DESIGN OF EXPERIMENTS FOR BOTH EXPERIMENTAL AND ANALYTICAL STUDY OF EXHAUST PLUME EFFECTS ON SONIC BOOM

Abstract

Computational fluid dynamics (CFD) analysis has been performed to study the plume effects on sonic boom signature for isolated nozzle configurations. The objectives of these analyses were to provide comparison to past work using modern CFD analysis tools, to investigate the differences of high aspect ratio nozzles to circular (axisymmetric) nozzles, and to report the effects of under expanded nozzle operation on boom signature. CFD analysis was used to address the plume effects on sonic boom signature from a baseline exhaust nozzle. Near-field pressure signatures were collected for nozzle pressure ratios (NPRs) between 6 and 10. A computer code was used to extrapolate these signatures to a ground-observed sonic boom N-wave. Trends show that there is a reduction in sonic boom N-wave signature as NPR is increased from 6 to 10. As low boom designs are developed and improved, there will be a need for understanding the interaction between the aircraft boat tail shocks and the exhaust nozzle plume. These CFD analyses will provide a baseline study for future analysis efforts. For further study, a design of experiments has been conducted to develop a hybrid method where both CFD and small scale wind tunnel

testing will validate the observed trends. The CFD and testing will be used to screen a number of factors which are important to low boom propulsion integration, including boat tail angle, nozzle geometry, and the effect of spacing and stagger on nozzle pairs. To design the wind tunnel experiment, CFD was instrumental in developing a model which would provide adequate space to observe the nozzle and boat tail shock structure without interference from the wind tunnel walls.

Design of Experiments for Both Experimental and Analytical Study of Exhaust Plume Effects on Sonic Boom

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Plume Effects on Sonic Boom for Isolated Nozzles

- Research to eliminate the operational restrictions for supersonic aircraft.
- Recent work has demonstrated reduction in forward boom signature; Shaped Sonic Boom Demonstration and Quie

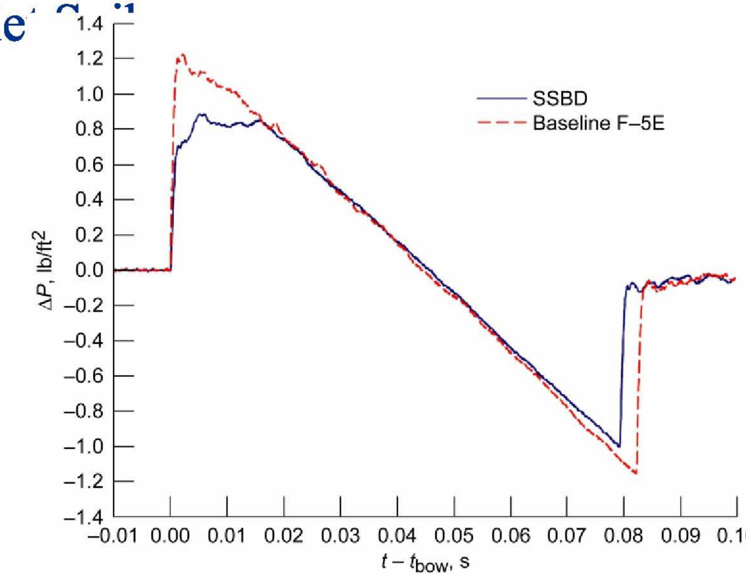
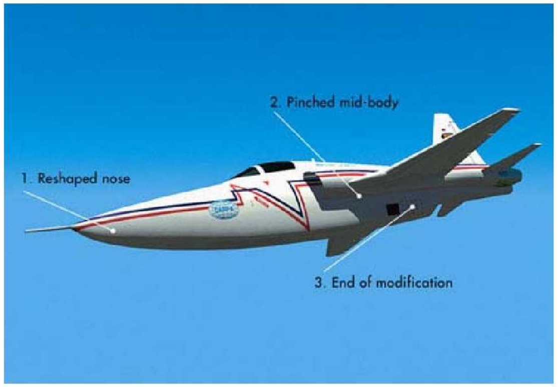


Figure 1.—Sample N-wave sonic boom signature. World's first ground-level shaped sonic boom recording in blue, baseline F-5E N-wave in red. SSBD flight 9, August 27, 2003 [*From AIAA 2005-0009].

Plume Effects on Sonic Boom for Isolated Nozzles

- Similar improvements are desirable for aft aircraft components, including effects of nozzle exhaust.
- Goal is to characterize the effects of exhaust plume contribution to sonic boom signature; exploit advantages, if any, or at least prevent excessive contribution to boom signature.
- Precedence exists for looking at isolated components to understand their contribution to sonic boom signature.



Plume Effects on Sonic Boom for Isolated Nozzles

- Outline
  - Objectives of analysis
  - Description of baseline nozzle and CFD analysis
  - Baseline CFD results
    - Variation of far field pressure signatures with Nozzle Pressure Ratio (NPR).
    - Variation of estimated boom signature with NPR.
  - Design of Experiments to explore a number of variables
    - Include boat tail angle, aspect ratio, nozzle spacing, and nozzle stagger.
  - Design of wind tunnel test rig to validate results
    - For use in the NASA GRC 1x1 Supersonic Wind Tunnel
    - Use of CFD to design model features

Plume Effects on Sonic Boom for Isolated Nozzles

Baseline Nozzle Study

Plume Effects on Sonic Boom for Isolated Nozzles

- Objectives
  - Apply modern CFD tools to the same “Nozzle 6” baseline configuration from the NASA-TN-D-5553 wind tunnel test
  - Provide a baseline for future studies
  - Extrapolate solutions using PCBoom to provide a baseline sonic boom N-wave
- Analysis shows over expanded and under expanded nozzle operation have an effect on the sonic boom N-wave
- Trend is consistent for an axisymmetric nozzle and a high aspect ratio nozzle.
- Demonstrates the feasibility of reducing the magnitude of the sonic boom N-wave by controlling nozzle plume interaction with the boat tail shock structure.

Plume Effects on Sonic Boom for Isolated Nozzles Baseline NASA TN-D-5553

- Baseline study by Putnam and Capone.
- Variety of nozzle tests on fully expanded Mach 1.7 to Mach 2.9 nozzles.
- Wind Tunnel test conditions at Mach 2.2 and 50,000 ft.
- "Nozzle 6" was selected for a CFD baseline study based on observed trends.
- Design Nozzle Pressure Ratio (NPR) = Pt/Po = 8.

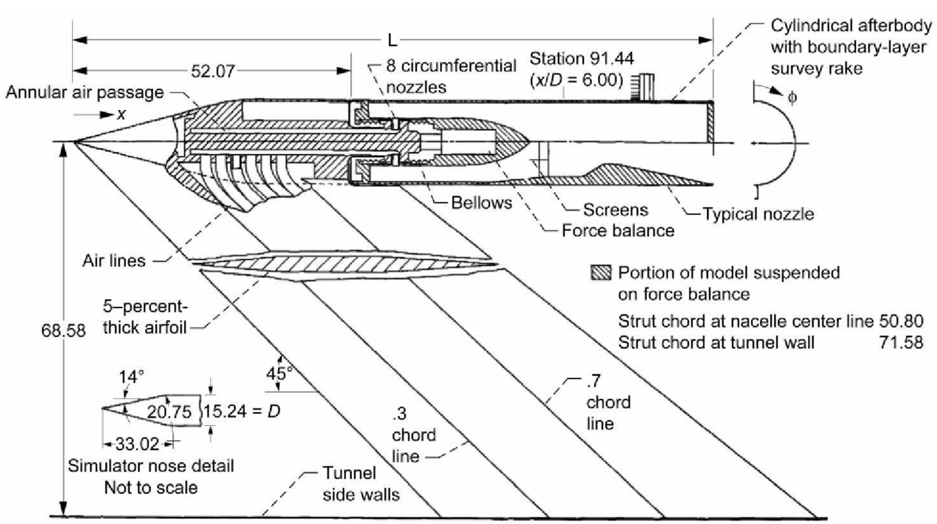


Figure 3.—Jet engine exhaust nozzle simulator from NASA TN–D–5553.

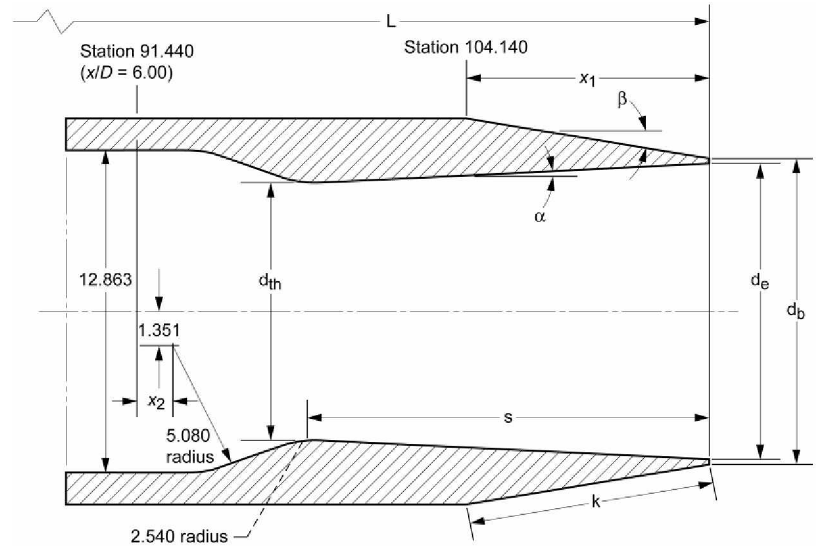
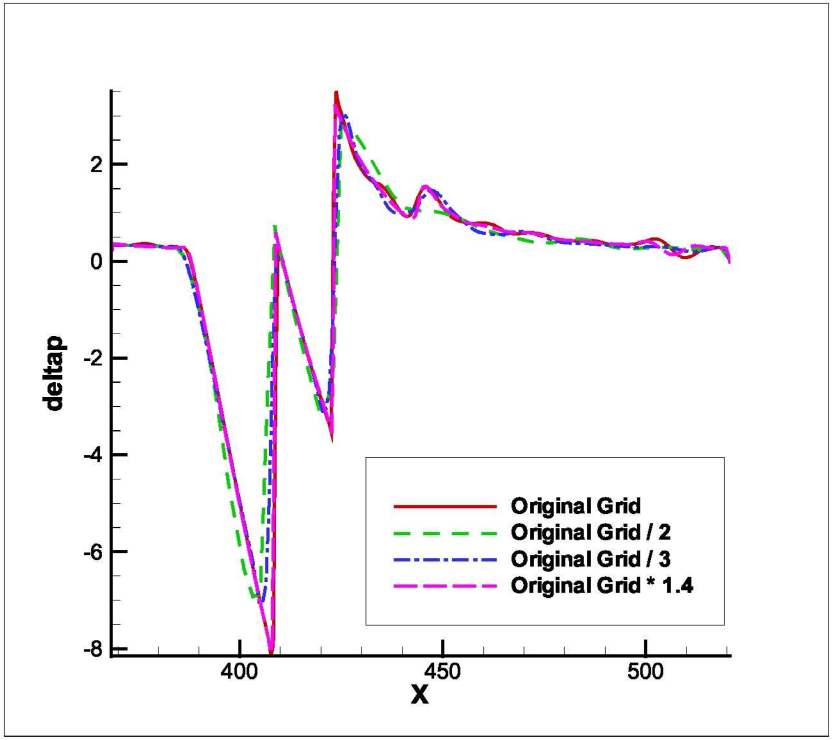


Figure 2.—Nozzle configuration from NASA TN–D–5553.

Plume Effects on Sonic Boom for Isolated Nozzles
CFD Grid

- CFD grid consisted of 511,299 grid points.
- Axisymmetric model.
- Grid study performed to select grid density.

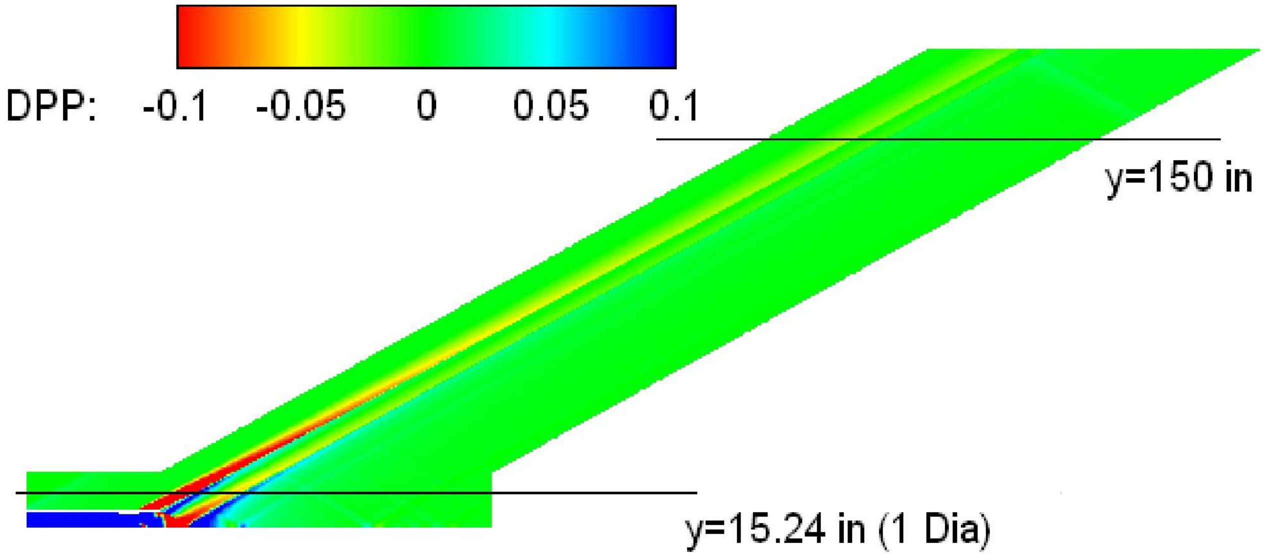


Plume Effects on Sonic Boom for Isolated Nozzles

Baseline “Nozzle 6” Results

Plume Effects on Sonic Boom for Isolated Nozzles
Cut Planes

- Analysis of CFD results included cut planes at two locations.
- Goals were comparison to NASA TN-D-5553.
- And extrapolation of far-field pressures to an estimated ground sonic boom signature.



Plume Effects on Sonic Boom for Isolated Nozzles
Comparison of Baseline CFD to NASA TN-D-5553

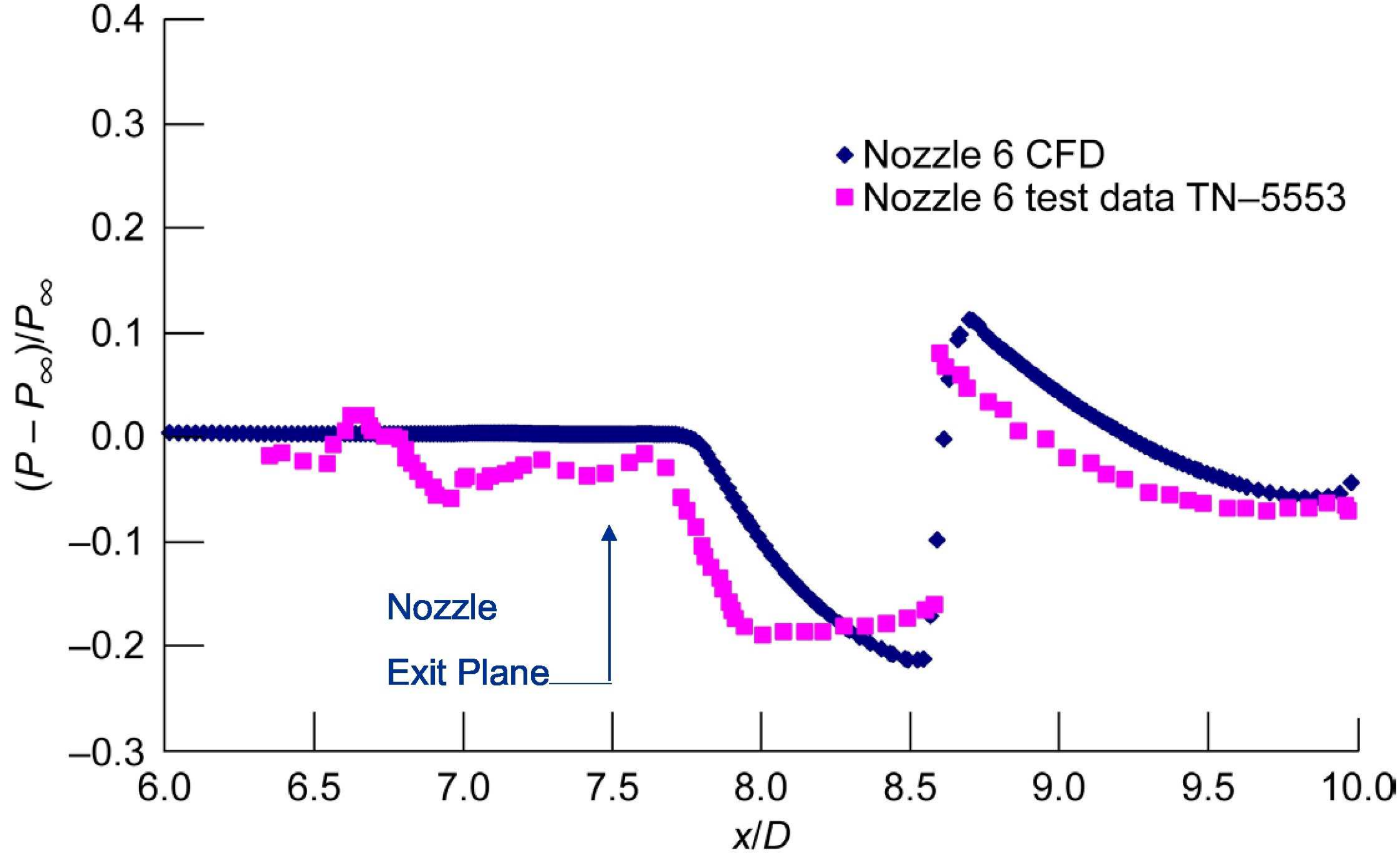


Figure 6.—Near field pressure profile $\Delta P/P_\infty$ at 1 nozzle diameter from baseline Nozzle 6 axial positions x/D from 6 to 10 comparisons to NASA TN–D–5553.

Plume Effects on Sonic Boom for Isolated Nozzles
Baseline CFD Near Field Pressure Signature

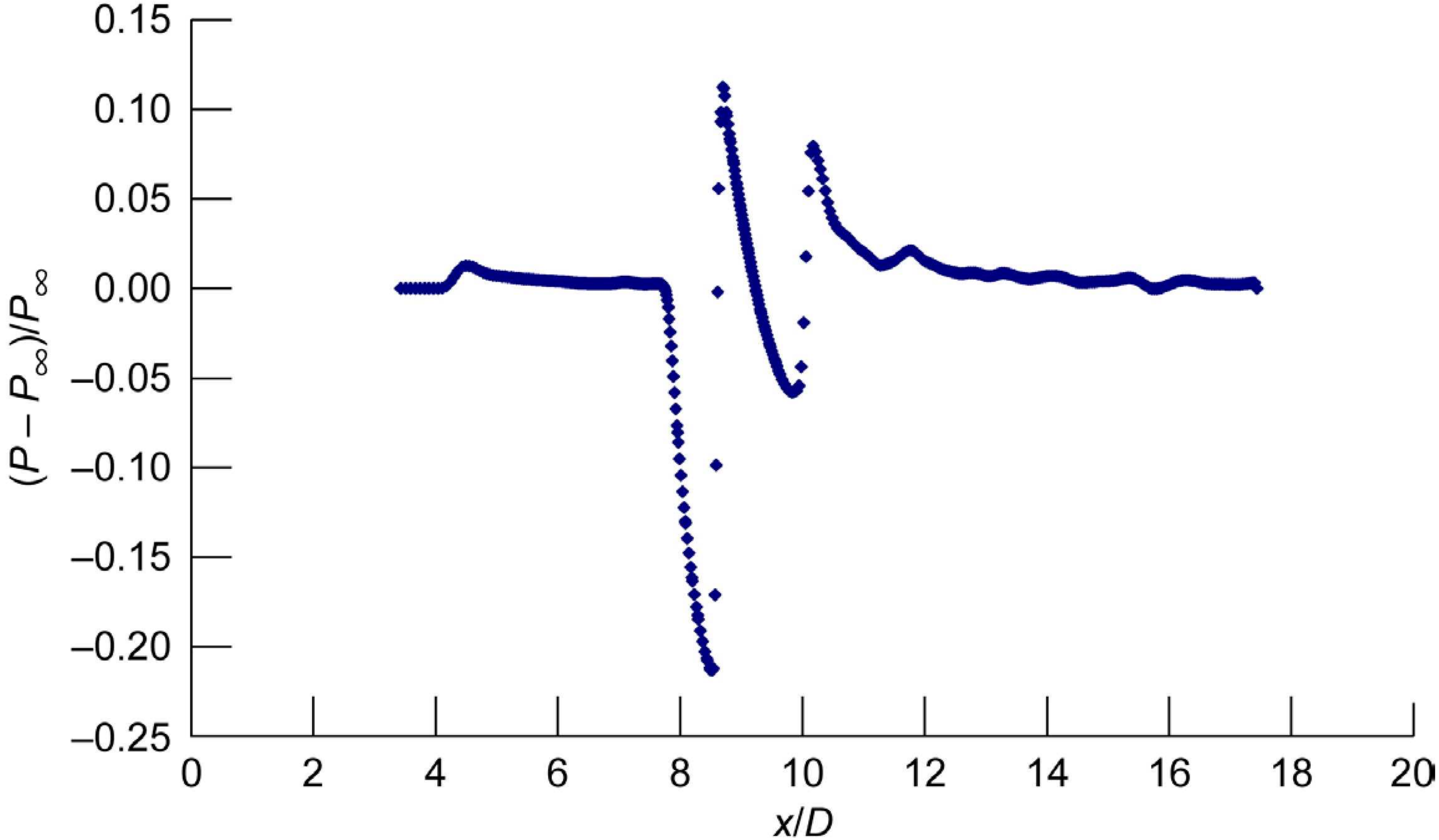


Figure 8.—Near-field pressure profile $\Delta P/P_\infty$ at 1 nozzle diameter from baseline Nozzle 6.

Plume Effects on Sonic Boom for Isolated Nozzles Baseline CFD Variation of far field pressures with Nozzle Pressure Ratio (NPR)

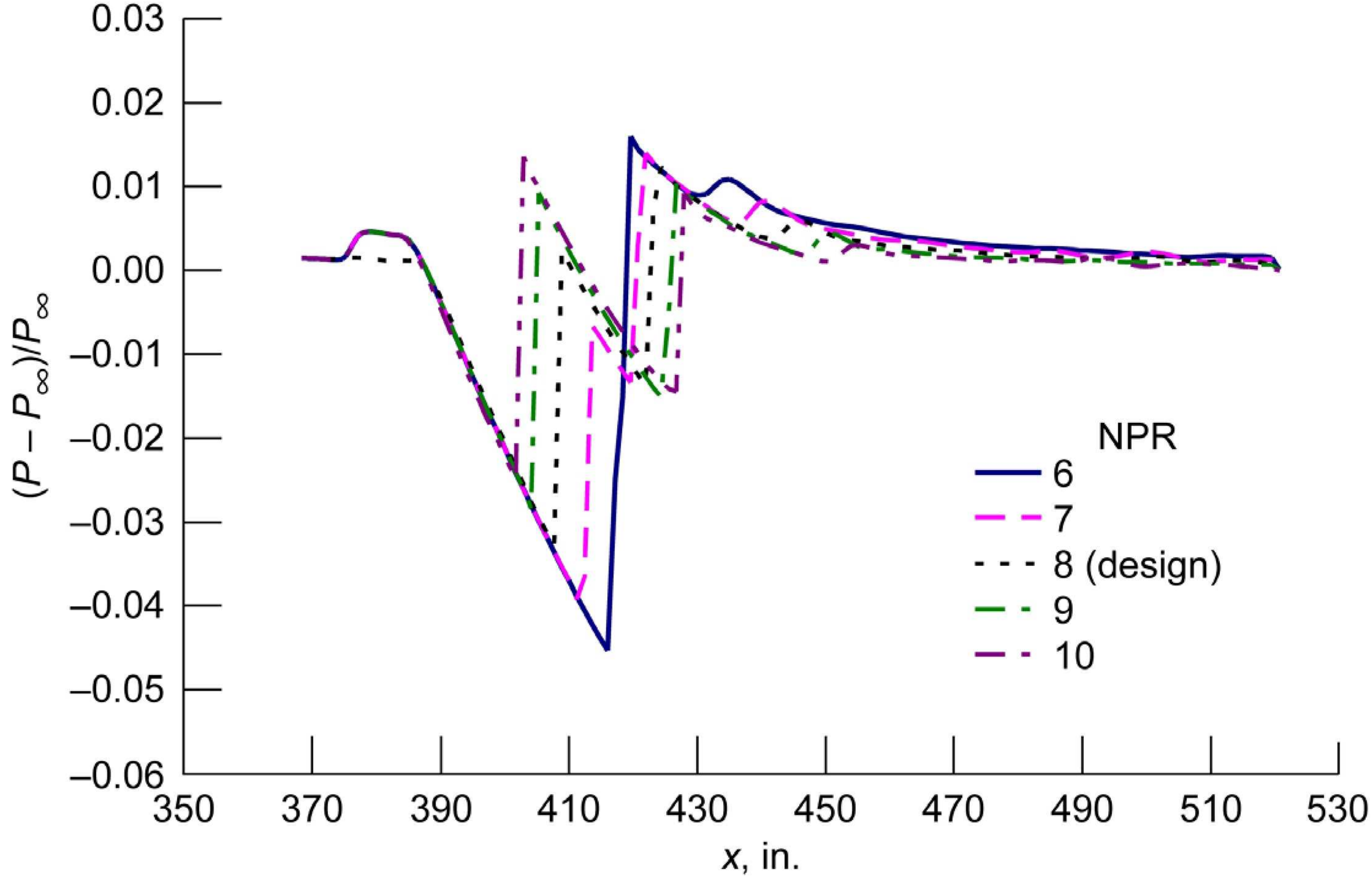


Figure 9.—Far-field pressure profiles $\Delta P/P_\infty$ at y = 150 in. from nozzle centerline. Baseline Nozzle 6 NPR 6 to 10.

Plume Effects on Sonic Boom for Isolated Nozzles Baseline Nozzle, differences in over expanded vs. under expanded nozzle flow

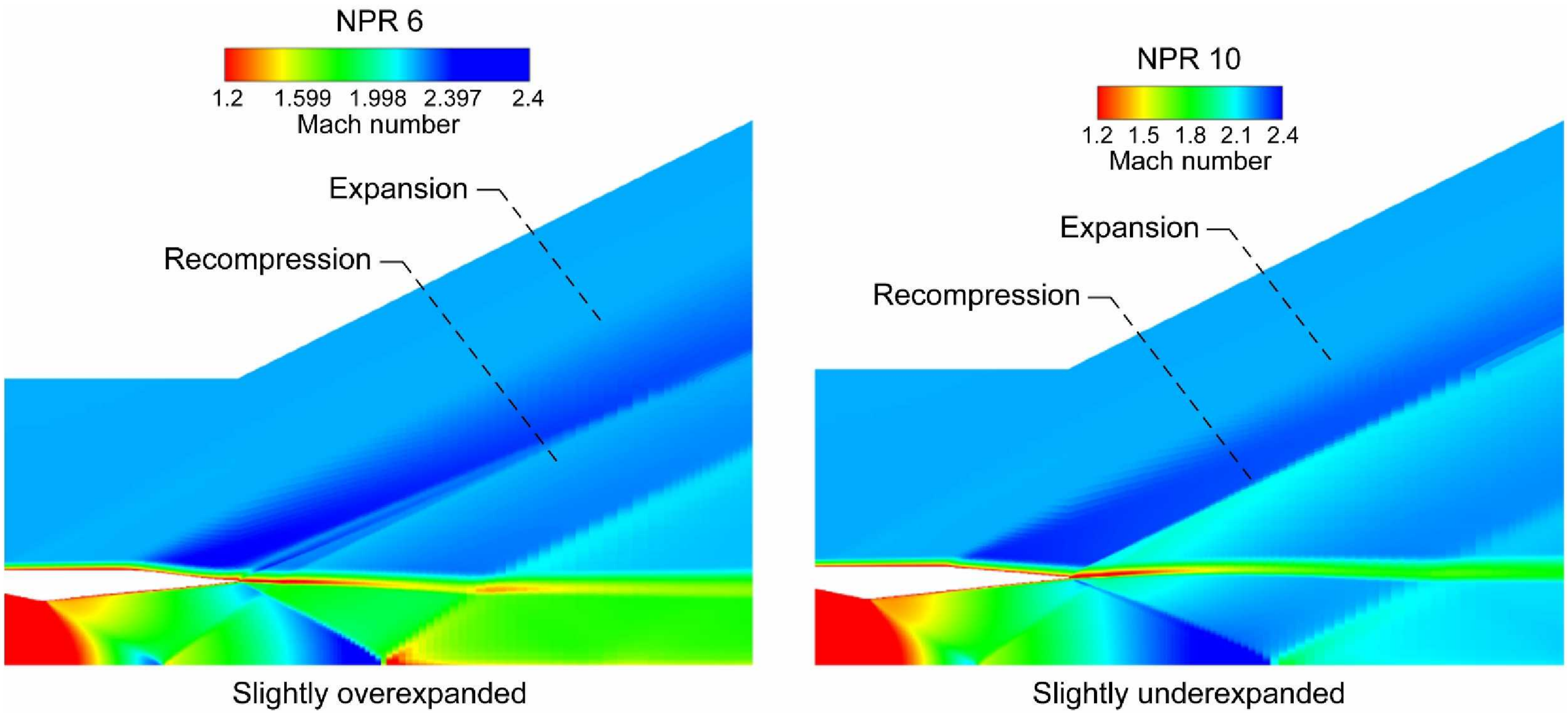


Figure 10.—Effect of nozzle operating conditions on the local shock waves. Baseline Nozzle 6 at NPR 6 and NPR 10.

Plume Effects on Sonic Boom for Isolated Nozzles Baseline Nozzle Estimated Ground Sonic Boom Contribution

- PCBoom was used to estimate the baseline nozzle ground sonic boom contribution.
  - Obtained from Wyle Labs.
  - PC based computer code.
  - Pressure signatures measured or computed off an aircraft can be propagated to an estimated ground level sonic boom pressure signature.

Plume Effects on Sonic Boom for Isolated Nozzles Baseline Nozzle Estimated Ground Sonic Boom Contribution

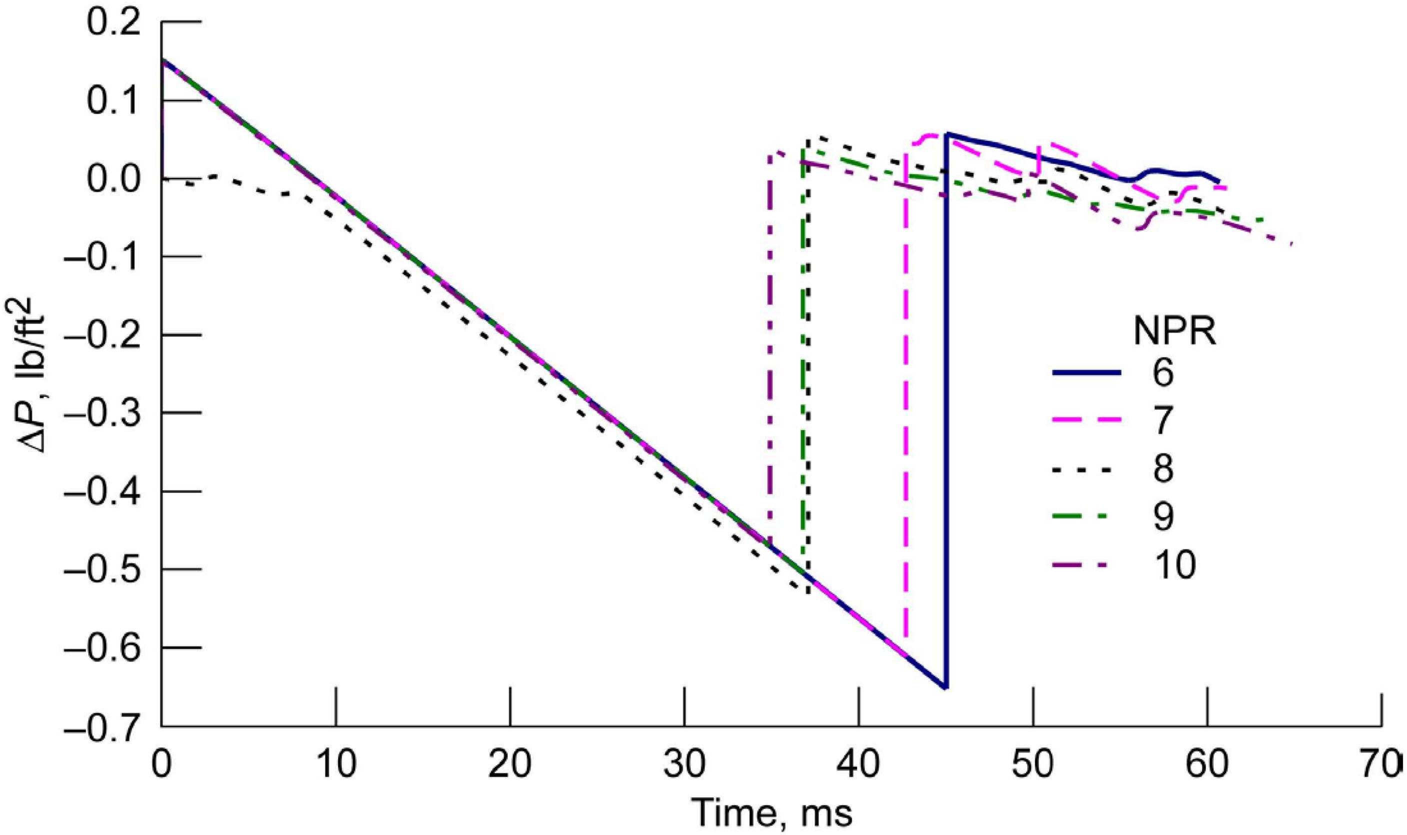


Figure 11.—Estimated sonic boom signature at ground through an ideal atmosphere. Baseline Nozzle 6 at NPR 6 to 10.

Plume Effects on Sonic Boom for Isolated Nozzles
Design of Experiments

Design of Experiments

Approach to study Plume Effects

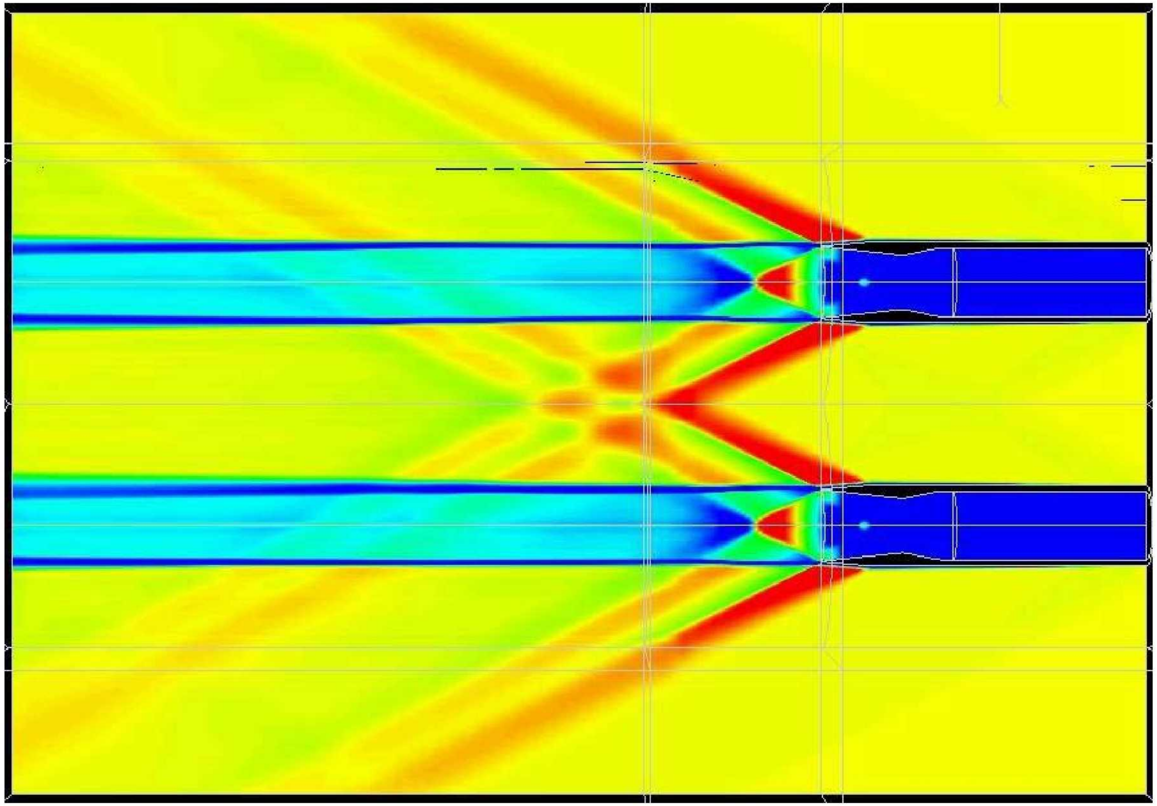
on Sonic Boom

Plume Effects on Sonic Boom for Isolated Nozzles
Design of Experiments

- Design of Experiments
  - Investigate variables for the nozzle plume effect on sonic boom signature
  - Most or all supersonic transport aircraft would have multiple engines.
    - Study nozzle spacing of 1 to 3 diameters
    - Study nozzle stagger of 0 to 3 diameters
  - Include effects that have already been observed
    - Study boat tail angle from 2 to 10 degrees
    - Study nozzle pressure ratio from 6 to 12
  - Include a broader range of flight Mach numbers, 1.6 to 2.8.
  - Include a study on 3-dimensional rectangular nozzles.
  - Use both CFD and 1x1 SWT data
  - Variables can be characterized with 8 CFD cases, validated with wind tunnel data.

Plume Effects on Sonic Boom for Isolated Nozzles Design of Experiments

- Design of Experiments
  - Example provided from a 3D nozzle pair CFD study to look for potential reductions in the sonic boom contribution for an exhaust nozzle pair vs the baseline case. Demonstrates interactions of shock waves from the nozzle plumes.



Mach Contours, Bottom view of nozzle pair at Mach 2 and design point NPR 8.

Plume Effects on Sonic Boom for Isolated Nozzles
Design of Experiments – Axisymmetric Nozzles

	MACH #	NPR	Boat Tail Angle	Spacing	Stagger
DE1	2.8	12	10	1	3
DE2	2.8	6	2	3	0
DE3	1.6	9	2	3	3
DE4	1.6	6	10	3	0
DE5	1.6	6	2	1	1
DE6	2.8	12	10	3	0
DE7	2.8	6	10	3	3

Experimental Design by Hal Haller – Real World Quality Systems

Plume Effects on Sonic Boom for Isolated Nozzles
Design of Experiments – Rectangular Nozzles

	MACH #	NPR	Boat Tail Angle	Aspect Ratio	Spacing	Stagger
DE1	1.6	6	2	2	1	0
DE2	1.6	6	2	16	3	3
DE3	1.6	12	10	2	3	0
DE4	1.6	12	10	16	1	3
DE5	2.8	6	10	2	1	3
DE6	2.8	6	10	16	3	0
DE7	2.8	12	2	2	3	3
DE8	2.8	12	2	16	1	0

Plume Effects on Sonic Boom for Isolated Nozzles Design of Experiments

- Design of Experiments objective
  - Near field and far field peak to peak pressure
  - Characterization of the near field boom signature allows prediction of an optimized signature based on results.

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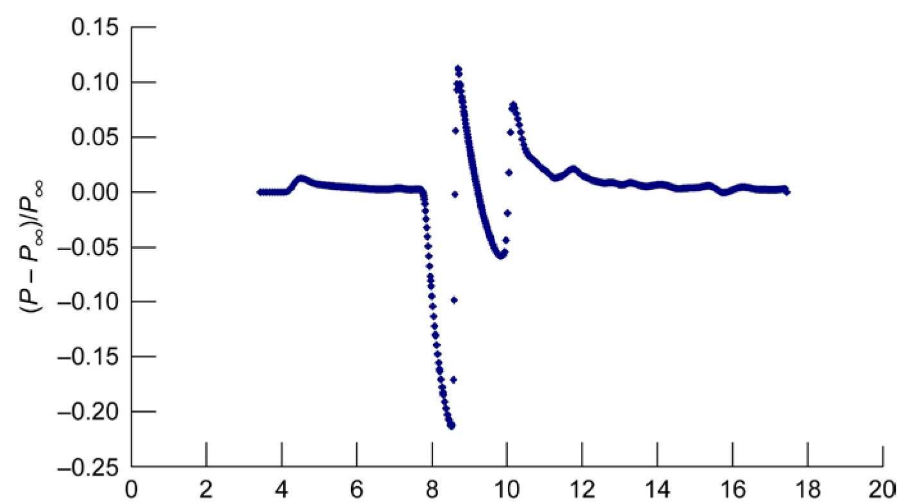


Plume Effects on Sonic Boom for Isolated Nozzles
1x1 SWT Model

Design of 1x1 SWT model

For validation experiments

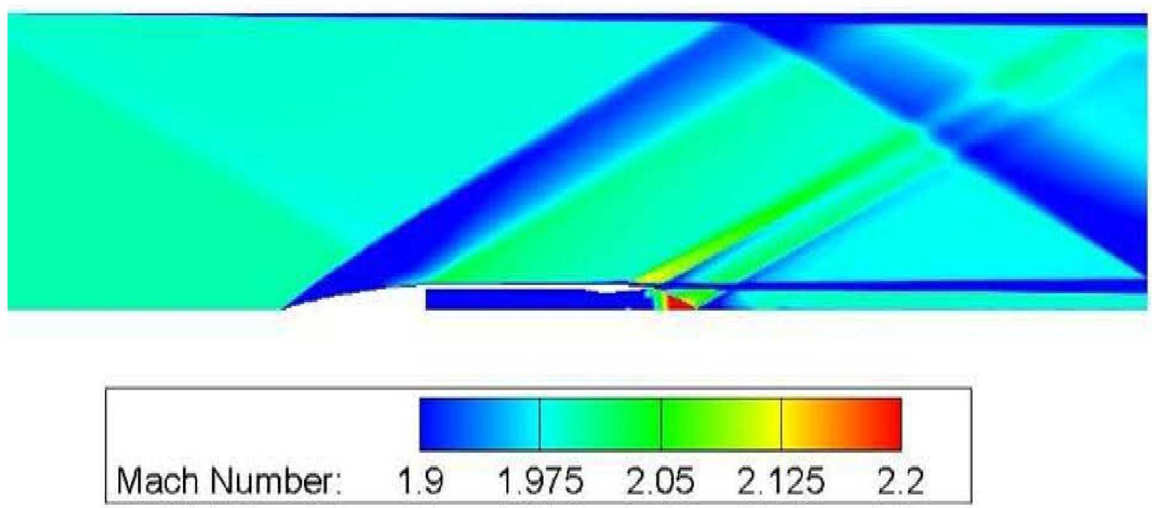
Plume Effects on Sonic Boom for Isolated Nozzles 1x1 SWT Model

- Design of 1x1 SWT model
  - First exhaust nozzle testing to be performed in the 1x1 SWT, driving design of new test hardware.
  - Tunnel wall reflections interfere with the nozzle exhaust.
  - Analysis was performed to reduce the amount of interference and get a plume length of 5 to 10 nozzle diameters downstream of nozzle exit, with no interference from reflections.

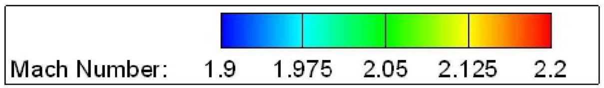
1x1 SWT

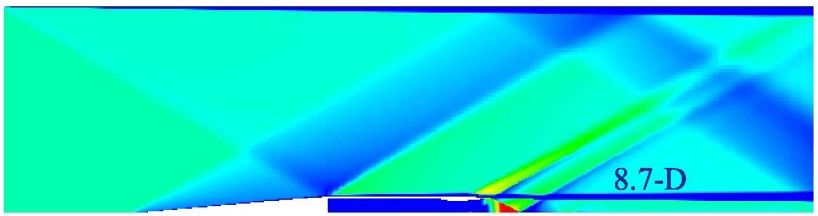
Plume Effects on Sonic Boom for Isolated Nozzles
1x1 SWT Model

- Design of 1x1 SWT model
  - CFD was performed to resolve interactions of nozzle plume with wall reflections. The following variables were studied:
    - Nosecone design
    - Model length
    - Strut size vs. internal airflow requirements

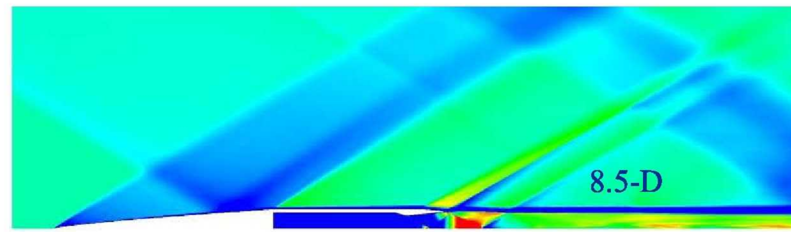


Plume Effects on Sonic Boom for Isolated Nozzles 1x1 SWT Model CFD Analysis Long Nosecones

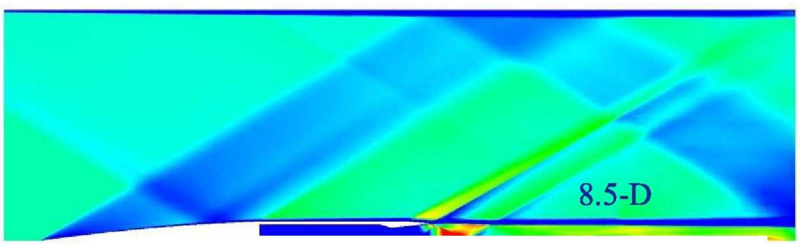




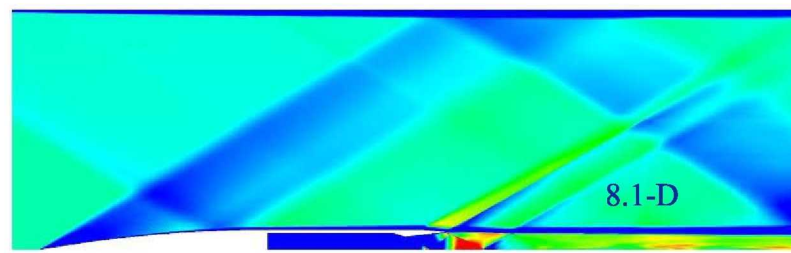
5 deg cone: 8.7 Dia. between nozzle exit and reflected shock wave at tunnel centerline



¾ Power Long: 8.5 Dia. between nozzle exit and reflected shock wave at tunnel centerline

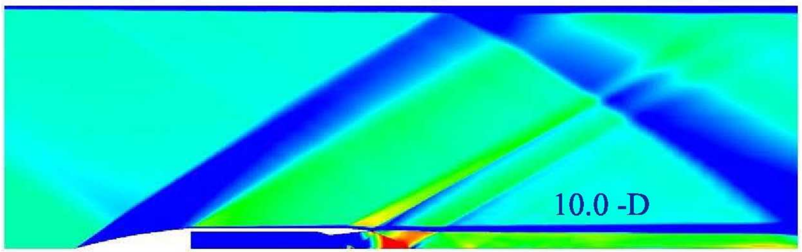


¾ Parabola Long: 8.5 Dia. between nozzle exit and reflected shock wave at tunnel centerline

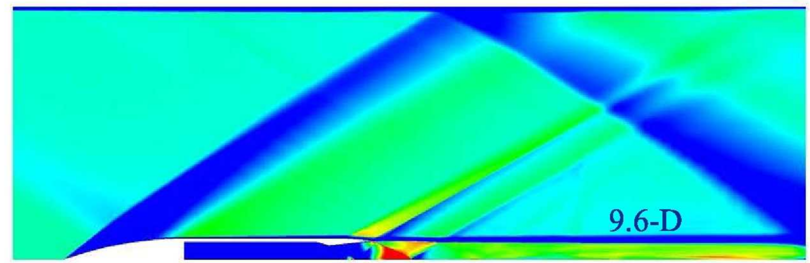


Long Ojive: 8.1 Dia. between nozzle exit and reflected shock wave at tunnel centerline

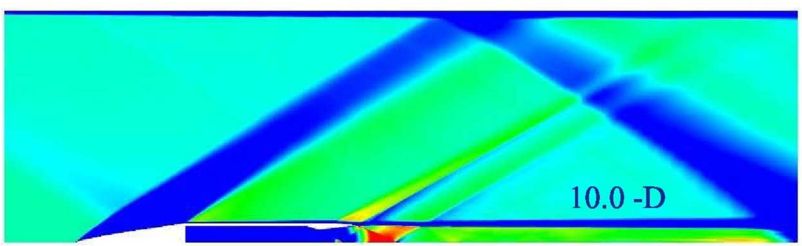
Plume Effects on Sonic Boom for Isolated Nozzles 1x1 SWT Model CFD Analysis Short Nosecones



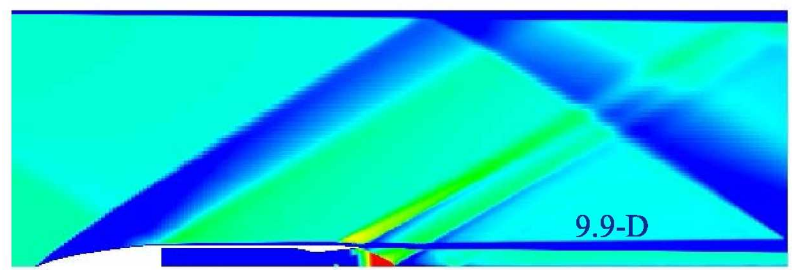
¾ Parabola Short: 10 Dia. between nozzle exit and reflected shock wave at tunnel centerline



Ojive Short: 9.6 Dia. between nozzle exit and reflected shock wave at tunnel centerline

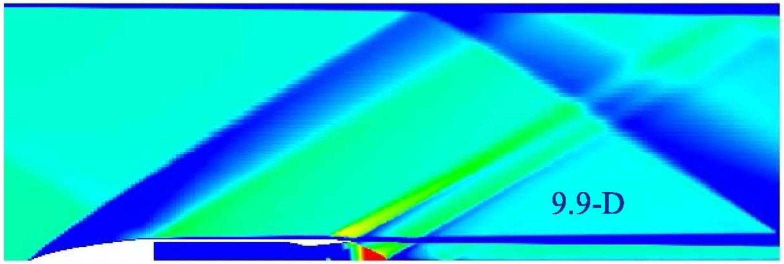


¾ Power Short: 10 Dia. between nozzle exit and reflected shock wave at tunnel centerline



Von Karman Short: 9.9 Dia. between nozzle exit and reflected shock wave at tunnel centerline

Plume Effects on Sonic Boom for Isolated Nozzles 1x1 SWT Model CFD Analysis Short Nosecones

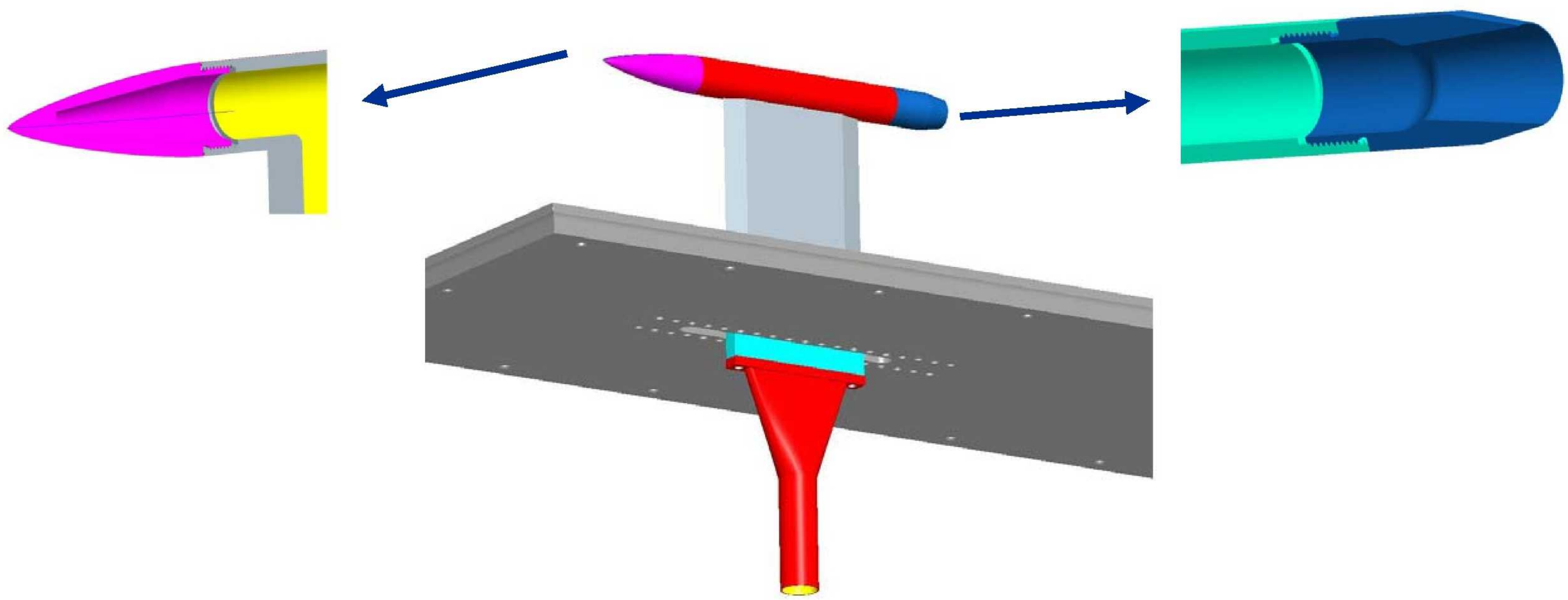


Von Karman Short: 9.9 Dia. between nozzle exit and reflected shock wave at tunnel centerline

- The Von Karman nose cone is a low drag nose with good flow qualities, so this was selected.
- The long nosecones had weaker shocks and provided about 8.5 diameters of unobstructed nozzle plume.
- The short nosecones had stronger shocks and provided 10 diameters of unobstructed nozzle plume.

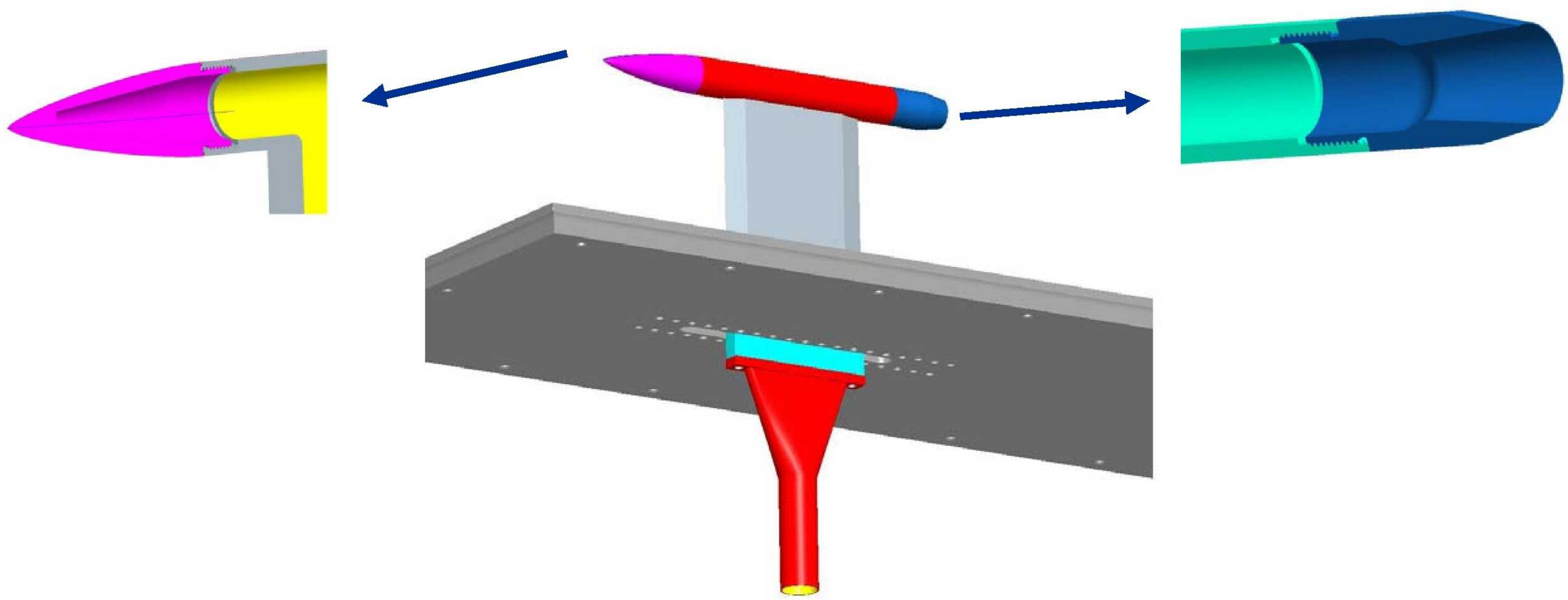
Plume Effects on Sonic Boom for Isolated Nozzles 1x1 SWT Model

- Model Design – Mini Jet Exit Rig
  - Mach 1.4 to Mach 3.0
  - NPR 6 to 12 at 50,000 ft conditions
  - Also designed for NPR 6 to 12 at 30,000 ft and 40,000 ft conditions.



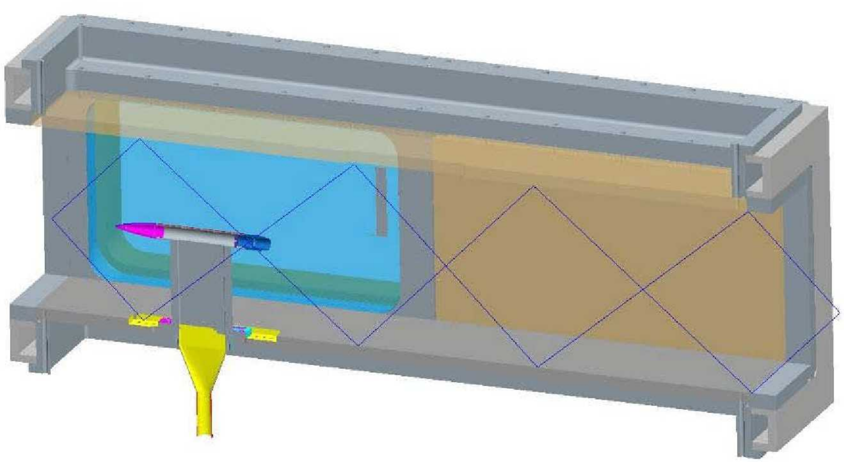
Plume Effects on Sonic Boom for Isolated Nozzles 1x1 SWT Model

- Model Design – Mini Jet Exit Rig
  - 1” Outer Diameter.
  - 9” overall length including nozzle.
  - 90 psi to 240 psi inlet pressure.
  - Choke plate at top of strut to obtain required mass flow and pressure upstream of choked test nozzles.



Plume Effects on Sonic Boom for Isolated Nozzles
1x1 SWT Model

- 1x1 SWT test
  - Validation data from the 1x1 SWT to include:
    - Schlieren images.
    - Near field static pressure profiles with an actuated probe.
  - Results used to guide future analysis and testing plans.
  - Lessons learned to reduce costs and errors for future large scale testing in the 8x6 SWT.



Plume Effects on Sonic Boom for Isolated Nozzles
Summary and Conclusions

- Modern CFD tools were used to analyze the “Nozzle 6” baseline configuration from the NASA TN-D-5553 wind tunnel test.

- Solutions were extrapolated using “PCBoom’ to provide a baseline sonic boom N-wave.

- Analysis shows over expanded and under expanded nozzle operation have an effect on the sonic boom N-wave for an isolated nozzle configuration. For the baseline axisymmetric “Nozzle 6”, there was a reduction in sonic boom signature from NPR of 6 to 10.

- Demonstrates the feasibility of reducing the magnitude of the sonic boom N-wave by controlling nozzle plume interaction with the boat tail shock structure. Much work is still needed to study the utility of these findings.

- The intent was to provide a baseline for future analysis efforts to study plume interaction trends on integrated aircraft and propulsion systems.

Plume Effects on Sonic Boom for Isolated Nozzles
Summary and Conclusions

- A Design of Experiments approach will be used to study the effect of significant variables for nozzle plume effects on near field shock structure, and therefore sonic boom signature.
  - Mach number, nozzle pressure ratio, boat tail angle, aspect ratio, nozzle spacing, nozzle stagger.

- The Design of Experiments will reduce both CFD analysis requirements and facility occupancy requirements.

- New capability for small scale supersonic exhaust nozzle testing is being developed for the 1x1 SWT at NASA GRC, which will provide a low cost test bed to validate analysis and test new ideas. CFD was heavily used in the design process, especially for shock reflections and nose cone design.

- Overall goal is to characterize the effects of exhaust plume contribution to sonic boom signature; exploit advantages, if any, and prevent excessive contribution to overall aircraft sonic boom signature.

Plume Effects on Sonic Boom for Isolated Nozzles
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