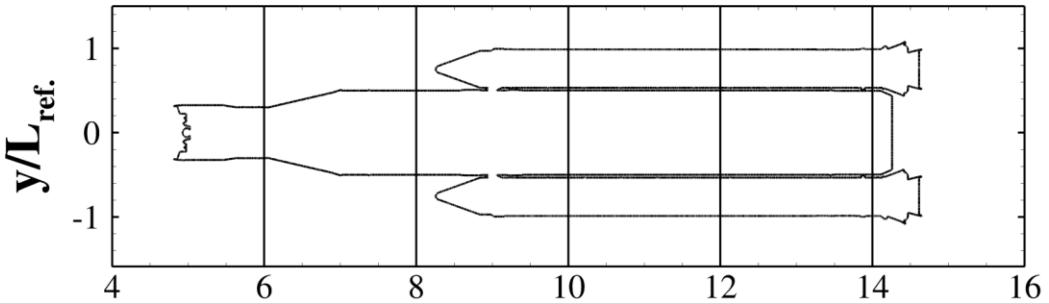
Model	CA (relative)
Unpowered	-6.86%
Reacting	-
Equivalent	+6.04%
Perfect Air	+8.91%



Results – M = 0.7, $\Delta x/L_{ref.}$= 0.5, LT

- Color contours of Mach number show qualitatively similar predictions
- In the equivalent and perfect air cases, high speed exhaust gas travels further downstream
- Core stage CA increases with decreasing exhaust gas modeling fidelity



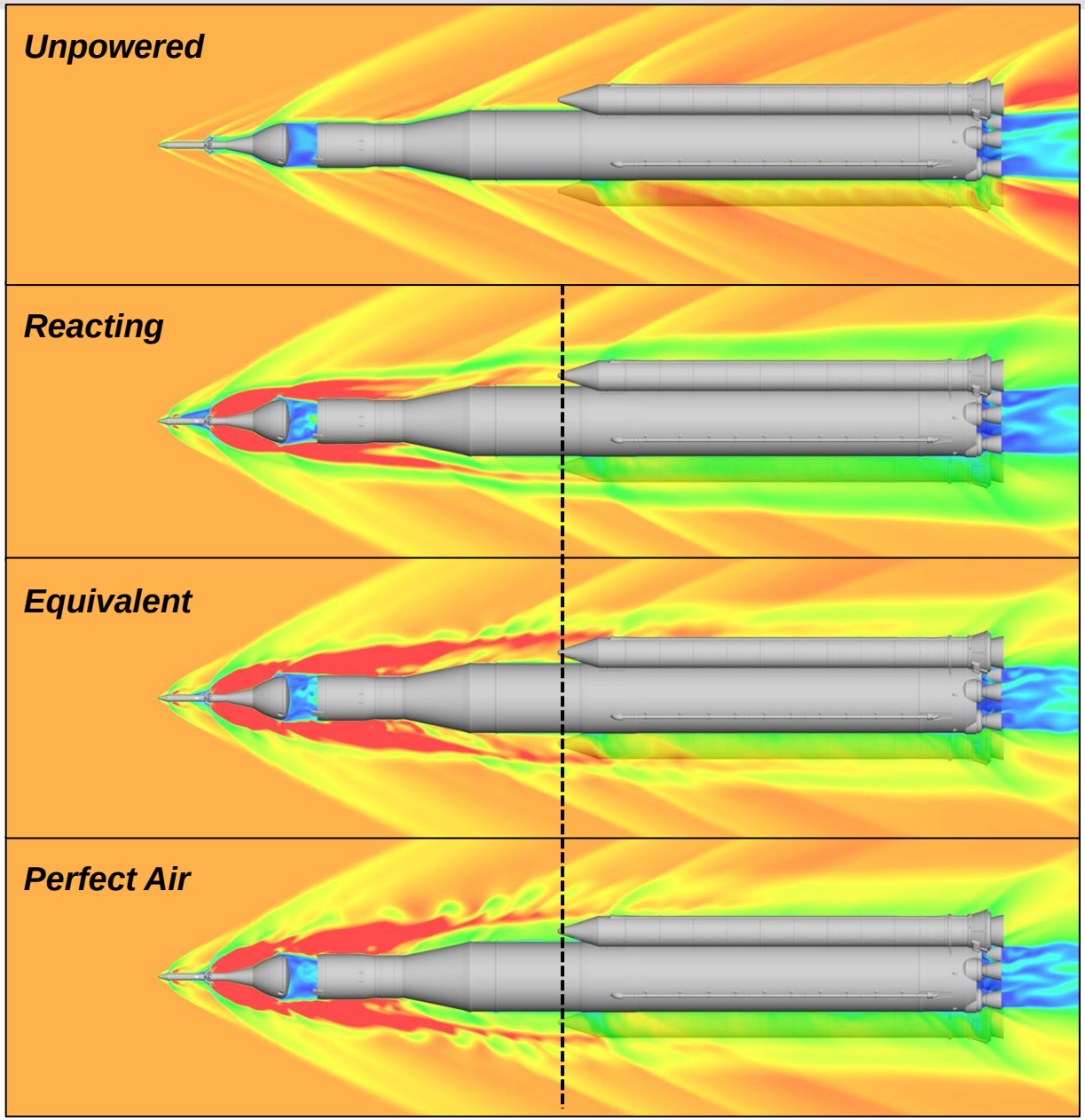


Model	CA (relative)
Unpowered	-6.86%
Reacting	-
Equivalent	+6.04%
Perfect Air	+8.91%

Results – M = 3.0, $\Delta x/L_{ref.}$= 0.5, LT

- **Notable differences between the unpowered and powered cases**
- **Differences between the models start to become evident near the launch vehicle stage adaptor (LVSA)**
- **Regardless, the core stage drag is predicted well between all cases**
  - The differences downstream of the LVSA do not seem to affect drag significantly

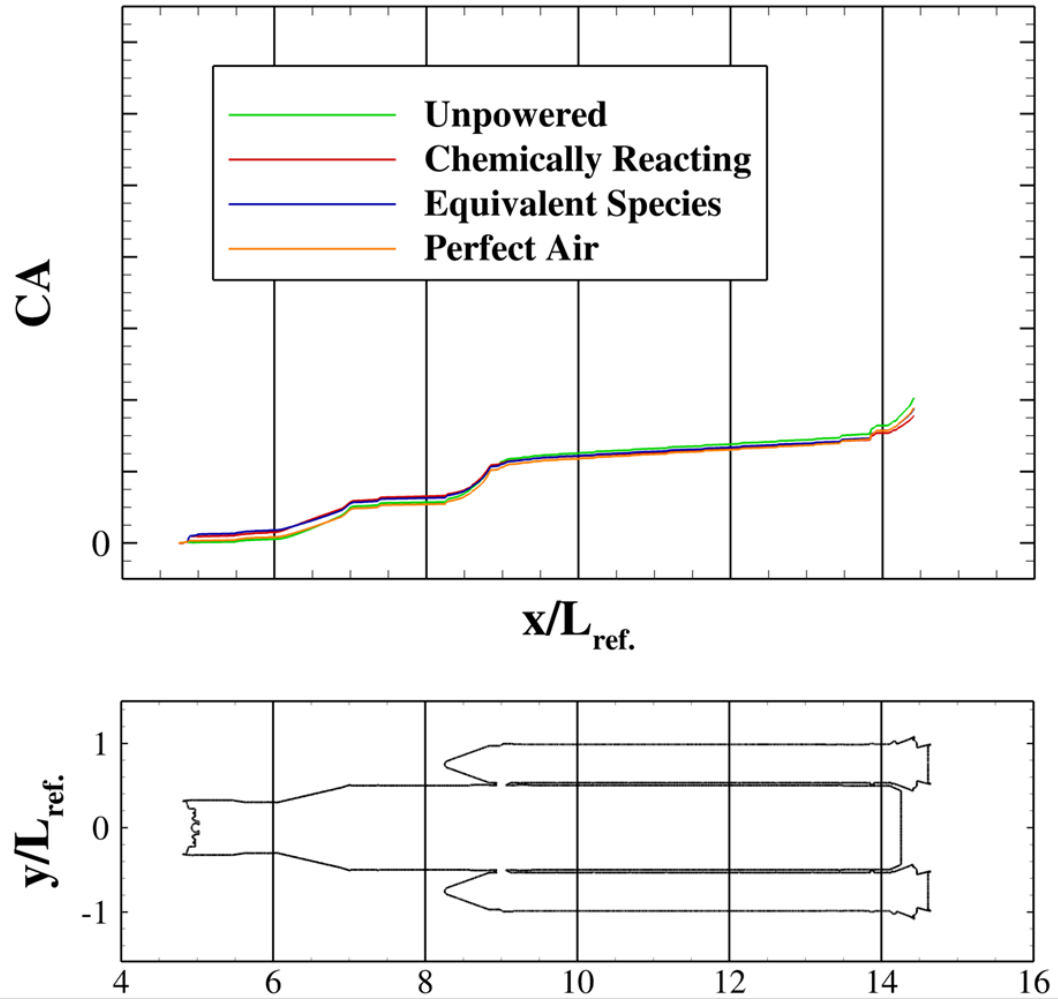
Model	CA (relative)
Unpowered	+14.44%
Reacting	-
Equivalent	+5.38%
Perfect Air	+5.81%



Results – M = 3.0, $\Delta x/L_{ref.}$= 0.5, LT

- **Notable differences between the unpowered and powered cases**
- **Differences between the models start to become evident near the launch vehicle stage adaptor (LVSA)**
- **Regardless, the core stage drag is predicted well between all cases**
  - The differences downstream of the LVSA do not seem to affect drag significantly

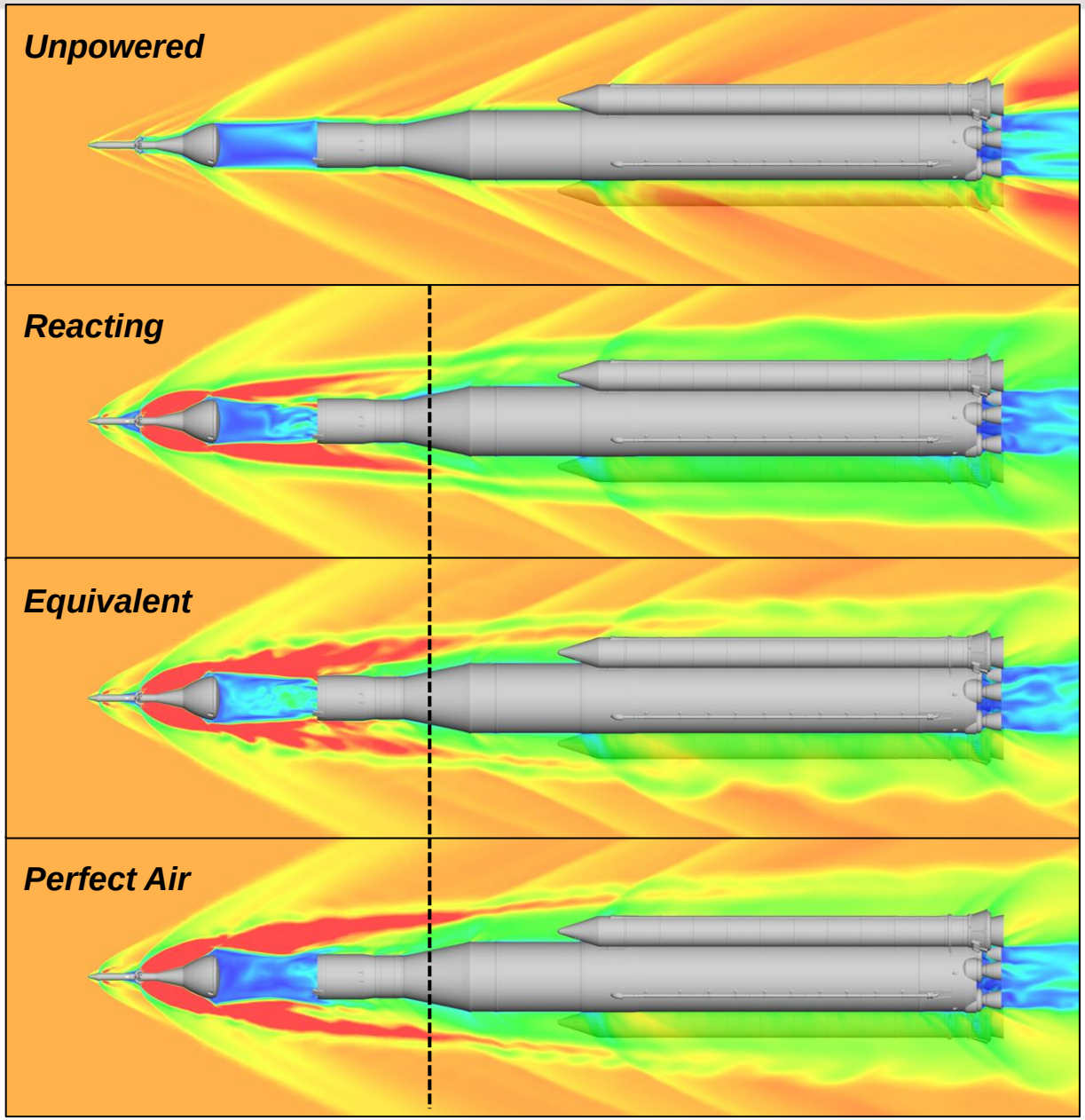
Model	CA (relative)
Unpowered	+14.44%
Reacting	-
Equivalent	+5.38%
Perfect Air	+5.81%



Results – M = 3.0, $\Delta x/L_{ref.}$= 1.5, LT

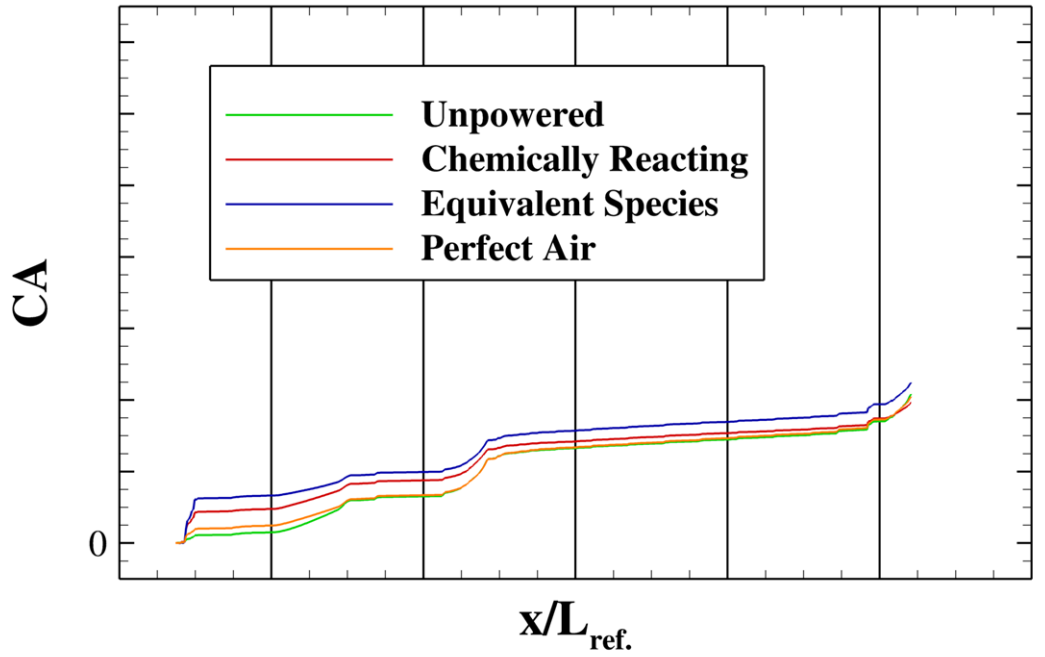
- The LAV wake region remains uninterrupted from the Orion heat shield to the cavity at the leading edge of the core stage
- The differences in the plume length persist
- Again, this does not seem to affect drag

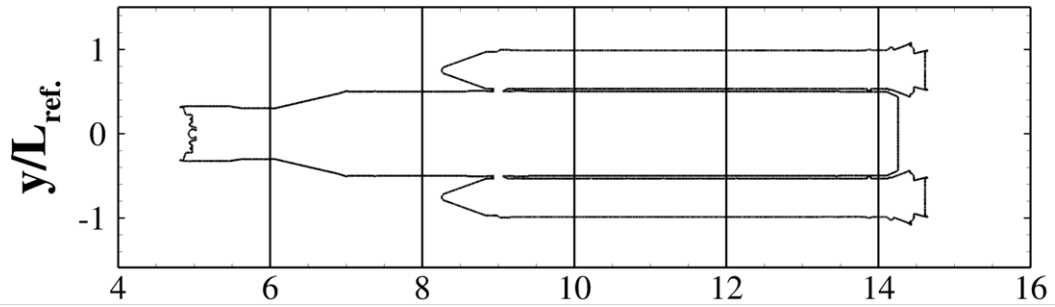
Model	CA (relative)
Unpowered	+5.29%
Reacting	-
Equivalent	+7.76%
Perfect Air	+3.59%



Results – M = 3.0, $\Delta x/L_{ref.}$= 1.5, LT

- The LAV wake region remains uninterrupted from the Orion heat shield to the cavity at the leading edge of the core stage
- The differences in the plume length persist
- Again, this does not seem to affect drag



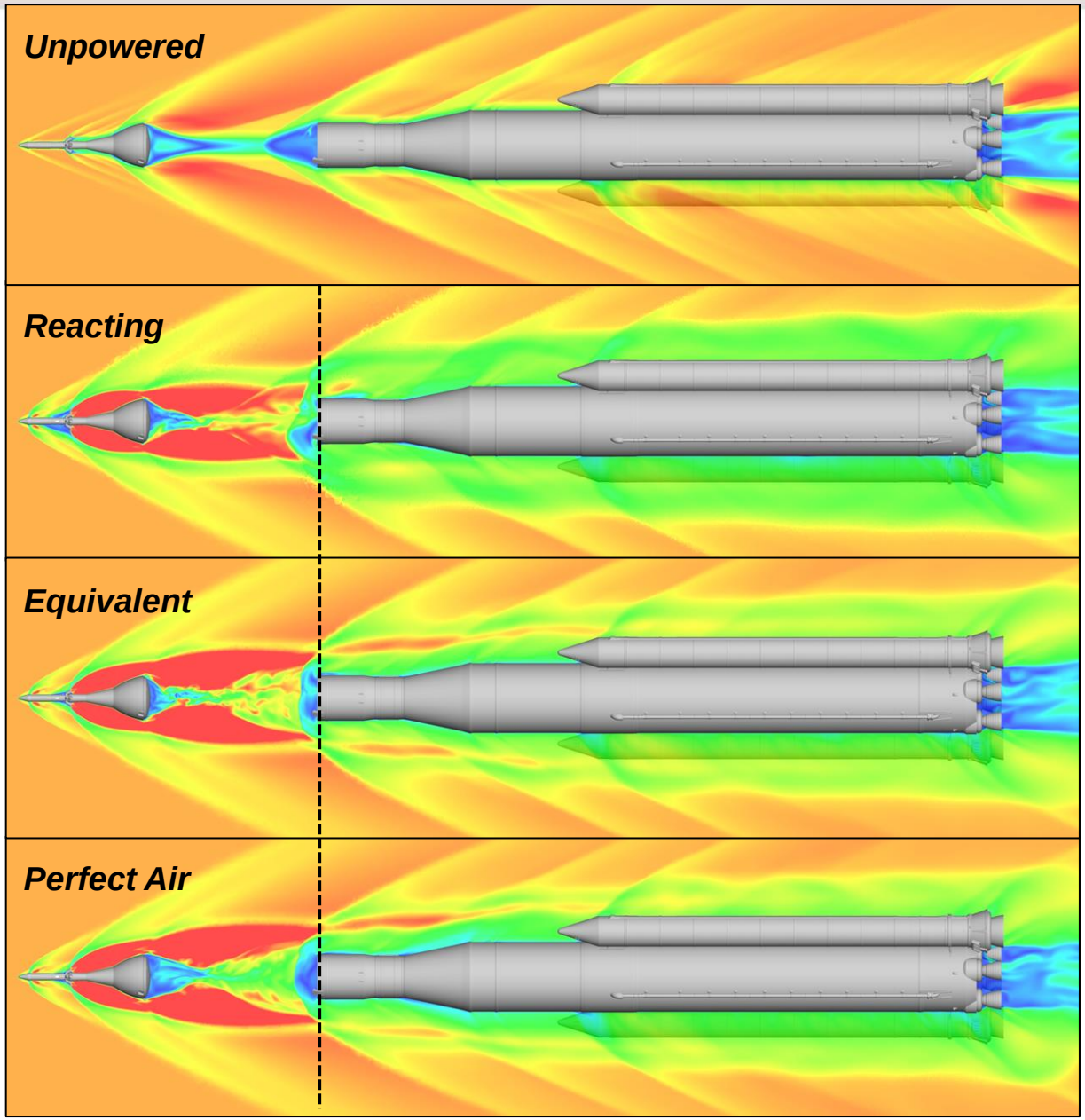


Model	CA (relative)
Unpowered	+5.29%
Reacting	-
Equivalent	+7.76%
Perfect Air	+3.59%

Results – M = 3.0, $\Delta x/L_{ref.}$= 2.5, LT

- Dramatic differences in the LAV wake region between the unpowered and powered cases
- This is represented in the differences in core stage CA
- The perfect air case now shows a large disagreement with the reacting case

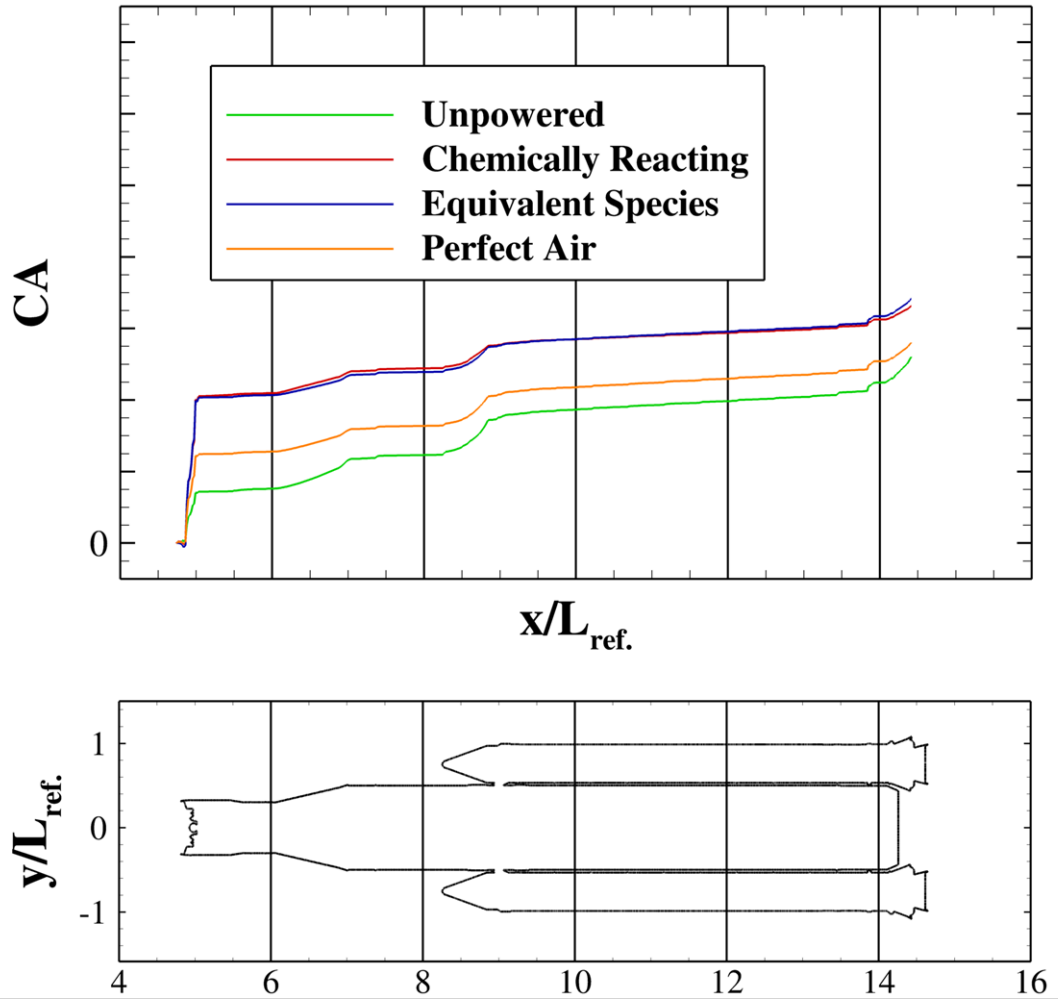
Model	CA (relative)
Unpowered	-24.58%
Reacting	-
Equivalent	-0.84%
Perfect Air	-18.25%



Results – M = 3.0, $\Delta x/L_{ref.}$= 2.5, LT

- Dramatic differences in the LAV wake region between the unpowered and powered cases
- This is represented in the differences in core stage CA
- The perfect air case now shows a large disagreement with the reacting case

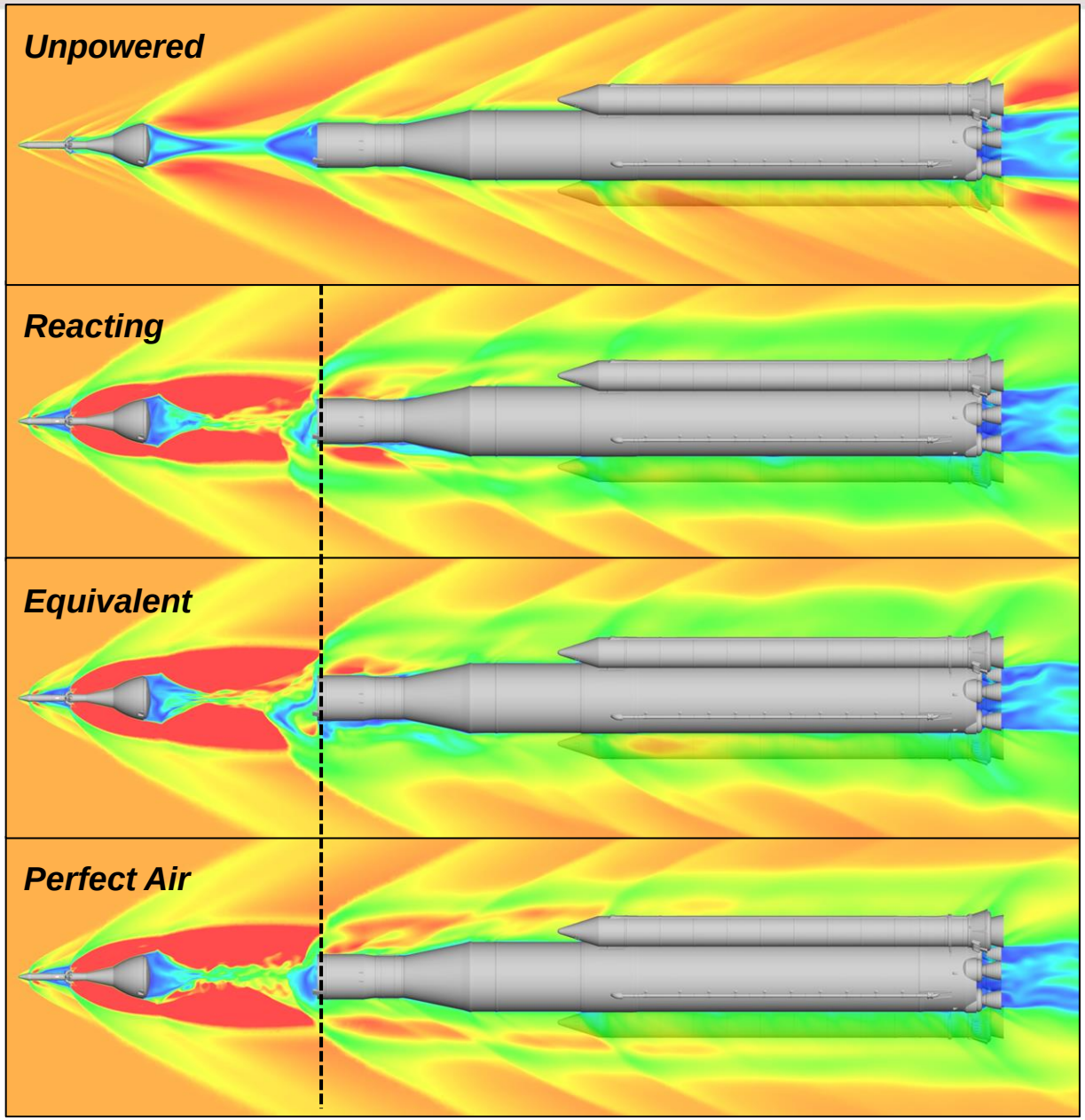
Model	CA (relative)
Unpowered	-24.58%
Reacting	-
Equivalent	-0.84%
Perfect Air	-18.25%



Results – M = 3.0, $\Delta x/L_{ref.}$= 2.5, HT

- Widening of the plumes at the higher thrust level is evident
- Yields a thicker region of near-wall, moderate-speed flow
- More high-speed exhaust gases recirculating in the LAV wake
- Perfect air disagreement persists

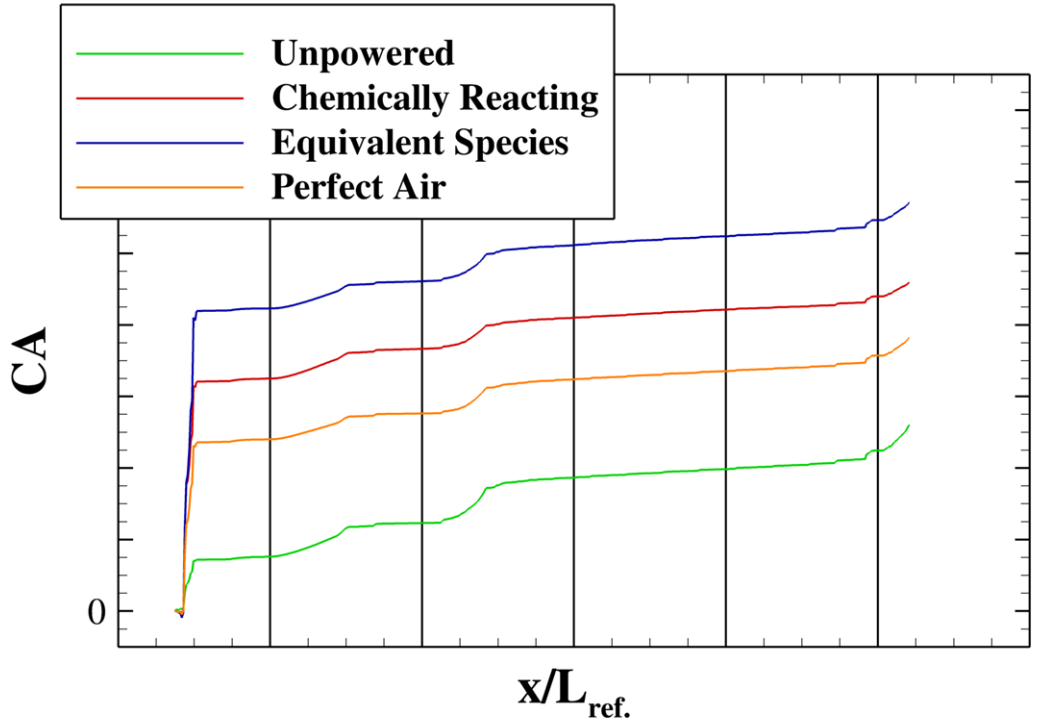
Model	CA (relative)
Unpowered	-44.18%
Reacting	-
Equivalent	+16.49%
Perfect Air	-20.68%



Results – M = 3.0, $\Delta x/L_{ref.}$= 2.5, HT

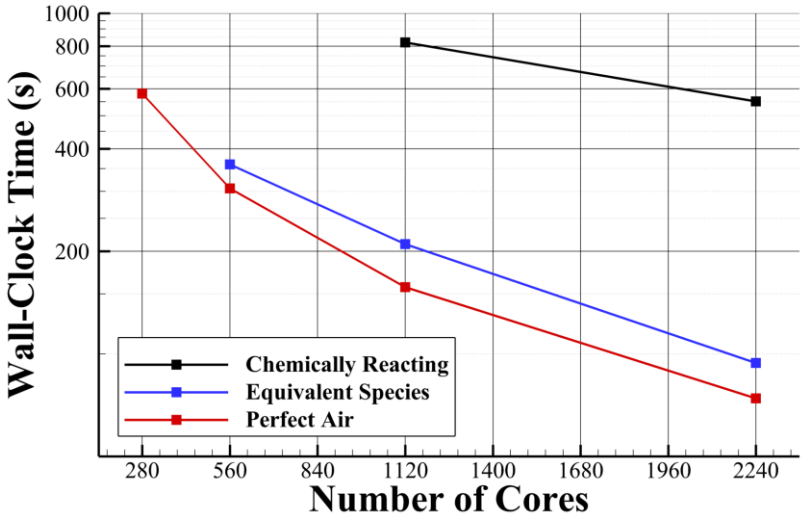
- Widening of the plumes at the higher thrust level is evident
- Yields a thicker region of near-wall, moderate-speed flow
- More high-speed exhaust gases recirculating in the LAV wake
- Perfect air disagreement persists

Model	CA (relative)
Unpowered	-44.18%
Reacting	-
Equivalent	+16.49%
Perfect Air	-20.68%



Conclusions

- **A series of viscous CFD simulations were conducted in order to study the effect of plume modeling fidelity during launch abort scenarios**
- **It was found that using a single equivalent specie, and in some cases, perfect air, to represent a mixture of gases was a viable method to predict core stage drag**
- **Shortcomings were seen when the mixture of gases passed through strong shocks, allowing further reactions to occur**
  - The changes in the composition of the exhaust gas are not account for in the simplified models
- **However, as shown on the right, the cost of the chemically reacting simulations is at least 4x more expensive**
- **The judicious use of the simplified models is appropriate for application to launch vehicle phenomena with plumes**
  - *e.g.,* booster separation, stage separation, ascent, LAV jettison



Acknowledgements

- A special thanks to Peter McCloud and Kirk Putnam from NASA Johnson Space Center for providing the authors with the Niu 2017 15-species, 30-reaction model

- All simulations were conducted on NASA Advanced Supercomputing (NAS) systems at NASA Ames Research Center