Abstract

Acoustic and flow-field experiments were conducted on exhaust concepts for the next generation supersonic, commercial aircraft. The concepts were developed by Lockheed Martin (LM), Rolls-Royce Liberty Works (RRLW), and General Electric Global Research (GEGR) as part of an N+2 (next generation forward) aircraft system study initiated by the Supersonics Project in NASA's Fundamental Aeronautics Program. The experiments were conducted in the Aero-Acoustic Propulsion Laboratory at the NASA Glenn Research Center. The exhaust concepts presented here utilized lobed-mixers and ejectors. A powered third-stream was implemented to improve ejector acoustic performance. One concept was found to produce stagnant flow within the ejector and the other produced discrete-frequency tones (due to flow separations within the model) that degraded the acoustic performance of the exhaust concept.

NASA's Environmentally Responsible Aviation (ERA) Project has been investigating a Hybrid Wing Body (HWB) aircraft as a possible configuration for meeting N+2 system level goals for noise, emissions, and fuel burn. A recently completed NRA led by Boeing Research and Technology resulted in a full-scale aircraft design and wind tunnel model. This model will be tested acoustically in NASA Langley's 14-by 22-Foot Subsonic Tunnel and will include dual jet engine simulators and broadband engine noise simulators as part of the test campaign. The objectives of the test are to characterize the system level noise, quantify the effects of shielding, and generate a valuable database for prediction method development. Further details of the test and various component preparations are described.

National Aeronautics and Space Administration

Advanced Jet Noise Exhaust Concepts in NASA's N+2 Supersonics Validation Study and the Environmentally Responsible Aviation Project's Upcoming Hybrid Wing Body Acoustics Test

Brenda Henderson, Mike Doty
NASA

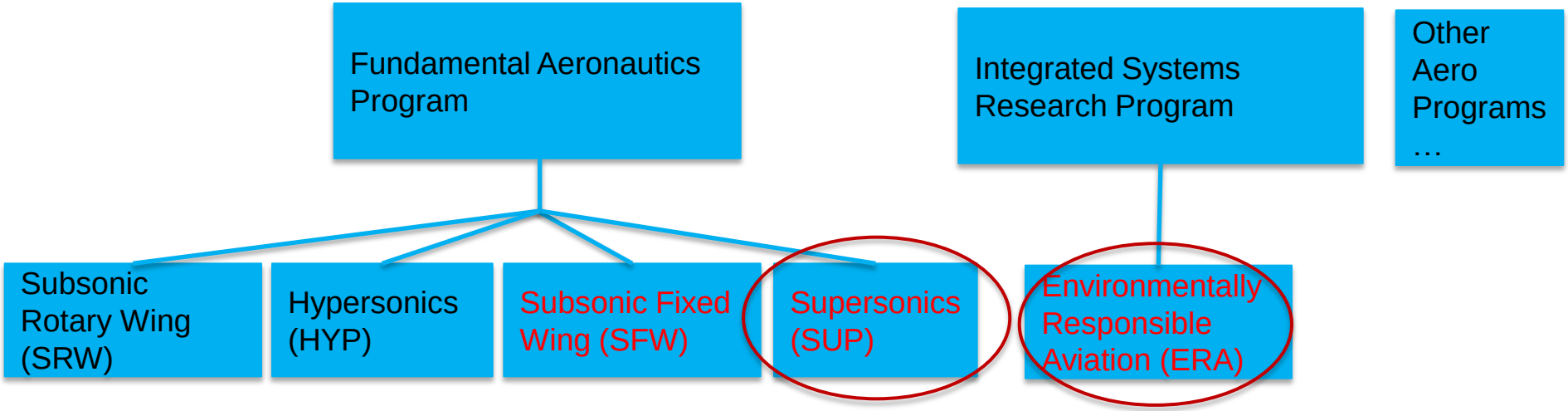
Virginia Tech Graduate Seminar
September 17, 2012
Blacksburg, Virginia

Outline

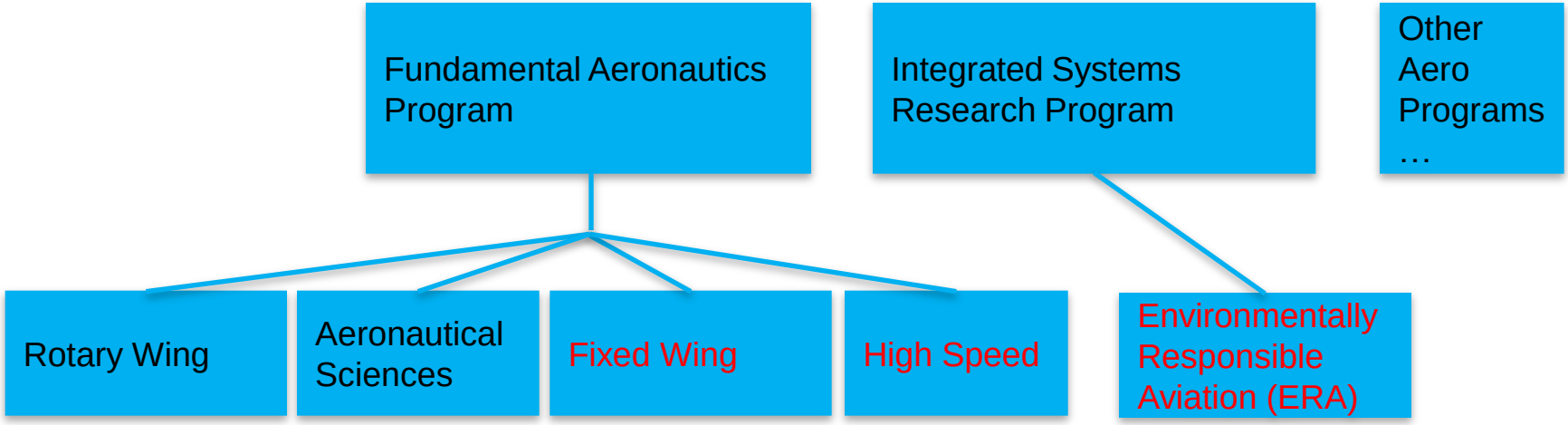
- Structure of NASA's Aeronautics Research Mission Directorate
- N+2 Supersonics Validation Study – exhaust noise experiments
- Conclusions from N+2 Supersonics Validation Study
- Environmentally Responsible Aviation's upcoming Hybrid Wing Body test

NASA Aeronautics Research Mission Directorate

Pre FY13



FY13 +



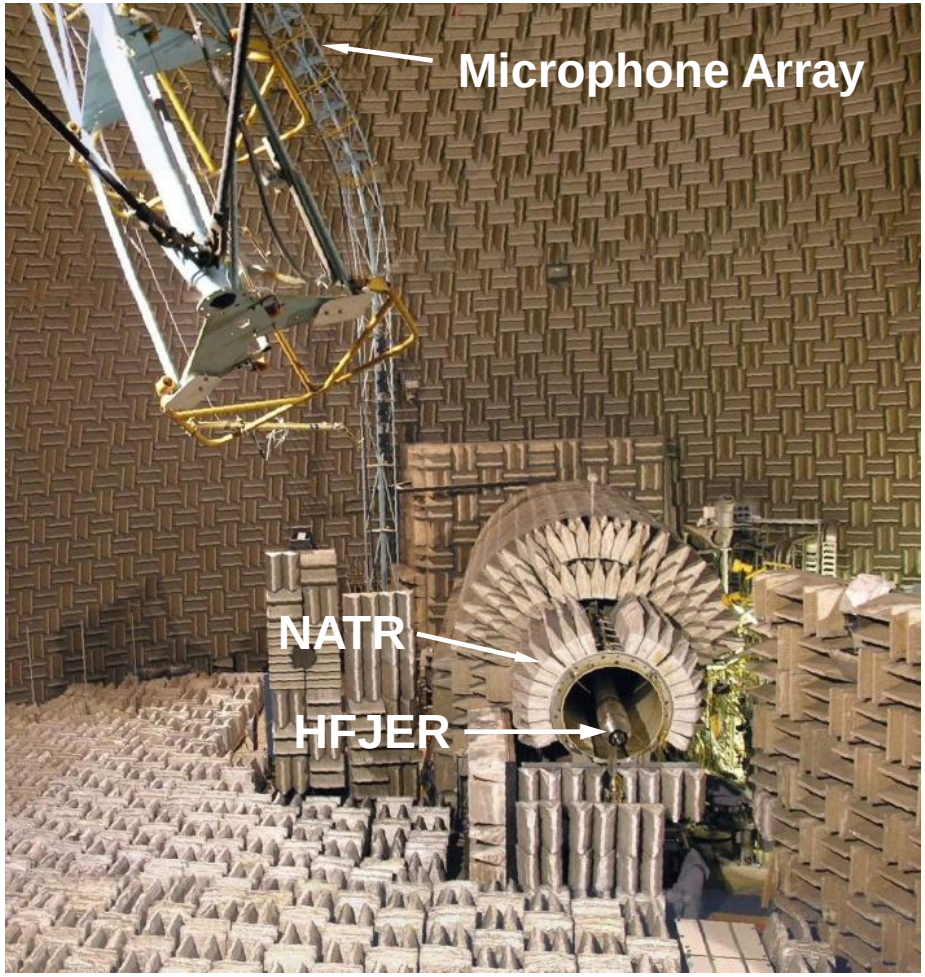
N+2 Supersonics Validation Study

Objective – validate integrated airframe propulsion technologies and design methodologies for a viable supersonics vehicle design with acceptable environmental and performance characteristics

- NASA NRA awarded to Lockheed Martin (LM) – propulsion concepts and hardware provided to LM by General Electric Global Research and Rolls-Royce Liberty Works
- Validation experiments tested airframe and propulsion technologies
- Exhaust concepts tested and evaluated at NASA Glenn Research Center

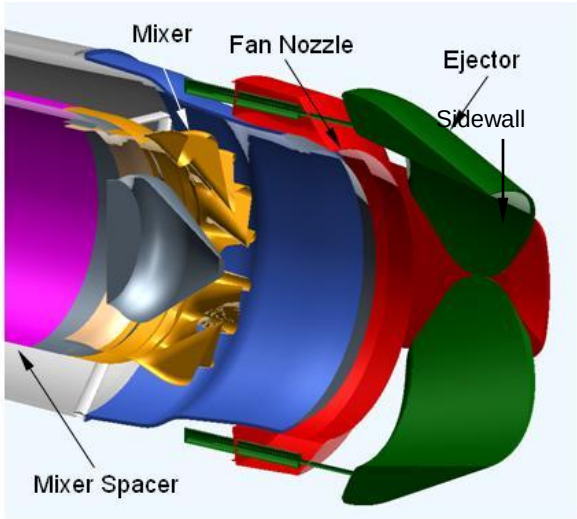
	N+2 Supersonic Transport Initial Goals
Environmental Goals	
Sonic Boom	65 - 70 PLdB, ~ 0.14 - 0.17 psf N-wave
Airport Noise (cumulative below stage 3)	10 - 20 EPNdB
Cruise Emissions	<10 EINOx
Performance Goals	
Cruise Speed	Mach 1.6 - 1.8
Range	4000 nm
Payload (passengers)	35 - 70
Fuel Efficiency (passenger-nm per lb of fuel)	3

Aero-Acoustic Propulsion Laboratory (AAPL)

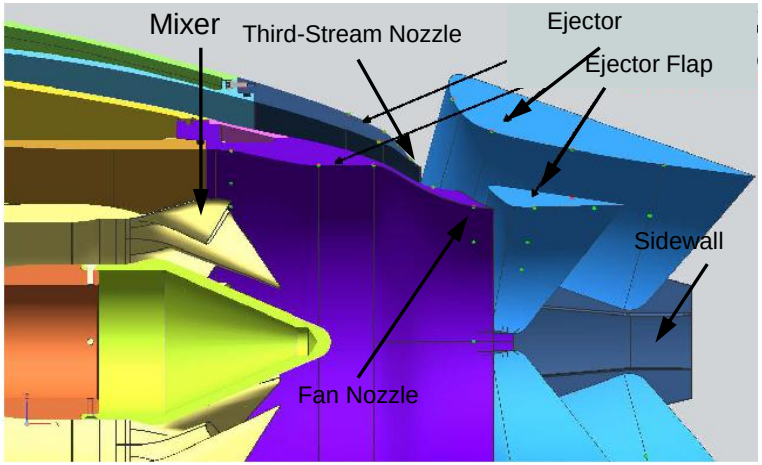


- AAPL
  - 65 foot geodesic dome
  - 45 foot microphone arc – 24 elements
- Nozzle Acoustic Test Rig (NATR)
  - 53 inch simulated flight stream
  - Maximum Mach number = 0.35
- High Flow Jet Exit Rig (HFJER)
  - 3-stream capability (3rd stream new)
  - Independent pressure control on all streams
  - Independent temperature control on fan and core streams
  - Fan and third-stream temperatures the same

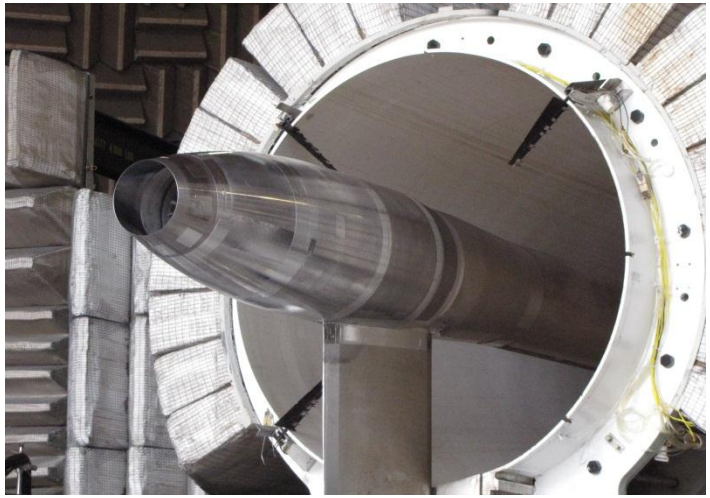
Rolls-Royce Liberty Works (RRLW) Hardware



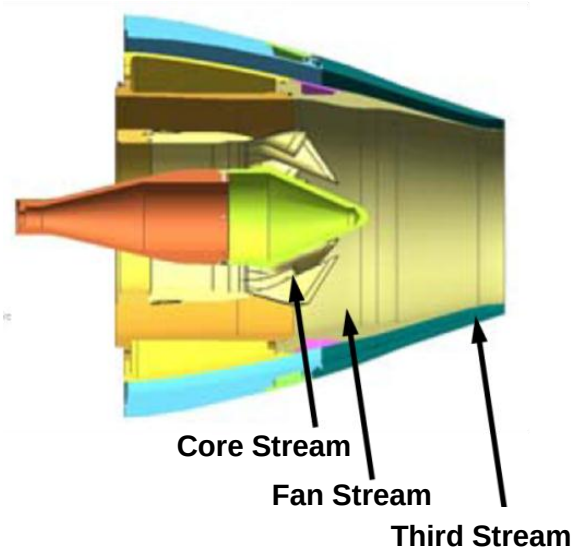
HVC Hardware (Predates N+2 Study)



N+2 HVC Hardware (HVC Hardware with significant modifications)



HVC Baseline
- Round fan nozzle
- Lobed-mixer core nozzle



N+2 HVC Baseline Hardware

RRLW Cycle Points

NPR_c	NPR_f	NTR_c	NTR_f	M_{fj}
		TT_c/Tamb	TT_f/Tamb	
1.6000	1.6000	2.9000	1.2900	0.00
1.8000	1.8000	2.9000	1.2900	0.00
1.6000	1.8000	2.6900	1.2900	0.00
1.6000	1.8000	3.0500	1.2000	0.00
1.6000	1.8000	2.9000	1.1000	0.00
1.6000	1.6000	2.9000	1.2900	0.30
1.8000	1.8000	2.9000	1.2900	0.30
1.6000	1.8000	2.6900	1.2900	0.30
1.6000	1.8000	3.0500	1.2000	0.30
1.6000	1.8000	2.9000	1.1000	0.30

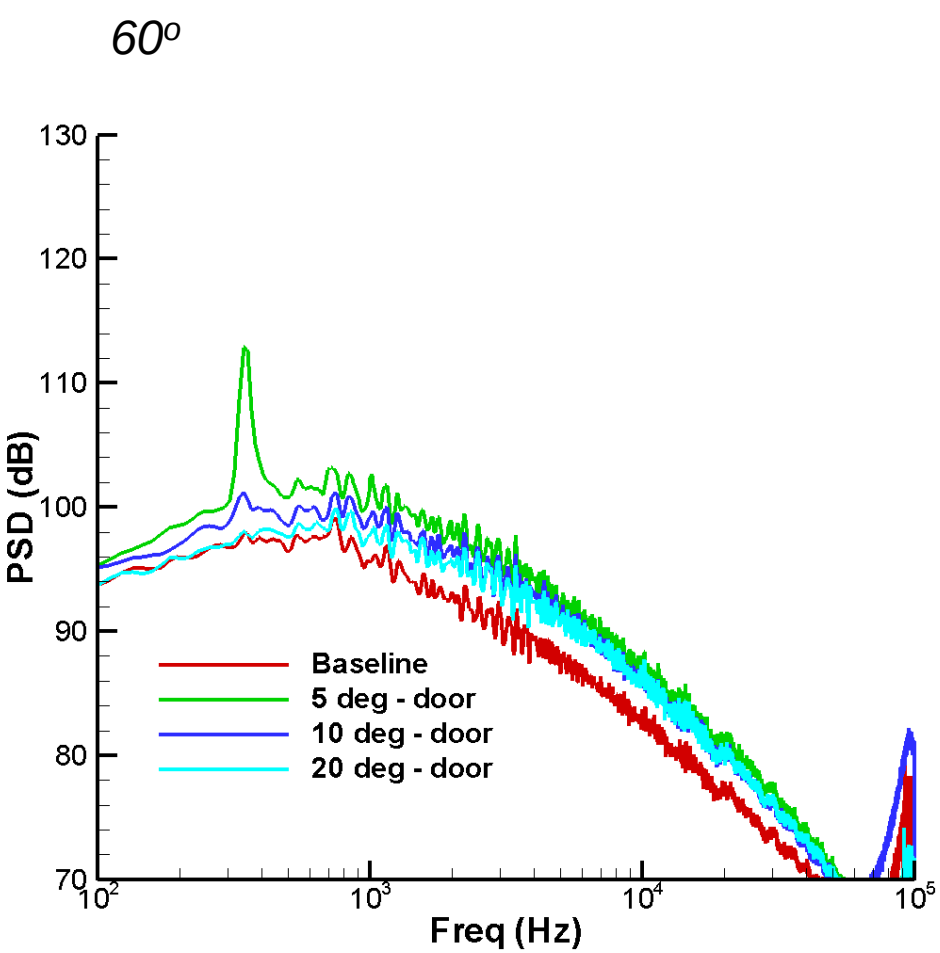
- HVC cycle points (N+2 HVC cycle points similar the NPR_t slightly below NPR_f)
- M_{fj} – free jet Mach number
- NPR – nozzle pressure ratio
- NTR – nozzle temperature ratio

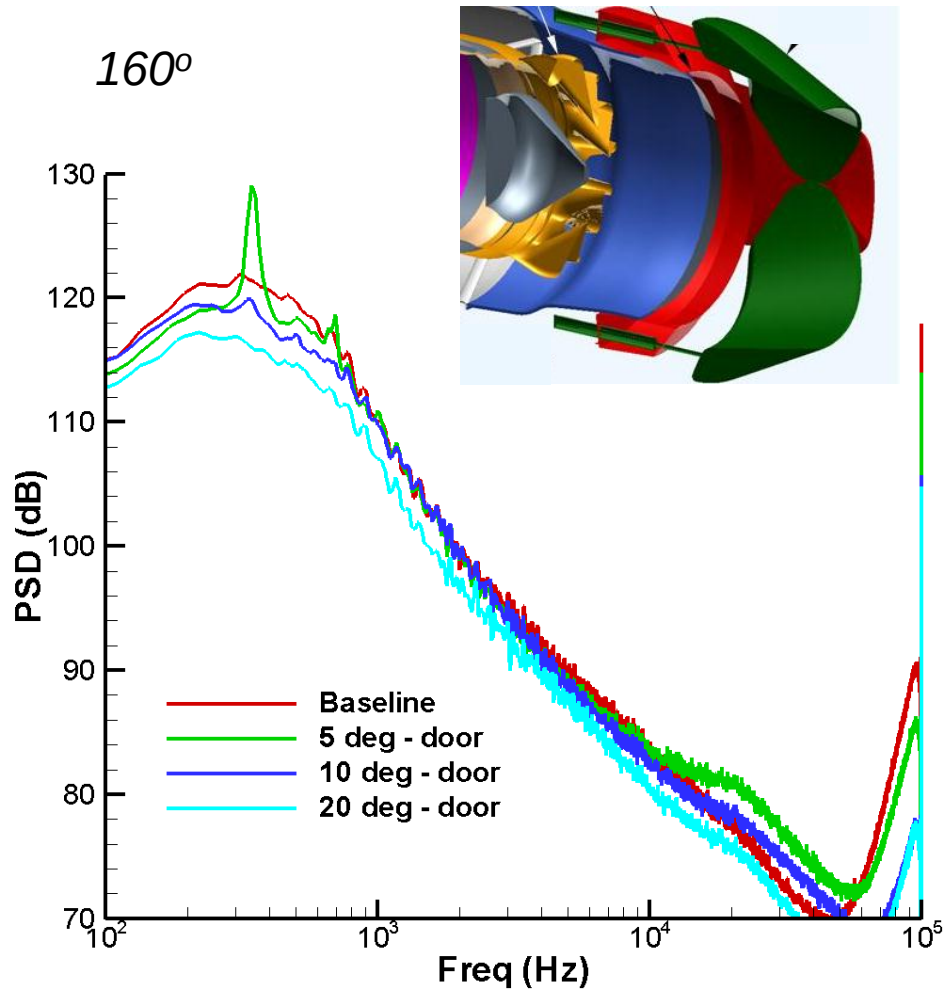
Subsonic Exhausts

Diagnostic Experiments Performed at NASA

- Far-field acoustics
- PIV (data acquired by Mark Wernet)
- Phased array
- Oil-film visualization

HVC Acoustic Results – M_{fj} = 0.0

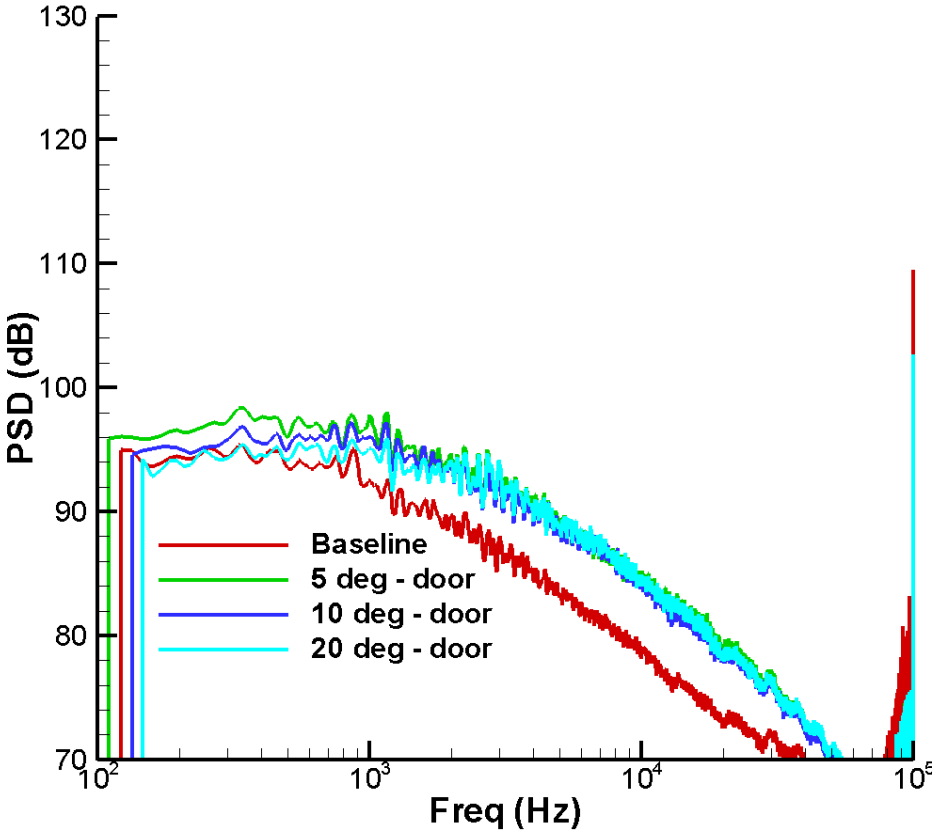




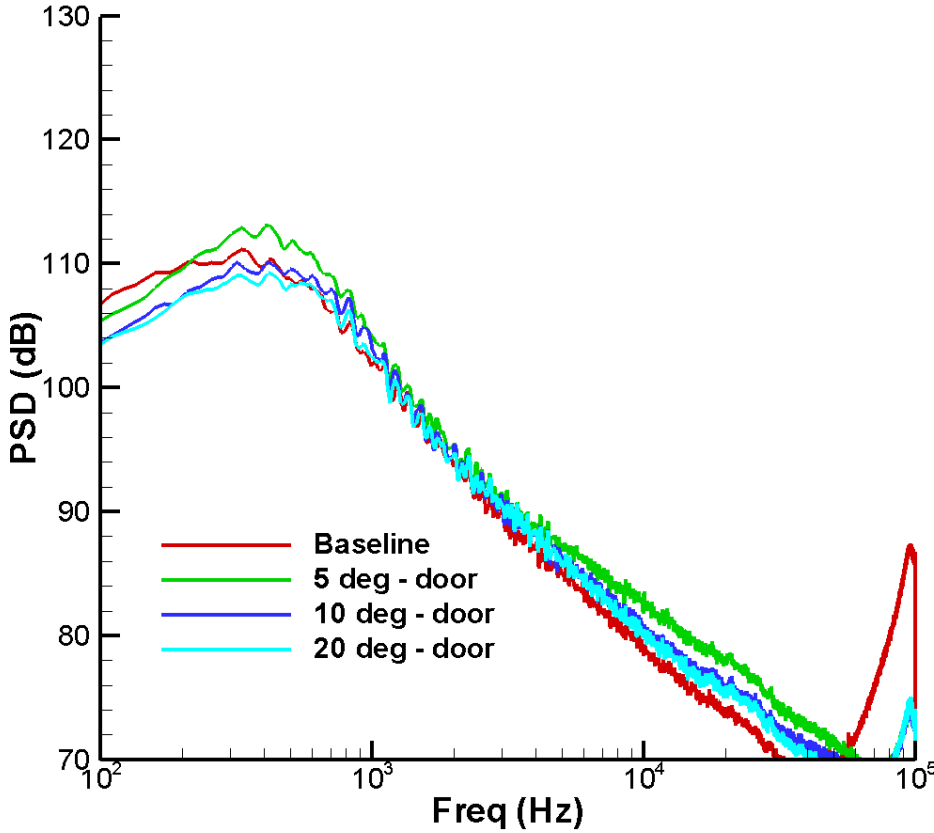
- Tone produced as smallest door angle
- Acoustic levels for baseline nozzle lower than HVC model in forward quadrant

HVC Acoustic Results – M_{fj} = 0.3

60º



160º

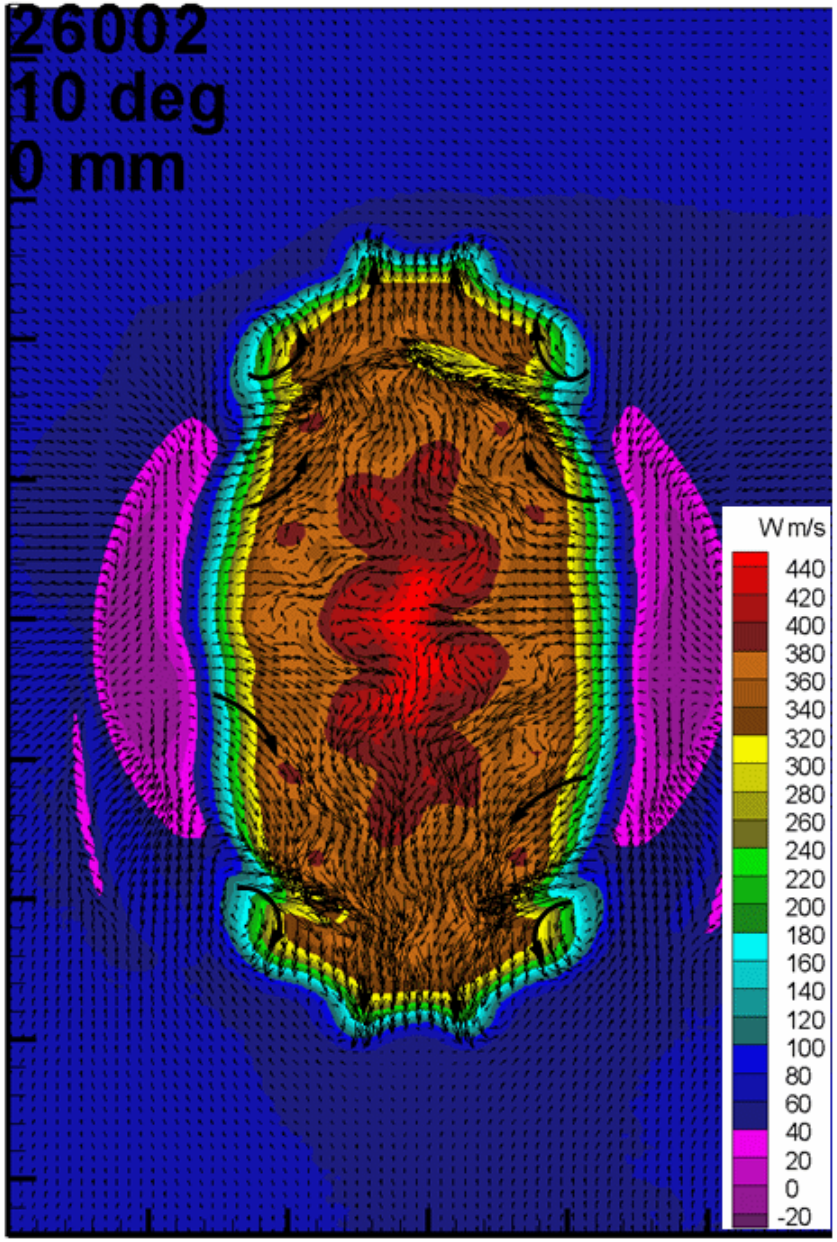


- In forward quadrant acoustic levels for baseline nozzle lower than HVC model
- In peak noise direction, acoustic levels for baseline nozzle lower than HVC at mid and high frequencies

HVC Cross-Stream PIV Results

NPR_c = 1.60
NPR_b = 1.80
TT_c = 1472R
TT_b = 700R
M_{fj} = 0.2

10° Door

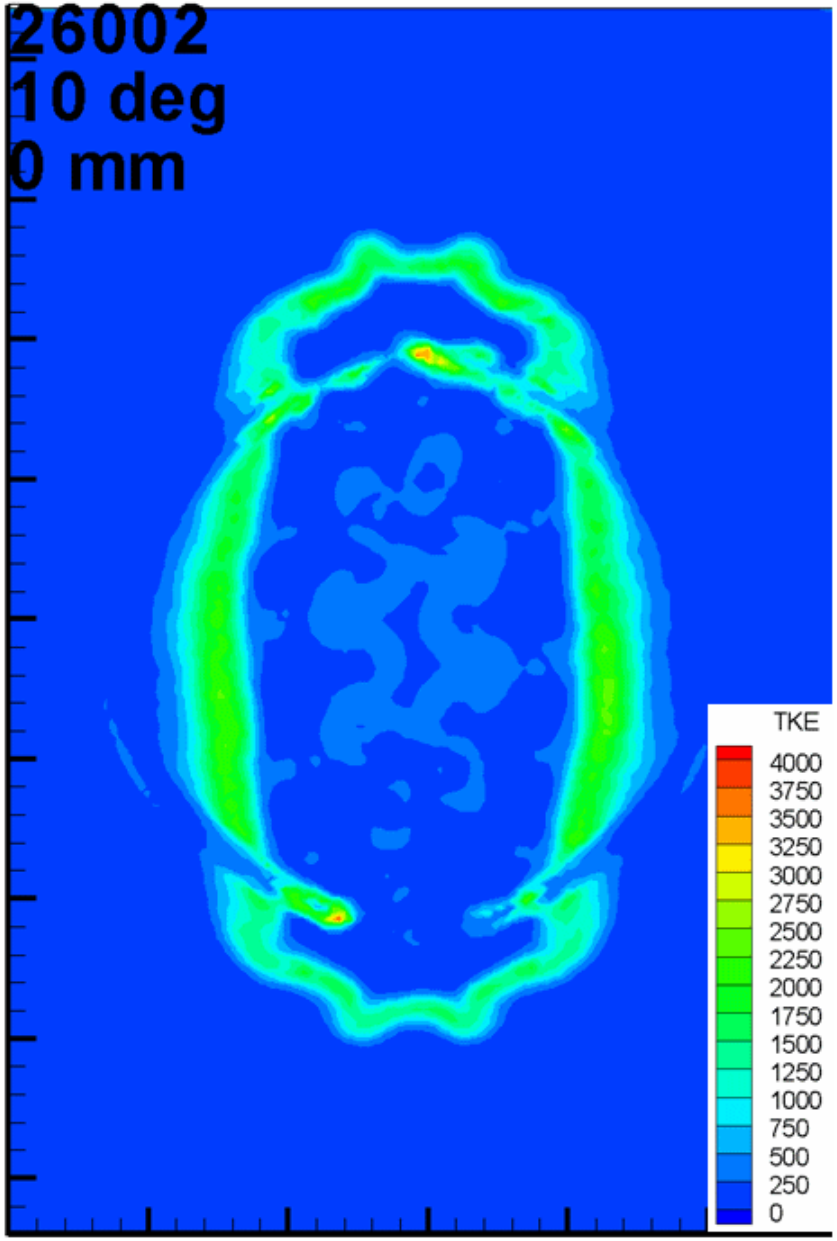


- Cross-stream mean axial velocity
- Purple is velocity below free stream
- Separation behind ejector doors
- Strong vortices set up by door-sidewall interface

HVC Cross-Stream PIV Results

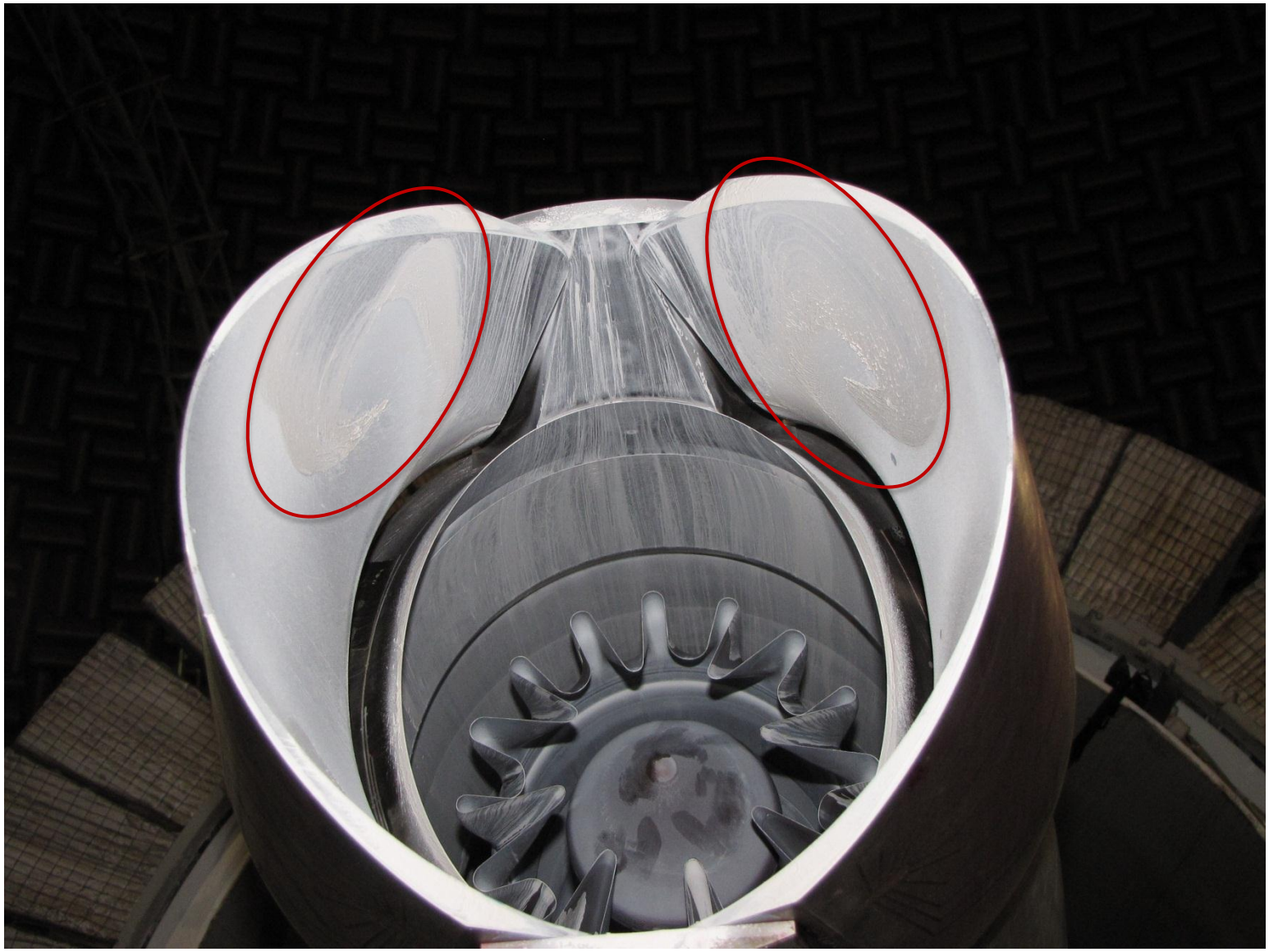
$NPR_c = 1.60$
$NPR_b = 1.80$
$TT_c = 1472R$
$TT_b = 700R$
$M_{fj} = 0.2$

10° Door

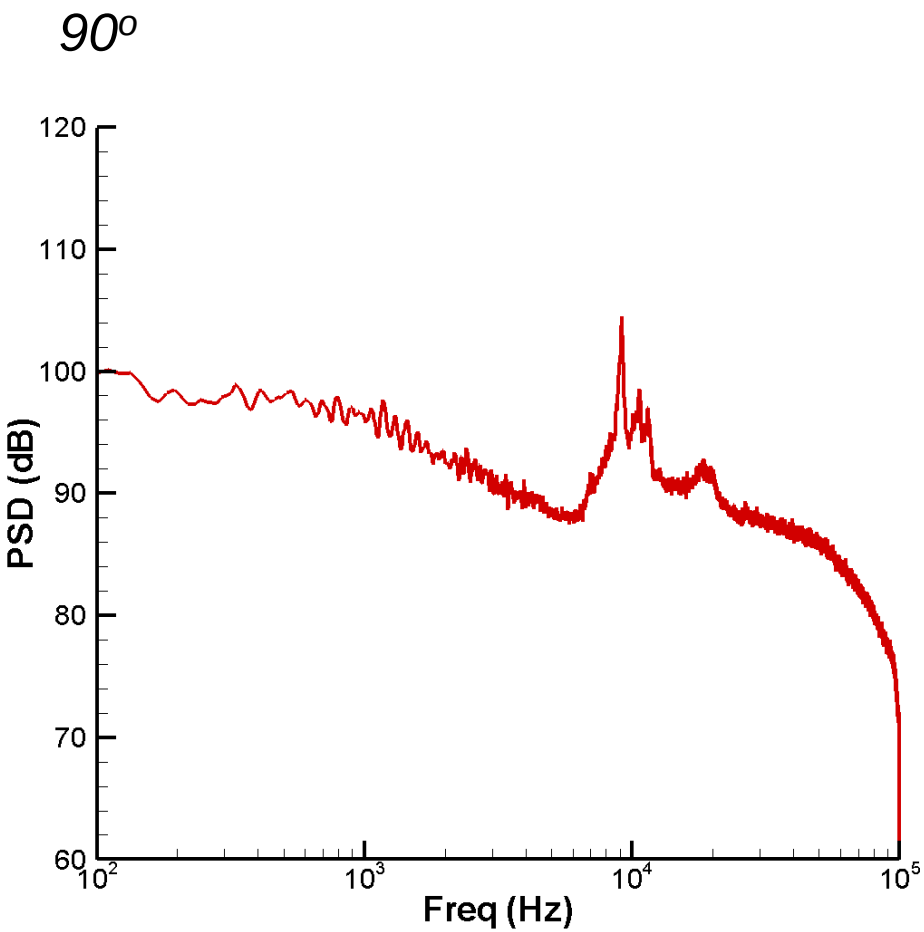


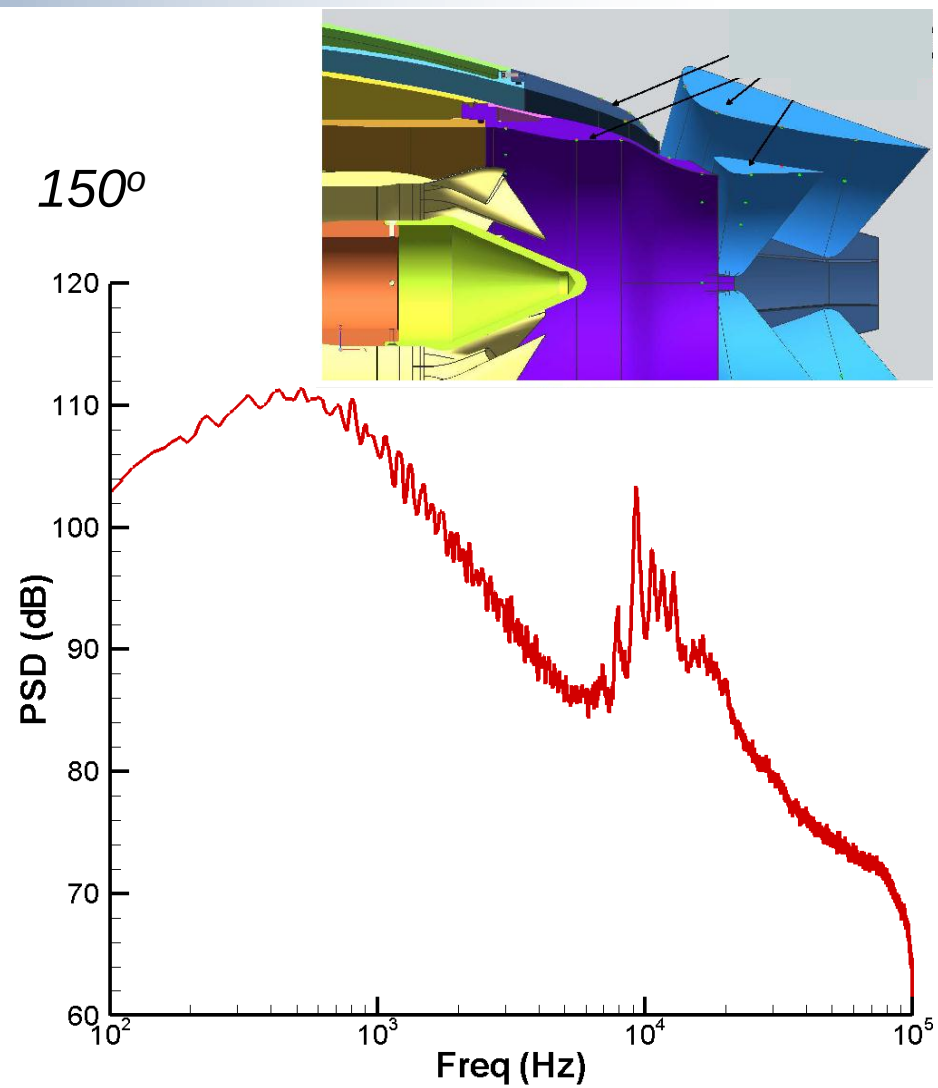
- Cross-stream TKE
- Strong vortices set up by door-sidewall interface stretches/augments shear layer turbulence downstream

Seed Pattern on Nozzle



N+2 HVC Acoustic Results – M_{fj} = 0.3



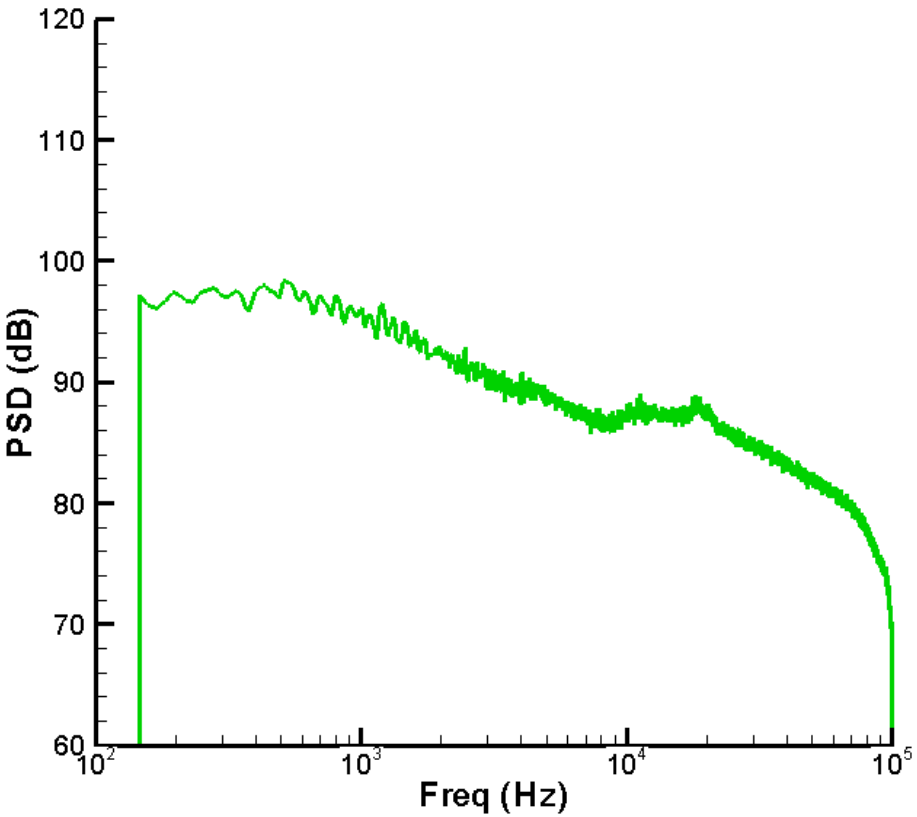


Multiple discrete-frequency tones produced by N+2 HVC model in as-built configuration

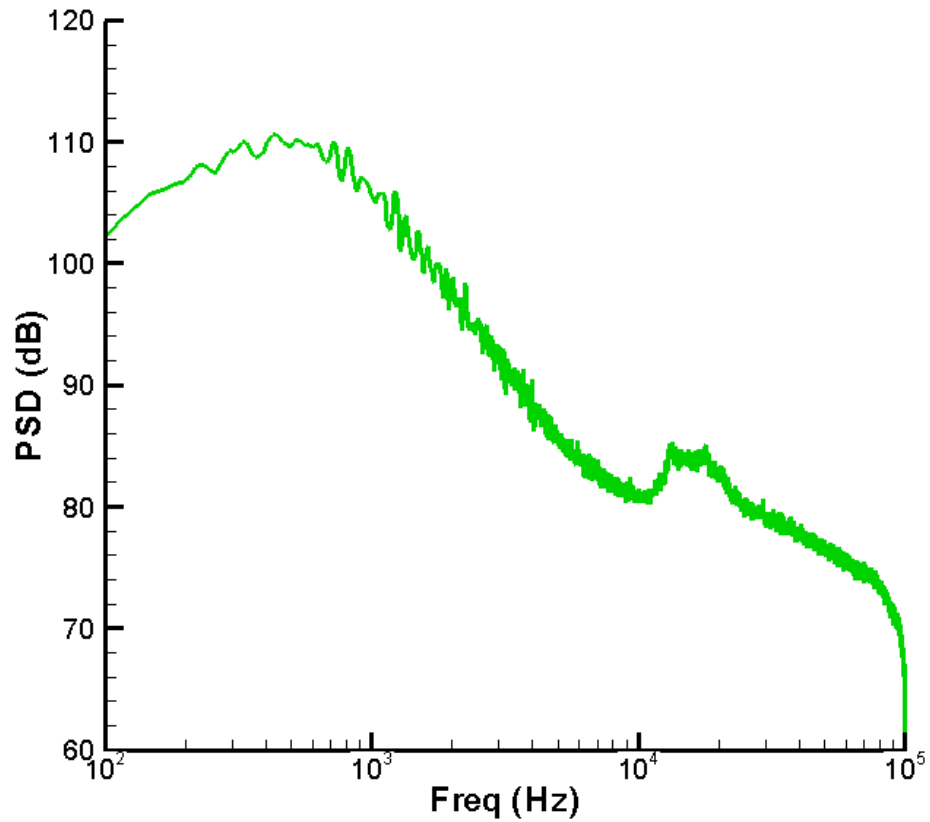
N+2 HVC Acoustic Results – M_{fj} = 0.3

Covered Ejector Flap

90º



150º

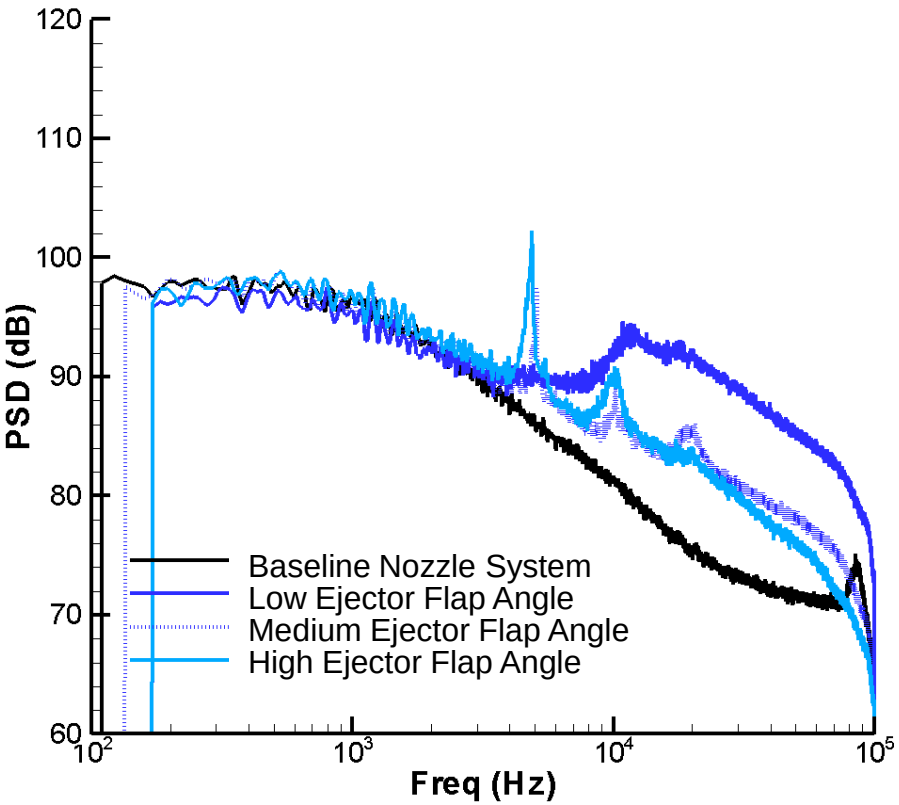


Discrete-frequency tones reduced by covering ejector flap

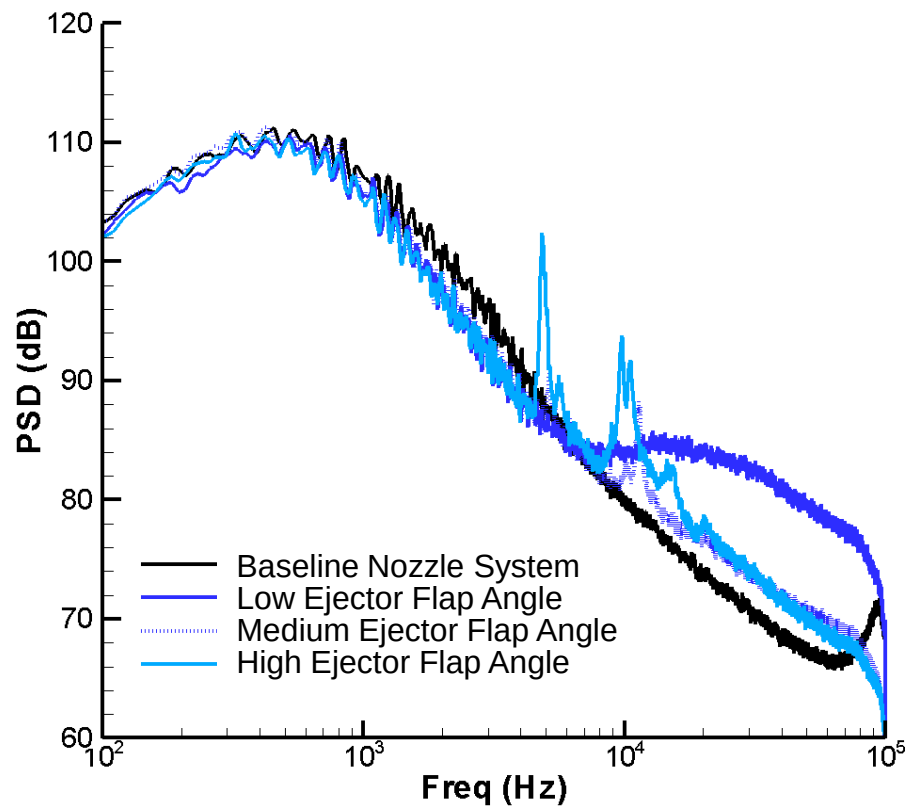
N+2 HVC Acoustic Results – M_{fj} = 0.3

Covered Ejector Flap

90º



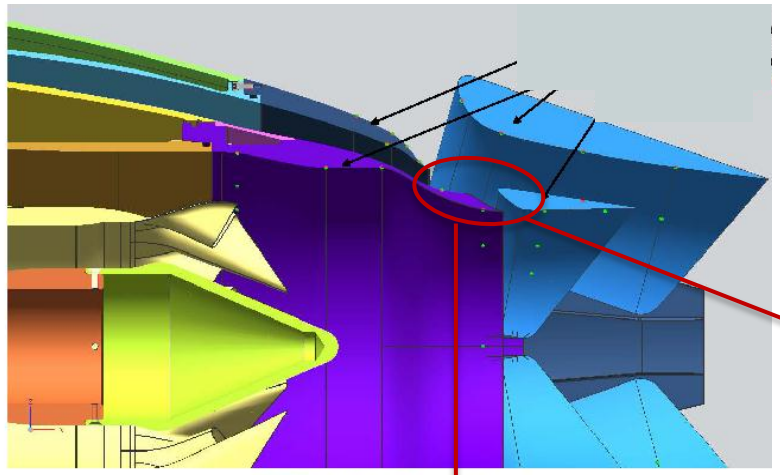
150º

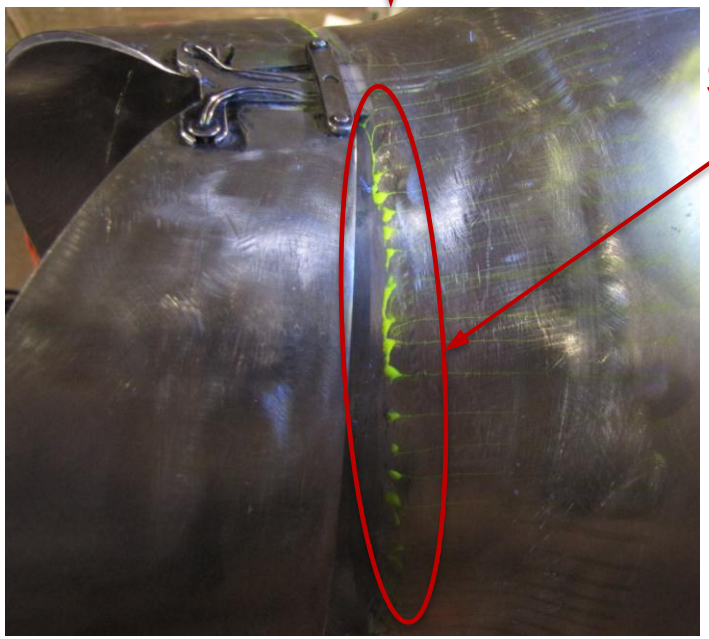


Tones could not be eliminated for all ejector flap angles
High-frequency levels always above baseline levels

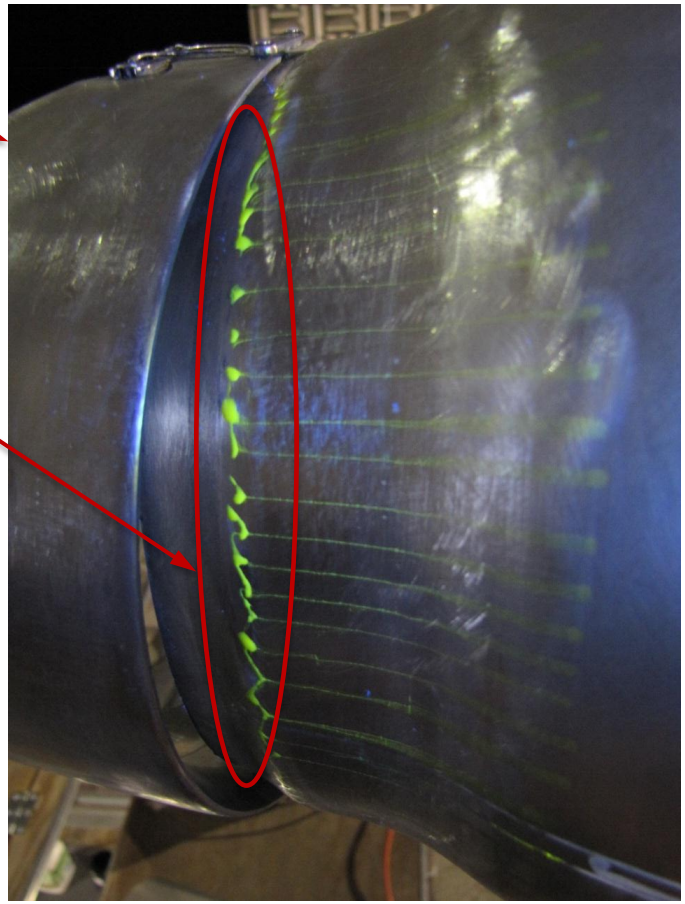
N+2 HVC Oil Visualization

As-Built Configuration



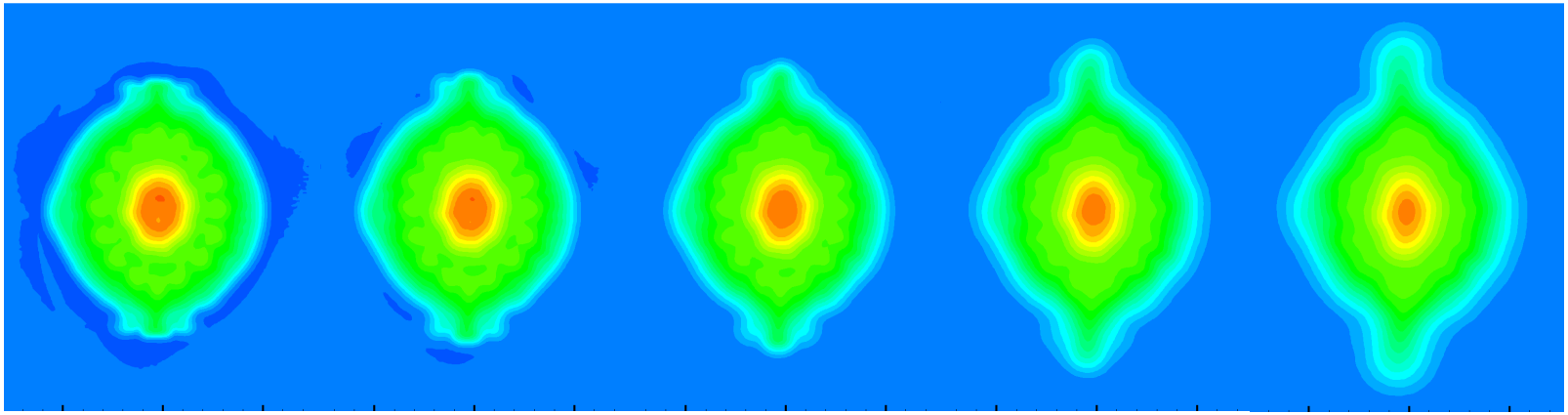


Separation

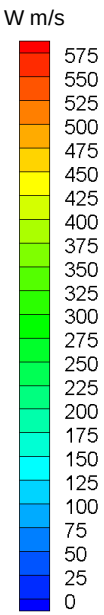


N+2 HVC PIV Results – M_{fj} = 0.2

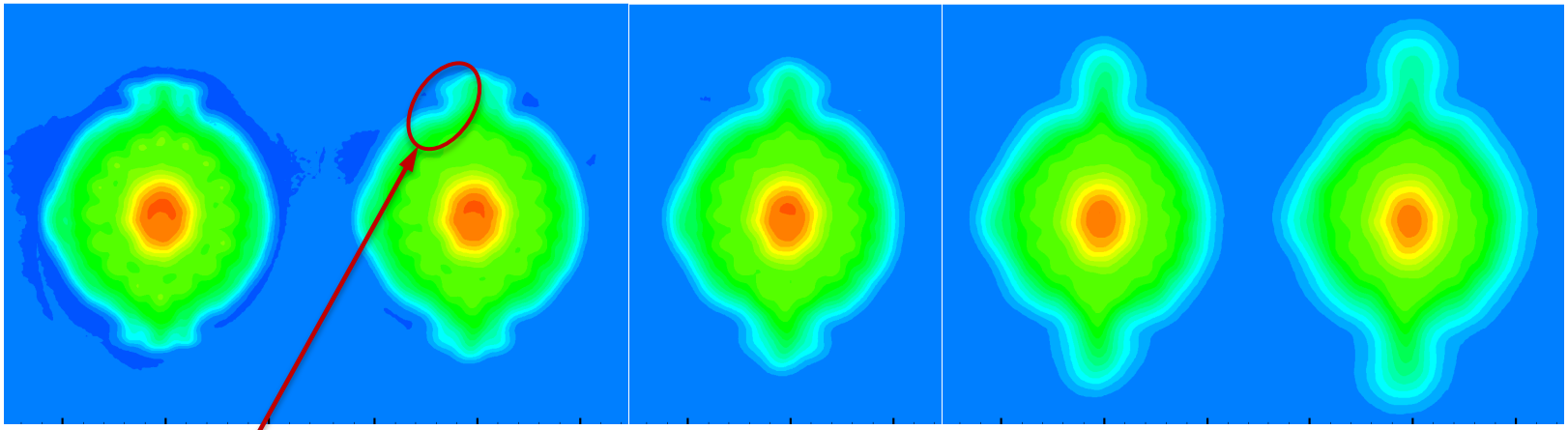
As-Built Configuration



0.1D *0.4D* *0.8D* *1.6D* *2.4D*



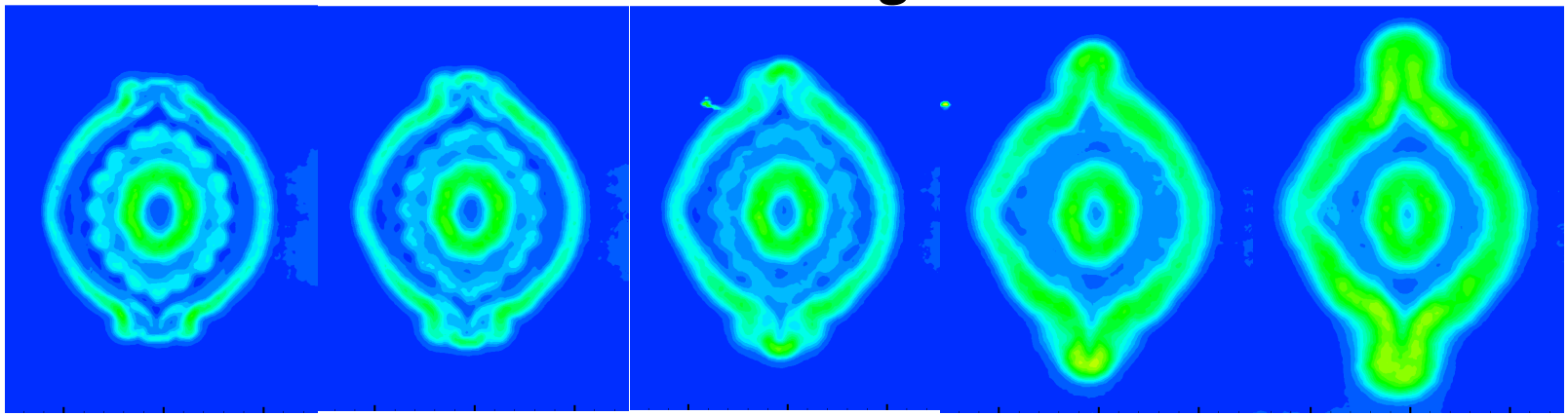
Covered Ejector Flap



Sidewalls have more pronounced impact on flow with covered ejector flap

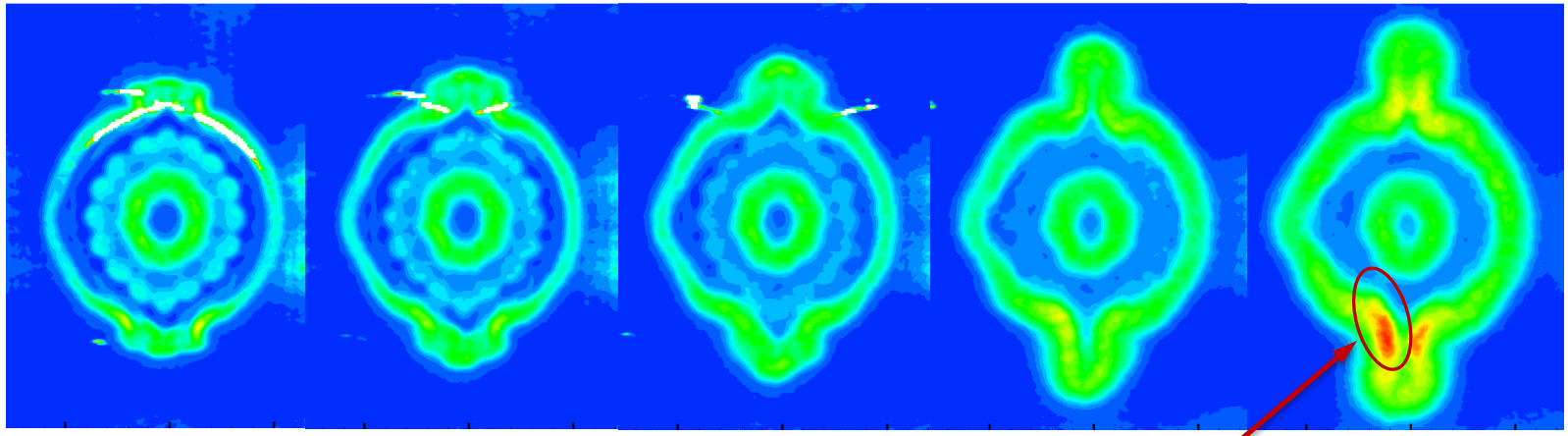
N+2 HVC PIV Results – M_{fj} = 0.2

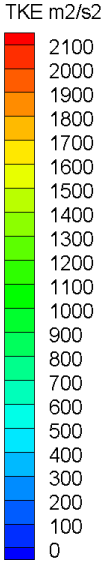
As-Built Configuration



0.1D *0.4D* *0.8D* *1.6D* *2.4D*

Covered Ejector Flap





Highest measured TKE levels in regions downstream of ejector/sidewall corners

Conclusions from N+2 Supersonics Validation Study – Exhaust Concepts

- All complex exhaust concepts suffered from separation for some cycle conditions
- Initial RANS CFD used to select flow lines did not detect flow separation
- Separation degraded acoustic performance of all models

Results from all N+2 Supersonics Validations Study exhaust concepts may be found at *Henderson, Brenda, Bridges, James, and Wernet, Mark (2012). "Jet noise reduction potential from emerging variable cycle technologies," AIAA-2012-3752.*

Environmentally Responsible Aviation (ERA) Project’s Upcoming Hybrid Wing Body (HWB) Acoustic Test

INVOLVEMENT/ACKNOWLEDGMENTS

- Planning stages

NASA

Thomas Brooks - Research Lead
Florence Hutcheson (NRA COTR)
Gregory Gatlin (NRA Alt.COTR)
Harry Haskin – Jet engine simulator/test config.
Tony Humphreys - Array development
Casey Burley - Prediction effort
Charles Lunsford - Acoustic testing config. coord.
Stephanie Heath - Consultant
Richard Walters - Facility eng.
James Bridges - JES cycle definition
Daniel Sutliff - Nacelle fan tone noise simulation
J. Berton, H.D. Kim, S. Jones, W. Haller - Engine data/pred.
Russell Thomas – SFW Acoustic Lead (API), LaRC
Charlotte Whitfield - Aeroacoustics Br. Head, LaRC
Michael Marcolini - Aeroacoustics Asst. Br. Head, LaRC

Academia

UCI - Dimitri Papamoschou

MIT – Zolti Spakovszky

Industry

Boeing - Ron Kawai (PI on NRA)
- Dick Odle
- Dave Pitera

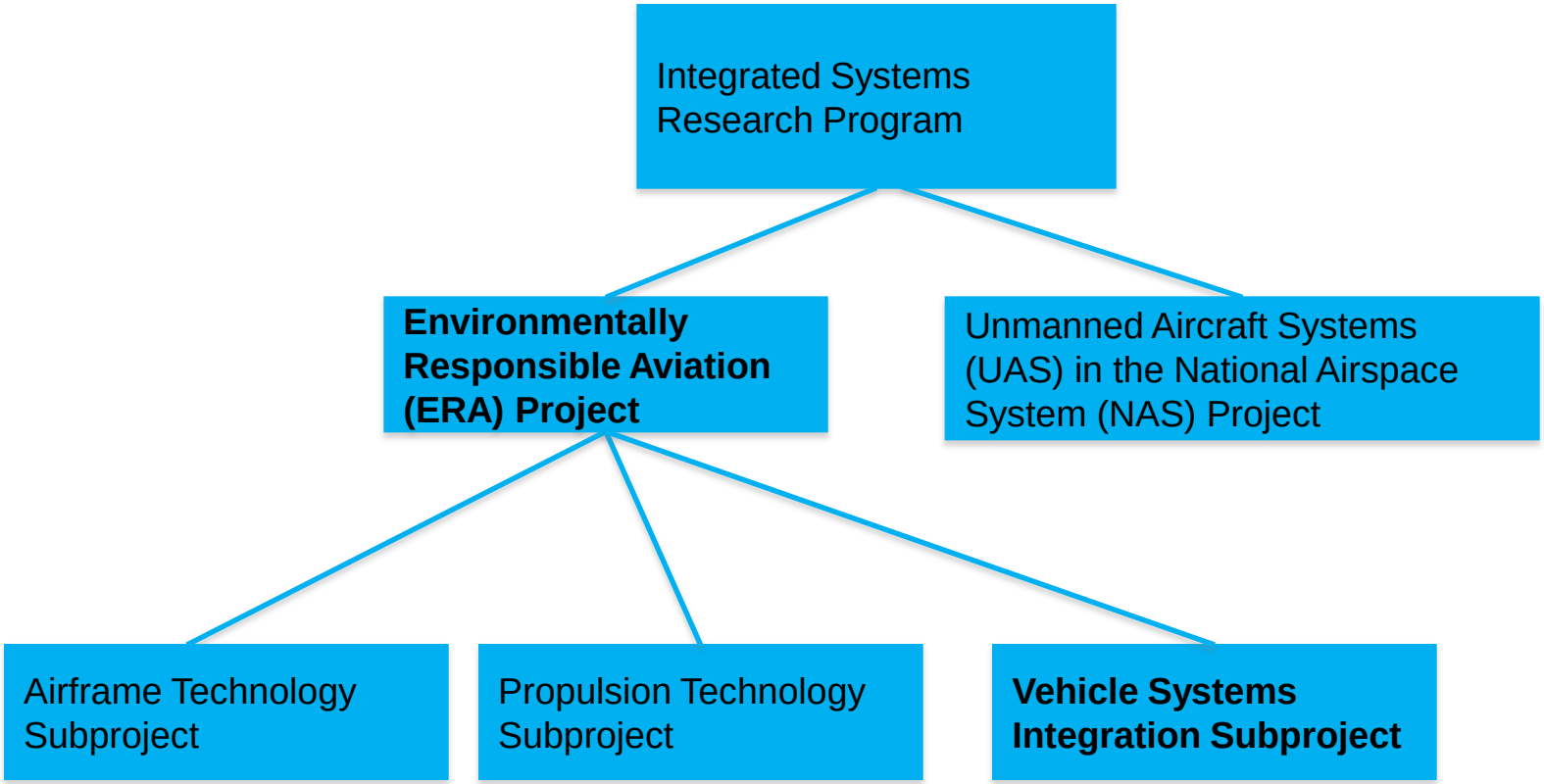
UTRC - Bob Schlinker
- John Simonich

- Upcoming Acoustic Test Execution

NASA and On-Site Contractors*

Thomas Brooks - PI
Ham Fernandez, Bob Bush, Russell Thomas, Charlotte Whitfield, Dan Hoad*, Stephanie Heath, Frank Quinto - Administrative
Florence Hutcheson - BENS testing
Mike Doty - CJES testing
Les Yeh* – Test Engineer
Casey Burley - Prediction effort
Tony Humphreys, Chris Bahr, Larry Becker*, Dan Stead*, Dennis Kuchta*, Taylor Spalt – Data management
Charles Lunsford - Photogrammetry
Harry Haskin, Doug Weber, Steve Syrett, Tom Popernack – Design
John Swartzbaugh, Clint Reese, James Allen, Shaun Reno, Mike Carr, Scott Bartram, Jaye Moen– Additional support

ERA OVERVIEW



- ERA Project created to explore and document feasibility, benefits and technical risk of vehicle concepts and technologies that reduce impact of aviation on the environment

- VSI Subproject identifies the best ways to integrate promising airframe and propulsion technologies

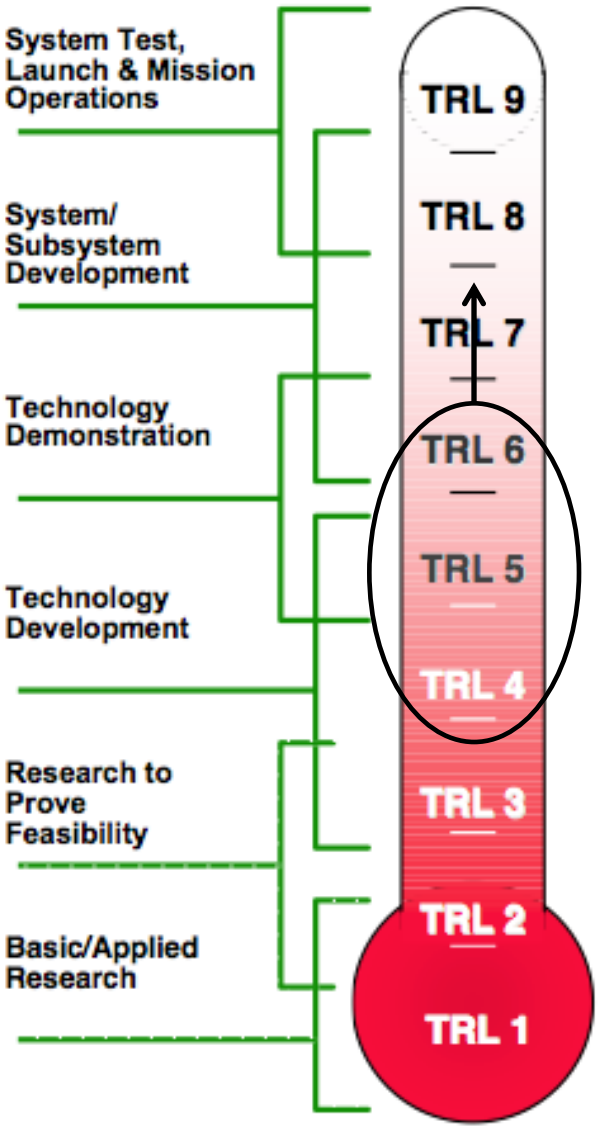
NASA'S METRICS

Subsonic Transport System Level Metrics

CORNERS OF THE TRADE SPACE	N+1 = 2015*** Technology Benefits Relative To a Single Aisle Reference Configuration	N+2 = 2020*** Technology Benefits Relative To a Large Twin Aisle Reference Configuration	N+3 = 2025*** Technology Benefits
Noise (cum below Stage 4)	-32 dB	-42 dB	-71 dB
LTO NO_x Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%	-50%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex* concepts

***Technology Readiness Level for key technologies = 4-6. ERA will undertake a time phased approach, TRL 6 by 2015 for "long-pole" technologies
** RECENTLY UPDATED. Additional gains may be possible through operational improvements
* Concepts that enable optimal use of runways at multiple airports within the metropolitan area

TECHNOLOGY READINESS LEVEL



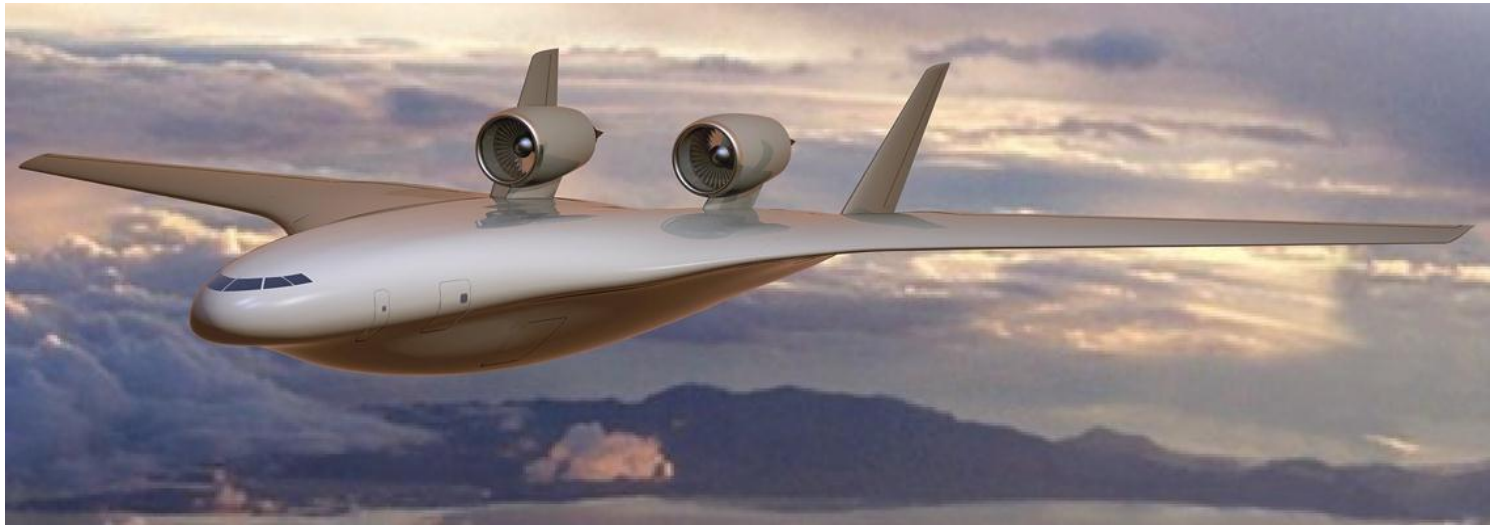
- ERA Focus is on maturing technologies

  - from mid-TRL ➔ deployment

  - subscale testing ➔ full scale flight testing

- Opportunity to team with both academia and industry

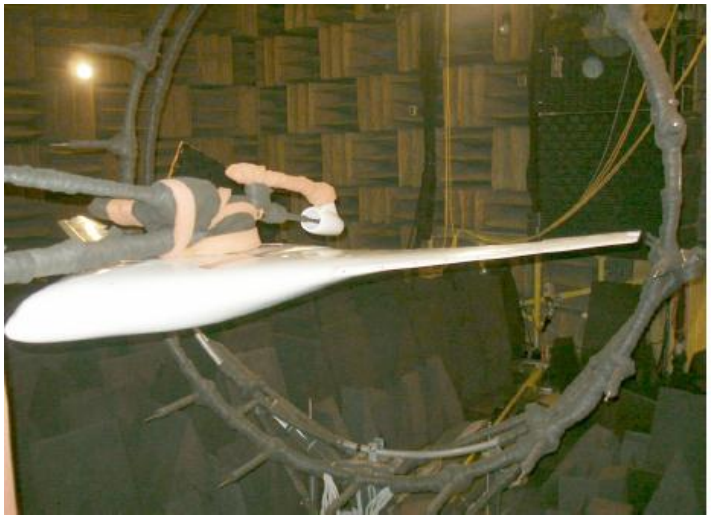
WHAT WOULD N+2 A/C CONCEPT LOOK LIKE?



- System level N+2 goals unlikely to be met with conventional tube and wing aircraft
- Hybrid wing body (HWB) is an unconventional aircraft with potential to simultaneously meet system level goals of noise, emissions, and fuel burn
- Combines the aerodynamic benefits of a flying wing design with acoustic shielding benefits of engines over the wing

HWB EVOLUTION - ACOUSTIC PERSPECTIVE

- As summarized by Russ Thomas (2007 Acoustics Technical Working Group Presentation), initial assessment of -42 dB noise goal based upon
  - Simple shielding experiment presented by Gerhold and Clark (2003)
  - Two studies using Aircraft NOise Prediction Program (ANOPP) by Hill (2004) and Hill and Geiselhart (2005)



From Gerhold and Clark, PAA workshop Dec. 2003

- While there were several simplifying assumptions in these early studies a major finding was the lack of experimental data to validate prediction methods

- The need was identified for a system level acoustic experiment to both
  - Demonstrate noise reduction capability of HWB
  - Provide valuable data for improved noise prediction capability

NASA RESEARCH ANNOUNCEMENT (NRA)

- NRA awarded to team led by Boeing Research and Technology

- Approximately three year effort starting late 2007 to
  - Define vehicle to meet system level goals
  - Deliver prediction methods and HWB test predictions
  - Fabricate wind tunnel model for aerodynamic and acoustic testing in NASA's 14-by 22-Foot Subsonic Tunnel

BOEING

PHANTOM WORKS

LANGLEY RESEARCH CENTER

MIT
GAS TURBINE LAB

GLENN RESEARCH CENTER

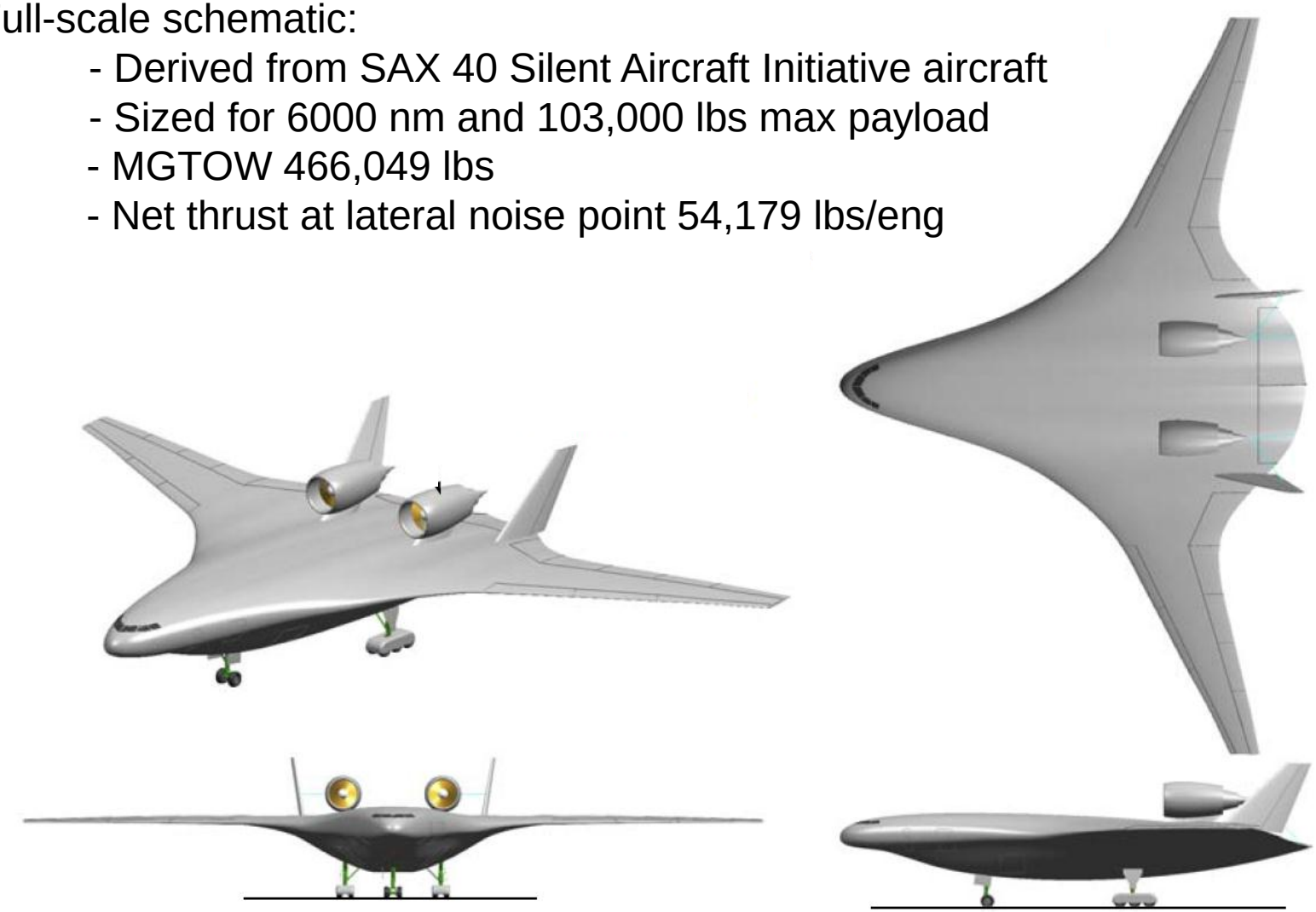
UCI
MECHANICAL AND AEROSPACE
ENGINEERING DEPARTMENT

United Technologies

PRATT & WHITNEY
UTRC

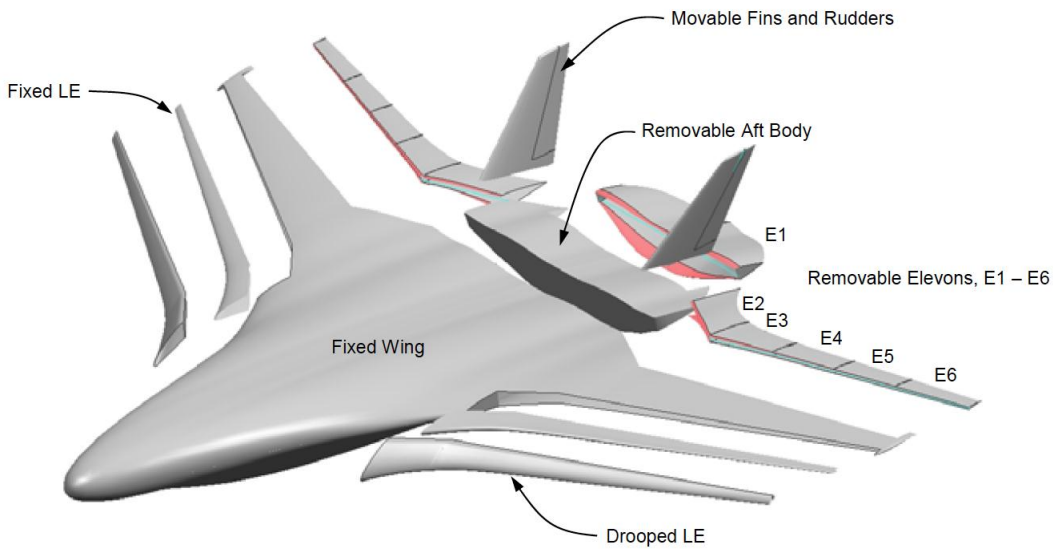
RESULTING HYBRID WING BODY DESIGN

- Full-scale schematic:
  - Derived from SAX 40 Silent Aircraft Initiative aircraft
  - Sized for 6000 nm and 103,000 lbs max payload
  - MGTOW 466,049 lbs
  - Net thrust at lateral noise point 54,179 lbs/eng



HWB MODEL

- Quiet Ultra Integrated Efficient Test Research Aircraft #1 (QUIET – R1)
  - 5.8% scale model with approximately 12.35 ft wingspan



- Modular model with capability for various
  - landing gear components
  - leading edge components
  - vertical tail components
  - elevon deflections

- Capability for mounting upright for conventional aerodynamic testing (above) or inverted for acoustic testing

HWB ACOUSTIC TEST OBJECTIVES

- Determine the noise spectra, levels, and directivity of a “low noise” HWB subsonic transport **and its components**

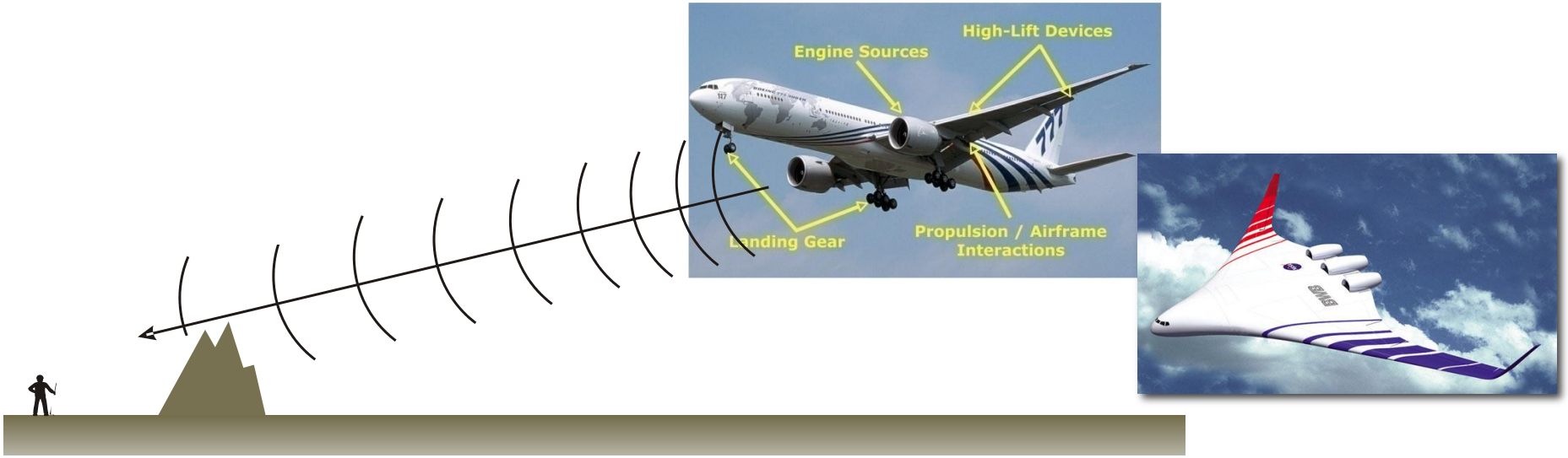
- Noise shielding parameters of the HWB and their effect on noise emission are an important part of this study

- Develop and validate new noise prediction capabilities of NASA’s Aircraft NOise Prediction Program 2 (ANOPP 2) for advanced vehicle design

ANOPP2

- **Total aircraft noise prediction capability for subsonic and supersonic aircraft**.
  - Predicts Aircraft source noise, propagation and impact at receiver
  - ANOPP2: mixed-fidelity prediction capability

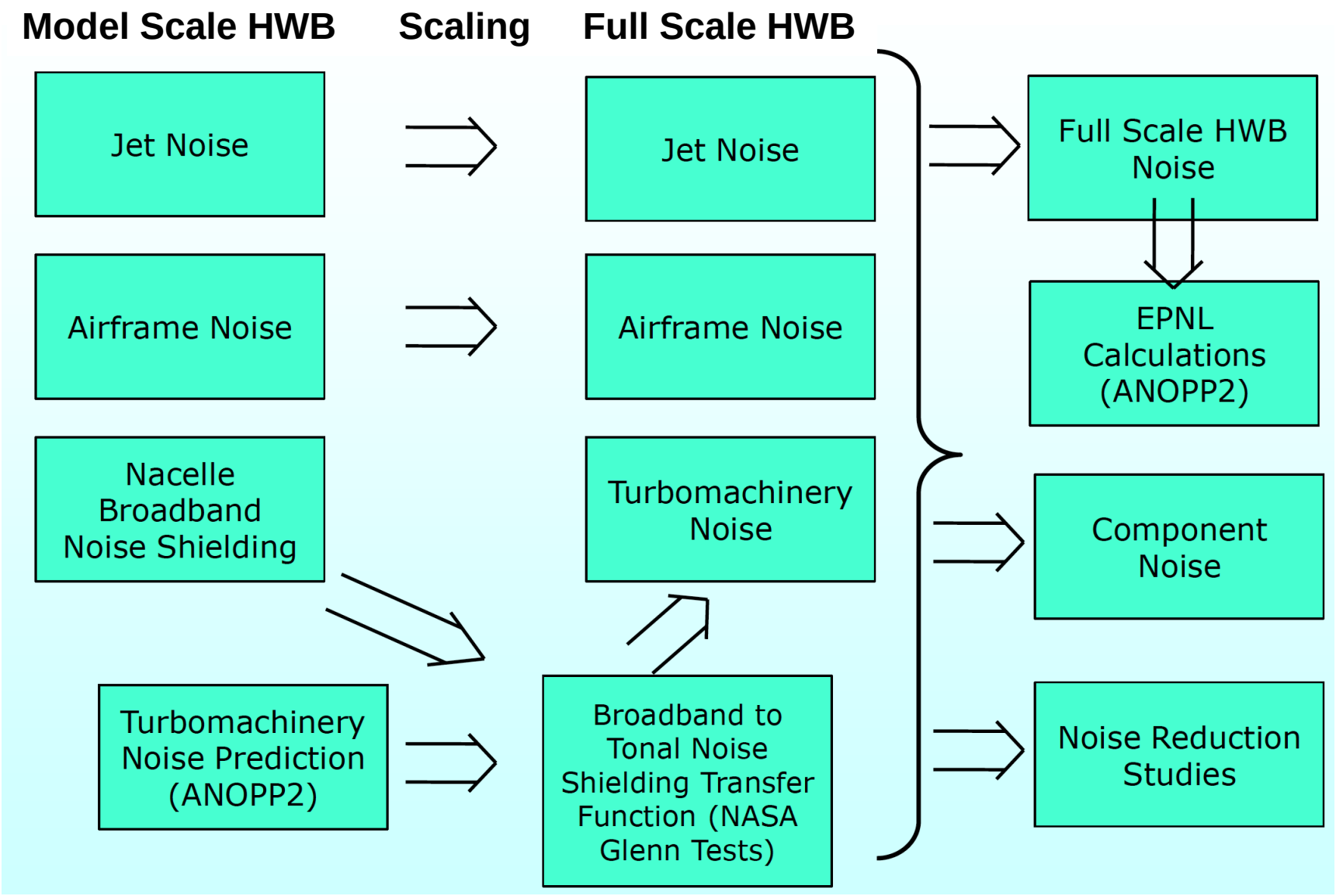
- **Current Emphasis in NASA:**
  - ANOPP2: Mixed-fidelity noise tools to enable system-level trades of noise against other performance parameters for conventional and unconventional aircraft.



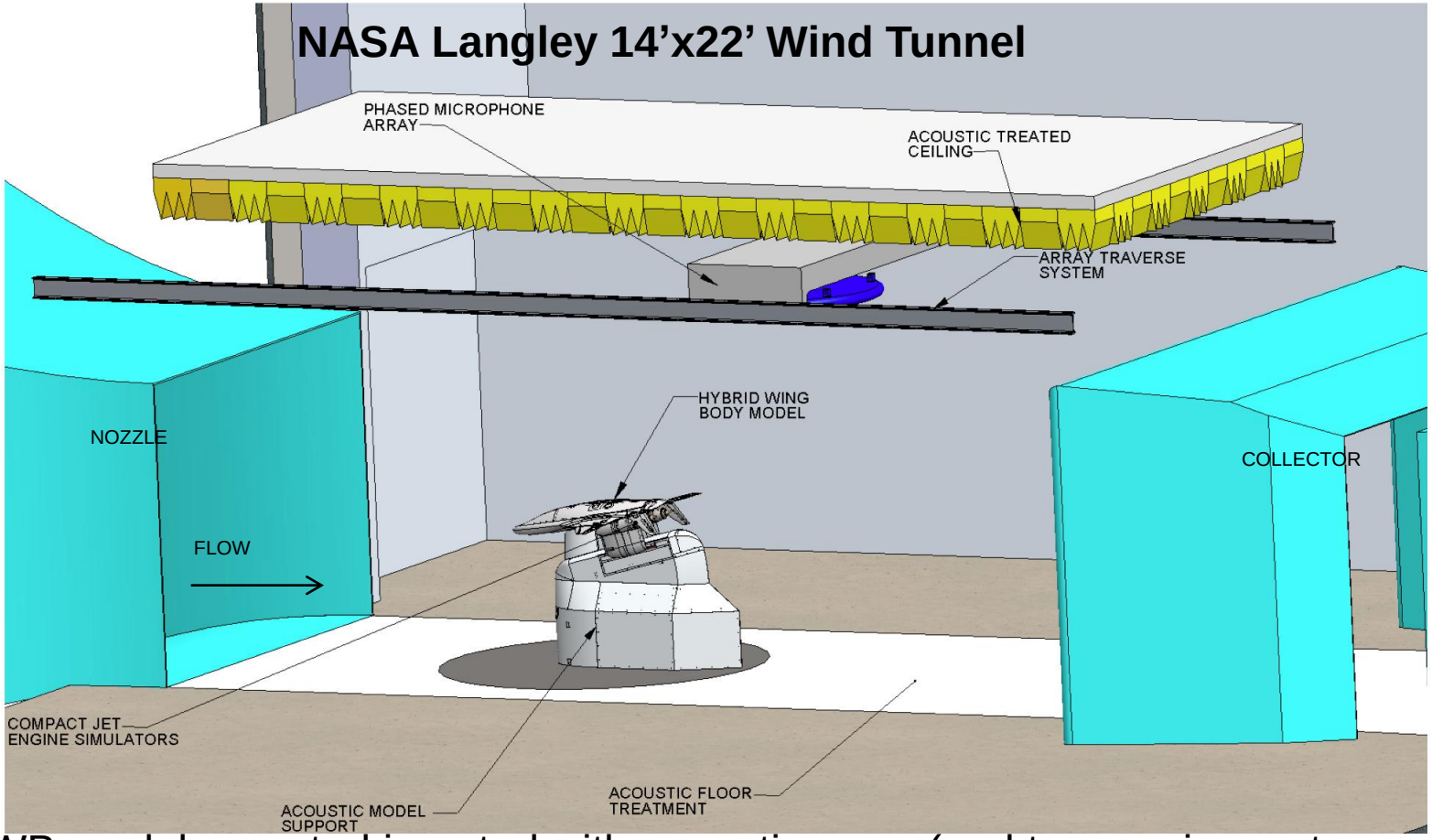
Receiver ← **Propagation** ← **Source**

Courtesy of Casey Burley

ACOUSTIC TEST APPROACH



ACOUSTIC TEST SET UP



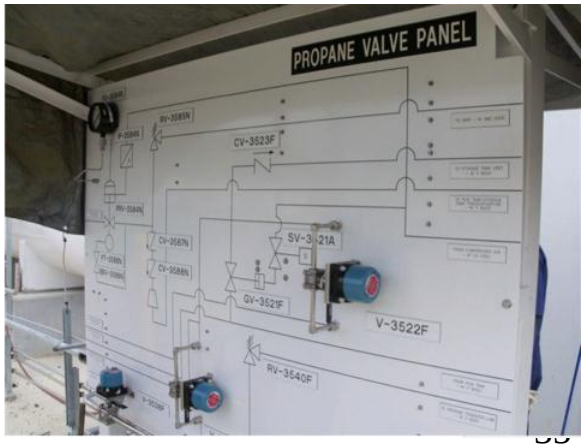
- HWB model mounted inverted with acoustic array (and tower mics, not shown) traversing above test article
- Acoustic testing with
  - Airframe only
  - Dual Broadband Engine Noise Simulators (BENS)
  - Dual Compact Jet Engine Simulators (CJES)

14’x22’ WIND TUNNEL UPGRADES

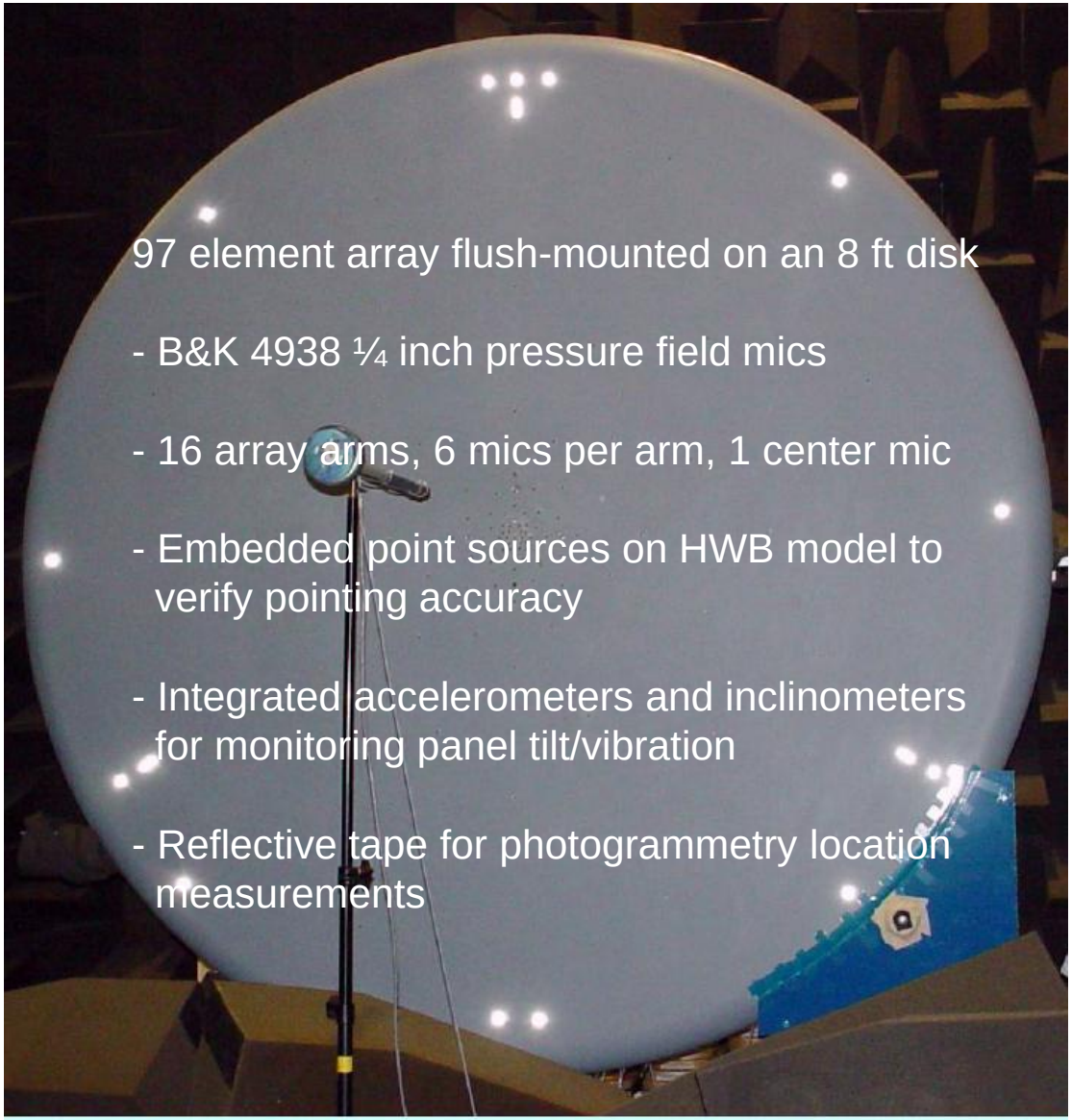
- **Traverse System**
  - 2-D traversing system to support the acoustic array with minimal vibration during tunnel operation

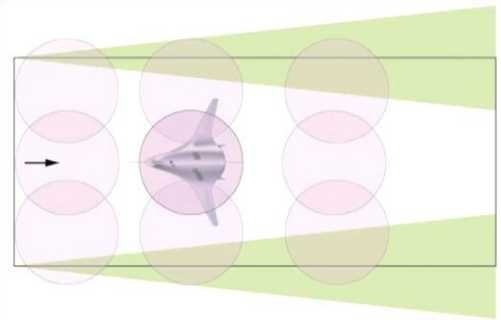
- **Ceiling treatment**
  - New 6” depth acoustic wedges replace 24” wedges to avoid interference with acoustic array, which needs to remain out of wind tunnel shear layer

- **Fuel delivery system**
  - Plumbing propane fuel capability to 14’x22’ including an outdoor test stand

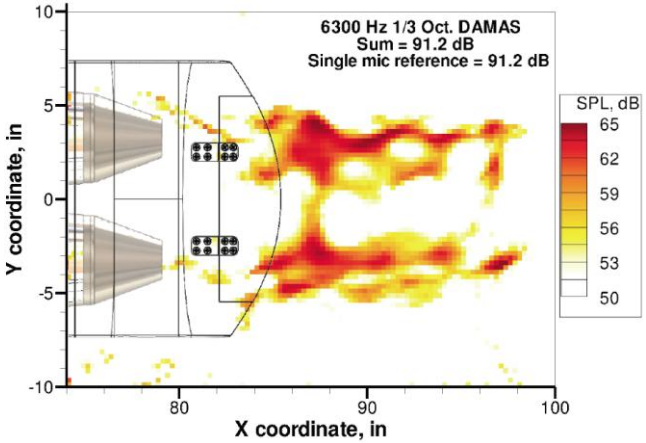


OVERHEAD PHASED ARRAY



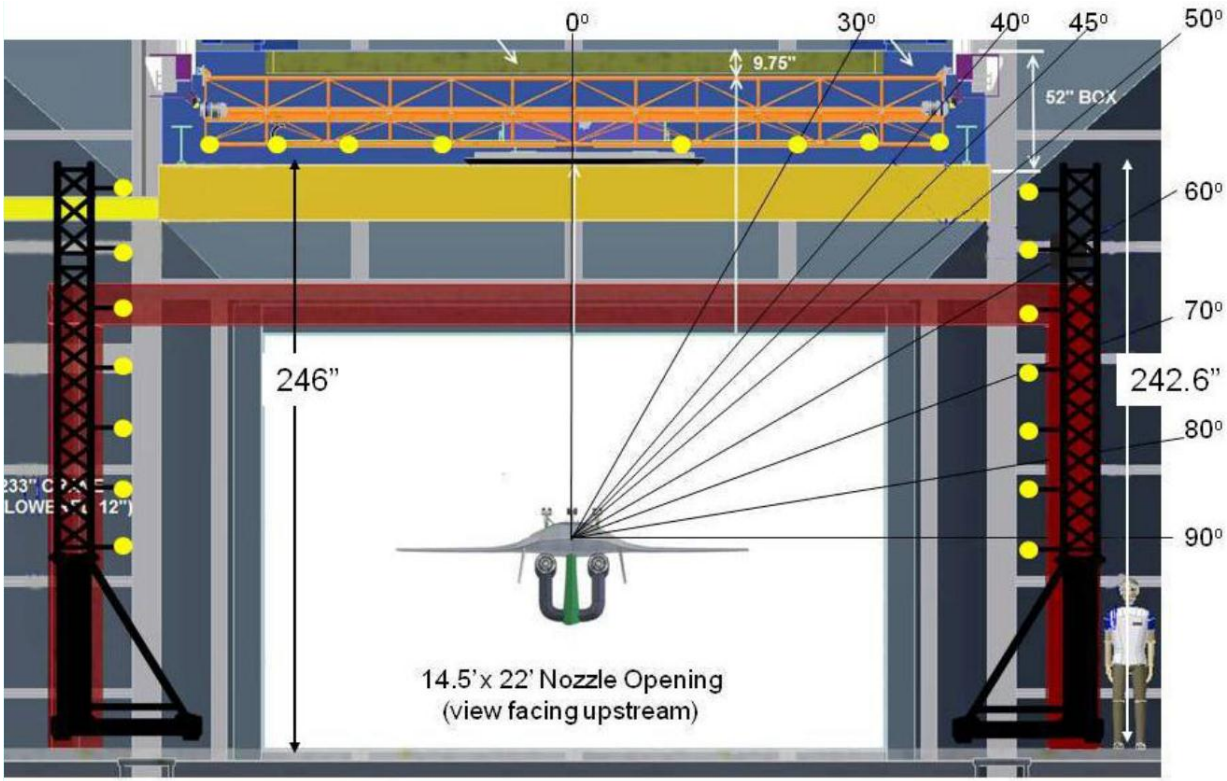


- 9-12 stations of array acquisition anticipated
- Using Deconvolution Approach for the Mapping of Acoustic Sources (DAMAS) for phased array processing



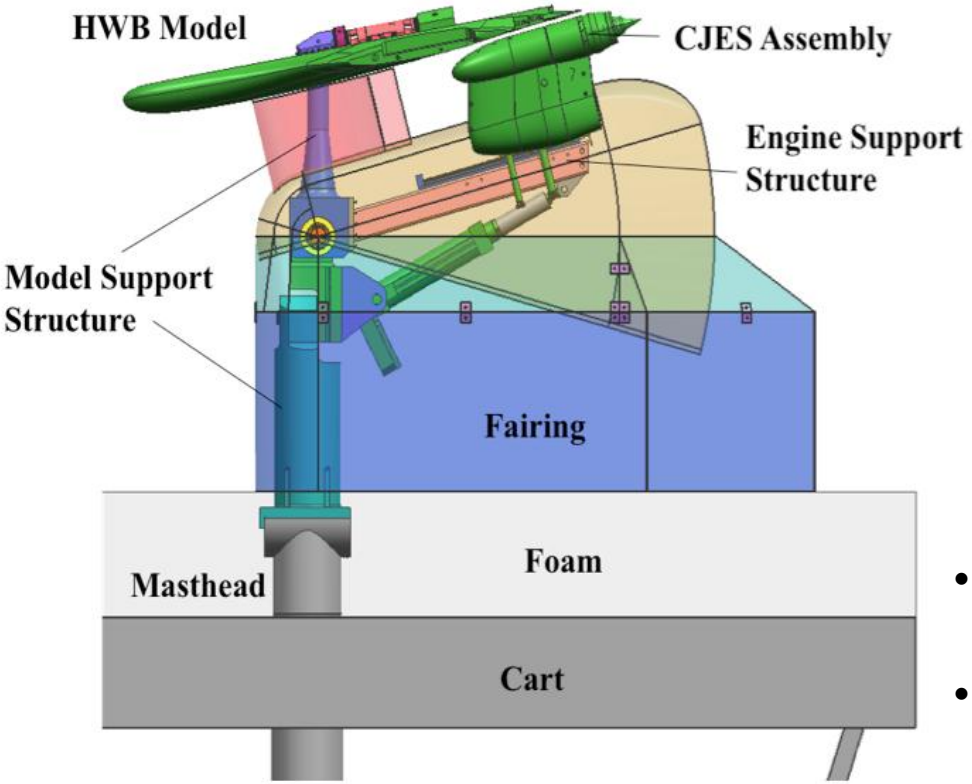
From Twin jet risk reduction study: AIAA 2012-2157

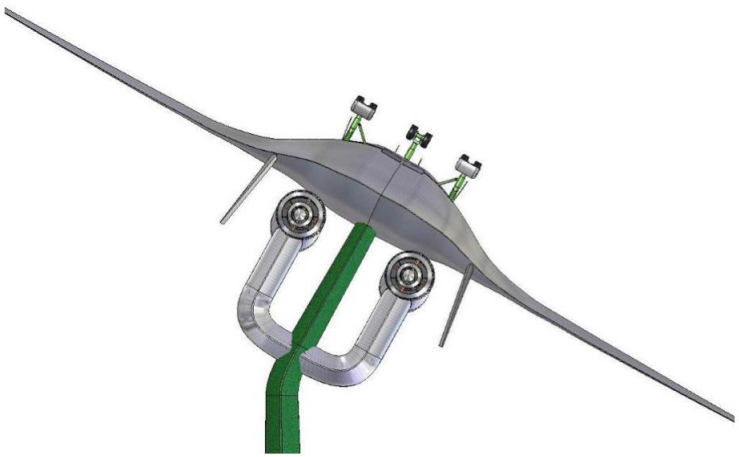
SIDELINE TOWER MICROPHONES



- Sideline acoustic coverage of HWB system is accomplished with 28 microphone dual tower array
  - 7 microphones per tower
  - 14 microphones on overhead traverse
  - B&K 4138 1/8 inch mics used to minimize angle response corrections

ACOUSTIC MODEL SUPPORT





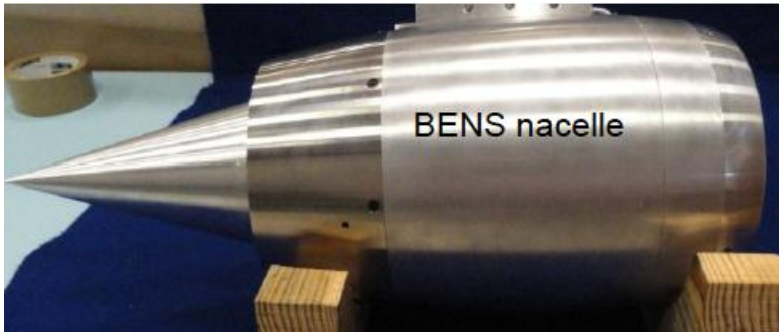
- Pitch variation from -25° to +5°
- Roll to -30° , 0° , or +30°

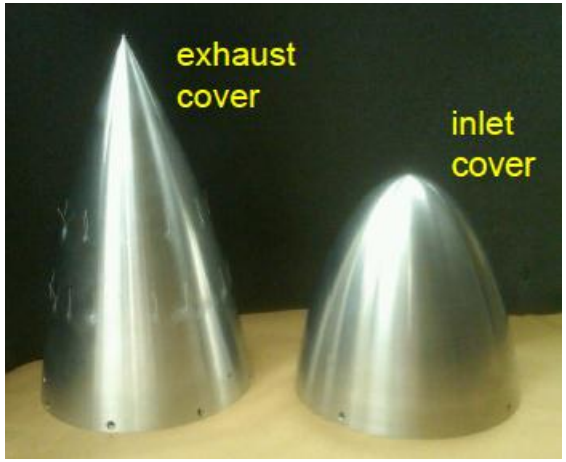
- CJES or BENS units can be installed at 5 discrete axial locations wrt model trailing edge for shielding effectiveness investigation:

  -0.5 *x/D* (downstream of trailing edge), 0.0 *x/D* (at trailing edge), and +1.5, +2.5, +3.0 *x/D* (upstream of trailing edge)

(where *x* refers to axial distance from fan nozzle exit plane to model trailing edge and *D* refers to fan nozzle diameter)

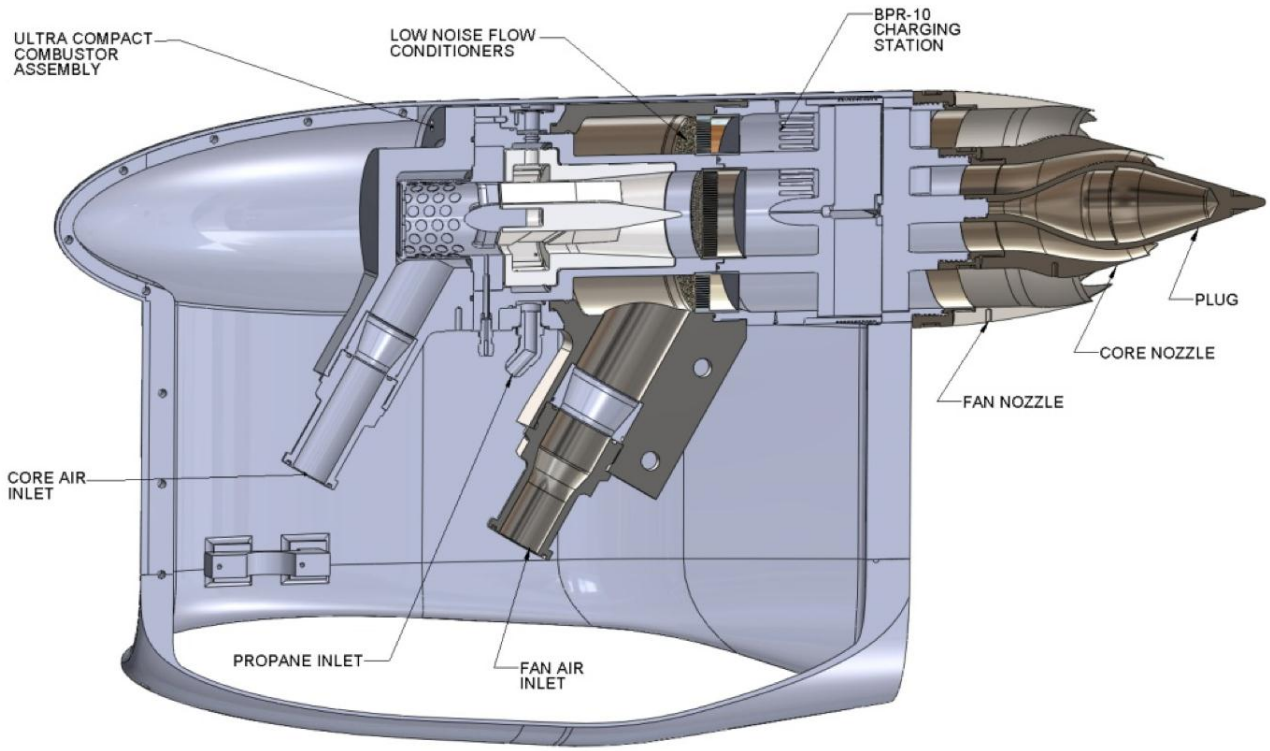
BROADBAND ENGINE NOISE SIMULATORS





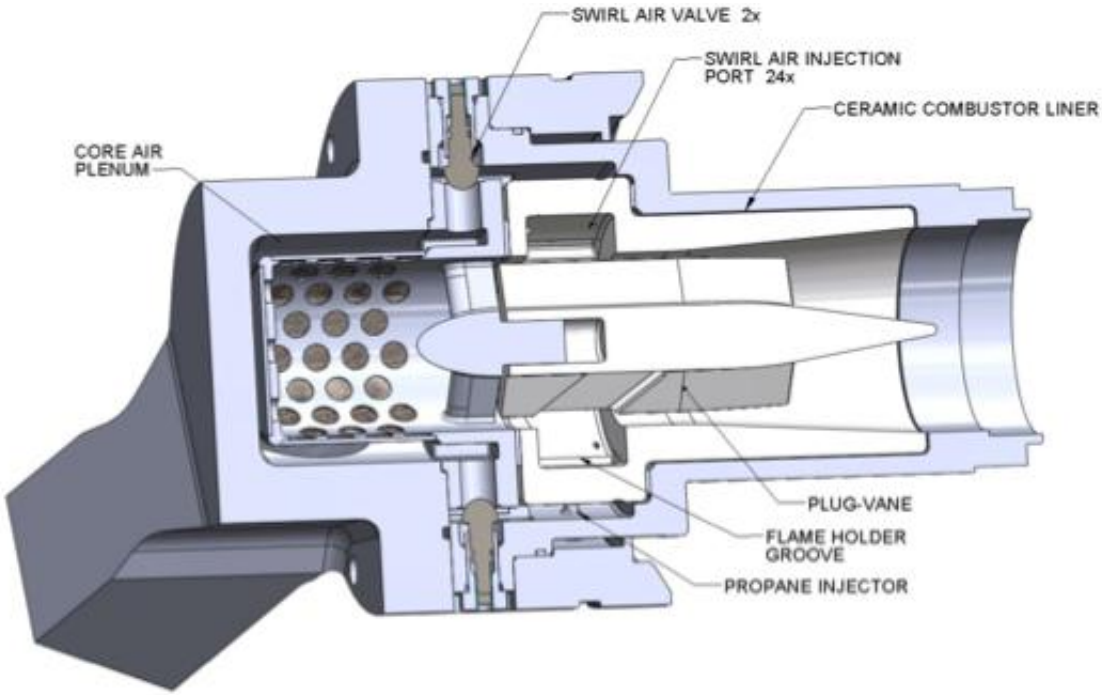
- Each BENS unit uses 3 sets of 4 impinging jets to generate broadband noise within the nacelle
- Simulates broadband engine noise, can isolate either upstream or downstream with covers
- Kulites embedded in each BENS nacelle to ensure consistent nearfield levels
- Tonal fan noise simulation addressed separately with piezoelectric fan at NASA Glenn because of power requirements needed for acceptable signal-to-noise in 14’x22’

COMPACT JET ENGINE SIMULATORS (CJES)



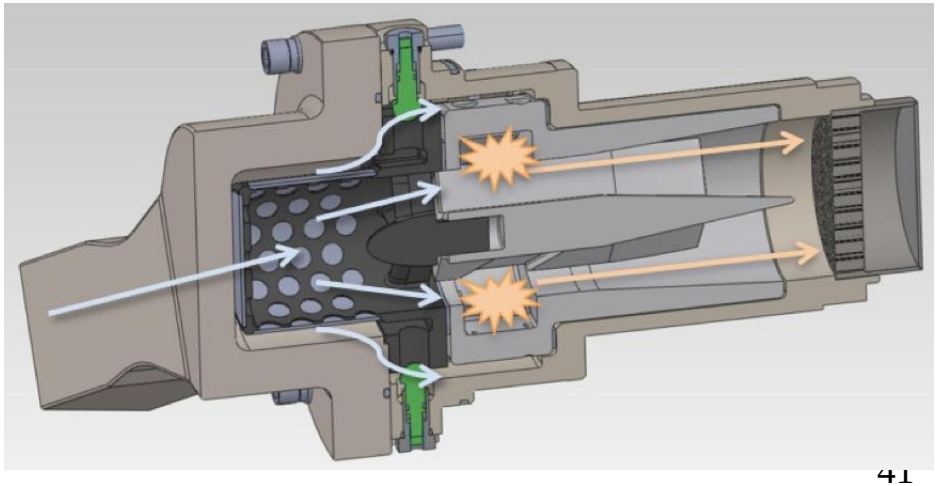
- Each CJES unit consists of a fan and core stream simulating various cycle points of a turbofan engine (BPR 10 in this case)
- Use gaseous propane to generate representative temperatures, up to ~ 1150° F for current test conditions

ULTRA-COMPACT COMBUSTOR (UCC)



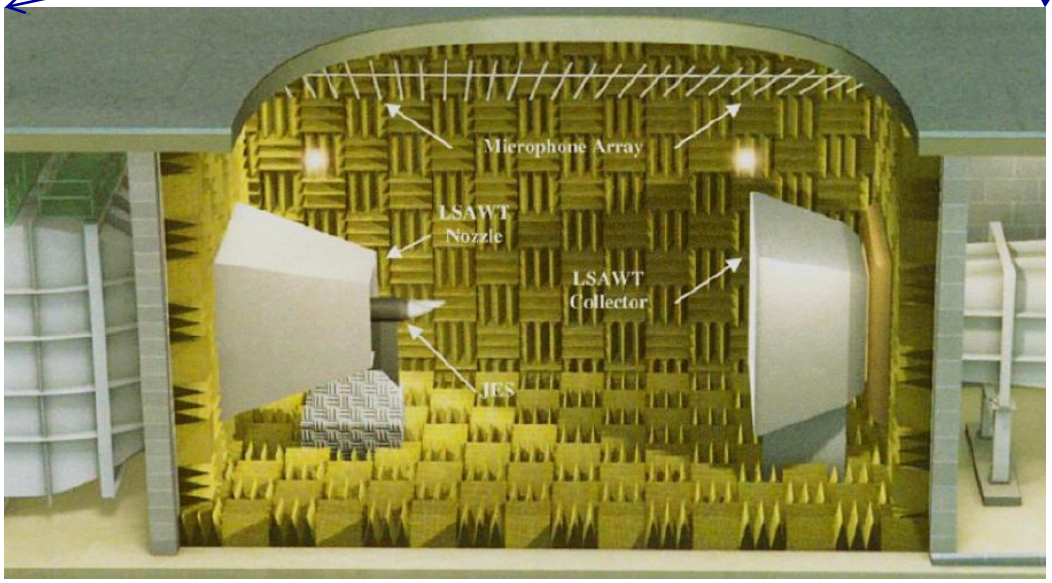
- Based on design at the Air Force Research Lab (AFRL) and consultation with J. Zelina
- Swirl air is injected on either side of fuel injectors

- High centrifugal loading shortens combustor length
- Passive swirl control using backpressure from inlet flow conditioner



CJES CHECKOUT AT JET NOISE LAB

NASA Langley Low Speed Aeroacoustic Wind Tunnel

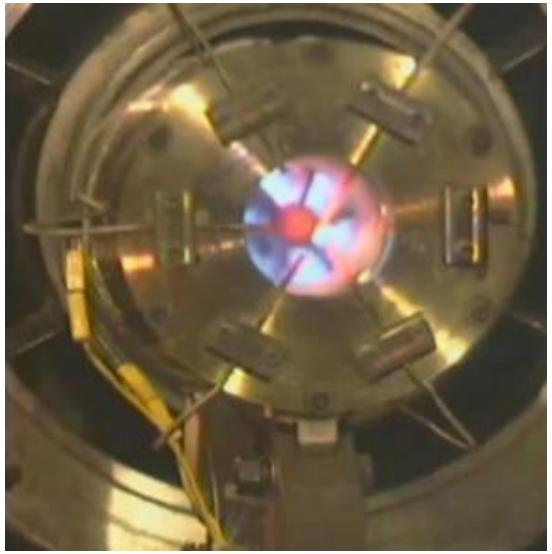


Compact nature of CJES evident in comparison to existing JES

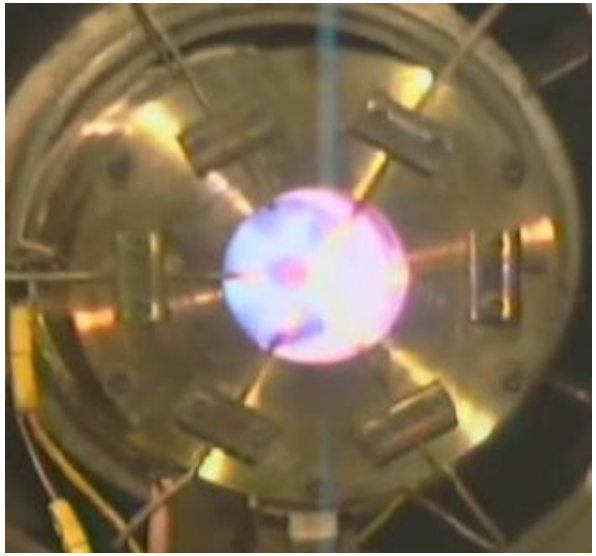
CJES CHECKOUT AT JET NOISE LAB

- Prior to assembly of entire CJES unit, combustor only was instrumented with a backplate containing several thermocouples and a Pitot probe
- Ratio of swirl air flow rate to axial flow rate recommended to be ~ 20% based on AFRL experience

First light – too much fuel!



Stable operation, flame in cavity



Too much axial velocity, plug acting as flameholder

SUMMARY

- Hybrid Wing Body combines aerodynamic benefits of flying wing with shielding opportunities in an effort to meet simultaneous system level goals for noise, emissions, and fuel burn

- Upcoming HWB Acoustic test in the 14’x22’ will

  - Characterize the system level noise of the HWB and quantify the effects of shielding on various noise components

  - Generate a database for developing and validating new noise prediction capabilities for NASA’s ANOPP 2

- Tunnel occupancy started September 12 … we are underway!

RELEVANT PUBLICATIONS 2009-2012

Thomas, Russell H., Burley, Casey L., Olson, Erik D., Recent Progress in Propulsion Airframe Aeroacoustics, Royal Aeronautical Society's Applied Aerodynamic Conference, 07/27/10 -07/28/10, Bristol U

Burley, Casey L., Brooks, Thomas F., Humphreys, William M., Rawls, John W., JR., ANOPP Landing Gear Noise Prediction Comparisons to Model-Scale Data, International Journal of Aeroacoustics, July 2009.

Humphreys, William M., Brooks, Thomas F., Noise Spectra and Directivity For a Scale-Model Landing Gear, International Journal of Aeroacoustics, July 2009

Lee, Seongkyu, Brentner, Kenneth S., Farassat, Fereidoun, Morris, Philip J., Analytic Formulation and Numerical Implementation of an Acoustic Pressure Gradient Prediction, Journal of Sound and Vibration, January 2009

Shah, P. N., Mobed, D., Spakovszky, Z S., Brooks, Thomas F., Humphreys, William M., Aero-Acoustics of Drag Generating Swirling Exhaust Flows, AIAA Journal April, 2010

Berton, Jeffrey J. Envia, Edmane, Burley, Casey, An Analytical Assessment of NASA's N+1 Subsonic Fixed
15th AIAA/CEAS Aeroacoustics Conference (30th AIAA Aeroacoustics Conference), 05/11/09-05/13/09, Miami, FL, AIAA-2009-3144

Brooks, Thomas F., Humphreys, William M., Plassman, Gerald E., DAMAS Processing for a Phased Array Study in the NASA Langley Jet Noise Laboratory, 16th AIAA/CEAS Aeroacoustics Conference, 06/07/10-06/09/10, Stockholm, SE., AIAA 2010-3780

Czech, Michael J., Thomas, Russell H., Elkoby, Ronen, Propulsion Airframe Aeroacoustic Integration Effects for a Hybrid Wing Body Aircraft Configuration, 16th AIAA/CEAS Aeroacoustics Conference, 06/07/10-06/09/10, Stockholm SE, AIAA 2010-3912

Farassat, Fereidoun, Dunn, Mark H., Tinetti, Ana F., Nark, Douglas M., Open Rotor Noise Prediction Methods at NASA Langley- A Technology Review, 15th AIAA/CEAS Aeroacoustics Conference, 05/11/09-05/13/09, Miami, FL

Gerhold, Carl H., Jones, Michael G., Brown, Martha C., Nark, Advanced Computational and Experimental Techniques for Nacelle Liner Performance Evaluation, 15th AIAA/CEAS Aeroacoustics Conference, 05/11/09-05/13/09, Miami, FL

Doty, Michael J., and Haskin, Henry H., Investigation of Flow Conditioners for Compact Jet Engine Simulator Rig Noise Reduction, 17th AIAA/CEAS Aeroacoustics Conference, 06/06/11-06/08/11, Portland, OR, AIAA 2011-2791

Doty, Michael J., Investigation of Twin Jet Aeroacoustic Properties in the Presence of a Hybrid Wing Body Shield, 18th AIAA/CEAS Aeroacoustics Conference, 06/04/12-06/06/12, Colorado Springs, CO, AIAA 2012-2157

Czech, Michael J., Thomas, Russell H., Elkoby, Ronen, Propulsion Airframe Aeroacoustic Integration Effects for a Hybrid Wing Body Aircraft Configuration, International Journal of Aeroacoustics, Vol. 11, No. 3+4, 2012.

Thomas, Russell H., Burley, Casey L., Olson, Erik D., Hybrid Wing Body Aircraft System Noise Assessment with Propulsion Airframe Aeroacoustic Experiments, International Journal of Aeroacoustics, Volume 11, number 3+4, 2012

Gatlin, Gregory M., Vicroy, Dan D., and Carter, Melissa B., Experimental Investigation of the Low-Speed Aerodynamic Characteristics of a 5.8-Percent Scale Hybrid Wing Body Configuration, 30th AIAA Applied Aerodynamics Conference, 25 - 28 June 2012, New Orleans, Louisiana, AIAA 2012-2669.