

Recent Progress In Engine Noise Reduction Technologies

ABSTRACT

Highlights from NASA-funded research over the past ten years for aircraft engine noise reduction are presented showing overall technical plans, accomplishments, and selected applications to turbofan engines. The work was sponsored by NASA's Advanced Subsonic Technology (AST) Noise Reduction Program. Emphasis is given to only the engine noise reduction research and significant accomplishments that were investigated at Technology Readiness Levels ranging from 4 to 6. The Engine Noise Reduction sub-element was divided into four work areas: source noise prediction, model scale tests, engine validation, and active noise control. Highlights from each area include technologies for higher bypass ratio turbofans, scarf inlets, forward-swept fans, swept and leaned stators, chevron/tabbed nozzles, advanced noise prediction analyses, and active noise control for fans. Finally, an industry perspective is given from General Electric Aircraft Engines showing how these technologies are being applied to commercial products. This publication contains only presentation vu-graphs from an invited lecture given at the 41st AIAA Aerospace Sciences Meeting, January 6-9, 2003.

Recent Progress in Engine Noise Reduction Technologies

Dennis Huff, NASA Glenn Research Center
Philip Gliebe, GE Aircraft Engines

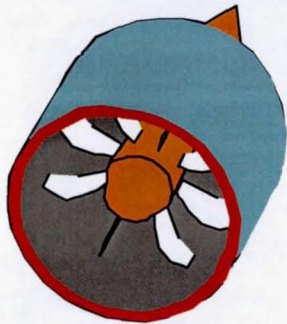
**41st AIAA Aerospace Sciences Meeting
January 6-9, 2003**

Advanced Subsonic Technology

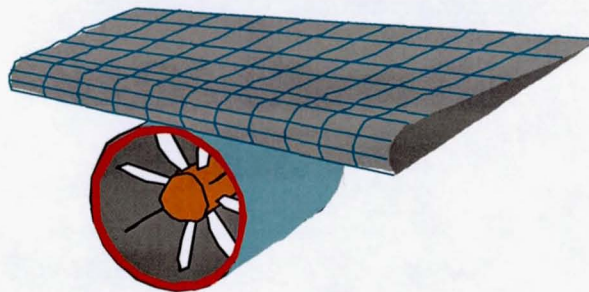
Noise Reduction

SUBELEMENTS

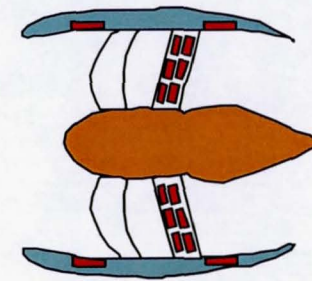
Engine Noise Reduction



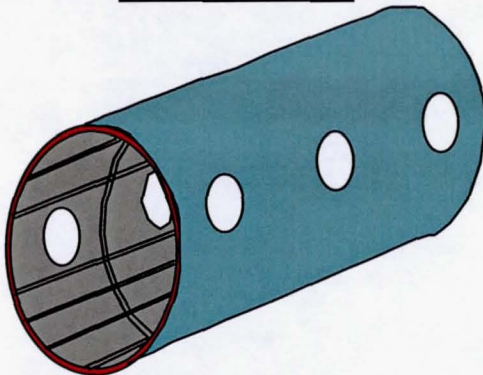
Acoustic/Aerodynamic Integration and System Evaluation



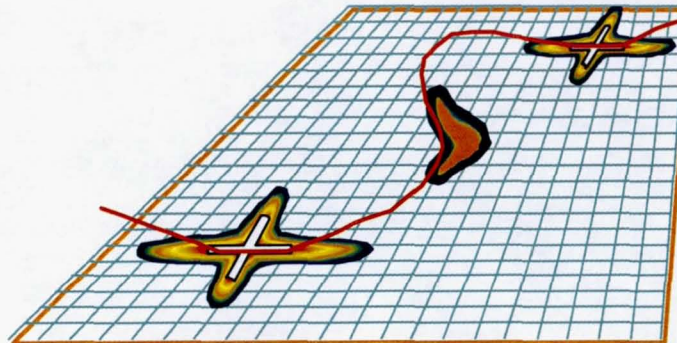
Nacelle Aeroacoustics



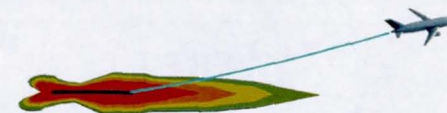
Interior Noise Reduction



Community Noise Impact



Technical Working Group



AAAE.....Morris*
Allison.....Dalton*
ALPA.....Davis*
ATA.....Young*
Boeing.....Craig*/Reed
Cessna.....Navaneethan
Delta.....Brown*
DFW.....Robertson*
GE.....Gliebe*
Goodrich.....Yu*
GTRI.....Ahuja
Gulf. Aero.....Hilton*
HMMH.....Miller

Honeywell.....Weir*
L&Brown.....Woosley
Lockheed.....Kuntz*/Golbe
MIT.....Clark/Waitz
N.O.I.S.E.....Burton*
Northrop.....Parente*/Schien
O'Hare.....Arman*
P&W.....Lord*/Morin
Sikorsky.....Millott
United.....Kastenhuber*
Univ.Ms.....Seiner
Vought.....Russell
 Williams.....Defever
Wyle.....Sharp

Ex-Officio:

NASA...Tenney
FAA.....Burleson

NASA
Bangert
Golub
Grady
Horne
Huff
Law
Posey
Powell
Shepherd
Silcox
Singer
Whitfield
Willshire
FAA
Skalecky

*Ad Hoc Steering Committee

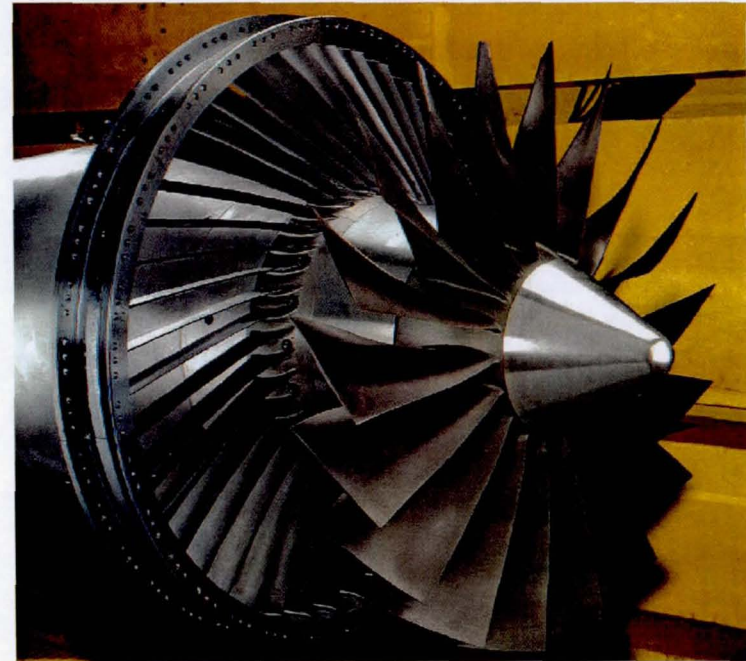


Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Engine Noise Reduction & Nacelle Aeroacoustics

GOAL: Provide technology for lowering engine noise while maintaining high performance for advanced turbofan engines.



Objectives

- 6 dB engine source noise reduction relative to 1992 technology
- ~2 dB from nacelle improvements (liners, etc.)

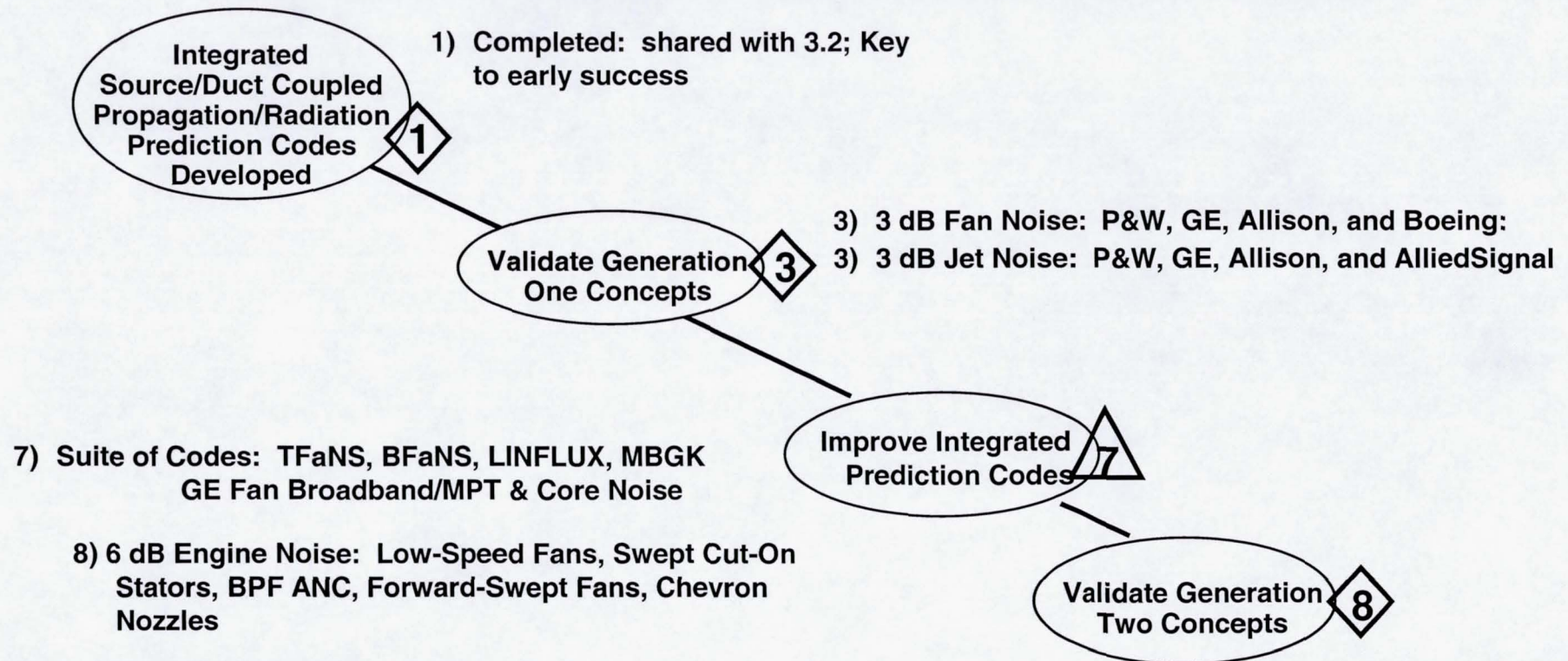


Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

ENGINE NOISE REDUCTION SUBELEMENT ROADMAP

FY94	FY95	FY96	FY97	FY98	FY99	FY00
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LEVEL 1 MILESTONES & DELIVERABLES:

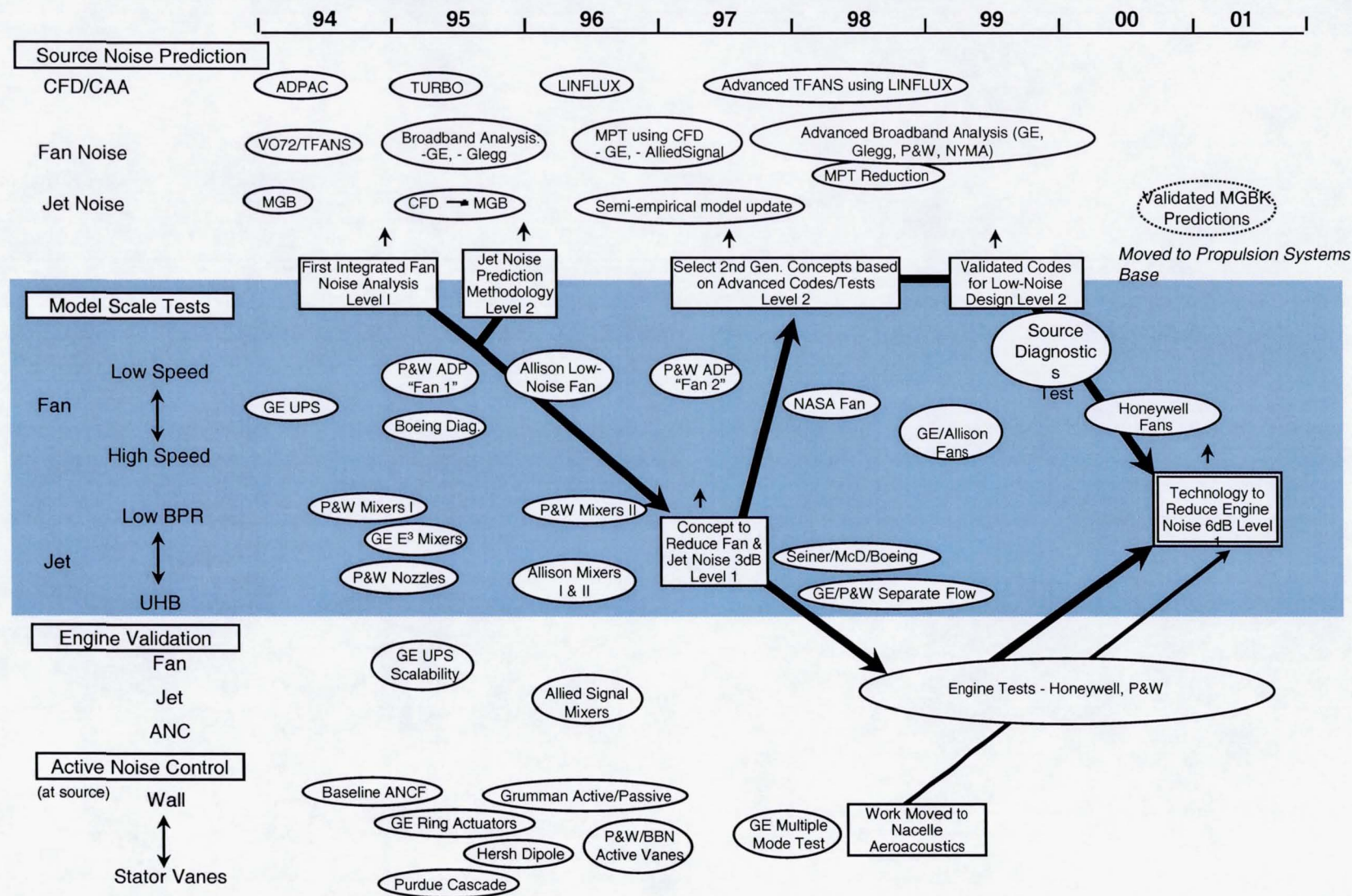
- ◆ First integrated fan noise source and propagation prediction code
- ◆ Concepts validated for 3 dB jet noise for 1.5-6 bypass ratio engines and 3 dB fan noise reduction relative to 1992 technology
- ▲ Validated codes for fan/jet/core low noise design
- ▲ Technology to reduce engine noise 6 dB relative to 1992 technology



Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Engine Noise Reduction Research Plan

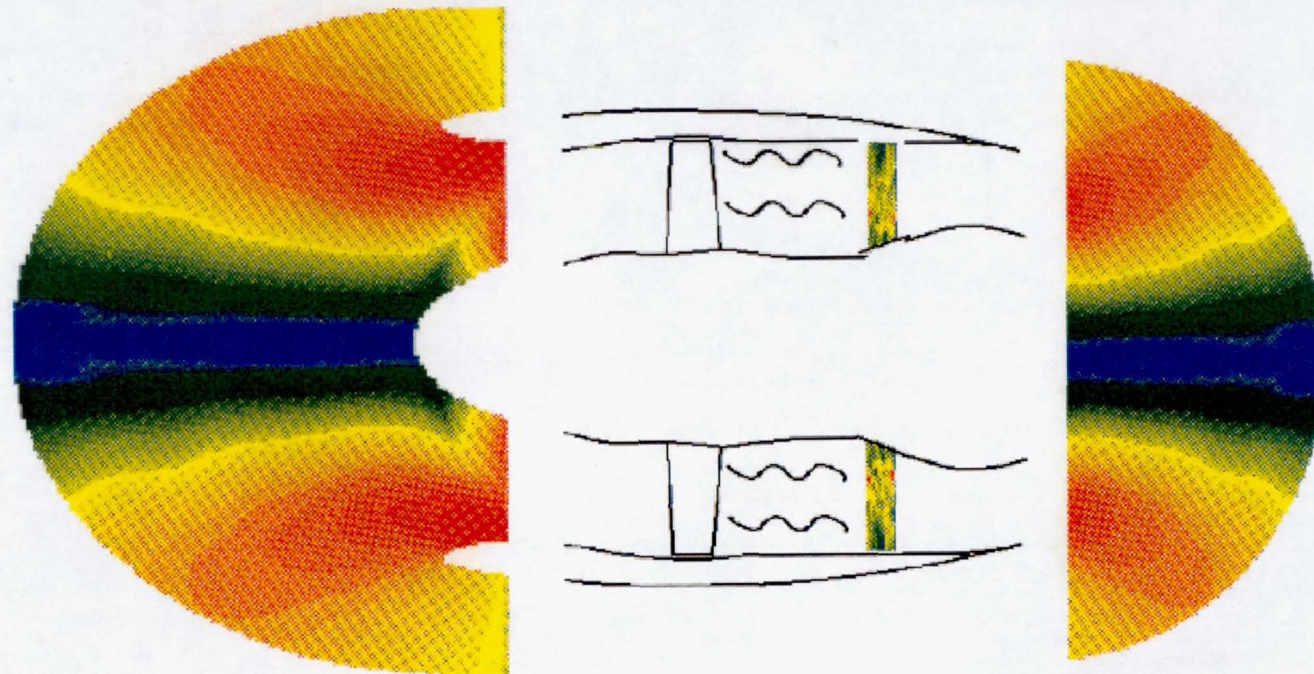


Source Noise Prediction

First Integrated Fan Noise Source and Propagation Prediction Code (1994)

TFaNS: **T**heoretical **F**an **N**oise **D**esign/**P**rediction **S**ystem

Joint Development By P&W/UTRC/NASA For Fully Coupled Interaction Tone Prediction



RADIATION

1994	Eversman Inlet/Aft Code
1996	Improved Eversman Code Caruthers Inlet/Aft Code
1998	Asymmetric Code

SOURCE

Classical Flat Plate Theory
LINFLUX : 3D Linearized Euler Code
TURBO : 3D Navier-Stokes Code Linear/Non-Linear



Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Engine Noise Reduction - Prediction Tools

Level 2 Milestone (2Q, 99): *Validated codes for fan/jet/core low noise design*

Fan Noise Source Models:

V072, TfaNS(SOURCE3D, CUP3D)

LINFLUX, TURBO, CFL3D => tone noise

BfaNS, Envia/Mani/Glegg => broadband noise

GE MPT Analysis

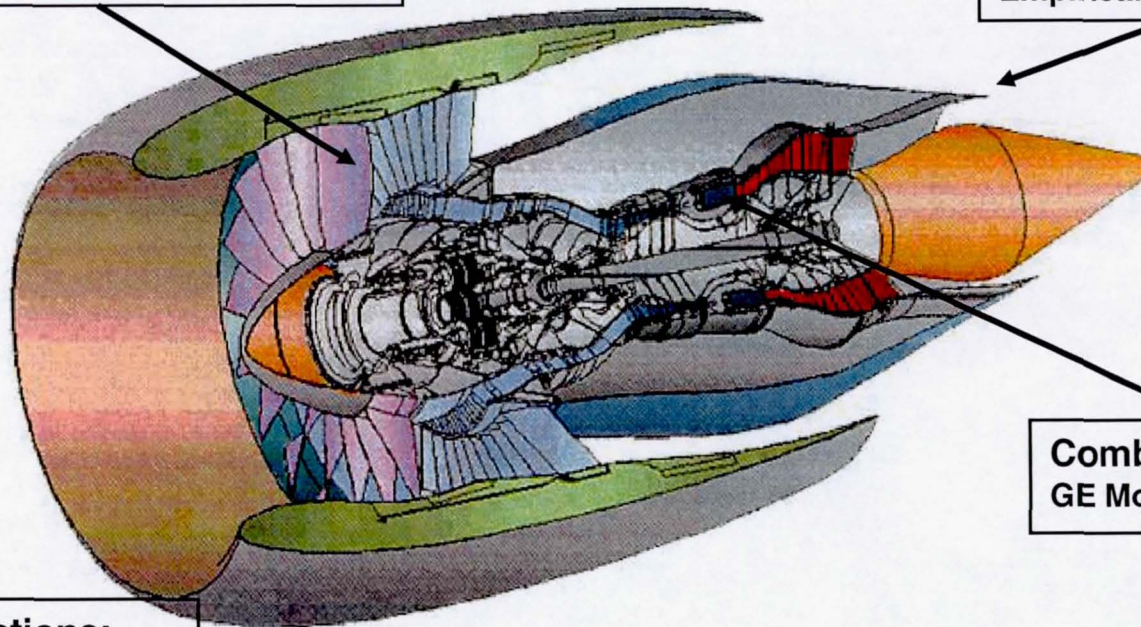
Jet Noise Models:

MGBK Code,
Empirical Codes

Combustion Noise:
GE Model

Directivity Predictions:

Eversman, Caruthers, TBIEM3D,
RDIFF/CDUCT, Rice



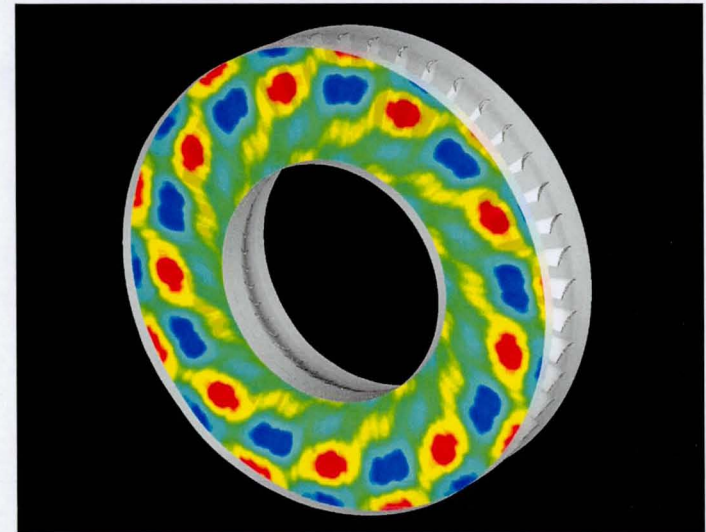
Fan Noise Prediction

Can predict stator noise fairly accurately but not the rotor noise.

➤ **Tone Noise: LINFLUX Code**

- ***Pros: 3D, Realistic flow & geometry
Captures quantitative details***
- ***Cons: Separate computation for mean flow
One frequency at a time***

Tone Power Level (dB)		
Mode	Theory	Data
1	113	114
2	100	100
3	101	106
4	102	101
Total:	114	115



➤ **Broadband Noise: BFaNS Code**

- ***Pros: Captures basic trends***
- ***Cons: Quasi-3D, simplistic flow & geometry
Inaccurate details***

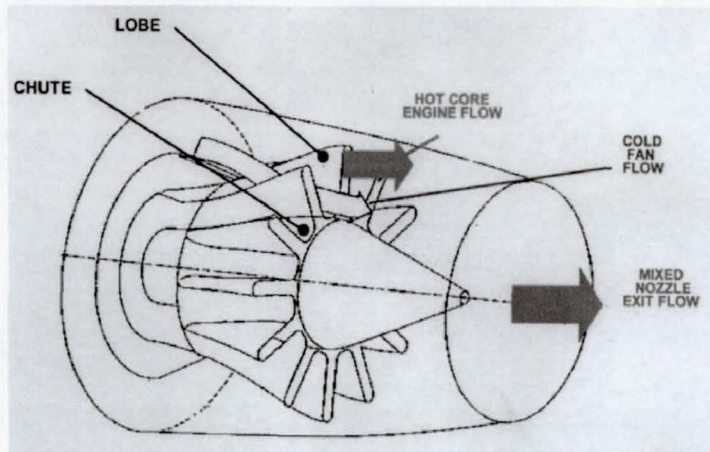
Total Power Level (1-50 kHz)			
Inlet		Exhaust	
Theory	Data	Theory	Data
121	121	123	124

Jet Noise Prediction

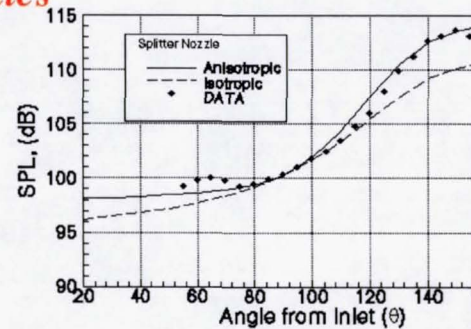
MODIFIED “MGB” CODE, now called “MGBK”

Combines CFD solutions with modeling of noise sources to predict far-field acoustics

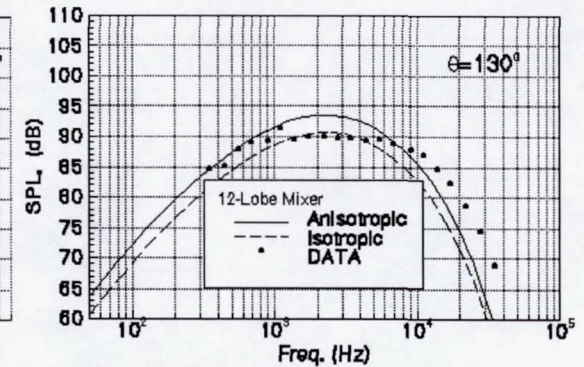
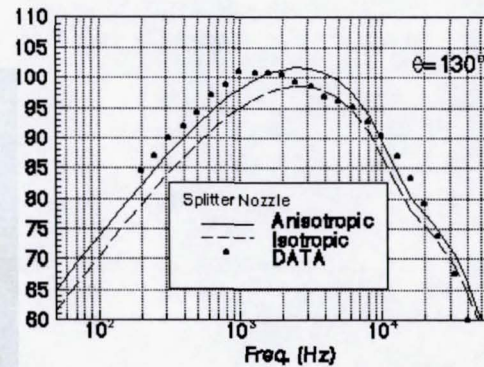
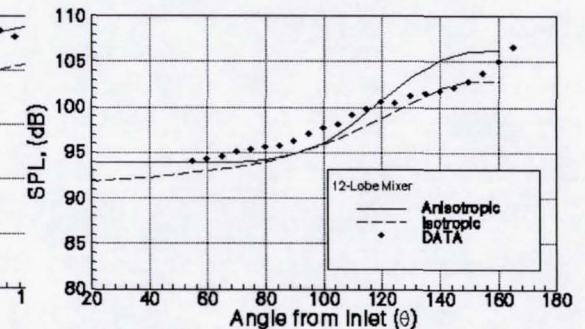
- Small-scale turbulence noise
- External mixing noise only
- Accounts for both self and shear noise
- Non-isotropic turbulence
- Can be extended to a 3D geometry (assumes flow is locally axisymmetric)



Splitter Nozzle



12-Lobe Mixer



Isotropy: $L_2 / L_1 = 1, \quad \overline{u_2^2} / \overline{u_1^2} = 1$

Anisotropy: $L_2 / L_1 = 0.8, \quad \overline{u_2^2} / \overline{u_1^2} = 0.7$

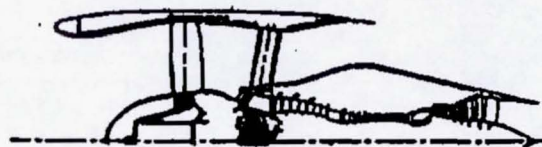
Model Scale Tests

LOW NOISE CYCLE/CONCEPT DEFINITION STUDIES

CONCEPTS SELECTED (1994)

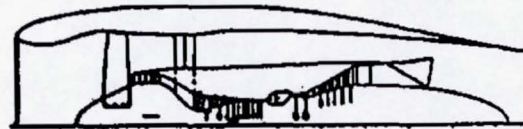
P&W ■ 2nd Generation Advanced Ducted Propulsor (ADP)

- Variable pitch
- Low tip speed
- High loading



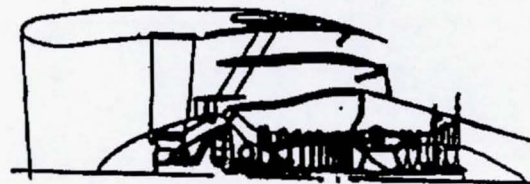
GE ■ Extensions of GE-90 Technology for Lower Noise

- Fixed pitch
- High tip speed
- Long duct, mixed flow
- Blade sweep



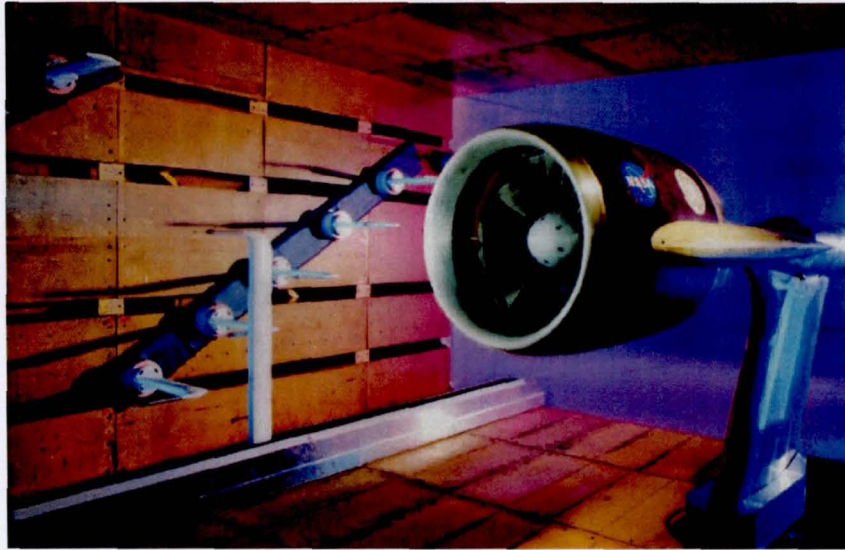
ALLISON ■ Ultra High Bypass for Short-Haul Applications

- Fixed pitch
- Low tip speed
- Swept stator



Fan Tests in the 9'x15' Wind Tunnel

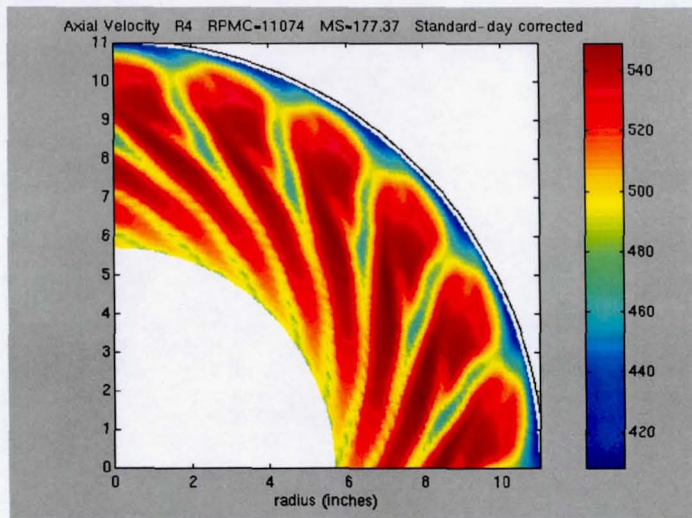
Comprehensive Tests of Many Model Fan/Nacelles Obtaining Aerodynamic, Acoustic & Structural Data



GE Universal Propulsion Simulator (1994)



P&W Advanced Ducted Propulsor (1995, 1996)

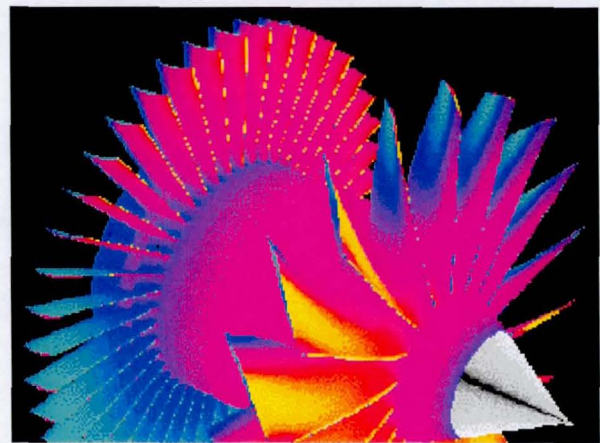


Detailed Flow Measurements

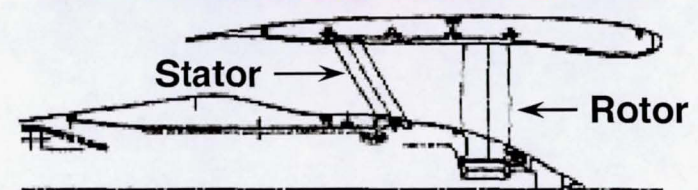
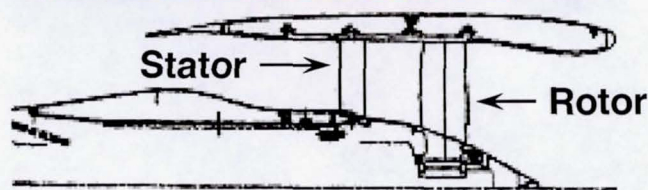
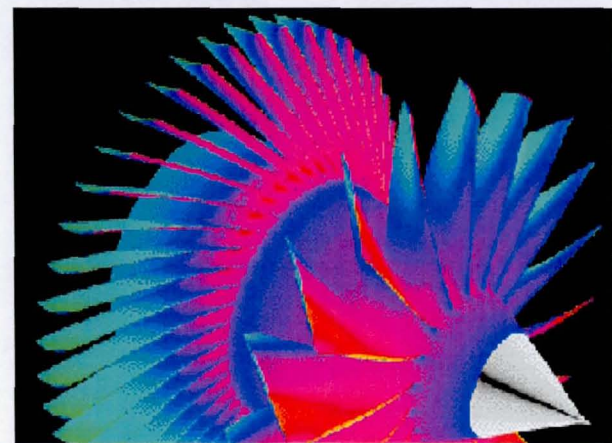
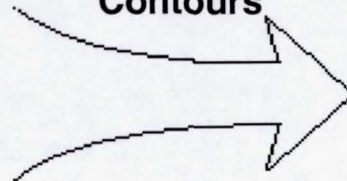


NASA Alternate Low Noise Fan (1997)

LOW-NOISE SWEEP AND LEANED STATORS DESIGN



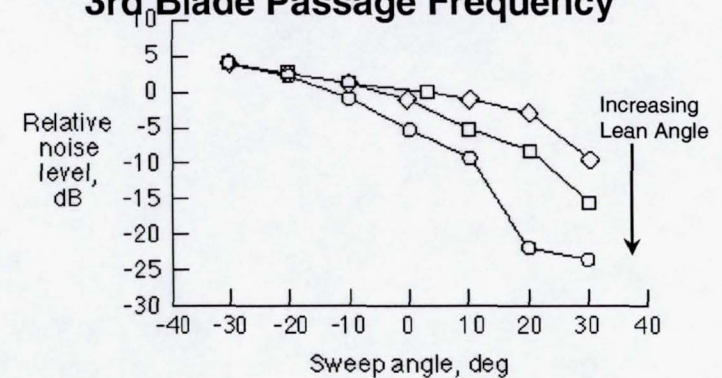
Static Pressure
Contours



- Numerical predictions indicate that interaction tones can be reduced to broadband noise levels of a fan
- Optimal sweep/lean designs predicted to meet 3 EPNdB fan noise reduction LI Milestone (1Q97)
- 22 inch model fan hardware tested in 9 x 15 Wind Tunnel, results verify predictions

Predicted Dominant Fan Tone

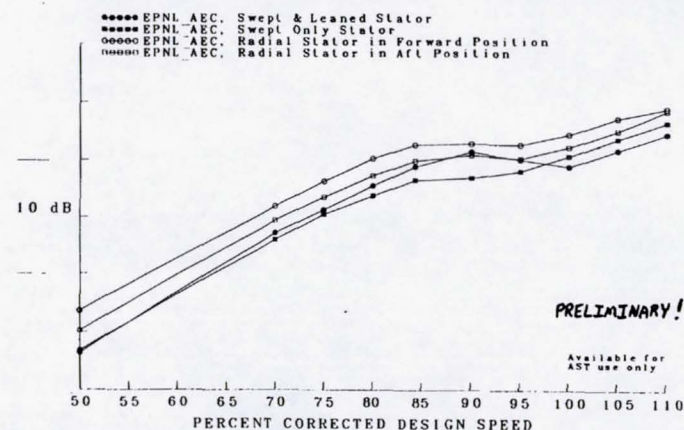
3rd Blade Passage Frequency



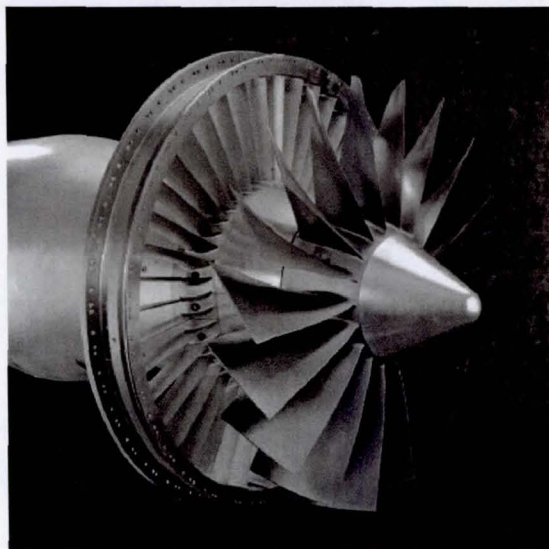
NASA/Allison Low-Noise Fan in 9x15 Wind Tunnel (1996)



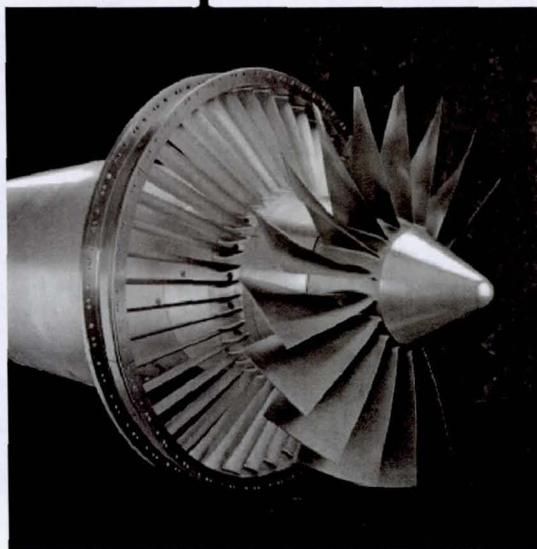
SIDELINE EPNL LEVELS FOR ALLISON FAN IN LeRC 9x15 LSWT
FICTITIOUS 2-ENGINE AIRCRAFT AND FLIGHT PATH
SCALE FACTOR = 3.5, $M = 0.25$
MAXIMUM EPNL FOR OBSERVER ON 2000 FT. SIDELINE



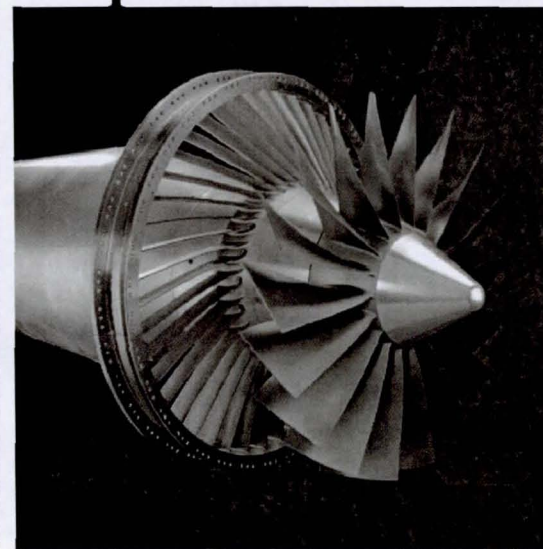
Baseline



Swept Stators



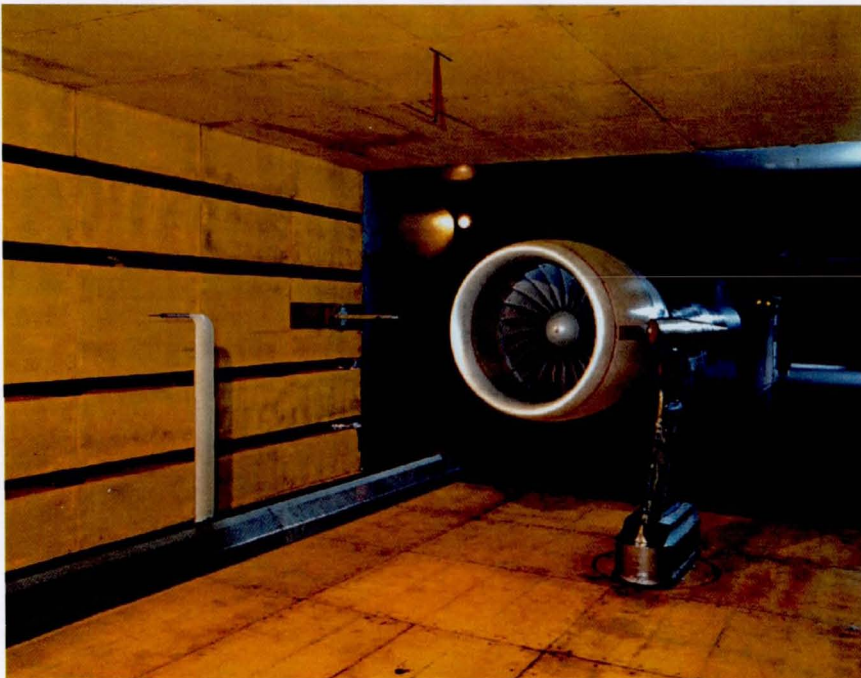
Swept/Leaned Stators



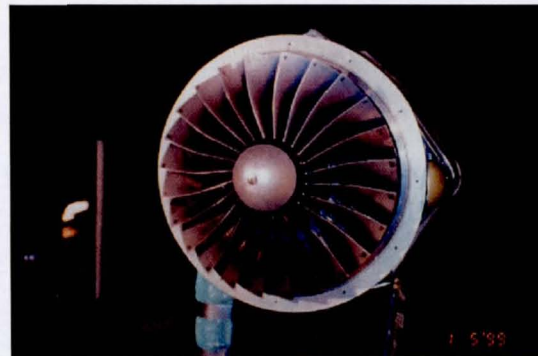
GE/Allison/NASA High Speed Fan Test (1998)

Objectives

- Demonstrate benefits of swept/leaned stators with high tip speed fans
- Determine “buzz saw” noise reduction using a forward-swept fan
- Supports 6dB engine noise reduction milestone in AST Noise Reduction Progr



9x15 Wind Tunnel Installation



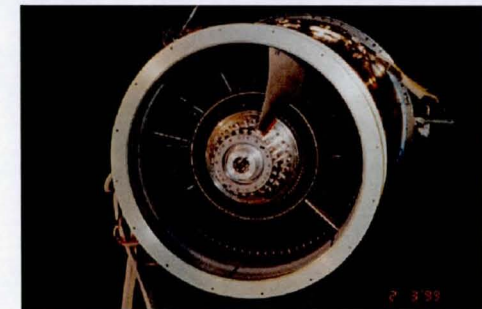
Wide-Chord Baseline Fan



Forward-Swept Fan



Shrouded Fan (GE Proprietary)



Swept & Leaned Stators



Engine Noise Reduction

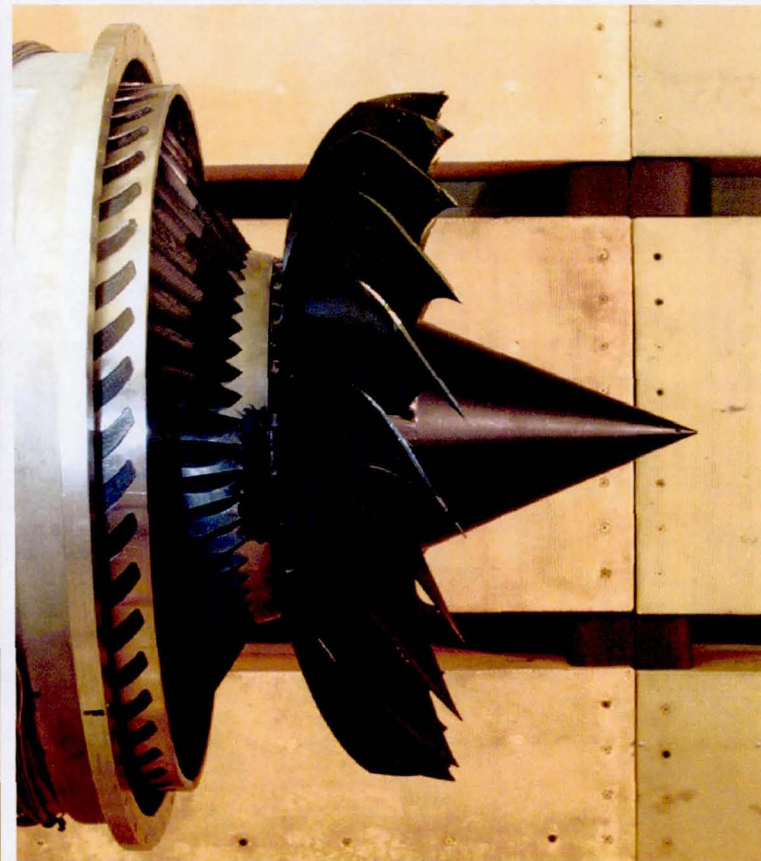
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Honeywell Quiet High Speed Fan (2000)

Baseline Fan



QHSF Fan

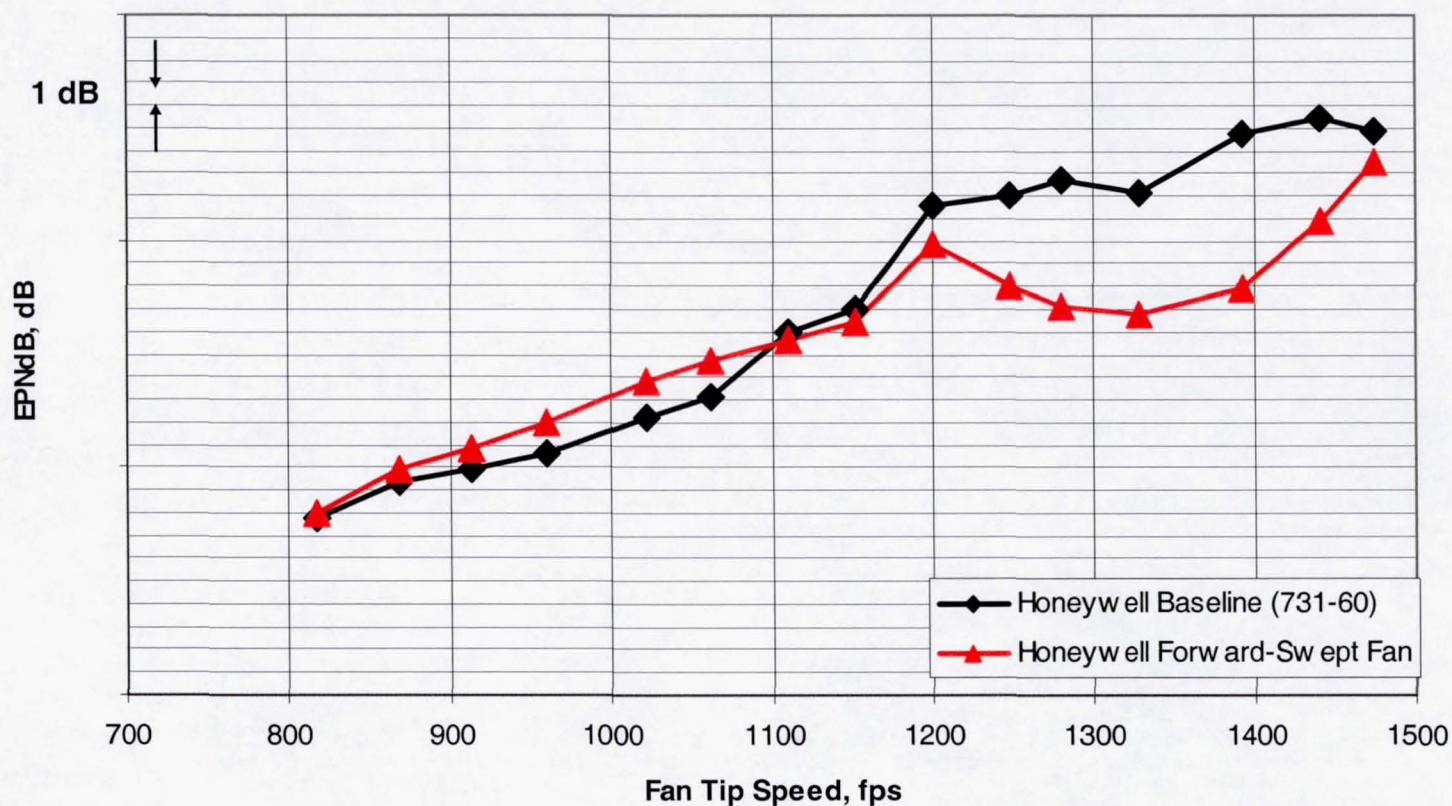




Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

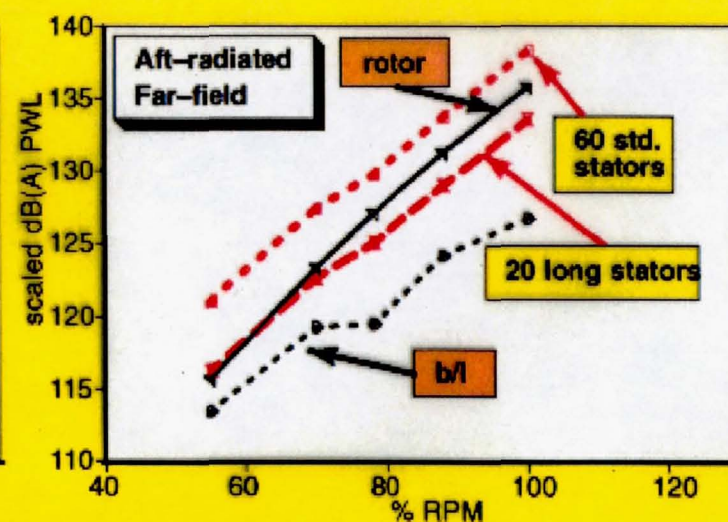
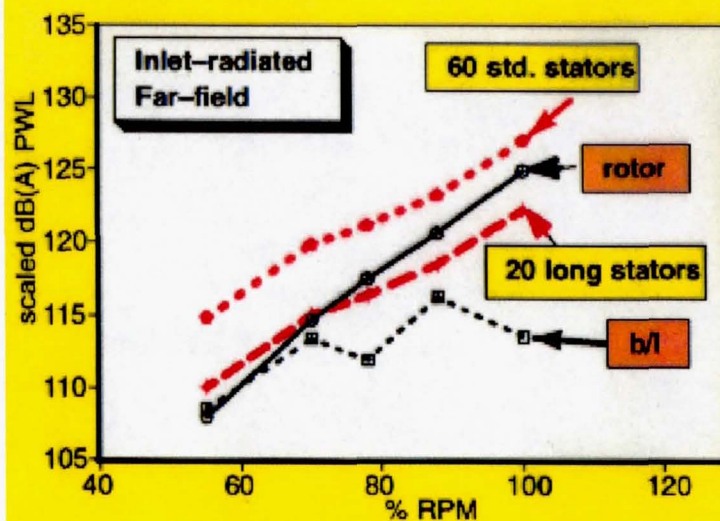
Noise Comparisons: 1500' Flyover, 30.7" Diameter Fan, Matched Thrust





Boeing 18-Inch Fan Rig Test Results (1995)

Components of Fan Broadband Noise





Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Source Diagnostics Fan Test in 9'x15' Wind Tunnel (1999)

Joint effort w/Glenn, Langley, GE & Boeing
2 Fans/3 Stator Combinations

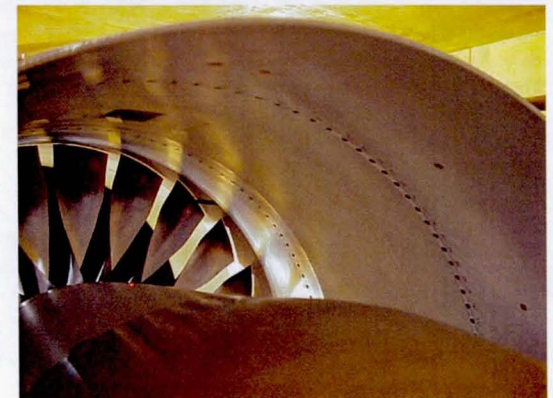
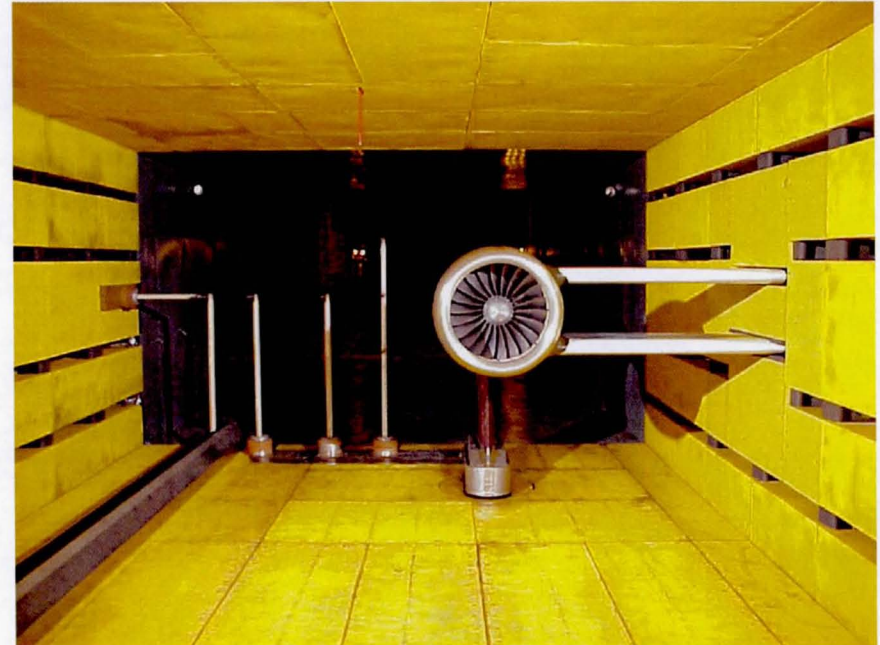
- “R4” Early GE-90 Design
- “M5” Higher Tip Speed, Matched P(r)
- Radial “Cutoff” Stators
- Radial “Cuton” Stators
- “Cuton” Swept Stators

Rotor-Alone Tests

- Self-Centering Nacelle Suspension System
- Maintained Stringent Fan Tip Clearances

Comprehensive Data Base

- Aerodynamic Performance
- Unsteady Surface Pressures on Stators
- LDV & Two-Point Hot Wire Flow Measurements
- Wall & Rotating Microphone Duct Mode Measurements
- Sideline Acoustics





Engine Noise Reduction

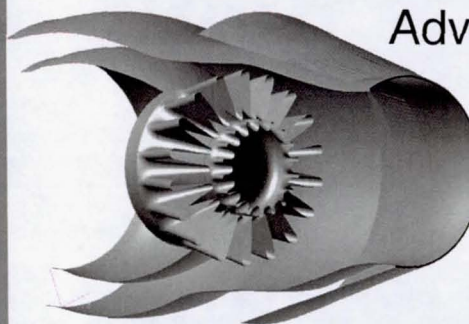
Aerospace Vehicle Systems Technology Program

Jet Noise - Full Scale Mixer Demonstration

- Showed 3 EPNdB jet noise benefit
- Validated design from MGB Code
- Attempted source separation using three-signal coherence technique
- Characterized exhaust plume T/P profile using the NASA Glenn rake
- Evaluated engine performance

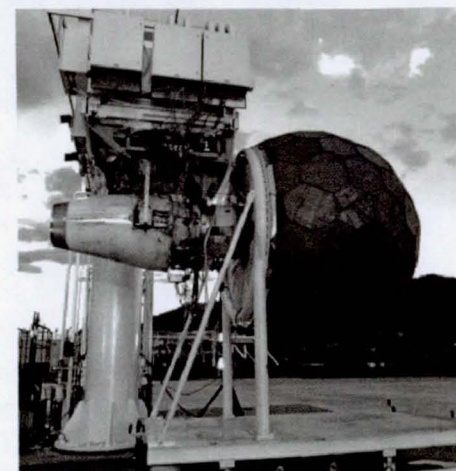
Three Test Configurations

TFE731-40 nozzle
Advanced Solid Mixer
Advanced Porous Mixer



Baseline Configuration	Compound nozzle with C-D exit
Takeoff Bypass Ratio	3.48
Primary jet Velocity	1600 ft/sec
Primary Jet Temperature	1120F
Secondary Jet Velocity	920 ft/sec
Secondary Jet Temp.	160F

Honeywell
San Tan
Acoustic
Test
Facility

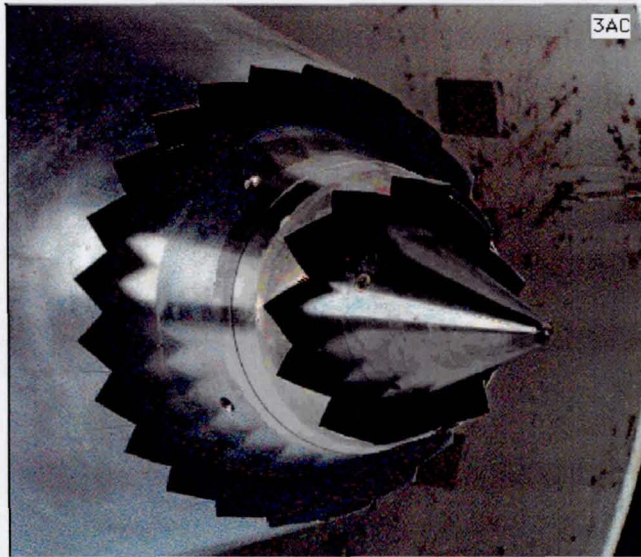


Jet Noise Reduction Research

1997 NASA/GE/P&W Separate Flow Nozzle Test

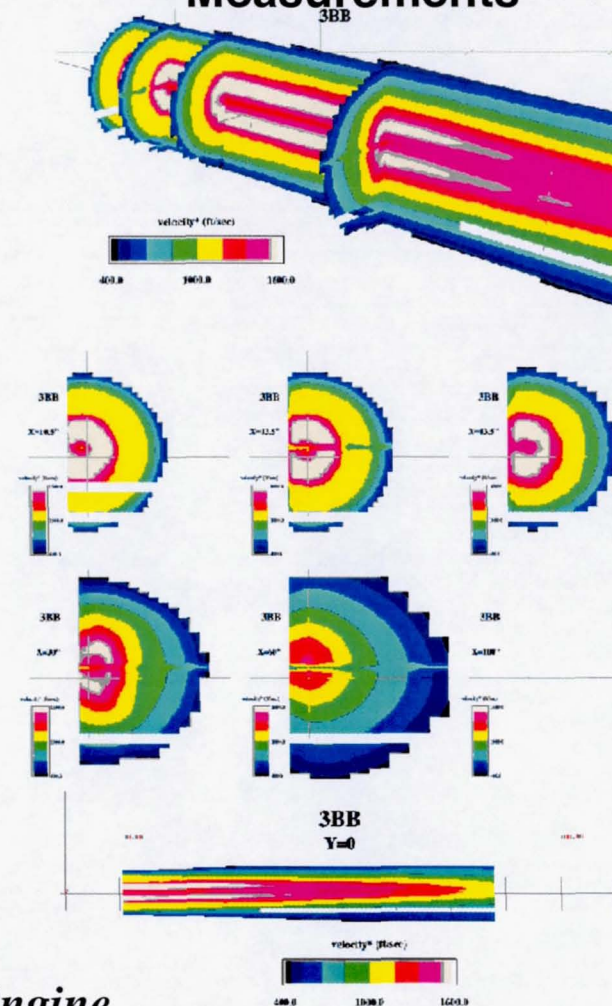
Nozzles of the Future

Fan Chevrons with Core Alternating Chevrons



GE CF34 Engine

Flow Field Measurements

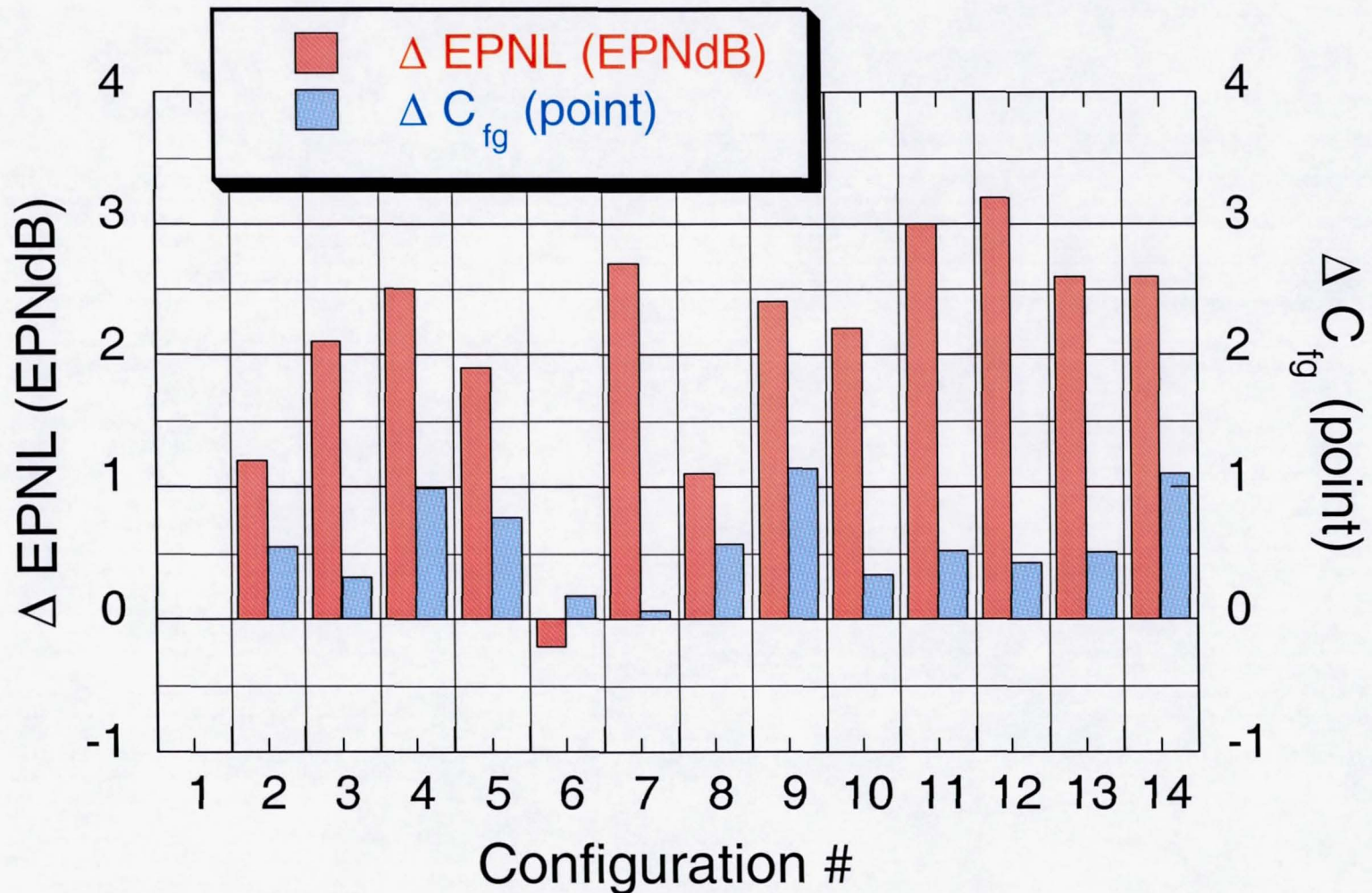




Engine Noise Reduction

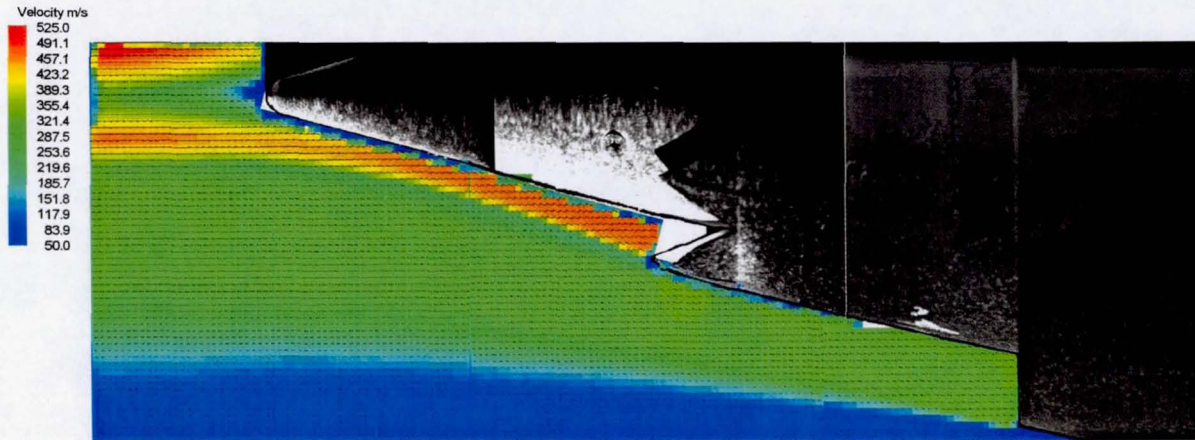
Aerospace Vehicle Systems Technology Program

Noise Reduction From Separate Flow Nozzle Concepts ~3 EPNdB Noise Reduction, Minimal Thrust Loss

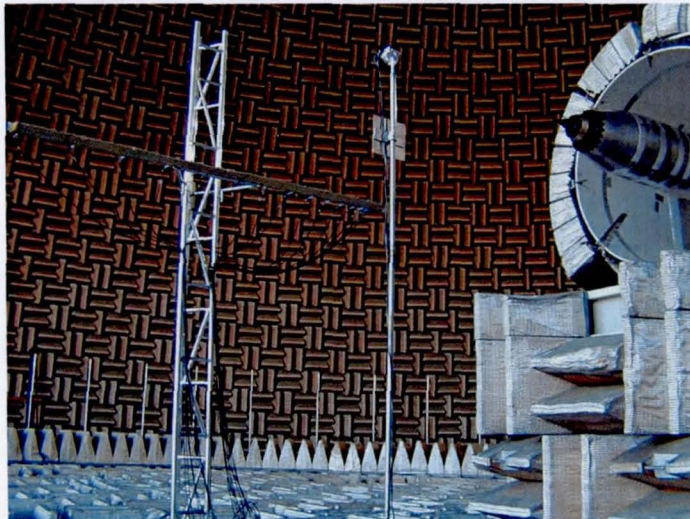


Jet Noise Source Measurements

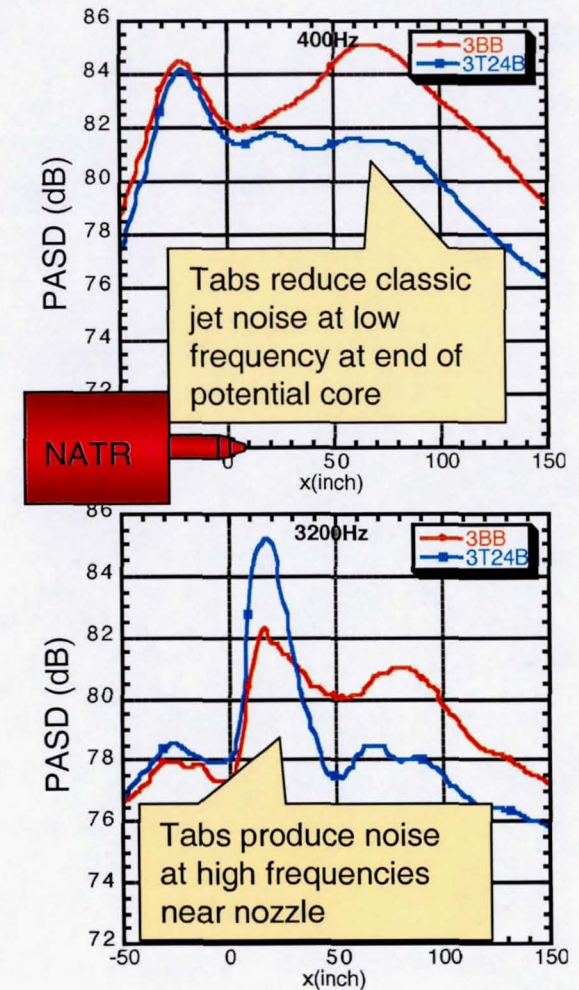
Particle Image Velocimetry, Phase Arrays



2-Component PIV Measurements of Chevron Nozzles
Finally getting turbulence data for hot, high-speed flows!

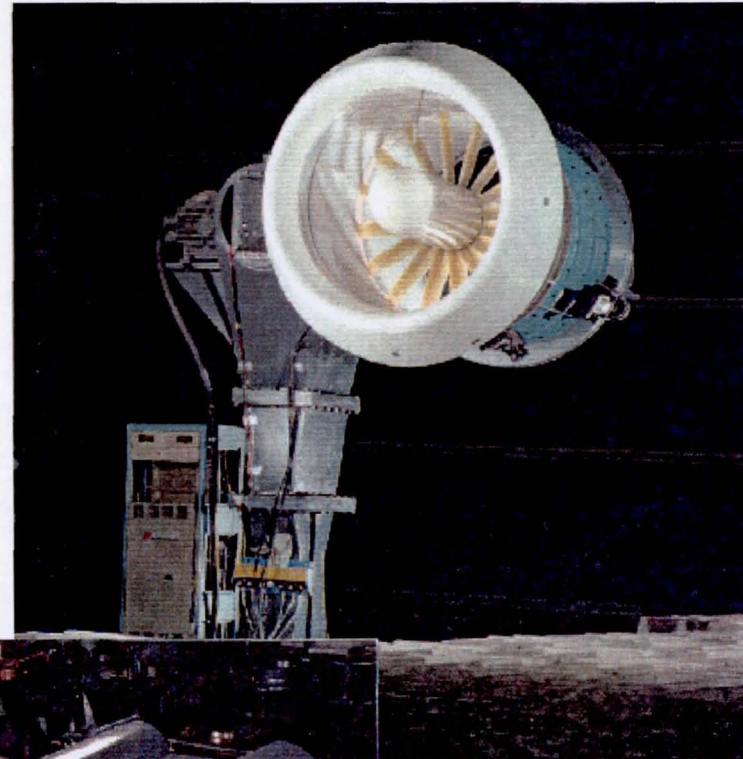
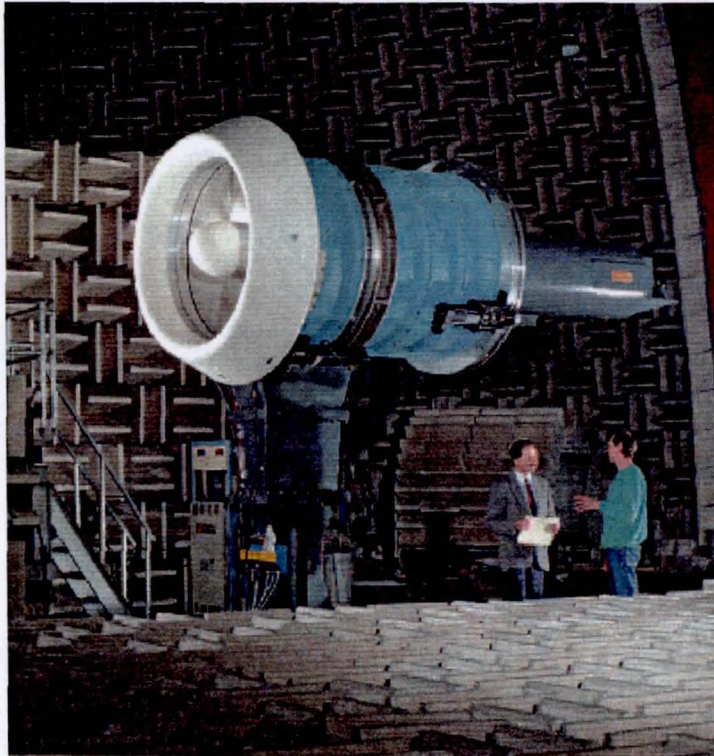


Source Location Using Phased Arrays



Active Noise Control

Active Noise Control Fan (ANCF)



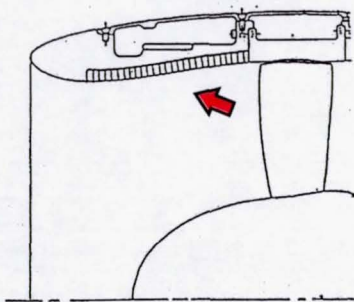
Fan Active Noise Control – ANCF Tests

Concept	Contractor	Targeted Mode(s)	Freq.	Direction	Test Date
Wall Actuators, Plate Radiators in ring	GE, CR&D	(6,0)	2BPF	Ex.	6-9/95
Active Resonators	HAE (Hersh Acoustical Engineering)	(4,0), (4,1) (2,0)	2BPF 1BPF	In.	1/96
Control Near Source, Wall Actuators up & downstream of Vanes	HAE	(4,0), (4,1)	2BPF	In. + Ex. (global)	3/96
Hybrid Active/Passive	Northrop Grumman/HAE	(4,0), (4,1)	2BPF	In.	3-4/96
On Scale Model P&W Fan		(9,0), (9,1)	2BPF	In.	11/96
Control at the Source "Active Vanes"	BBN (UTRC, P&W, Purdue)	(4,0), (4,1)	2BPF	In. + Ex. (global)	7/97
Wall Actuators (high radial orders)	GE, CR&D, HAE, BYU	(2,0), (2,1), (2,2) (2,0), (2,1), (2,2), (2,3)	2BPF	In./Ex. In.	6-9/98 +1/99
Wall Actuators (high order, global)	HAE, CEST	(2,0), (2,1), (2,2) (2,0), (2,1), (2,2), (2,3)	2BPF	In. + Ex. (global)	3/99
Active Vanes (high order, global, control simplification)	BBN, HAE	(2,0), (2,1), (2,2) (2,0), (2,1), (2,2), (2,3)	2BPF	In. + Ex. (global)	5-6/01

Fan Noise Reduction Research

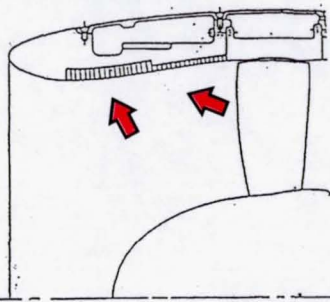
1996 NASA/Northrop Grumman Active Noise Control Fan Test

**Uniform
Passive**



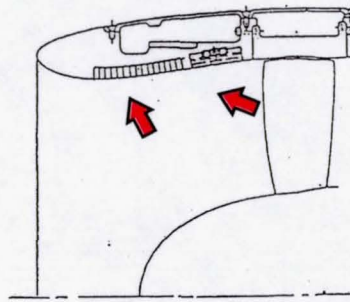
Near Grazing Incidence
Fan Noise; Modest
Overall Attenuation.

**Two Segment
Passive**



Initial Segment
Scatters Modes into
Higher Order Radial
Modes.
Limited Bandwidth of
Attenuation Since
Liner is Efficient only
near Design RPM.

Hybrid Active/Passive



Initial Active Control
Segment Compensates
for Changing Parameters
Resulting from Mode
Mixture Variations with
Fan Speed. High Band-
width of Attenuation.

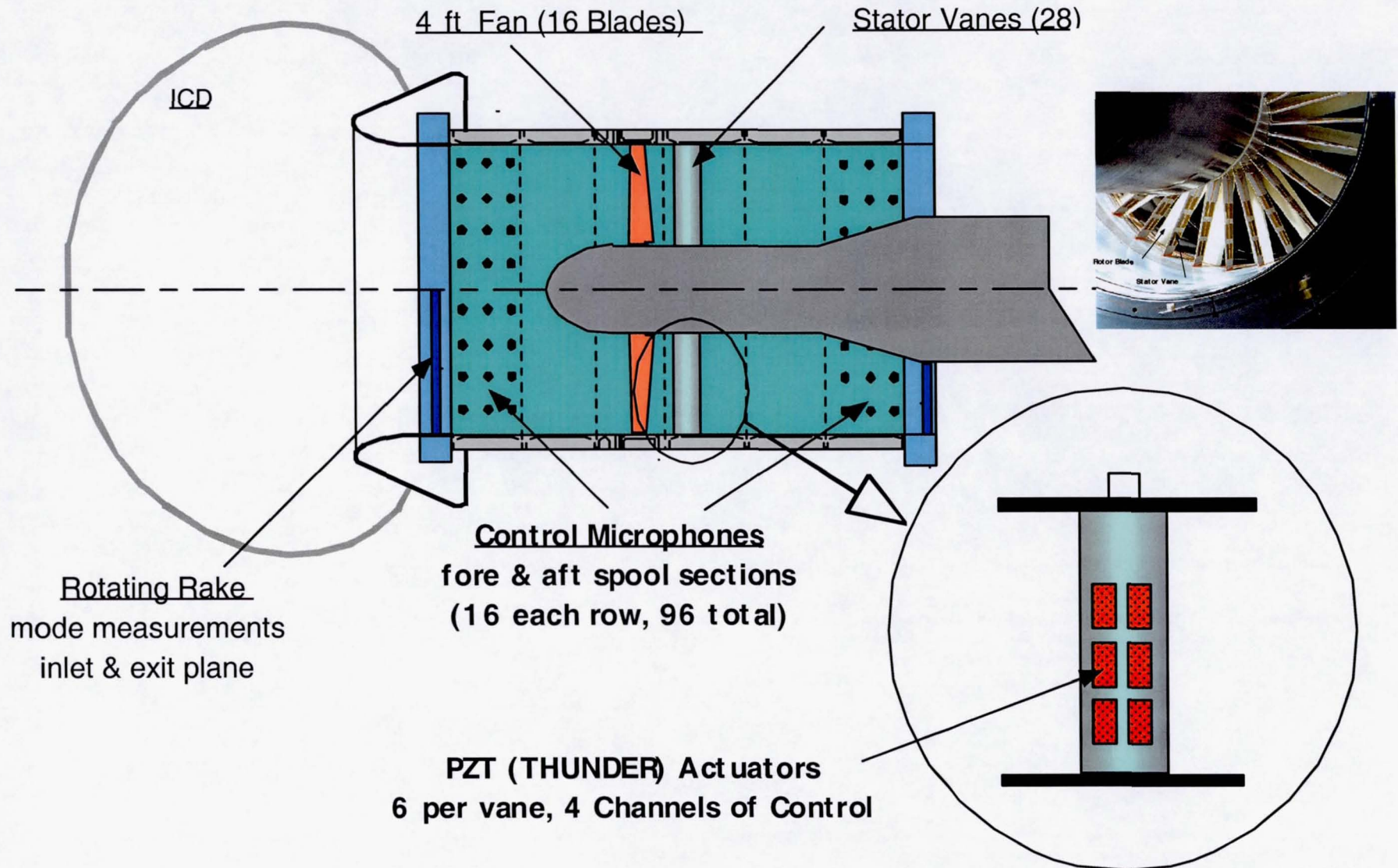
- Superior Performance Relative to Conventional Uniform Passive Liners Over Extended Fan Speeds
- 3 to 10 dB Attenuation Increase Over Uniform Passive Liners for ADP Fan over the Speed Range of 5200 to 6000 RPM



**Northrop Grumman Hybrid
Active/Passive Liner Installed
in the NASA ADP Fan Rig at the
NASA LeRC 9'x15' Wind Tunnel**

Fan Noise Reduction Research

1998 NASA/BBN Active Noise Control Fan Test



Engine Validation



Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

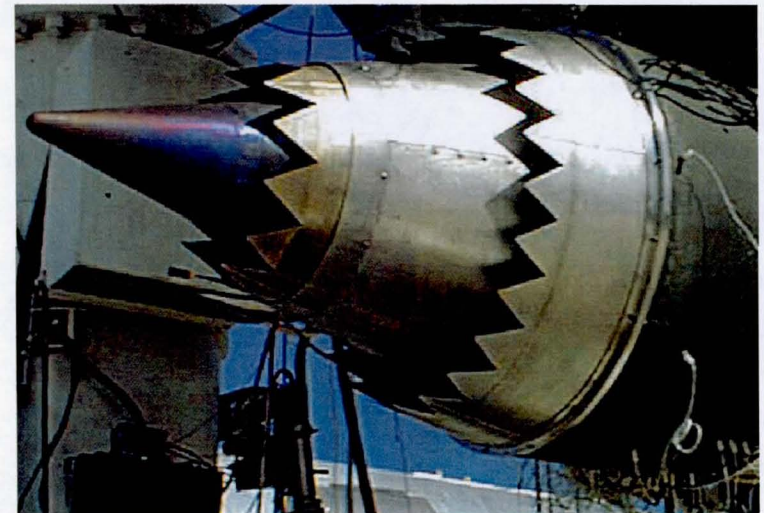
Validate Noise Reduction Technology Through Large-Scale Component Testing (Milestone No. 1A3.1; Due 4Q, FY01)

Milestone met through two static engine tests:

- 1.) Pratt & Whitney PW4098 tested in 1999 and 2001
- 2.) Honeywell TFE731-60 tested in 1999



**PW4098 Engine at C-11 Test
Stand in West Palm Beach**



**TFE731-60 Engine at
San Tan Test Facility**

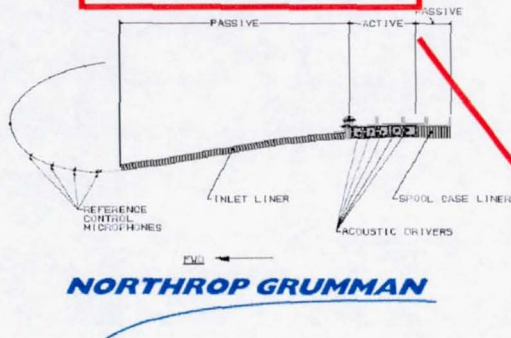


Engine Noise Reduction

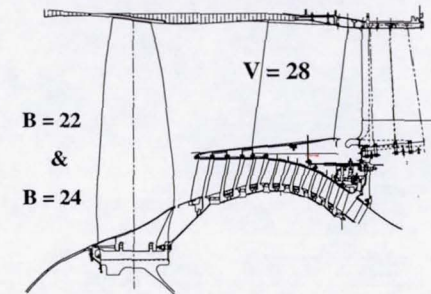
Aerospace Vehicle Systems Technology Program

PW4098 Engine Test

Active-Passive Liner



Fan Blade # Change and Low Number/Cuton FEGV



Scarf Inlet

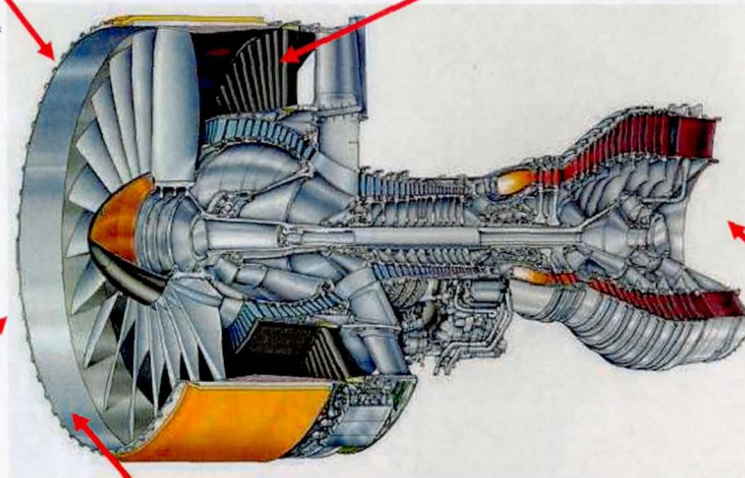


BOEING

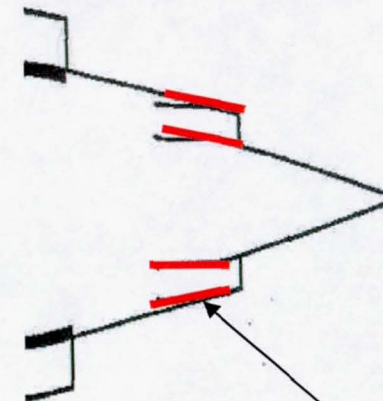


Pratt & Whitney
A United Technologies Company

Advanced PW Fan Case Treatment



Treated Primary Nozzle



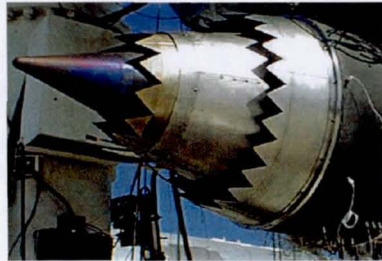
Treatment



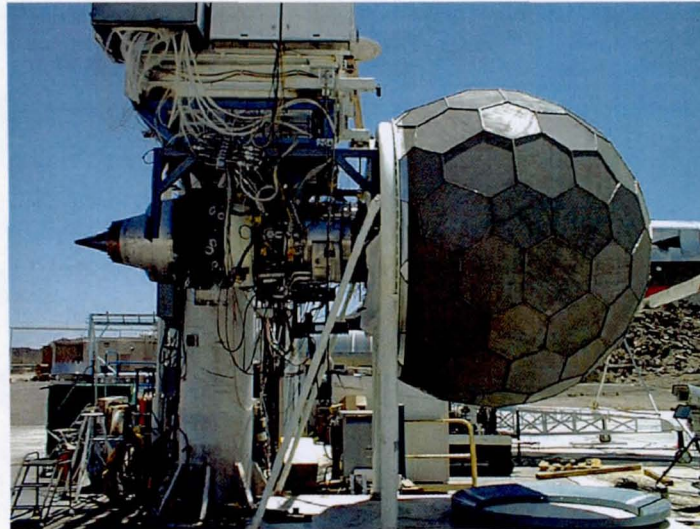
Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Honeywell TFE731-60 Engine Test



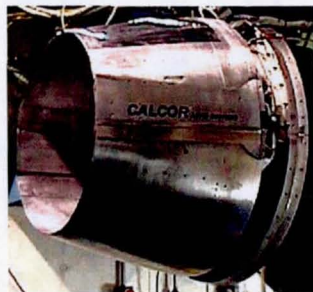
Chevron Nozzles



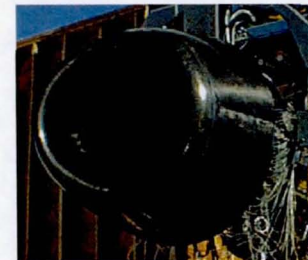
**TFE731-60 Engine with
Inflow Control Device (ICD)**



Rotating Microphone



Variable Area Nozzle



Scarfed Inlet



Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Honeywell EVNRC Flight Demonstration of Noise Reduction Concepts

Objectives

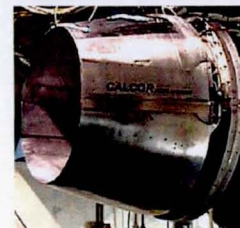
- Demonstrate concepts from static tests will work in flight
- Obtain performance and diagnostic data for QAT concept development

Approach

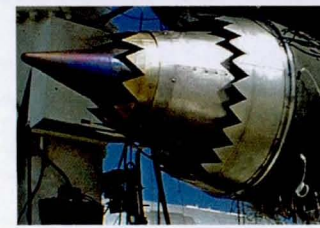
- Conduct flight tests of TFE731-60 engine on Honeywell Falcon 20
- Perform comparisons with existing static data
- Share resources with Glenn, Langley and Boeing

Benefit

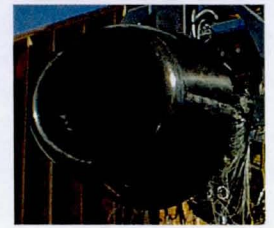
- Concepts fully demonstrated at flight conditions



Variable Nozzle



Chevron Nozzle



Scarf Inlet



Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Engine Noise Reduction Technologies Entering QAT

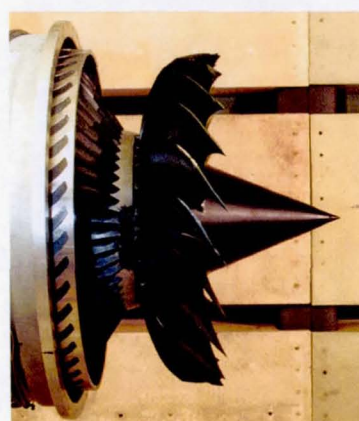
Higher BPR Propulsion



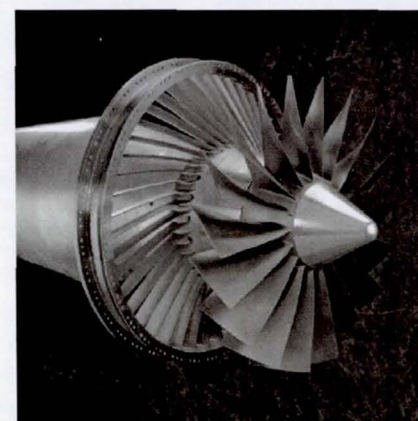
Scarfed Inlets



Forward-Swept Fans



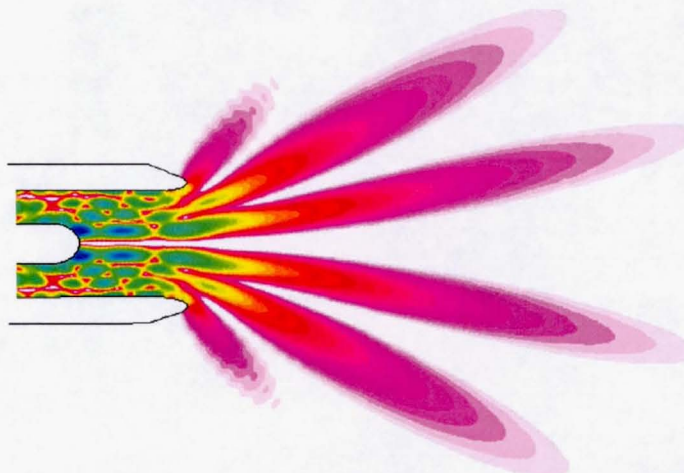
Swept/Leaned Stators



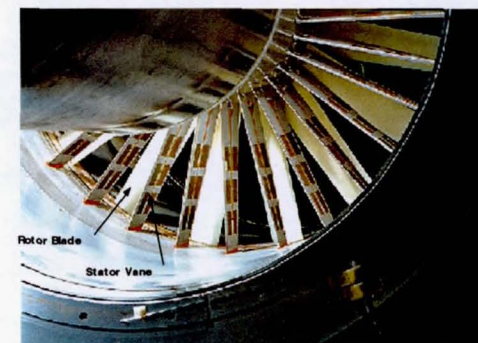
Chevron Nozzles



Noise Prediction



Active Noise Control



NASA AST Noise Reduction Technology

Applications to Product Engines

Philip R. Gliebe
GE Aircraft Engines

AIAA 41st Aerospace Sciences Meeting
January 6-9, 2003
Reno, Nevada



Engine Noise Reduction Technology Programs - Approach

Three - Pronged Approach:

- Detailed Scale Model and Engine Experimental Investigations
- Prediction Model and Code Development To Describe Noise Generation and Reduction Physics - Develop Design Tools
- Propulsion System Acoustic Modeling
 - Concept Benefit Analysis
 - Screening of Most Promising Noise Reduction Concepts



Basic Physics of Engine Noise Generation

Steady Flow



Unsteady Flow

- Rotor Flow Hits a Stator
- Stator Flow Hits a Rotor
- Turbulence - Jets, Boundary Layers, Combustion, etc.



Pressure Waves



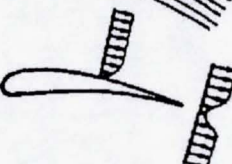
Noise

***“When the source is Clear, the
Solution is near” - NLR***



Fundamentals of Noise Generation

Source Sound Power -
$$W \propto \rho \cdot L^2 \cdot V_{char}^N$$

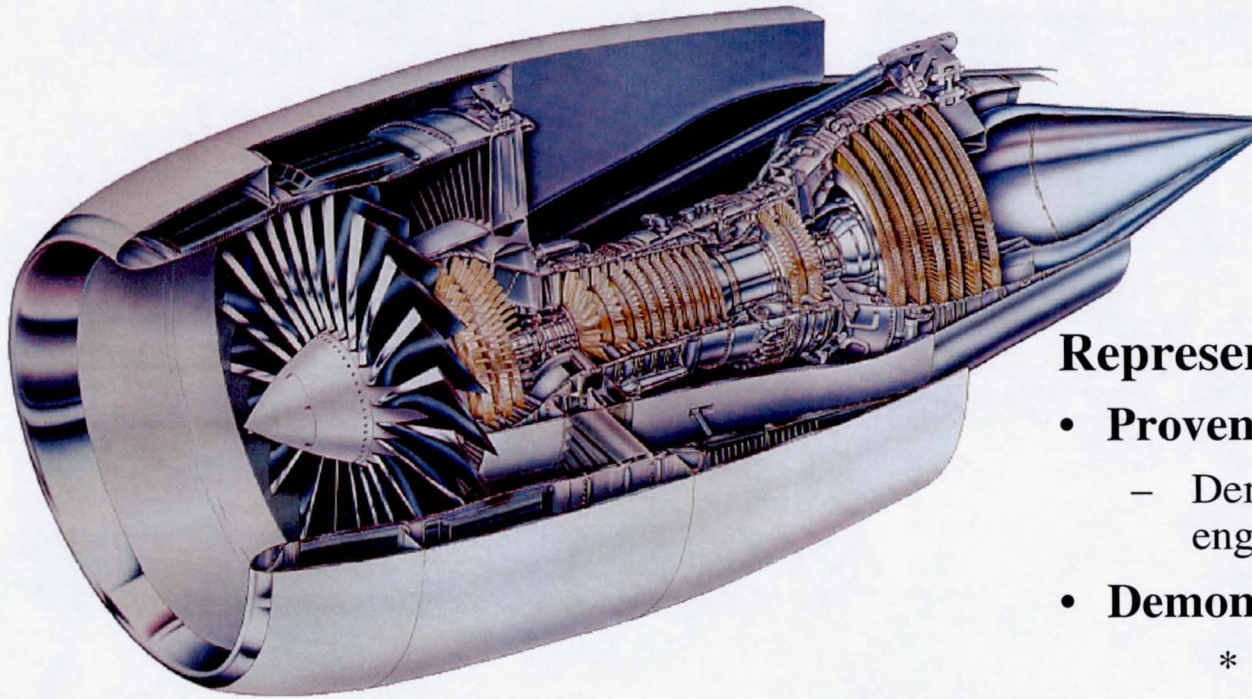
	Mechanism	Component	Velocity Dependence
Volume displacement 	Fluctuating Mass	Combustor	4th-power
Forces on the fluid 	Fluctuating Force	Fan, LPC, LPT	6th-power
Shear stresses 	Fluctuating Shear Stress	Fan, Jet, Boundary Layers	8th-power

Characteristic Velocity Is a Key Parameter In Determining Noise Source Strength – Reducing Jet Velocity is a Strong Driver For Reducing Engine Noise



Advanced Cycle & Core Technology Engines

The GE90



Represents the application of:

- **Proven technologies**
 - Demonstrated by CF6 and CFM56 engines
- **Demonstrated new technologies**
 - * Composite fan blades
 - * E³ 23:1 HP compressor
 - * Dual annular combustor
 - * High Bypass Ratio
 - * Fan Optimized for Low Noise
 - * Advanced Liner Designs
 - * High Bypass Ratio ~ 9:1
 - * Low Jet Velocities

*Unique GE90 Noise Technologies ...
London QC 0.5 at Arrival,
QC 1 to 2 at Departure*



Jet Noise Reduction Technology



Focus on Jet Noise Reduction Through Development of Mixing Enhancement Devices with Minimal Performance Loss



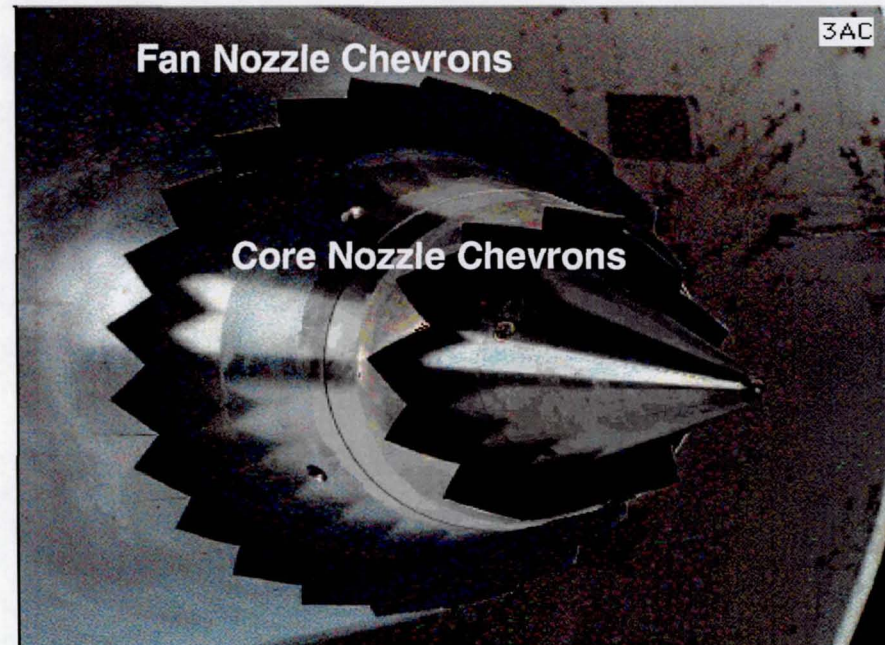
Advanced Chevron Exhaust Nozzles

Fan Chevrons with Core Alternating Chevrons

**Initial Concept Benefits
Demonstrated in NASA
AST-Sponsored Tests**

Work Continuing

- Increase Noise Reduction
- Scale model tests show modest improvements
- Minimizing performance loss is a significant challenge



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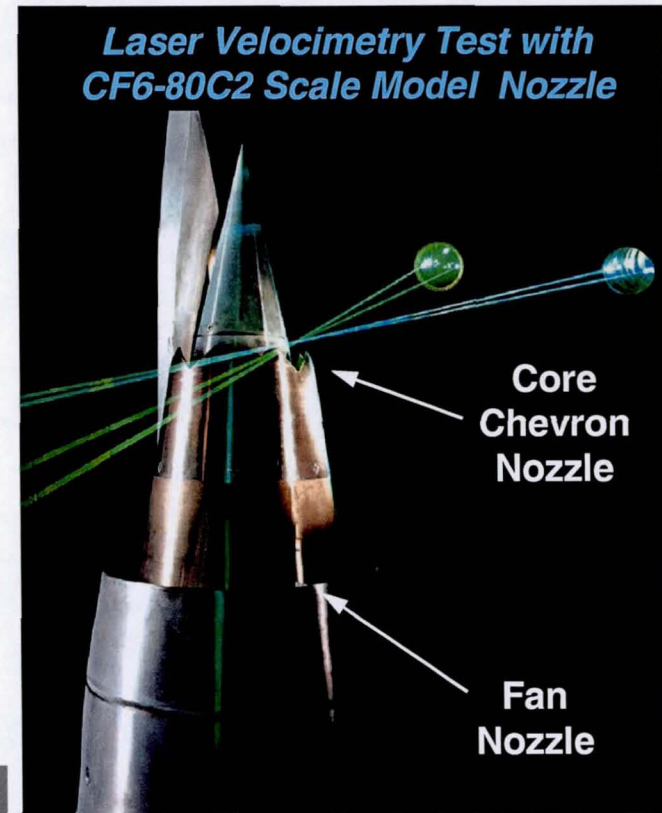
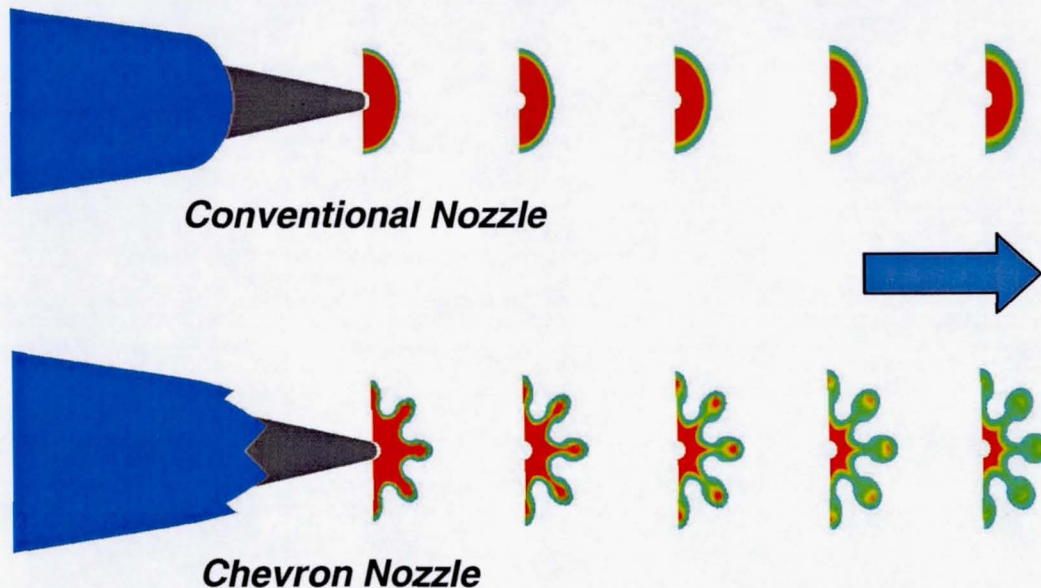
EX-1105 01-02

**Over 50 Chevron Nozzle configurations Tested in the GE Scale
Model Jet Acoustics (Cell 41) Facility**



Advanced Chevron Exhaust Nozzles

Chevrons Create Vortices Which Enhance Jet Exhaust Gas Mixing



Chevron Nozzle Development

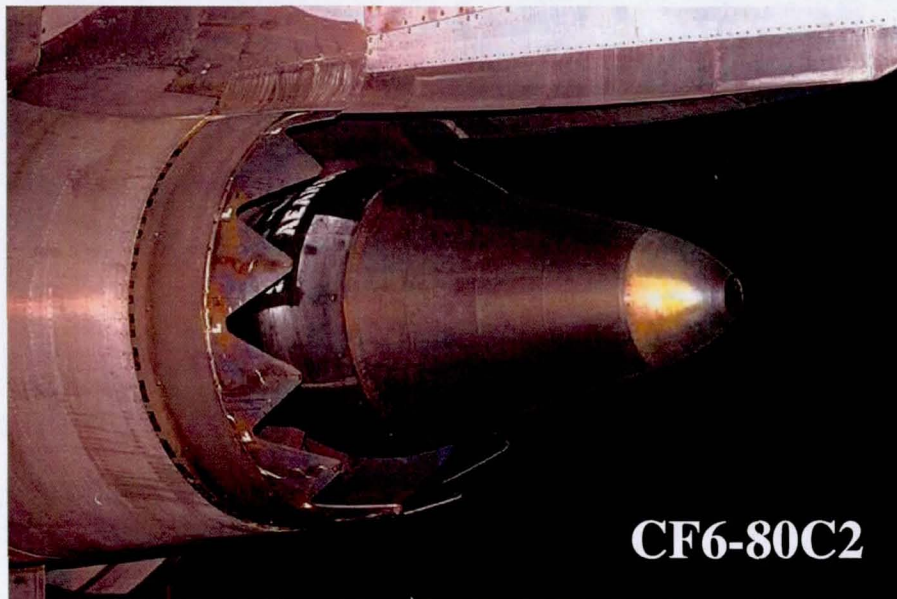
- CFD to rapidly screen potential designs
- High quality acoustics and performance testing for design optimization
- **Establish Link Between Flow and Noise**

Scale Model Acoustics and Performance Testing

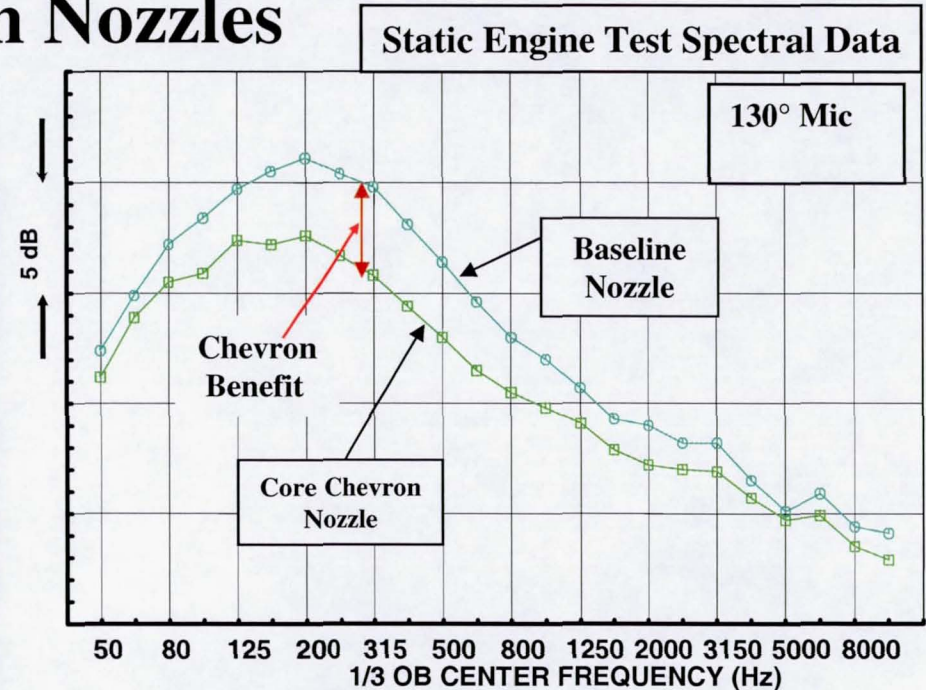


Validation on Full-Scale Engines

Static Engine Tests of Chevron Nozzles



CF6-80C2



Chevron Nozzle Benefits:

- Engine Tests Confirm Model Test Results
- Up To 2.5 EPNdB Cumulative System benefit for a BPR=5 engine
- Minimal Performance Impact



CF34-8C



Jet Noise Reduction Technology

Future Chevron Nozzle Development and Challenges

- **Second Generation Chevron Designs**

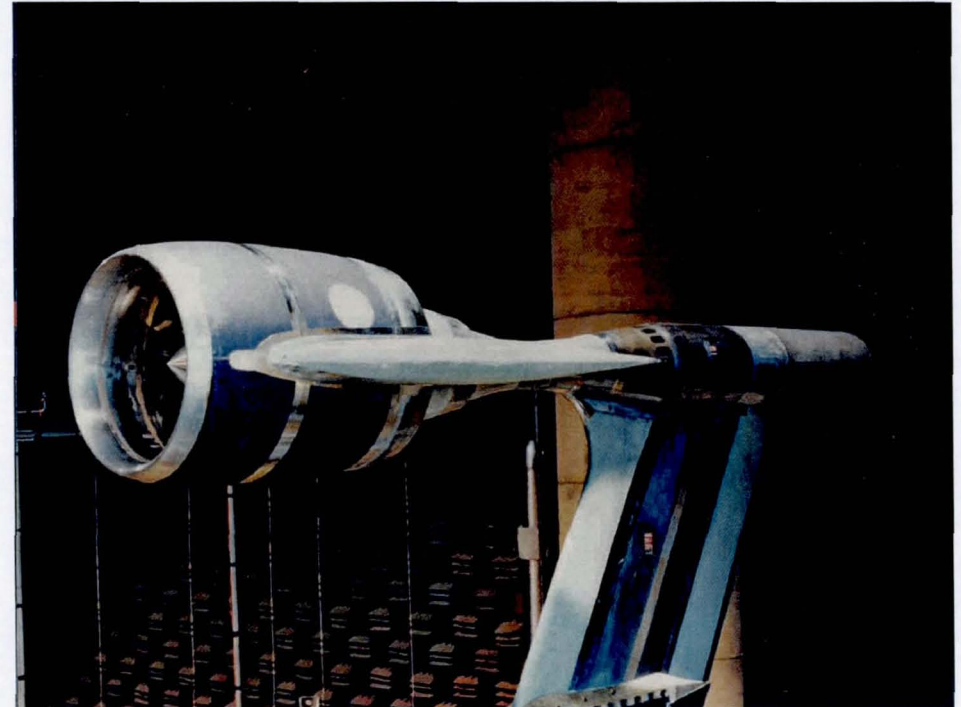
- A project has been initiated to develop effective Fan nozzle Chevrons
- Current Chevron designs have been optimized for engines with bypass ratios of ~ 6 and are less effective for higher bypass ratios cycles with lower jet velocities
- Work is underway to develop Second Generation Chevrons that perform well for high bypass ratio engines
- Development of low-loss Chevron Designs Underway
 - Smart Materials Chevrons
 - Fluidic Chevrons



Fan Noise Reduction Technology

Fan Noise Reduction Technology

- **GE Universal Propulsion Simulator (UPS)** has produced:
 - invaluable fan noise design database
 - improved aero/acoustic understanding of fan/OGV interaction
- **Recent NASA AST-Funded Tests:**
 - High Tip Speed CF6 type fans (HSF)
 - Source Diagnostic test of GE90 type fans (SDT)
- **Joint GE/Boeing UPS test of Growth GE90-115B Fans**
 - 3 Fan Rotor configurations
 - Acoustic liner Studies



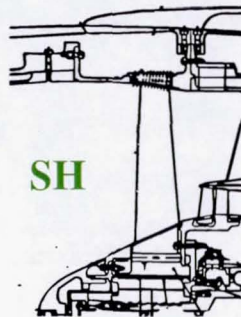
*The GE UPS is an Invaluable Tool for the Development
of Low Noise, High-Performance Fan Technology*



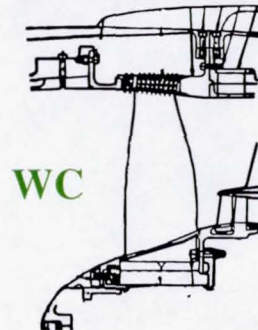
Fan Noise Reduction Technology

NASA AST High Speed Scale Model Fan Test

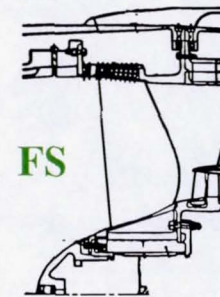
Rotors



34-Blade Shrouded Rotor
Baseline ~CF6-80E1



24-Blade
Wide Chord Radial Rotor



Forward-Swept Wide Chord Rotor
Allison Design

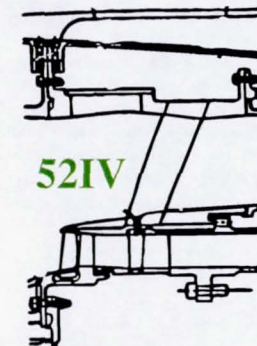
OGV's



80 OGVs - Modest Sweep
Baseline ~CF6-80E1



80 OGVs - Swept & Leaned



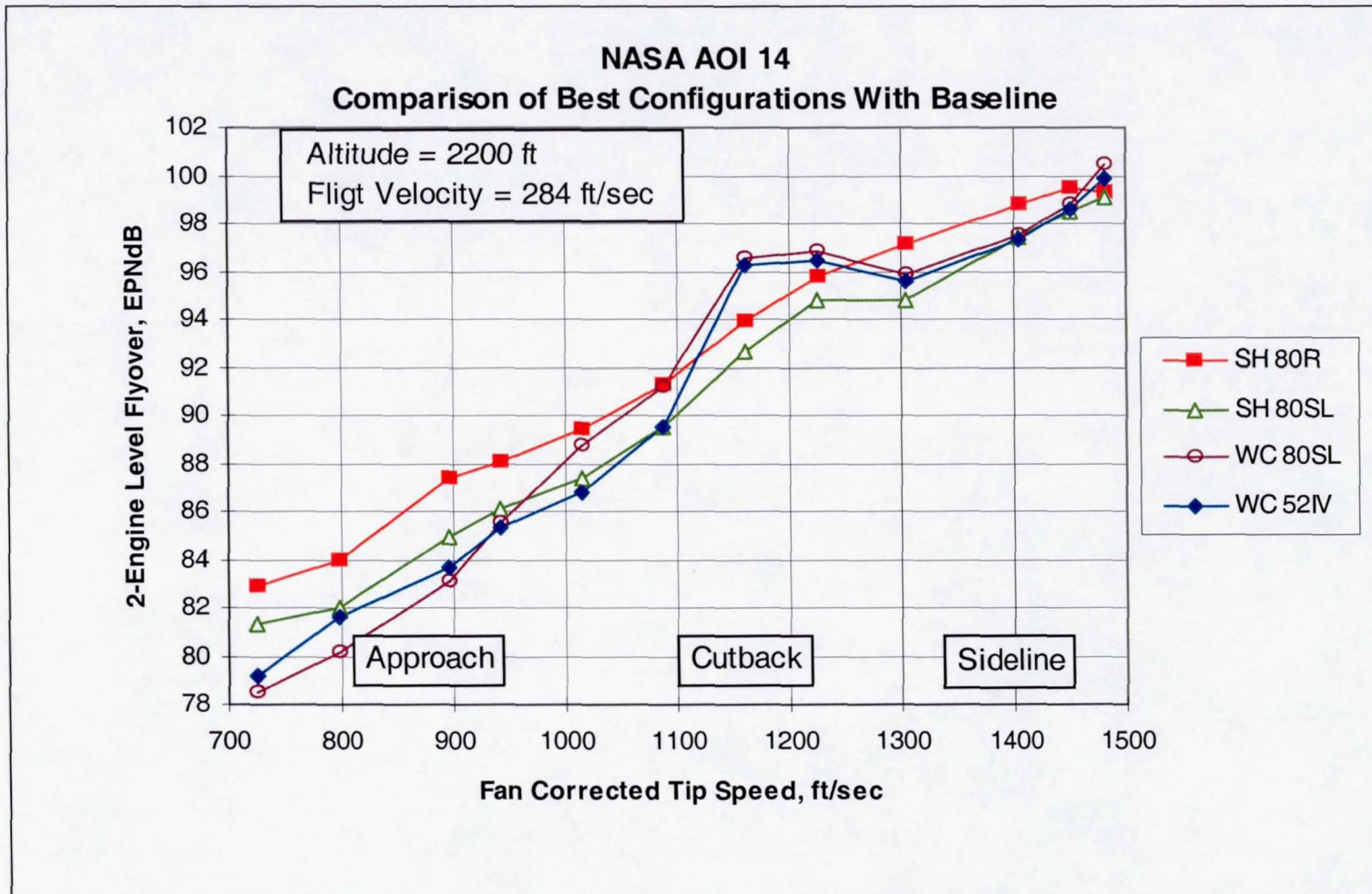
Integral Vane-Frame (52 Vanes)
a'la GE90

***CF6-Size Engine Swept & Leaned OGV Reduces Fan Noise by 3-EPNdB
Without Aerodynamic Performance Loss - Great Achievement!***



Fan Noise Reduction Technology

Best Configurations Comparisons - CF6 Size





Fan Noise Reduction Technology

Acoustic Benefits Summary (Fan Noise Only)

CF6 Size - Cumulative Margin Improvement

Rotor Type	WC	-3.8	-1.5	-3.4
	SH	0	Baseline	-5.0
	FS	-1.1	+3.7	-2.8
		52IV	80R	80SL
		OGV Type		



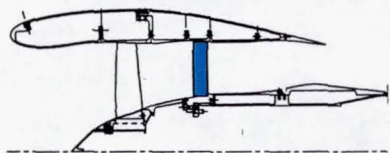
Fan Noise Reduction Technology

NASA AST Source Diagnostic Test

Two Rotor Designs:

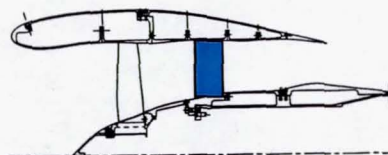
- R4 - Alternative to M4 (Early GE90 Design)
 - 1215 ft/sec Design Tip Speed
 - 1.5 Fan Pressure Ratio
 - 22 Blades
- M5 - Higher Speed Version of M4
 - 1350 ft/sec Design Tip Speed
 - 1.5 Fan Pressure Ratio
 - 22 Blades

Three Vane Designs:



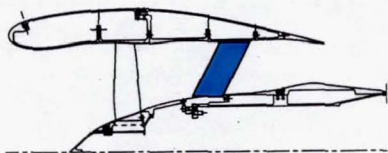
Baseline

- 54 Vanes, Integral Vane-Frame Design
- Cut off Blade Passing Tone
- Similar to GE90 Architecture



Low Vane Count

- 26 Vane Version of Baseline
- Low Vane Count Introduced to Reduced Broadband Noise
- Cut on Blade Passing Tone



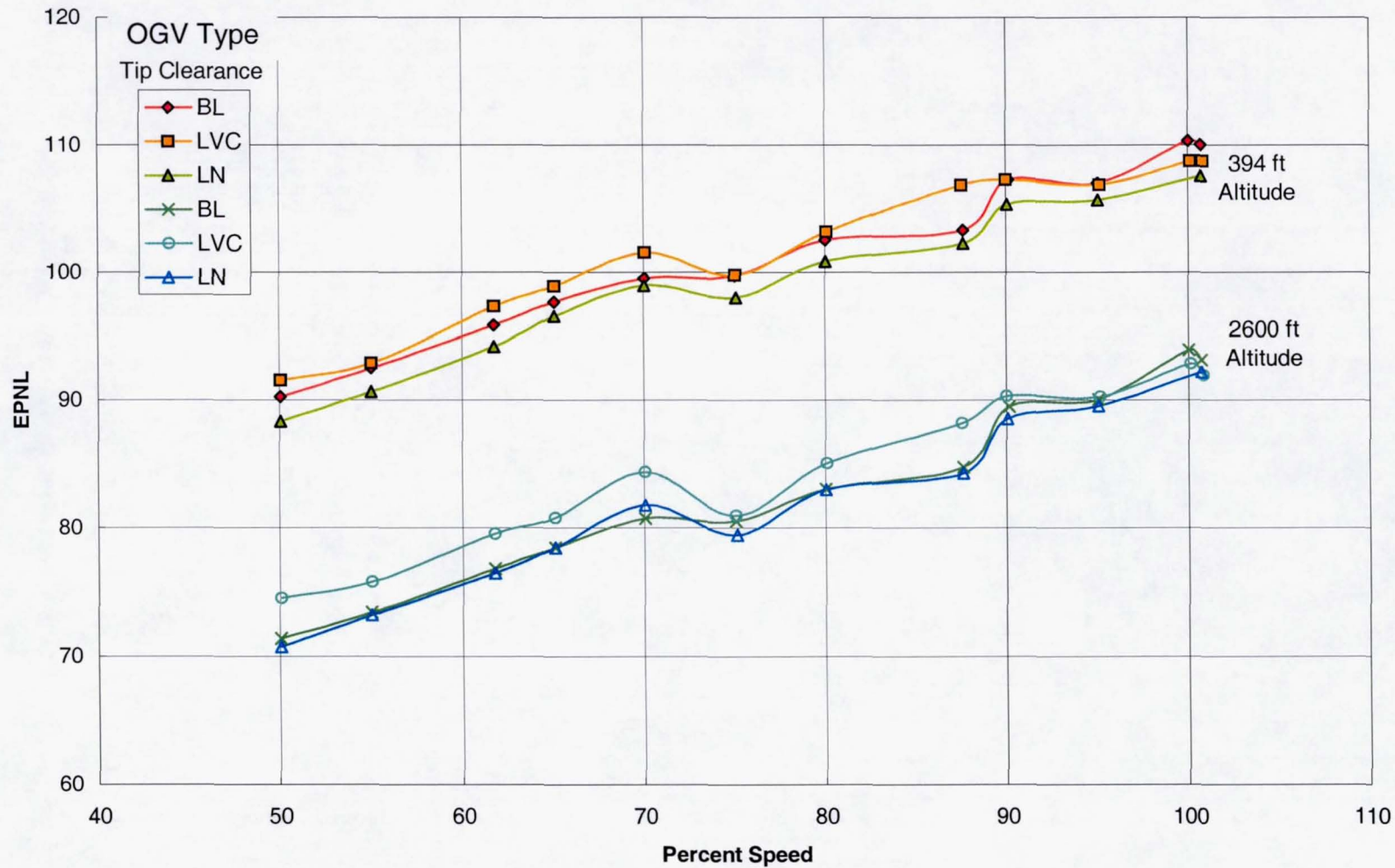
Low Noise Vane

- 26 Vanes Swept Version of Low Vane Count
- Cut on Blade Passing Tone
- Sweep Introduced to Reduce BPF



Fan Noise Reduction Technology

Effects of OGV Design - R4 Blade
Nominal Tip Clearance
Scaled to Full Size





Fan Noise Reduction Technology

Acoustic Benefits Summary (Fan Noise Only) Full Size - Cumulative Margin Improvement

Rotor Type		OGV Type		
		54BL	LVC	LN
R4	Baseline	+2.5	-4.5	
M5	+1.0	-1.8	-2.9	



Fan Noise Reduction Technology

Noise Reduction Technology for Growth GE90

***Development of Fan Noise Reduction
Technologies through Scale Model Fan/Nacelle
Wind Tunnel Demonstration and
Prediction/Design Tool Validation Tests***



Fan Noise Reduction Technology

Joint Boeing/GEAE UPS GE90-115B Acoustic and Performance Testing in Boeing LSAF

Acoustic Evaluation Of Three Different Fan Blade Types



**Fwd
Swept**



**High Flow
Swept**



Radial



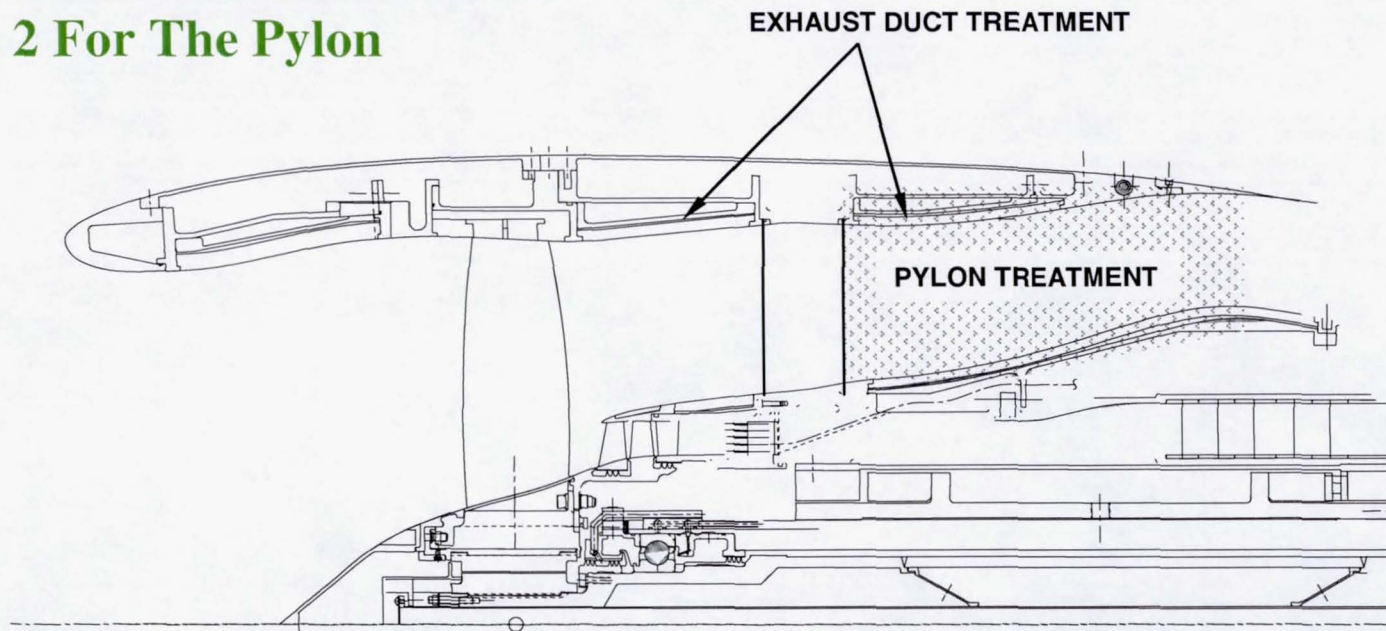


Fan Noise Reduction Technology

Joint Boeing/GEAE UPS GE90-115B Test in Boeing LSAF

Test Evaluation of Acoustic Treatment Designs:

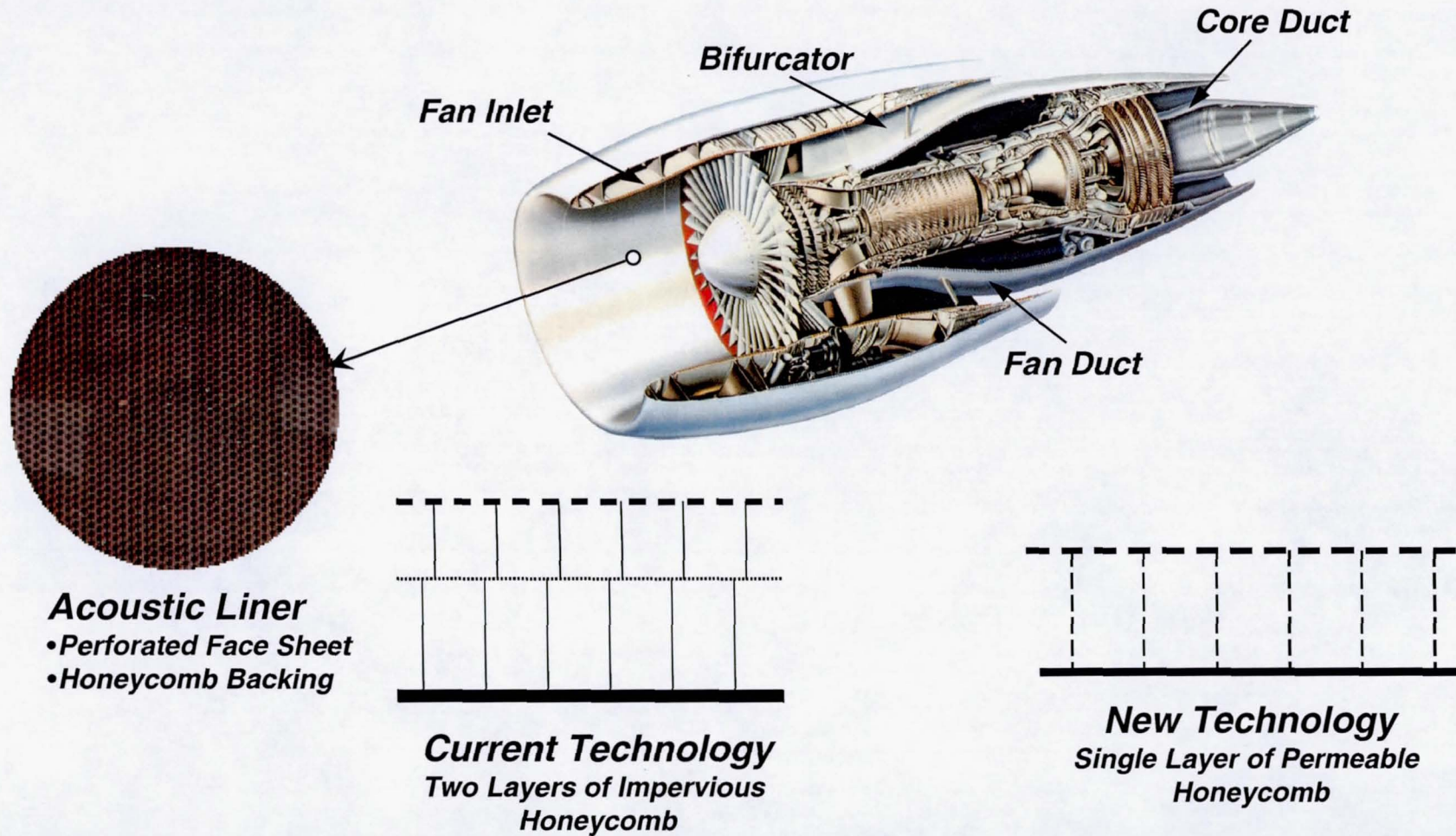
- 3 For The Exhaust Duct
- 2 For The Pylon



**Data Used to Optimize the GE90-115B Treatment Design
and Validate Treatment Design Tools**



Acoustic Liner Technology



New Acoustic Liner Technology Promises Improved Noise Suppression & Reduced Manufacturing Costs

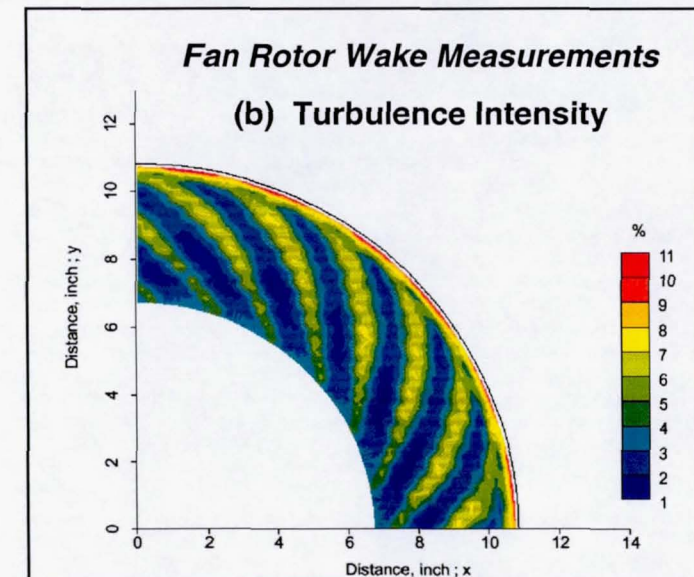
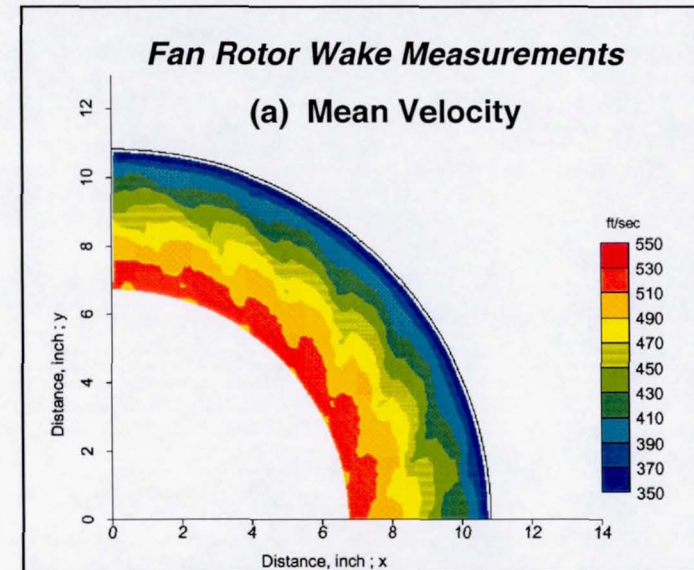


Fan Noise Reduction Technology

Advanced Tools Development

Establish linkage between fan flow field and noise through:

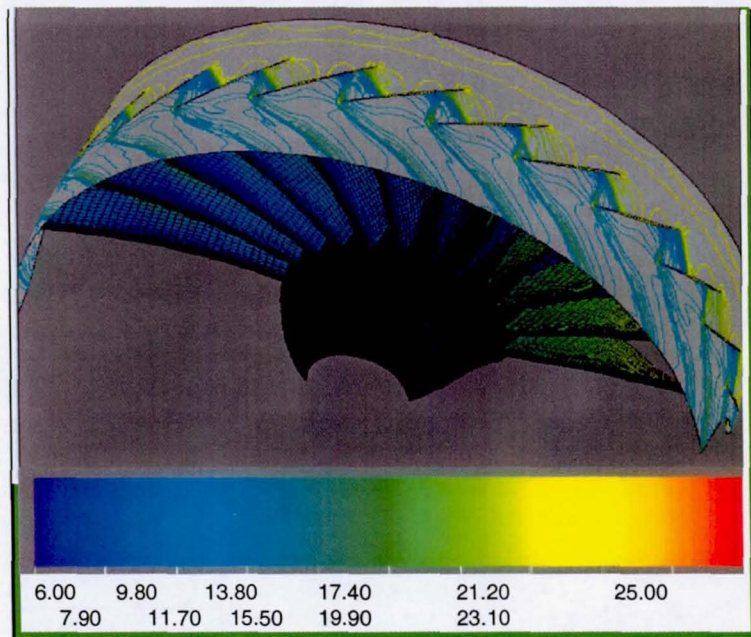
- Diagnostic Flow Field Measurements
- CFD Analysis
- Advanced Aeroacoustic Computational Modeling
- Validation With High-Quality Controlled Experimental Fan Data





Better Codes & Databases for Acoustic Design

Fan & Nacelle Noise Evaluation Tools



Aeroacoustic Computer Codes & Models



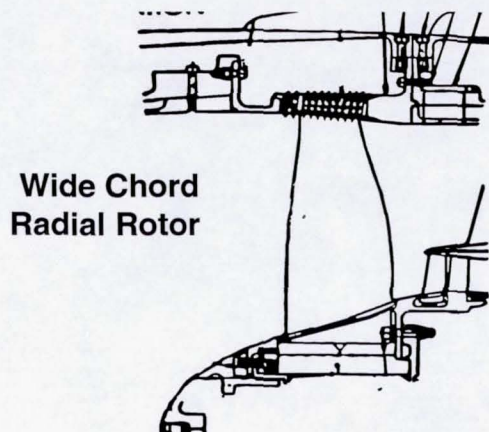
Scale Model Fan Test Vehicle

Scale Model Testing Validates Analysis Prior to Full Engine Test

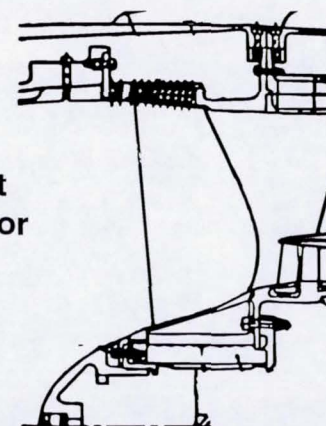


Better Codes - MPT Noise Analysis

Multiple Pure Tone Noise Analysis

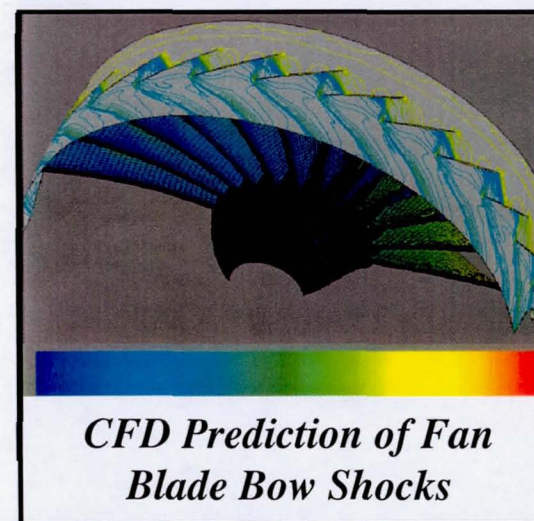
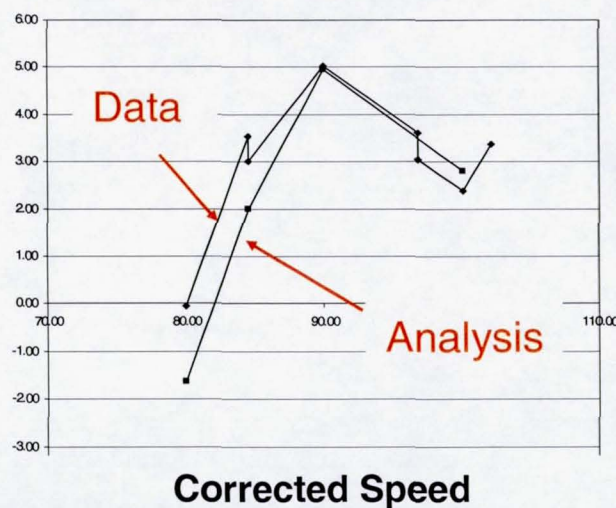


Wide Chord
Radial Rotor



Forward-Swept
Wide Chord Rotor

Delta MPT Noise
Radial - Forward Swept
Wide Chord Rotor

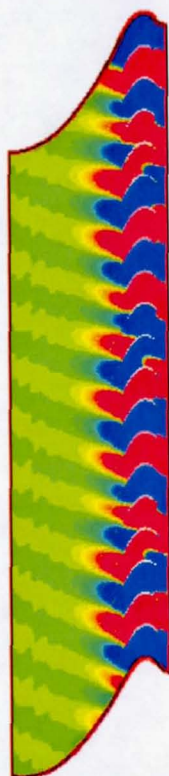


**CFD-Based Analysis Method Developed in AST Program
Being Used to Assess Fan Designs for MPT (Buzzsaw) Noise**



Better Codes - Turbine Acoustic Analysis

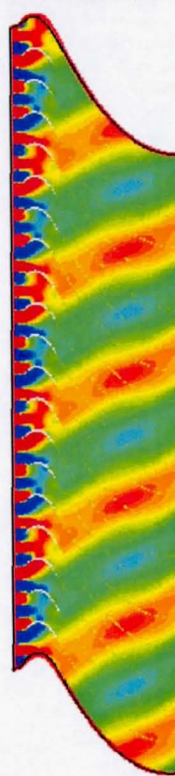
50 Vanes
120 Blades



20 Blade
Passages
(1/6 Wheel)

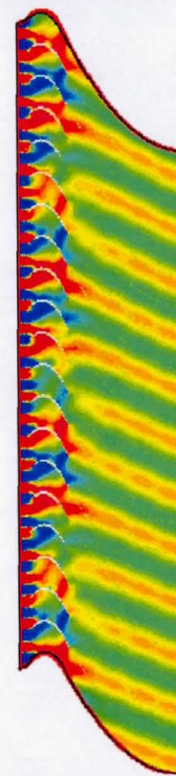
All Acoustic Modes
Cut-Off

150 Vanes
120 Blades



Fundamental
Number Blades - Number Vanes
Mode Cut-On

170 Vanes
120 Blades



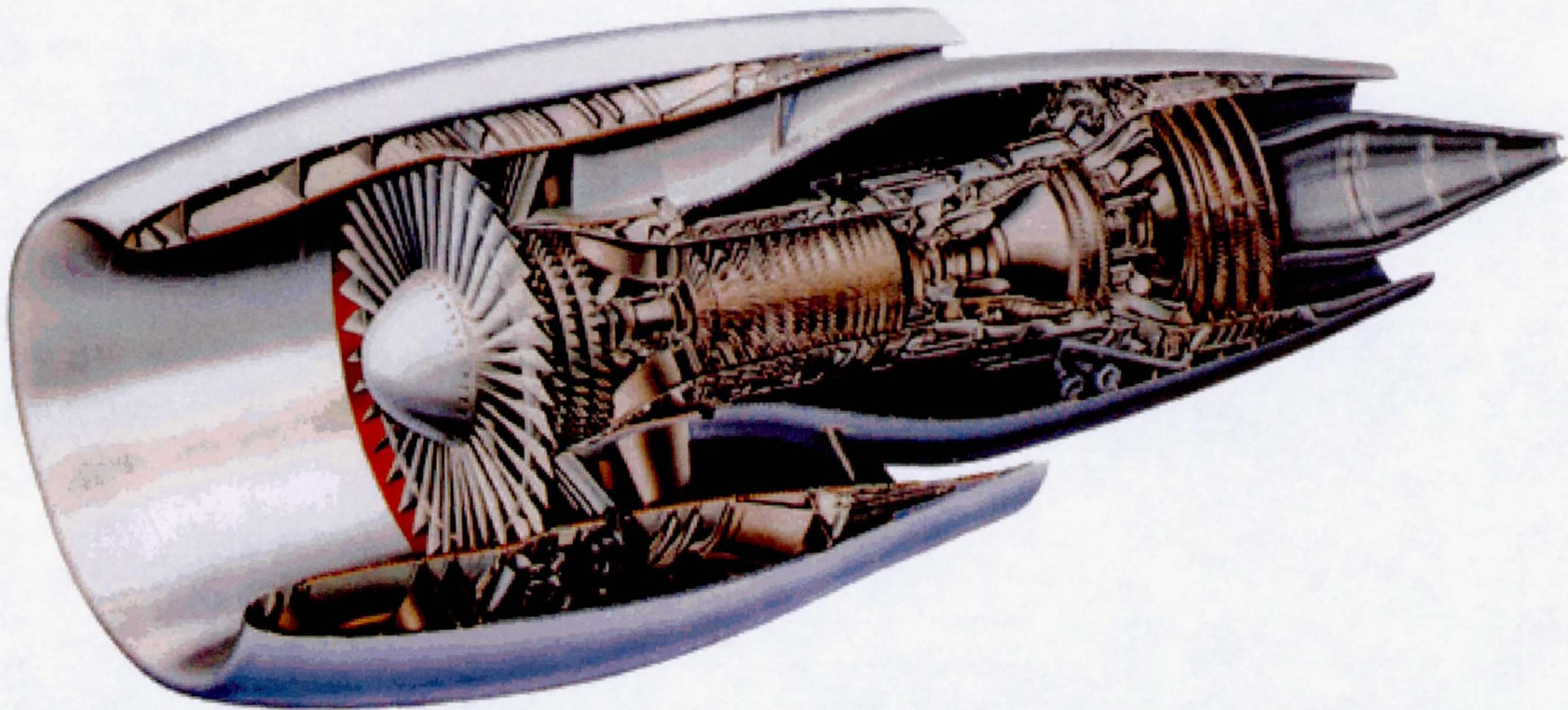
Higher Spatial Harmonic
 $2 \times \text{Number Blades} - \text{Number Vanes}$
Mode Cut-On

**3D CFD Being Used to Assess Acoustic Cut-off
for LP Turbines**



In-Service Engine Noise Upgrade Packages

Noise Reduction Upgrades Under Study For CF6-50-Powered Aircraft

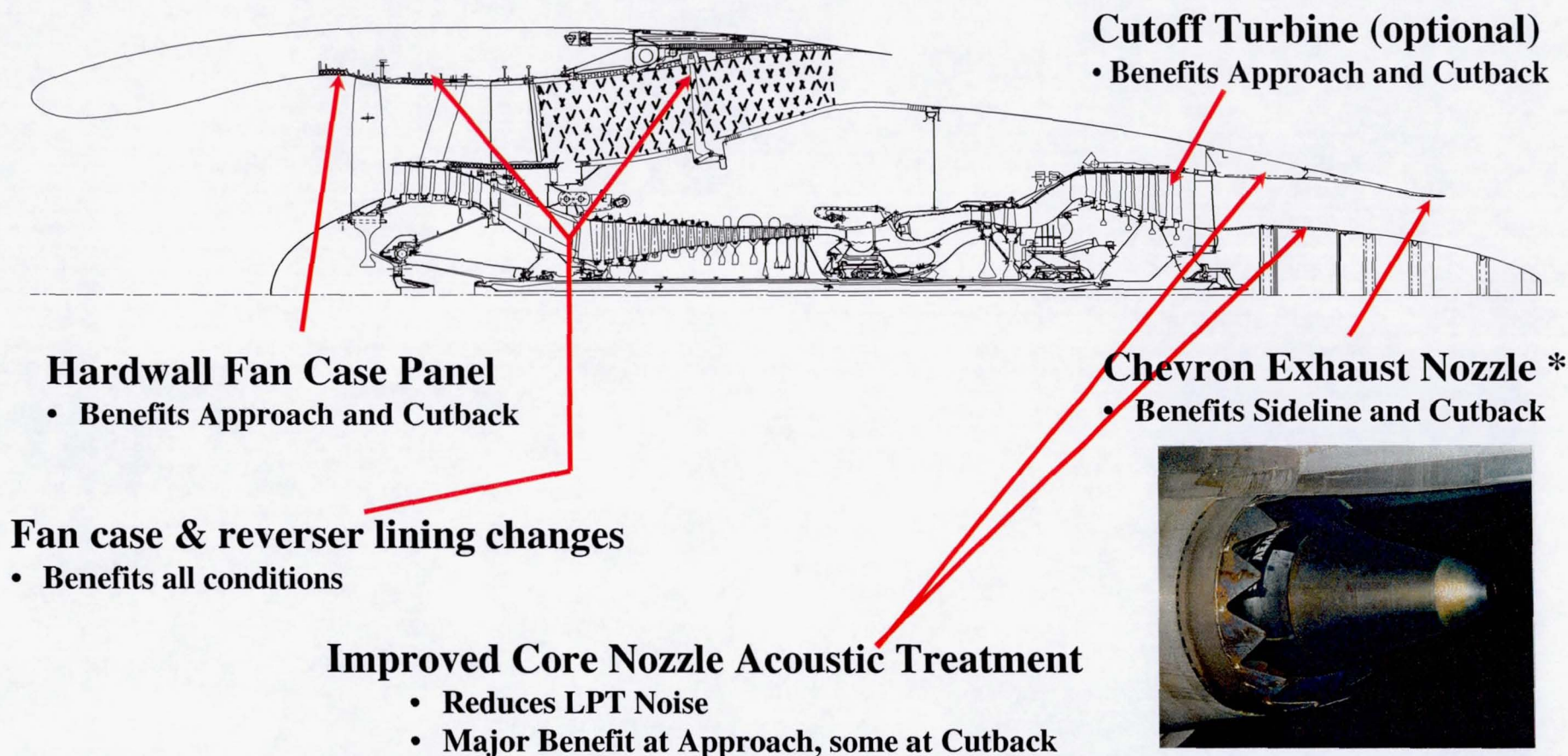


Evaluations of the noise reduction packages shows the ability to achieve Chapter 3 with 5 EPNdB Cumulative Margin



In-Service Engine Noise Upgrade Packages

*Potential Noise Reduction Upgrades
For CF6-50 Powered Aircraft*



Upgrade Package Will Improve Noise Margin at All 3 Certification Points



Engine Validation

Noise Reduction Technology Validation



Engine Noise, Noise Reduction Features, and Diagnostic Measurements Evaluated at GE's Peebles, Ohio Outdoor Acoustic Test Site



Engine Validation

Noise Reduction Technology Development

*Barrier Testing to Isolate
Engine Sources, Evaluate
Noise Reduction Concepts*

- *Jet Noise*
- *Fan Noise*
- *Combustor Noise*
- *Turbine Noise*
- *Liner Suppression*



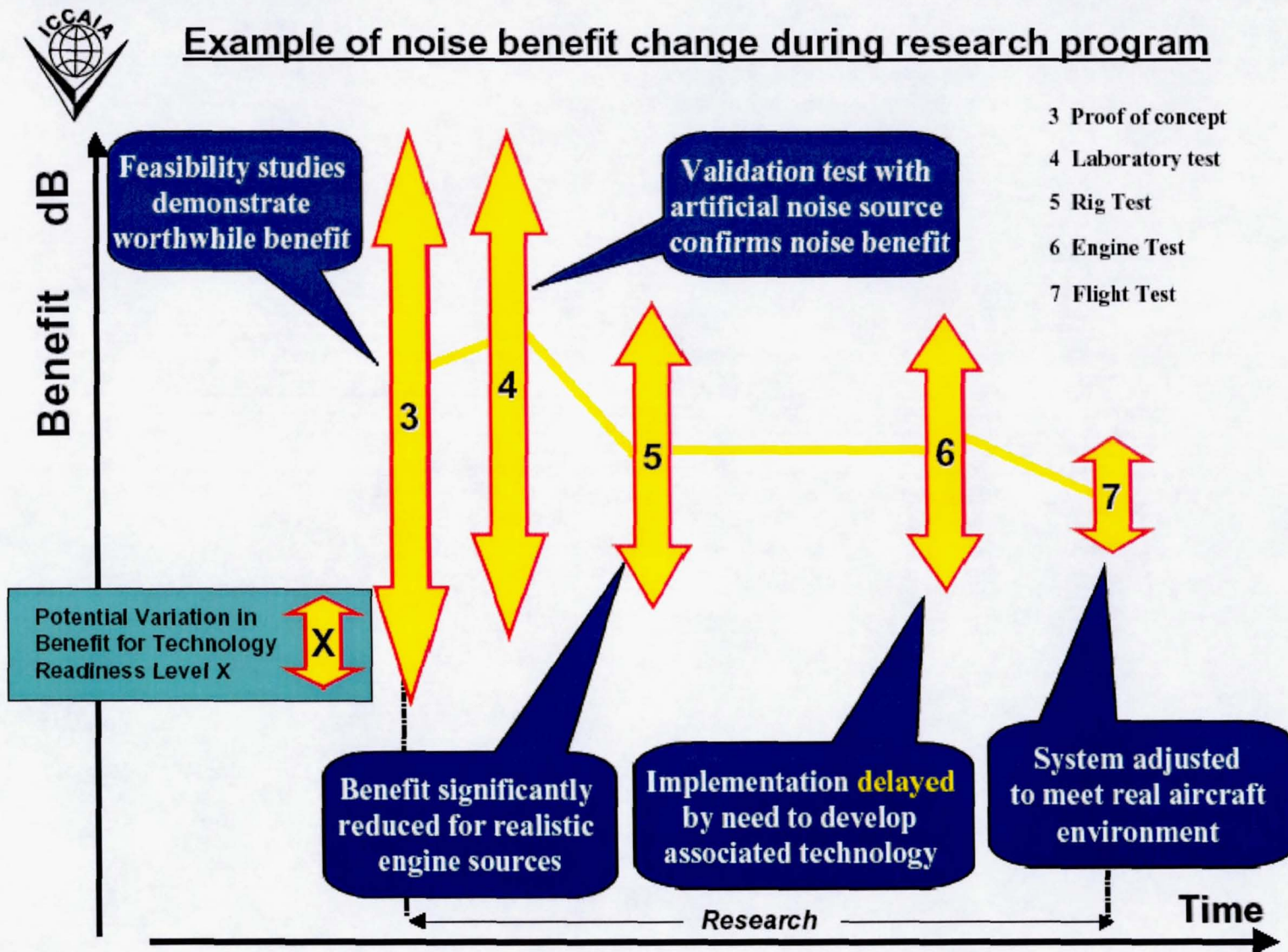
**Swept/Leaned OGV Design
Tested On CFM56 Engine**



**Chevron Nozzle Tested
on CF6 Engine**



Noise Reduction Technology Transition





AST Noise Reduction Technology

Summary & Future Prospects

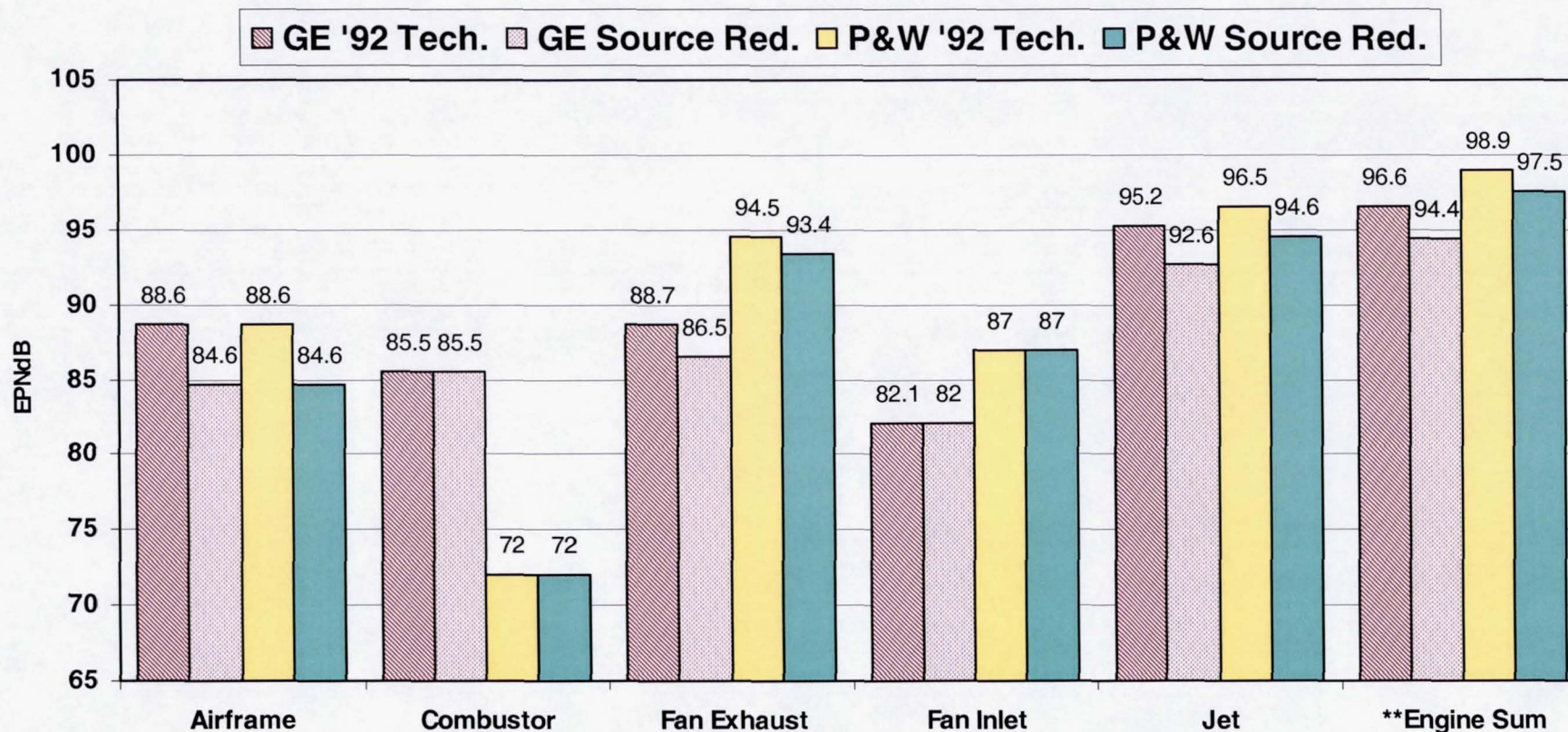
- **Considerable Progress Has Been Made in Noise Reduction Technology**
- **New Products likely to Have “GE90-Like” Cycles - an inherent noise advantage**
- **Some concepts are maturing - Chevron Nozzles, Advanced Inlet Acoustic & Exhaust Treatment, Swept Vanes - available for potential application to existing products and product derivatives**
- **Introduction of noise reduction technologies takes time:**
 - **Concept Demonstration to production readiness - 5+ years**
 - **Realization - Some Benefit is lost in the transition - 20 to 25%**
 - **Time for new products to significantly penetrate the fleet and have a significant community noise impact**
- **New Concepts/Technologies Have to be Mature and Cost Effective!**
- **Future Focus - Noise Reduction Technologies which provide benefits to both Industry and the Environment**



Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Engine Noise Reduction for Large Quad - Sideline
Comparison of GE and P&W Studies, BPR=5, Source Reduction Only
(Tabs/Chevrans, Swept Stators)

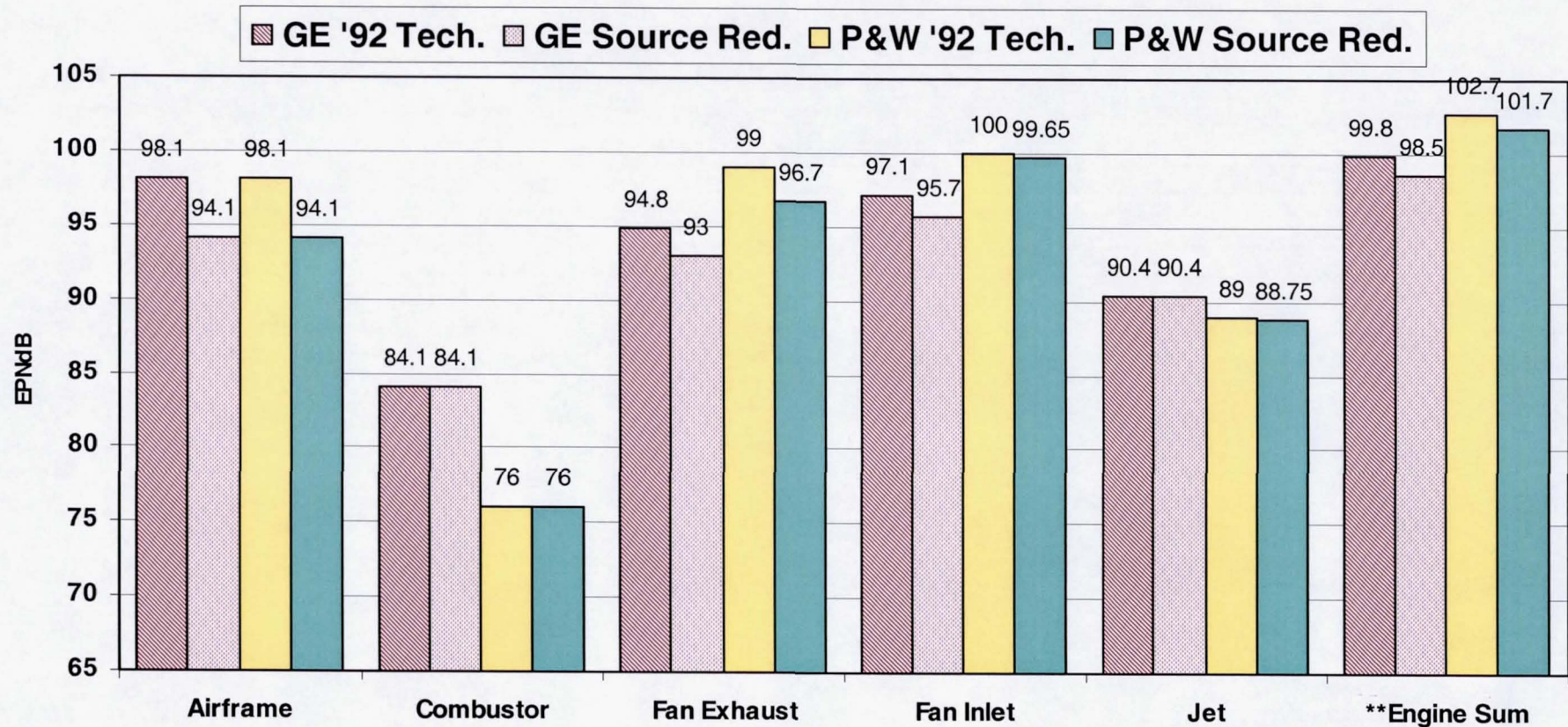




Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Engine Noise Reduction for Large Quad - Approach
Comparison of GE and P&W Studies, BPR=5, Source Reduction Only
(Tabs/Chevrons, Swept Stators)

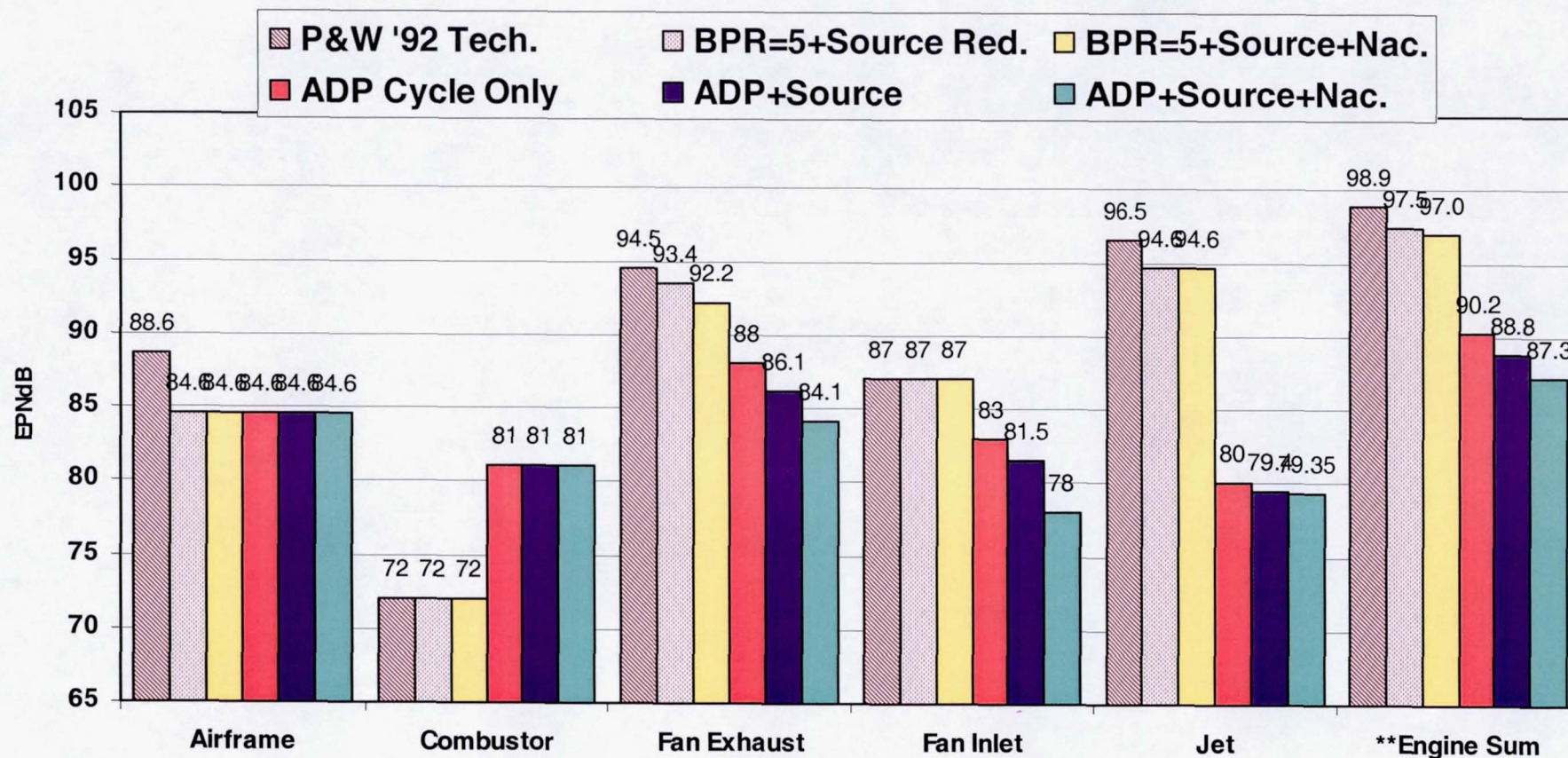




Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Engine Noise Reduction for Large Quad - Sideline Results From P&W Study





Engine Noise Reduction

Aerospace Vehicle Systems Technology Program

Engine Noise Reduction for Large Quad - Approach Results From P&W Study

